Advances in Reliability, Safety and Security

ESREL 2024
Collection of Extended Abstracts

Network Analysis To Evaluate Resilience Of Urban Transit Systems

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Keywords: resilience, graph theory, network analysis, transit systems

Urban transit systems are vulnerable to failures caused by accidents, maintenance schedules, natural hazards, and manmade attacks (Zhang et al., 2018). To ensure a safe and reliable operation of urban transit systems, the performance of transit systems and the impact of disruptions must be quantified under different scenarios to identify the most vulnerable assets and inform the allocation of resources towards risk management (Chopra et al., 2016; Dersin et al., 2022). This work proposes a graph-based, data-driven approach for evaluating the resilience of transit systems by investigating the use of network analysis approaches that combine observed data with flow simulation to examine the response of the system under different disruptive scenarios (Yadav et al., 2020). The analysis is conducted using a case study of the Washington Metropolitan Area Transit Authority (WMATA) for which the network is shown in Figure 1.

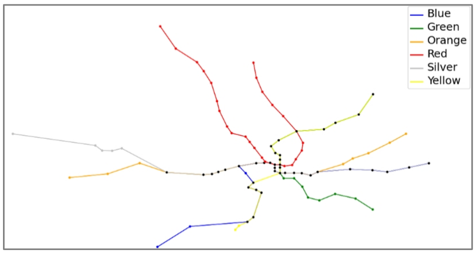

Fig. 1. WMATA Metrorail network represented in L-space.

Our work begins with an exploratory data analysis that identifies important network patterns. For example, the rail network is a scale-free network with a small average node degree and central highly connected nodes that make the system vulnerable to targeted station closures. In addition, as shown in Figure 2, incidents duration is the longest on weekend evenings, a busier time for the metro network. Finally, the metro red line, which is the busiest line on the network, operates as a stand-alone line, without any other backup line. This makes traffic redistribution more difficult when the line faces disruptions.

We model disruption scenarios through simulation that is informed by data on historical incidents as well as considerations of future uncertain conditions. The aim is to measure the response of the disrupted network by measuring its reduction in connectivity, as well as the number of displaced passengers. Historical trends of accidents and station closures are used to simulate the most likely scenarios and evaluate their impact of the system-level performance. Our findings show that the closure of a single station can heavily impact the flow of the network and reduce its capacity. Additionally, we simulate climate-driven disruptions based on future climate projections of precipitation that may influence the inundation of metro stations (Yufeng et al., 2021; Zhen et al., 2023).

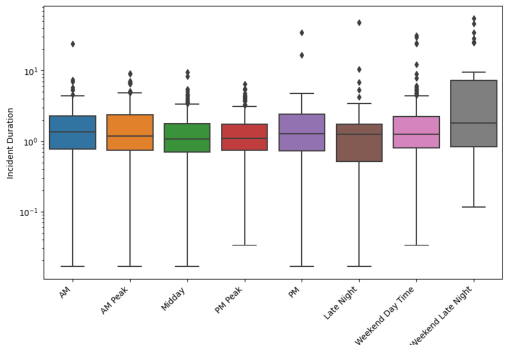

Fig. 2. Rail incident duration by time of day.

Finally, we investigate how the coupling between metro rail and bus systems can help improve the resilience of transit systems. Our analysis finds that the closure of certain metro stations will cause an increase in passenger demand on different lines that are expected to be absorbed by the bus network. These passengers will try to find another route through the metro or exit the system in search for other modes of transportation. Table 1 shows that the distance to an alternative option varies between stations. When the risk assessment of rail and bus systems is decoupled, the ability to absorb shocks from one system to the other is underestimated. As such, we propose a network-based approach (Bing et al., 2023; Ma et al., 2019) to capture the cascading effects planning for the resilience of interdependent networks.

Table 1. Distances from a rail station to the closest mode of transportation.

	Rail station to closest rail station (km)	Rail station to closest bus station (km)
Average	1.012	0.117
Standard Deviation	1.016	0.298
Minimum	0.116	0.005
Maximum	7.706	2.196

The proposed network analysis can help transit authorities assess the performance of the multimodal system, allowing for continuous improvement and optimization of the transit performance. By identifying critical nodes and edges within the network, planners can ensure that alternative routes and backup services are available in case of disruptions or emergencies, and that traffic can flow smoothly between rail and bus. This approach can help inform the design and allocation of resources towards building resilient infrastructure systems.

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