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Autonomous Systems Laboratory
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Model-based Optimal Control of Autonomous Mobility-on-Demand Systems in Multi-modal Transportation Networks

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Atlanta, 27.6.2018

Optimal Operation of Intermodal AMoD Systems

Vehicle Autonomy

Car Sharing

Optimal Operation of Intermodal AMoD Systems

Vehicle Autonomy

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Car Sharing

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Public Transit

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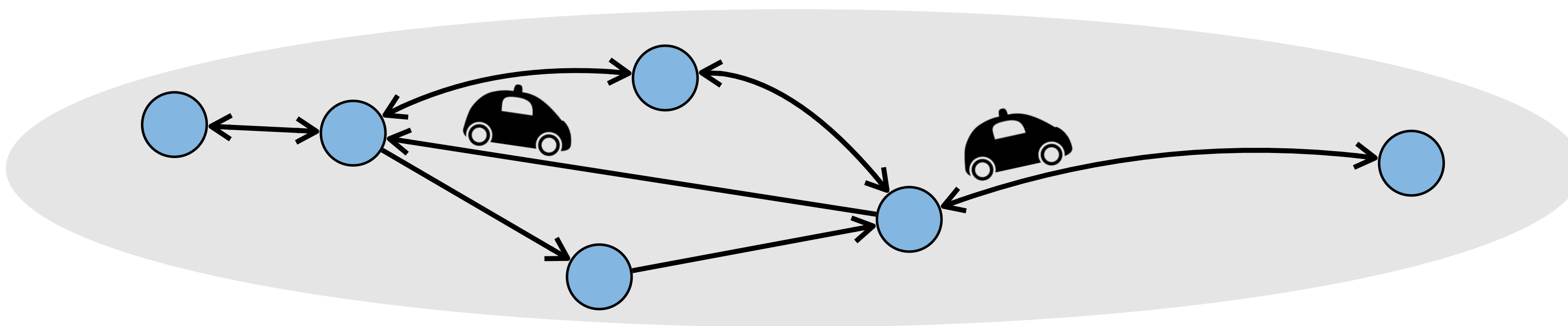
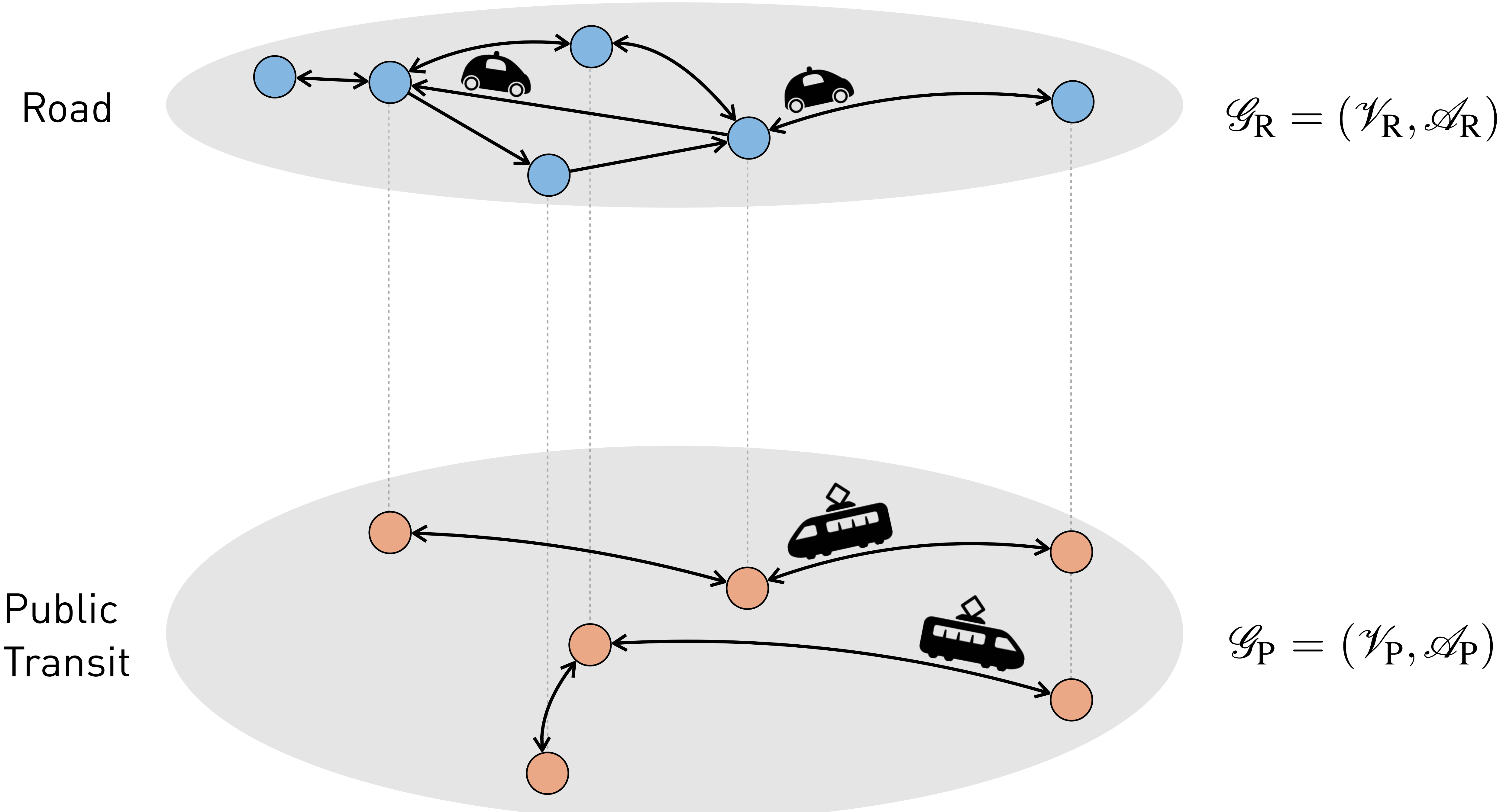
Intermodal Autonomous Mobility-on-Demand

Road

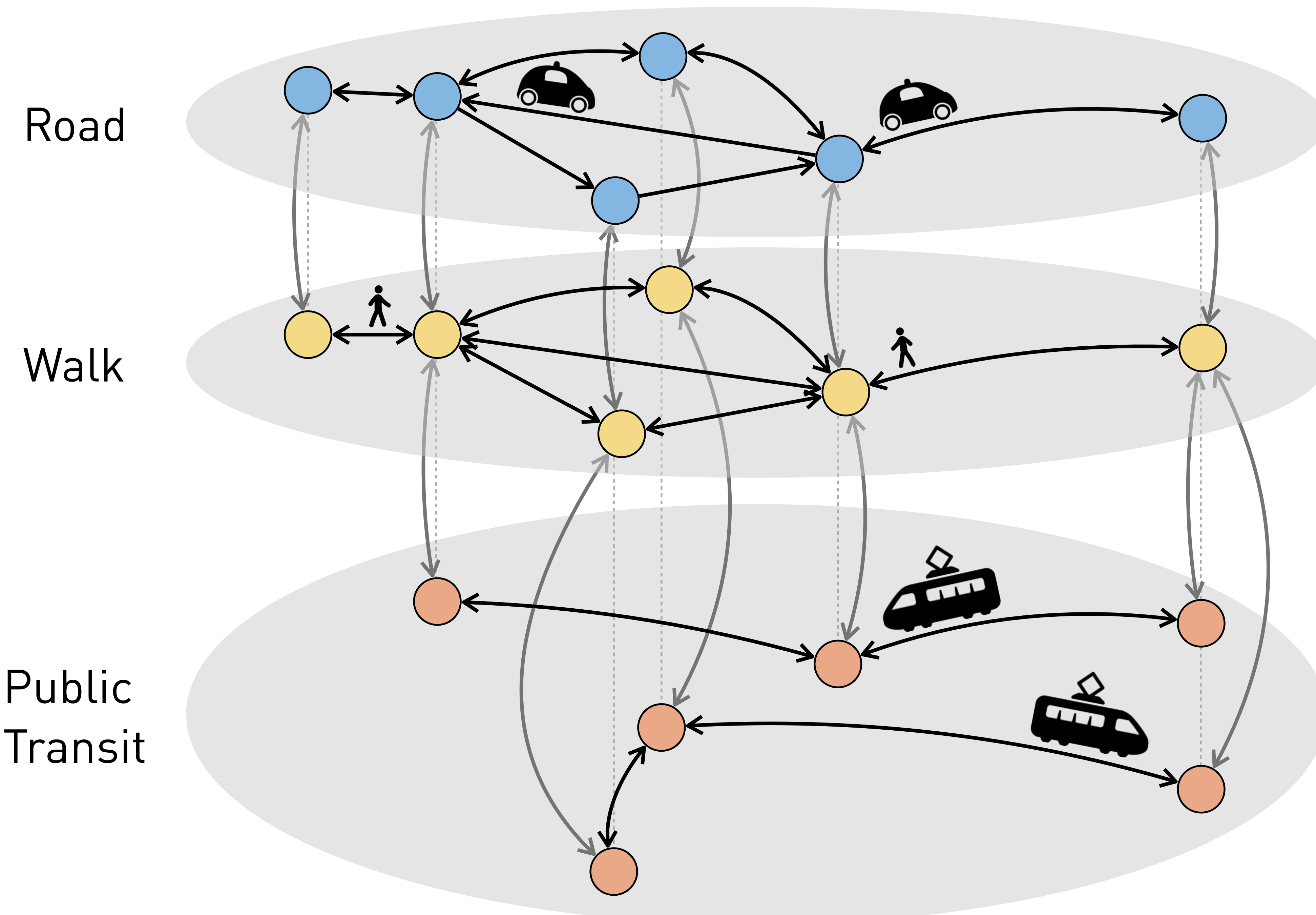


$\mathscr{G}_{\mathrm{R}} = (\mathscr{V}_{\mathrm{R}}, \mathscr{A}_{\mathrm{R}})$

Intermodal Autonomous Mobility-on-Demand



Intermodal Autonomous Mobility-on-Demand



$$\mathcal{G}_{\mathrm{R}} = (\mathcal{V}_{\mathrm{R}}, \mathcal{A}_{\mathrm{R}})$$

$$\mathcal{G}_{\mathrm{W}} = (\mathcal{V}_{\mathrm{W}}, \mathcal{A}_{\mathrm{W}})$$

$$\mathcal{G}_{\mathrm{P}} = (\mathcal{V}_{\mathrm{P}}, \mathcal{A}_{\mathrm{P}})$$

Network Flow Model

Advantages

- Highly scalable (LP)
- Very expressive

Network Flow Model

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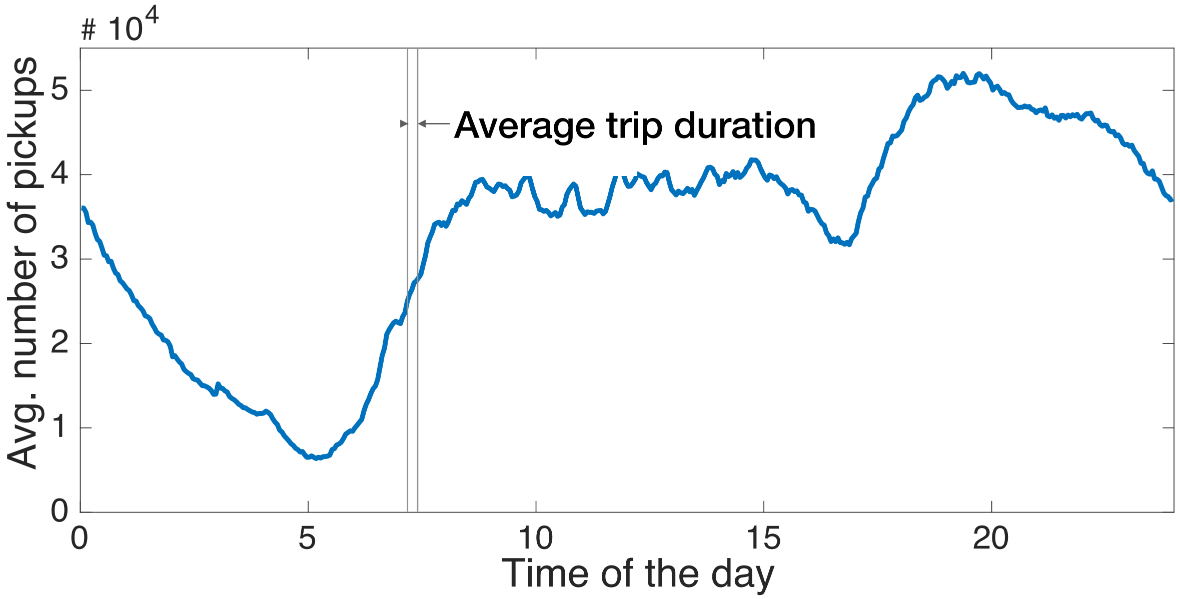
- Highly scalable (LP)
- Very expressive

Assumptions

- No stochasticity → Stochastic process in expectation [Iglesias et al. 2018]
- Continuum approximation → Flow decomposition and sampling
- One passenger per car → In line with current trends

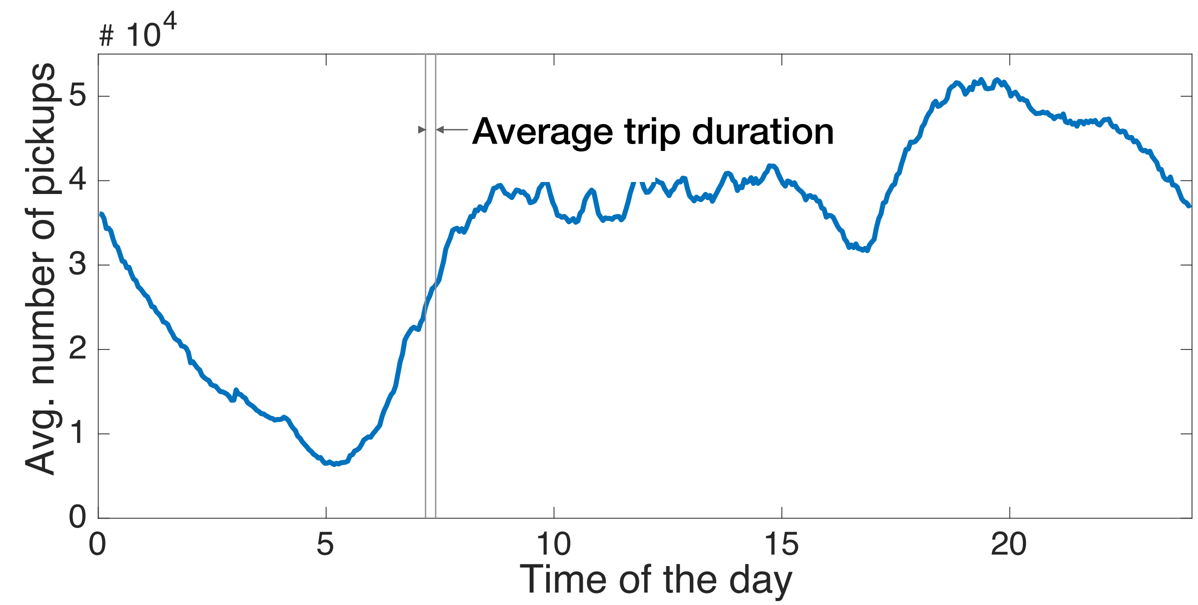
Network Flow Model - Assumptions

- Demand is **time-invariant**

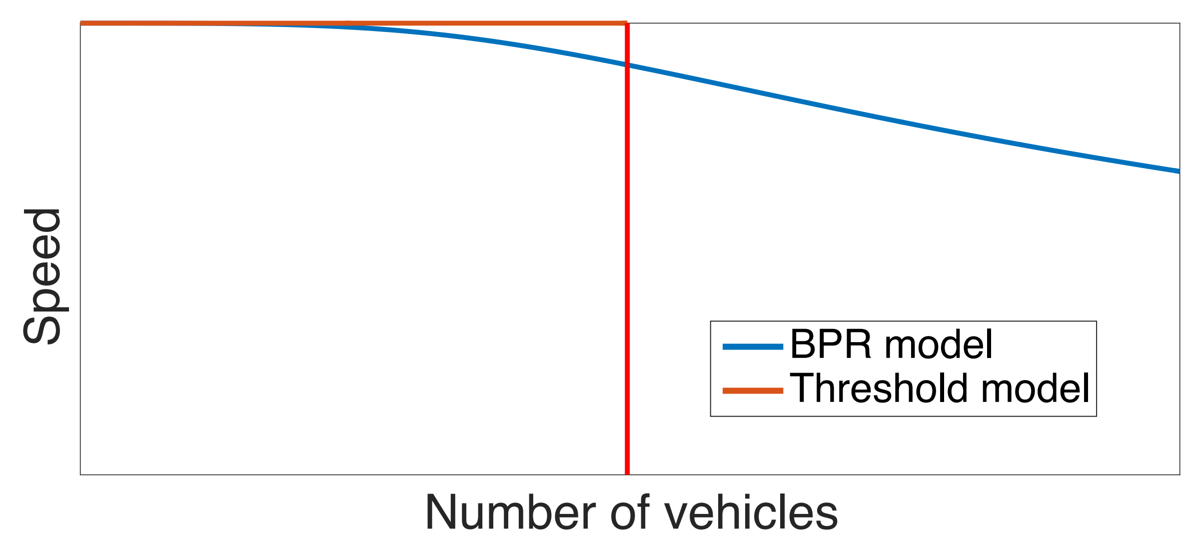


Network Flow Model - Assumptions

- Demand is **time-invariant**



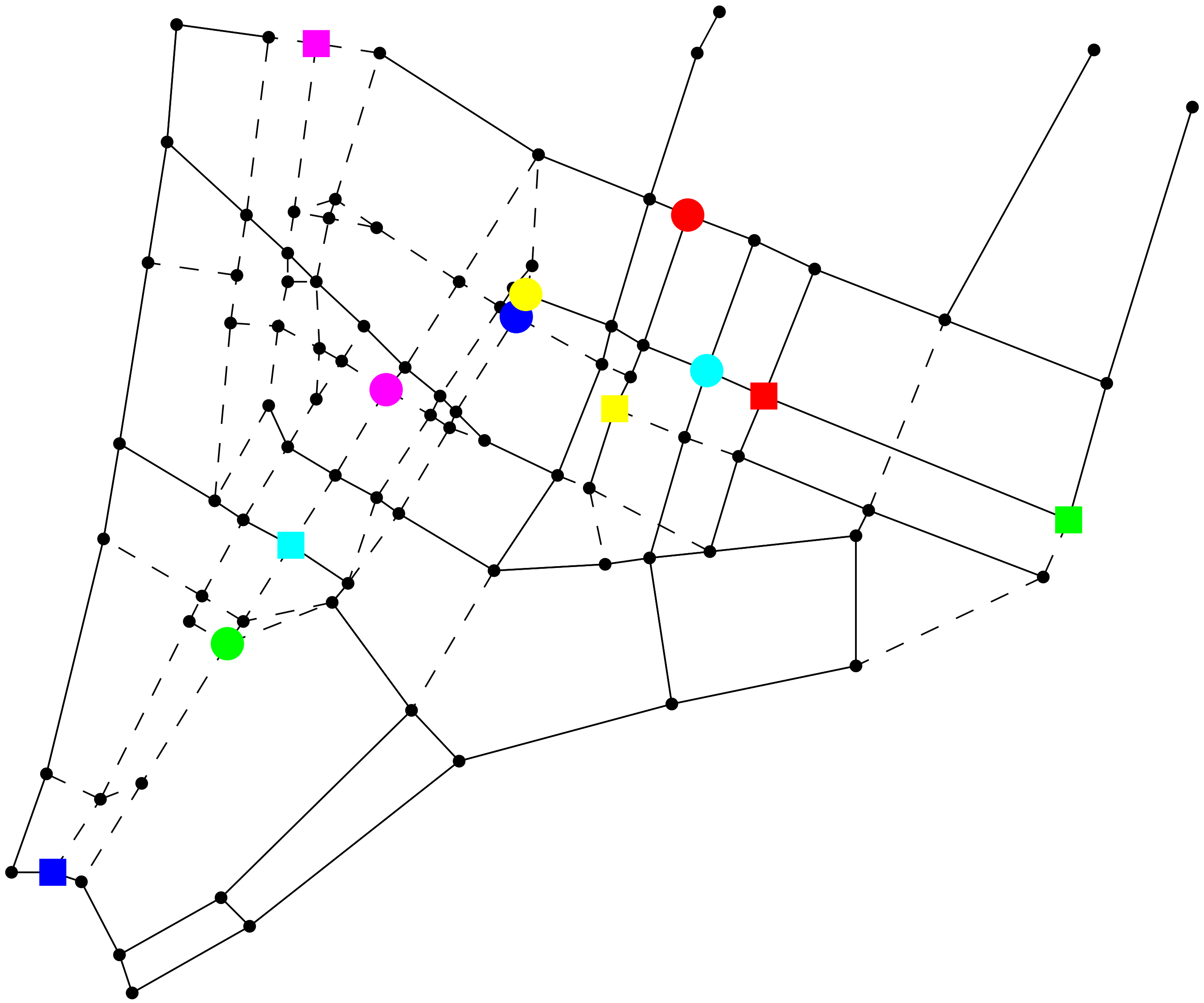
- Congestion as a **threshold**



Network Flow Model

Transportation requests

- Origin
- Destination
- Rate of demand (customers/minute)



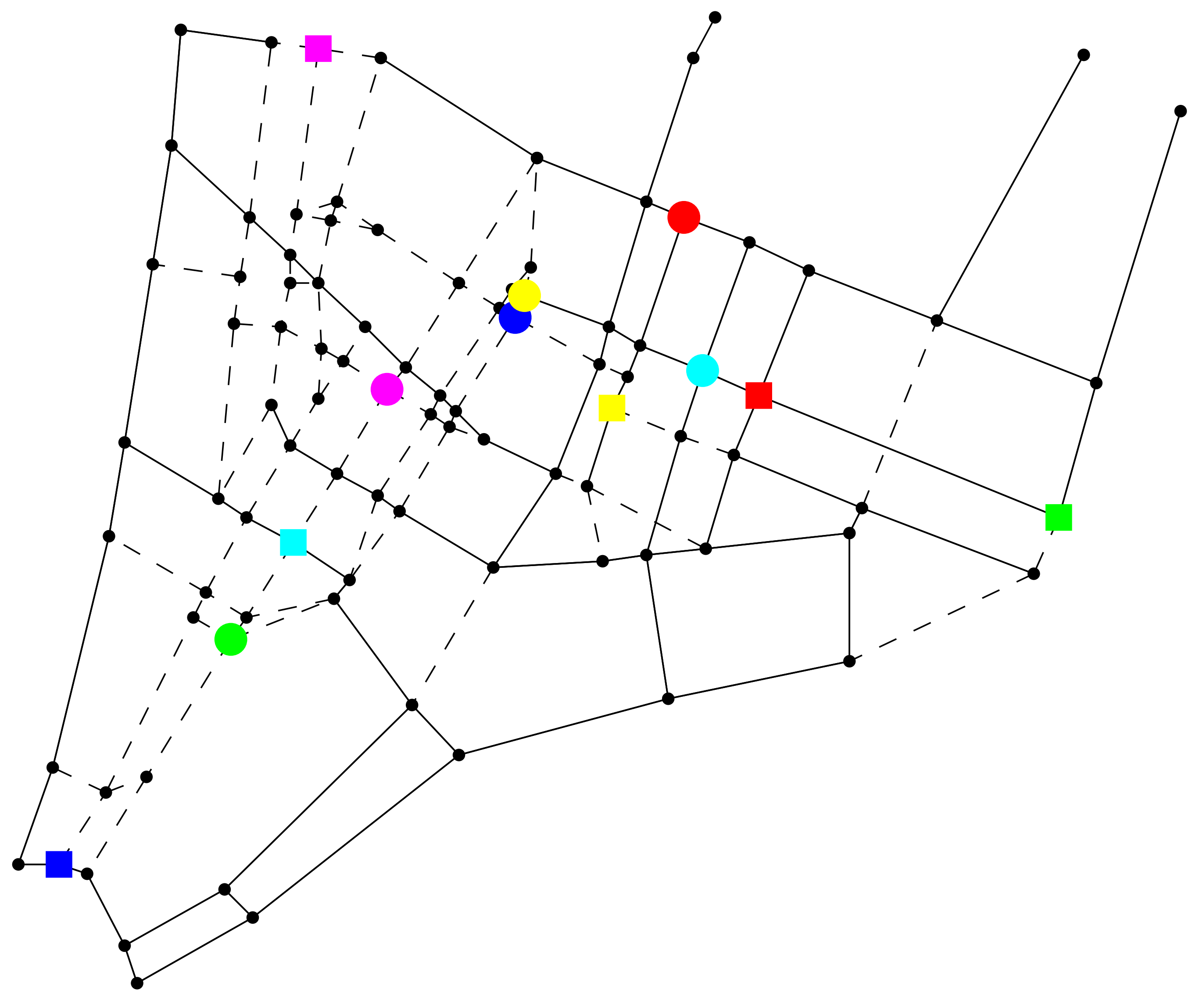
Network Flow Model

Transportation requests

- Origin
- Destination
- Rate of demand (customers/minute)

Network model

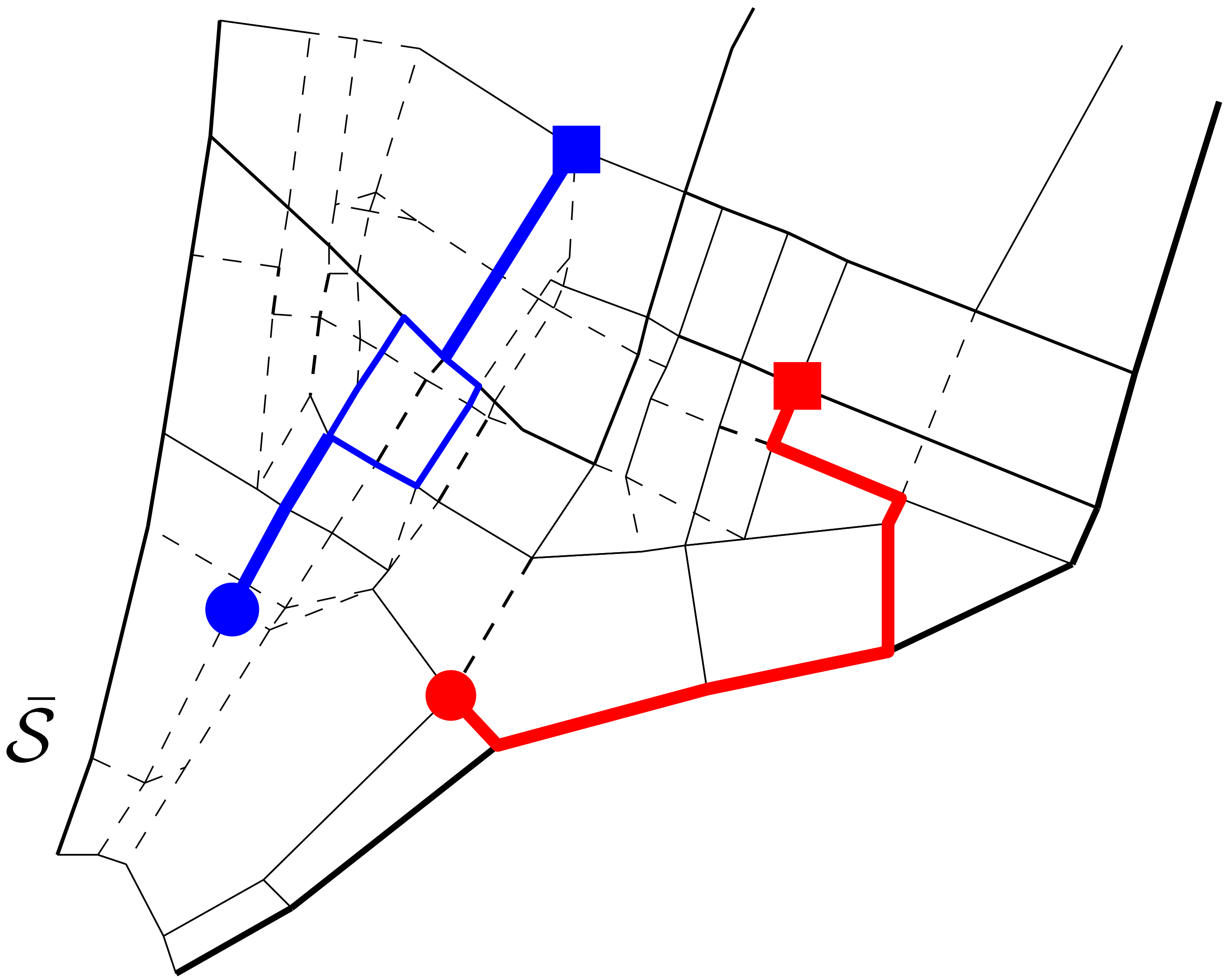
- Nodes: intersections and stops
- Capacitated arcs: roads, walk, switch and public transit



Network Flow Model - Assumptions

Flows

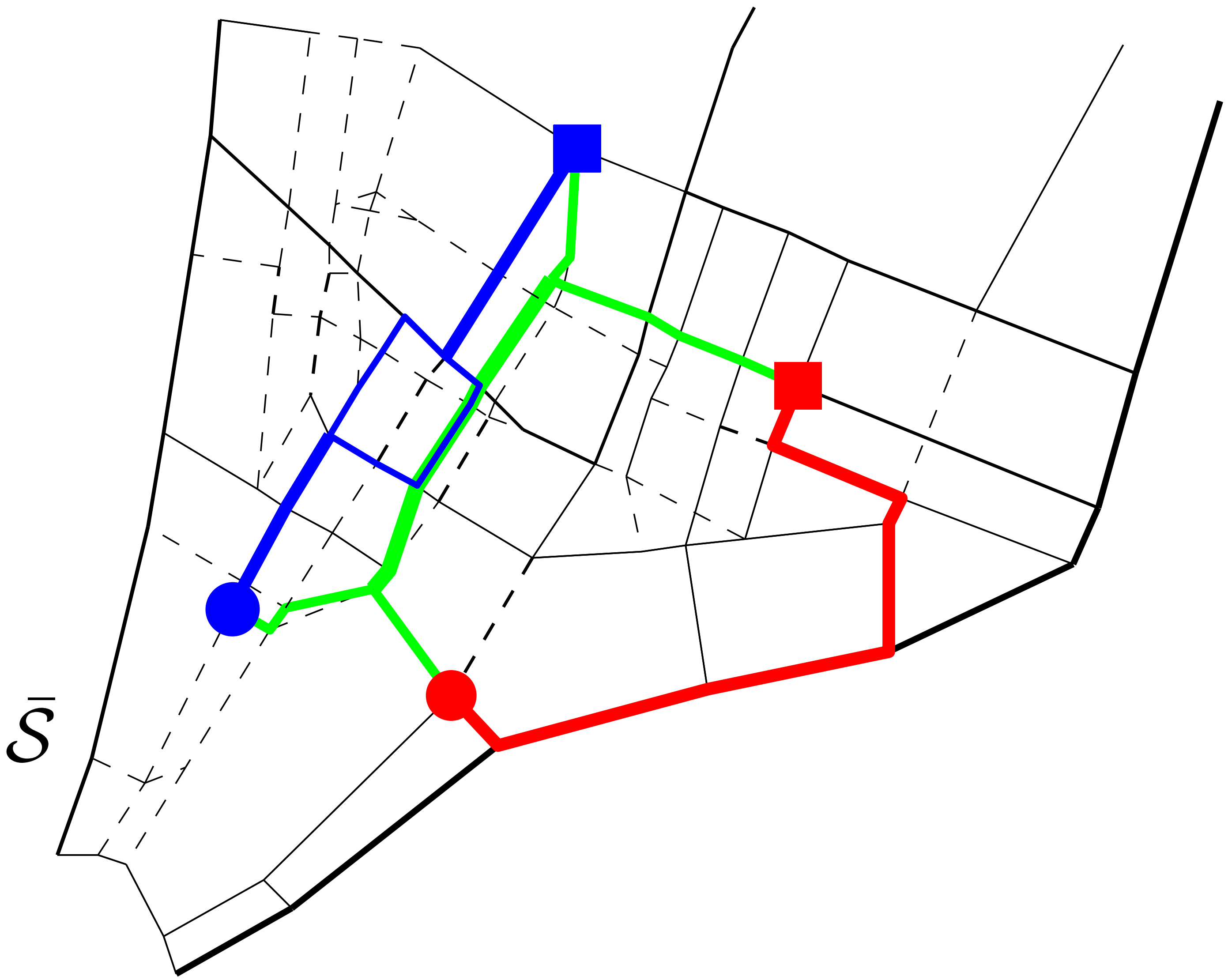
- Customer flows $f_m(i, j)$
- Rebalancing flows



Network Flow Model - Assumptions

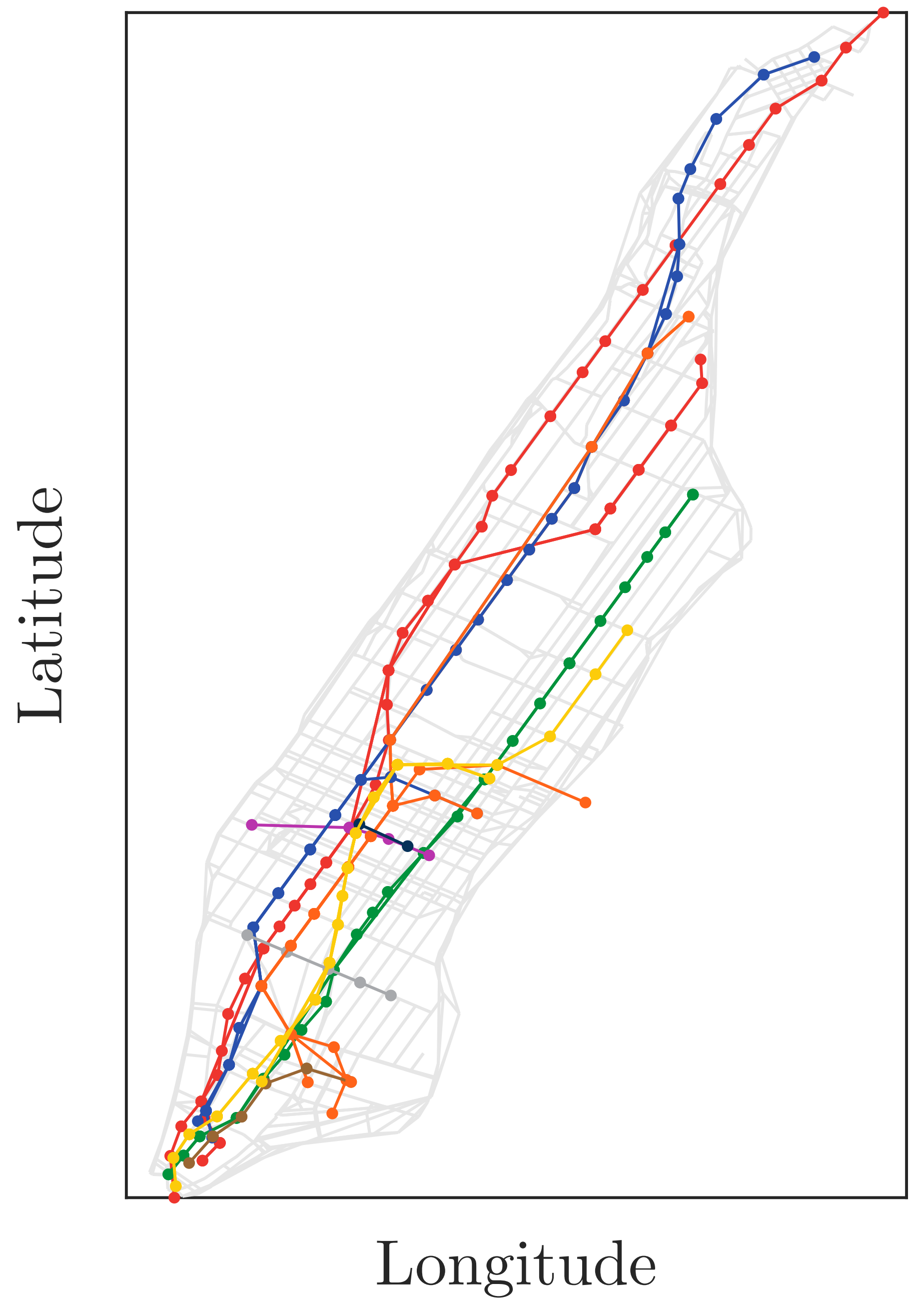
Flows

- Customer flows
- Rebalancing flows $f_0(i, j)$



Intermodal AMoD - Full Graph - Manhattan

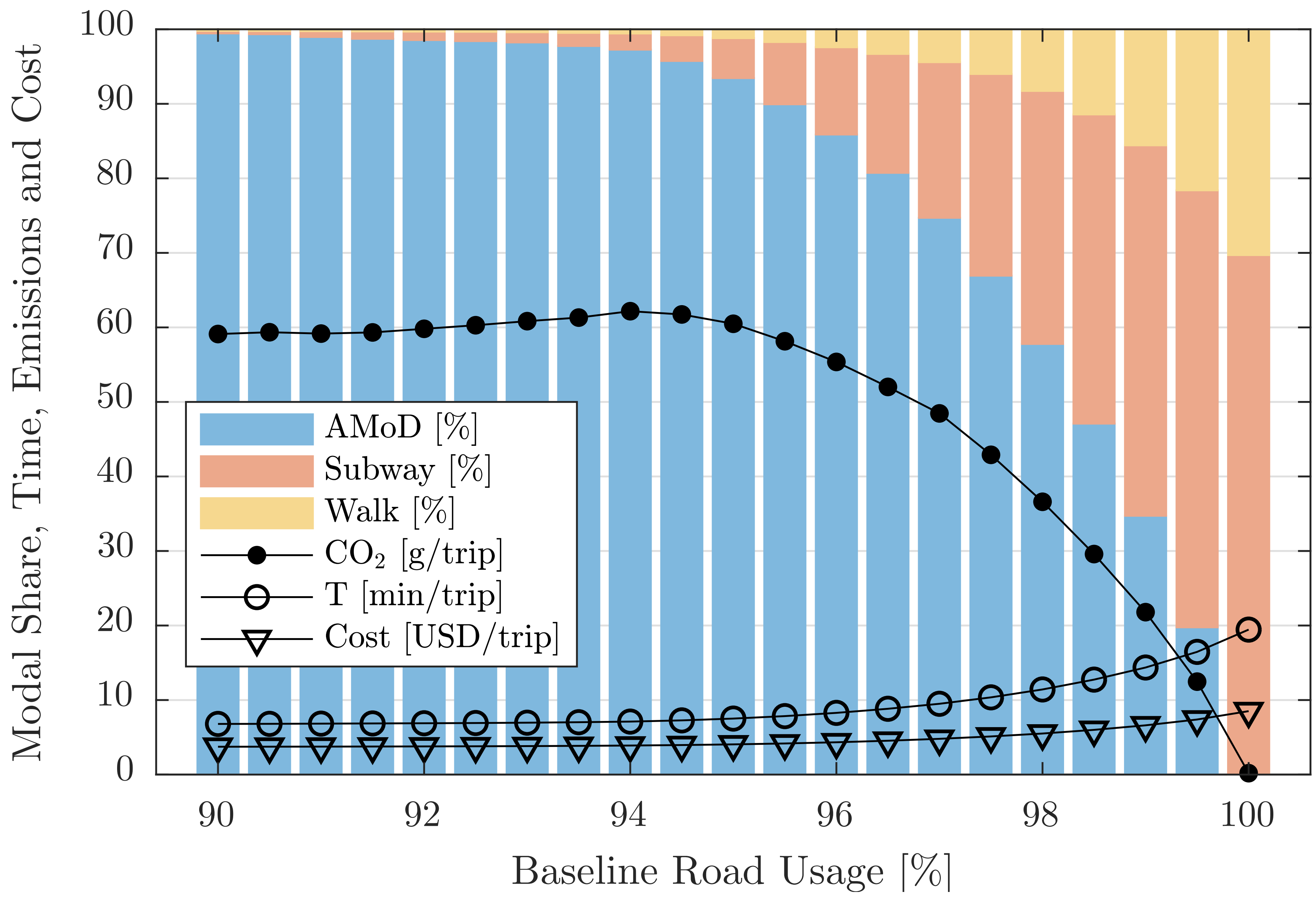
54000 taxi rides during rush hour, distributed in 6774 origin destination pairs



Compute optimal control strategies to maximise social welfare

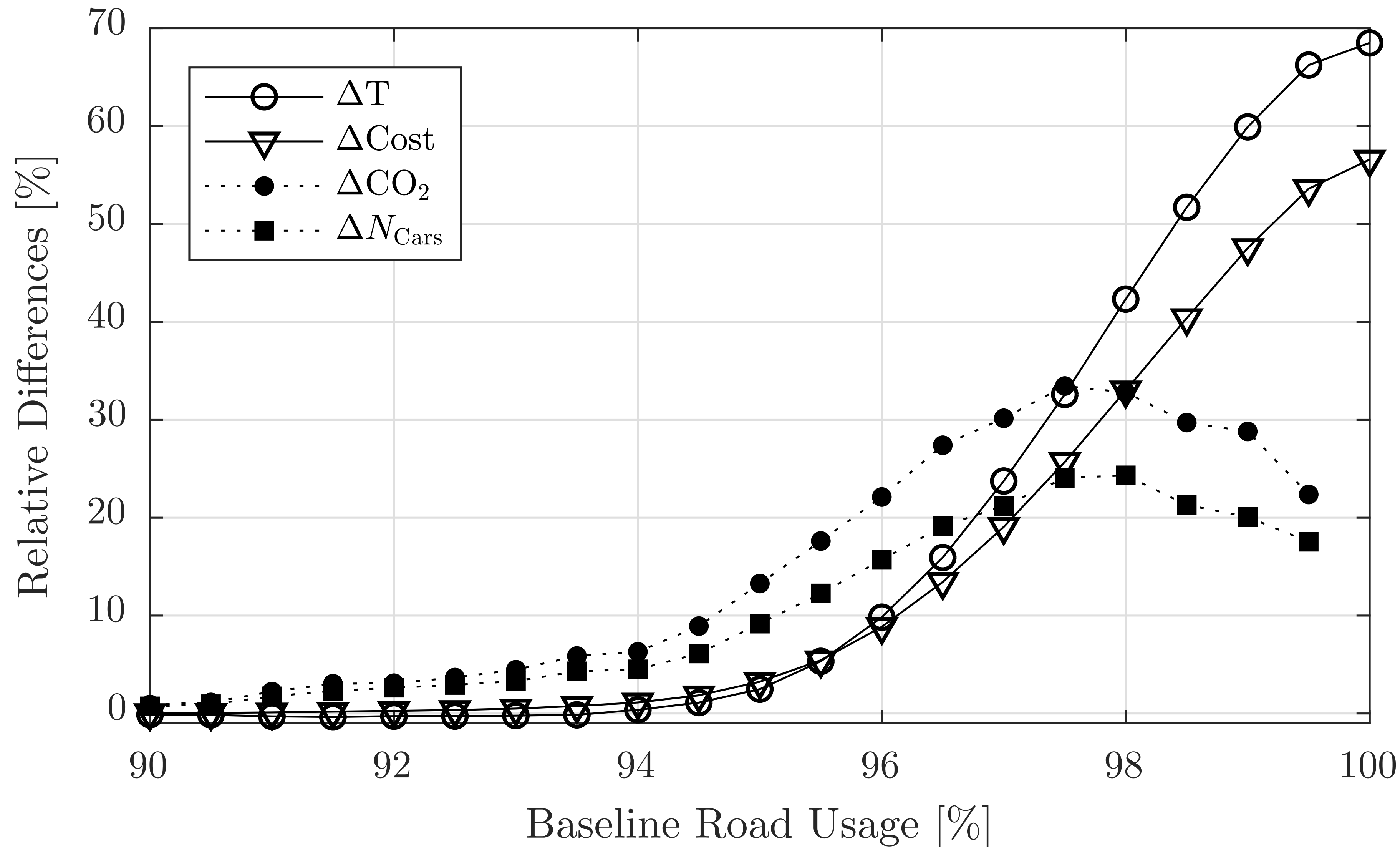
Case Study - NYC

I-AMoD - Optimal Control Policy for Different Road Capacities



Case Study - NYC

Pure AMoD VS I-AMoD - Optimal Control Policy for Different Road Capacities



Coordination with public transit significantly reduces **travel times, number of vehicles, emissions** and **cost**!

Outlook

- Real-time operational algorithms
- Stochastic effects: demand, congestion and delays
- Interaction with the power grid
- Human-centred metrics: comfort and switch-over costs

Network Flow Model

Extended Graph

$$G = (\mathcal{V}, \mathcal{A}),\ \mathcal{V} = \mathcal{V}_{\mathrm{R}} \cup \mathcal{V}_{\mathrm{P}} \cup \mathcal{V}_{\mathrm{W}},\ \mathcal{A} = \mathcal{A}_{\mathrm{R}} \cup \mathcal{A}_{\mathrm{P}} \cup \mathcal{A}_{\mathrm{W}} \cup \mathcal{A}_{\mathrm{RW}} \cup \mathcal{A}_{\mathrm{PW}}$$

Conservation of Customers

$$\sum_{i \in \mathcal{V}} f_m(i,j) + \mathbf{1}_{j=o_m} \cdot \alpha_m = \sum_{k \in \mathcal{V}} f_m(j,k) + \mathbf{1}_{j=d_m} \cdot \alpha_m \quad \forall m \in \mathcal{M}, \forall j \in \mathcal{V}$$

Conservation of Vehicles

$$\sum_{i \in \mathcal{V}_{\mathrm{R}}} \left(f_0(i,j) + \sum_{m \in \mathcal{M}} f_m(i,j) \right) = \sum_{k \in \mathcal{V}_{\mathrm{R}}} \left(f_0(j,k) + \sum_{m \in \mathcal{M}} f_m(j,k) \right) \quad \forall j \in \mathcal{V}_{\mathrm{R}}$$

Network Flow Model

Capacity of Road and Public Transportation

$$f_0(i,j) + \sum_{m \in \mathcal{M}} f_m(i,j) \leq c_{\mathrm{R}}(i,j), \ \forall (i,j) \in \mathcal{A}_{\mathrm{R}}$$

$$\sum_{m \in \mathcal{M}} f_m(i,j) \leq c_{\mathrm{P}}(i,j), \ \forall (i,j) \in \mathcal{A}_{\mathrm{P}}$$

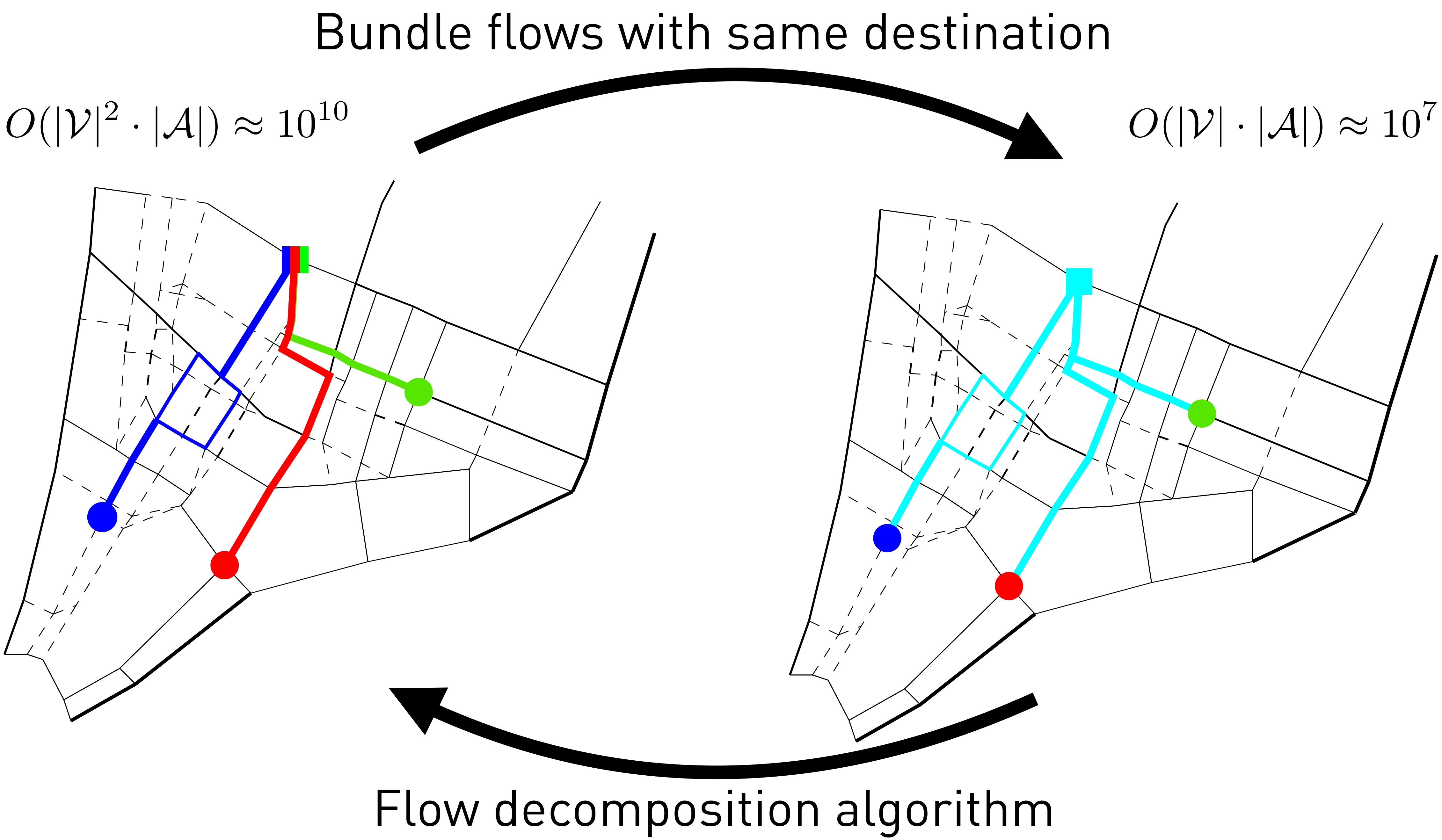
Objective Social Welfare: **time, operational costs** and **energy**

$$\min_{f_m(i,j), f_0(i,j)} \sum_{(i,j) \in \mathcal{A}} \sum_{m \in \mathcal{M}} V_{\mathrm{T}} \cdot t_{ij} \cdot f_m(i,j)$$

$$+ \sum_{(i,j) \in \mathcal{A}_{\mathrm{R}}} (V_{\mathrm{D,R}} \cdot d_{ij} + V_{\mathrm{E}} \cdot e_{\mathrm{R},ij}) \cdot \left(f_0(i,j) + \sum_{m \in \mathcal{M}} f_m(i,j) \right)$$

$$+ \sum_{(i,j) \in \mathcal{A}_{\mathrm{P}}} V_{\mathrm{D,P}} \cdot d_{ij} \cdot \sum_{m \in \mathcal{M}} f_m(i,j)$$

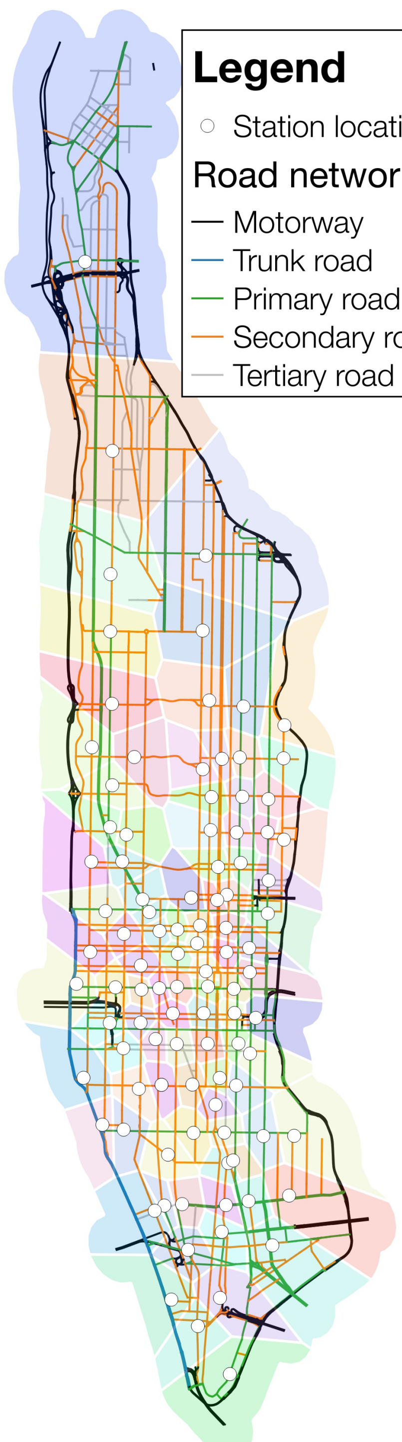
Network Flow Model - Flow Bundling



Theorem: Flow bundling is lossless [Rossi et al. 2018]

Intermodal AMoD - AMoD and Pedestrian

Manhattan Road Network - Data from OpenStreetMap

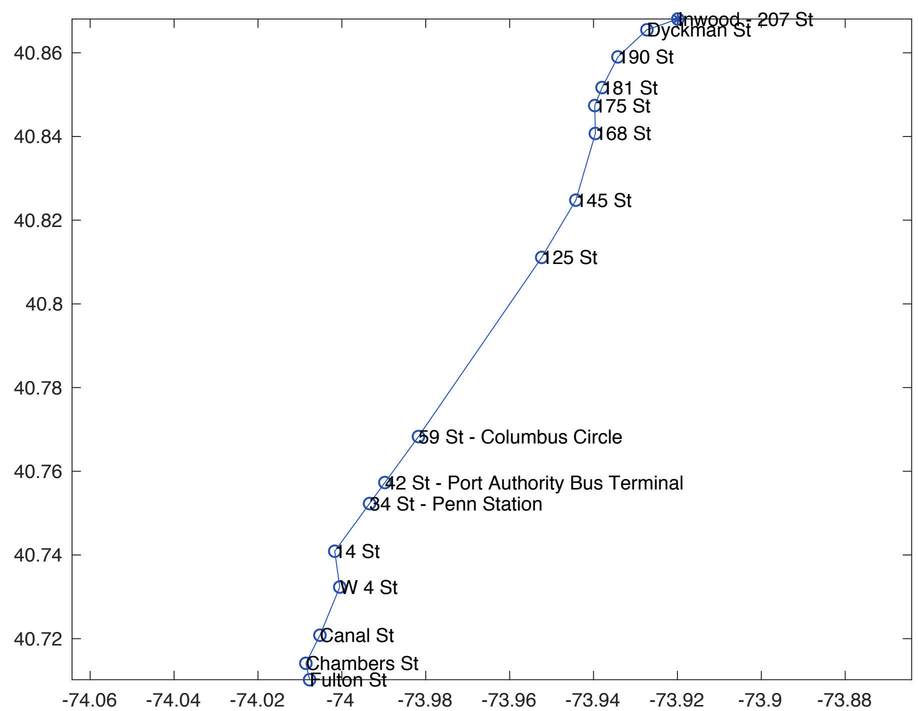


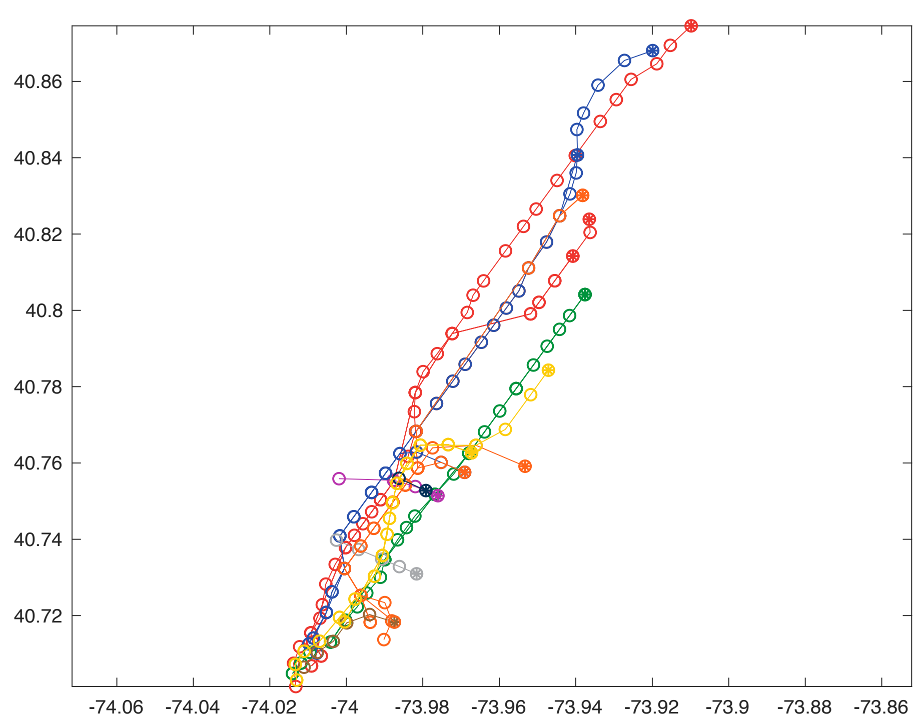
Consider 54000 taxi rides during rush hour, distributed in 6774 origin destination pairs

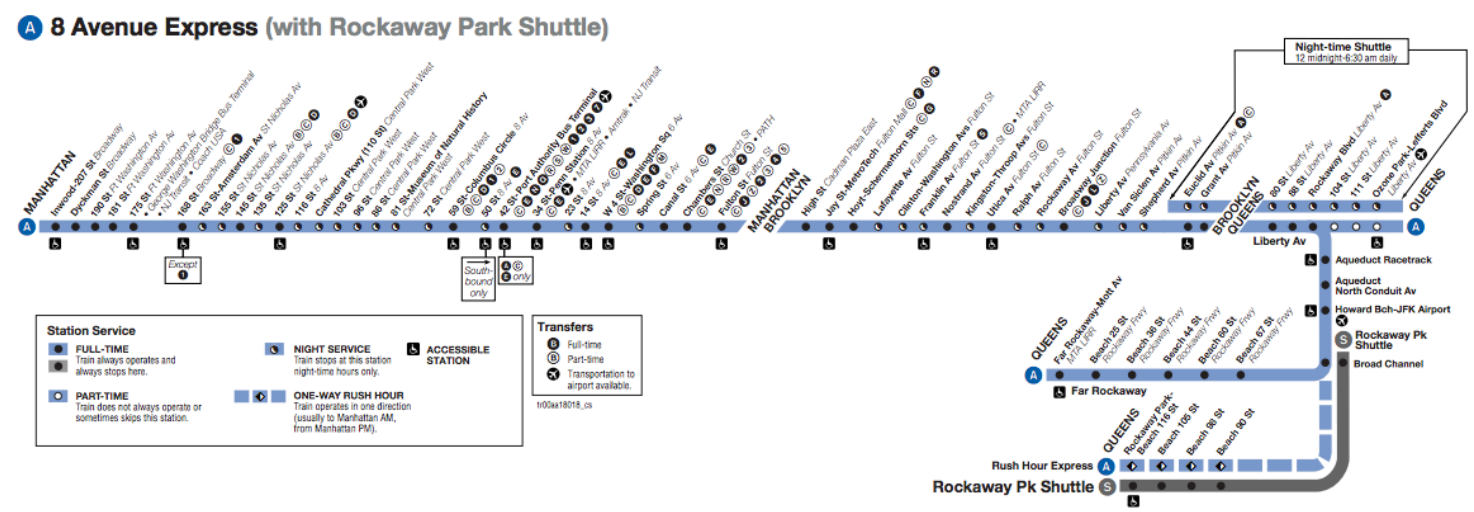
Since cabs are only a fraction of the vehicles, we will assume a baseline road usage of 90-100%

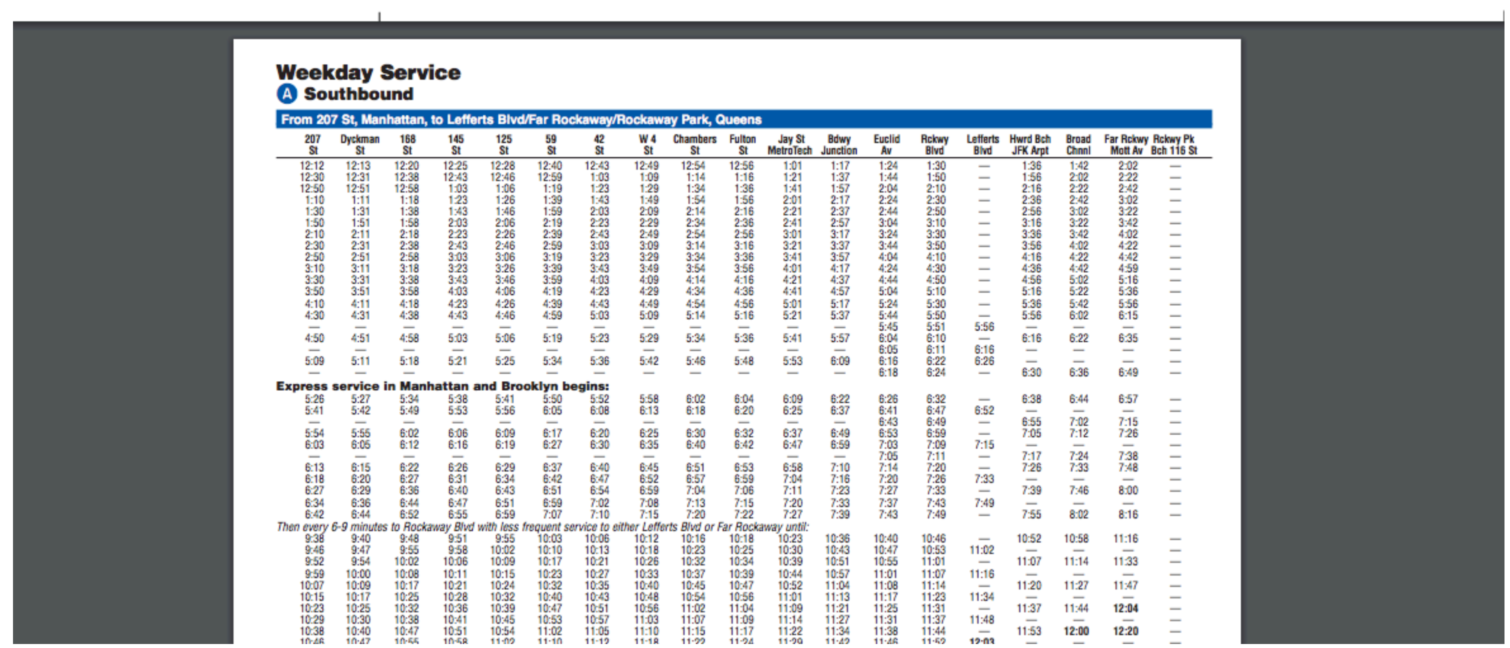
Intermodal AMoD - Subway

Manhattan Subway Network - Data from data.cityofnewyork.us and mta.info





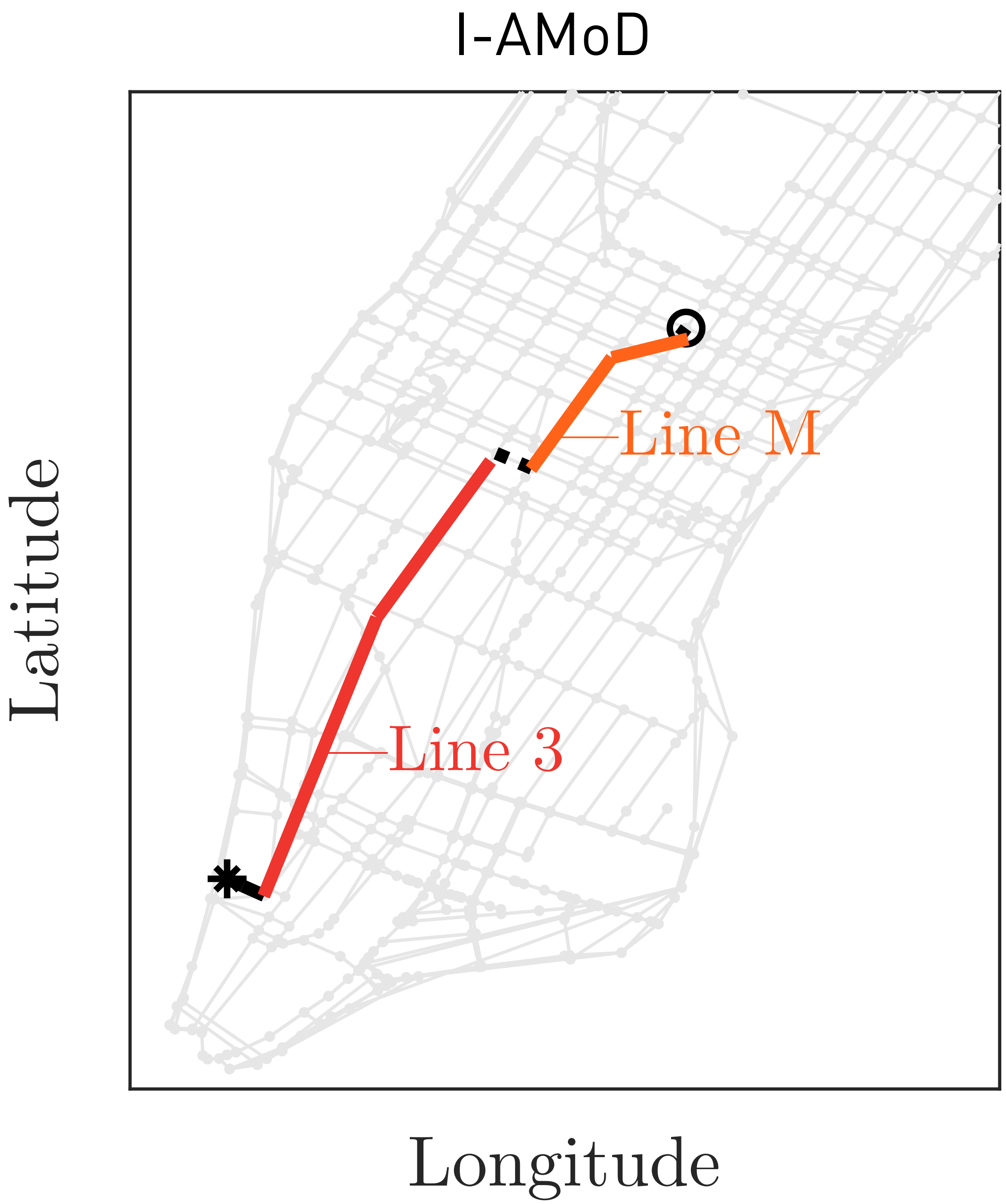


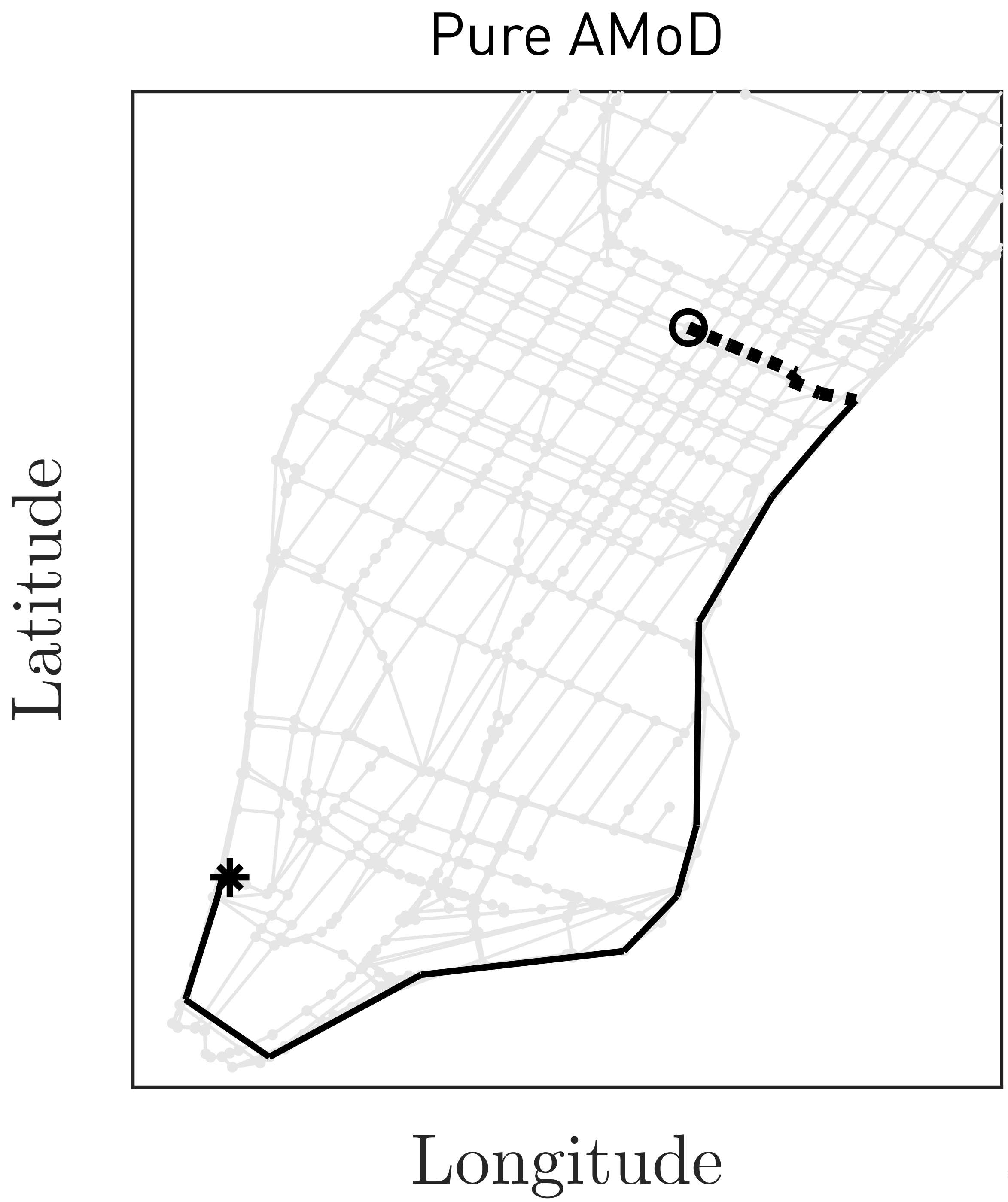


Very advanced format...

Case Study - NYC - 98% Road Usage

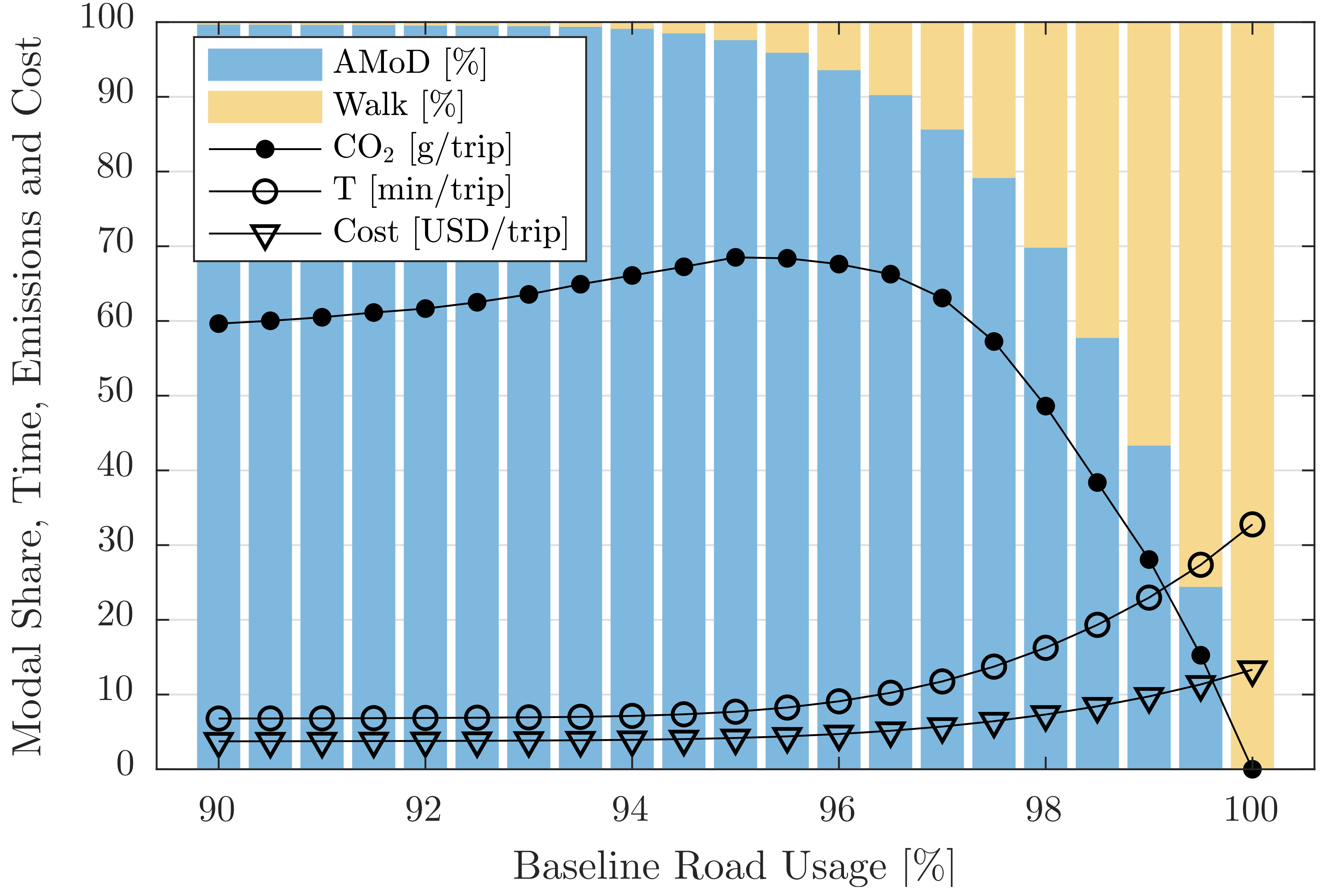
Sample optimal paths





Case Study - NYC

Pure AMoD - Scan in road capacity



A Socially Optimal Road Tolling Scheme

Municipality wants to relieve congestion through road tolls

The New York Times

N.Y. / REGION

Congestion Plan for Manhattan Gets Mixed Reviews

By WINNIE HU and VIVIAN WANG JAN. 19, 2018

Congestion constraint and dual multipliers

$$f_0(i,j) + \sum_{m \in \mathcal{M}} f_m(i,j) - c_{\mathrm{R}}(i,j) \leq 0,\ \forall (i,j) \in \mathcal{A}_{\mathrm{R}} \quad \leftrightarrow \quad \mu_{\mathrm{cR}}(i,j) \geq 0$$

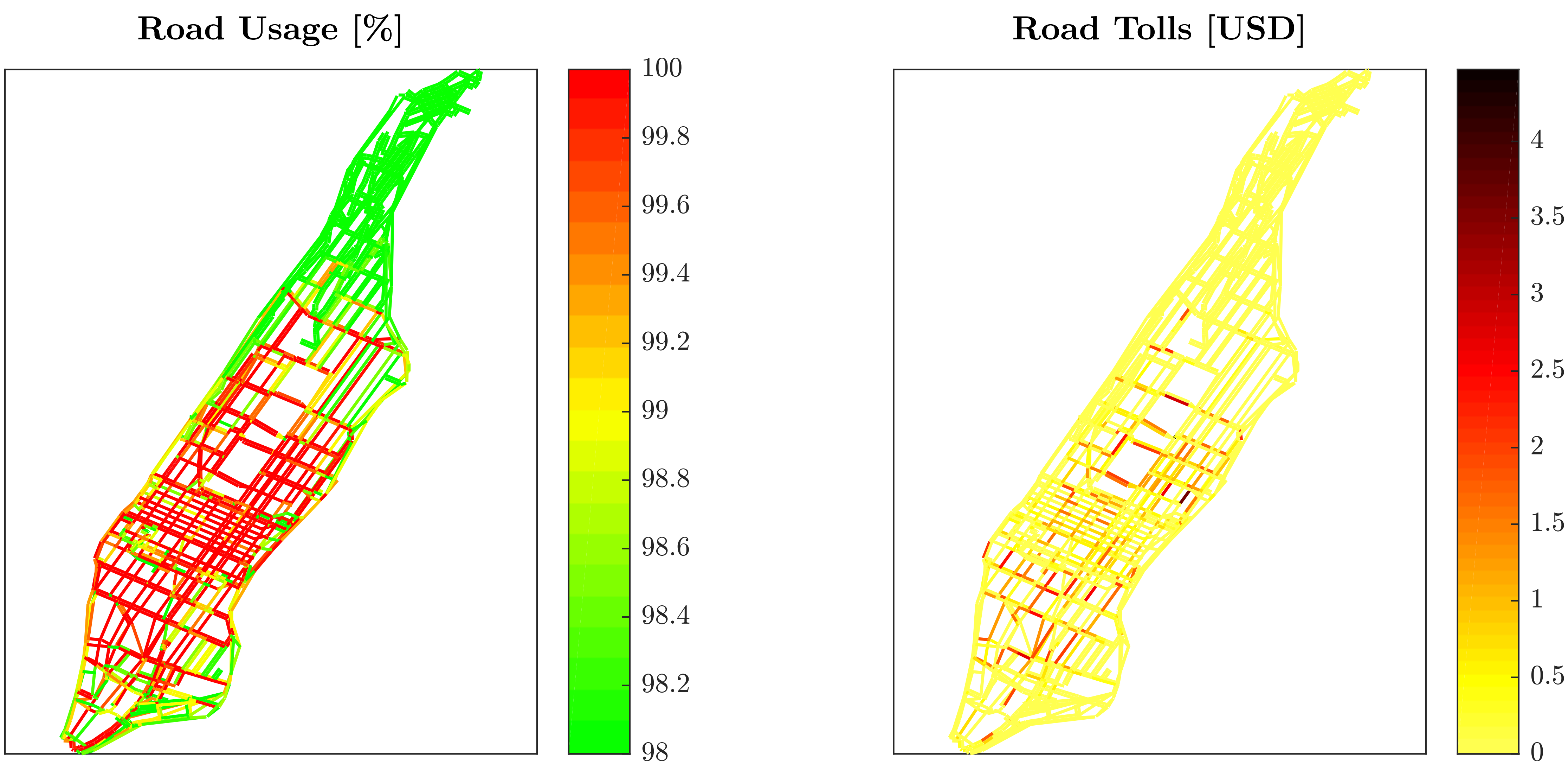
Optimal road tolls are the dual multipliers of the road congestion constraints

$$t_{\mathrm{R}}(i,j) = \mu_{\mathrm{cR}}(i,j)$$

Theorem: Tolling scheme guarantees social optimum [Salazar et al. 2018]

Case Study - NYC - 98% Usage

I-AMoD - Tolling scheme



The average surcharge would be about **$2** VS almost **$6 with pure AMoD**.
In line with Cuomo's per-trip surcharge of **$2-5**! [New York Times, Jan 2018]