Capacity planning for demand-responsive multimodal transit

Presentation

Author(s):
Martin-Iradi, Bernardo; Corman, Francesco; Geroliminis, Nikolas

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ETH zürich

Institut für Verkehrsplanung und Transportsysteme
Institute for Transport Planning and Systems

Capacity planning for demand-responsive multimodal transit

Bernardo Martin-Iradi, ETH
Francesco Corman, ETH
Nikolas Geroliminis, EPFL

DADA closing event
31. May 2024

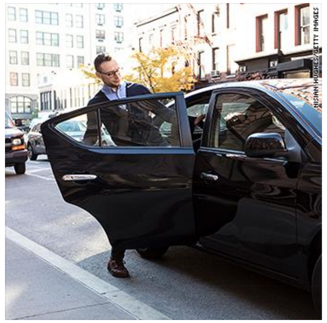
D BAUG

Challenges in mobility & logistics

Aging infrastructure and fleet

Growing congestion

Rising customer expectations

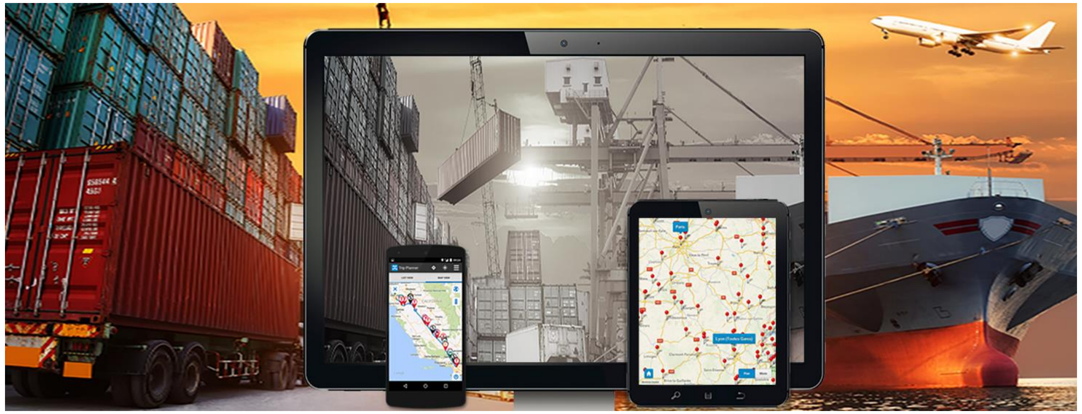


Environmental footprint

Innovation and opportunities

Vehicles: IoT, electrification

Business models: digital platforms



→ Coordination opportunities to create economies of scale, and consolidate operations across mobility systems

"How": analytics and optimization capabilities to support emerging innovations in transportation and logistics

On-demand multimodal transit in the mobility landscape

The New York Times — October 11, 2019

Who's Afraid of a Transit Desert?

CURBED — June 4, 2021

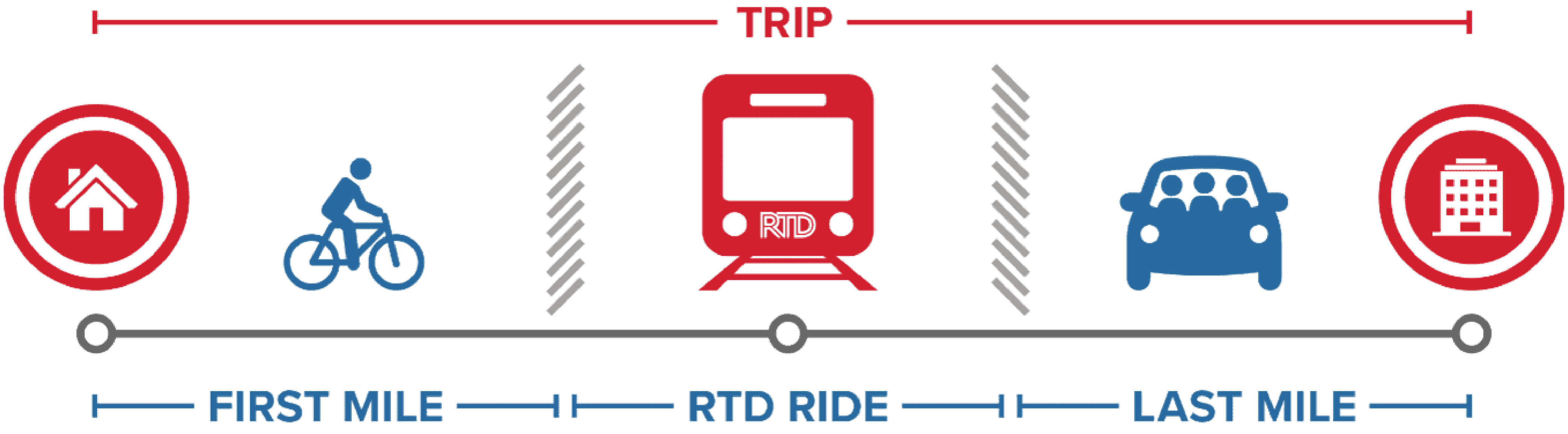
Why Your Uber Ride Is Suddenly Costing a Fortune

On-demand multimodal transit systems enhance public transport with the flexibility of demand-responsive services

On-demand multimodal transit system (ODMTS)

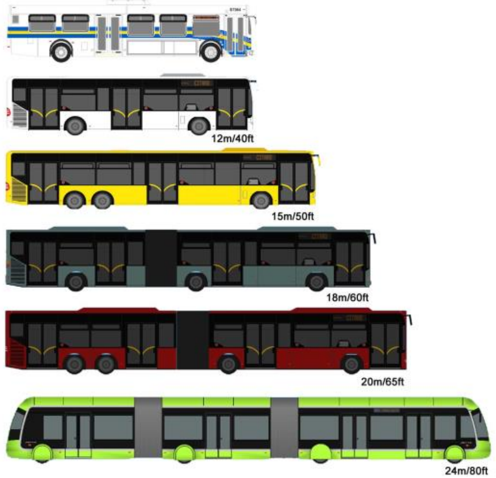
- Transit-centric system integrated with on-demand services
- Potential for:
  - Reducing costs
  - Improving service level
  - Alleviating congestion and pollution

Doing **“more”** with **“less”**



On-demand multimodal transit (ODMTS)

Existing work	**Proposed model**
Fixed transit system	**Transit scheduling**
Homogeneous fleet	**Heterogenous fleet**
Static demand	**Stochastic demand**



Contributions

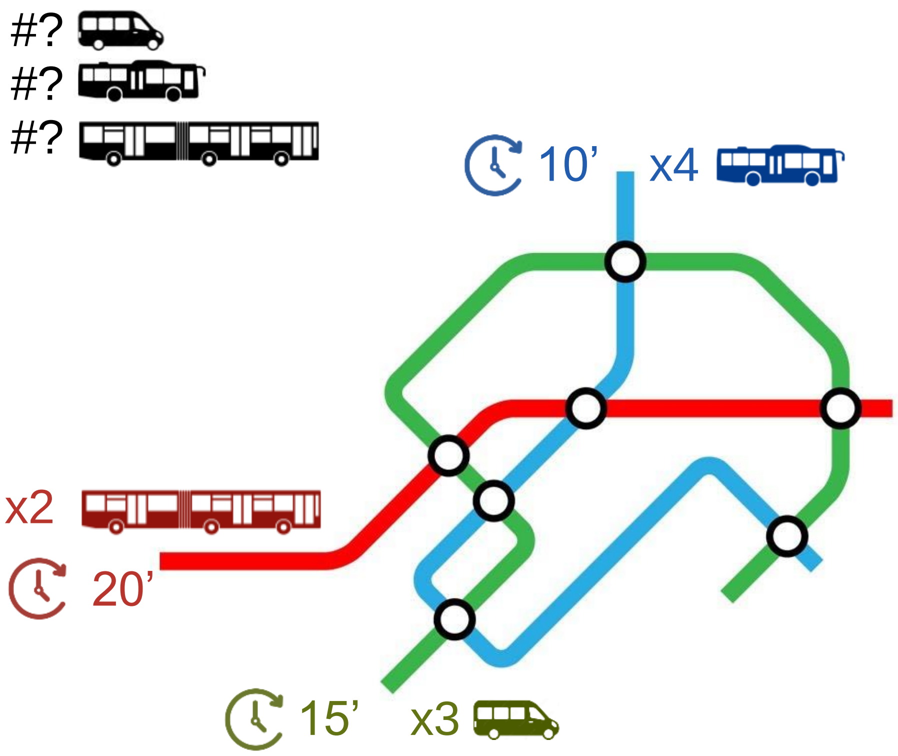
On-demand multimodal transit planning and operations

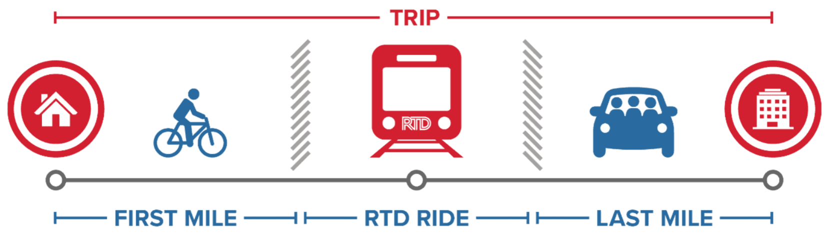
Model formulation	**Two-stage stochastic integer optimization formulation with tight network-based second-stage structure**
Double decomposition	**Double decomposition approach: Benders decomposition and column generation**
Computational scalability	**Scalability of the algorithm: high-quality solutions in otherwise intractable instances**
Practical impact: win-win outcomes	**Benefits toward efficient, equitable and sustainable urban mobility**

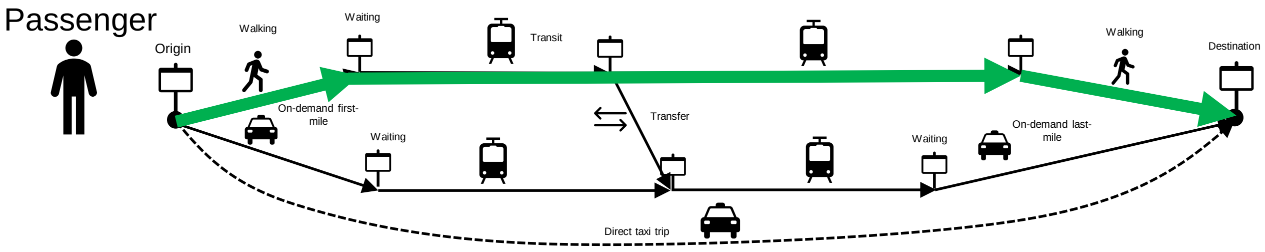
Problem statement

First-stage problem:
Transit planning and fleet sizing

Second-stage problem:
Demand-responsive operations



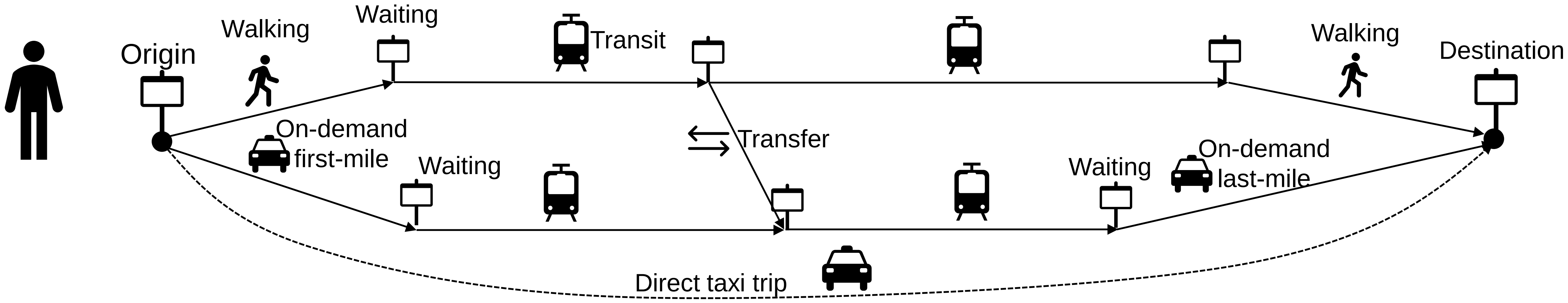




Time-space network

Second-stage problem: Demand-responsive operations

Mode choices: (1) Only transit, (2) Transit + OD service, (3) OD door-to-door



Time-space network for passenger trip planning

Decision variables

First-stage problem: Transit planning and fleet sizing

$$q_{lfbp} = \begin{cases} 1 \text{ if line } l \text{ runs with freq } f \text{ using vehicles } b \text{ on schedule } p, \\ 0 \text{ otherwise.} \end{cases}$$

$$z_{dl} = \begin{cases} 1 \text{ if passengers from origin}-\text{destination } d \in OD \text{ use line } l, \\ 0 \text{ otherwise.} \end{cases}$$

$$v_d = \text{ number of first/last mile services to cover demand on origin}-\text{destination } d \in OD.$$

Second-stage problem: Demand-responsive operations

$$y_{ras} = \begin{cases} 1 \text{ if arc } a \text{ is used for passenger trip } r \text{ in scenario } s, \\ 0 \text{ otherwise.} \end{cases}$$

Two-stage stochastic optimization

$$\min \underbrace{\sum_{d\in OD}(c_d^V v_d + \sum_{\ell\in\mathcal{L}_d} c_{d\ell}^Z z_{d\ell})}_{\text{Mode choice costs}} + \underbrace{\sum_{\ell\in\mathcal{L}}\sum_{f\in\mathcal{F}_{\ell b}}\sum_{b\in\mathcal{B}}\sum_{p\in\mathcal{P}_{\ell f}} c_{\ell fbp}^Q q_{\ell fbp}}_{\text{Transit planning costs}} + \underbrace{\sum_{s\in\mathcal{S}}\pi_s(\sum_{r\in\mathcal{R}_s}\sum_{a\in\mathcal{A}_r}\hat{c}_{ras}y_{ras})}_{\text{Passenger travel costs}}$$

s.t.

First-stage:

$$\sum_{b\in\mathcal{B}}\sum_{f\in\mathcal{F}_{\ell tb}}\sum_{p\in\mathcal{P}_{\ell tf}} q_{\ell ftbp} = 1 \qquad \forall \ell\in\mathcal{L}$$

Transit scheduling

$$\sum_{d\in OD_\ell} D_d z_{d\ell} \le \sum_{b\in\mathcal{B}}\sum_{f\in\mathcal{F}_{\ell b}}\sum_{p\in\mathcal{P}_{\ell f}} C_b^B N_{\ell fk} q_{\ell fbp} \qquad \forall \ell\in\mathcal{L}$$

Line capacity

Second-stage:

$$\sum_{a\in\mathcal{A}_r^+(i)} y_{ras} - \sum_{a\in\mathcal{A}_r^-(i)} y_{ras} = \begin{cases} 1 \text{ if } i=\hat{o}_{rs} \\ -1 \text{ if } i=\hat{d}_{rs} \\ 0 \text{ otherwise} \end{cases} \qquad \forall i\in\mathcal{V}, r\in\mathcal{R}_s, s\in\mathcal{S}$$

Passenger routing

$$\sum_{a\in\mathcal{A}^{TB}(\ell)} y_{ras} \le \bar{z}_{(o_r,d_r)\ell} \qquad \forall r\in\mathcal{R}_s, \ell\in\mathcal{L},, s\in\mathcal{S}$$

$$\sum_{r\in\mathcal{R}_s|(o_r,d_r)=d}\ \sum_{a\in\mathcal{A}^{DV}\setminus\{(\hat{o}_{rs},\hat{o}_{ds})\}} y_{ras} \le \bar{v}_d \qquad \forall s\in\mathcal{S}, d\in OD$$

$$\sum_{a\in\mathcal{A}^{TR}(\bar{q}_{\ell fbp})} y_{ras} \le \bar{q}_{\ell fbp} \qquad \forall r\in\mathcal{R}_s, \ell\in\mathcal{L}, b\in\mathcal{B}, f\in\mathcal{F}_{\ell b}, p\in\mathcal{P}_{\ell f}, s\in\mathcal{S}$$

Linking constraints

$$\sum_{a\in\mathcal{A}_{\ell fbqh}^+(n)}\sum_{r\in\mathcal{R}_s} n_r y_{ras} \le C_b^B \bar{q}_{\ell fbp} \qquad \forall b\in\mathcal{B}, n\in S_\ell\setminus\{S_\ell^1, S_\ell^L\}, \ell\in\mathcal{L}, f\in\mathcal{F}_{\ell b}, p\in\mathcal{P}_{\ell f}, h\in\mathcal{H}_p, s\in\mathcal{S}$$

Vehicle capacity

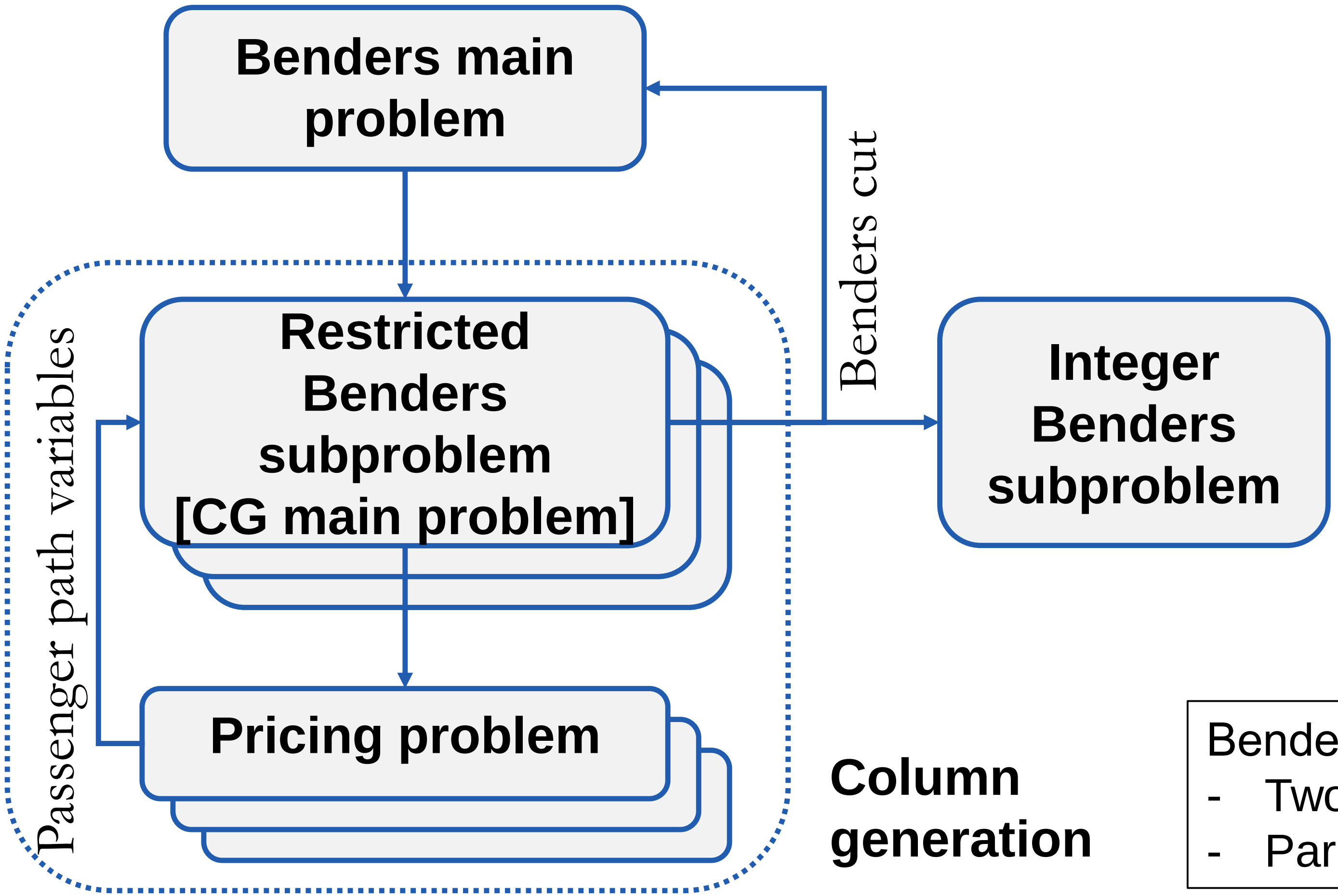
$$\boldsymbol{q},\boldsymbol{z},\boldsymbol{y} \text{ binary}, \quad \boldsymbol{v} \text{ integer}$$

Solution algorithm

First-stage problem

Second-stage relaxation

Passenger routing problem



Benders' enhancements:
- Two-phase approach
- Pareto-optimal cuts

Case study: Zurich's bus and tram network

3-10 bus/tram lines

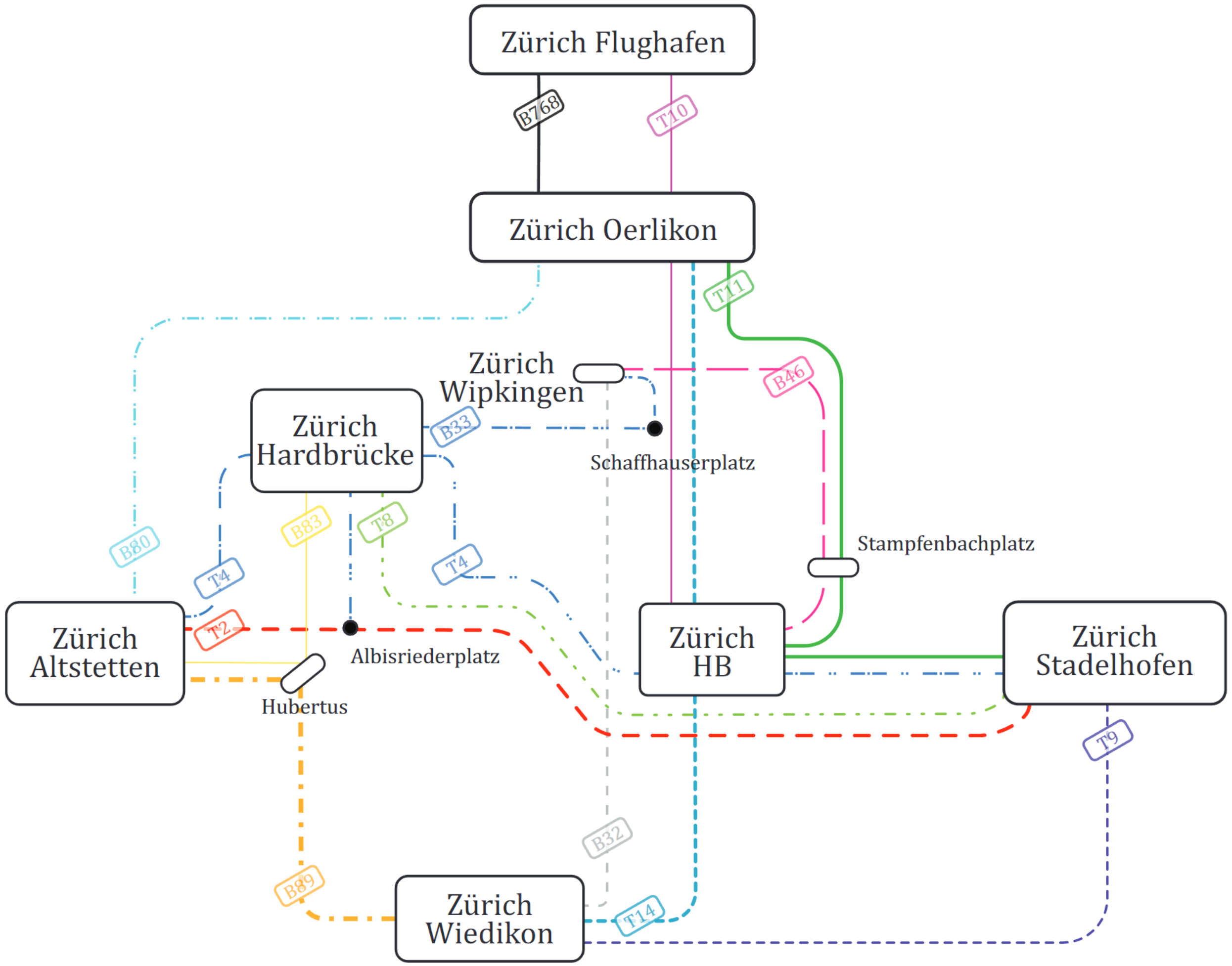
+100 stops

+1000 OD pairs

5-20 demand scenarios

1 hour horizon

Travel times from Google Maps, Uber, and OpenStreetMap



Scalability of algorithm

- **Direct** models
  - Fast for the smallest instances: **3** lines, and **5** demand scenarios
  - But scales very poorly (~50k nodes and ~100k arcs)

- **Benders** decomposition
  - Scales better: **5** lines, and **10** demand scenarios (~80k nodes and ~150k arcs)
  - Still relies on full variable enumeration

- **Double** decomposition (Benders and column generation)
  - Scales best: **10** lines and **20** demand scenarios, and probably **more** (+120k nodes and +200k arcs)
  - Tight relaxations with few columns

Benefits of stochastic optimization

Out-of-sample evaluation of **our model** and a **deterministic equivalent** (mean scenario).

Value of the stochastic solution (average across all instances): **Overall objective -6%**

Transit

Fleet costs	**+28%**
Ridership	**x5**
Utilization	**+8%**

Higher costs to serve more passengers

OD service

F/L mile costs	**+41%**
Distance	**-6%**
Direct trips	**-12%**

Mode switch leading to total operational savings

Passenger

Cost of travel	**-9%**
Arrival delay	**+4%**

Reductions in travel costs while maintaining service

Benefits of multimodal integration

Out-of-sample evaluation of **our model** and a **non-integrated equivalent** (no first/last mile services).

Value of the multimodal solution (average across all instances): **Overall objective -8%**

Transit		OD service		Passenger	
Fleet costs	+37%	Distance	-6%	Cost of travel	-9%
Ridership	x6	Direct trips	-14%	Arrival delay	+44%
Utilization	+9%				

Results in the same direction but more emphasized

Benefits of fleet heterogeneity

Out-of-sample evaluation of **our model** and a **homogeneous fleet equivalent** (single transit vehicle type).

Value of the heterogenous fleet solution (average across all instances): **Overall objective -1%**

Transit

Fleet costs	+10%
Ridership	x1.8
Utilization	+1%

OD service

F/L mile costs	+11%
Distance	-1%
Direct trips	-2%

Passenger

Cost of travel	-0.2%
Arrival delay	-2%

Milder differences in solutions

Work in progress

- Stress-test case study:
  - Real-life data on demand
  - Pareto frontier: Sensitivity analysis and parameter calibration

- Strengthen formulation:
  - On-demand service pooling

- Practical viability:
  - Analysis of benefits and incentives for integration and collaboration.

Conclusions

On-demand multimodal transit planning and operations

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Computational scalability	**Scalability of the algorithm: high-quality solutions in otherwise intractable instances**
Practical impact: win-win outcomes	**Benefits toward efficient, equitable and sustainable urban mobility**

Thank you!

Dr. Bernardo Martin-Iradi
Postdoctoral researcher – Transport Systems
bernardo.martin-iradi@ivt.baug.ethz.ch

ETH Zürich
Institute for Transport Planning and Systems (IVT)
Stefano-Franscini-Platz 5
8093 Zurich

www.ivt.ethz.ch