IMPACT: IMproving flood-disruPted road networks resilience with dynAmic people-Centric digital Twins

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THE BARTLETT SCHOOL OF SUSTAINABLE CONSTRUCTION

DAFNI Data & Analytics Facility for National Infrastructure

Background and Context

The IMPACT project addresses the critical challenge of improving road network resilience during flood events through innovative digital twin technology. As highlighted in Agenda 2030, resilient infrastructure (SDG 9) is essential for achieving all Sustainable Development Goals, yet remains one of the least well-delivered objectives. Climate change has intensified flood events, making the UK's road networks increasingly vulnerable and creating an urgent need for effective resilience solutions. Current approaches to traffic management during floods face severe limitations in addressing congestion risks, which can have cascading effects across entire urban systems. These approaches rely on static network characteristics that fail to capture the dynamic evolution of flood impacts. They lack sufficient integration of real-time flood modeling with network measurements, leaving decision-makers with incomplete situational awareness. These combined limitations create significant challenges for transportation authorities trying to manage congestion during floods, ultimately leading to extended traffic delays, stranded vehicles, and potentially life-threatening situations when emergency services cannot reach their destinations.

The IMPACT project responds to these challenges by developing integrated "user-road-flood" cross-domain systems, consisting of a datahub, data engine, and resilience enabler. These components work together to create dynamic digital twins that can assess and improve road network performance during flooding. By integrating multimodal transportation datasets, the project evaluates dynamic relationships between transportation systems and flood events, enabling more effective response strategies.

Domain: Infrastructure Systems Engineering
Key words: transportation network resilience, geospatial data integration, and climate adaptation.

Dynamic Exposure & Graph Structure

Dynamic Exposure Based on Road-grid Intersection

The dynamic exposure assessment overlays the road network (R) with grid cells (G) to identify flood-affected road segments (Fig 4). Individual road segments (r) are analyzed for their intersection with grid cells containing varying inundation depths (dg), ranging from 0m (dry) to 0.45m (severely flooded). When a road segment intersects with grid cells having inundation depths exceeding the critical threshold of 0.3m, it receives an exposure flag (Ef(k) = 1), marking it as impassable. This approach enables precise tracking of which road segments become compromised as flooding progresses, allowing for accurate assessment of network vulnerability and more effective emergency response planning during flood events.

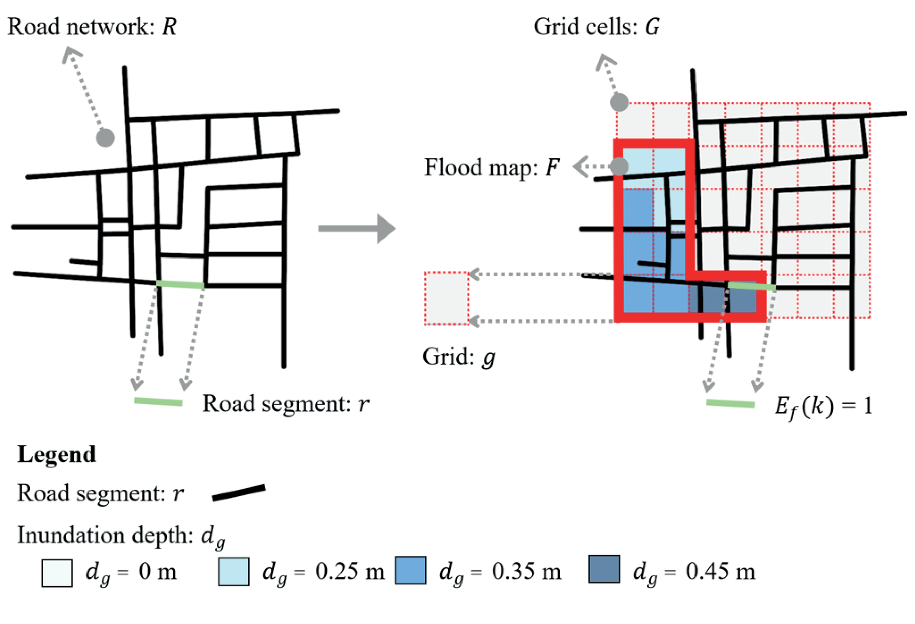

Figure 1. Intersection between road segments and grid cells

Line Graph of Transportation Networks

Treating roads as nodes and the connections between nodes as edges (line graph, Fig 1b of the original graph, Fig 1a) allows for detailed road-level feature modeling, naturally captures interactions between roads, effectively handles complex intersections, and enhances the physical consistency of the model. This approach improves the model's adaptability to dynamic traffic conditions, resulting in more accurate and reliable traffic flow predictions.

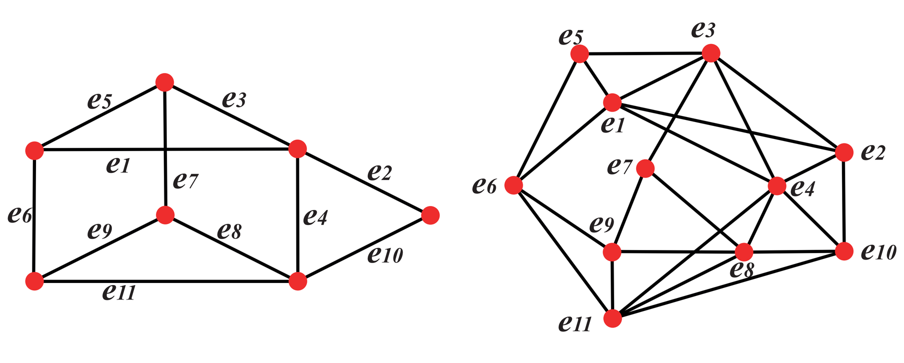

Figure 2. Comparison between the original network (a) and the corresponding line graph (b)

Project Framework

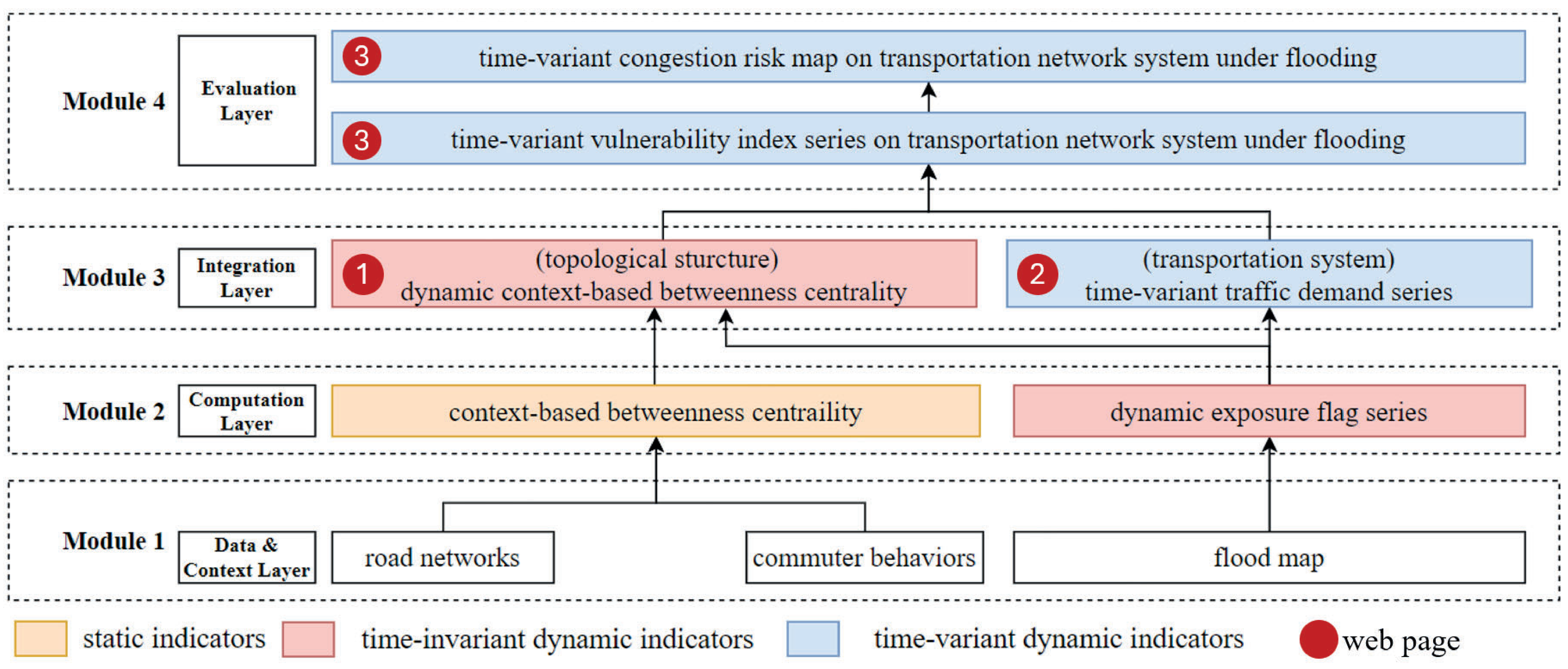

Figure 3. Hierarchical Framework for Flood-Induced Congestion Risk Assessment

Our project introduces a hierarchical four-module framework for assessing dynamic congestion risks in transportation networks under flooding conditions. As shown in Figure 3.

Module 1(Data and Context Layer) serves as the foundation, integrating three essential data streams: road networks that form the physical infrastructure, commuter behaviours that represent travel patterns, and flood maps that indicate areas of potential inundation.

Module 2(Computation Layer) processes this base data to generate two critical indicators. First, it calculates context-based betweenness centrality as a static indicator of road segment importance within the network. Second, it produces dynamic exposure flag series that track the temporal evolution of flood impacts on the road network.

Module 3(Integration Layer) synthesizes these computations into two parallel analytical streams. The topological structure analysis generates dynamic context-based betweenness centrality, while the transportation system analysis produces time-variant traffic demand series. This dual approach captures both the structural and functional aspects of network performance under flooding.

Module 4 (Evaluation Layer) represents the culmination of all previous analyses, generating two key outputs: time-variant vulnerability index series that measure the network's dynamic susceptibility to disruption, and time-variant congestion risk maps that visualize the evolving patterns of traffic congestion risk across the network during flood events. These modules form a cohesive framework that systematically addresses the complexity of assessing dynamic congestion risks in transportation systems under flooding.

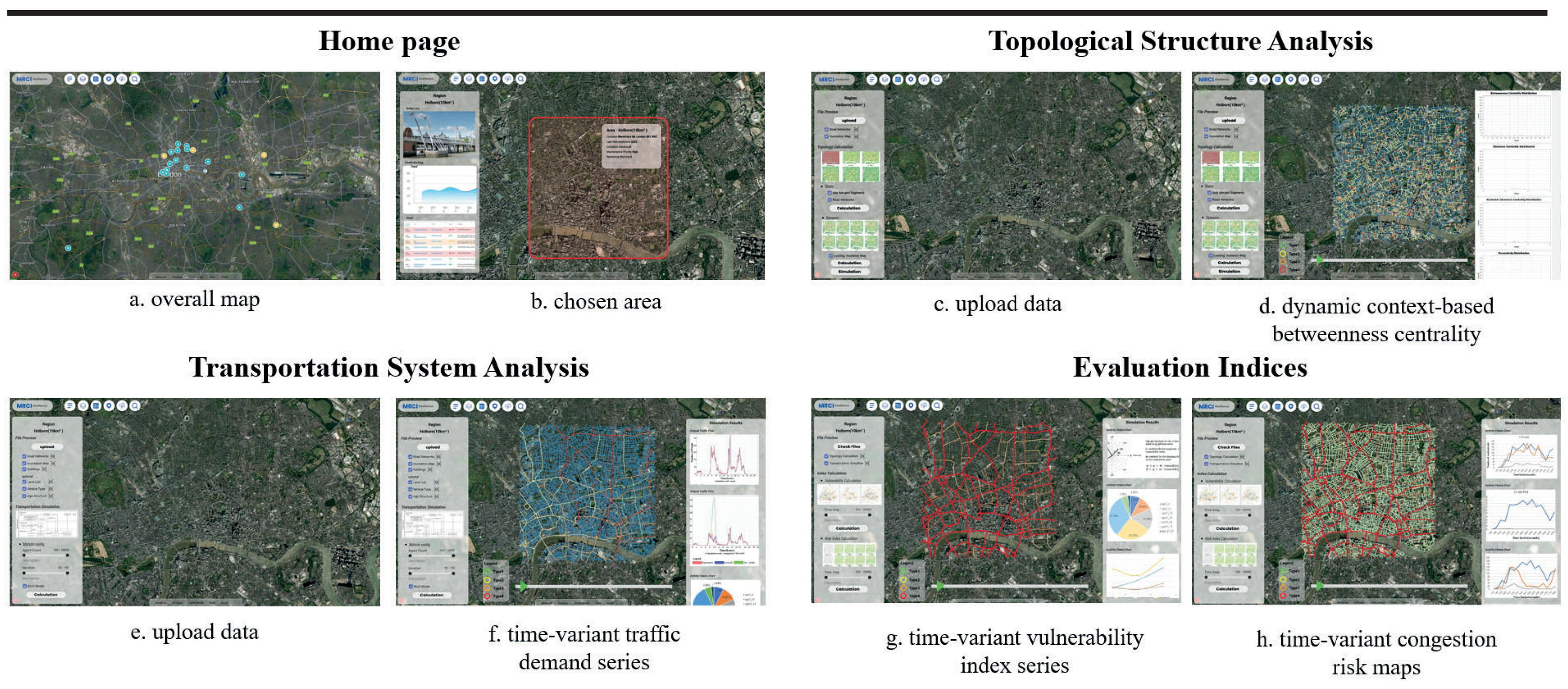

Figure 4. Dynamic flood-induced traffic congestion risk assessment platform

Based on our hierarchical framework, we developed a comprehensive digital platform (as shown in Figure 4) for assessing and managing flood impacts on transportation networks. The platform interface, as shown in the figure, progresses through four key functional areas. The Home Page provides spatial orientation with both overview and detailed area maps. The Topological Structure Analysis section enables users to upload network data and visualize dynamic context-based betweenness centrality across the road network. The Transportation System Analysis component processes traffic data to generate time-variant traffic demand visualizations. Finally, the Evaluation Indices section delivers actionable intelligence through vulnerability index series and congestion risk maps that evolve as flood conditions change. This integrated platform transforms the theoretical framework into a practical decision support tool for both emergency response and infrastructure planning.

Benefits of Data Sharing

Access to Data Sets:

Access to key datasets, such as multimodal behaviour data from transport networks, is crucial for analysing infrastructure systems' resilience during flood events. This data provides insights into infrastructure performance, vulnerability, and interdependencies during extreme conditions.

Identified Benefits of Data Sharing:

a) Decision-Making: Shared data improves flood impact modeling, aiding resilience planning.
b) System Interoperability: Enhances cross-sector integration for resilience strategies.
c) Cost & Resource Optimization: Reduces duplication, saving costs and resources.
d) Collaboration: Fosters innovation and cohesion among government, industry, and academia.

Outcomes of Data Sharing:

a) Real-Time Monitoring: Enables tools for faster, effective flood response.
b) Predictive Modeling: Supports proactive infrastructure performance models.
c) Policy Development: Informs robust resilience and adaptation policies.
d) Public Benefits: Boosts safety and mobility through resilient infrastructure.

Stakeholders Benefiting

a) Government: Informs policy and regulation.
b) Companies: Optimizes operations and addresses vulnerabilities.
c) Researchers: Advances knowledge and solutions.
d) Communities: Gains safer, resilient infrastructure.

Barriers of Data Sharing

Barrier Categories

a) Privacy & Legal:
Sensitivity and ownership issues.
b) Commercial:
Cost and licensing challenges.
c) Cultural & Organisational: Discoverability and resistance obstacles.
d) Technical: Interoperability, metadata, and context deficiencies.

Identified Barriers

a) Privacy & Legal: Sensitive multimodal traffic data (e.g., vehicle/individual tracking) raises privacy concerns; commercial data may be withheld for competitive reasons; unclear ownership complicates sharing.
b) Commercial: The financial burden of collecting, processing, and distributing traffic data can outweigh its perceived value, discouraging stakeholders from participating in sharing initiatives.
c) Cultural: Traffic data is often scattered across disparate sources, making it difficult to locate or access. Within organisations, reluctance to share frequently arises from a limited awareness of data-sharing benefits, slowing collaboration.
d) Technical: Proprietary data formats and a lack of universal standards hinder seamless integration across systems. Additionally, inadequate metadata, inconsistent quality, and missing contextual details—like collection methods or timing—undermine the data's reliability and usefulness.

Lessons Learnt & Recommendations

Our research into data sharing for flood-resilient transportation networks has yielded valuable insights that can guide future initiatives. We discovered that cultural and organizational resistance often poses greater challenges than technical issues, highlighting the need for better stakeholder education about data sharing benefits. The quality of metadata emerged as a critical factor, with poor documentation significantly hampering the usability and integration of multimodal traffic data. Early and consistent engagement with stakeholders proved essential for addressing privacy, licensing, and governance concerns, while adopting FAIR principles (Findable, Accessible, Interoperable, and Reusable) demonstrably improved data usability and fostered trust among participants. Particularly effective practices included cross-sector partnerships between researchers and industry, implementation of data anonymization methods, and standardization of sharing agreements and metadata formats. Moving forward, we recommend prioritizing enhanced metadata standards development and streamlining data-sharing agreement templates to reduce administrative barriers. With future funding, the project would aim to expand multimodal traffic data sharing practices, enhance digital twin capabilities for transport network resilience, refine legal frameworks for data ownership, and promote best practices through comprehensive guidelines. By addressing these priorities, significant advancements can be made in transportation system resilience against climate-related challenges, ultimately improving infrastructure performance and public safety during flood events.

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