One Rule to Bring Them All: Investigating Transport Connectivity in Public Transport Route Generation for Equitable Access

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Motivation and Research Context

- **Route generation depends on optimization metrics**
- **Classical metrics may prioritize efficiency over equity**
- **This creates a gap with real planning needs**
- **Equity- and resilience-based metrics possibly offer better alignment**

Problem Setup: Transit Network Design

Given city graph: $C = (N, E_s, D)$

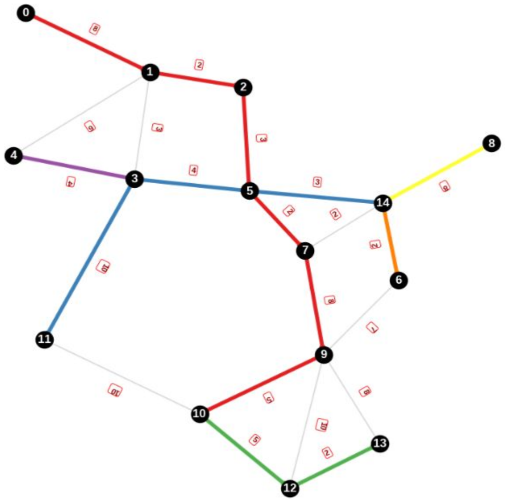
N — set of n transit stops

$E_s = \{(i, j, \tau_{ij})\}$ — edges with travel times $\tau_{ij} > 0$

$D \in \mathbb{R}^{n \times n}_{\geq 0}$ — demand matrix

T^R_{ij} — shortest travel time from i to j via network R

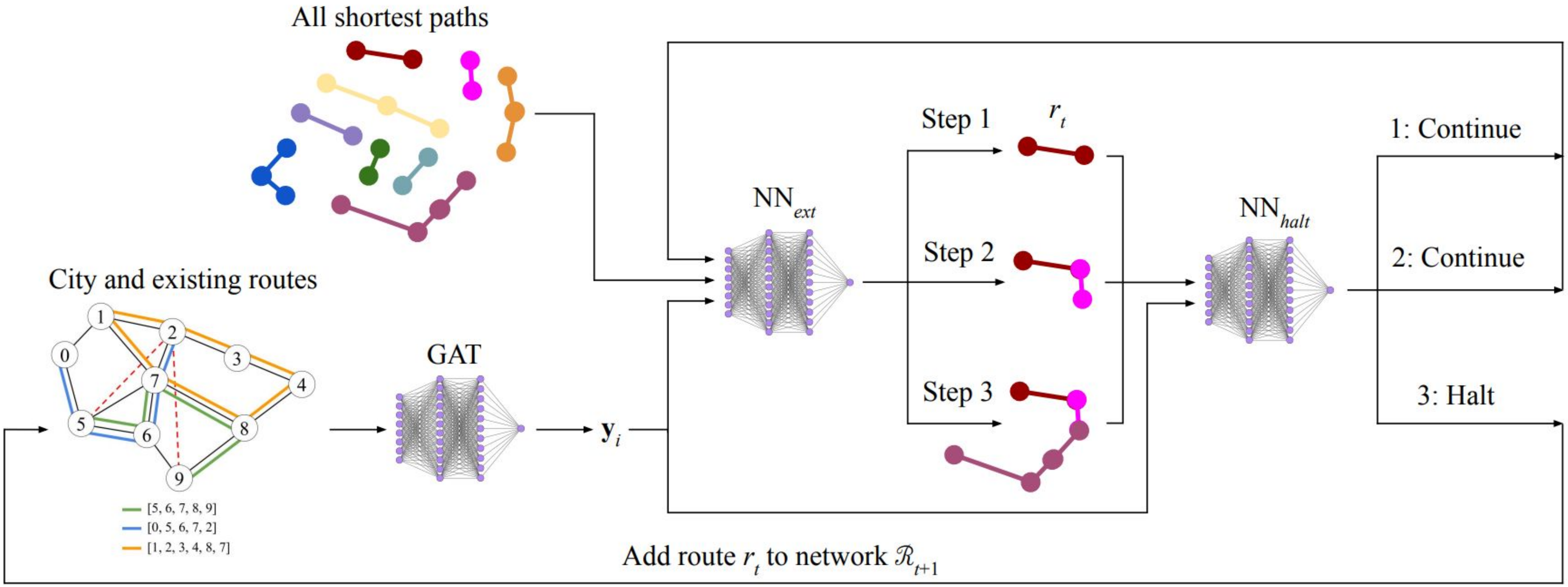
τ_{uv} — travel time on street edge from stop u to stop v



Generated routes example

Holliday, A., & Dudek, G. (2024). A Neural-Evolutionary Algorithm for Autonomous Transit Network Design.

Neuro Evolutionary Algorithm



Holliday, A., & Dudek, G. (2024). A Neural-Evolutionary Algorithm for Autonomous Transit Network Design.

Objective Function: Baseline Structure

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Passenger cost (average travel time):

$$C_p(C,R) = \frac{\sum_{i,j} D_{ij} T_{ij}^R}{\sum_{i,j} D_{ij}}$$

Operator cost (total route traversal time):

$$C_o(C,R) = \sum_{(u,v) \in r} \tau_{uv} + \sum_{(v,u) \in r} \tau_{vu}$$

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Demand-weighted transport connectivity

$$C_w(C, R) = \frac{1}{n} \sum_{i=1}^{n} \operatorname{median}\left\{ T_{ij}^{R} \cdot \frac{D_{ij}}{\max_k D_{ik}} \right\}$$

Metrics effect comparison

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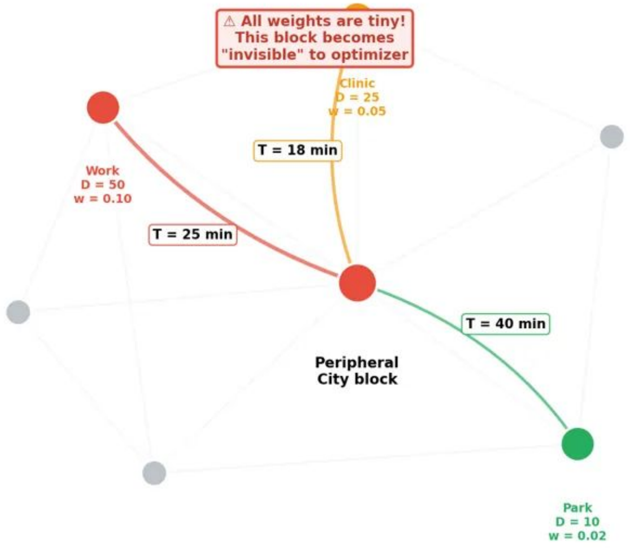
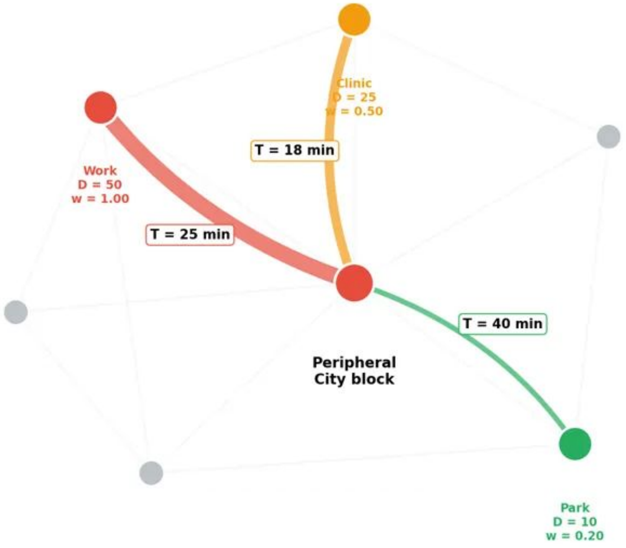
Mean Travel Time
Normalisation per sum demand

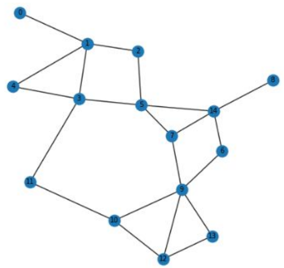


Out Metric
Normalisation per row

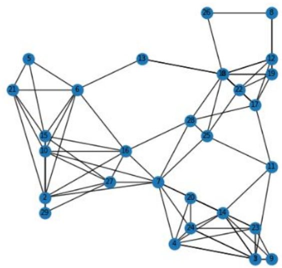


Synthetic Data Benchmarks

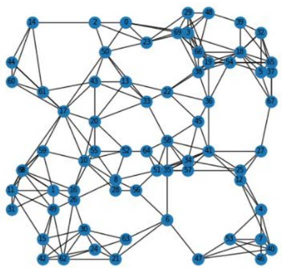
Mandl



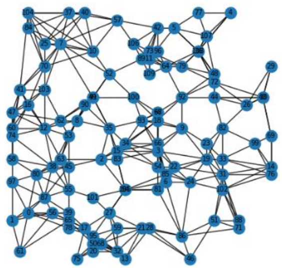
Mumford0



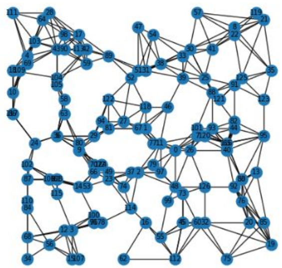
Mumford1



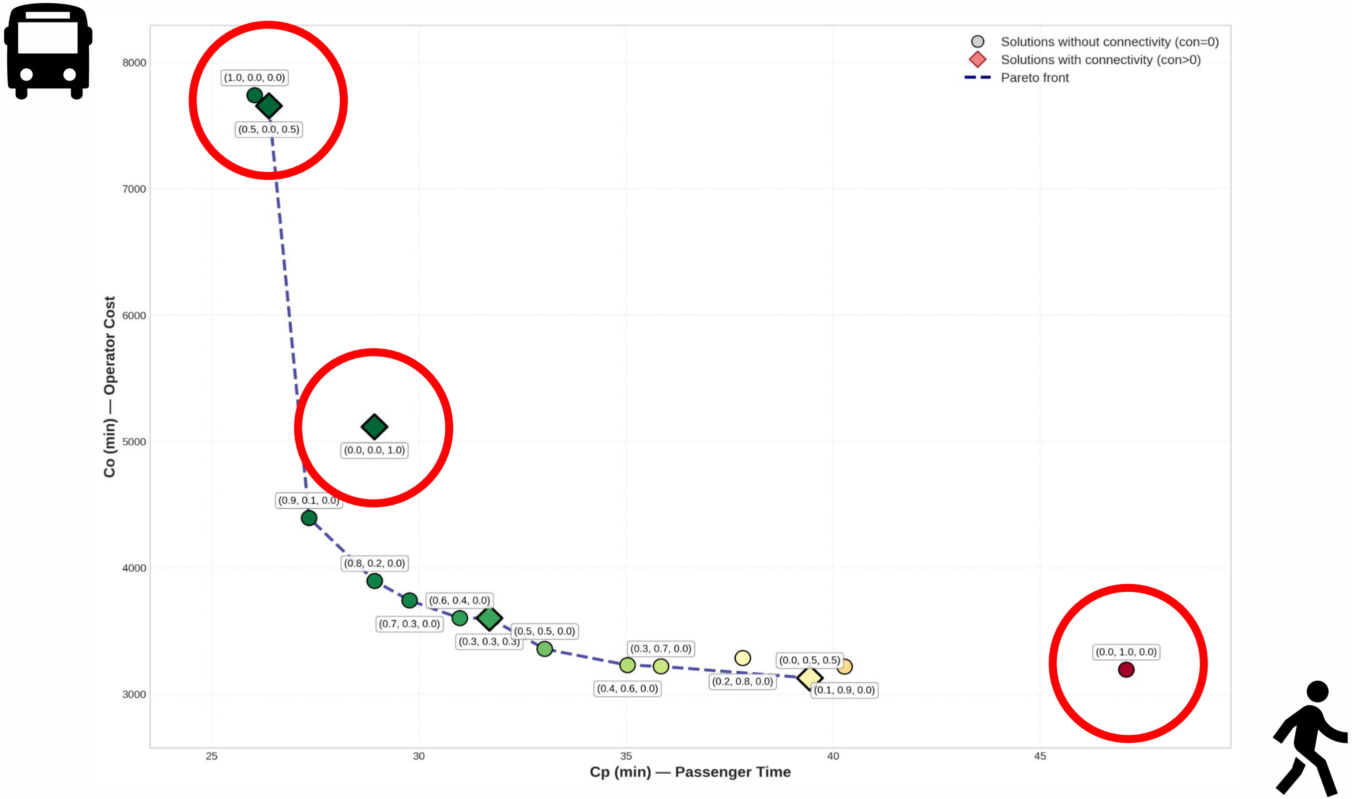
Mumford2



Mumford3

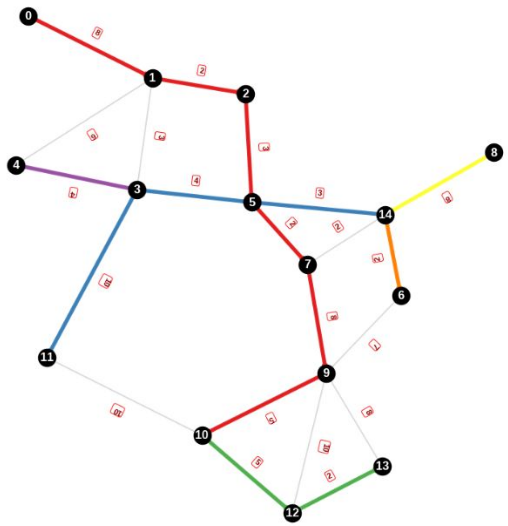


Pareto frontier on Mumford2

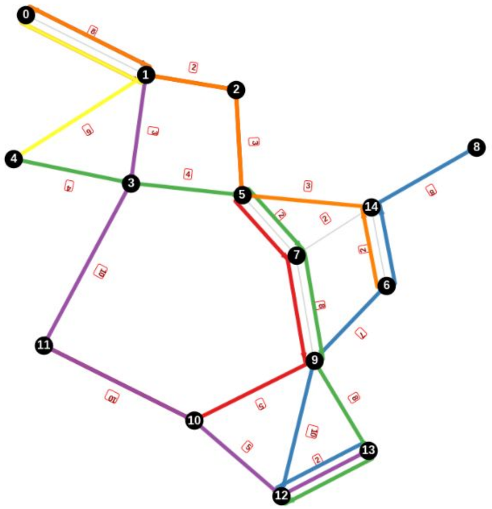


Route Network Morphologies under Different Objectives

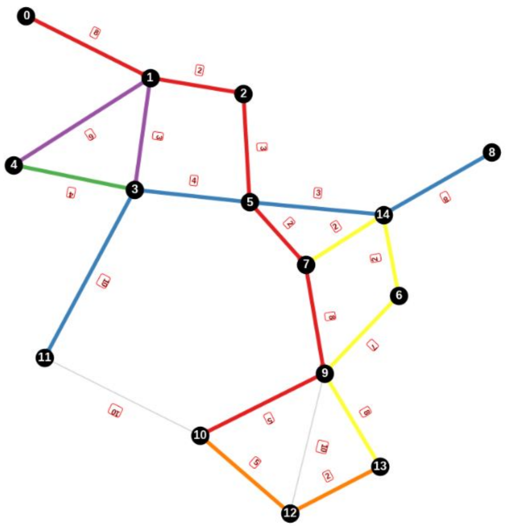
Route Set – Operator



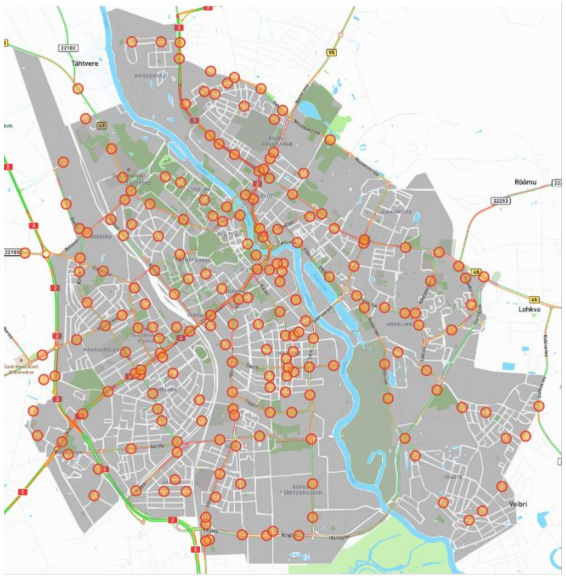
Route Set – Passenger



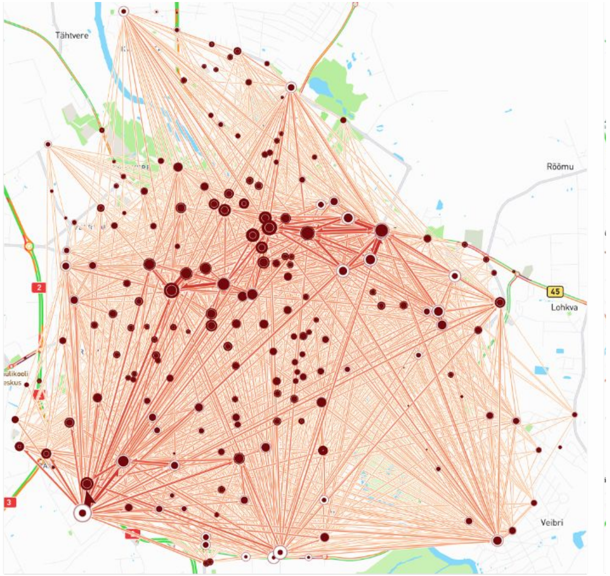
Route Set – Connectivity



Real-World Case Study: Data Preparation for Tartu

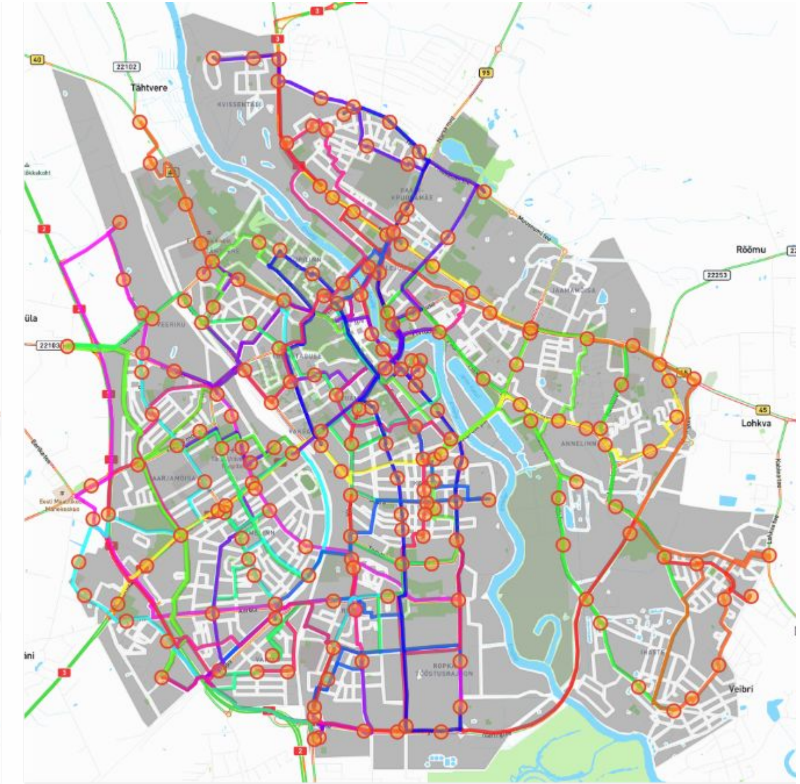


OSM Data



BlocksNet OD matrix

Generated Routes on Tartu

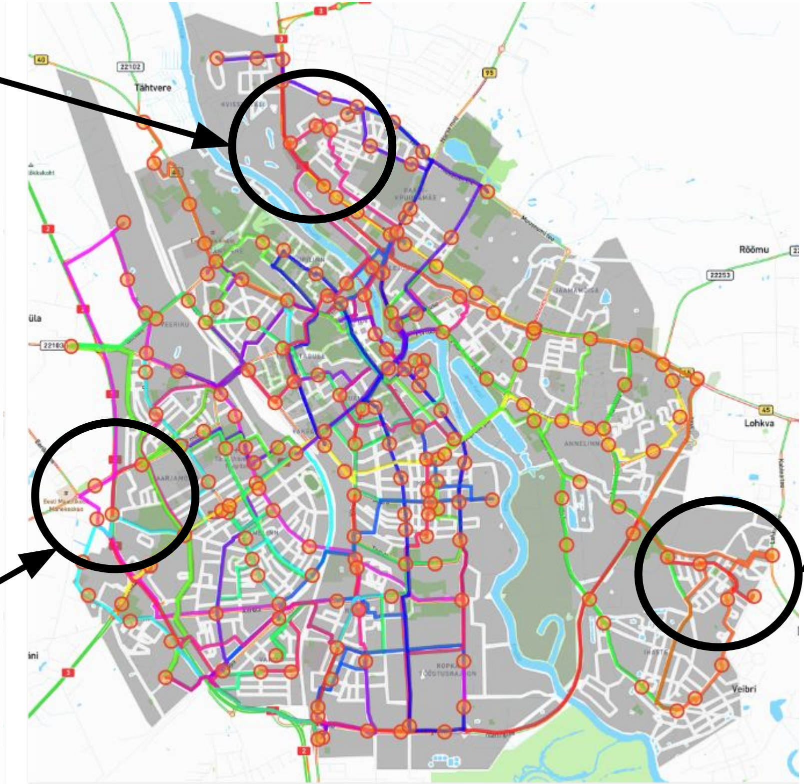


Generated Routes on Tartu

Step-like

overlapping geometry

Strange loop



Access graph Metrics

tM – Time budget at which average degree grows fastest;

DM – Average node degree at tM

D30 – Average node degree at 30 minutes

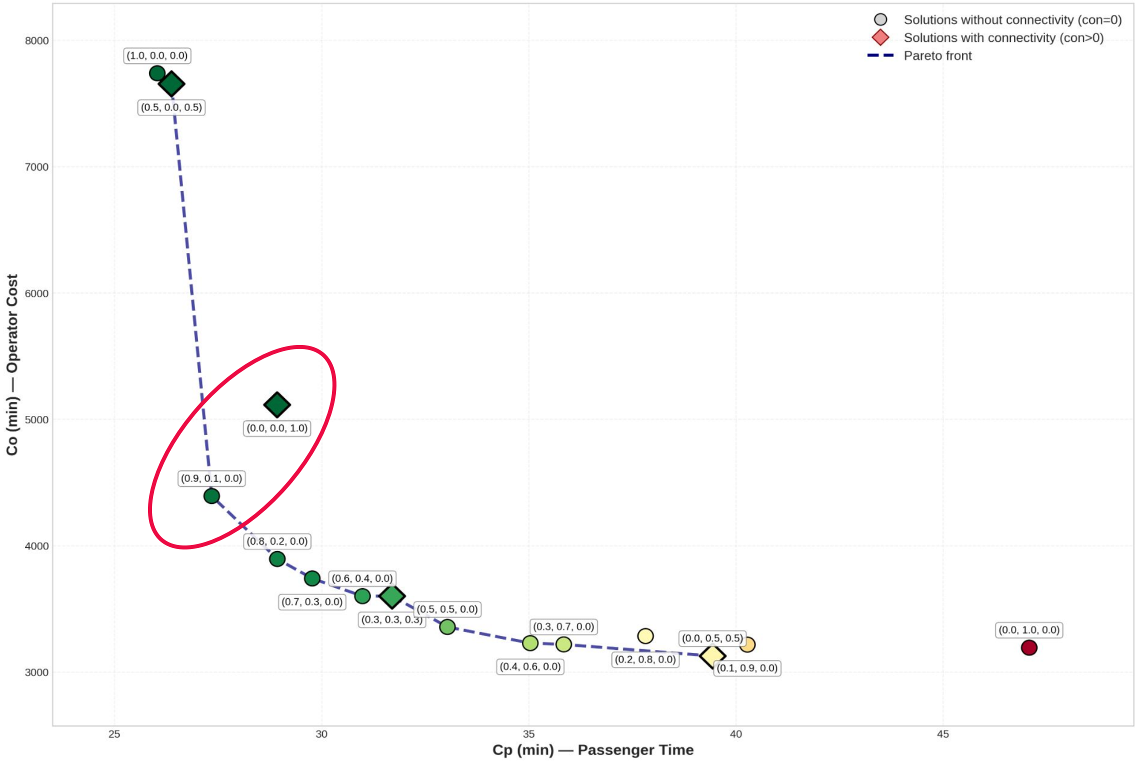
Algebraic connectivity – the second smallest eigenvalue of the graph Laplacian matrix.

Šfiligoj, T., Peperko, A., & Cats, O. (2025). ***Access graph: A novel graph representation of public transport networks for accessibility analysis*.**

Mumford2 Experiments Results

Perspective	t max ↓	t M ↓	DM ↑	D30 ↑	AC ↑	Cp ↓	Co ↓	Ccon ↓
Passenger	76	24	47.6	69.4	1.01	26.0	7738	22.2
Operator	264	30	26.9	26.9	0.08	47.1	3192	33.9
Balanced	74	24	46.0	67.3	0.77	27.4	4392	22.5
Ours	71	28	57.4	64.1	0.96	28.9	5114	22.2

Pareto frontier on Mumford2



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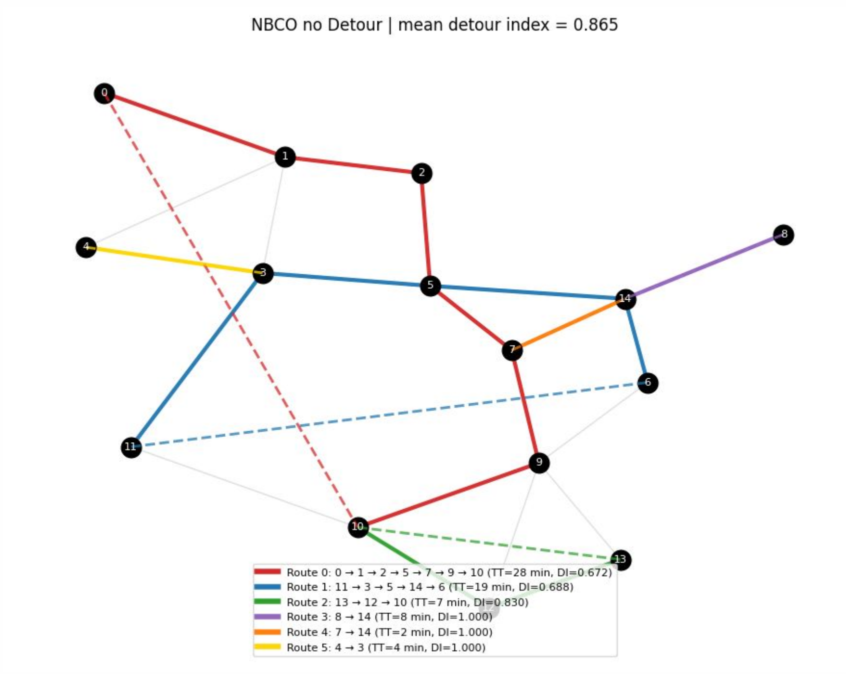
Tartu Experiment Result

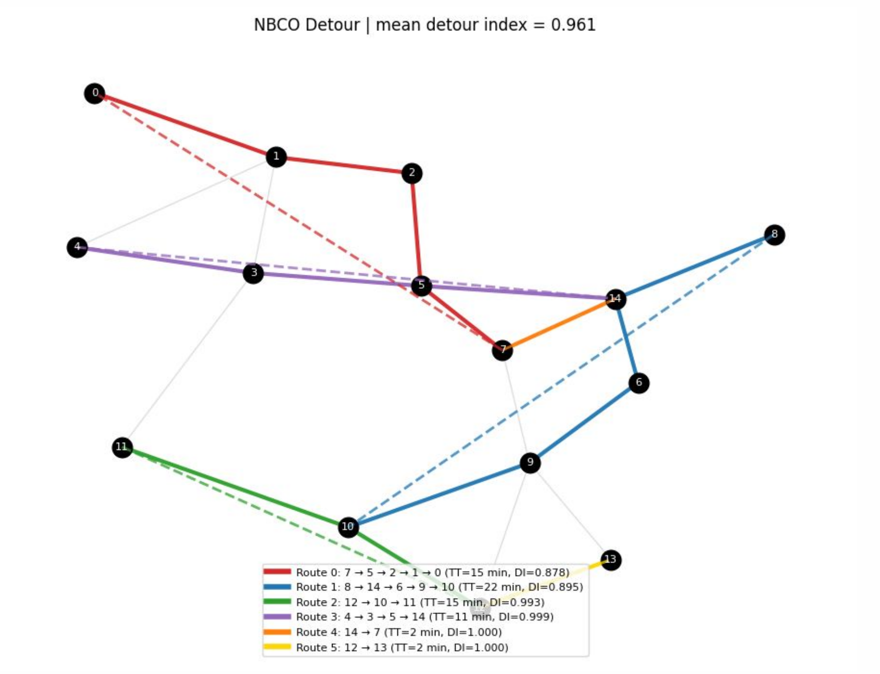
Perspective	tmax ↓	tM ↓	DM ↑	D30 ↑	AC ↑	Cp ↓	Co ↓	Ccon ↓
Passenger	50	26	73.45	126.92	1.02	17.9	1432	13.2
Operator	62	30	84.96	84.96	0.54	24.0	1328	16.6
Balanced	53	26	67.19	118.46	1.02	18.6	1205	13.6
Ours	56	26	69.94	121.58	1.20	19.1	1540	13.5

Conclusions

- **Passenger and operator costs are insufficient.**
- **Solutions with similar costs differ structurally.**
- **Results depend on the structure of the graph.**
- **Synthetic benchmarks do not reflect real cities.**

Future Work: Geometry-Aware Objectives





Thanks for your attention!

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Acknowledgments: This work supported by the Ministry of Economic Development of the Russian Federation (IGK 000000C313925P4C0002), agreement No139-15-2025-010.

Problem Setup: Transit Network Design

Find: $R = \{r_1, \ldots, r_S\}$ — set of routes

Constraints:

Every node in N is reachable from every other node via R

$|R| = S$ fixed number of routes

$\text{MIN} \leq |r| \leq \text{MAX} \quad \forall r \in R$

Each route contains no cycles

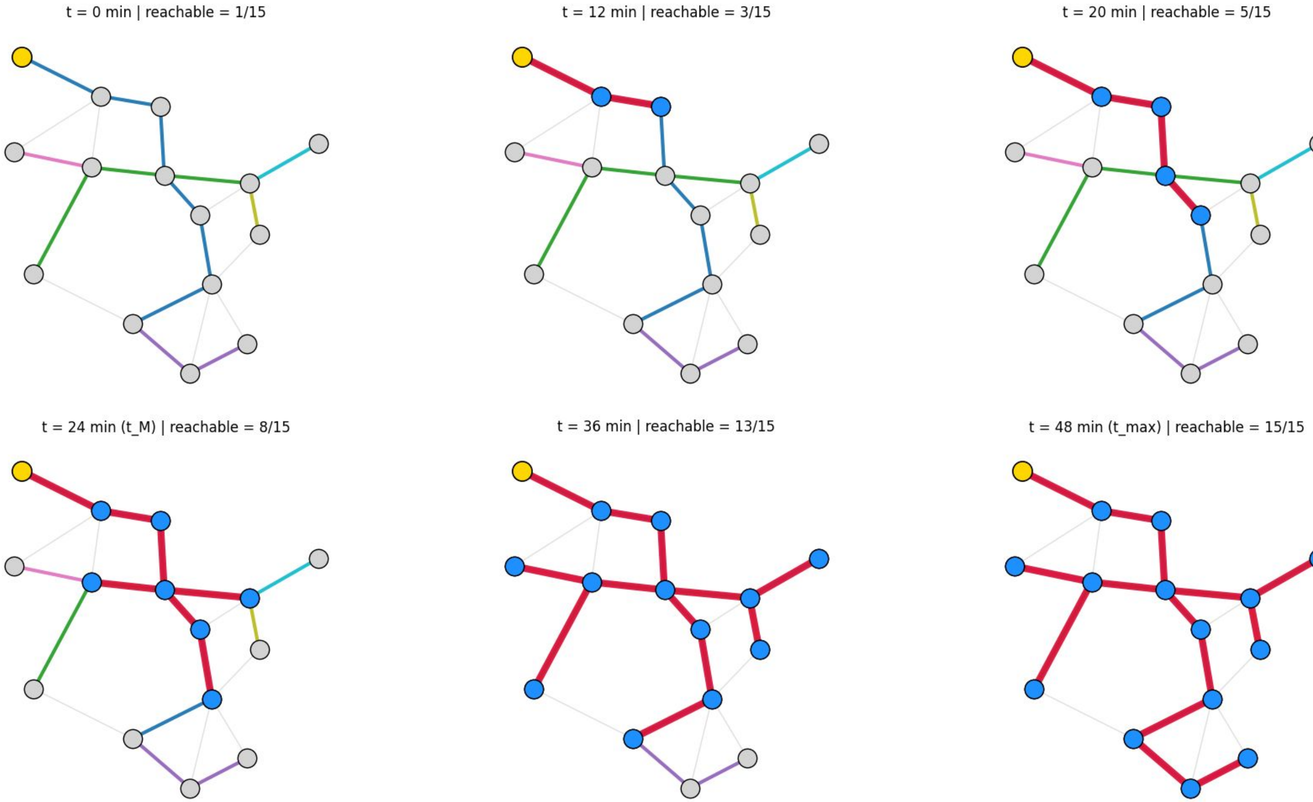
Each node appears at most once in any route

Street graph is symmetric

All routes are traversed in both directions

Holliday, A., & Dudek, G. (2024). A Neural-Evolutionary Algorithm for Autonomous Transit Network Design.

Accessibility Graph: Temporal Evolution on Mandl Graph



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Time of maximum connectivity growth

Generalized travel time matrix:

$$G = T^{\text{veh}} + w_{\text{trans}} \cdot N_{\text{trans}}$$

$$t_M = \underset{t_b}{\operatorname{argmax}} \frac{\Delta D(t_b)}{\Delta t}$$

T^{veh} — shortest travel time

N_{trans} — number of transfers

$w_{\text{trans}} = 5\ min$

Time of maximum connectivity growth