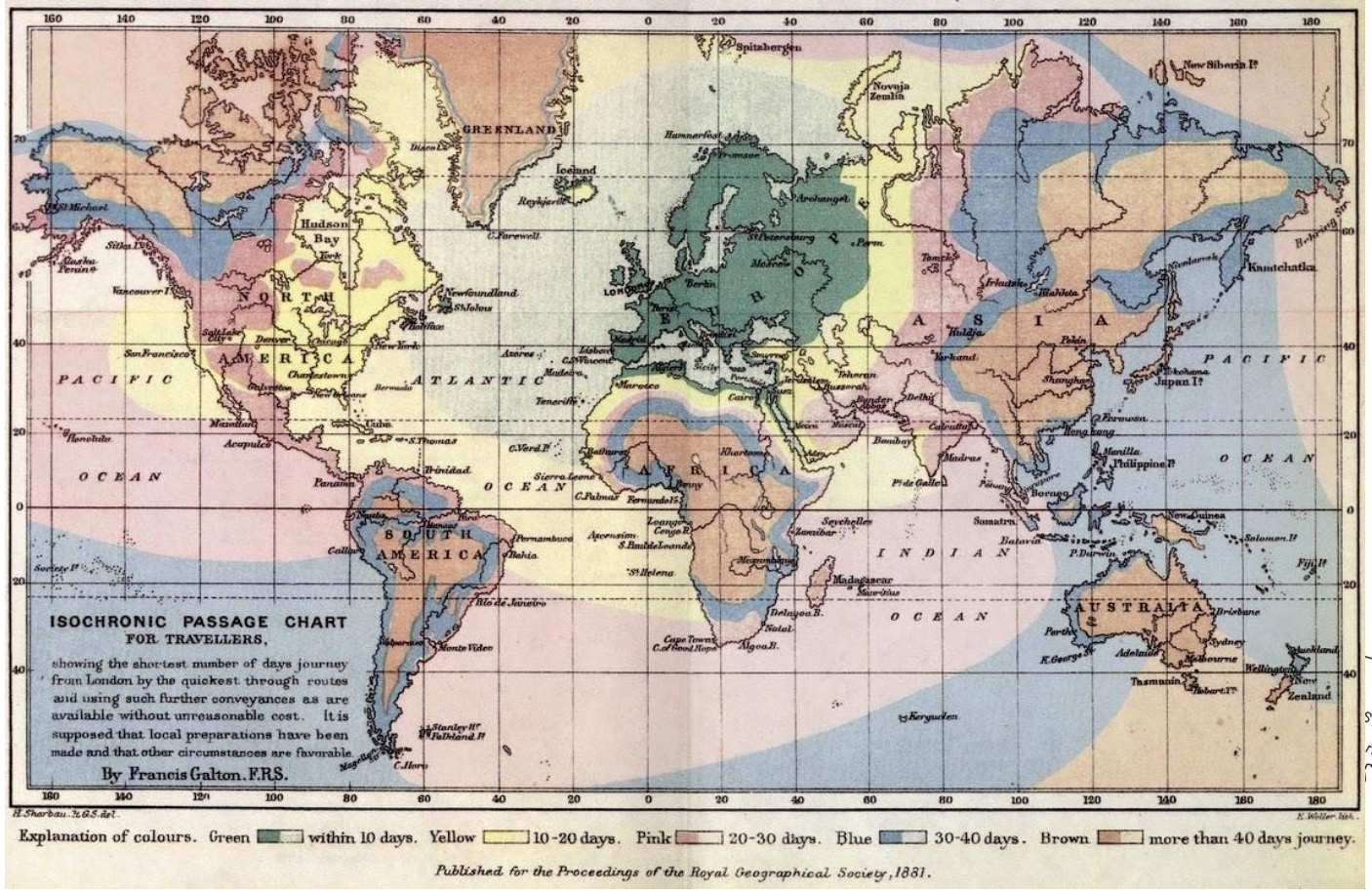
Graphs and Data in Passenger Transport Systems

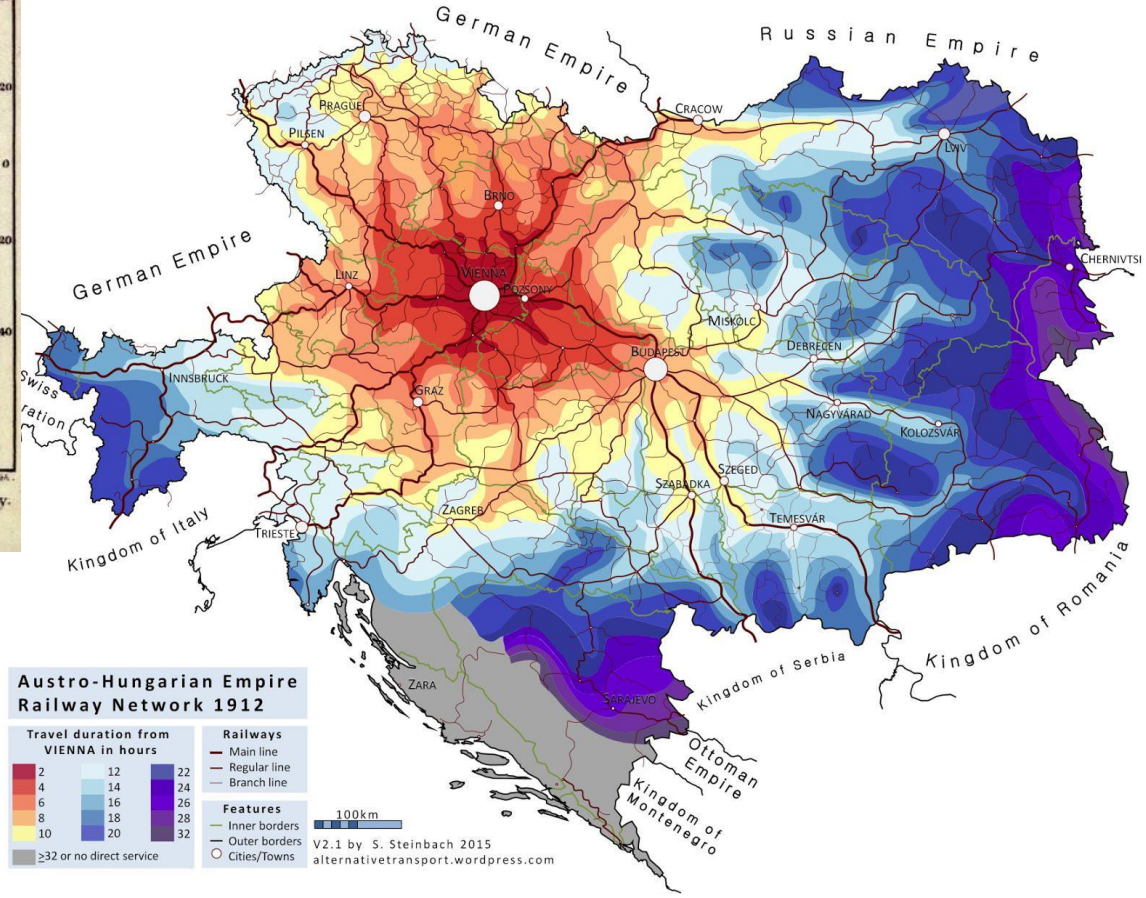
Oded Cats, with contributions by lab members

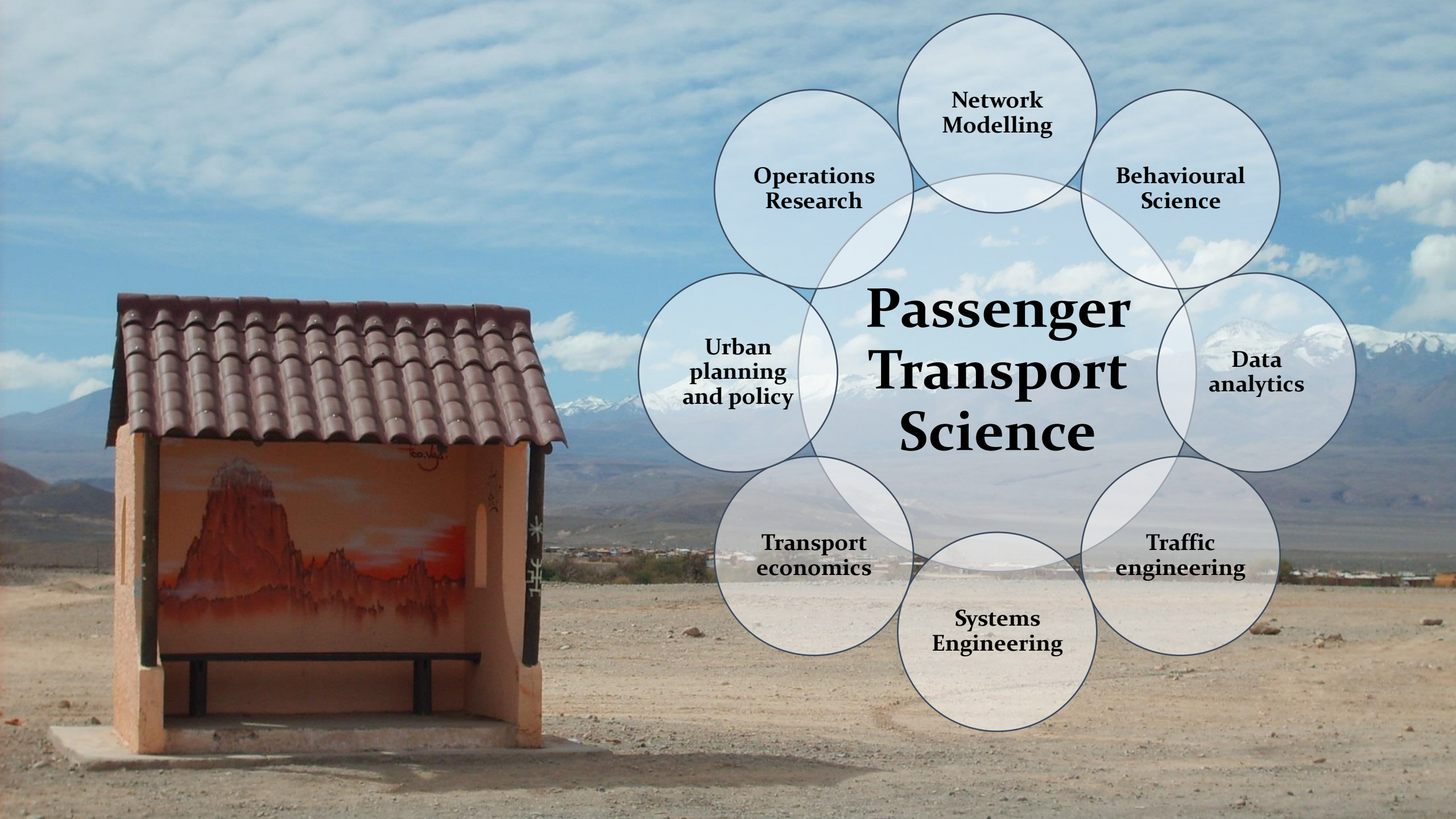
Lab Smart Public Transport

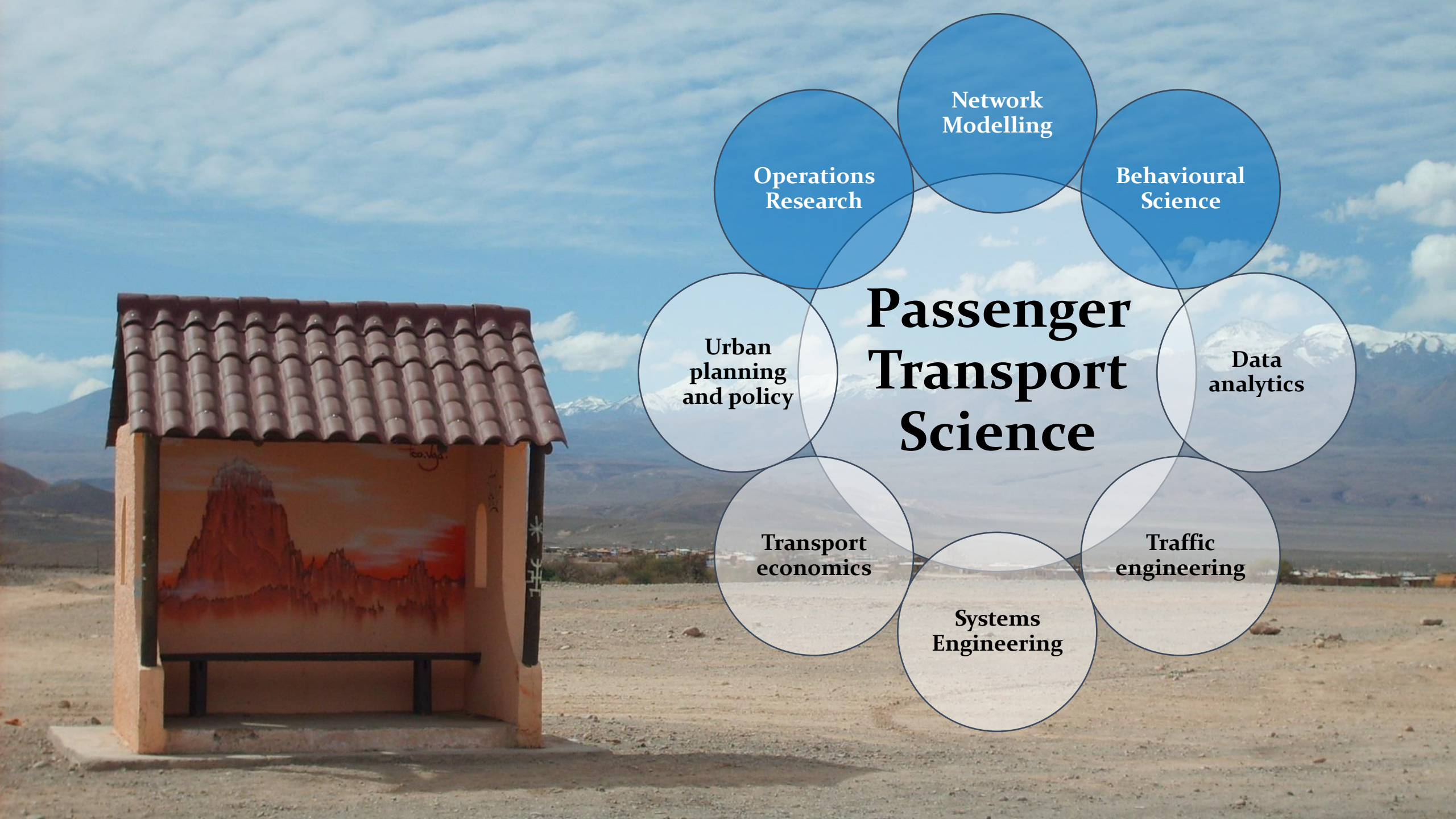
Graphs & Data Seminar Series, 5 June 2025

TU Delft


ISOCHRONIC PASSAGE CHART
FOR TRAVELLERS,
showing the shortest number of days journey from London by the quickest through routes and using such further conveyances as are available without unreasonable cost. It is supposed that local preparations have been made and that other circumstances are favorable
By Francis Galton. F.R.S.
Explanation of colours. Green within 10 days. Yellow 10-20 days. Pink 20-30 days. Blue 30-40 days. Brown more than 40 days journey.
Published for the Proceedings of the Royal Geographical Society, 1881.


German Empire
Russian Empire
German Empire
Kingdom of Italy
Kingdom of Serbia
Kingdom of Romania
Ottoman Empire
Kingdom of Montenegro
Swiss ration
PRAGUE
PILSEN
CRACOW
LVIV
BRNO
LINZ
VIENNA
POZSONY
CHERNIVTSI
MISKOLC
DEBRECEN
BUDAPEST
INNSBRUCK
GRAZ
NAGYVÁRAD
KOLOZSVÁR
SZEGED
SZABADKA
ZAGREB
TEMESVÁR
TRIESTE
ZARA
SARAJEVO
Austro-Hungarian Empire
Railway Network 1912
Travel duration from VIENNA in hours
2 4 6 8 10 12 14 16 18 20 22 24 26 28 32
≥32 or no direct service
Railways
Main line
Regular line
Branch line
Features
Inner borders
Outer borders
Cities/Towns
100km
V2.1 by S. Steinbach 2015
alternativetransport.wordpress.com


Network Modelling
Operations Research
Behavioural Science
Urban planning and policy
Passenger Transport Science
Data analytics
Transport economics
Traffic engineering
Systems Engineering


Network Modelling
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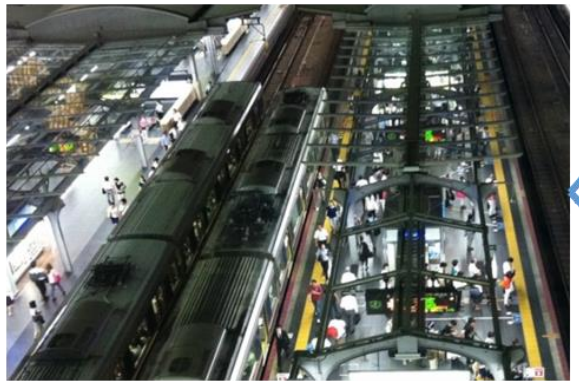


Networks

Operations

Behaviour

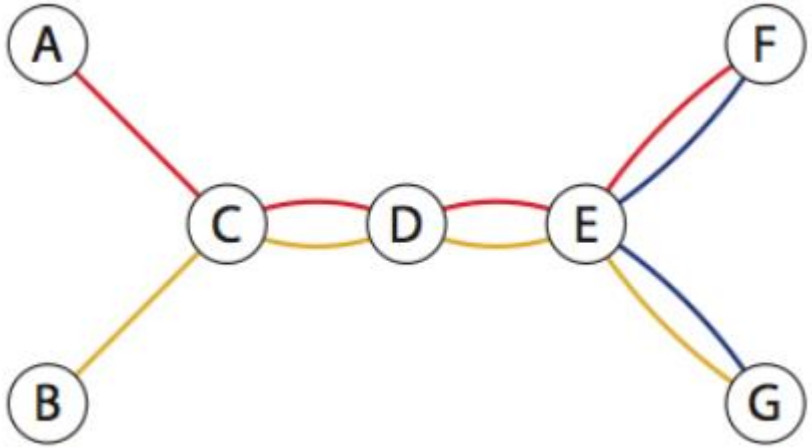
Public transport services


Verklaring van symbolen
Grote overstapstations
Belangrijke overstapstations
Eindstations en overstapstations voor regionaal vervoer
Overige stations
Treindienst NS
Treindienst Arriva
Treindienst Syntus
Treindienst Connexxion
Treindienst Veolia
Treindienst DB Regionalbahn Westfalen
Treindienst NS Hispeed, met toeslag/ Service NS Hispeed, with supplement
Internationale verbindingen


Pagina 1: treinseries ma-do tot 20 uur
Pagina 2: treinseries vrijdag tot 20 uur
Pagina 3: treinseries na 20 uur
Pagina 4: treinseries Weekend
Spoorkaart 2023

PT NETWORK GRAPH REPRESENTATIONS

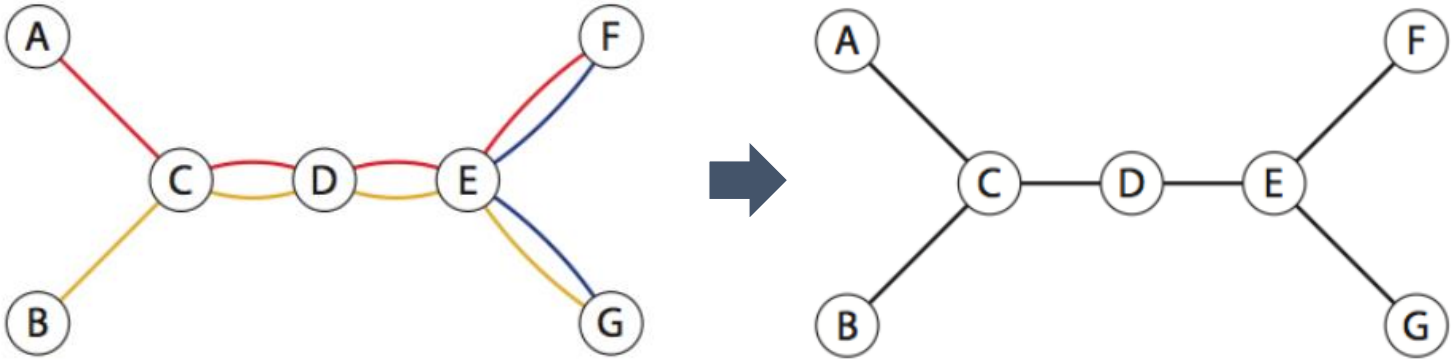
- Infrastructure (L) space
- Service (P) space
- Transfer possibility (C) space
- Transfer journey (B) space



INFRASTRUCTURE (L) SPACE

- Nodes – stations
- Links – line/corridor segments

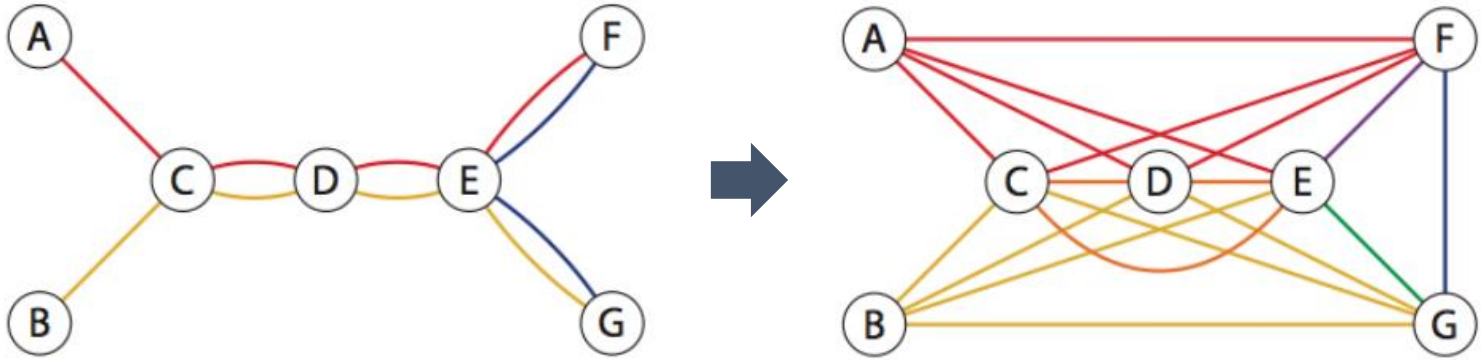
Connecting any pair of consecutive stations along a line



SERVICE (P) SPACE

- Nodes – stations
- Links – direct service connections

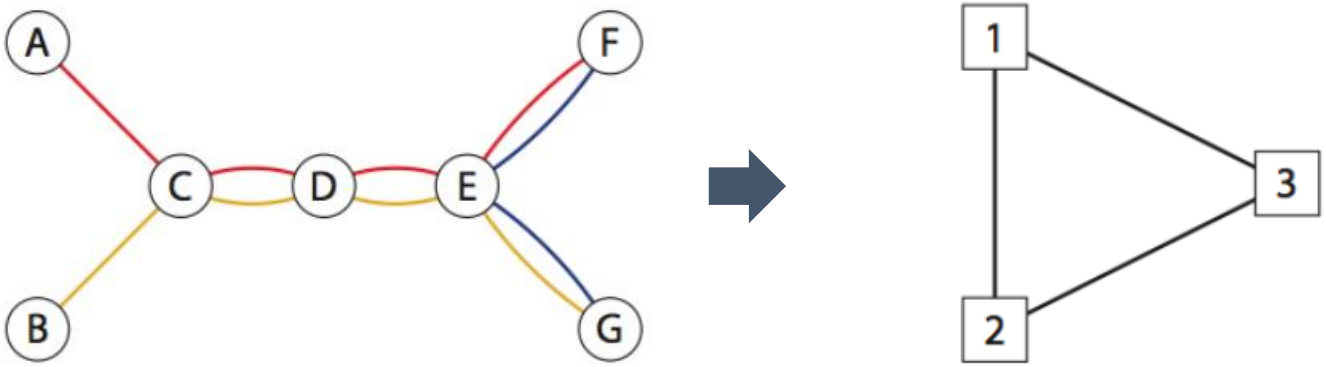
Connecting any pair of stations that are served by a common line



TRANSFER POSSIBILITY (C) SPACE

- Nodes – lines
- Links – common transfer station

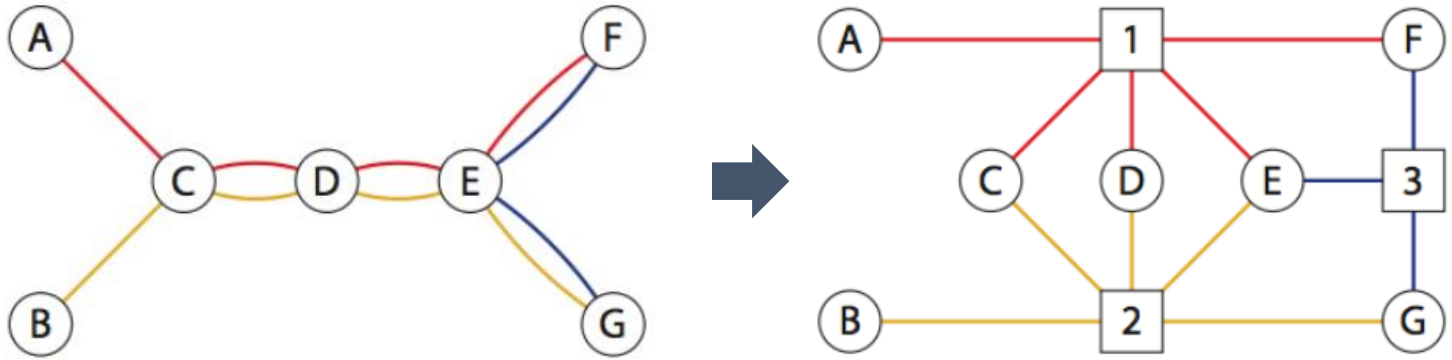
A dual graph of the Infrastructure-space

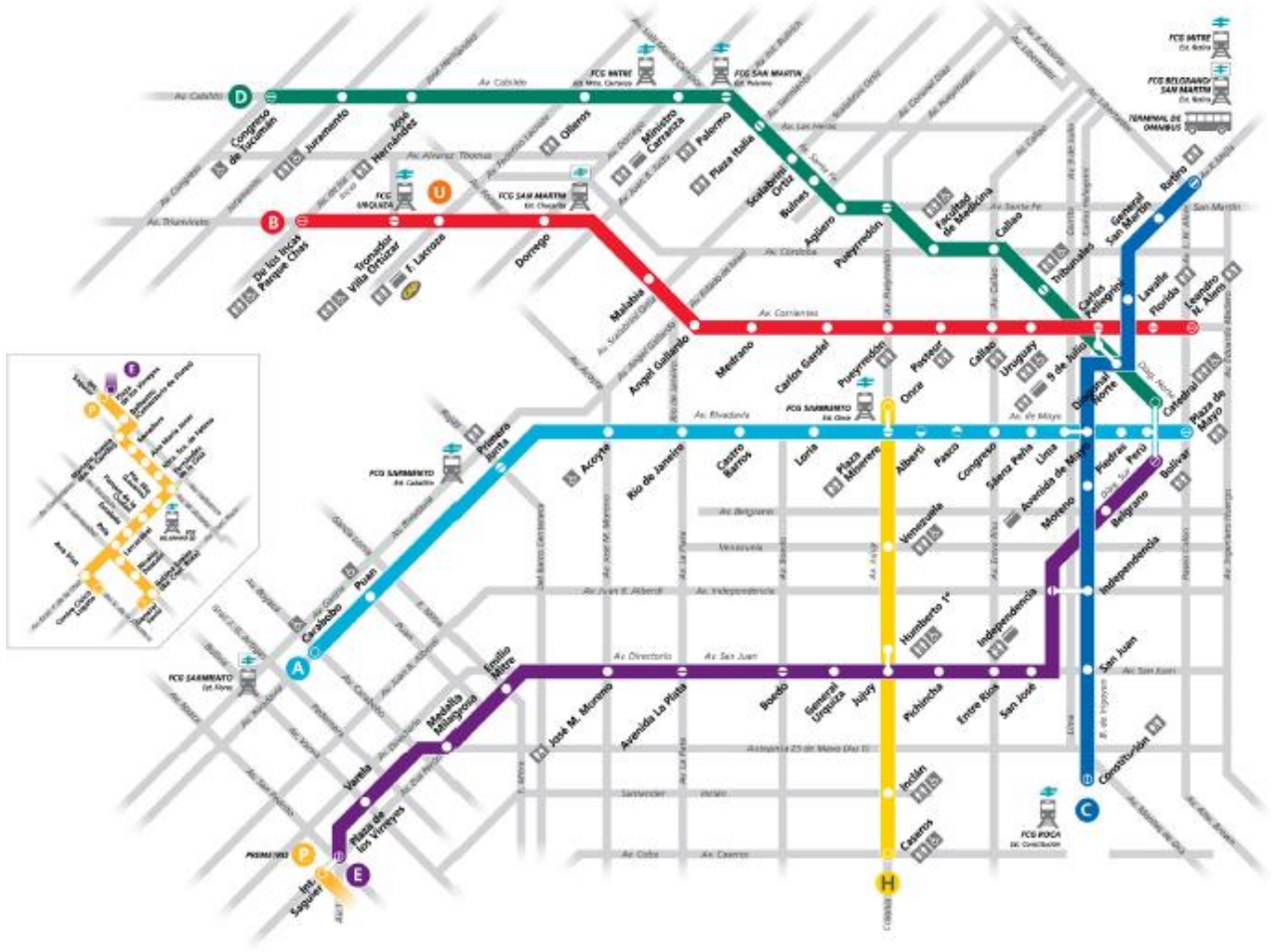


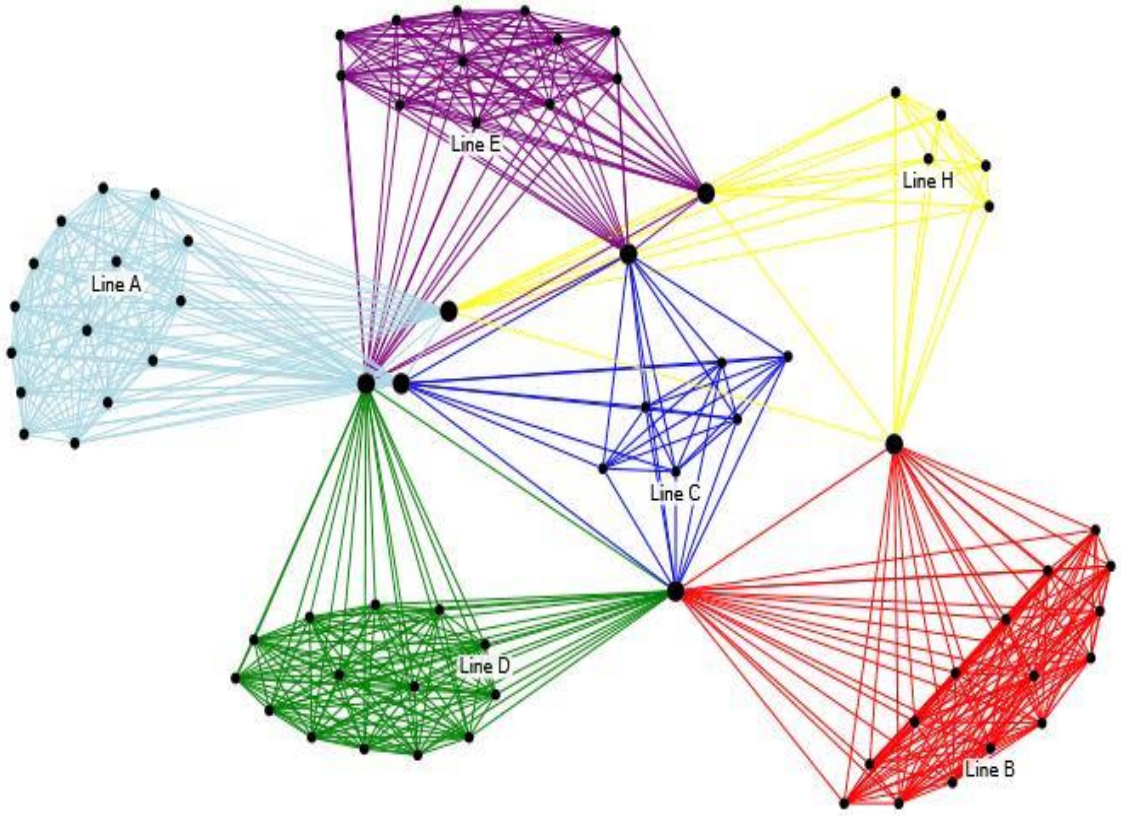
TRANSFER JOURNEY (B) SPACE

- Nodes – stations and lines
- Links – service segments

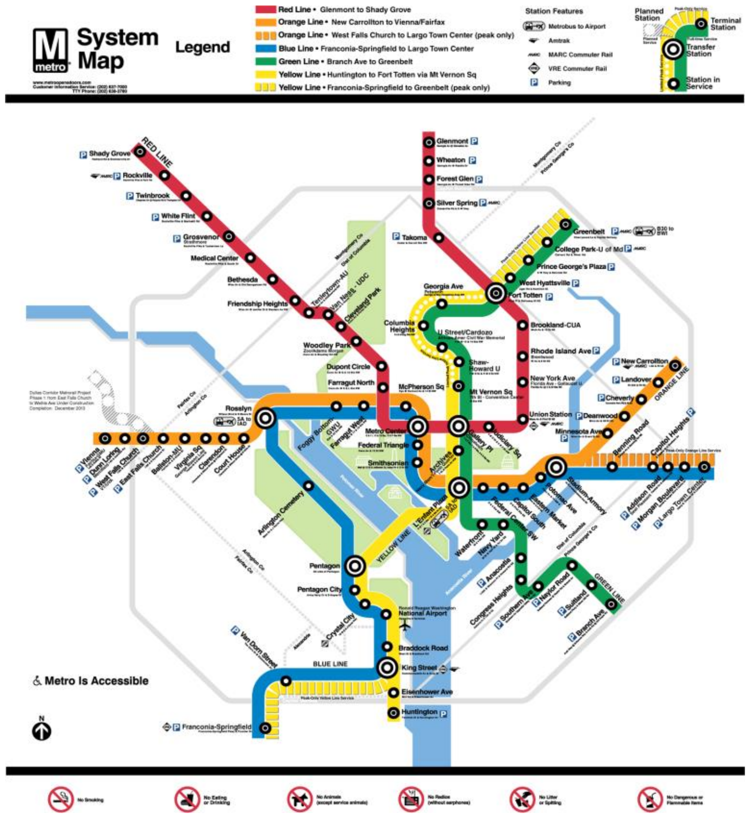
Connecting to ‘line nodes’ all ‘station nodes’ that are served by this line



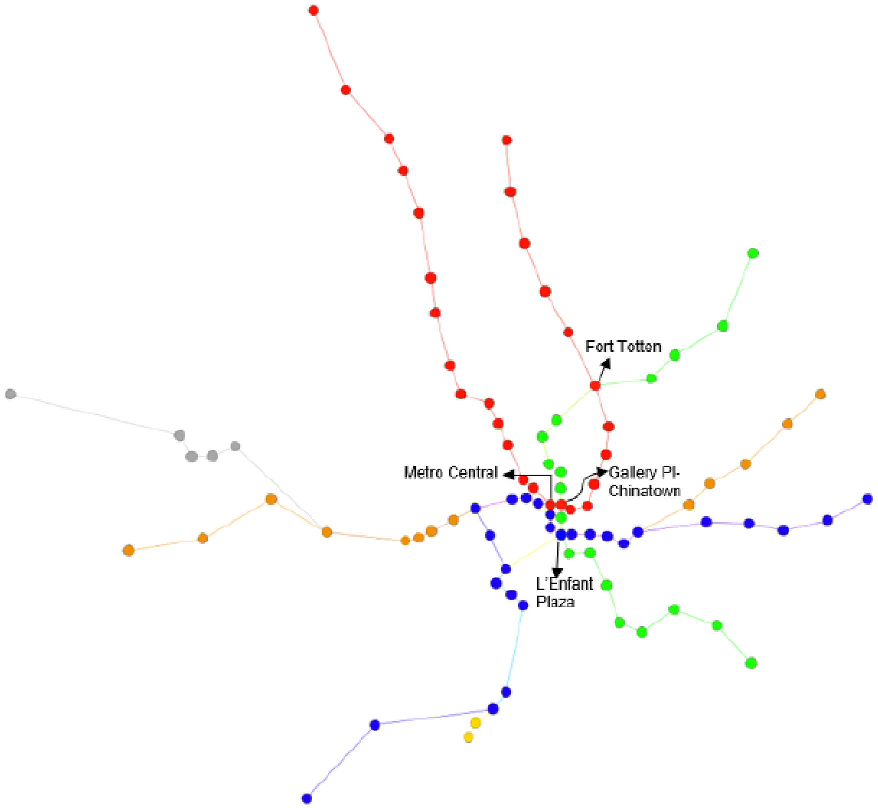




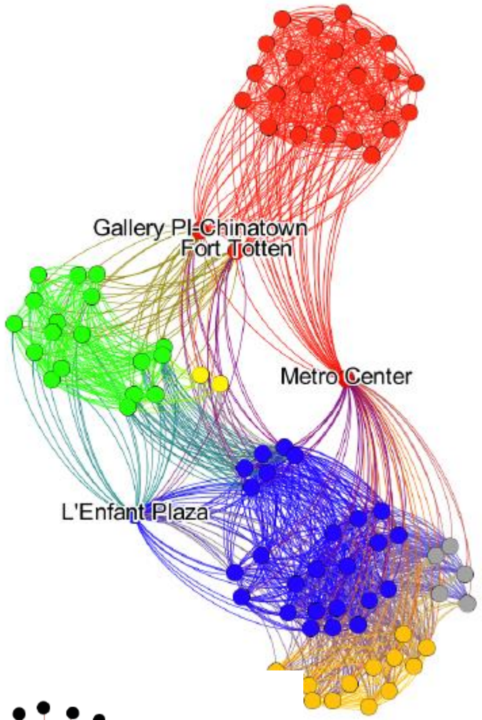
Created with NodeXL (http://nodexl.codeplex.com)



System Map
Legend
Red Line • Glenmont to Shady Grove
Orange Line • New Carrollton to Vienna/Fairfax
Orange Line • West Falls Church to Largo Town Center (peak only)
Blue Line • Franconia-Springfield to Largo Town Center
Green Line • Branch Ave to Greenbelt
Yellow Line • Huntington to Fort Totten via Mt Vernon Sq
Yellow Line • Franconia-Springfield to Greenbelt (peak only)
Metro Is Accessible



Fort Totten
Metro Central
Gallery Pl-Chinatown
L'Enfant Plaza



Gallery Pl-Chinatown
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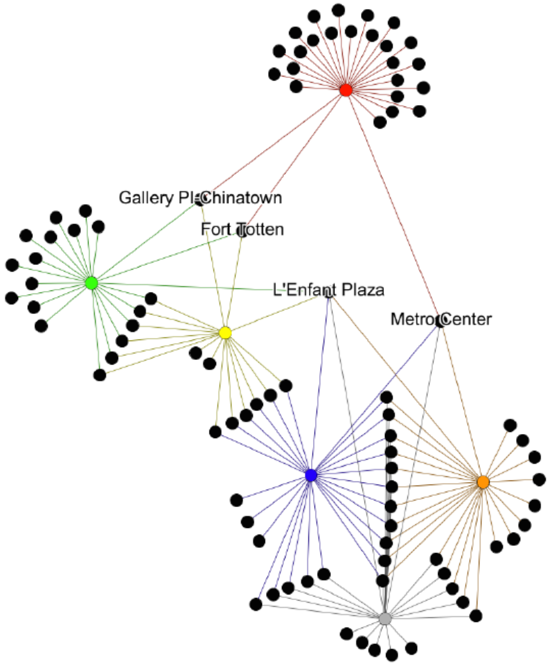

Gallery Pl-Chinatown
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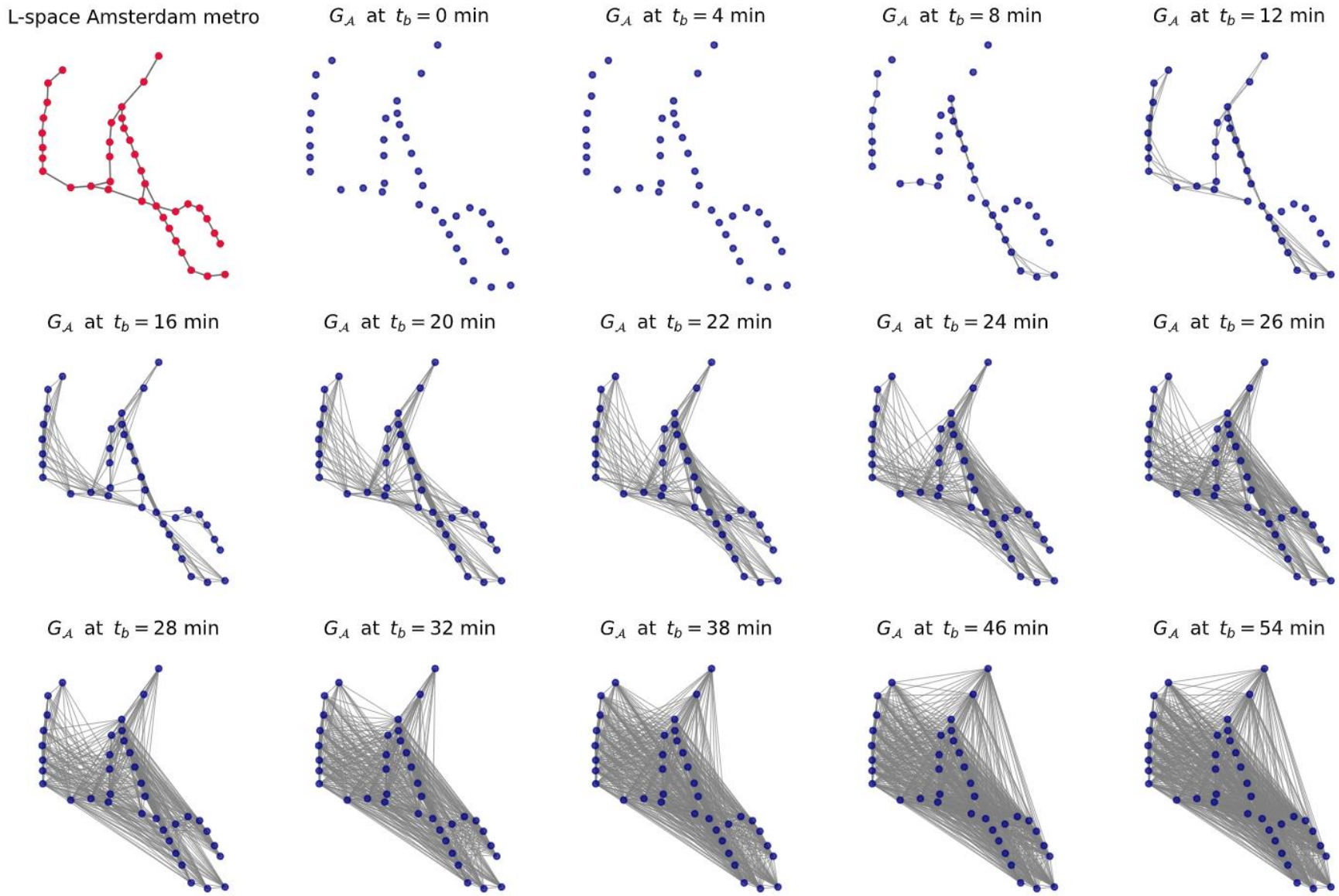
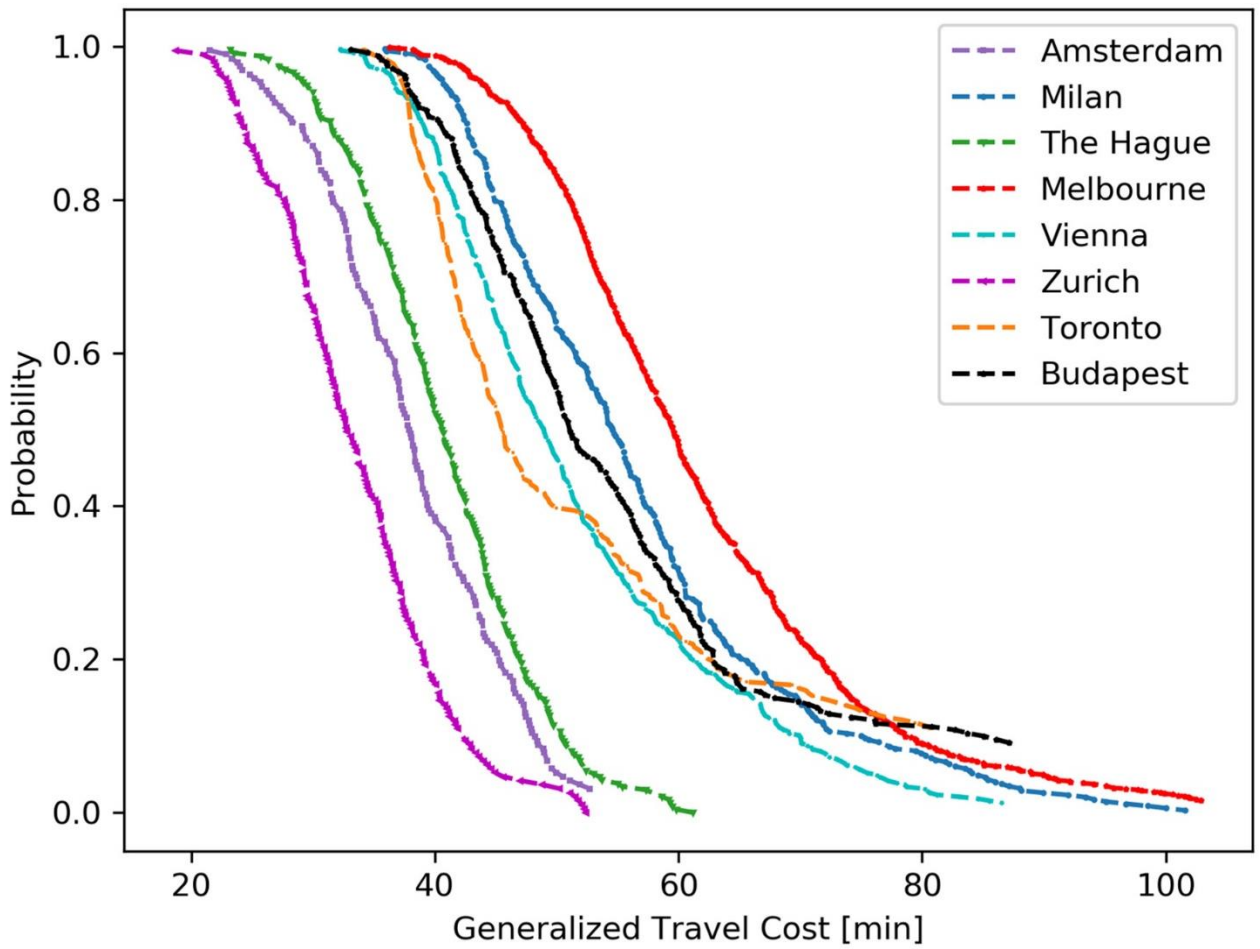
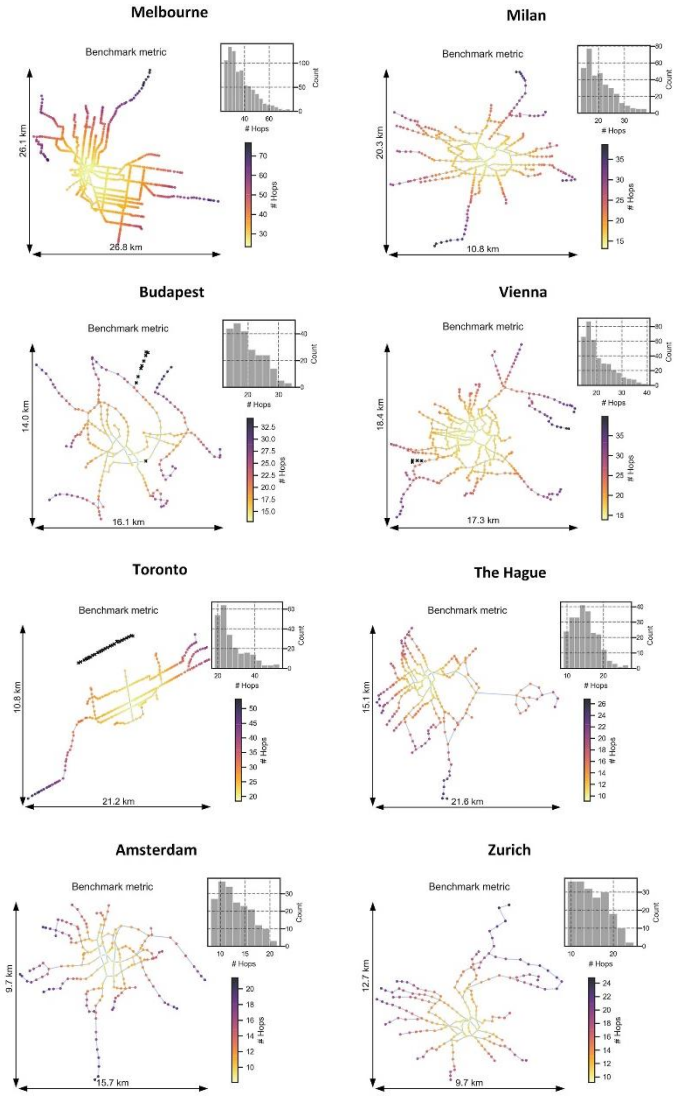


Šfiligoj et al. (2025). Access Graph: a Novel Graph Representation of Public Transport Networks for Accessibility Analysis. Working paper.

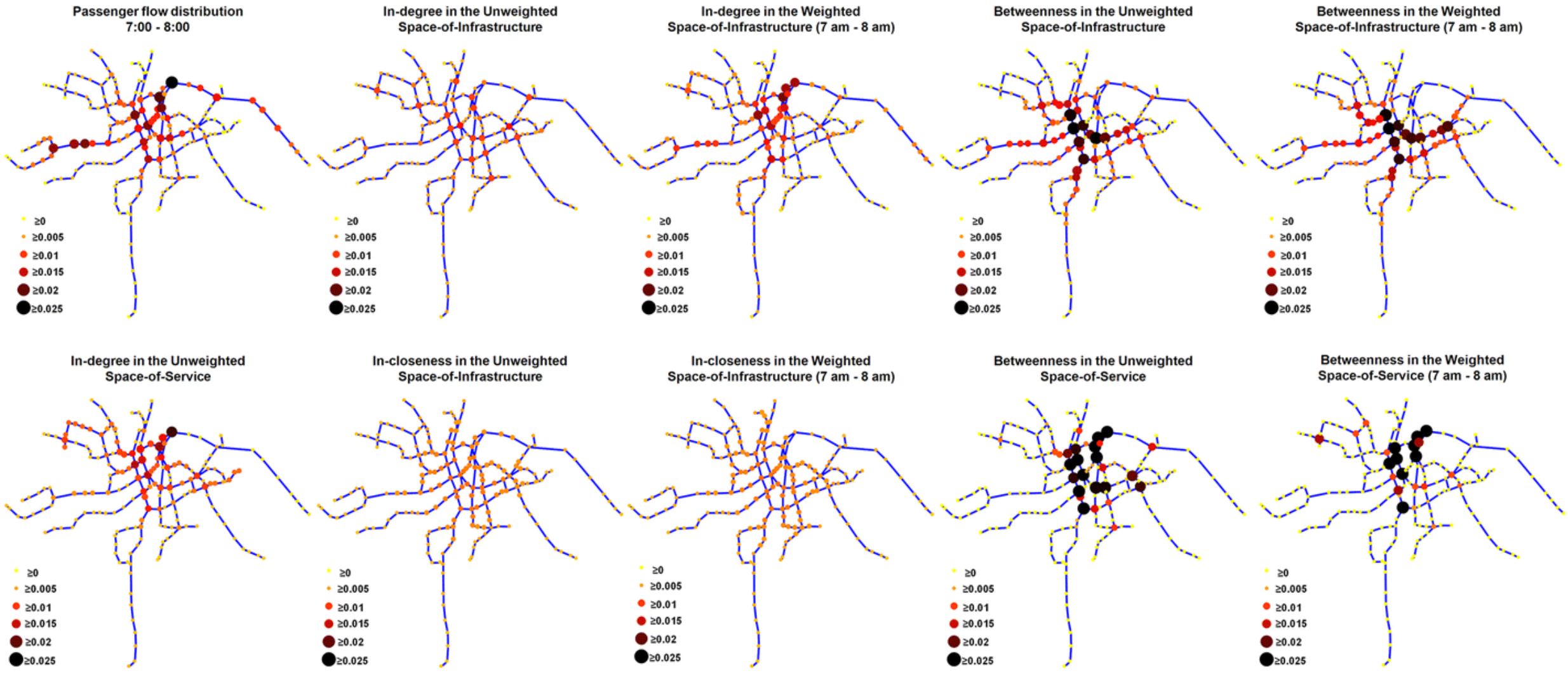
ACCESSIBILITY





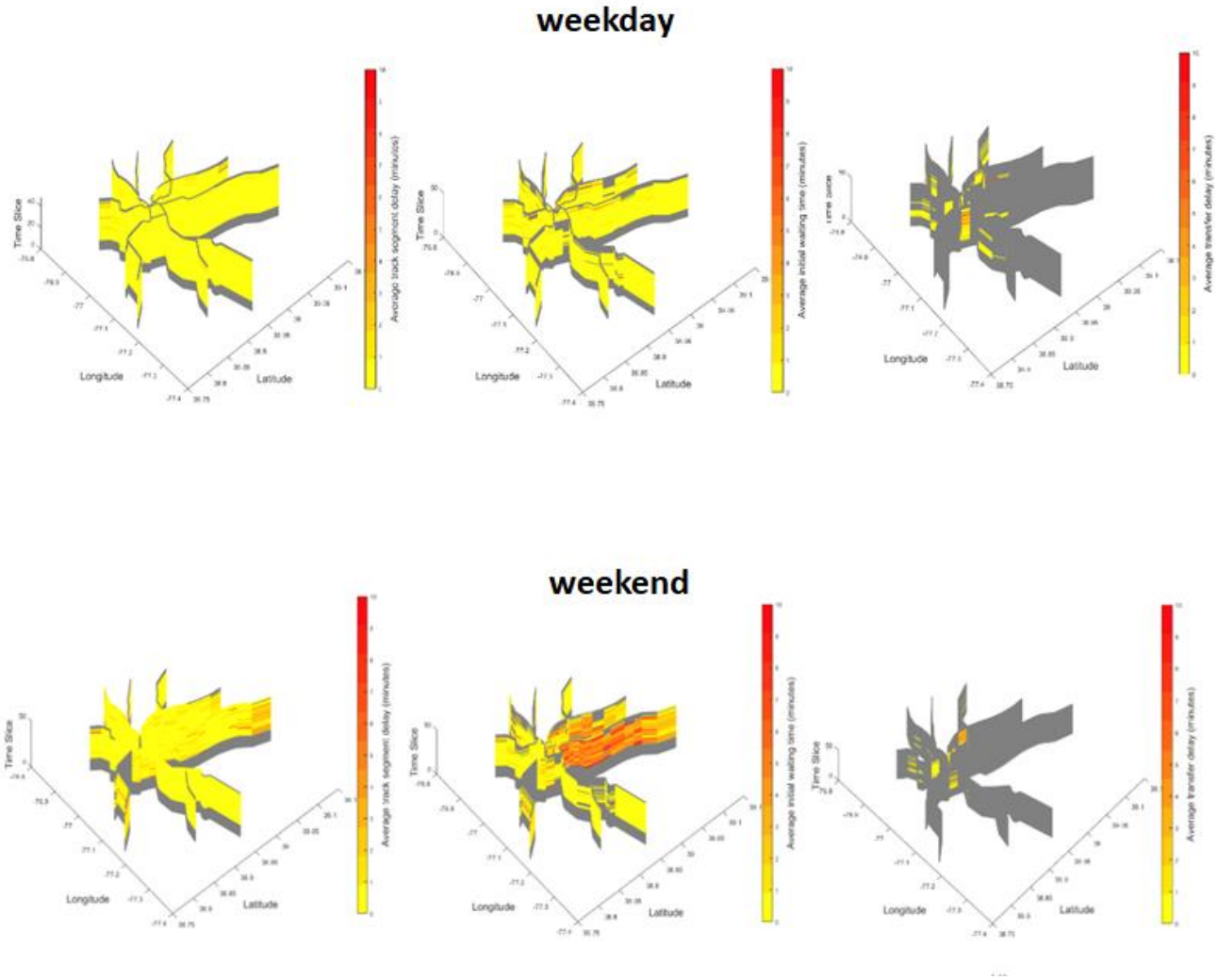
Luo et al. (2019). Integrating Network Science and Public Transport Network Accessibility Analysis for Comparative Assessment. *Journal of Transport Geography*.

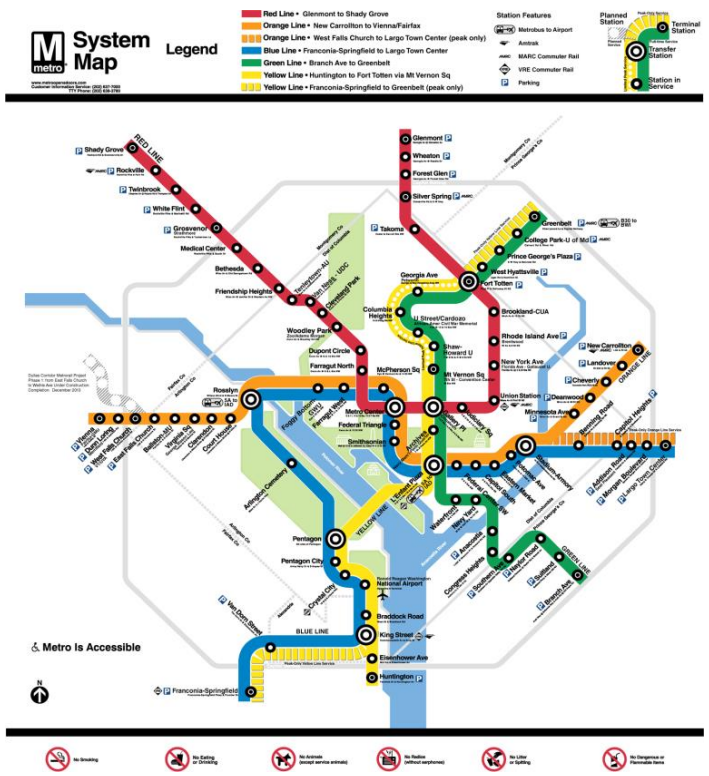
DEMAND DISTRIBUTION



Luo et al. (2020). Can Passenger Flow Distribution be Estimated Solely based on Network Properties in Public Transport Systems? *Transportation*.

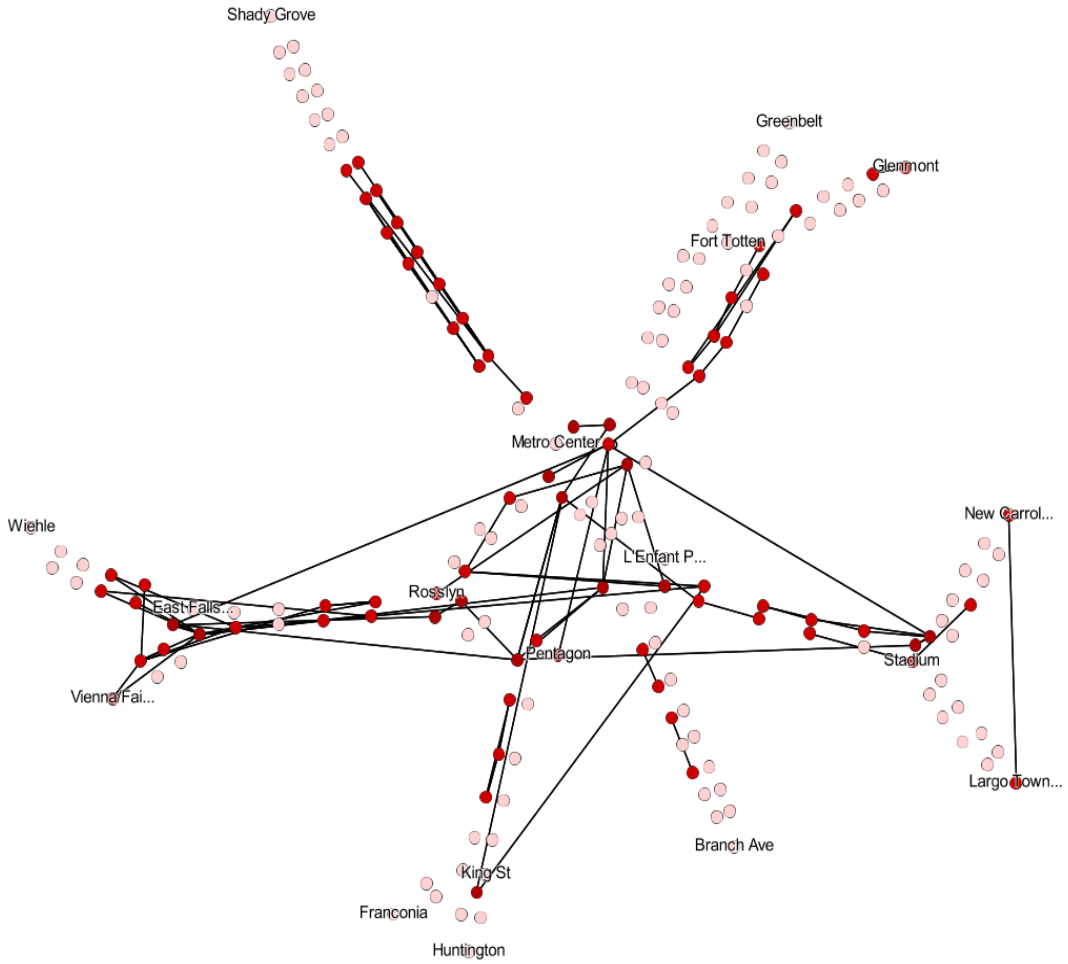
PASSENGER DELAY

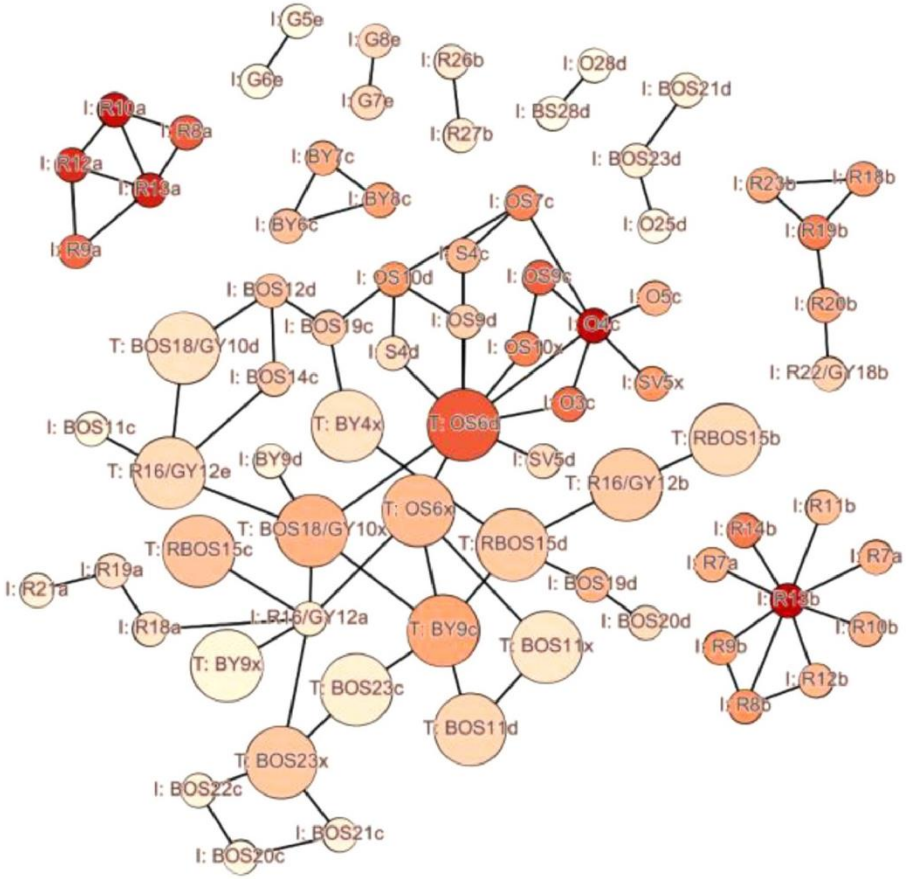




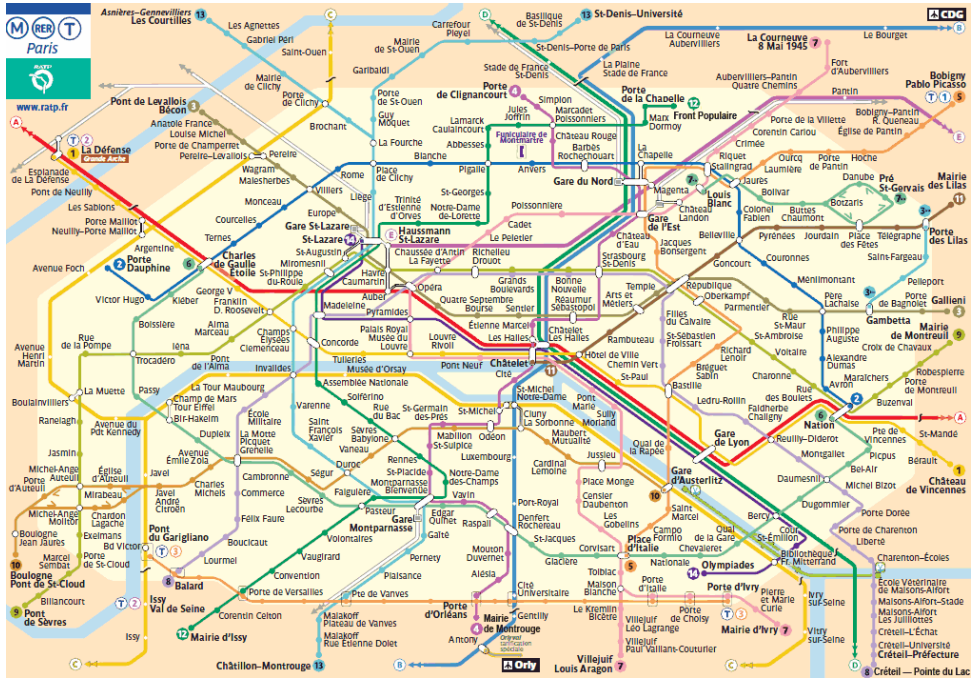
Krishnakumari et al. (2020). Estimation of Metro Network Passenger Delay from Individual Trajectories. *Transportation Research Part C.*

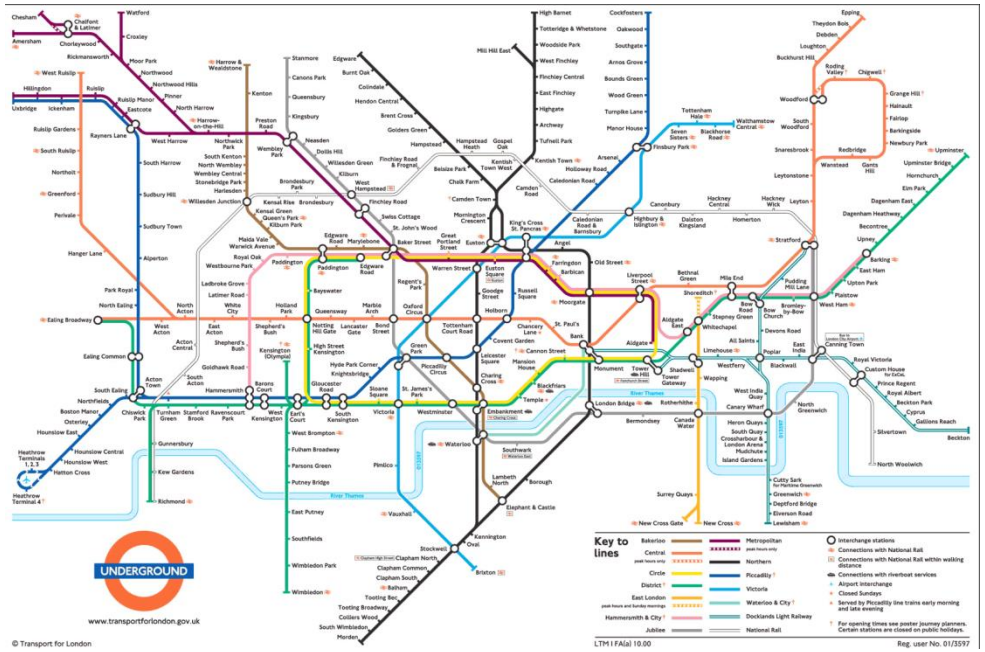
DELAY PROPAGATION





Cats and Hijner (2021). Quantifying the Cascading Effects of Passenger Delays. *Reliability Engineering & System Safety*.





LONDON VS. PARIS

Which metro system is more vulnerable?

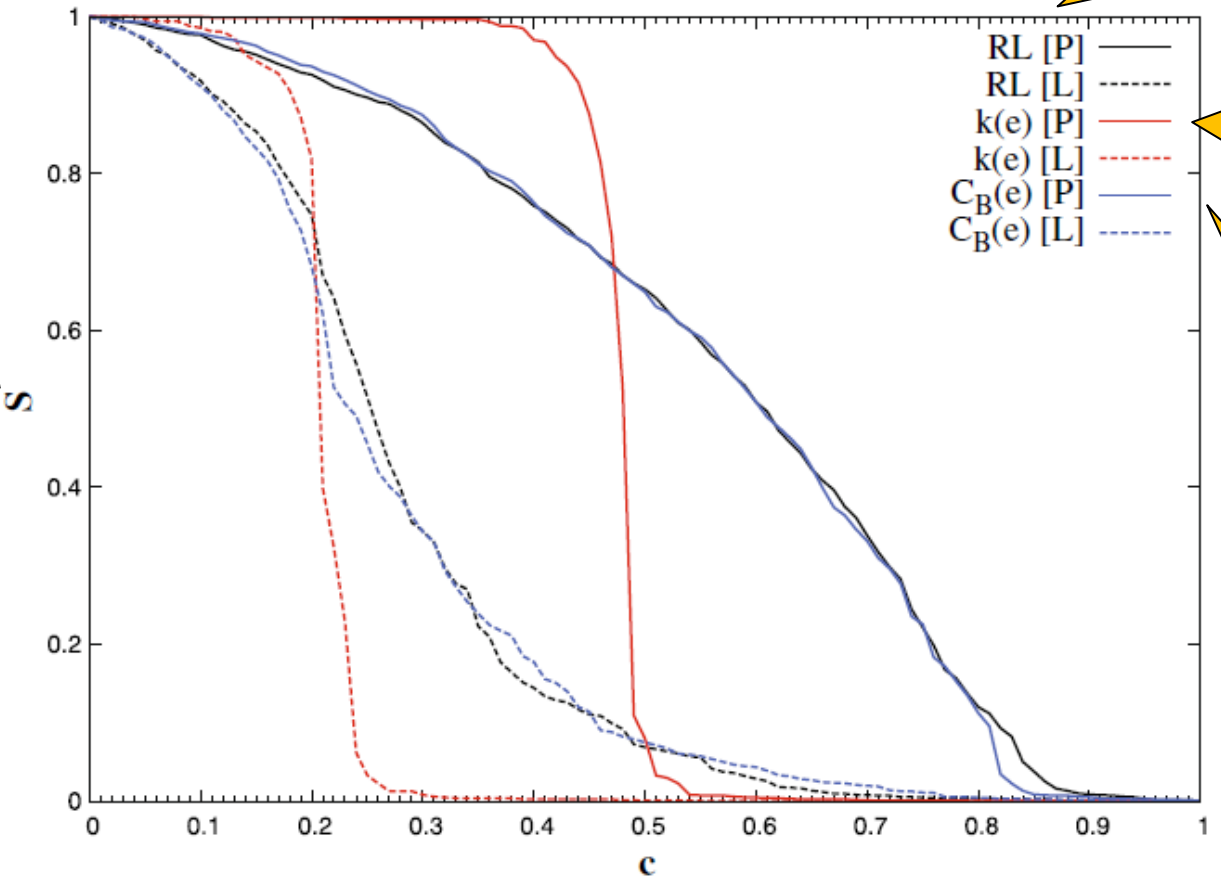
NETWORK VULNERABILITY

Random link removal

Remove highest degree

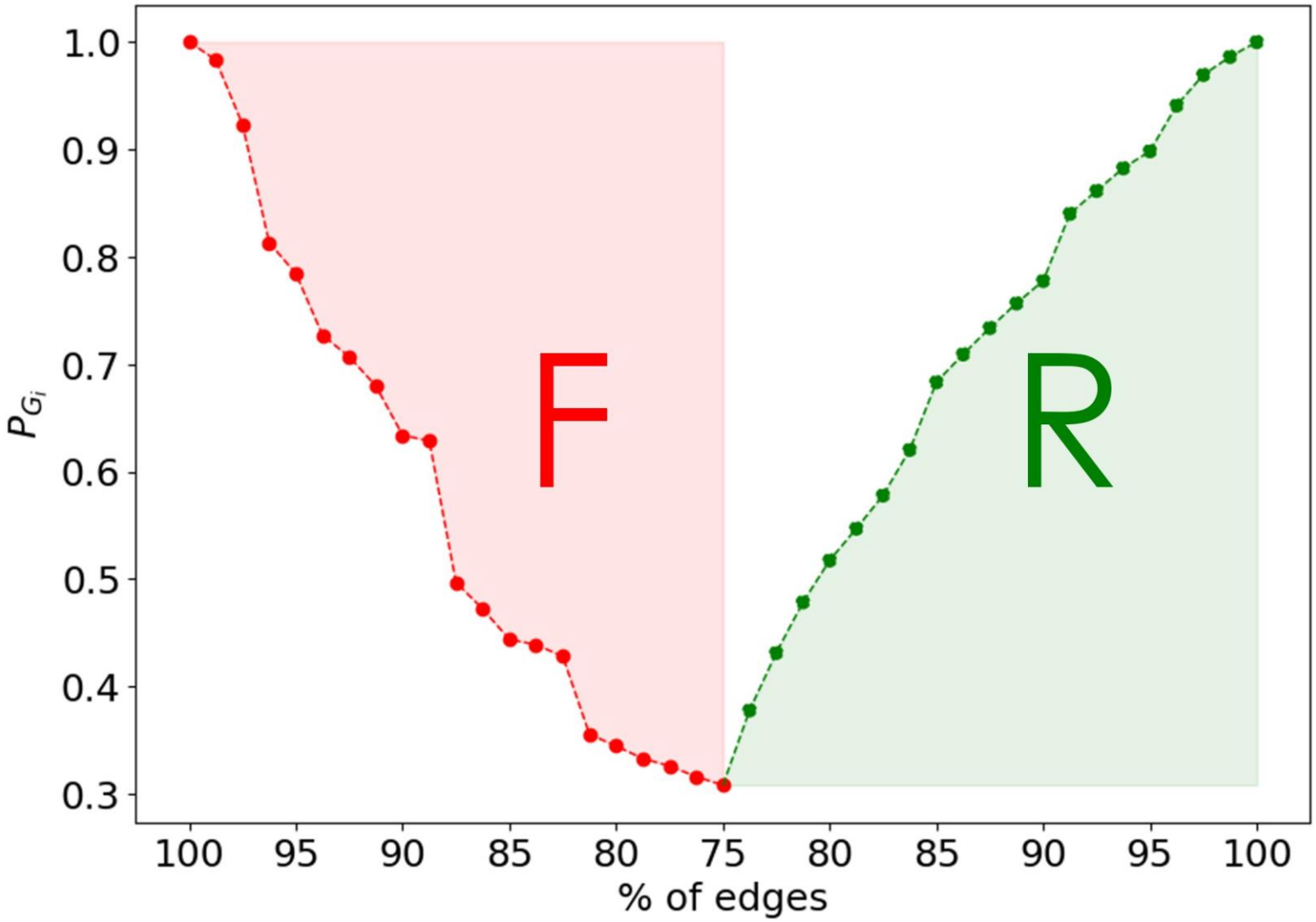
Remove highest BC

Relative size of the largest component of the network

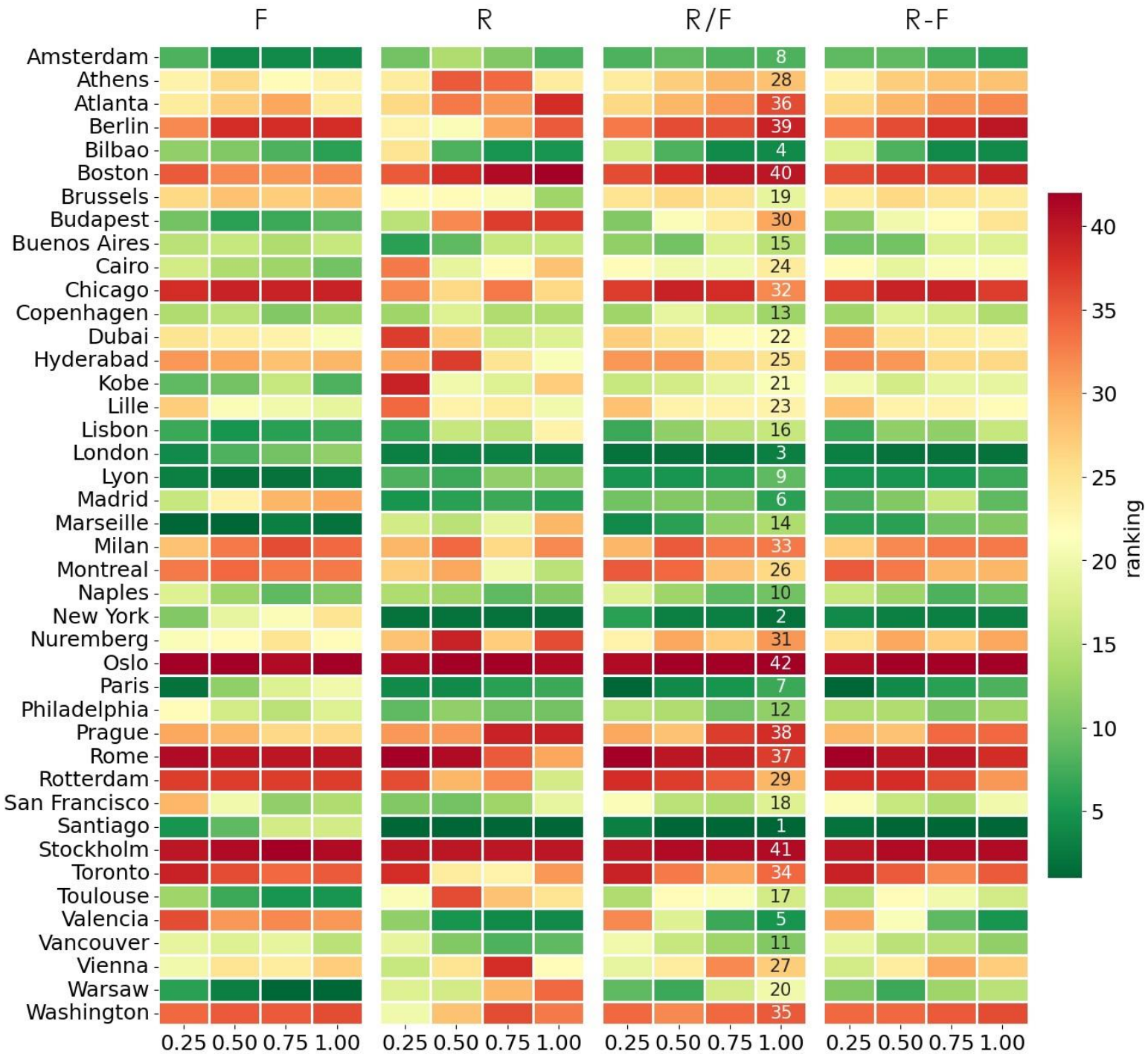


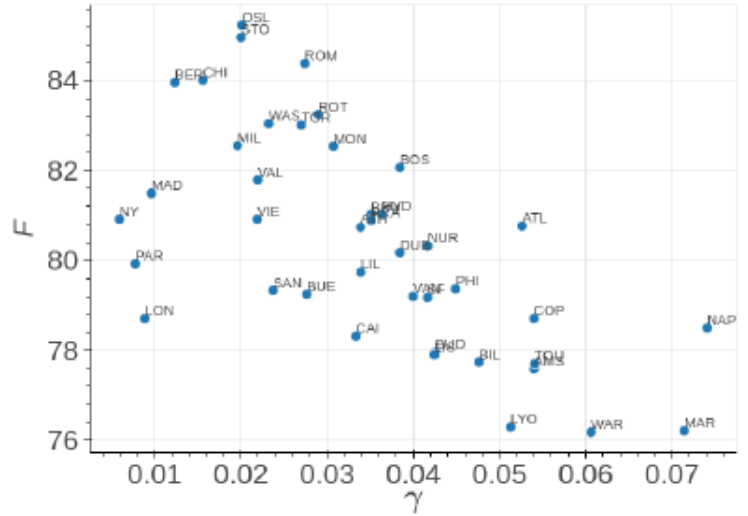
von Ferber et al. (2012). A Tale of Two Cities: Vulnerabilities of the London and Paris Transit Networks. *Journal of Transportation Security.*

VULNERABILITY AND RECOVERABILITY

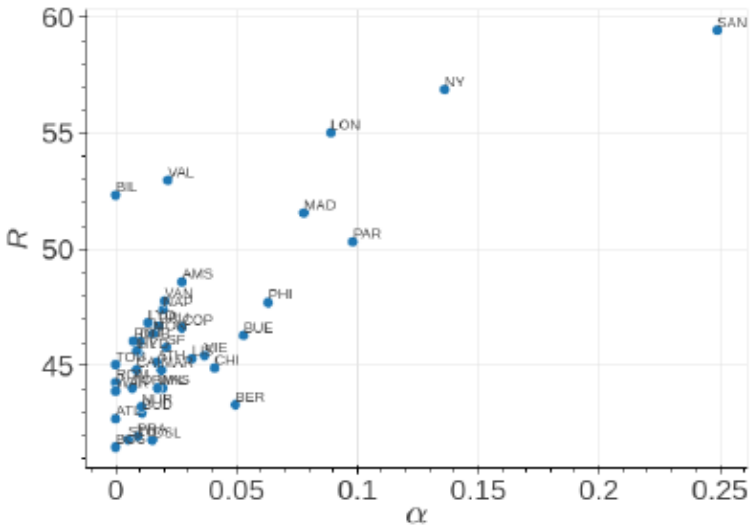


Massobrio and Cats (2024). Topological Assessment of Recoverability in Metro Networks. *Communication Physics*.



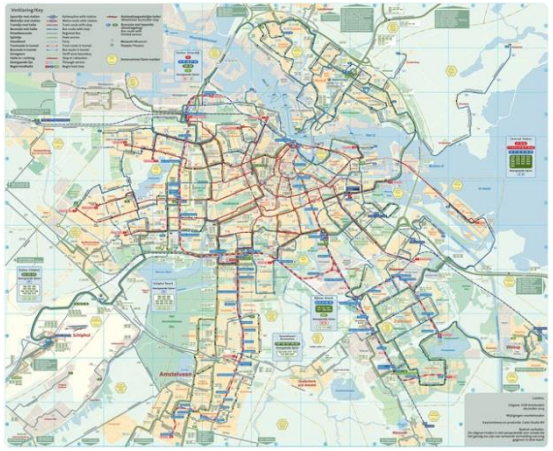


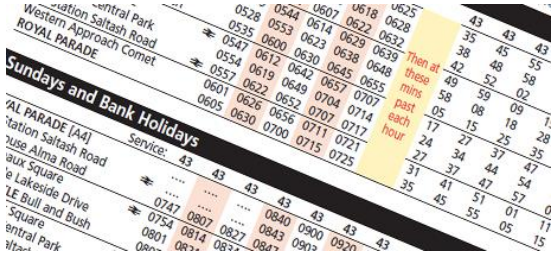
(a) F indicator versus density γ



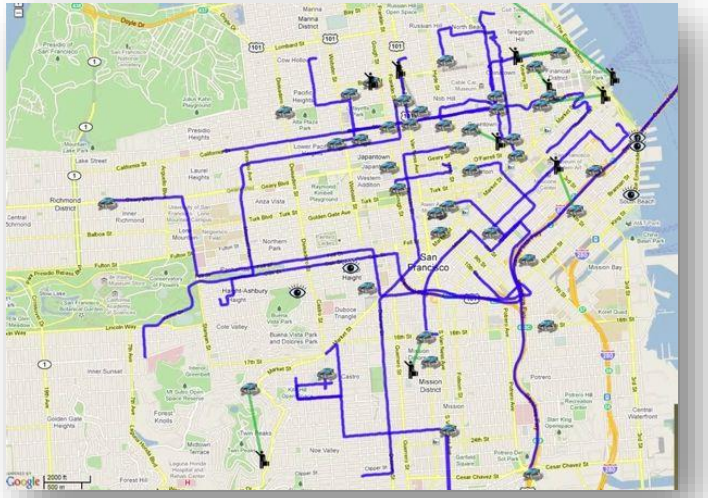
(b) R indicator versus meshedness α

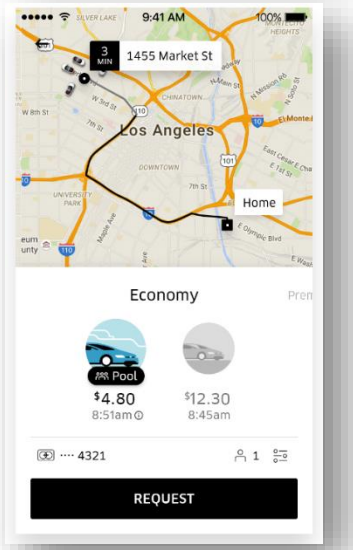
Mobility-on-Demand

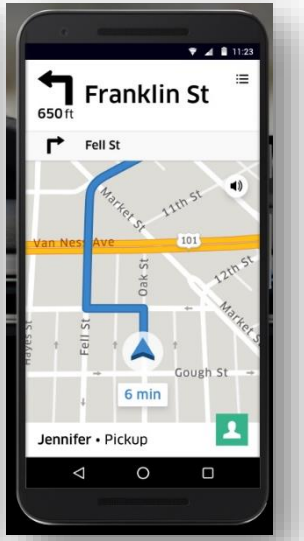



Sundays and Bank Holidays
Then at these mins past each hour

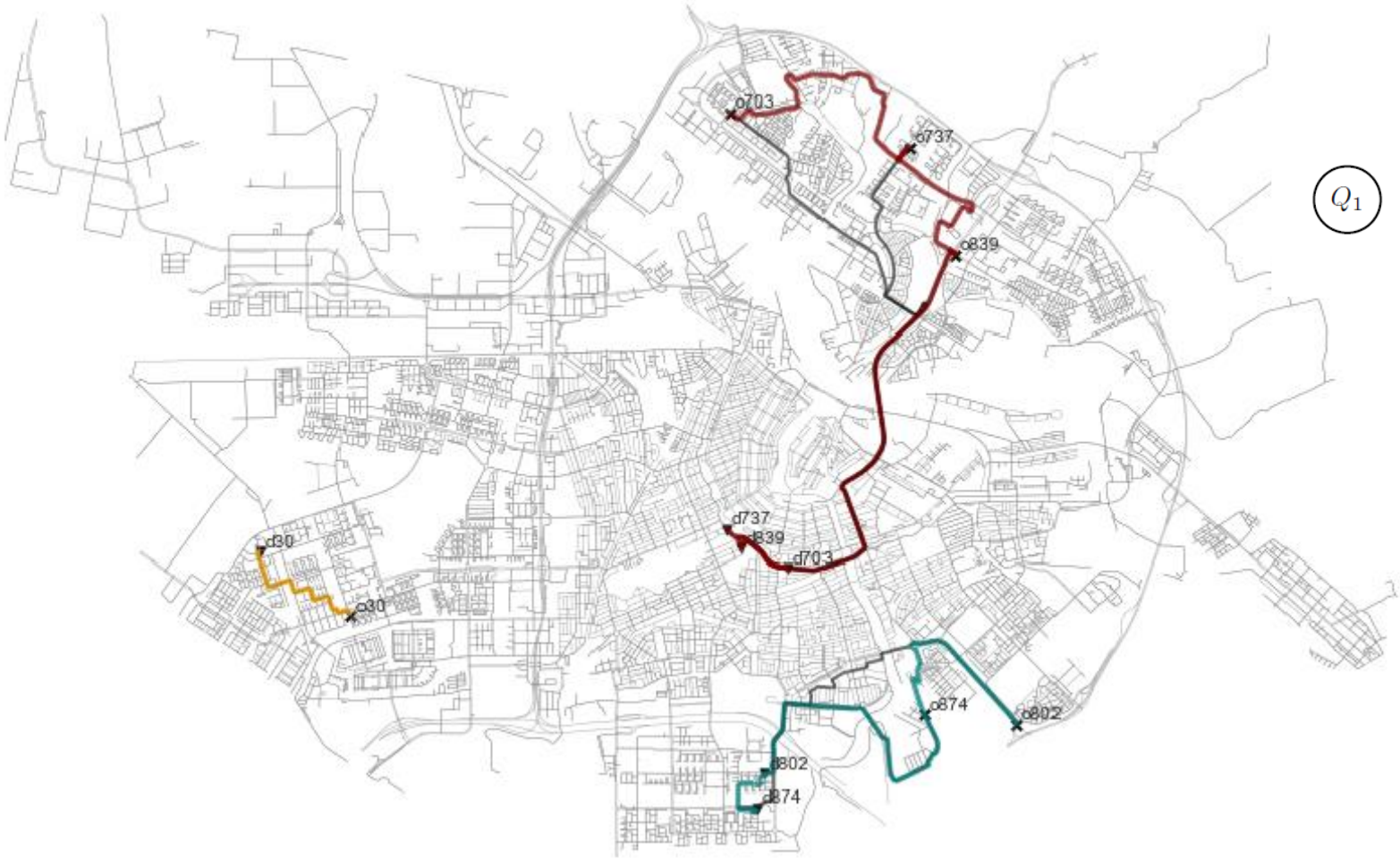

Ej i trafik
Klar för trafik

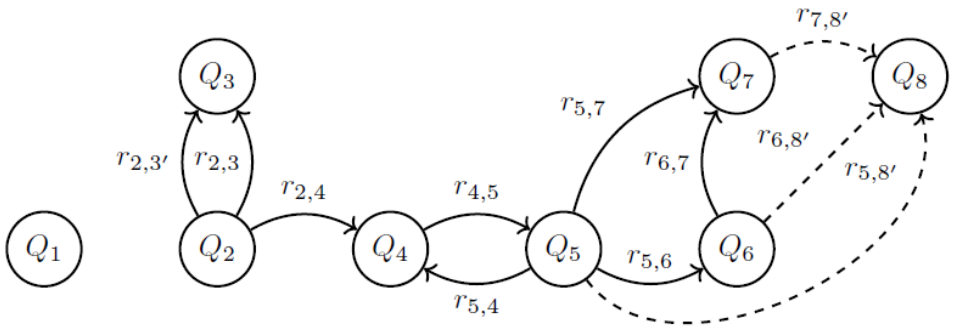



9:41 AM
100%
3 MIN
1455 Market St
Los Angeles
Home
Economy
Pool
$4.80
8:51am
$12.30
8:45am
···· 4321
1
REQUEST


Franklin St
650 ft
Fell St
Van Ness Ave
Gough St
6 min
Jennifer • Pickup

EXACT MATCHING OF ATTRACTIVE SHARED RIDES





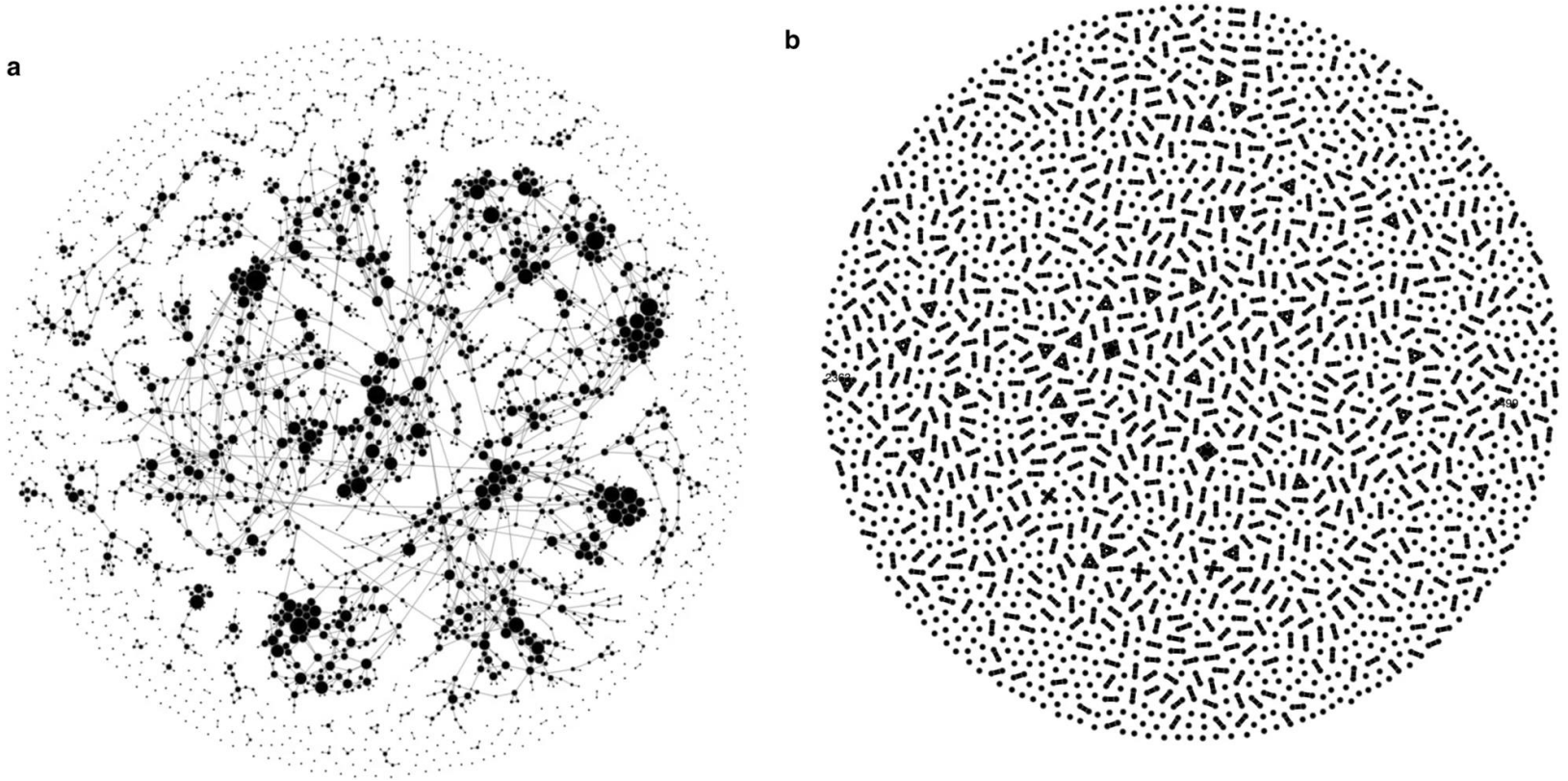
Maximum detour that yields an attractive shared ride

$$\delta_i = \left(\frac{1}{\beta^s} - 1\right) t_i + \frac{\beta^c}{\beta^t \beta^s} \lambda l_i$$

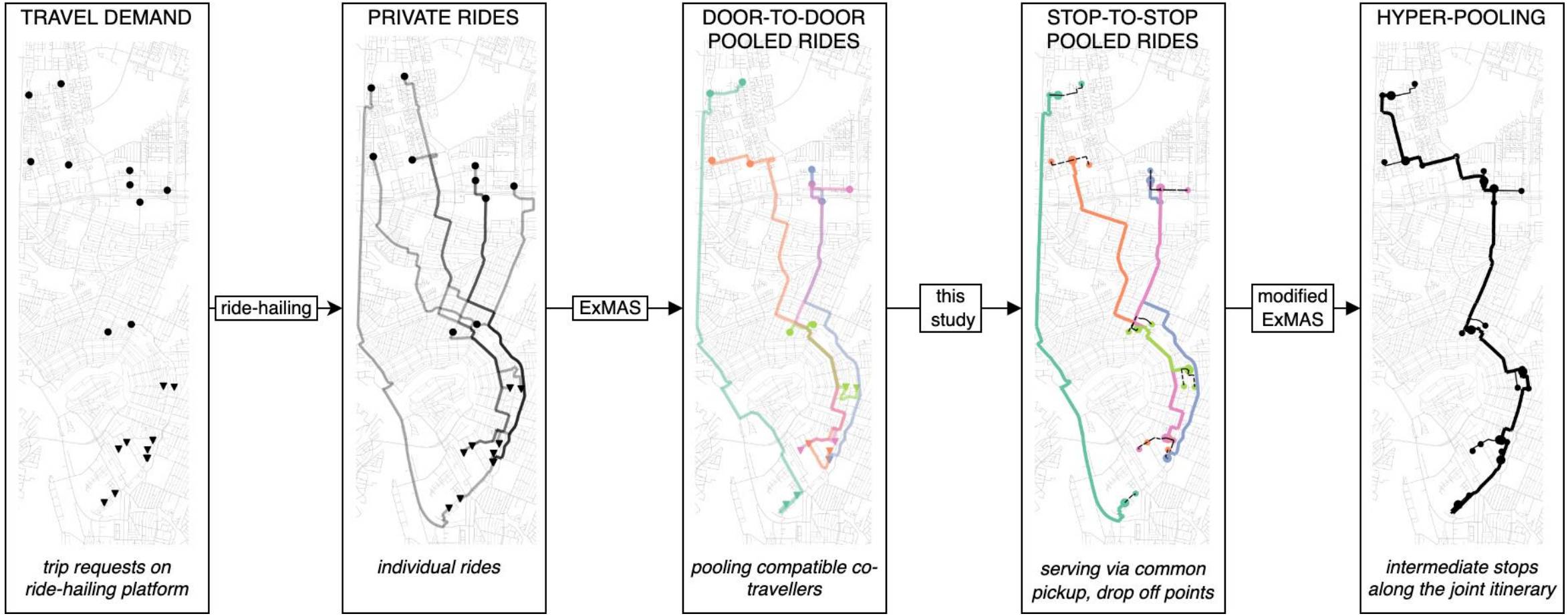
Kucharski and Cats (2020). Exact Matching of Attractive Shared Rides (ExMAS) for System-wide Strategic Evaluations. *Transportation Research Part B*.

VIRUS SPREADING IN RIDE-POOLING NETWORKS

- Combine epidemiological and behavioural shareability models
- Constructing and controlling contact graphs



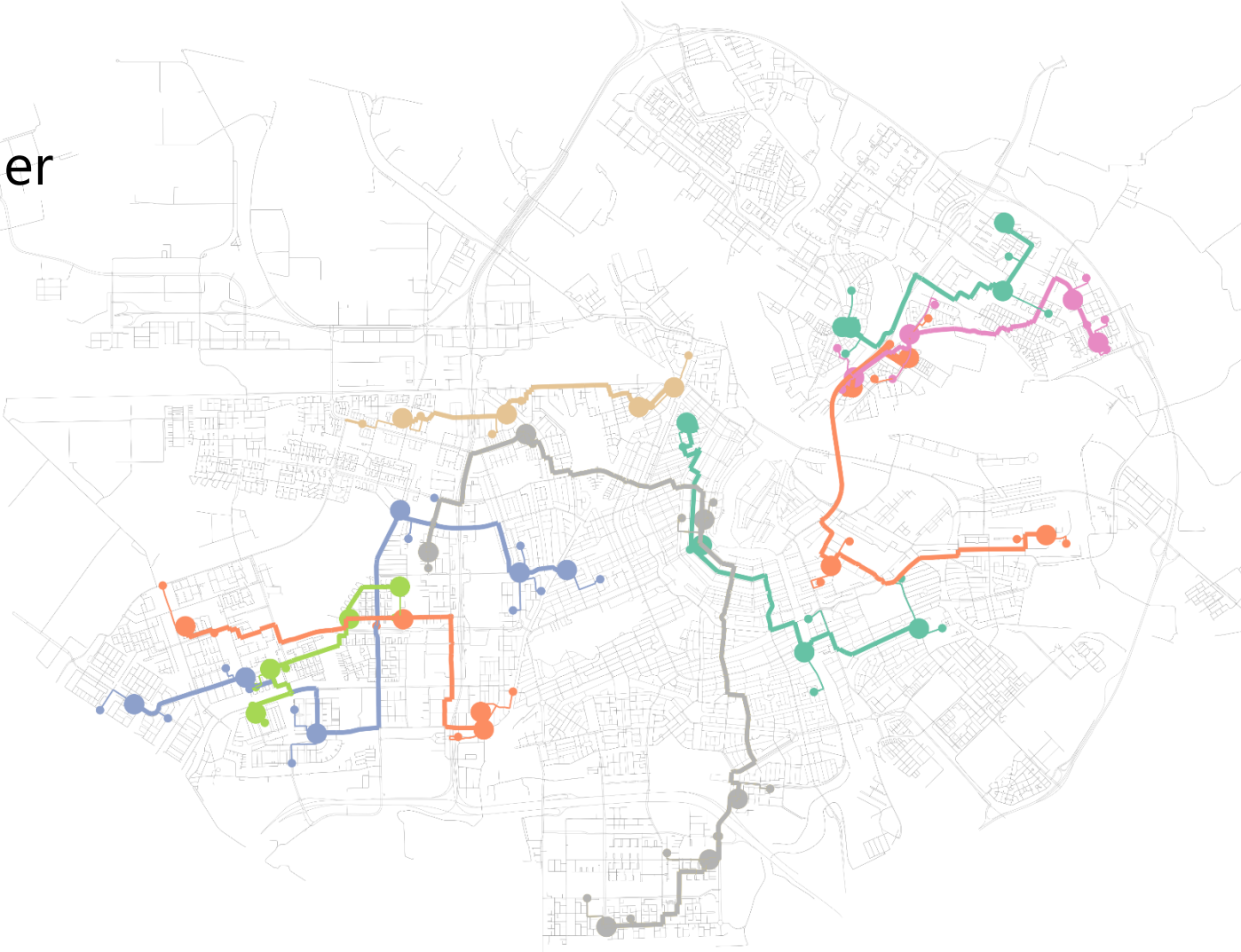
TRANSITIZING EXMAS



Kucharski and Cats (2024). Hyper Pooling Private Trips into High Occupancy Transit Like Attractive Shared Rides. *npj Sustainable Mobility and Transport.*

HYPER-POOLING

- Up to 14 passengers pooled together
- 13% decrease in total passengers disutility (D2D pooling by 4.3%)
- 37.5% decrease in vehicle-hours



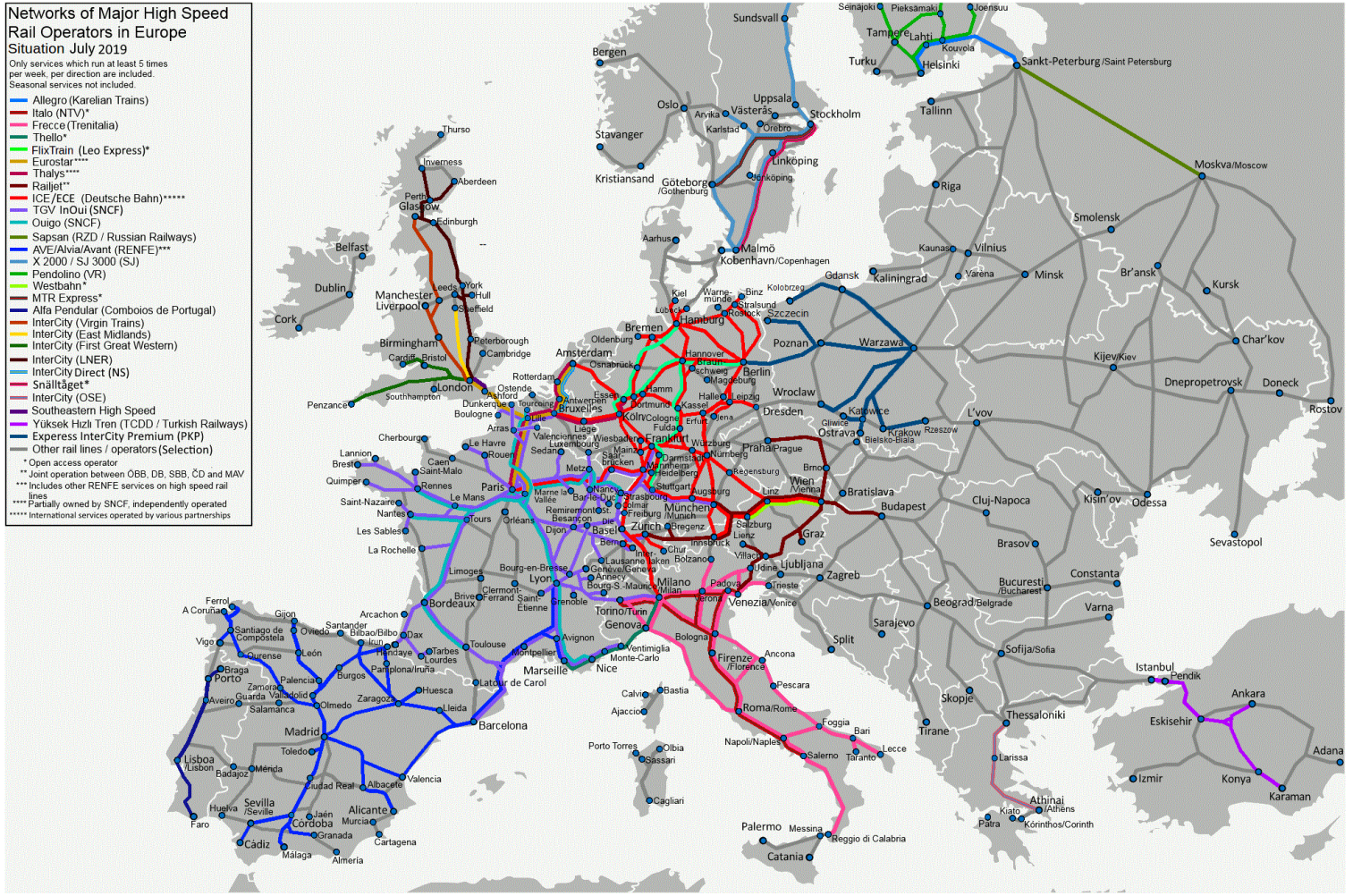
Kucharski and Cats (2024). Hyper Pooling Private Trips into High Occupancy Transit Like Attractive Shared Rides. *npj Sustainable Mobility and Transport.*

Long-distance services

A EUROPEAN NETWORK? CURRENT STATE OF AFFAIRS

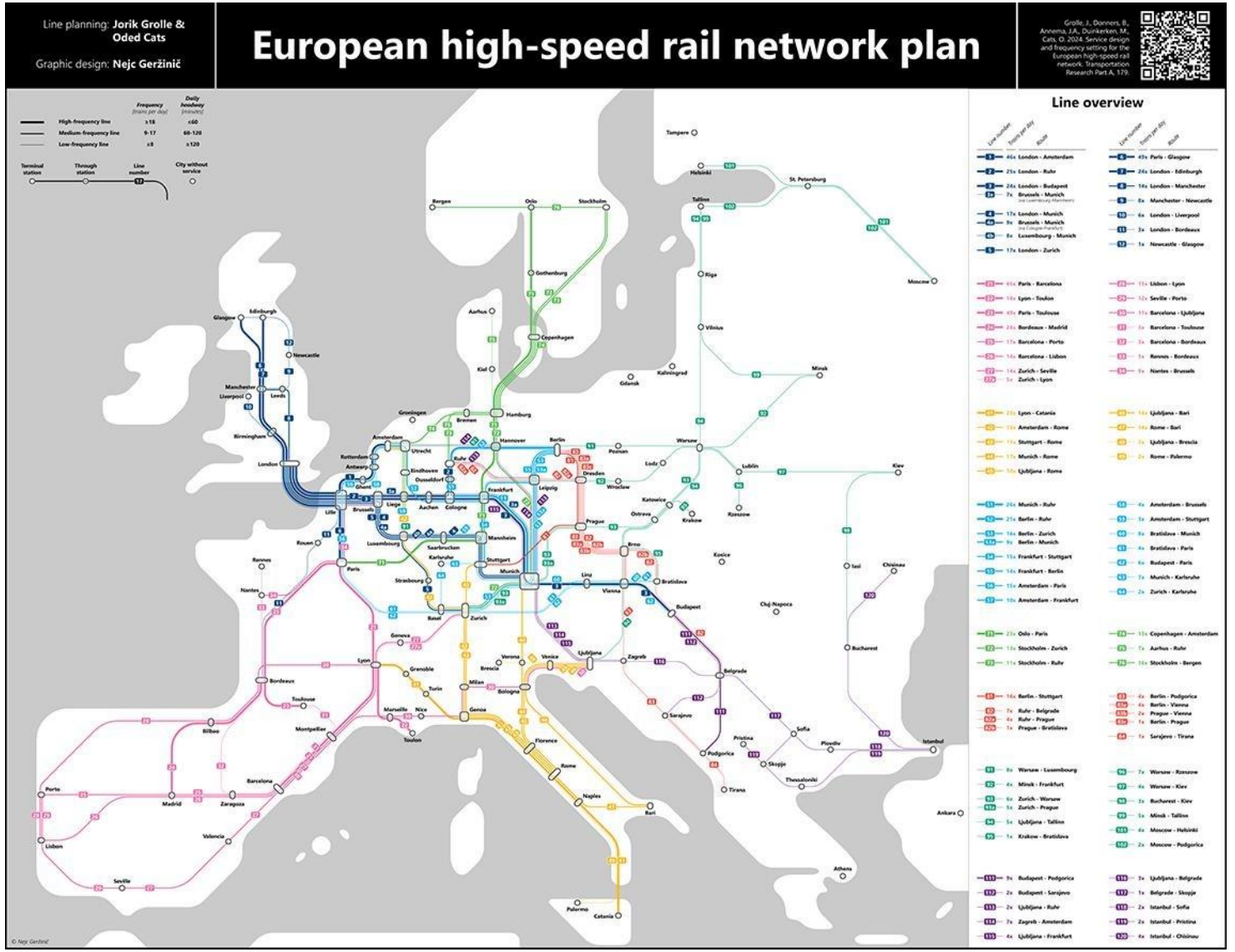
"A patchwork of poorly connected national high-speed rail networks"

European Court of Auditors (2018)



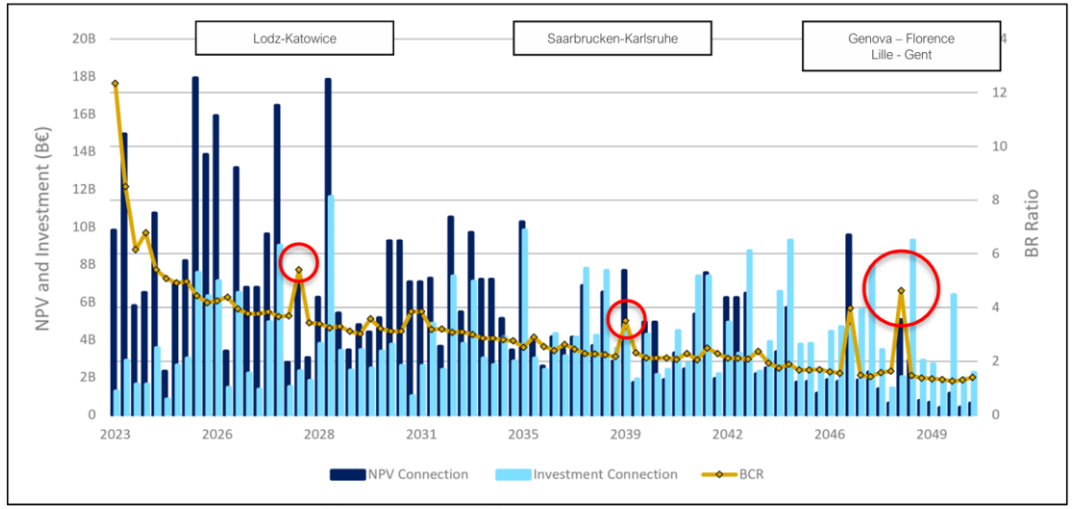
EUROPEAN RAIL SERVICE DESIGN

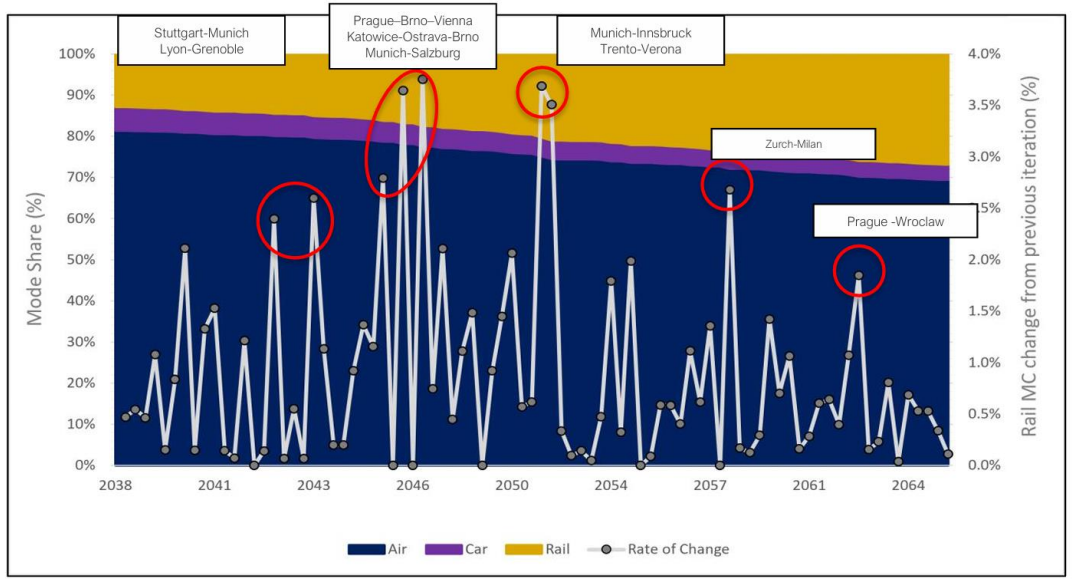
- A ‘unified’ High Speed Rail (HSR) network with endogenous demand
- Accounting for externalities
- Formulating and solving (using a heuristic) the Line Design and Frequency Setting Problem for HRS
- No market competition dynamics (co-evolution)

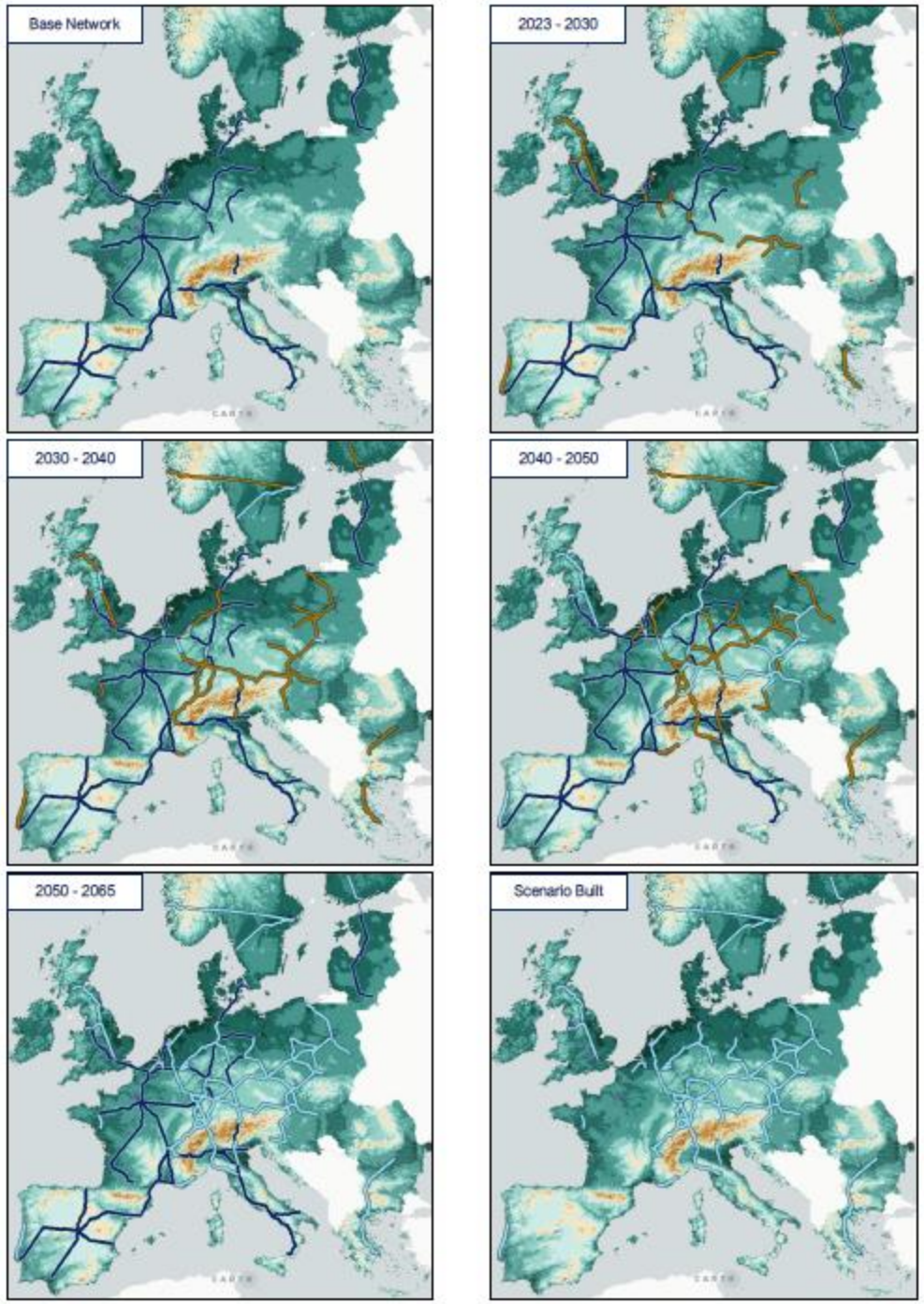


Grolle et al. (2024). Service Design and Frequency Setting for the European High-Speed Rail Network. *Transportation Research Part A.*

NETWORK EVOLUTION





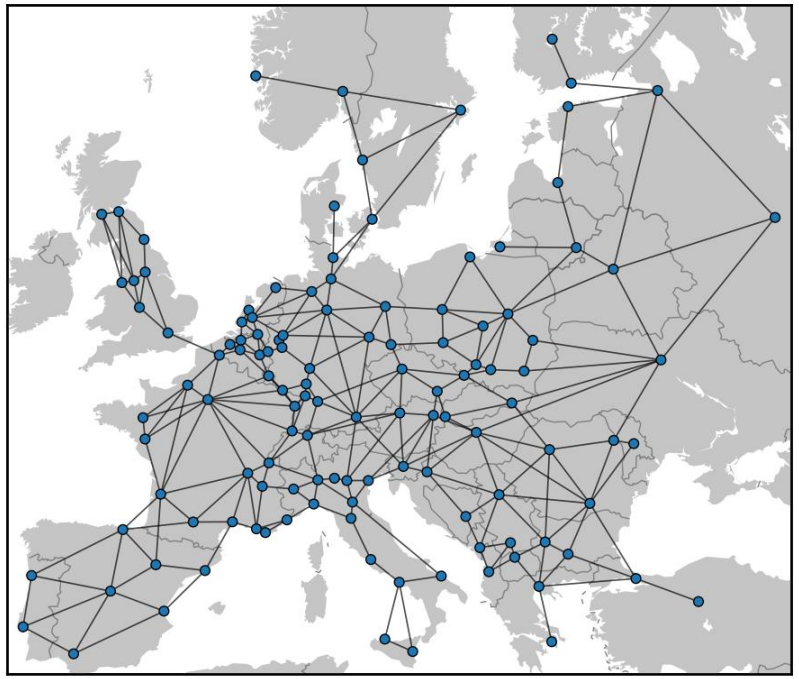


Borgogno et al. (2025). The European High-Speed Rail Network: A Growth-Based Modeling Approach. *Working paper.*

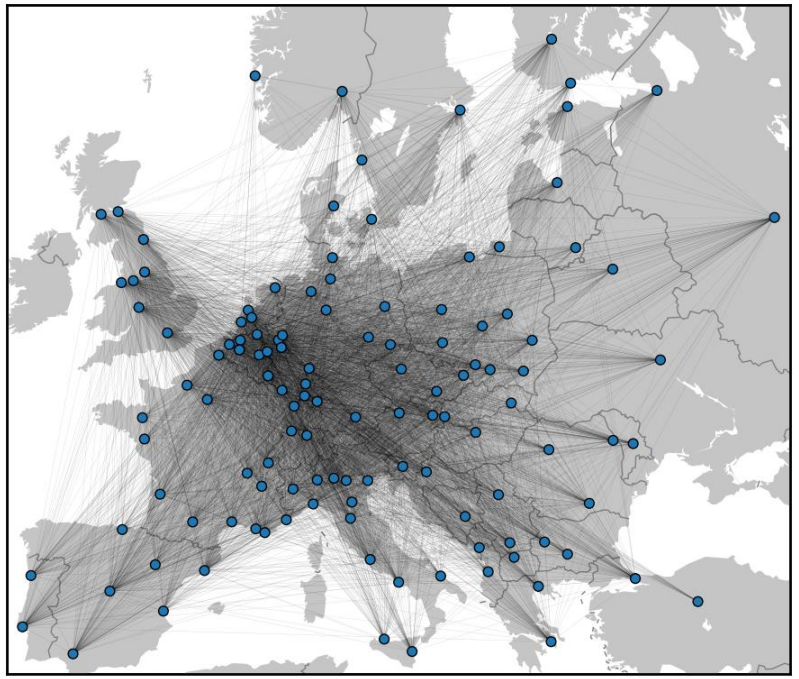
Lab Smart Public Transport

MULTI-LAYER MULTI-MODAL ROBUSTNESS

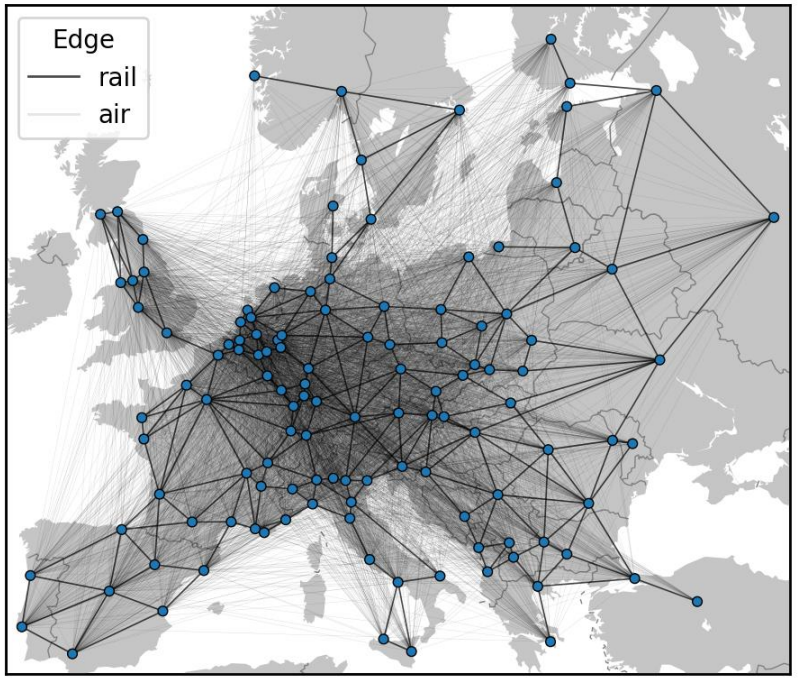
Rail network



Air network

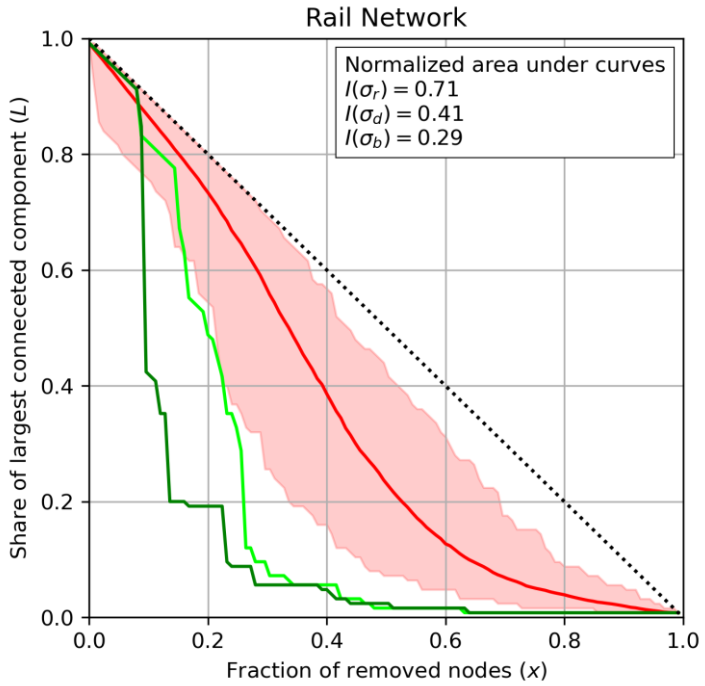


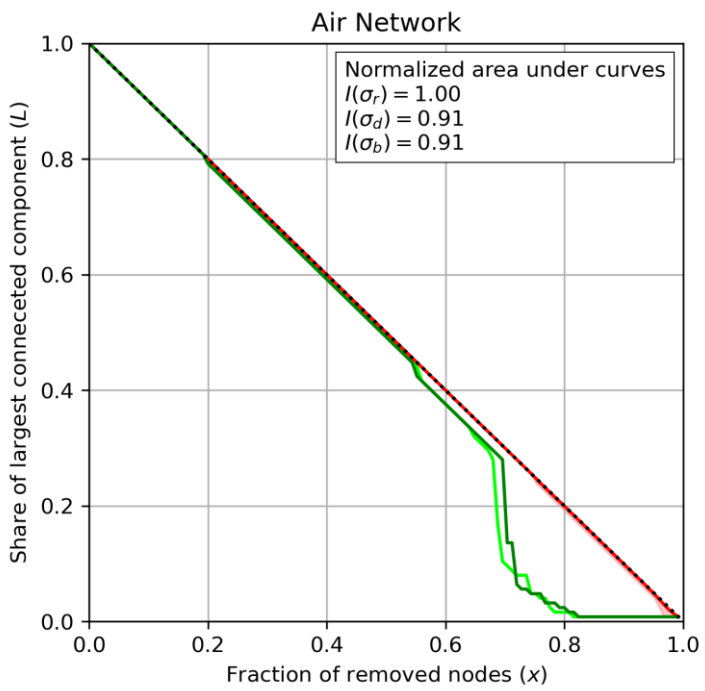
Multi Modal Network

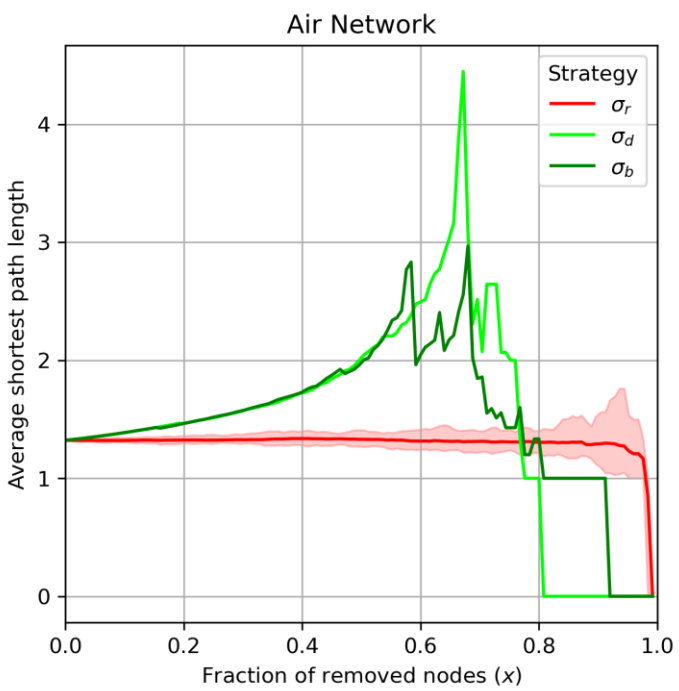


Ippolito and Cats (2025). Multi-Modal and Multi-Layer Robustness Analysis of the European Rail and Air Networks. *Scientific Reports.*

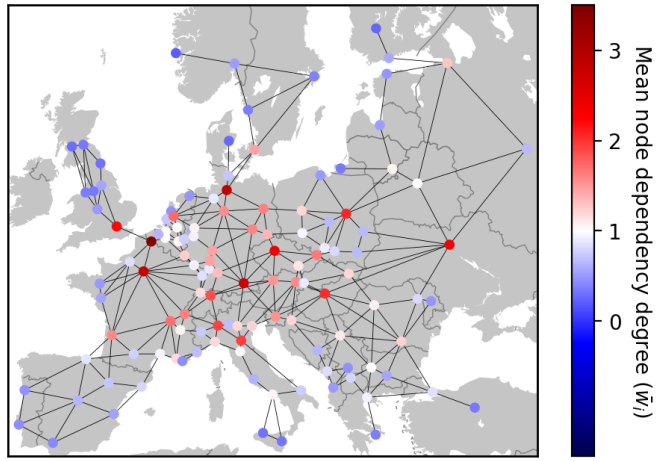
MULTI-LAYER MULTI-MODAL ROBUSTNESS

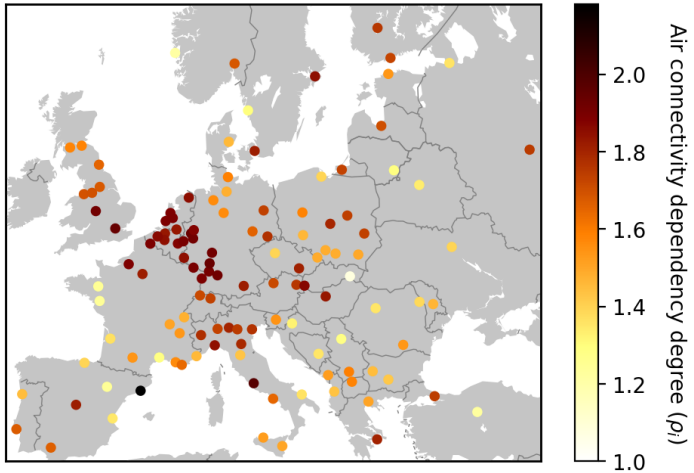


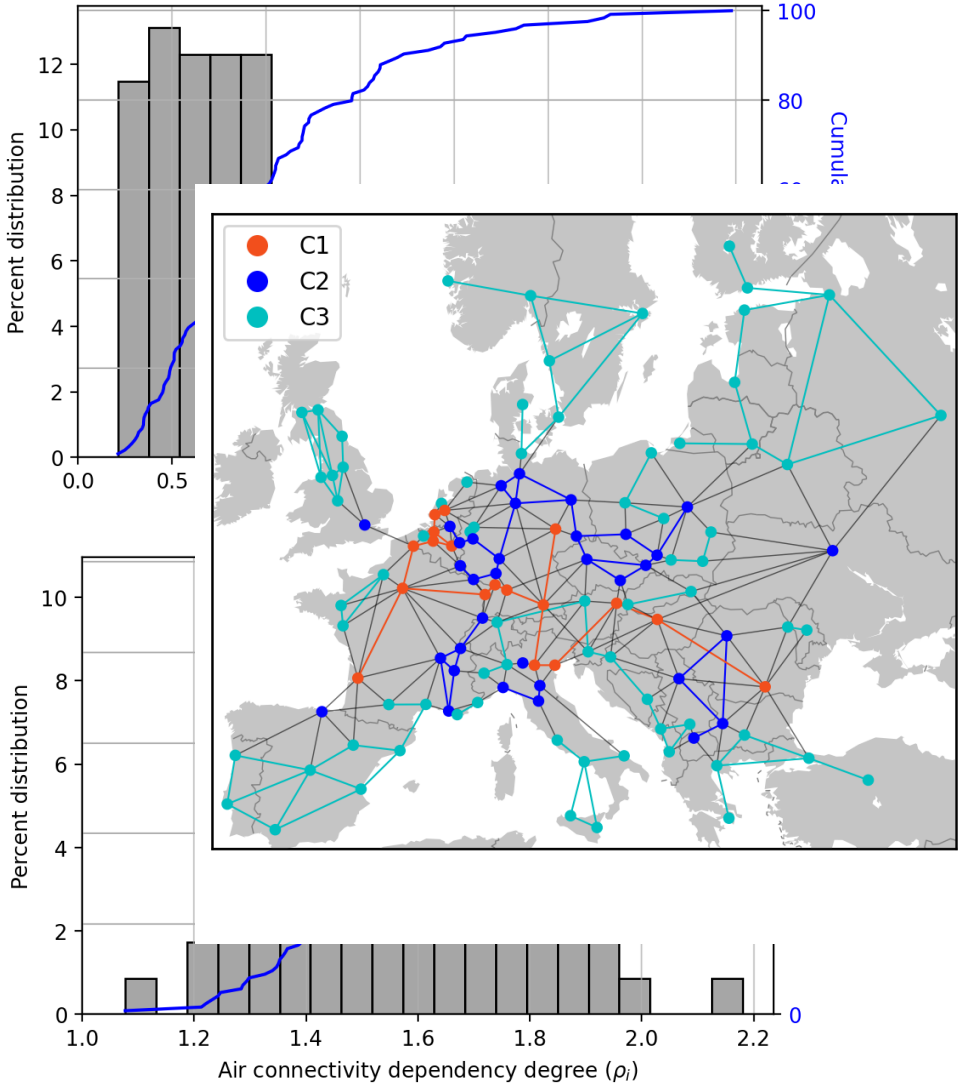


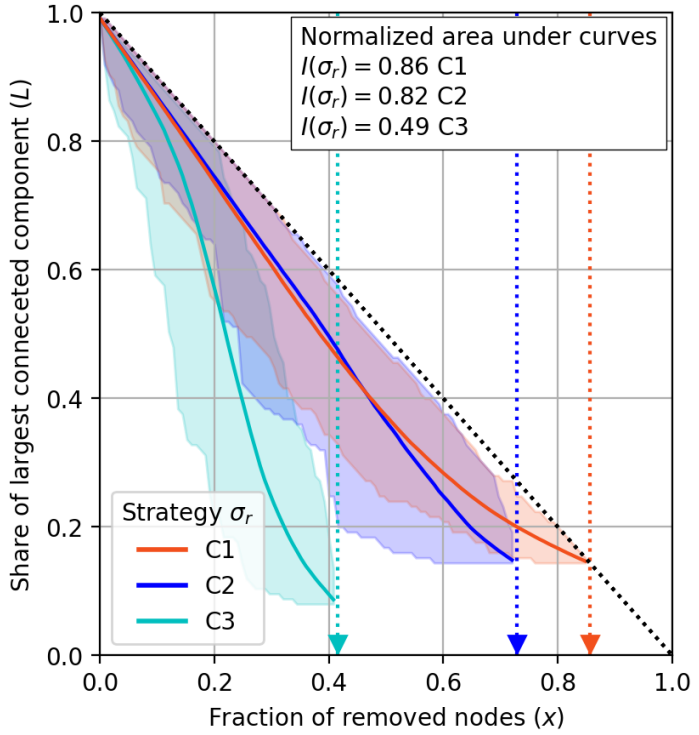


Ippolito and Cats (2025). Multi-Modal and Multi-Layer Robustness Analysis of the European Rail and Air Networks. *Scientific Reports.*






C1
C2
C3
Percent distribution
Air connectivity dependency degree (ρ_i)


Normalized area under curves
$I(\sigma_r) = 0.86$ C1
$I(\sigma_r) = 0.82$ C2
$I(\sigma_r) = 0.49$ C3
Strategy σ_r
C1
C2
C3
Share of largest connected component (L)
Fraction of removed nodes (x)

Graphs and Data in Passenger Transport Systems

Oded Cats, with contributions by lab members

Welcome to reach out with any ideas or questions or if you are interested in any of the (working) papers: o.cats@tudelft.nl

Smart Public Transport Lab

Graphs & Data Seminar Series, 5 June 2025

TU Delft