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Faculty of Applied Engineering

TU Delft

Topological analysis of recoverability in multi-modal public transport networks

European Transport Conference (ETC)

Renzo Massobrio, Oded Cats and Peter Hellinckx

17 September 2025

1. Motivation

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Reducing the impact of disruptions is key for providing attractive PT services.

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Our goal

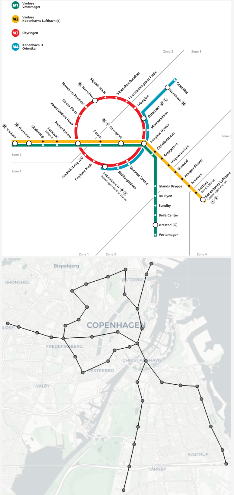
Study the recoverability of multi-modal PT networks.

Main RQ

How do different modes influence the robustness and recoverability of multi-layer PT networks?

2. Modelling PT networks as graphs

Building a dataset of PTNs (I)



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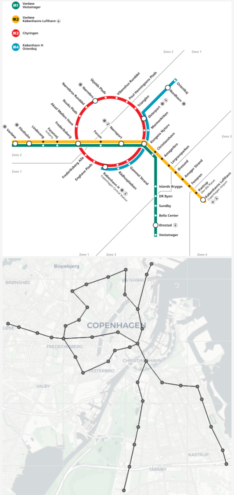

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- stop/station location
- line/route connections

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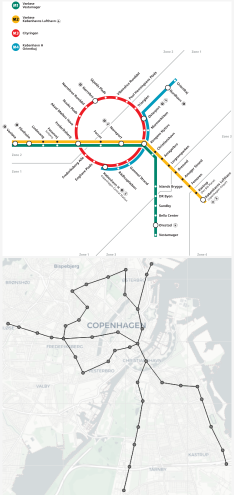

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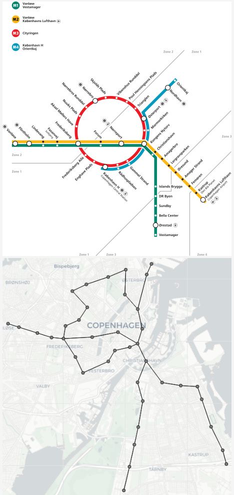

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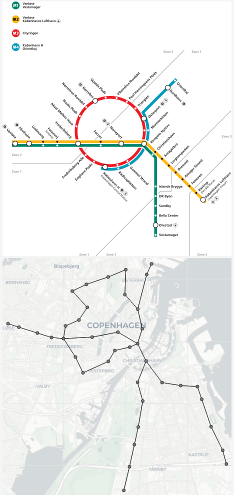

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Solution

General Transit Feed Specification (GTFS)

Building a dataset of PTNs (II)

1. Get GTFS data for each network (`database.mobilitydata.org` and operators' websites)

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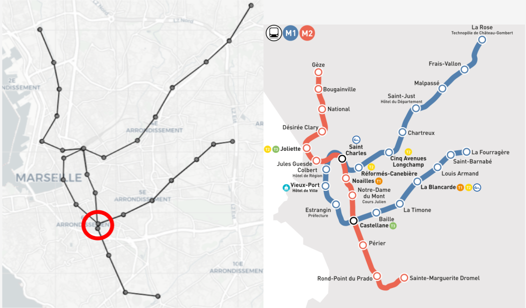
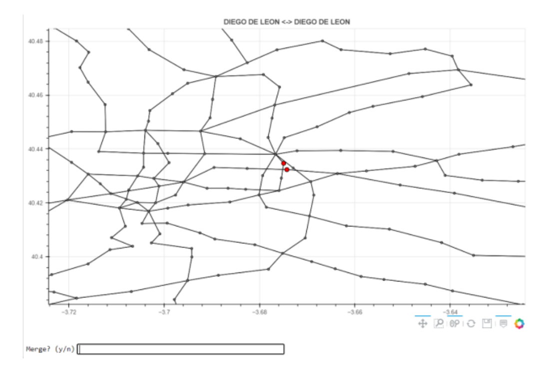
1. Get GTFS data for each network (`database.mobilitydata.org` and operators' websites)
2. We use GTFSpy library:
   - select a representative day and filter a range of hours (5 a.m. to midnight).
   - initial graph with average travel time and number of vehicles



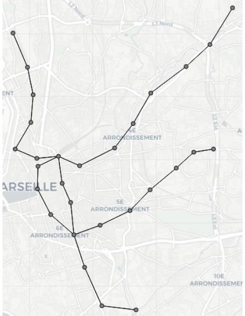
Building a dataset of PTNs (III)

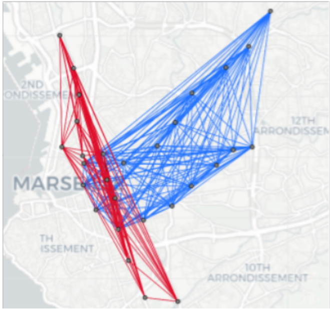
3. Graph post-processing
   - 3.1 Automatic merging of overlapping nodes
   - 3.2 Merge recommender based on location and name similarity
   - 3.3 Manual merge tool



Building a dataset of PTNs (IV)

4. Build final graphs:
   - L-space (space of infrastructure): labeled with in-vehicle travel time
   - P-space (space of service): labeled with waiting time





Benchmark of 51 metro networks. Larger and more insightful than previous works.

https://doi.org/10.4121/21316824

https://doi.org/10.4121/21316950

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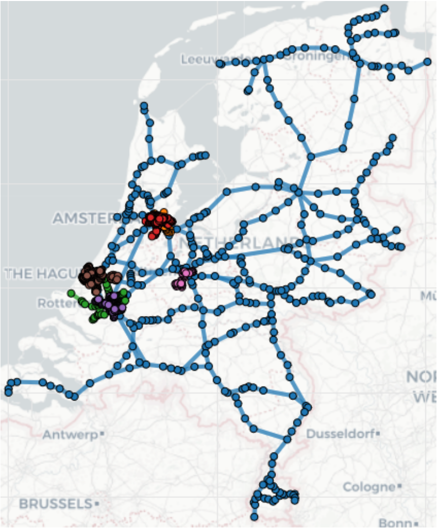
Modelling multi-layer PT networks

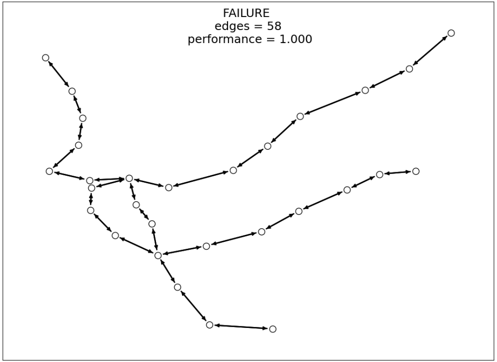
Multi-layer networks

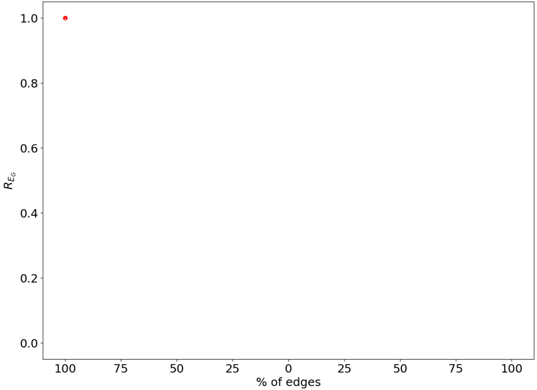
- We modelled the Dutch (rail-based) PT system
- We model each mode (rail, metro, tram) as a layer
- We connect layers with "walking" edges



3. Measuring recoverability of PTNs

Methodology (I)





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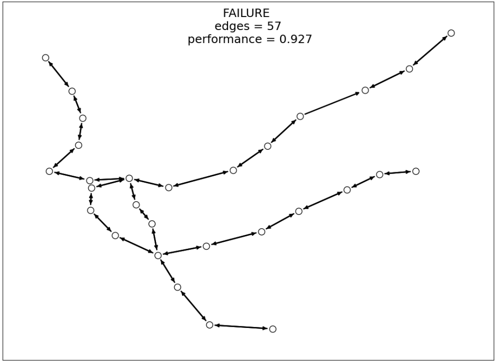

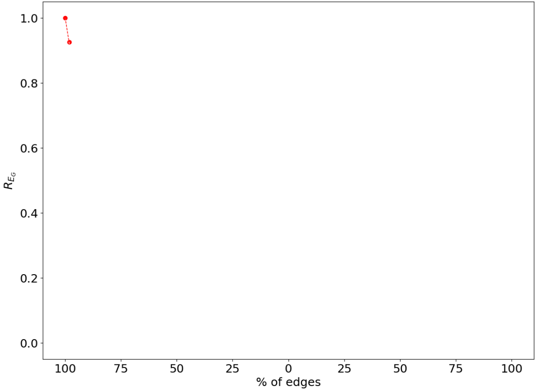

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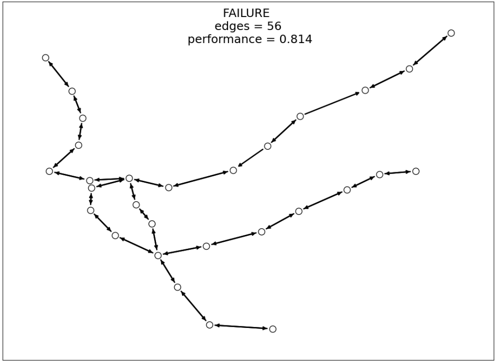

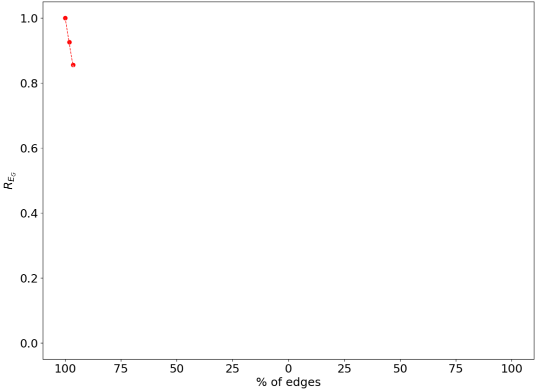

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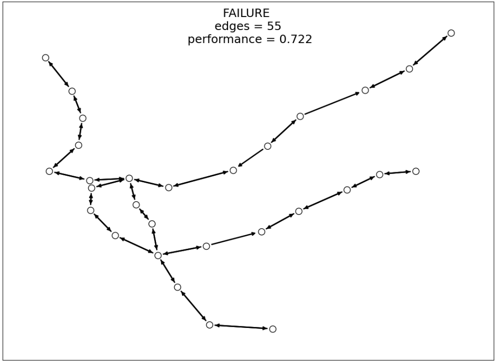

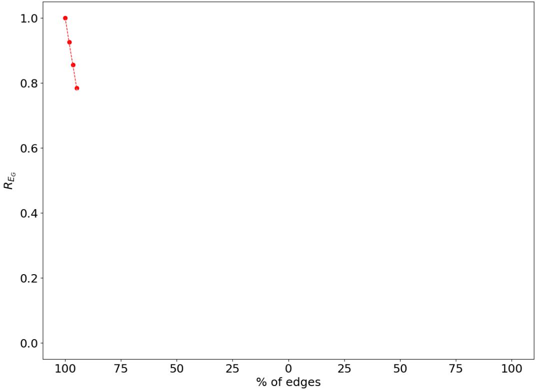

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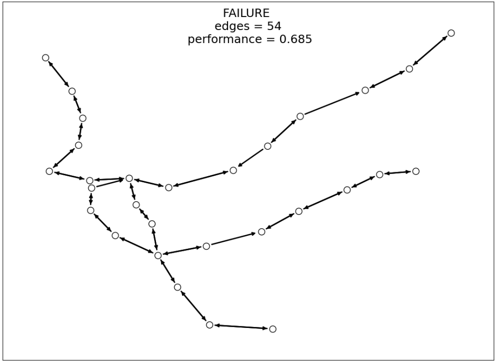

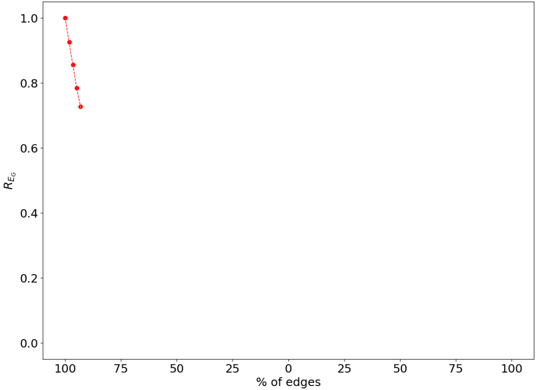

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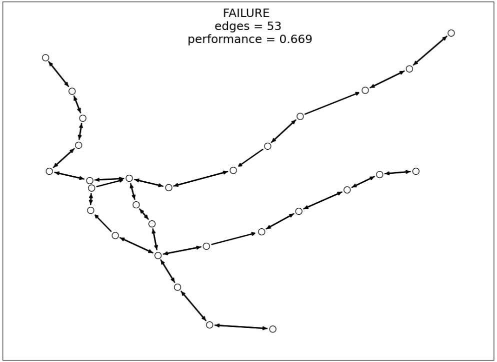

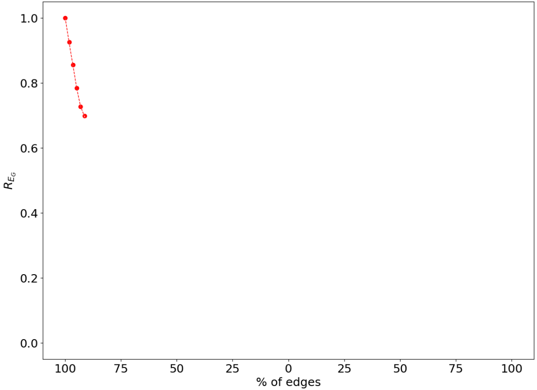

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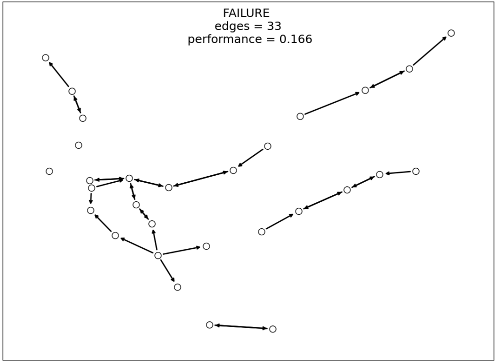

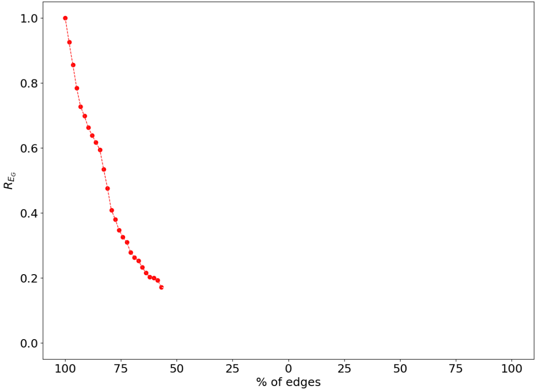

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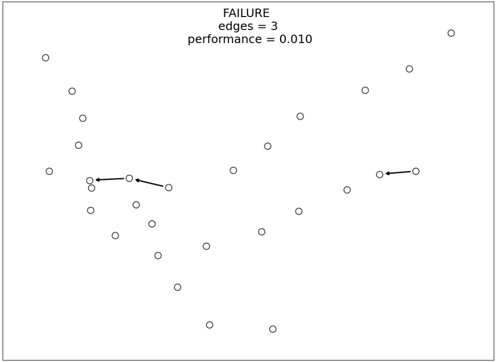

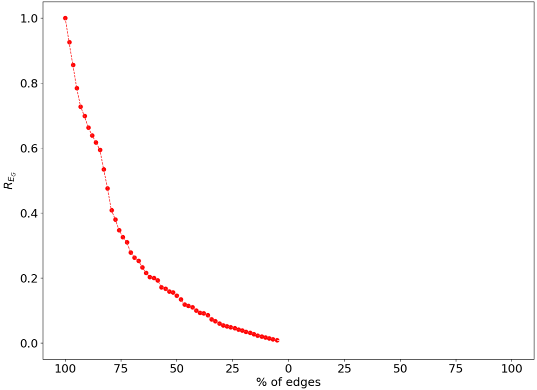

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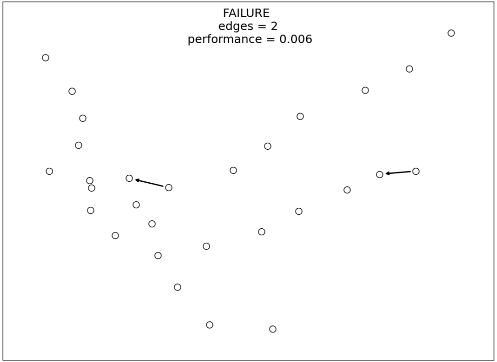

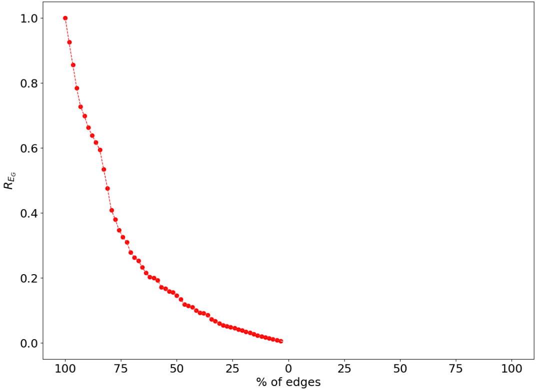

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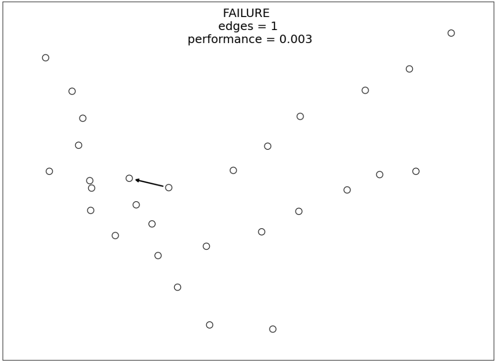

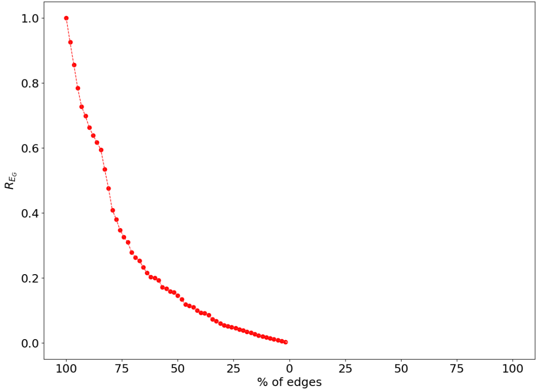

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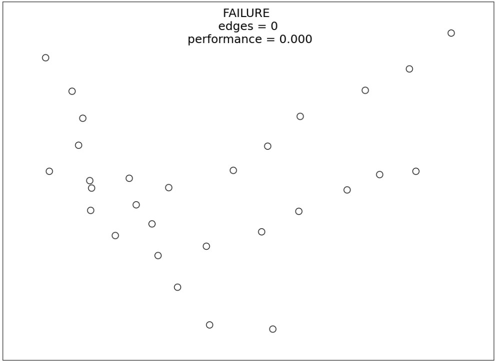

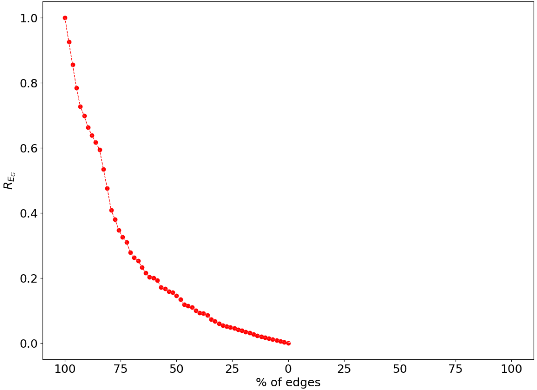

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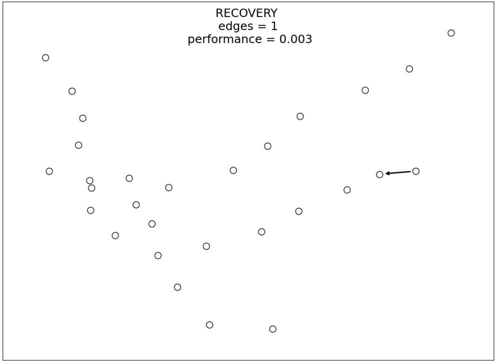

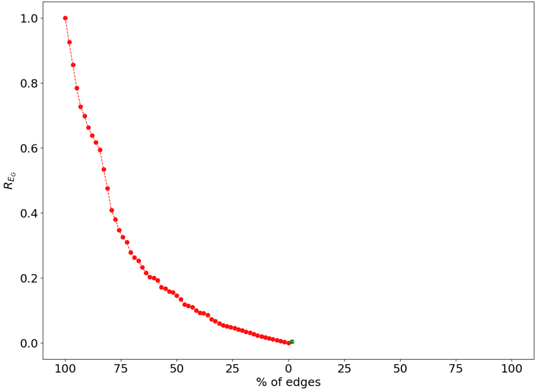

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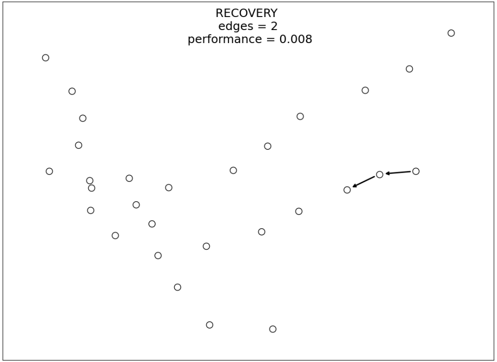

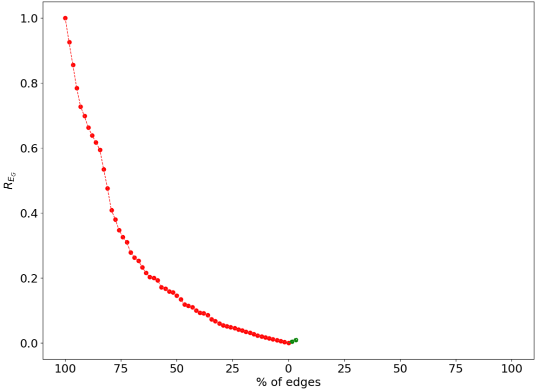

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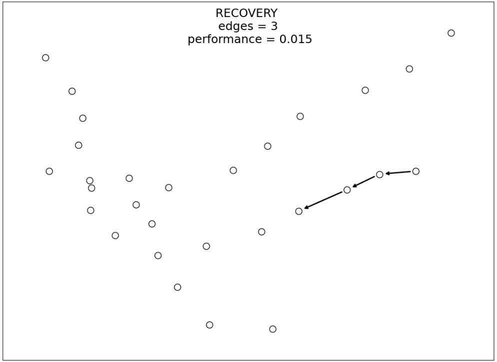

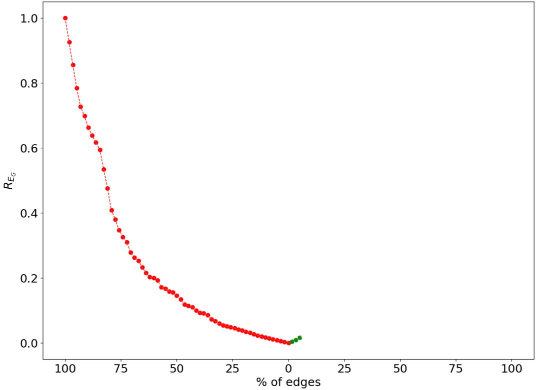

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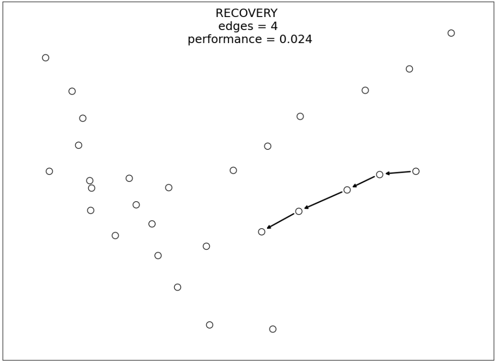

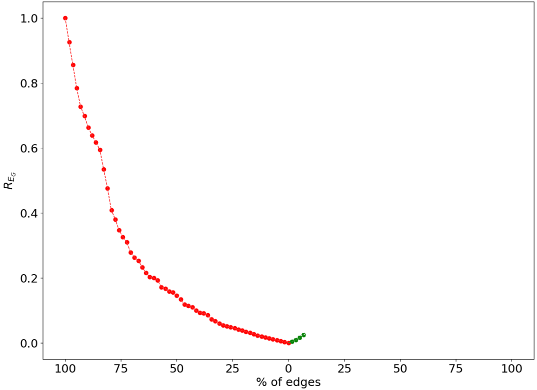

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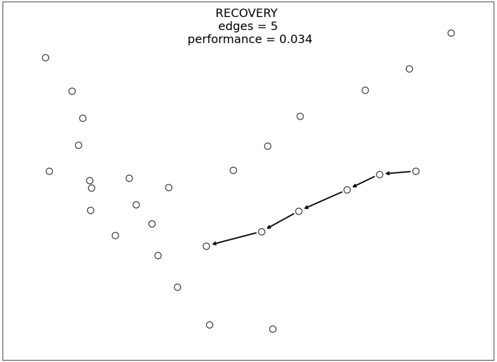

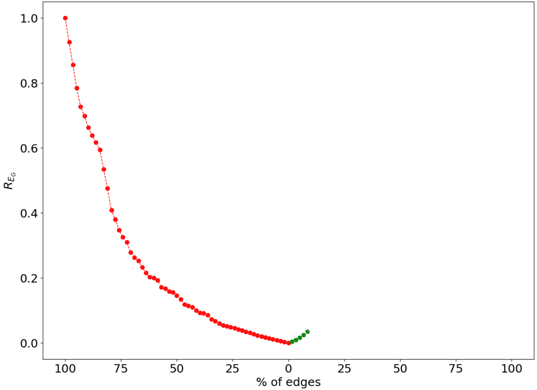

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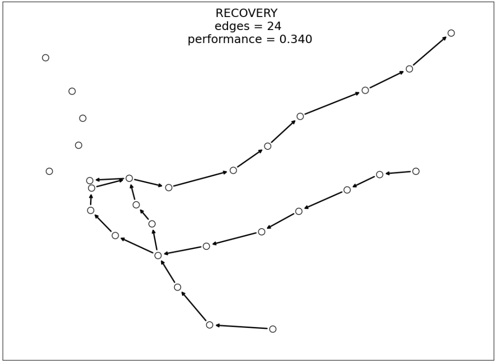

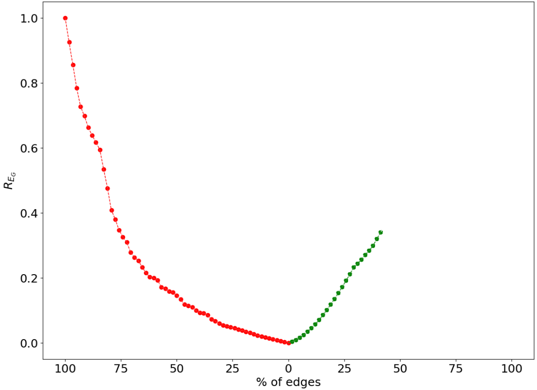

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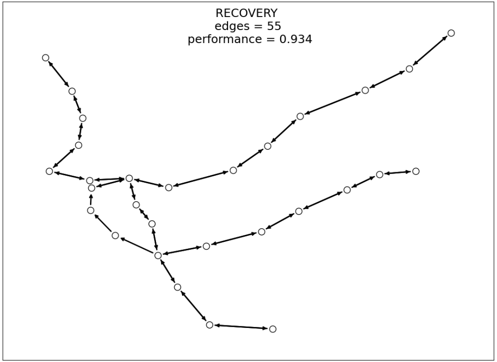

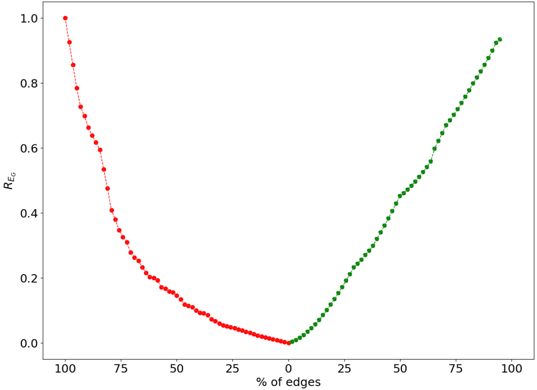

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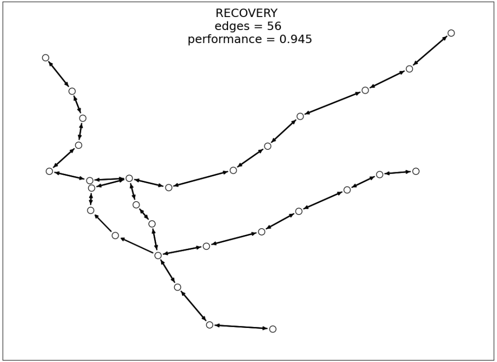

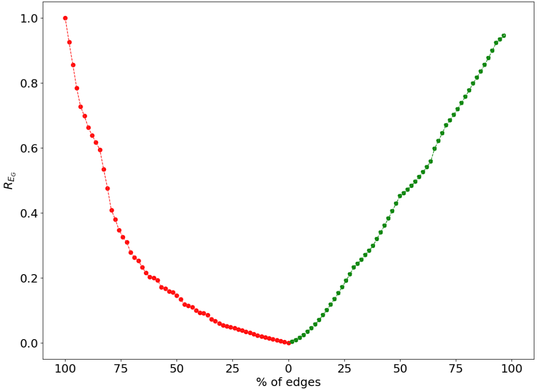

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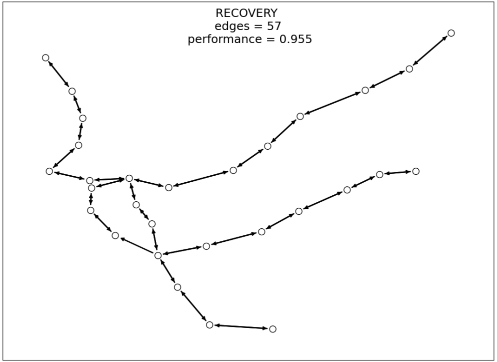

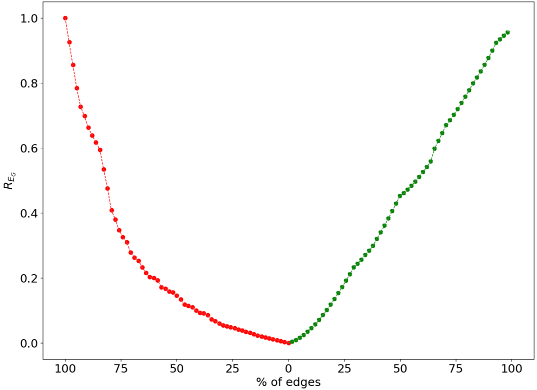

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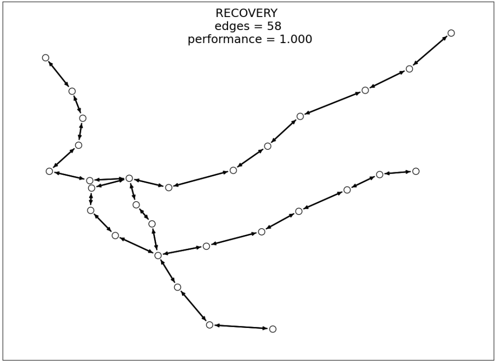

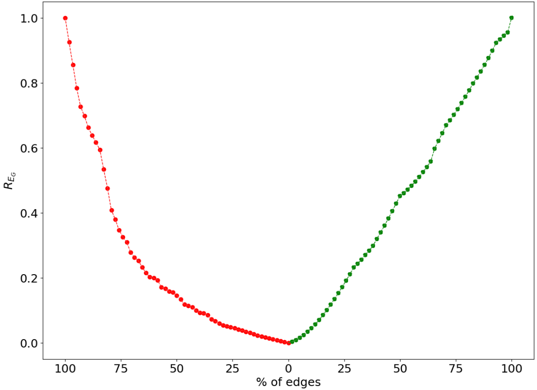

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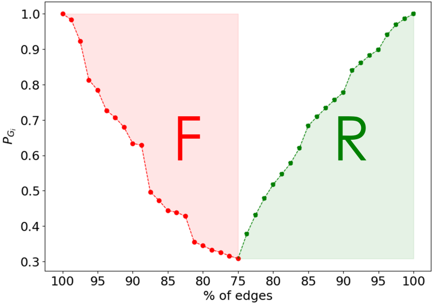
Methodology (II)



Problem formulation

- Random removal of links. Greedy recovery strategy.
- Efficiency as a function of Generalized Travel Cost between all pairs of stations.

$$\mathrm{GTC}(i,j) = \min_{sp_i \in sp_1,\ldots,sp_m} \left[\text{in\_vehicle\_time}(sp_i) + \alpha \times \text{waiting\_time}(sp_i) + \beta \times \text{n\_transfers}(sp_i) \right]$$

- F: cumulative performance loss, R: cumulative performance gain

Previous results - Recoverability in metro networks

communications physics Article

https://doi.org/10.1038/s42005-024-01596-8

Topological assessment of recoverability in public transport networks

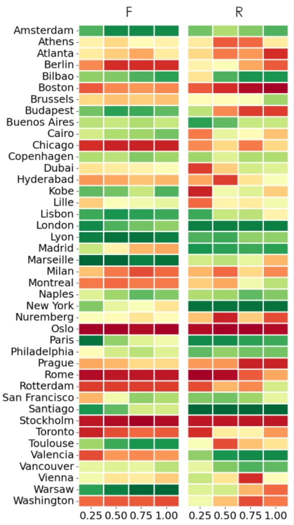
Check for updates

Renzo Massobrio[1,2] & Oded Cats[2]

Reducing the impact of disruptions is essential to provide reliable and attractive public transport. In this work, we introduce a topological approach for evaluating recoverability, i.e., the ability of public transport networks to return to their original performance level after disruptions, which we model as topological perturbations. We assess recoverability properties in 42 graph representations of metro networks and relate these to various topological indicators. Graphs include infrastructure and service characteristics, accounting for in-vehicle travel time, waiting time, and transfers. Results show a high correlation between recoverability and topological indicators, suggesting that more efficient networks (in terms of the average number of hops and the travel time between nodes) and denser networks can better withstand disruptions. In comparison, larger networks that feature more redundancy can rebound faster to normal performance levels. The proposed methodology offers valuable insights for planners when designing new networks or enhancing the recoverability of existing ones.

Main results

- more efficient and denser networks can better **withstand disruptions**
- larger networks that feature more redundancy can **recover faster**



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4. Recoverability of multi-modal PTNs

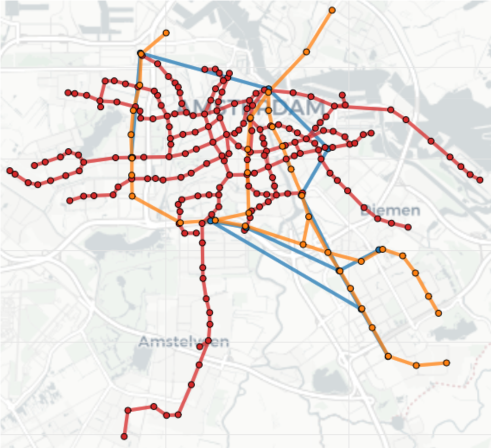
Recoverability of multi-modal PTNs

Extended methodology

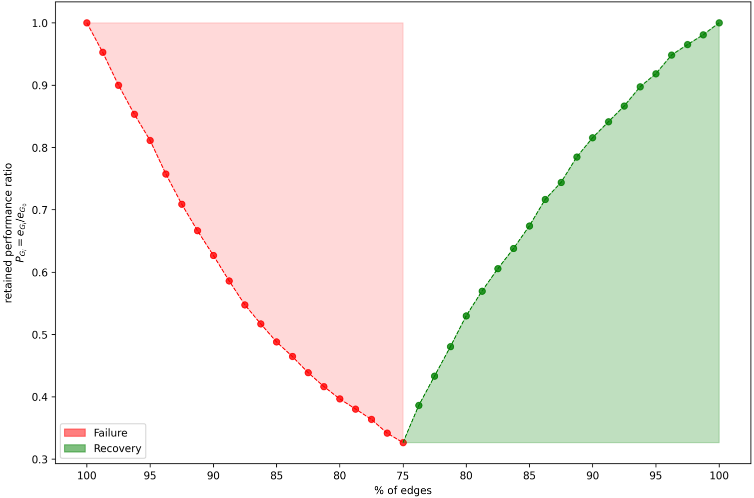
- We use multi-layer graphs that allow transfers between modes
- We extend the GTC to account for walking time and a penalty for transferring between modes
- We disrupt one mode (e.g., metro) and assess the retained performance with/without other modes.

Preliminary experiments

Amsterdam case study: **metro** + tram + rail

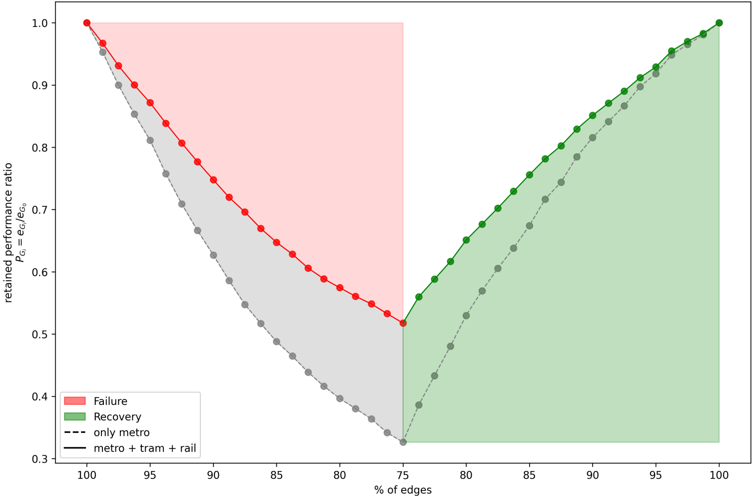


Preliminary results (I) - Retained performance



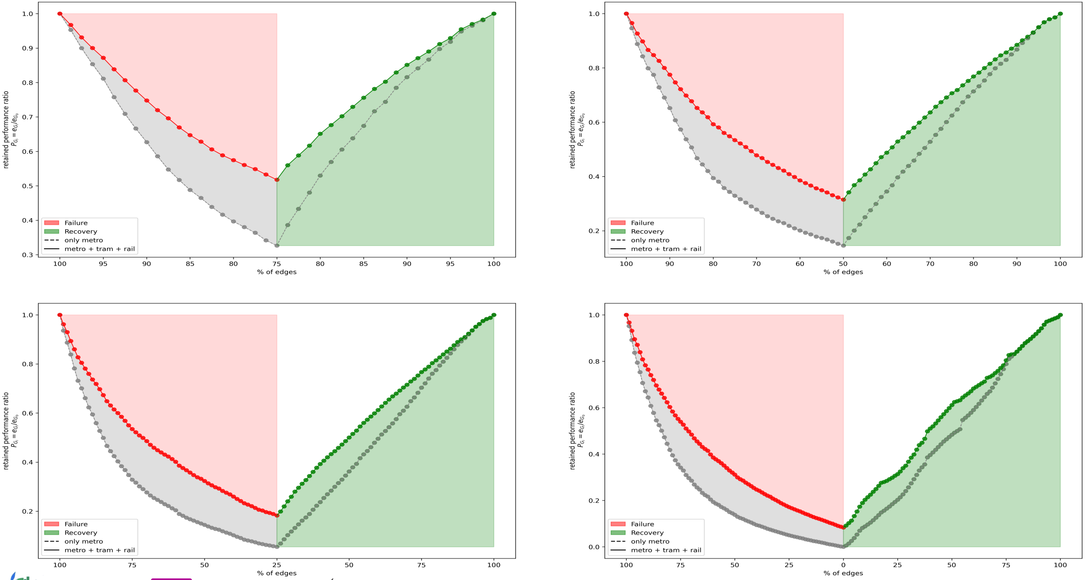
Only metro

Preliminary results (I) - Retained performance



Metro + tram + rail

Preliminary results (II) - Varying disruption levels



Preliminary results (III) - Retained performance

removed edges	cumulative performance loss **(F)**			cumulative performance gain **(R)**		
	only metro	multimodal	**improvement (%)**	only metro	multimodal	**improvement (%)**
25 %	10.15	7.04	**30.40**	18.07	19.65	**8.86**
50 %	29.36	21.27	**27.51**	30.48	34.40	**12.94**
75 %	52.26	40.04	**23.37**	40.12	46.88	**16.91**
100 %	76.44	62.19	**18.63**	49.62	57.14	**15.15**

Main takeaways

- Up to 30% cumulative performance saved during disruptions thanks to multi-modal networks
- Higher cumulative performance gains during recovery after larger disruptions

5. Outlook

Outlook

Summary

- Modelled the Dutch PT network as a multi-layer graph
- Studied the recoverability of Amsterdam metro and its relation to other modes
- Results show that multimodality leads to more robust and recoverable networks

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Next steps

- Complete the experiments for other cities and mode combinations
- Extend the analysis to other networks
- Simulate other disruptions (e.g., nodes, cascading)

Thank you for your attention!

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