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Recovery time and propagation effects of passenger transport disruptions

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HIGHLIGHTS

- A method to evaluate public transport network vulnerability.
- Using a non-equilibrium dynamic transit operations model.
- Modelling and quantifying temporal and spatial spillover effects of disruptions.
- Effects on network saturation and network recovery time are evaluated.
- The method is applied to the case of Stockholm rapid public transport system.

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ABSTRACT

We propose a method to evaluate public transport network vulnerability. We study the evolution of the passenger Volume Over Capacity (VOC) ratio throughout the network to measure the spatial and temporal extent of the impacts caused by an unplanned service segment disruption. The VOC ratio provides an indication of the on-board travel comfort, an important level-of-service indicator, as well as reflects the residual capacity for absorbing additional demand. Because of the dynamic nature of public transport systems, disturbances propagate through the network in both time and space. Our modelling approach is able to capture transit system dynamics and quantify the extent to which the network exhibits spillover effects. We apply the method to the case of the rapid public transport system of Stockholm Sweden We demonstrate how the changes in network saturation and the corresponding recovery time can be quantified.

1. Introduction

Society relies on the supply of a number of critical infrastructure systems – such as electric power, water supply, communication and information networks – which have become gradually more complex and interdependent. If the performance of one of those systems is reduced considerably, society can suffer extremely severe consequences. The transport system is critical for societies in developing and developed countries as it enables the movement of people and goods between origins and destinations.

The research field related with the risk of severe transport network disruptions and their impacts is generally called vulnerability analysis. The term "vulnerability" refers to the susceptibility of a system to experience severe performance

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impacts in consequence of exceptional disruptions, unlike ''unreliability'' which refers to inherent and recurrent performance variations. ''Robustness'' is the antonym of vulnerability and therefore describes the capability of a system to absorb shocks and withstand disruptions. Taleb [1] suggested that systems should aspire to become anti-fragile by getting more robust, i.e. more able to cope with shocks, rather than aim for a rigid design that prevents shocks from occurring altogether. While both vulnerability and robustness refer to the consequences of disruptions on network functionality once they occur, ''resilience'' demands also a rapid recovery back to normal operations and performance [2]. Resilience analysis must thus consider the deterioration of system functionality and performance caused by an initial negative event, ''incident'', which may provoke consequences beyond the specific location and time at which the incident occurs. For example, on January 18, 2018, gusts of up to 140 km/h have caused the cancellation of the majority of trains in the Netherlands, more than 6 h after the adverse weather conditions were encountered. Hence, the notion of network resilience calls for the analysis of system dynamics and the development of advanced methods for representing supply and demand time-dependency and analysing network flow (re-)distribution in the event of a disruption.

This study focuses on public transport networks, which is a fundamental component of transport systems. Because of the growth in population, travel demand and motorization, traffic induces growing externalities such as increasing congestion and negative environmental impacts. Public transport may alleviate some of the negative consequences of mobility. However, to be an attractive alternative for travellers, it must be able to withstand or quickly recover from disturbances such as infrastructural and vehicular malfunctions. Knowledge about the distribution and magnitude of the impacts of potential service disruptions is crucial to effectively allocate resources for the prevention, mitigation and restoration of disruption of public transport services. A large variety of incidents may afflict public transport systems: they could be unexpected, provoked voluntarily or involuntarily by men or triggered by natural phenomena. They may span from adverse weather to terror attacks, technical failures, strikes or the breakdown of physical components.

Public transport network vulnerability has been often studied in terms of network topology. In these studies, the public transport system is represented as a graph where nodes, corresponding to stations or stops, are connected by links which represent service segments [3,4]. Disruptions are then simulated by removing graph's elements (nodes or links) randomly or by means of ''directed attacks'', i.e. selecting and deactivating links or nodes according to different centrality measures, such as the highest degree or betweenness centrality [5]. After each removal, vulnerability is evaluated in terms of the decrease in network's performance, measured as the change of some selected topological and connectivity properties. For example, Latora and Marchiori [6] evaluate the vulnerability of the Boston subway transportation system as the change of the network efficiency, i.e. the average of the reciprocal of the shortest distances between all node pairs in the network. As an alternative performance indicator, the relative size S of the largest connected component of the network is used by Angeloudis and Fisk [7] and Han and Liu [8] to assess the vulnerability of twenty of the world largest subway networks and of ten Chinese subway systems, respectively. In a similar work, von Feber et al. [9] compare the public transport systems of London and Paris in terms of vulnerability, introducing as indicator the area under the curve $S(c)$ as a function of the fraction c of removed nodes or links. The same approach is applied by Zhang et al. [10] in their study of the topological vulnerability of the Shanghai subway network. Derrible and Kennedy [11] analyse the robustness of 33 metro systems worldwide in terms of the number of cyclic paths available in the network, an indicator of network redundancy.

The analysis of public transport network vulnerability using a strictly topological approach has considerable shortcomings. Such studies neglect a large number of factors, most importantly the notion of lines and their implications for passenger route choice, line operations and the need to transfer. Topological studies effectively assume that the removal of a link is equivalent to the network without this link to start with, with the remaining segments supposed to continue functioning independently. However, unplanned disruptions can cause adverse effects because service providers and users cannot adjust to them upfront. Travel demand and in particular the effect on passenger rerouting and the number of affected users need to be explicitly considered. The availability of information about alternative routes and the duration of the incident is expected to play an important role in determining the consequences of public transport disruptions. Moreover, the dynamics of public transport system lead to the propagation of disturbances across the network due to knock-down effects on infrastructure and rolling stock and spillover effects due to the redistribution of passengers flows and capacity limitations. It is thus crucial to represent the interaction between supply and demand and their inherently stochastic processes in the public transport system.

To overcome these drawbacks, recently some vulnerability studies which model network loading have been developed, allowing the evaluation of additional important factors such as the level of congestion and delays. For example, Rodríguez-Núñez and García-Palomares [12] evaluate consequences of disruptions as the increase in average travel time, assuming that diverted travellers choose the fastest route available (i.e. all-or-nothing assignment). In addition, impacts of disruptions are analysed in terms of missed trips, i.e. the number of trips which cannot be completed because of the disturbance. Similarly, De-Los-Santos et al. [13] estimate the increase of the overall travel time of all passengers in the network after a link failure. Cats and Jenelius [14] developed a detailed dynamic robustness analysis using a dynamic agent-based transit assignment model. The latter is used to assess the increase in overall changes in passenger welfare measured in terms of total generalized travel costs. In Taleb [1] systems are considered vulnerable if the negative impacts increase disproportionally to the magnitude of capacity reductions. The existence of this kind of vulnerable systems is shown by Cats and Jenelius [15], where unplanned service disruptions with half the capacity reduction resulted in more than half as much delay. Shelat and Cats [16] propose two local link criticality indicators for measuring spillover effects and analyse them for planned disruptions using a static stochastic user equilibrium transit assignment model.