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Vulnerability of Transportation Networks: The New York City Subway System under Simultaneous Disruptive Events

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Abstract

This paper addresses the topic of transportation network vulnerability within the context of the New York City subway system. We propose a network model for it and an approach based on shortest-path passenger flow simulations in order to quantify delays experienced by passengers arising from disruptive events, particularly from those that occur simultaneously. We determine if and to what extent the effect under such simultaneous scenarios is greater than it would be had the same disruptions occurred as separate events. Our findings can be useful in supporting the planning decisions necessary to prepare for the harmful consequences arising from disruptions to complex urban networks.

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*Keywords:*vulnerability; urban mobility; network analysis; transportation systems

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1. Introduction & Literature Review

The topic of vulnerability in transportation networks is a well-researched area aiming to support municipal governments and associated entities with the intelligence necessary to better understand and mitigate exposure to disruptive events within the urban environment. Multiple transportation studies delve into vulnerability analysis based on single network disruptions. This paper may bring new insight to the field by studying the effect of simultaneous disruptions and examining their cumulative impact. In particular, we aim to measure any synergistic effects, showing that the combined impact of simultaneous disruptions may be "greater than the sum of its parts", and identify key sensitive locations in the city based on this synergy. Such knowledge can be useful for city planners who design the strategies that mitigate the vulnerabilities associated with urban rail transit networks. Our research may also provide for a method by which to best allocate resources to manage demand, reduce delays, and increase the security and resiliency of the subway system of New York City, one of the longest and busiest subway systems, with 5.7 million rides daily over 236 miles (380 km) of rail to nearly 500 stations and 24 hour/7 day a week service[1].

There are two main traditions in transportation network vulnerability analysis [2] within which we can situate the analysis presented in this paper. The first tradition is characterised as a *topological analysis*, which constructs an abstract network of a transport system, without the real-world data on demand. The second tradition is characterised as a *system-based analysis,* which also relies on network topologies, but incorporates transit data to better capture the economic effects of disruptions. Our work falls within this second tradition, as our analysis draws from service schedule, passenger volume and origin-destination data.

To date, most works in system-based vulnerability analysis are dedicated to road networks, including Wollmer (1964)[3], Ratcliff *et al*. (1975) [4], and Ball *et al*. (1989) [5], Berdica (2002) [6], D'Este and Taylor (2003) [7], Nicholson (2003) [8], Jenelius *et al*. (2006) [9], Chen *et al*. (2007), El-Rashidy and Grant-Muller (2014) [10]. These approaches define the impact of a disruption on a road network alternately through demand (Jenelius and Mattsson, 2012) [11] and economic value (Ukkusuri and Holguín-Veras, 2007)[12]. Jenelius and Mattsson [11] find that the impact of disruptions are largely determined by the demand of the affected area, while Ukkusuri and Holguín-Veras [12] describe the importance of thinking and measuring impact based on economic value, in the tradition of welfare economics. In addition, there is an emphasis on considering the nature of the potential disruption. Kim and Yeo (2016) [13] emphasize the importance of locality and time in evaluating the impact of a disruption, while Li and Ozbay (2012) [14] take on a more nuanced approach to the effect of a disruption, moving from the traditional binary scenarios of disruption events to a multi-status approach.

In our analysis, we follow a similar pattern of looking at network vulnerability, as Jenelius (2009) [15] does in aggregating supply and demand side indicators. In addition, we structure the New York City subway network model to allow for disruption scenarios at the geographic, station, platform and line levels.

While the research for road networks is extensive, far fewer works can be found on demand-based subway vulnerability analysis. Xu, Mao and Bai (2016) [16] incorporate passenger flow data into traditional, static, network models and identify critical stations based not only on topological parameters but also the real-life traffic data, which is unavailable in our NYC case.

Yin*et al*. (2016) [17], Kim *et al.* (2016) [18], Zhao (2015) [19] also deal specifically with various subway system networks across the globe, but their focus is on identifying critical network nodes when evaluating the impact of disruptions on the system. Kim *et al.* [18] and Zhao [19] find that certain combination of nodal disruptions can have a more significant impact on network performance, for example, in a case when passengers cannot get to their destination because no alternative paths are available among the lines, allowing the authors, Yin *et al*. [17], to identify robust and vulnerable disruption scenarios at different levels.

Our paper defines its own measure for identifying critical nodes based on a combination of economic value, denoted by travel time between origin and destination stations, and demand, denoted by passenger flow between origin and destination stations. We introduce the concept of 'synergy' in order to evaluate the effect of simultaneous node disruptions. In addition, while most of the mentioned studies rely on readily available passenger origin-destination data, our model incorporates a novel approach to estimating passenger flow directionality, for cases involving systems which lack routing data, as is the case for studies involving the New York City subway system.