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Robustness assessment of link capacity reduction for complex networks: Application for public transport systems

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ABSTRACT

Network robustness refers to as the capacity to absorb disturbances with a minimal impact on system performance. Notwithstanding, network robustness assessment has been mostly confined to the analysis of complete link breakdown based on topological metrics. We propose reliability indicators that encompass changes in network performance with respect to the entire range of possible capacity reductions. Link criticality and degradation rapidity are measured by constructing network degradation curve that describe the relation between local capacity reduction and global change in network performance. We develop a public transport robustness assessment model which computes passenger flow distribution and network performance metrics under planned capacity reductions. The model is applied to the urban rail-bound network of Amsterdam. Link criticality and degradation rapidity are studied by performing a full-scan impact analysis which demonstrates how the robustness indicators introduced in this paper contribute to a more complete assessment of network robustness.

1. Introduction

Social-technical systems are subject to man-made, technical and natural disruptions. Systems are considered robust based on their capacity to absorb disruptions with a minimal impact on system performance. The performance can be measured in terms of the worst affected component, total transmission costs or the extent to which the system has disintegrated (e.g. size of the largest sub-network that remains connected). Even though robustness of critical infrastructures such as mass public transport networks (PTN) is high on the planning and policy agenda [22], there is lack of knowledge on how to assess and quantify network robustness towards a range of possible disruptions. While disruptions of critical infrastructure are often limited to a partial reduction in link transmission capacity, most research has focused on complete link breakdown (i.e. link removal) with few noticeable exceptions [10,35]. The analysis performed in the latter does not allow for a network robustness analysis because it either did not propose a method to integrate information from various link-level capacity reduction scenarios or did not perform a full-scan network analysis.

A system can be considered robust with respect to disruptions on a certain component if minor disturbances of its performance do not have severe consequences on the overall system performance, i.e., when overall travel time reliability remains constant under minor capacity reductions. Hence, robustness is not merely based on the magnitude of the ramifications of a complete breakdown but should also refer to the trajectory that describes how different disruption severity influence severity in network degradation. The latter provides information on the overall range of values and the sensitivity of network performance to alterations in the performance of individual network elements. The commonly asked question who is the weakest link becomes thus multi-dimensional and requires expanding our toolset for quantifying network robustness.

The primary objective of the current study is to propose reliability indicators that encompass changes in network performance with respect to the entire range of possible capacity reductions and can be used in a wide range of domains. To this end, two robustness indicators are conceptualized and formulated by constructing performance curves to allow quantifying the absolute change and the first moment of the degradation in network performance as a function of link capacity reductions. This study contributes to the state-of-the-art of network robustness by enabling the quantification of network robustness in terms of network transmission losses for the range of possible capacity reductions. The analysis of these indicators allows identifying the extent and the relation between capacity reduction and performance reductions and thus support infrastructure management and capacity allocation. The indicators are demonstrates in the context of PTN, where network performance

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under disruptions is modelled using a passenger load (re-)distribution model. The impacts of disruptions on the robustness of PTN have long been an understudied topic, in particular in the context of partial degradations.

Assessing the impact of different capacity reduction scenarios on the robustness of the PTN is not only important for efficiency reasons, but also for reliability and safety considerations. Various capacity-related definitions of network reliability were proposed in the literature for road networks [2,12,13,32,35]. Some of these definitions can be transferred to the public transport domain when measuring day-to-day travel time variations. For example, planners can monitor whether during planned maintenance periods the reliability of individual lines or indeed the whole PTN stays within a certain margin in relation to normal operations. Alternatively, a probabilistic notion of network reliability performance can refer to the probability that the network can accommodate a certain traffic demand at a pre-defined desired service level.

Most related work on safety assessment of (public) transport systems focuses on system-level analysis [17,26,27,34]. Only limited work has been done on the relation between (link) capacity reduction and safety. It is expected that different maintenance plans will have a different impact on the reliability, safety and associated costs for a public transport network. It is for example expected that a full closure of a link will be safer for maintenance crews, but will have a larger effect (per time unit) on the workings of the rest of the network. Another aspect that might be relevant in this context is that of vehicle operators: slower moving metros and trams, i.e., with reducing the capacity on a line, can be expected to lead to fewer errors [39] as operators have more time to react to unexpected events.

Even though public transport constitutes critical infrastructure in many urban and regional transport systems, only little is known about the determinants of its vulnerability and methods and techniques to analyse and mitigate the impacts of disruptions. The vast majority of previous studies focused on road networks [13,46], the degradations of its physical infrastructure and its evaluation [32,47,49]. While these studies provide some relevant conceptual foundations, the vulnerability analysis techniques have only limited transferability to public transport. PTN are characterized by greater complexity due to the relation between the infrastructure and service layers. In the context of PTN, the nonlinear properties of network effects and probabilistic flow distribution may result in non-trivial relations between the magnitude of the failure and its consequences.

The ability of PTN to maintain their function under circumstances which strongly deviate from plan is essential to their robustness. PTN are prone to recurrent disruptions, ranging from mechanical and technical problems (e.g. vehicle breakdown, switch failure) to traffic accidents and suicide attempts [11]. Many of these causes, in addition to planned construction and maintenance works, result with limited traffic capacity. The performance of the rail-bound Amsterdam network in the case of planned capacity reductions is thereof selected to demonstrate the proposed indicators and the insights gained by their measurement.

Different kinds of planned capacity reductions are performed by system managers in urban public transport networks. These reductions can vary from a reduced speed or frequency on a link to a full link closure due to maintenance routines or in conjunction with construction works. In some cases, project manager can trade-off between the extent of capacity reduction and its duration. However, there is lack of knowledge on the impacts of such decisions on passengers' travel costs, including the consideration of rerouting possibilities and disconnected passengers.

The remaining of this paper is organized as follows. The following section reviews related work on alternative approaches to measuring network performance and distinguishing between four types of network robustness measures. Two robustness indicators, *link criticality* and *degrading rapidity,* are proposed, formulated and illustrated in Section 3. A general network robustness assessment procedure and its specification for an application to public transport systems is presented in Section 4 along with the passenger flow distribution and the calculation of network performance metrics. Section 5 details the application of this model to the urban rail network in Amsterdam including the experiment set-up and the statistical and spatial analysis of the proposed robustness indicators. The paper concludes with a discussion of study implications and directions for future research.

2. Related work

There is a large body of related work on network robustness. This section provides an overview of the main approaches found in the literature, starting by considering network performance indicators followed by examining network robustness indicators.

2.1. Measuring network performance

Network performance indicators aim at quantifying the functioning of a network, allowing the comparison of different conditions or configurations of the same network, or different networks altogether. Network performance indicators can be categorized into three main groups of studies, with an increasing level of detail: infrastructures studies, service network studies and flow distribution studies.

The network performance indicators used in infrastructure studies are, in general, topological indicators based on graph theory. The network performance in these studies is, for example, expressed in terms of global connectivity expressed as the minimum number of links that needs to be removed to disconnect the remaining nodes from each other [3,36], the largest connected component of the network [38] or changes in accessibility [24]. These indicators are referred by Faturechi and Miller-Hooks [19] as topological measures of effectiveness (MOE). Such purely topological infrastructure studies and corresponding indicators neglect the state of the networks in terms of saturation and flow distribution. The advantage of such indicators is that they can be applied to a wide variety of networks. The main disadvantage is that they only consider topological indicators and thus cannot, for example, differentiate between a network with congestion and the same network without congestion. When considering PT networks, infrastructure indicators discard the notion of lines and corresponding service network characteristics for which the same disruptions can have different effects on the network performance. For example, using a topological approach, a link breakdown results with remaining links operating normally although in practice upstream and downstream links of the same line will be affected.

When the state of the network is considered, more detailed analysis of the performance of the network is possible. Public transport studies that include the service network define different transport lines which are superimposed on top of the physical infrastructure. The representation of both topological and service layers allow to consider transfers, link travel times and line waiting times. The network performance can then be measured as the mean travel time between all the OD-pairs or the mean number of transfers over all the OD-pairs. Berche et al. [3] for example represented the largest metro networks in the world using both an infrastructure representation as well as a service network representation and examined the effect of random attacks on the performance of the network. They expressed the effect in terms of the change in the size of the largest cluster and the average inverse mean shortest path length. Another example by Ellens et al. [16] considers the effective resistance between all pairs of vertices in a power grid, leading to the notion of effective graph resistance, which allows the analysis of robustness of a power grid without looking at the actual power flow.

The most detailed network indicators also consider flow and link capacity [33], making it possible, for example, to study flow distribution and congestion in networks. Such indicators always need to take the physical infrastructure into account, which makes them more detailed but also less widely applicable. Examples of networks, other than transport networks, that have been studied using more specific perfor-