

Assessing flood-conditioned power dependency of rail transit systems and its effects on resilience under climate change

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1 INTRODUCTION & SCOPE OF WORK

Modern transport systems face challenges that are different from those encountered by the pioneering engineers who built them in earlier centuries. Two pressing challenges are the increasing water-related hazard risks posed by climate change (IPCC, 2023) and the growing system dependencies among various domains due to electrification and digitalisation (Pant et al., 2024). Multimodal urban rail transit (URT) systems —such as metros, light rail, and trams— are socio-technical systems that exemplify such complexities and are vulnerable to climate hazard risks. In recent years, notable metro flooding incidents have occurred in several cities, including New York in 2012, 2021, and 2023, Brussels in 2016, Sydney in 2020, London and Zhengzhou in 2021, Milan, Madrid, and Hong Kong in 2023, Valencia in 2024, and Paris in 2025, with observed significant equipment damage, extensive service suspension, and even passenger fatalities due to carriages being trapped in flooded tunnels.

Rainfall-induced surface water flooding disrupts URT operations not only directly by inundating stations and tracks and making them unsafe to access, but also indirectly by damaging power substations and interrupting electricity supply. Such functional dependency on electric power introduces additional vulnerability to URT systems, exposing the network to cascading failures and prolonged service disruptions. Incorporating this dependency into URT flood resilience evaluations is therefore essential to capture system-wide risks. To date, only a few studies have examined the resilience of URT under power dependency. Existing work predominantly relies on multilayer network-based approaches to represent rail and power systems and the connections between them (Goldbeck et al., 2019; Ilalokhoin et al., 2023; Liu et al., 2024). These studies typically focus on functional dependency, whereby failures of power system components trigger cascading failures in connected URT components. Using stress-test approaches, resilience is then quantified through changes in system performance or functionality, employing either topological indicators such as the proportion of functioning nodes, betweenness centrality, and global network efficiency, or operational indicators including delay minutes and unmet travel demand.

Despite these efforts, there are notable limitations in existing studies. First, disruption scenarios in resilience assessments are often hypothetical, relying on random or targeted component failures (Guo et al., 2025; Liu et al., 2024, 2025) or other simplified illustrative scenarios (Adjetei-Bahun et al., 2016; Da Silva Fradique et al., 2025; Hao et al., 2023; Ilalokhoin et al., 2023; Rinaldi et al., 2001; J. Sun et al., 2020; Wang et al., 2025), rather than explicitly representing real-world conditions of natural hazards such as flooding (Li et al., 2025). As a result, studies accounting for flood-conditioned geographical dependencies between rail transit and power systems remain scarce. Furthermore, while dependency between rail transit and power systems is widely acknowledged, existing studies rarely provide an explicit, quantitative measure of the degree of hazard-conditioned power dependency of URT, nor do they systematically examine how variations in this dependency under changing flood and climate scenarios influence URT resilience. This limitation also applies to resilience assessments of other dependent infrastructure systems, where hazard-conditioned degrees of dependency are seldom explicitly characterised (Rinaldi et al., 2001). Finally, data availability has been widely recognised as a major challenge in interdependent infrastructure resilience studies (Rinaldi et al., 2001;

Shamsi & Helmrich, 2025; W. Sun et al., 2022; Tong et al., 2025). Detailed asset-level dependency data are often inaccessible due to data scarcity or sensitivity, which limits the feasibility and scalability of fine-grained dependency simulation in large-scale infrastructure resilience assessments. This long-standing challenge calls for methods capable of capturing dependency effects using readily available spatial information to produce meaningful insights.

To address these limitations, this study develops a hazard-conditioned system dependency framework to (1) assess the degree of power dependency of URT under varying flood scenarios, (2) quantify URT flood resilience based on system performance loss, and (3) systematically examine how variations in hazard-conditioned power dependency reshape URT resilience to flood risks. The model simulates URT service disruptions caused by direct station and track flooding, cascading effects arising from substation flooding, and the subsequent dynamic recovery process. The methodology is demonstrated through a case study of the London URT network, which is stress-tested by flood risks of varying return periods and climate scenarios. This study makes the following contributions to research on the resilience of (inter)dependent infrastructure systems:

- (1) It proposes for the first time the concept of a hazard-conditioned degree of system dependency that characterises how inter-system dependency varies across hazard scenarios, thereby reflecting real-world, hazard-driven dependency dynamics.
- (2) The metric of flood-conditioned degree of dependency is formulated in a data-efficient manner, reframing hazard-conditioned system dependency as a measurable system property that can be characterised using readily available high-level spatial information rather than detailed asset-level dependency data that are often difficult to obtain. This formulation enables scalable and transferable analysis of hazard-conditioned dependency across many other (inter)dependent infrastructure systems.
- (3) Through climate-informed flood scenarios, the assessment results (are expected to) provide insights into the criticality of power dependency in URT resilience under evolving climate risks and to offer evidence to inform resilience planning and climate adaptation for URT, with the aim of reducing URT service disruption impacts on society.

2 METHODOLOGY

An overview of the methodology is provided below. First, a multilayer network model is constructed to simulate the dependent URT-power systems. The URT network layer represents the rail transit network, where nodes correspond to stations and edges represent track segments connecting stations, weighted by travel time. The power network layer represents electricity supply infrastructure, with nodes representing substations and edges representing distribution lines connecting them. Directed inter-layer links are then introduced from power substations to URT stations and track segments to represent power supply dependency, which are inferred based on geographical proximity. Second, all URT and power network components are georeferenced and integrated with flood risk maps to derive location-specific flood exposure and flood depth under different return-period and climate scenarios. Following this, a metric is designed to measure the degree of flood-conditioned power dependency of URT. Subsequently, disruptions to URT services are simulated by disabling stations and tracks that are directly and indirectly interrupted due to floods. This is followed by simulating the recovery process, considering recovery time, resources, and their constraints. Next, URT resilience is quantified using the total unmet travel demand during the disruption period and the system recovery time. Finally, correlations between the degree of power dependency and URT system resilience are examined across flood scenarios and visualised through scenario-based plots.

3 RESEARCH OUTCOMES

This study is currently ongoing, and results have not yet been obtained. The London URT case study is expected to yield assessment results on (1) flood-conditioned degree of power dependency of the London URT under different flood risk scenarios, (2) URT flood resilience, and (3) how variations in flood-conditioned power dependency correlate with URT resilience.

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