Autonomous and Connected Transportation Systems
Modeling, Control, and Deployment

Mauro Salazar, Ramon Iglesias, Stephen Zoepf and Marco Pavone

Auckland, 27.10.2019

Overview

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1. How can we design **profitable** and **sustainable** mobility systems that leverage **autonomous vehicles**?

2. What will these new forms of mobility and transportation mean for **society**?

3. How can we ensure that such technologies benefit all members of society, improving **equity** rather than undermining it?

Goal of the Workshop

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2. Identify **modeling** and **control** methodologies to address them

3. **Share insights** from early deployments and turn such insights into an **actionable research roadmap**

Agenda - Morning

09:00-09:30	Mauro Salazar	Introduction Autonomous Mobility-on-Demand for Future Urban Mobility
09:30-10:00	Krishna Selvam	Ride-sharing Marketplace: Designing from Efficiency
10:00-10:30	Coffee Break	
10:30-11:00	Francesco Ciari	Planning Shared Automated Vehicle Fleets: Specific Modeling Requirements and Concepts to Address Them
11:00-11:30	Raphael Stern	Controlling Mixed Human and Autonomous Traffic
11:30-12:00	Salomon Wollenstein	How Many Smart Cars Does It Take to Make a Smart Traffic Network?
12:00-14:00	Lunch Break	

Agenda - Afternoon

13:30-14:00	Michael Levin	Maximum-stability Dispatch Policy for Shared Autonomous Vehicles
14:00-14:30	Michal Čáp	Understanding the Fundamental Trade-offs in Large-scale Mobility-on-demand Systems
14:30-15:00	Javier Alonso-Mora	Predictive Routing and Multi-objective Fleet Sizing for Shared Mobility-on-demand
15:00-15:30	Coffee Break	
15:30-16:00	Emilio Frazzoli	Autonomous Mobility-on-Demand: What is Known and What is Not Known
16:00-16:30		Feedback and Discussion on Future Directions

Autonomous Mobility-on-Demand for Future Urban Mobility

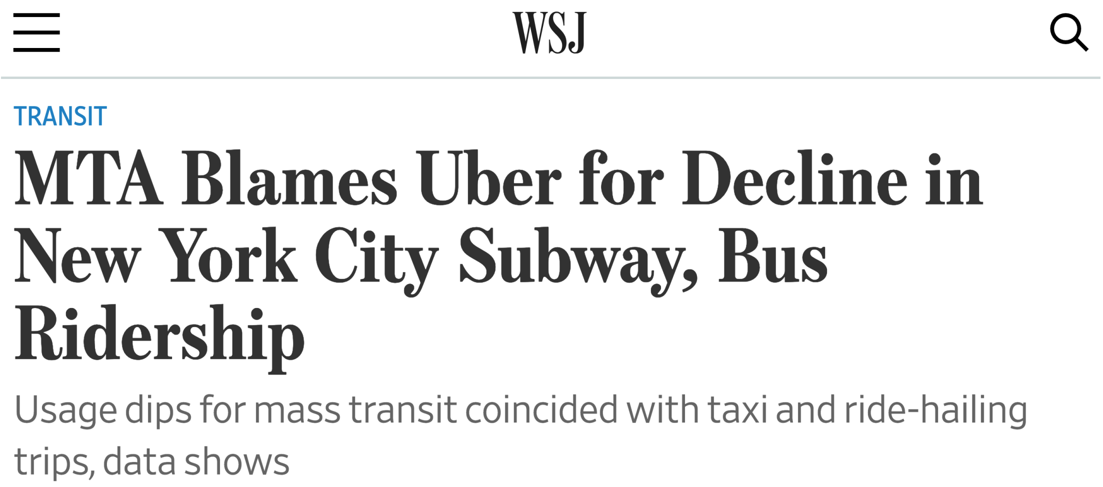
Mauro Salazar and Marco Pavone

Facts about Mobility

Challenges

Facts about Mobility

Challenges

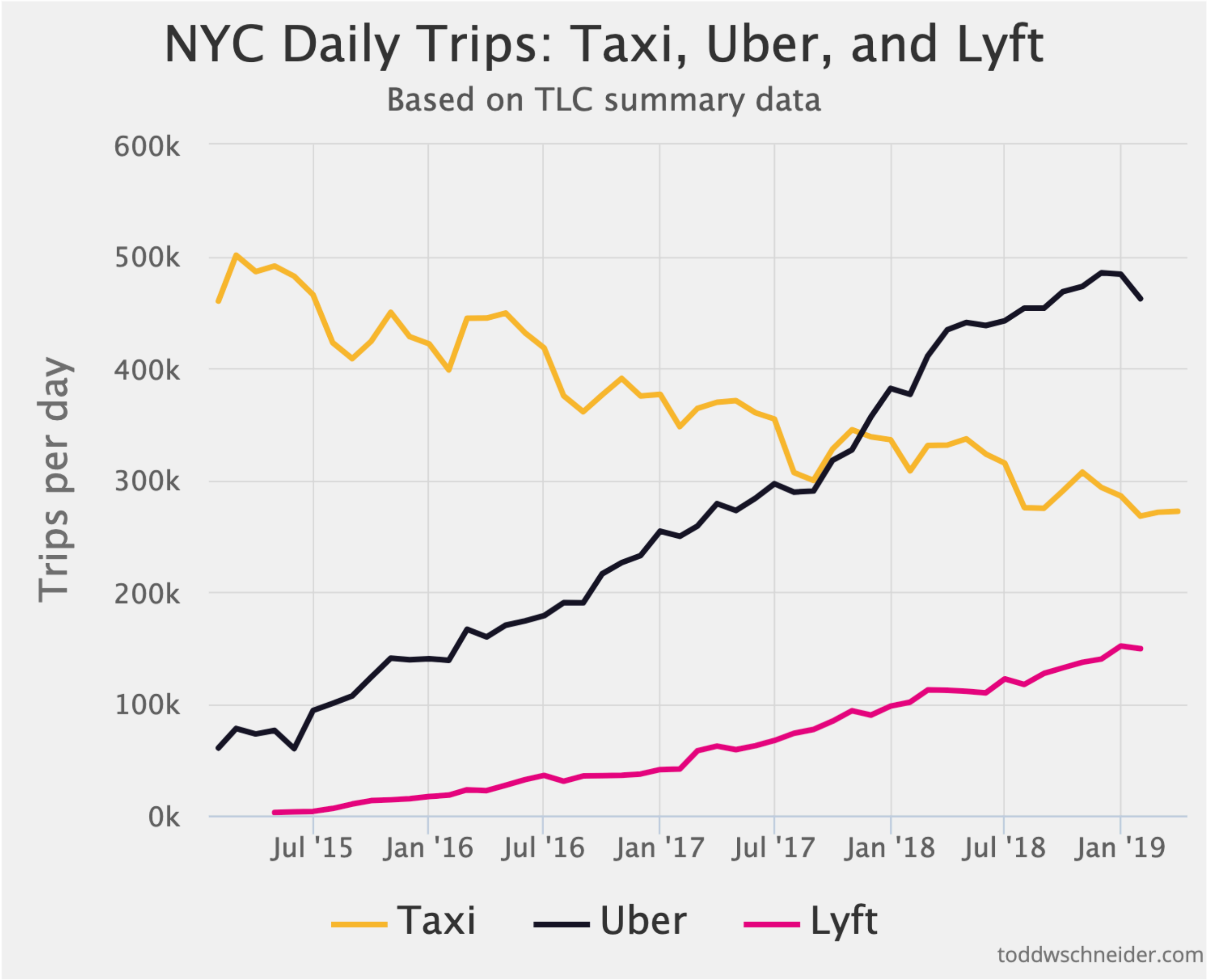


WSJ

TRANSIT

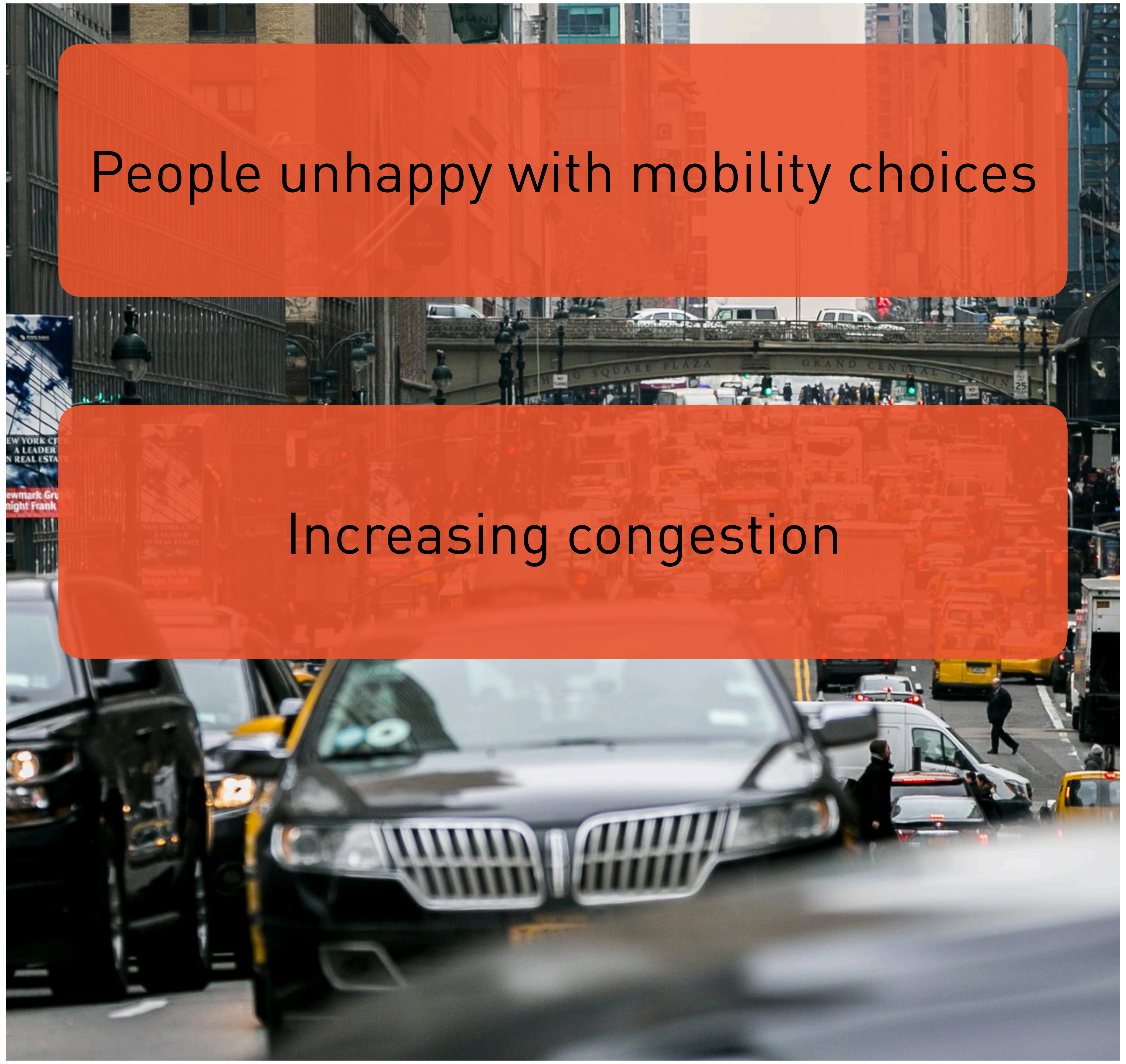
MTA Blames Uber for Decline in New York City Subway, Bus Ridership

Usage dips for mass transit coincided with taxi and ride-hailing trips, data shows



Facts about Mobility

Challenges



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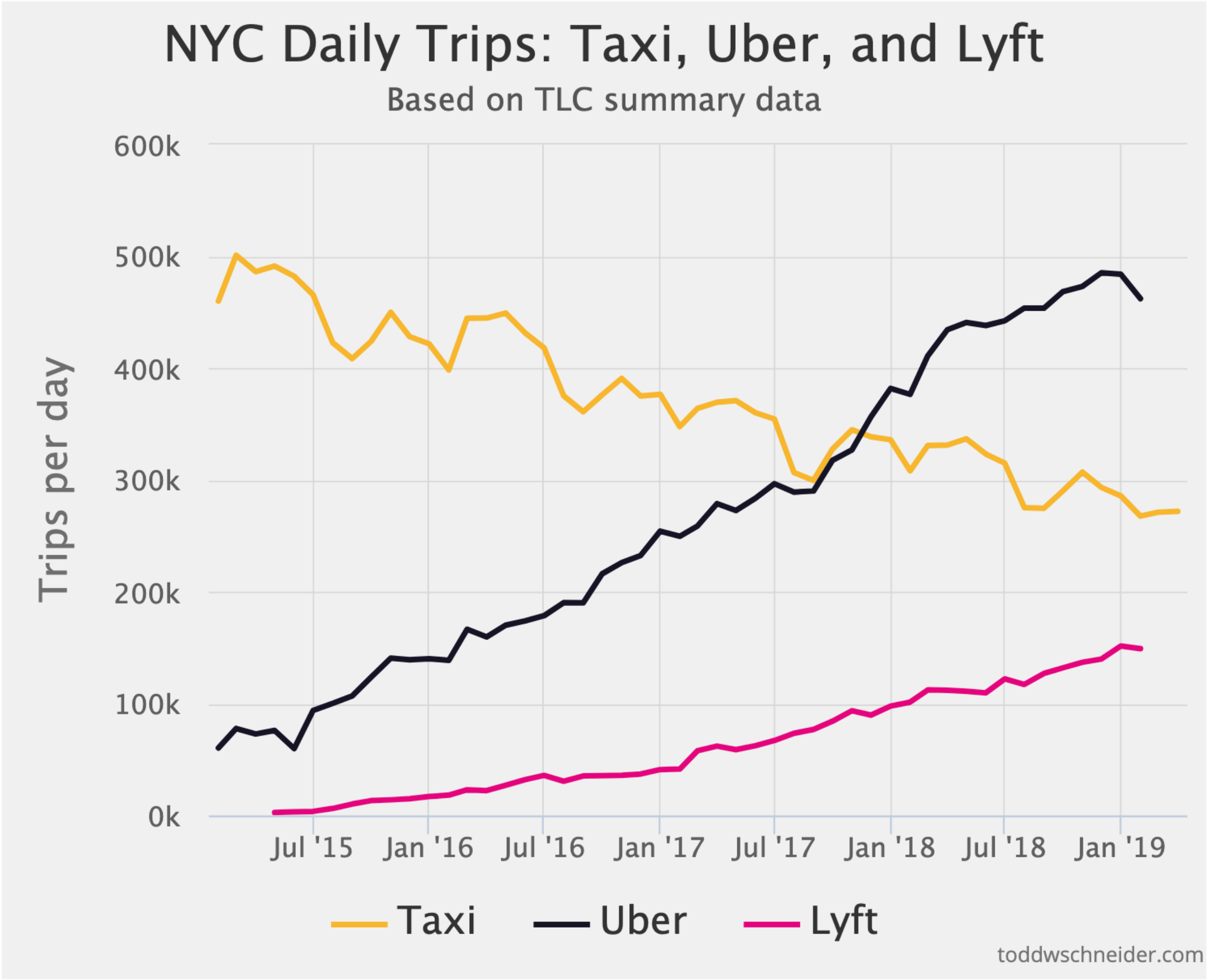


The New York Times

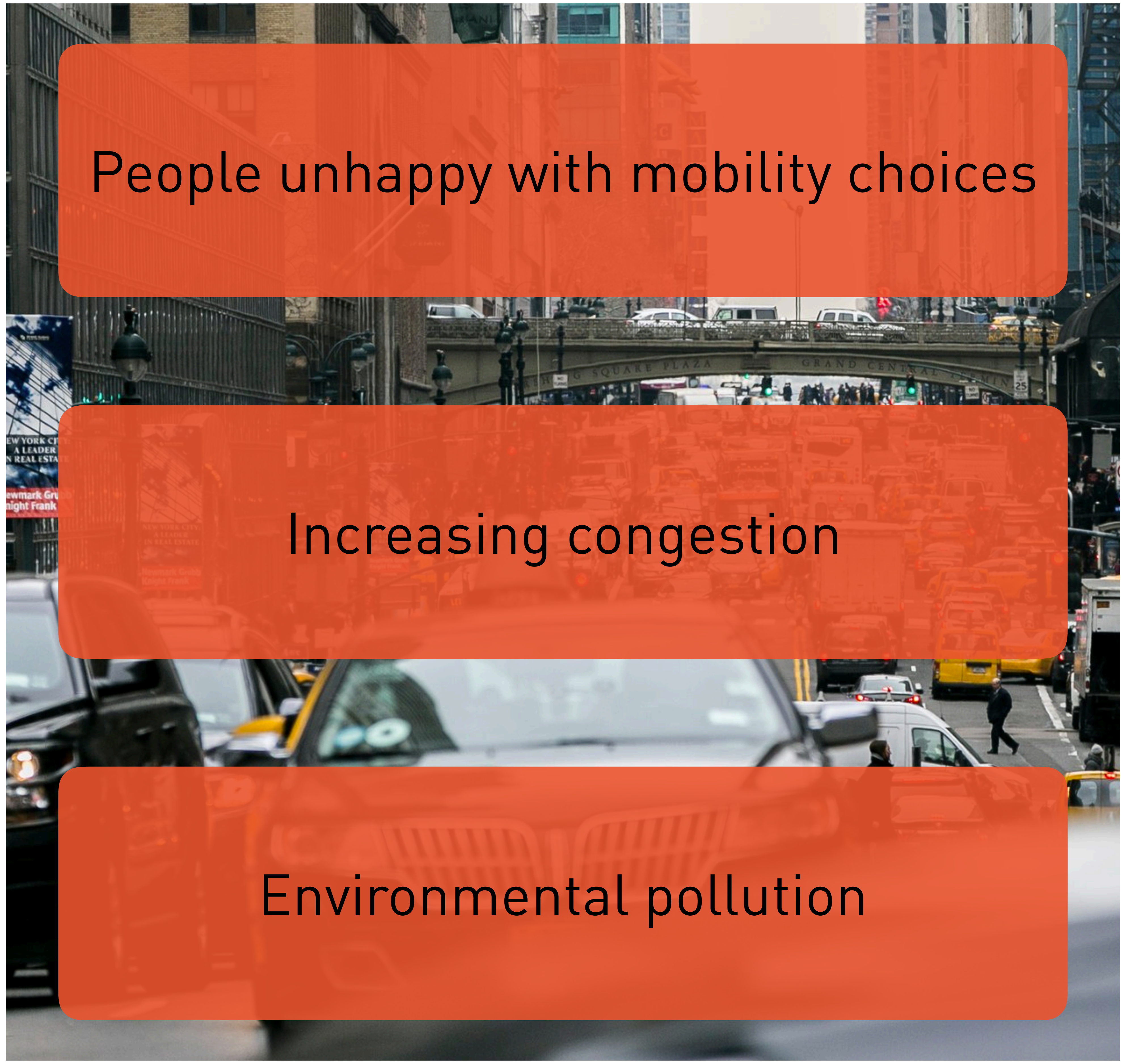
Over $10 to Drive in Manhattan? What We Know About the Congestion Pricing Plan

Stuck and Stressed: The Health Costs of Traffic

The physical and psychological toll of brutal commutes can be considerable.

Facts about Mobility

Challenges



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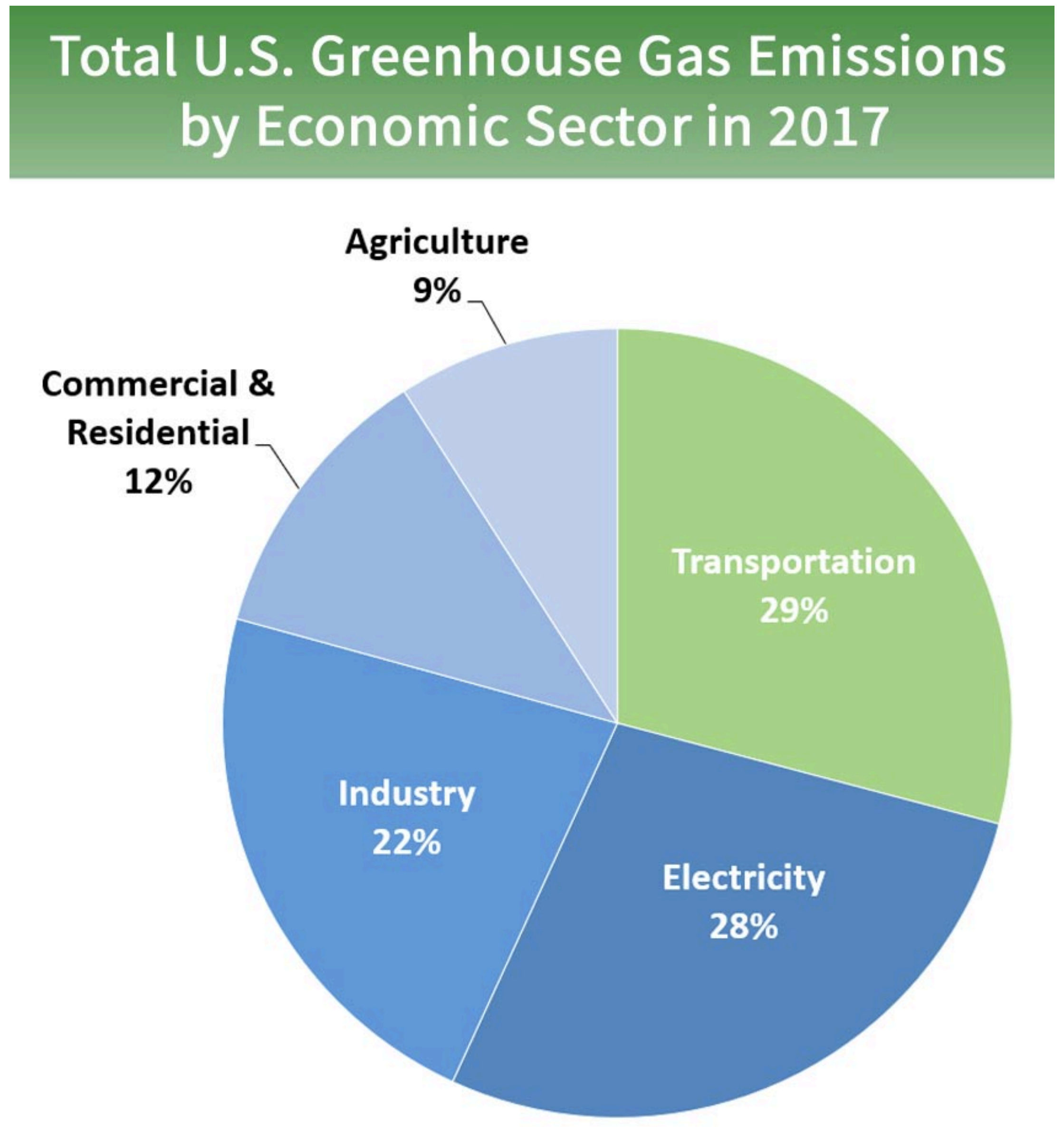
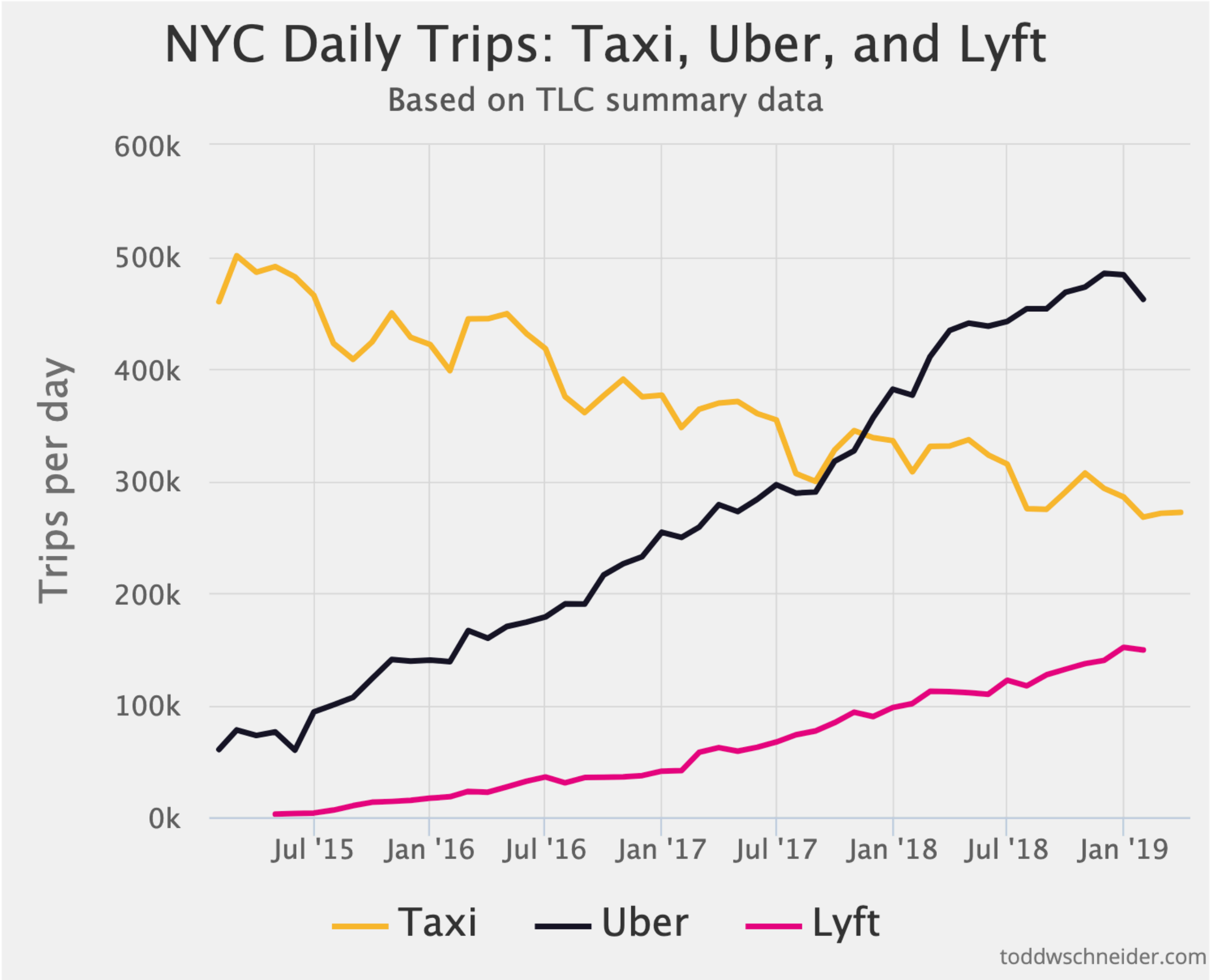


U.S. Environmental Protection Agency (2019). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017



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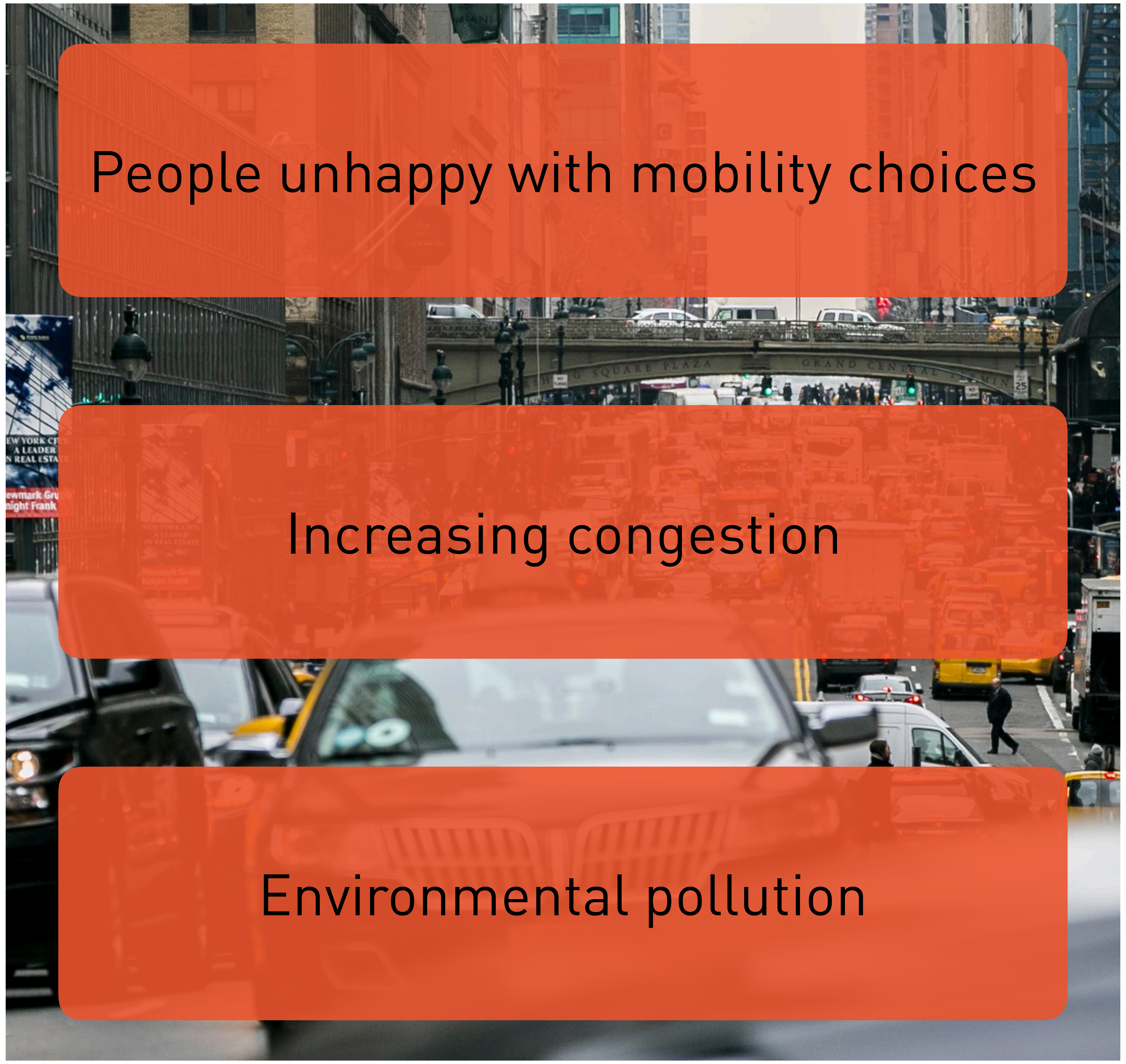


People unhappy with mobility choices

Increasing congestion

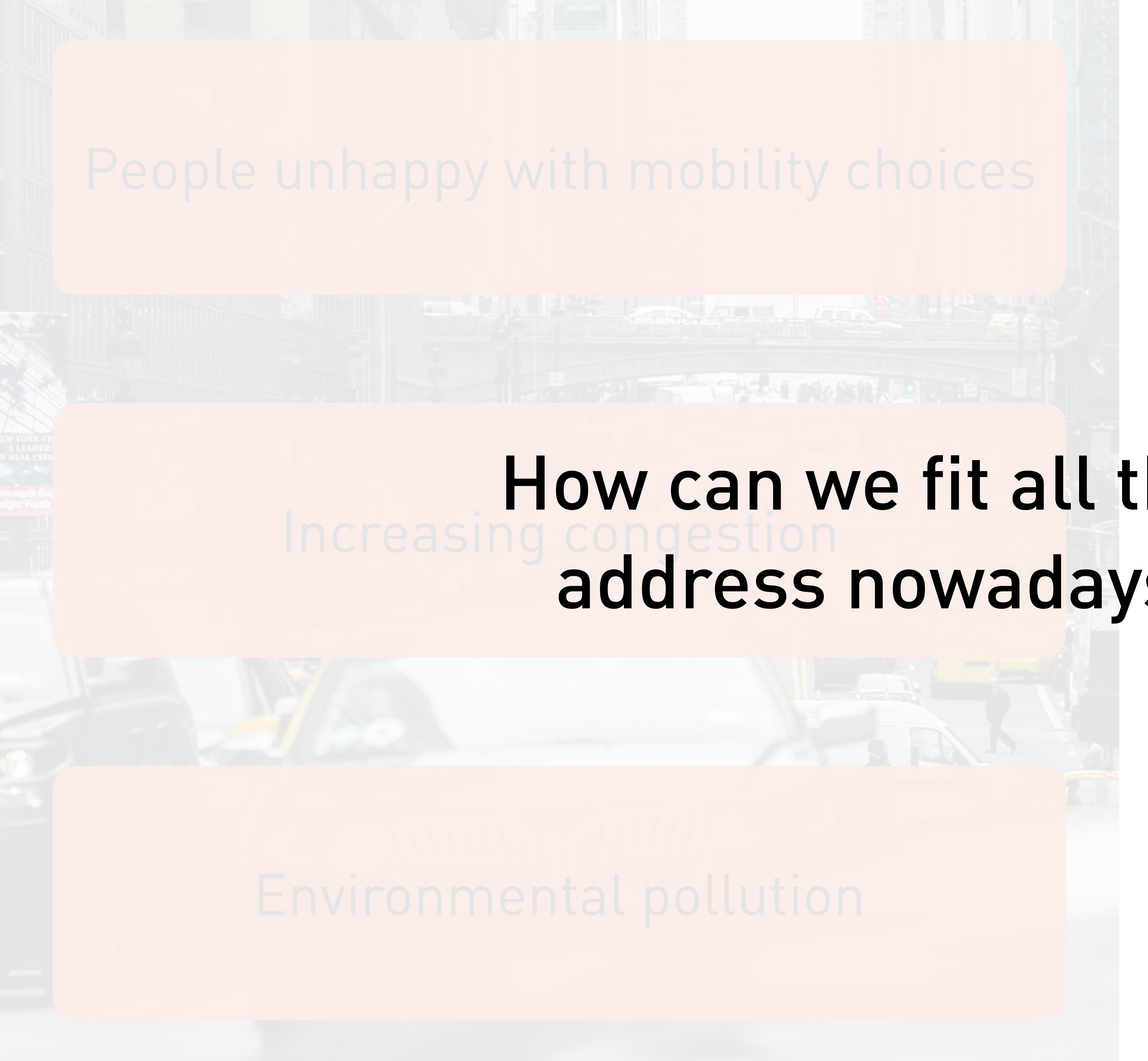
Environmental pollution

Opportunities

- Sharing Economies
- Powertrain Electrification
- Autonomous Vehicles
- Special Purpose Design
- Internet of Things
- Wireless Communications

Facts about Mobility

Challenges



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Opportunities

- Sharing Economies
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- Autonomous
- Special Purpose Design
- Internet of Things
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How can we fit all these opportunities together to address nowadays and future mobility issues?

Autonomous Mobility-on-Demand (AMoD)

Vehicle Autonomy

Car Sharing

+

UBER

Centrally controlled fleets of **self-driving cars** providing on-demand mobility

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CAR 2GO

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autolib'

Centrally controlled fleets of **self-driving cars** providing on-demand mobility

Requirements: AMoD needs to be...

Economically-viable

Socially-inclusive

Environmentally-friendly

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Vehicle Autonomy

\+

Car Sharing

Centrally controlled fleets of **self-driving cars** providing on-demand mobility

Requirements: AMoD needs to be...

Need **algorithmic tools** to **design** and **operate** future mobility systems

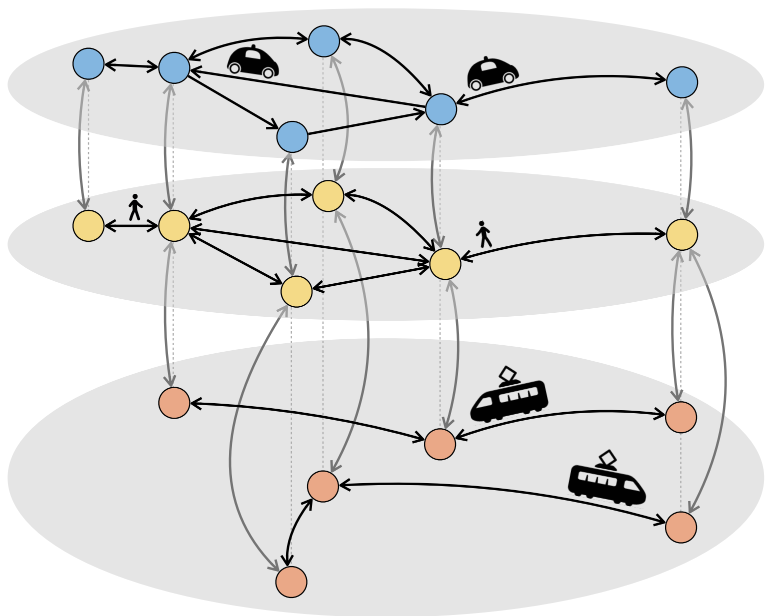
Economically-viable

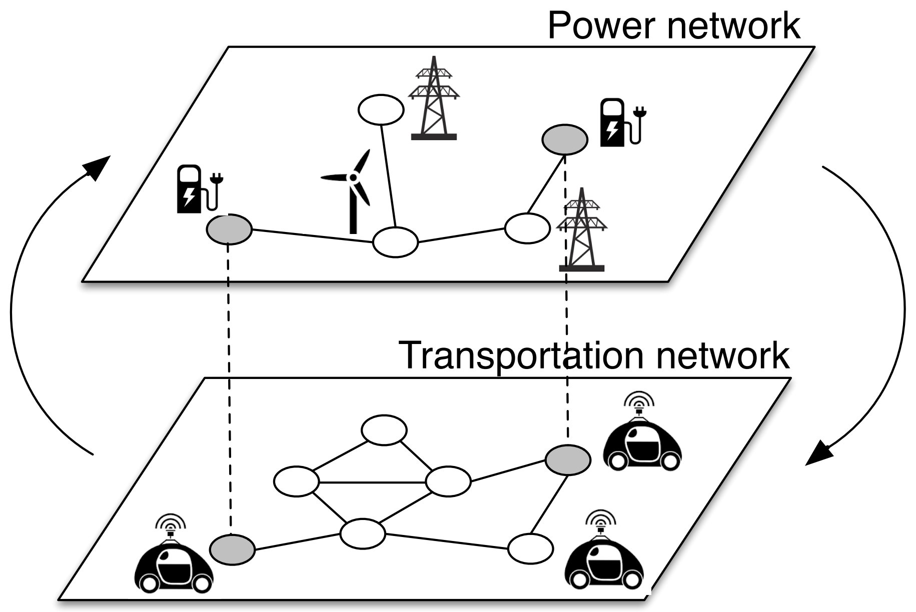
Socially-inclusive

Environmentally-friendly

Autonomous Mobility-on-Demand

Interaction with Infrastructure

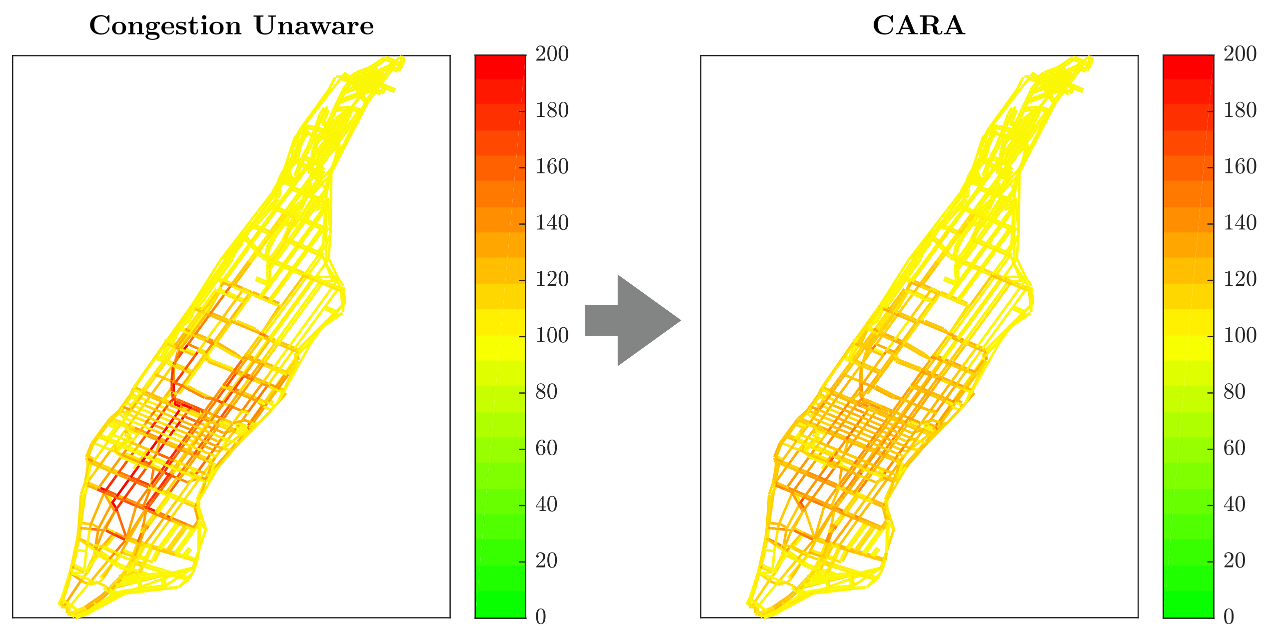




Salazar et al. ITSC18, T-ITS19
Zardini et al. TRB20

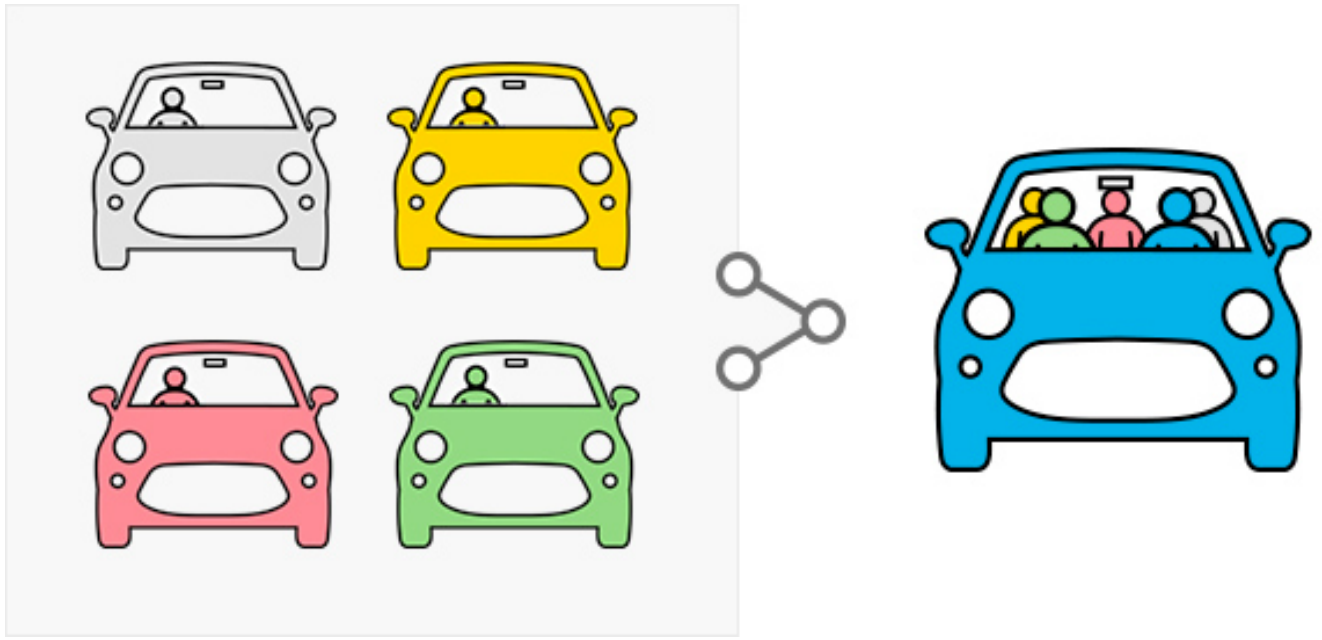
Rossi et al. RSS18,
Boewing et al. ACC20

Congestion-aware Routing



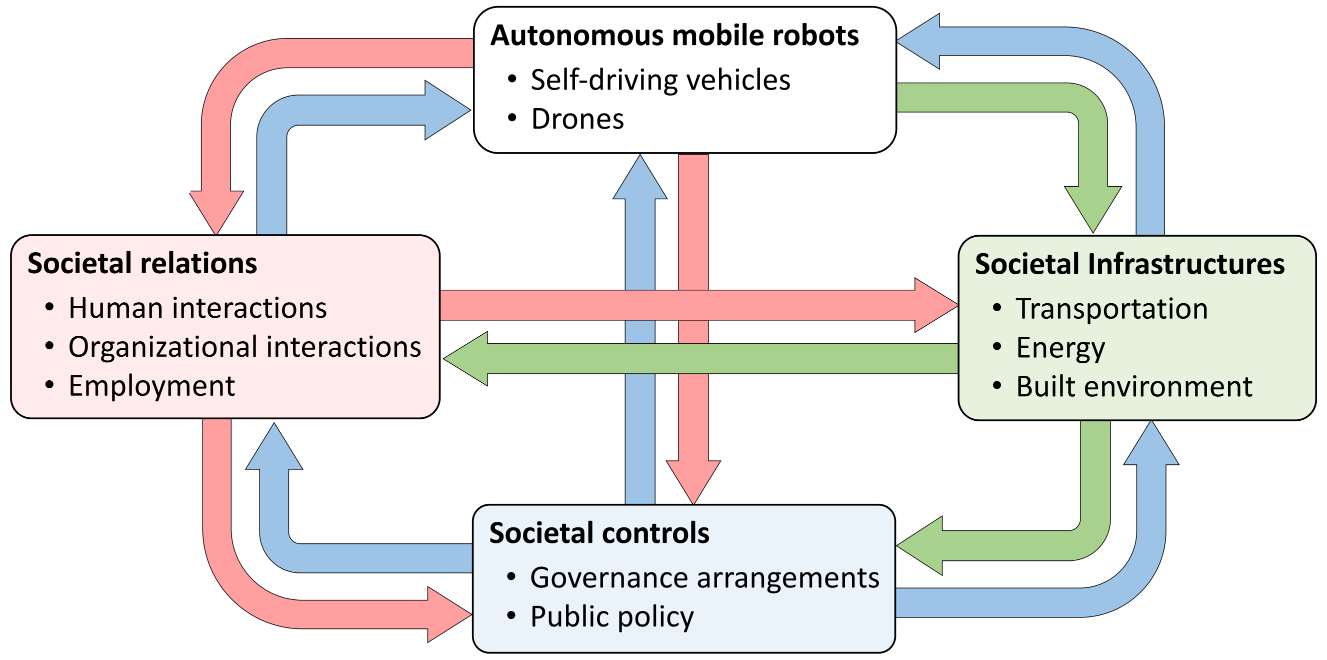
Salazar et al. ECC19, INFORMS18, Solovey et al. RSS19

MPC Algorithms



Tsao et al. ICRA19, Zgraggen et al. ITSC19

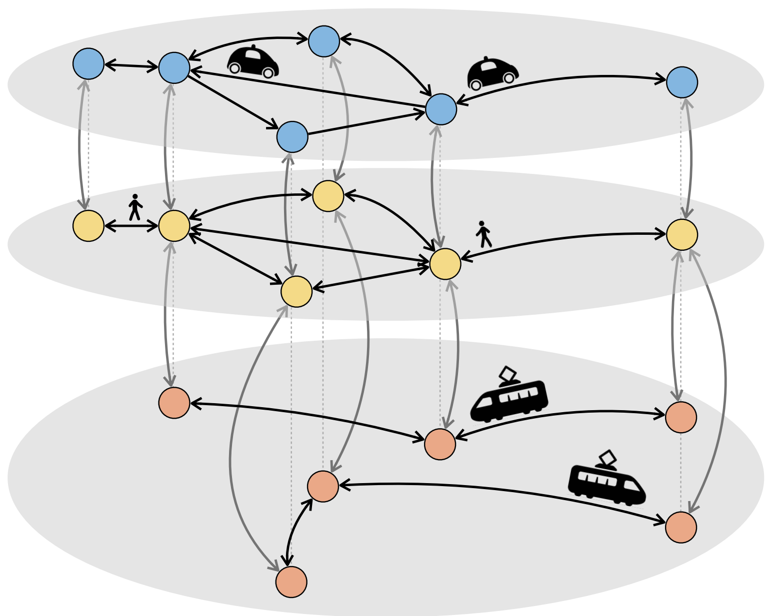
Societal Implications



Lanzetti et al. INFORMS19

Autonomous Mobility-on-Demand

Interaction with Infrastructure



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Manhattan

Jeenah Moon for The New York Times

Manhattan

The New York Times

Congestion Pricing

News about Congestion Pricing, including commentary and archival articles published in The New York Times.

Latest Search

Jan. 16, 2018 — Cuomo's Congestion Pricing for New York City Begins to Take Shape

Jan. 19, 2018 — Congestion Plan for Manhattan Gets Mixed Reviews

Jan. 22, 2018 — In Protests, a Hint of the Fight to Come Over Congestion Pricing

WSJ

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MTA Blames Uber for Decline in New York City Subway, Bus Ridership

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Jan. 29, 2018 — LETTER — Mobility Is a Mess in New York

March 31, 2018 — Congestion Pricing Falters in New York, Again

April 9, 2018 — Congestion Pricing Plan for Manhattan Ran Into Politics. Politics Won.

July 20, 2018 — Pave Over the Subway? Cities Face Tough Bets on Driverless Cars

March 26 — NEW YORK — Over $10 to Drive in Manhattan? What We Know About the Congestion Pricing Plan

Jeenah Moon for The New York Times

Will AMoD Save the Day?

Vehicle Autonomy

+

Car Sharing

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Road Traffic Efficiency

Road Traffic Efficiency

Why Public Transit?

Why Public Transit?

Why Public Transit?

Optimal Operation of Intermodal AMoD Systems

Vehicle Autonomy

\+

Car Sharing

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Public Transit

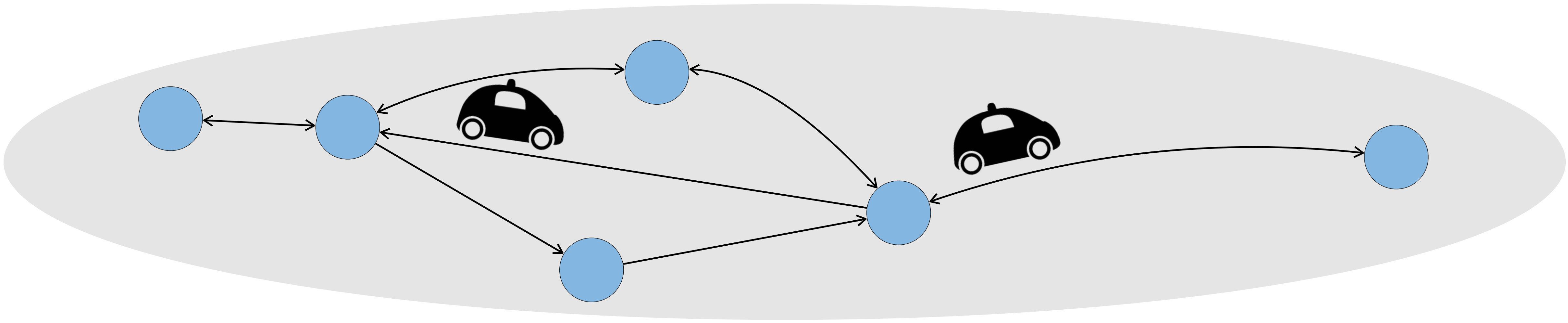
\+

?

[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Intermodal Autonomous Mobility-on-Demand

Road

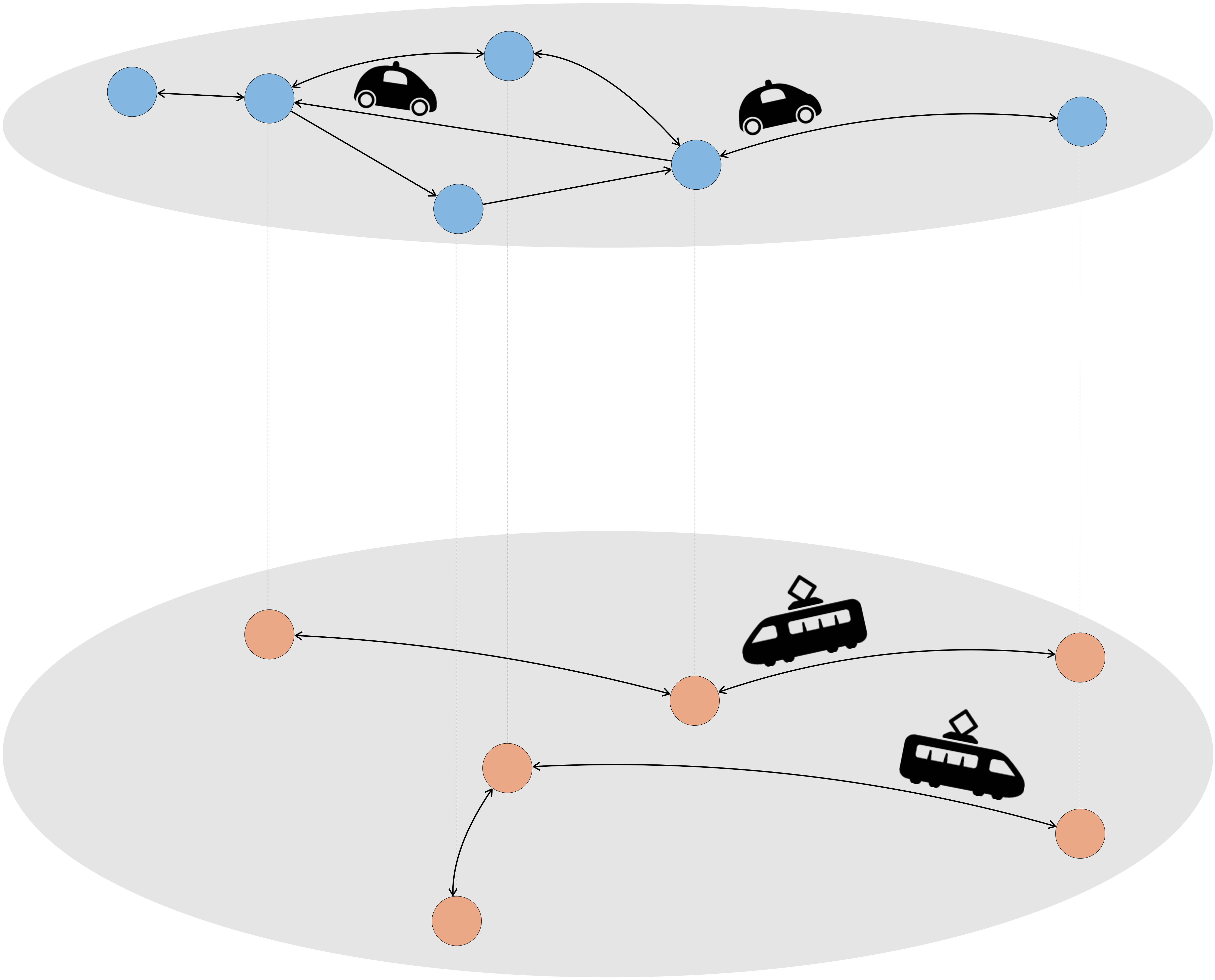


[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Intermodal Autonomous Mobility-on-Demand

Road

Public Transit



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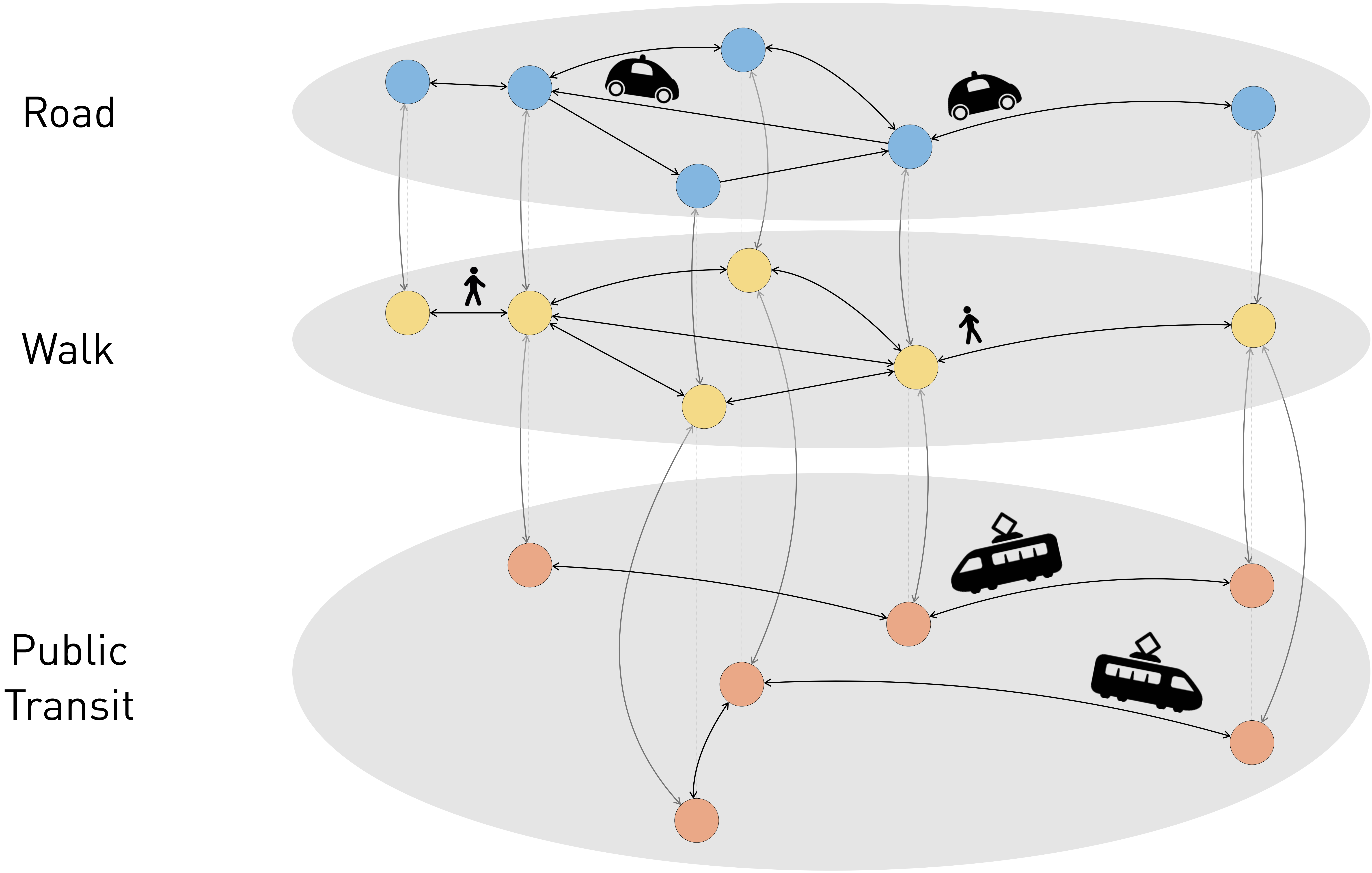


[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Network Flow Model

Advantages

- Highly scalable (LP)

- Very expressive

[Salazar, Rossi, Schiffer, Onder, Pavone, ITSC18; Salazar, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Network Flow Model

Advantages

- Highly scalable (LP)
- Very expressive

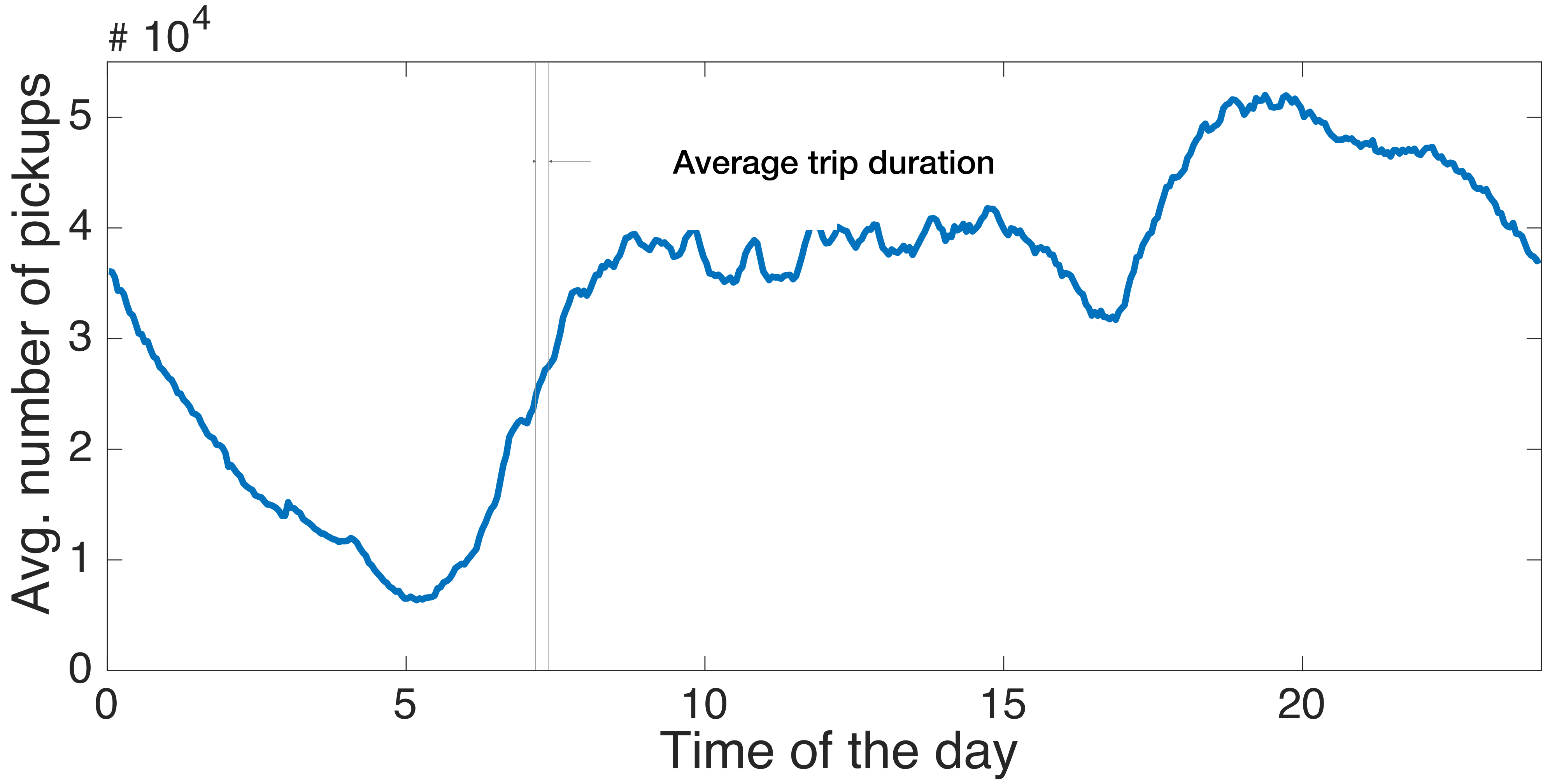
Assumptions

- 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

[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Network Flow Model - Assumptions

- Demand is **time-invariant**



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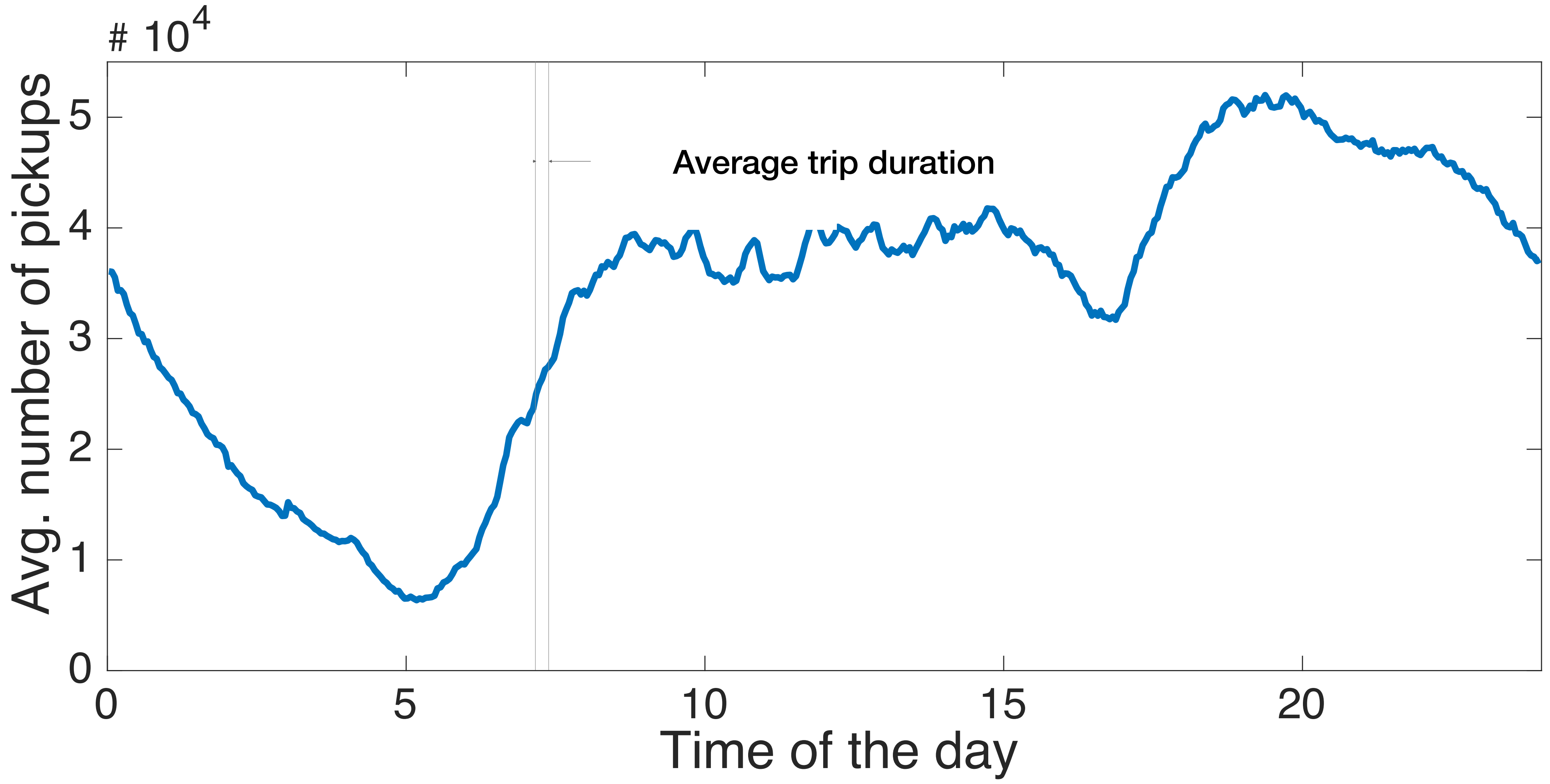
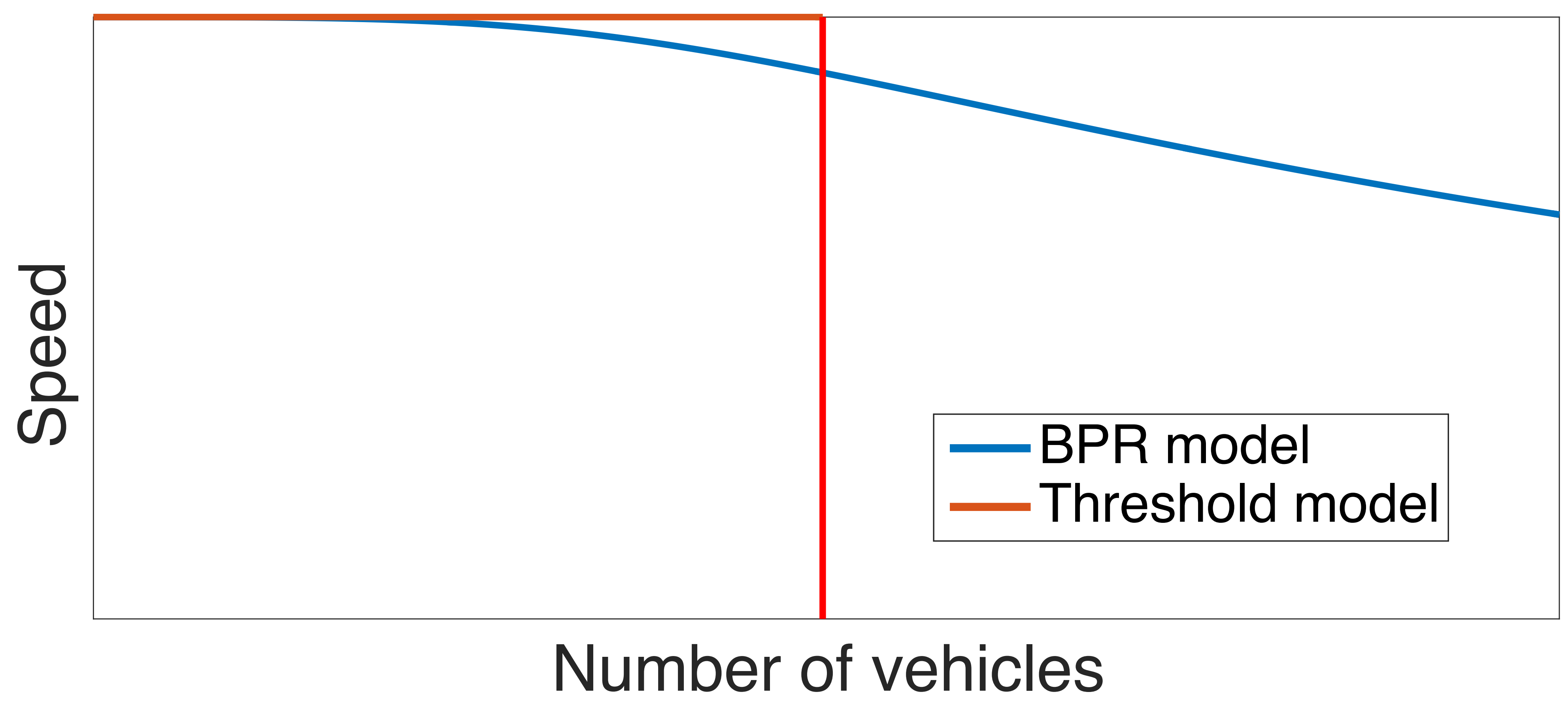


- Congestion as a **threshold**

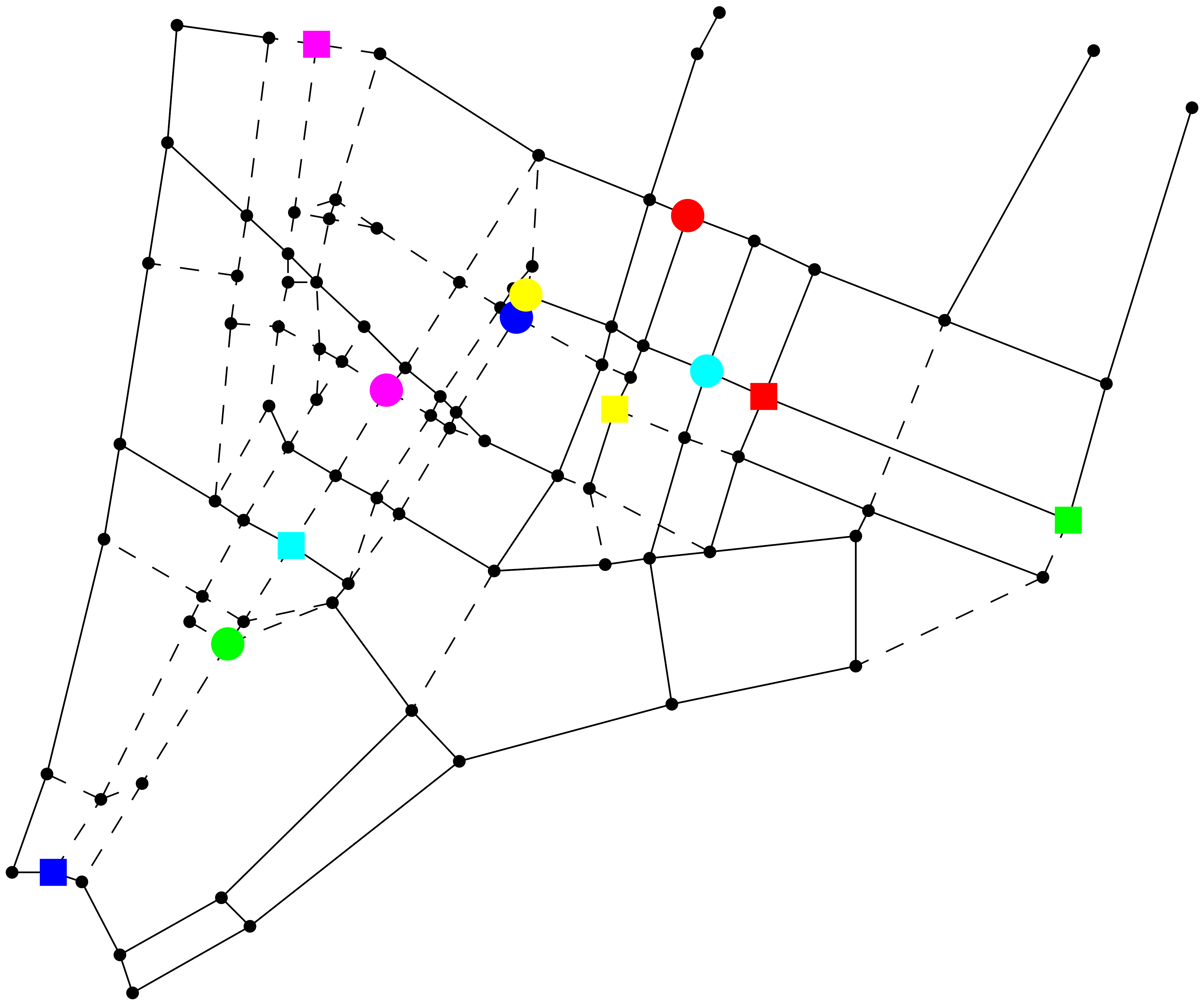


[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Network Flow Model

Transportation requests

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



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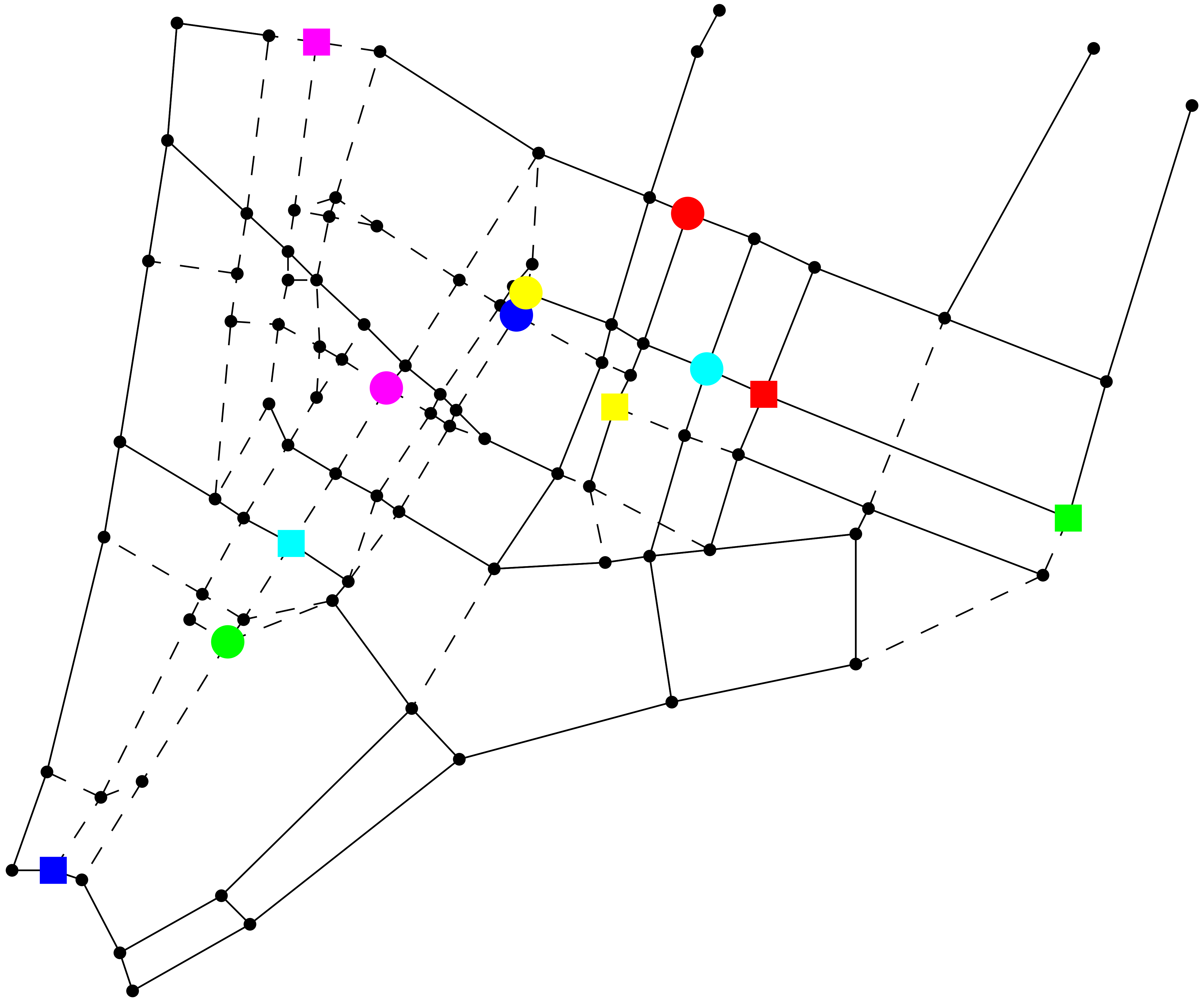


Network model

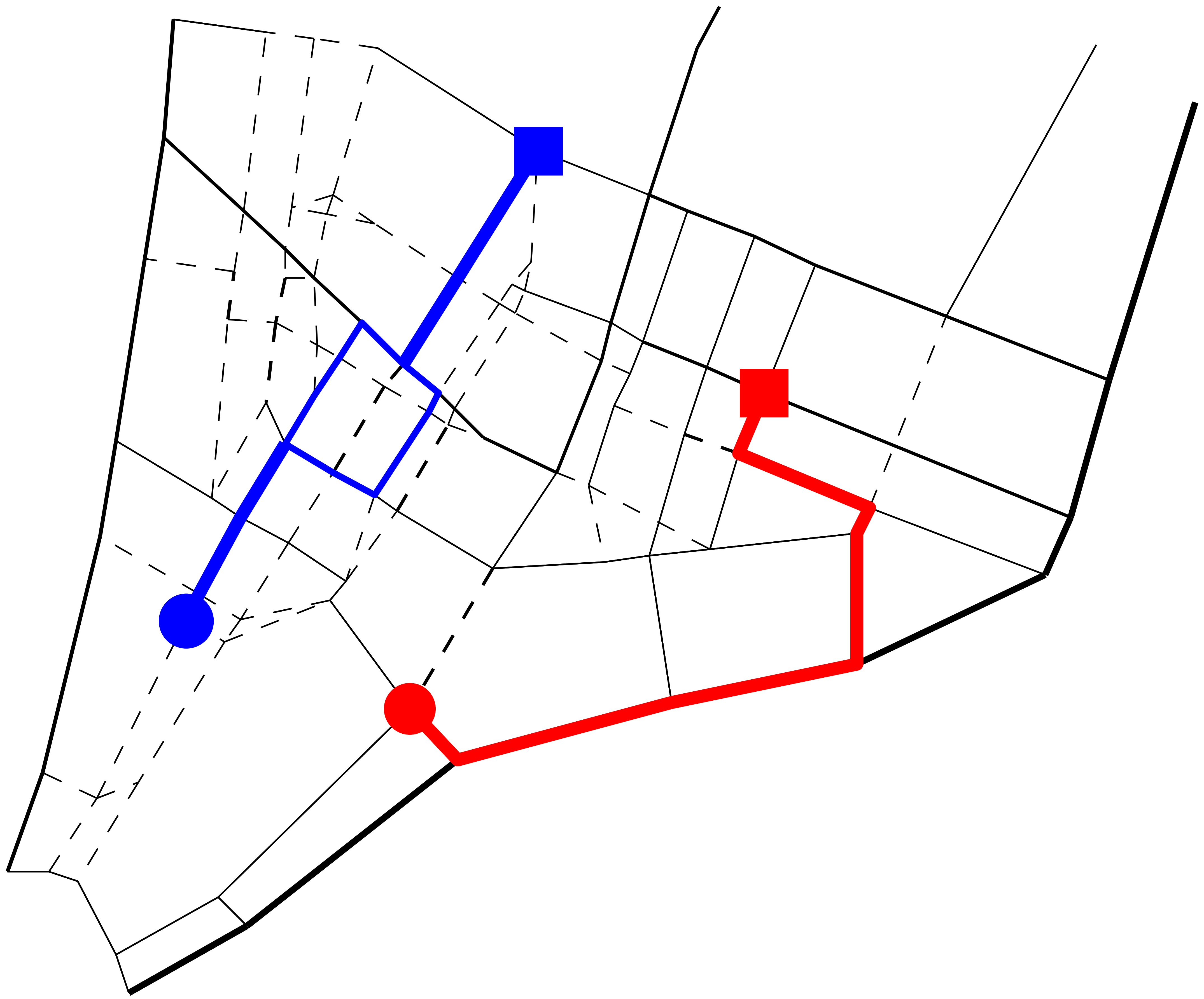
- Nodes: intersections and stops
- Capacitated arcs: roads, walk, switch and public transit

[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Network Flow Model

Flows

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



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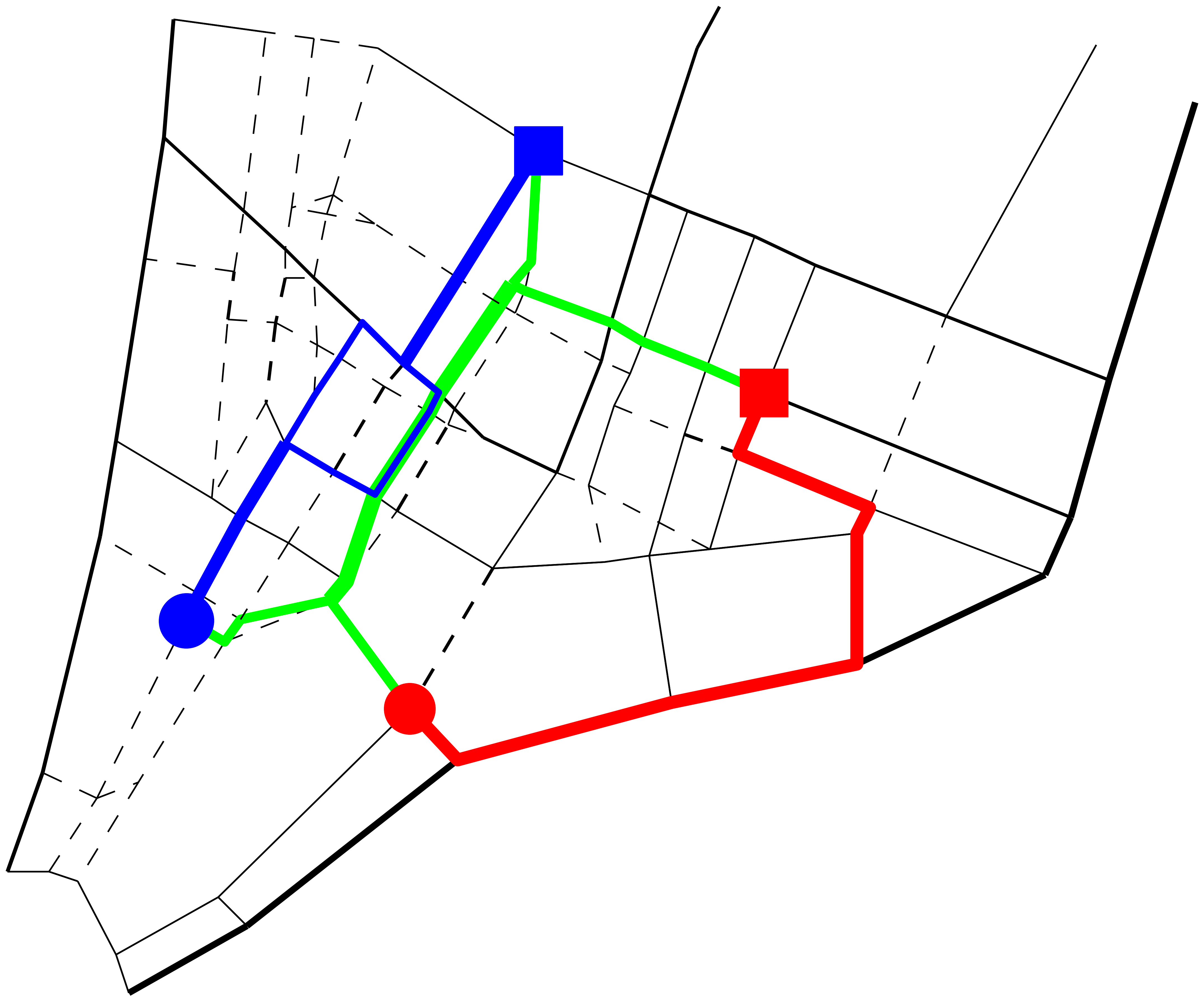
Network Flow Model

Flows

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



[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Network Flow Model

Extended Graph

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

[Salazar, Rossi, Schiffer, Onder, Pavone, ITSC18; Salazar, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

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Conservation of Customers

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

[Salazar, Rossi, Schiffer, Onder, Pavone, ITSC18; Salazar, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

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Conservation of Vehicles

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

[Salazar, Rossi, Schiffer, Onder, Pavone, ITSC18; Salazar, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Network Flow Model

Capacity of Road and Public Transportation

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

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

[Salazar, Rossi, Schiffer, Onder, Pavone, ITSC18; Salazar, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

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

$$\begin{aligned}\min_{\{f_m(\cdot,\cdot)\}_m, f_0(\cdot,\cdot)} & \sum_{(i,j)\in\mathcal{A}} \sum_{m\in\mathcal{M}} V_{\mathrm{T}} \cdot t_{ij} \cdot f_m(i,j) \\ & + \sum_{(i,j)\in\mathcal{A}_{\mathrm{R}}} (V_{\mathrm{D,R}} \cdot s_{ij} + V_{\mathrm{E}} \cdot e_{\mathrm{R},ij}) \cdot \left(f_0(i,j) + \sum_{m\in\mathcal{M}} f_m(i,j) \right) \\ & + \sum_{(i,j)\in\mathcal{A}_{\mathrm{P}}} V_{\mathrm{D,P}} \cdot s_{ij} \cdot \sum_{m\in\mathcal{M}} f_m(i,j)\end{aligned}$$

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Network Flow Model

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Let us now consider a case study...

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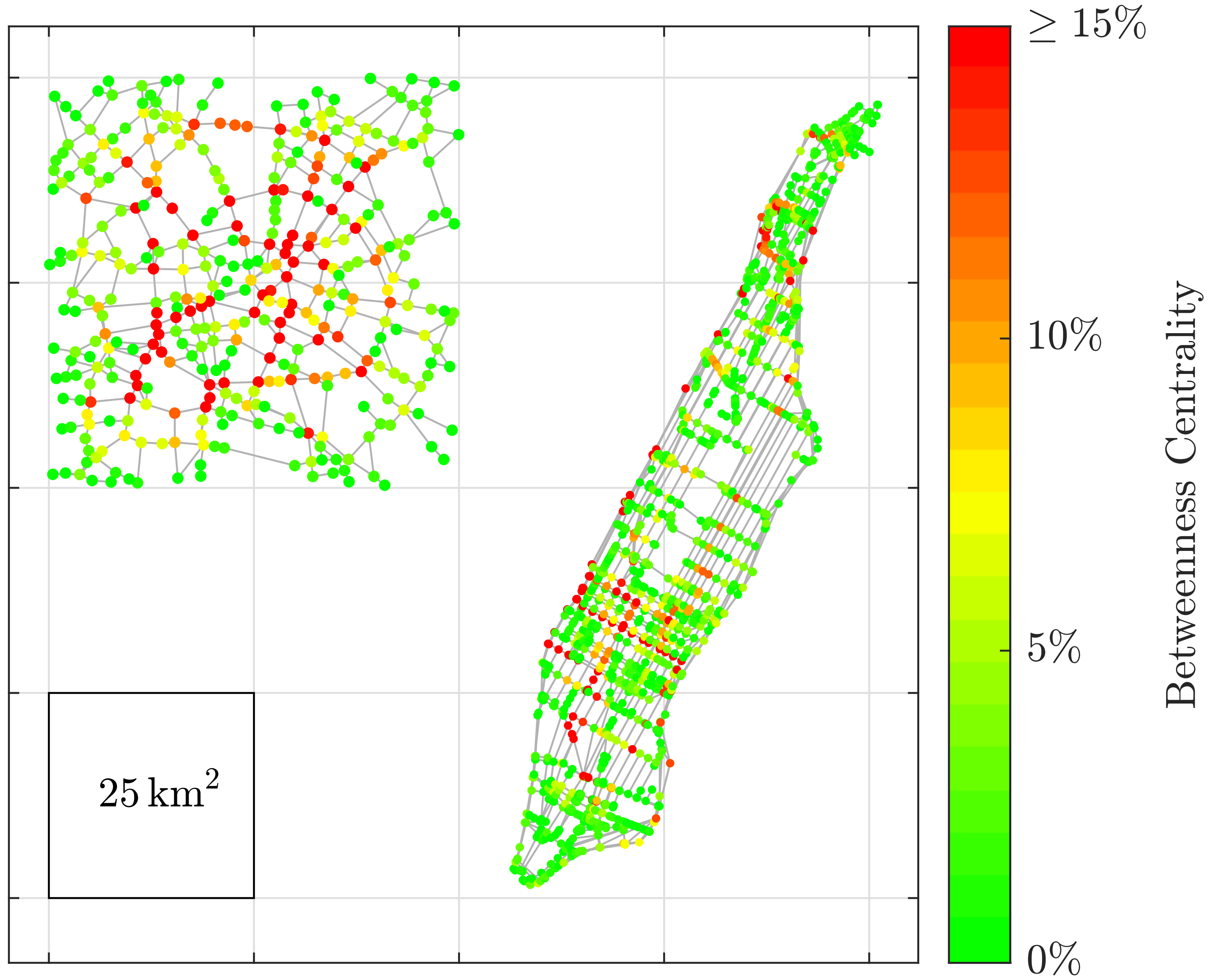
Intermodal AMoD - Berlin and NYC

REQUESTS IN BERLIN AND NYC.

	NYC	Berlin
M	8,658	2,646
$\sum_{m\in\mathcal{M}} \alpha_m$	44.943 1/s	3.771 1/s
$\sum_{m\in\mathcal{M}} \alpha_m \Vert o_m - d_m \Vert_2 / \sum_{m\in\mathcal{M}} \alpha_m$	2.4 km	4.0 km



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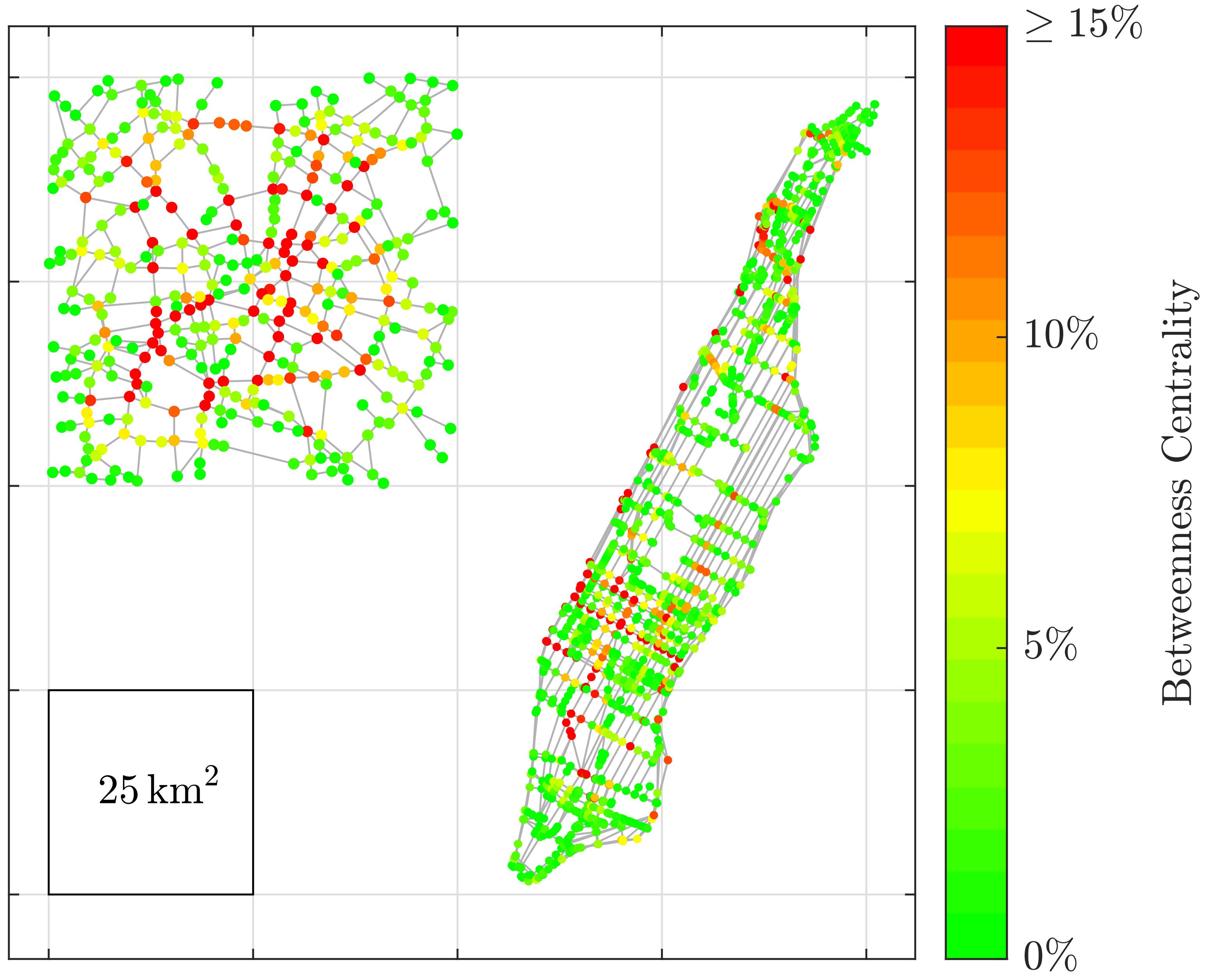
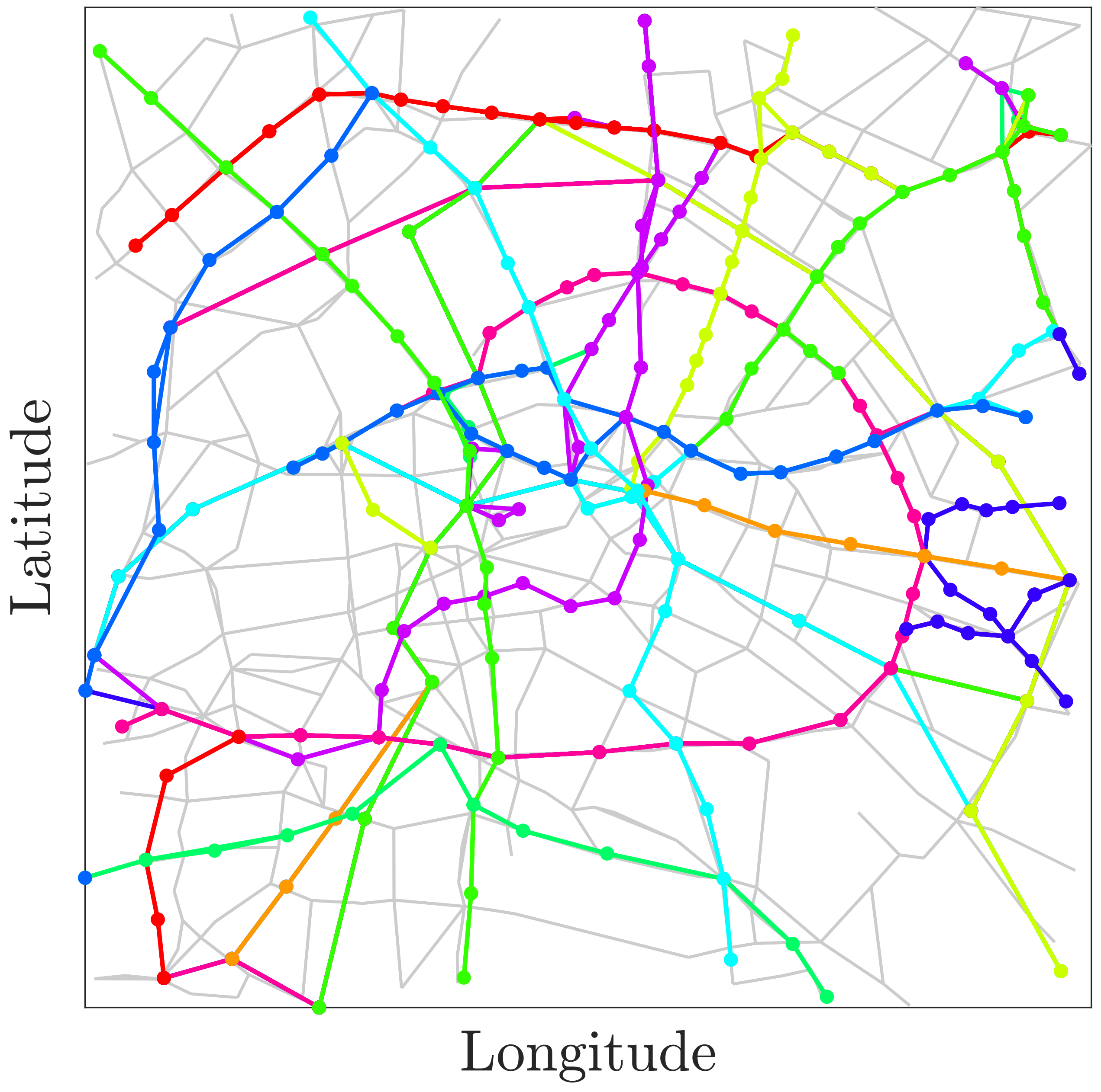
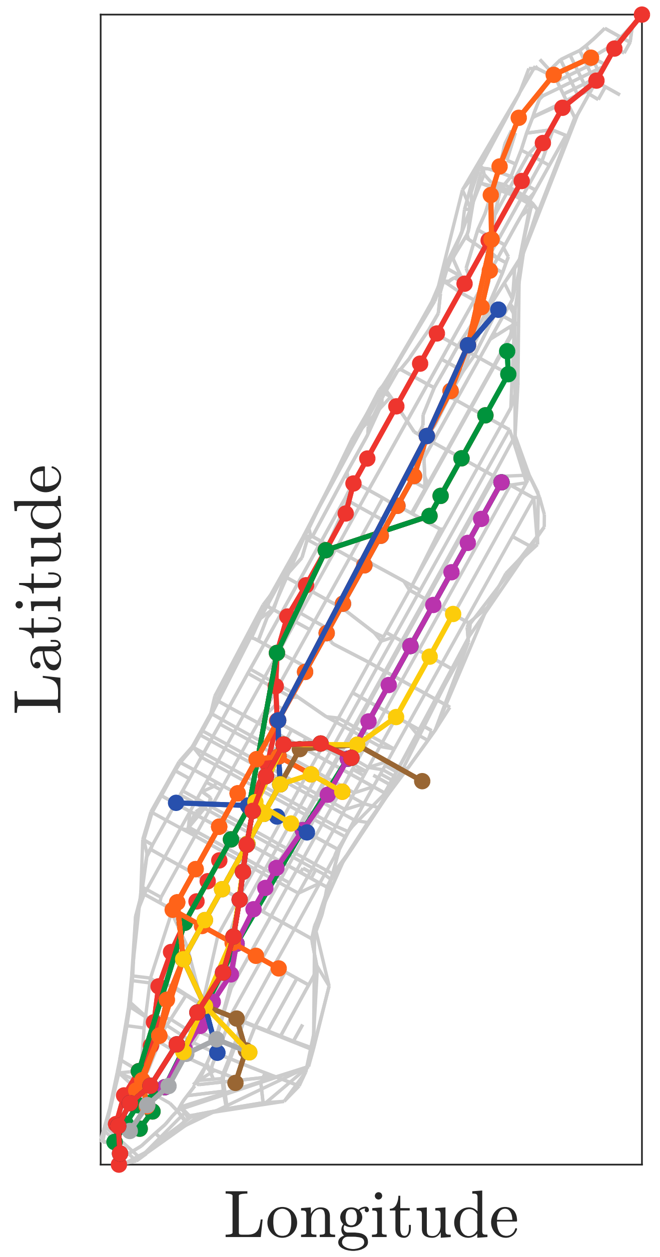
$\sum_{m\in\mathcal{M}} \alpha_m \lVert o_m - d_m \rVert_2 / \sum_{m\in\mathcal{M}} \alpha_m$	2.4 km	4.0 km







[Salazar, Rossi, Schiffer, Onder, Pavone, ITSC18; Salazar, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

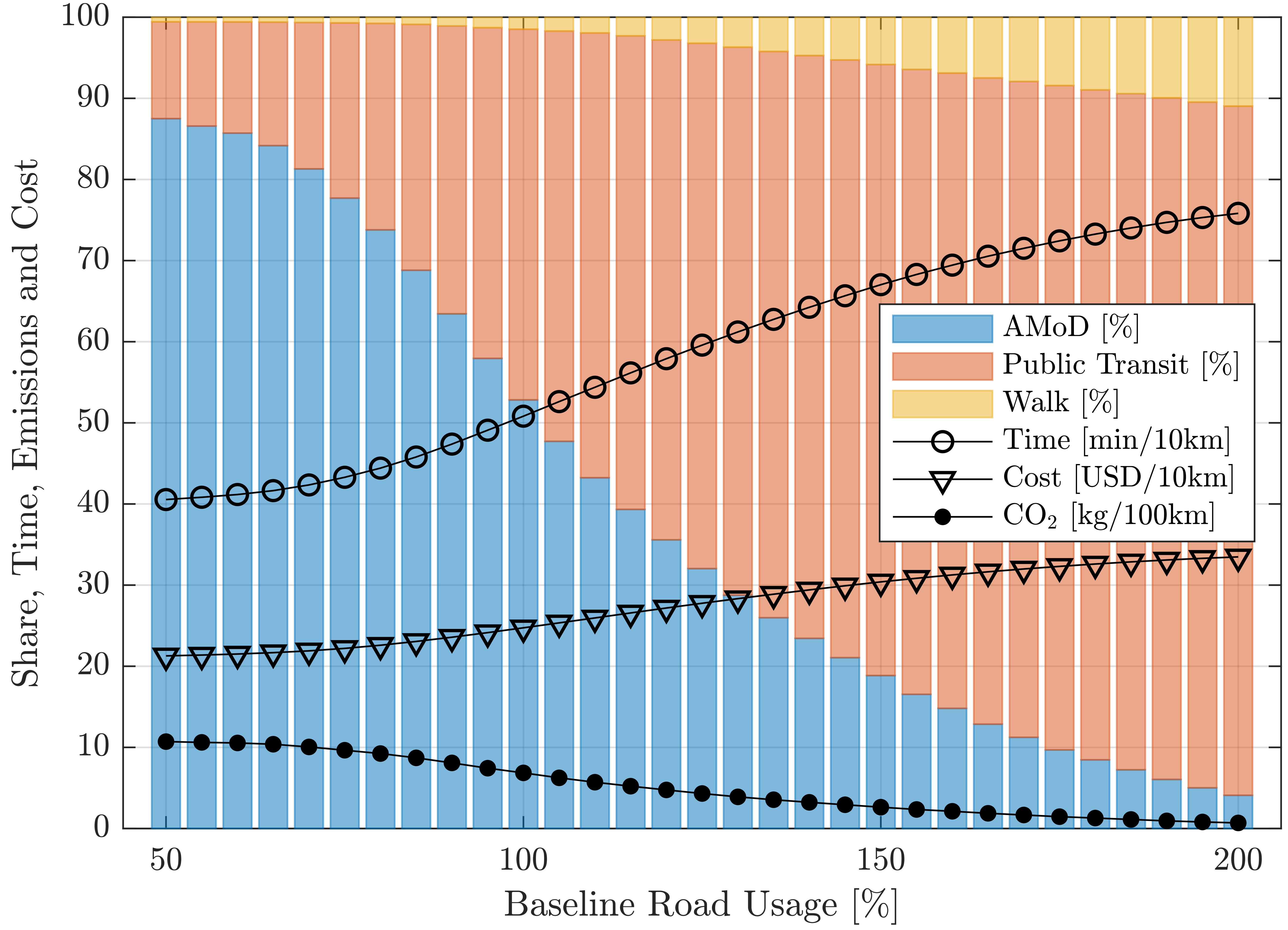
Case Study - Berlin

I-AMoD - Scan in Exogenous Traffic

[Salazar, Rossi, Schiffer, Onder, Pavone, ITSC18; Salazar, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

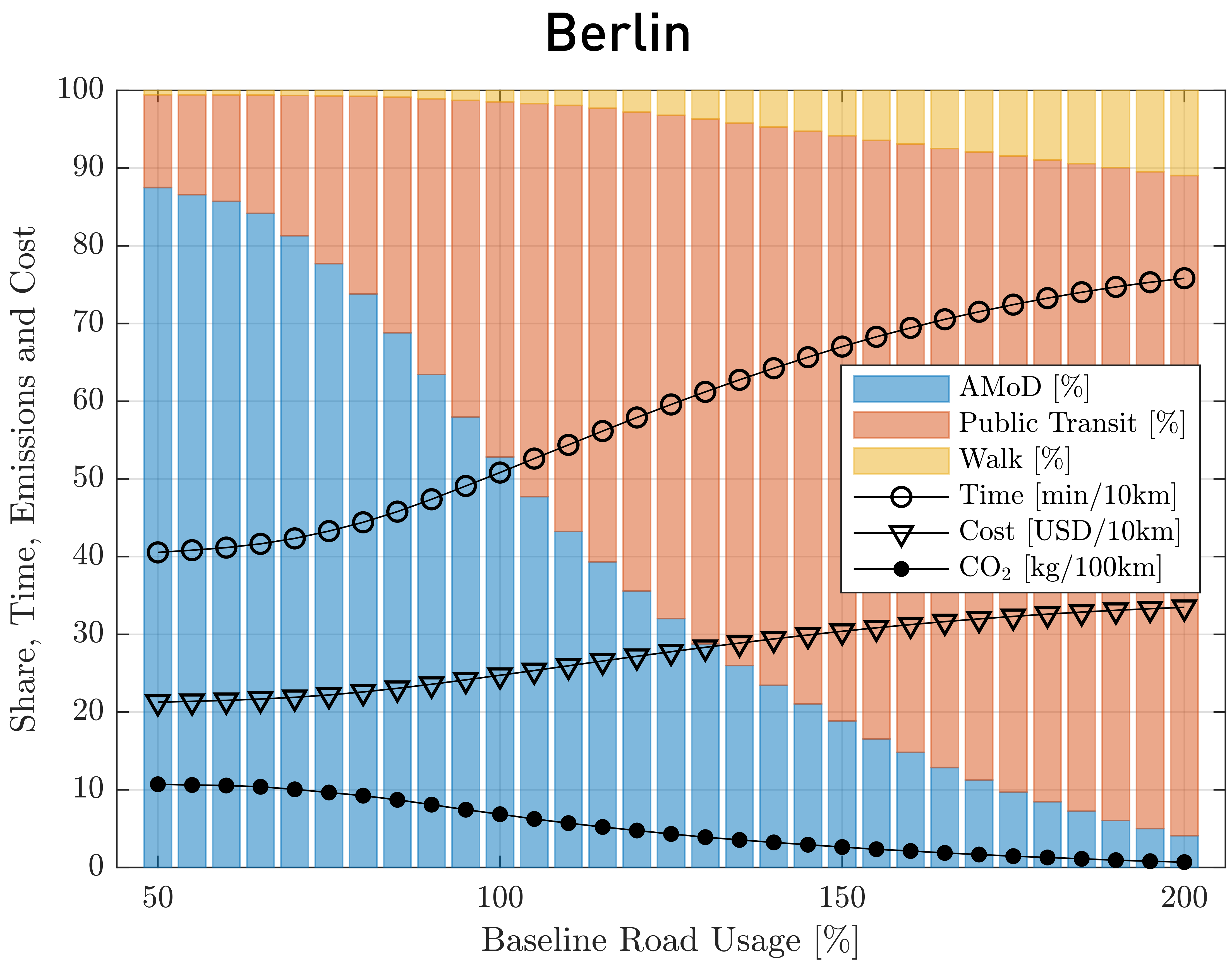
Case Study - Berlin

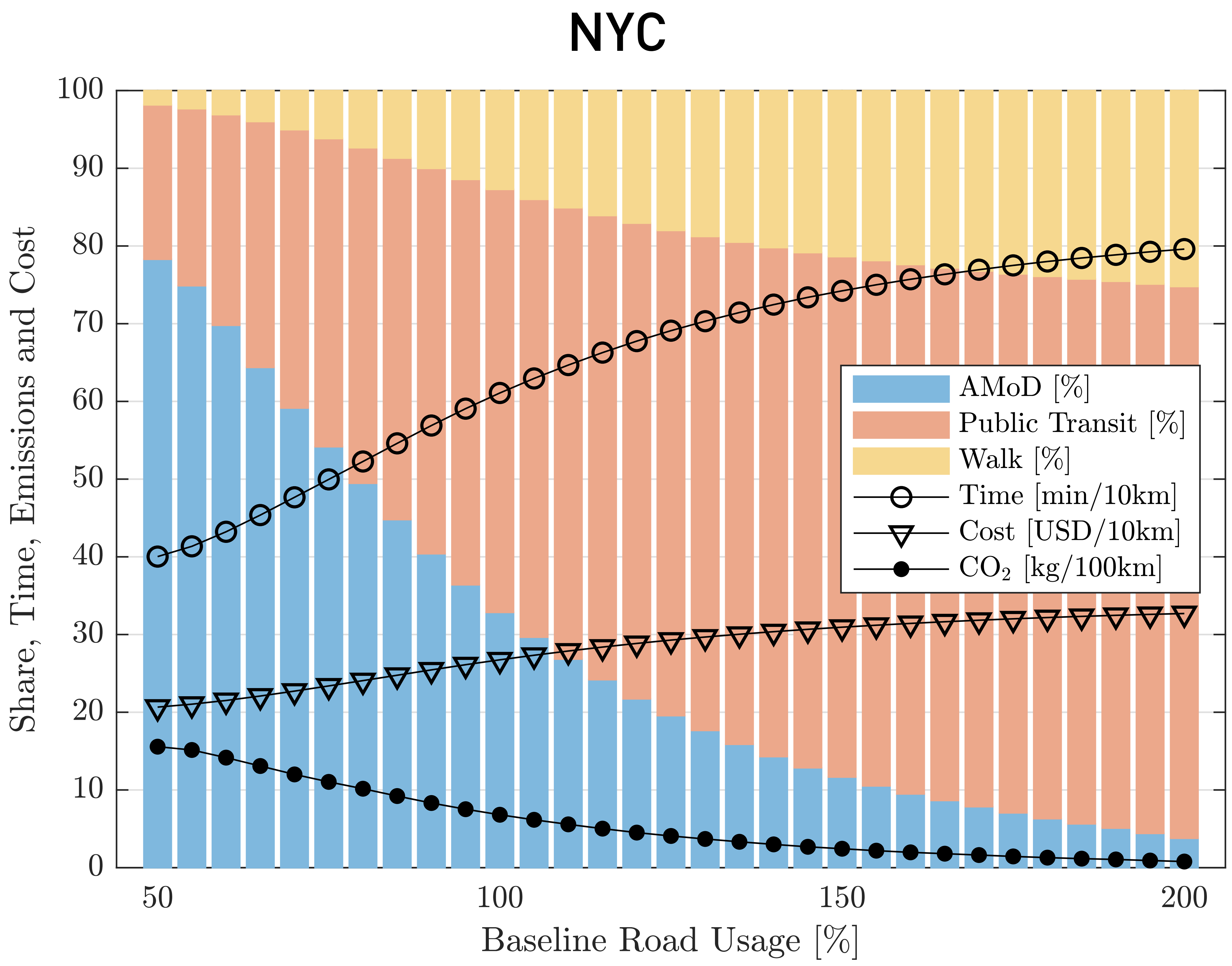
I-AMoD - Scan in Exogenous Traffic



[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Case Study - Berlin VS NYC





[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

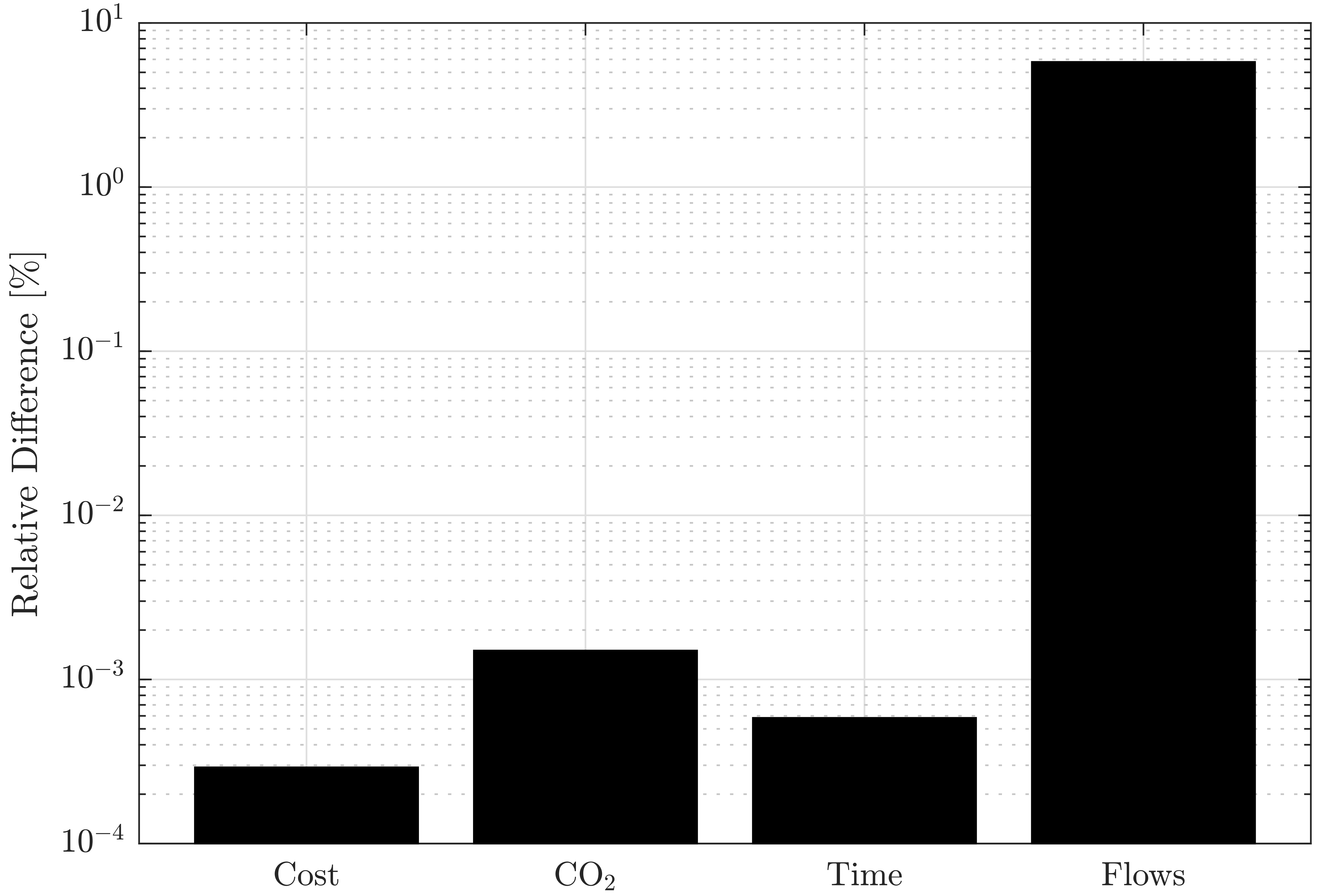
Case Study - NYC

I-AMoD - Fractional VS Integer Solution, what are the differences?

[Salazar, Rossi, Schiffer, Onder, Pavone, ITSC18; Salazar, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Case Study - NYC

I-AMoD - Fractional VS Integer Solution, what are the differences?



[Salazar, Rossi, Schiffer, Onder, Pavone, ITSC18; Salazar, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Case Study - NYC

What is the impact of the vehicle size and powertrain type?

Lightweight
Battery Electric

[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Case Study - NYC

What is the impact of the vehicle size and powertrain type?

Lightweight
Battery Electric

Lightweight
IC Engine

[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Case Study - NYC

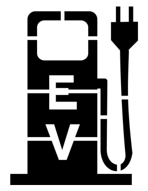
What is the impact of the vehicle size and powertrain type?

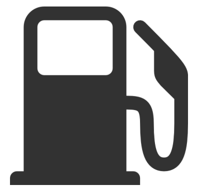
Lightweight Battery Electric	Lightweight IC Engine
Sport Utility Battery Electric	Sport Utility IC Engine

[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

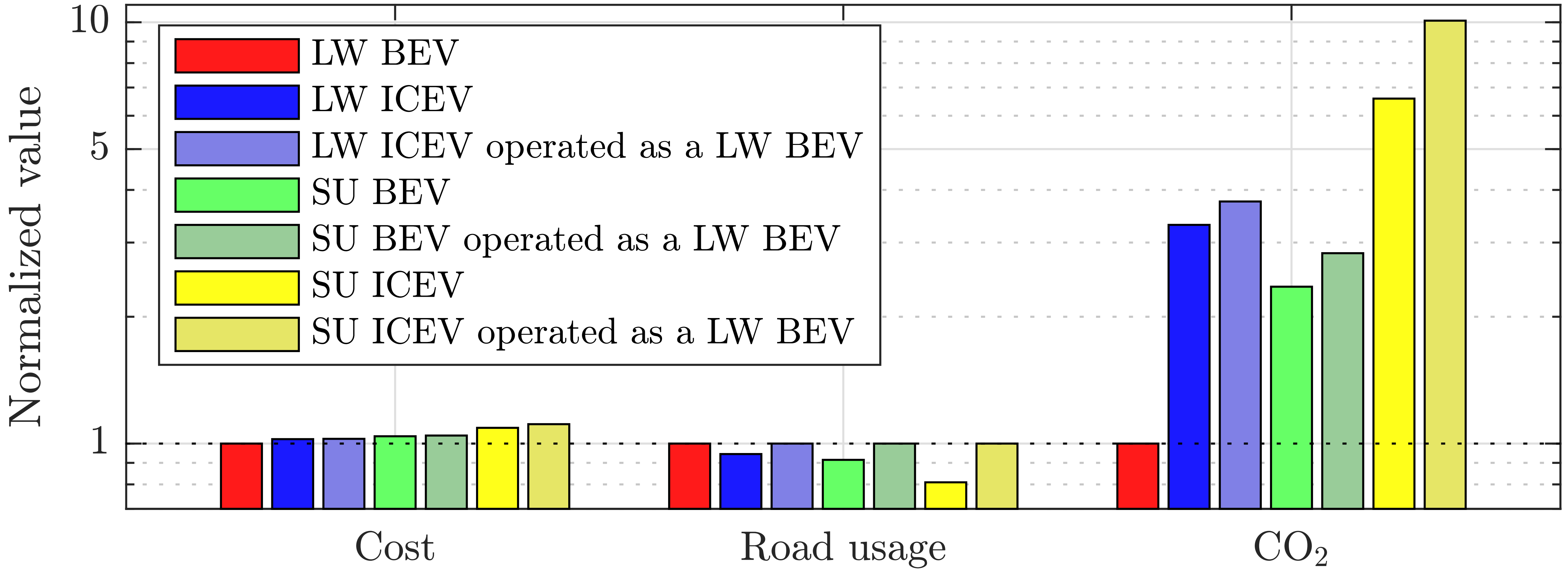
Case Study - NYC

What is the impact of the vehicle size and powertrain type?





	Lightweight Battery Electric	Lightweight IC Engine
	Sport Utility Battery Electric	Sport Utility IC Engine



[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

Case Study - NYC

I-AMoD - Sample optimal path

[Salazar, Rossi, Schiffer, Onder, Pavone, ITSC18]

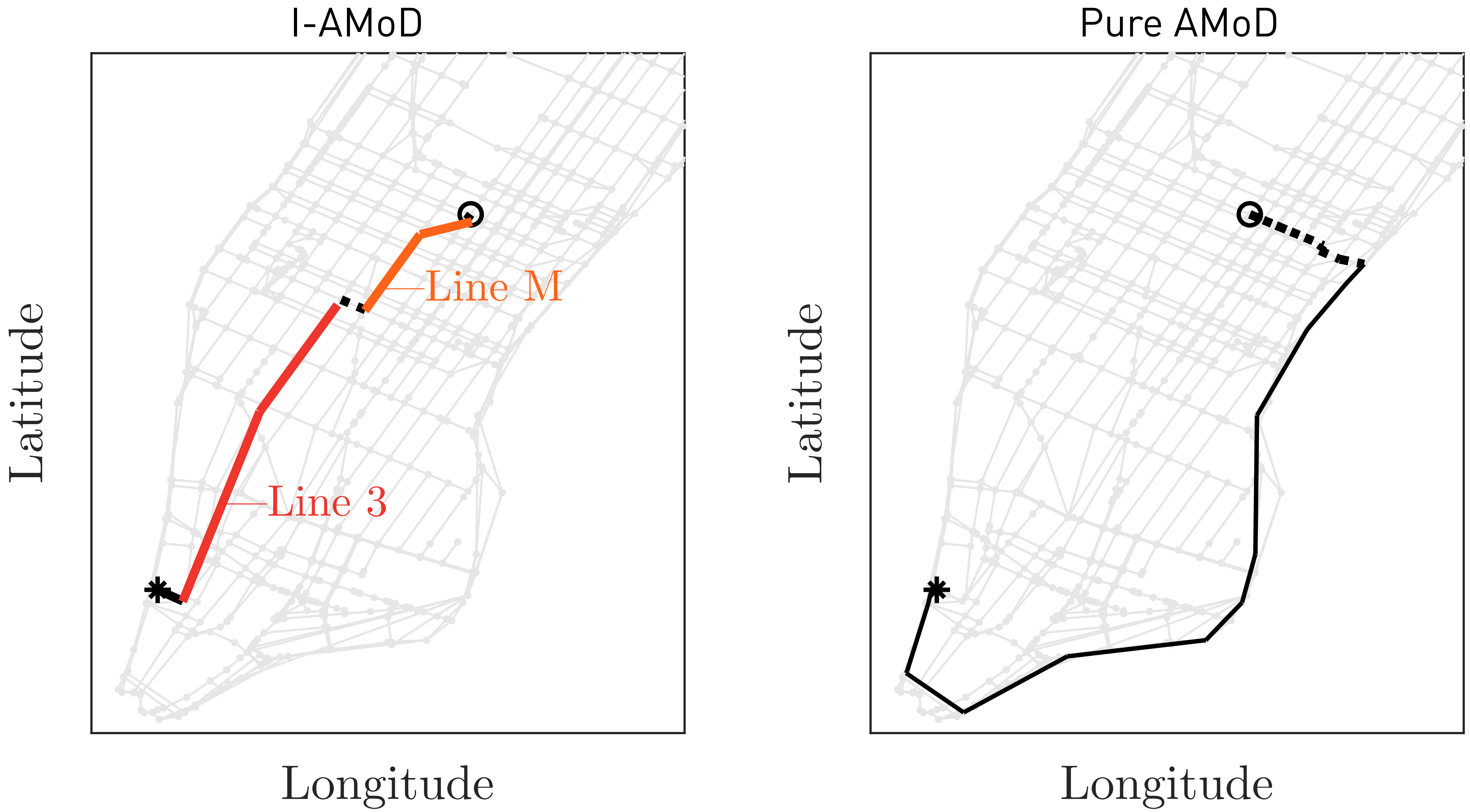
Case Study - NYC

I-AMoD - Sample optimal path

[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18]

Case Study - NYC

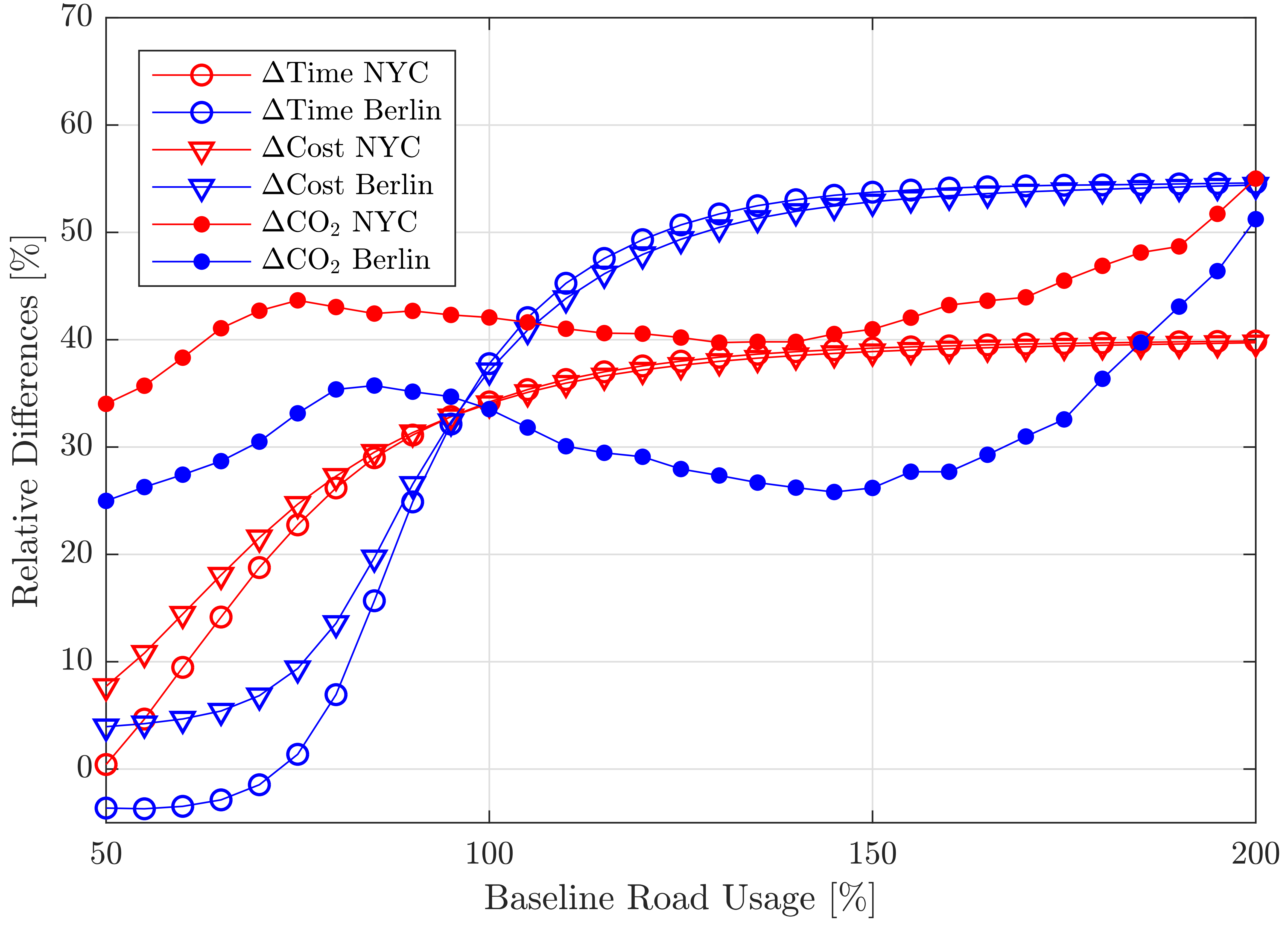
Sample optimal paths



[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18]

Case Study - NYC and Berlin

Pure AMoD VS I-AMoD - Relative Difference

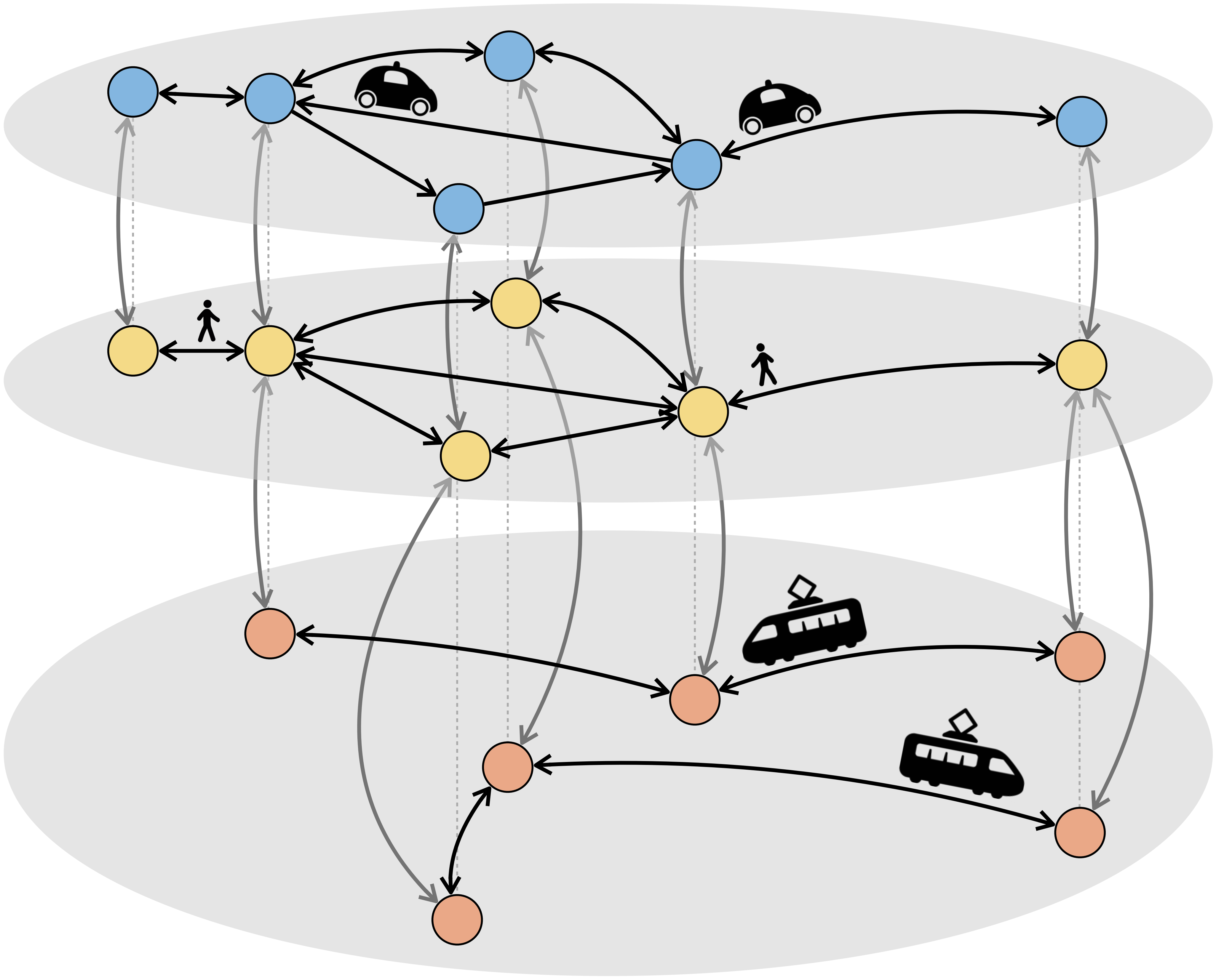


Coordination with public transit significantly reduces **travel times, number of vehicles, emissions** and **cost**!

[**Salazar**, Rossi, Schiffer, Onder, Pavone, ITSC18; **Salazar**, Lanzetti, Rossi, Schiffer, Pavone, T-ITS19]

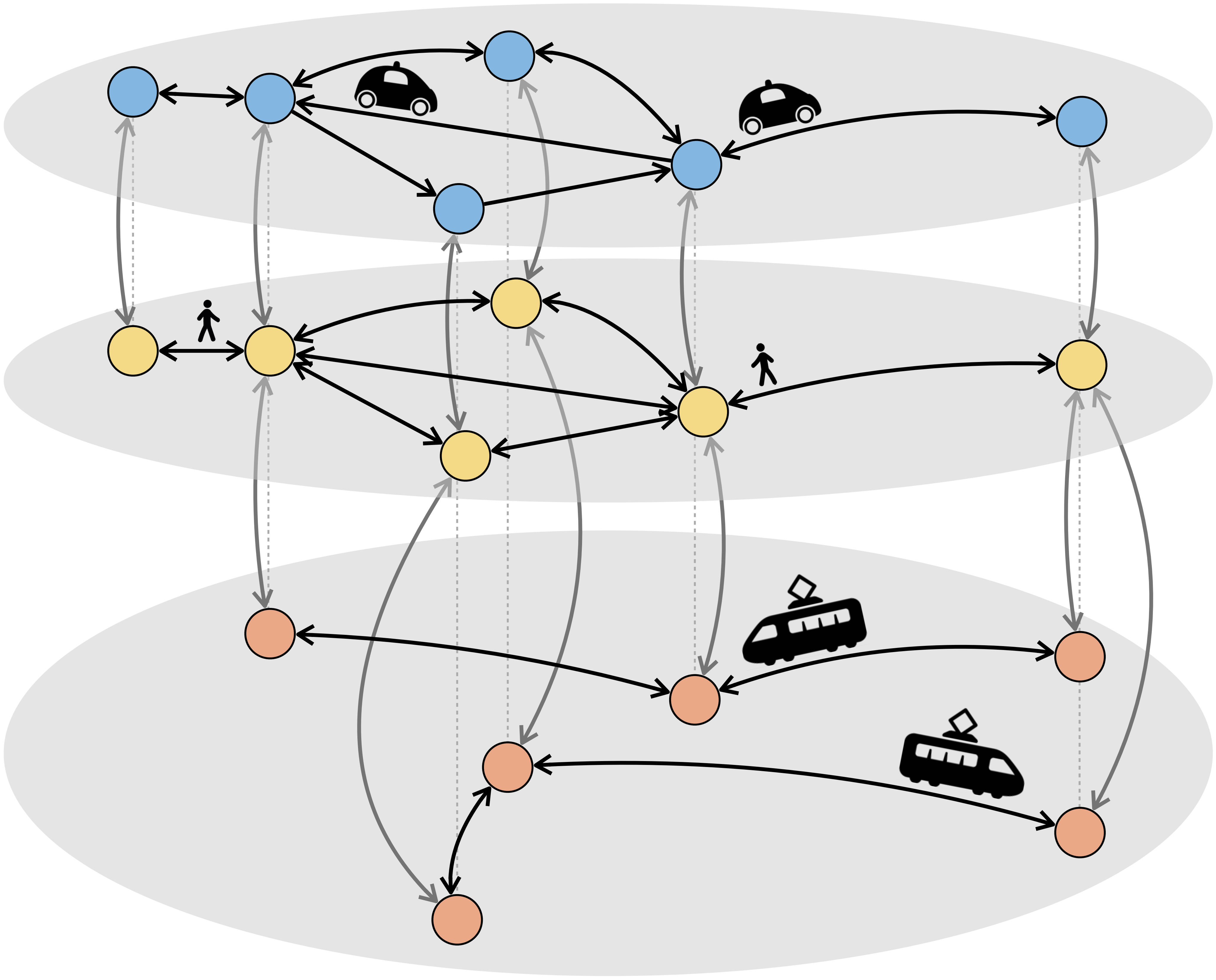
Intermodal Autonomous Mobility-on-Demand

Time-invariant Model for **Analysis and Planning**



Intermodal Autonomous Mobility-on-Demand

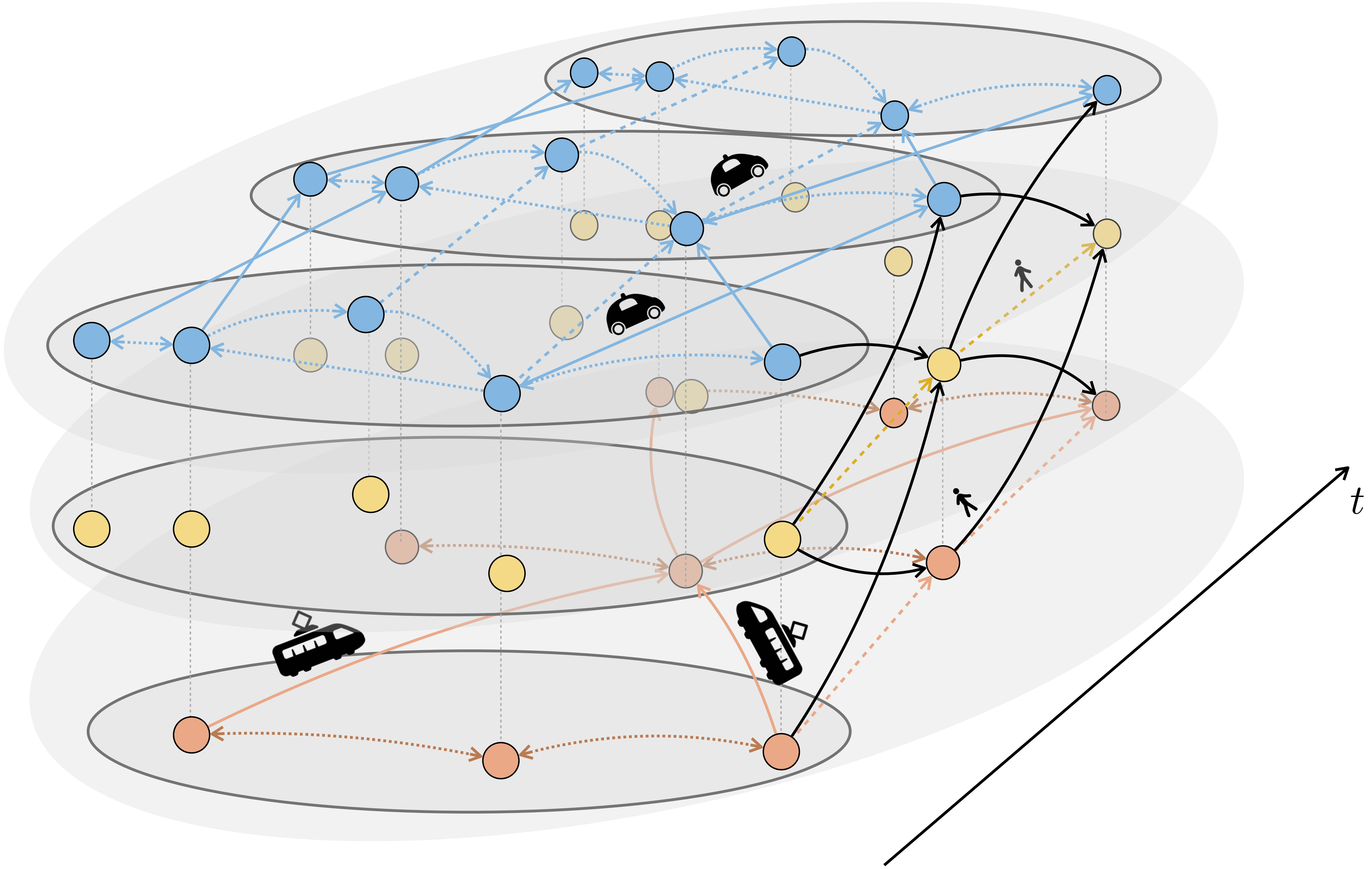
Time-invariant Model for **Analysis and Planning**



Where do we go from here?

Intermodal Autonomous Mobility-on-Demand

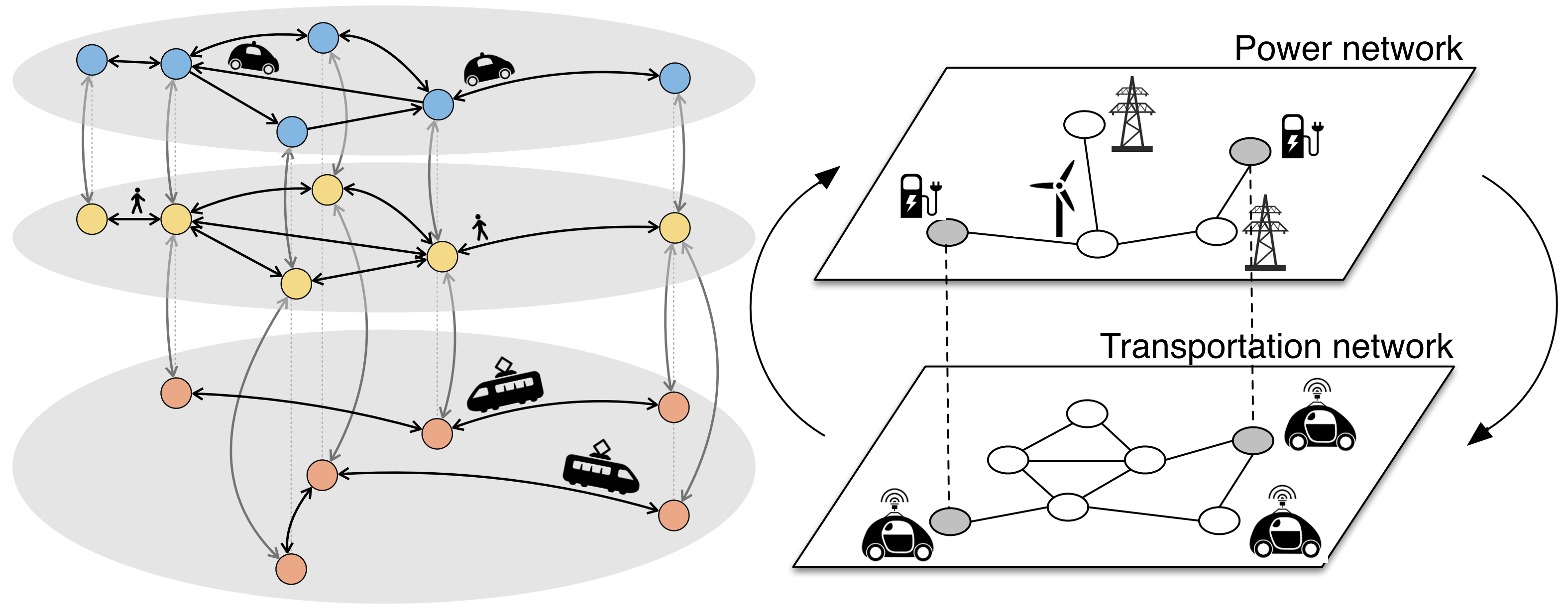
Time-variant Model for **Control and Operation**: MPC for Intermodal Routing



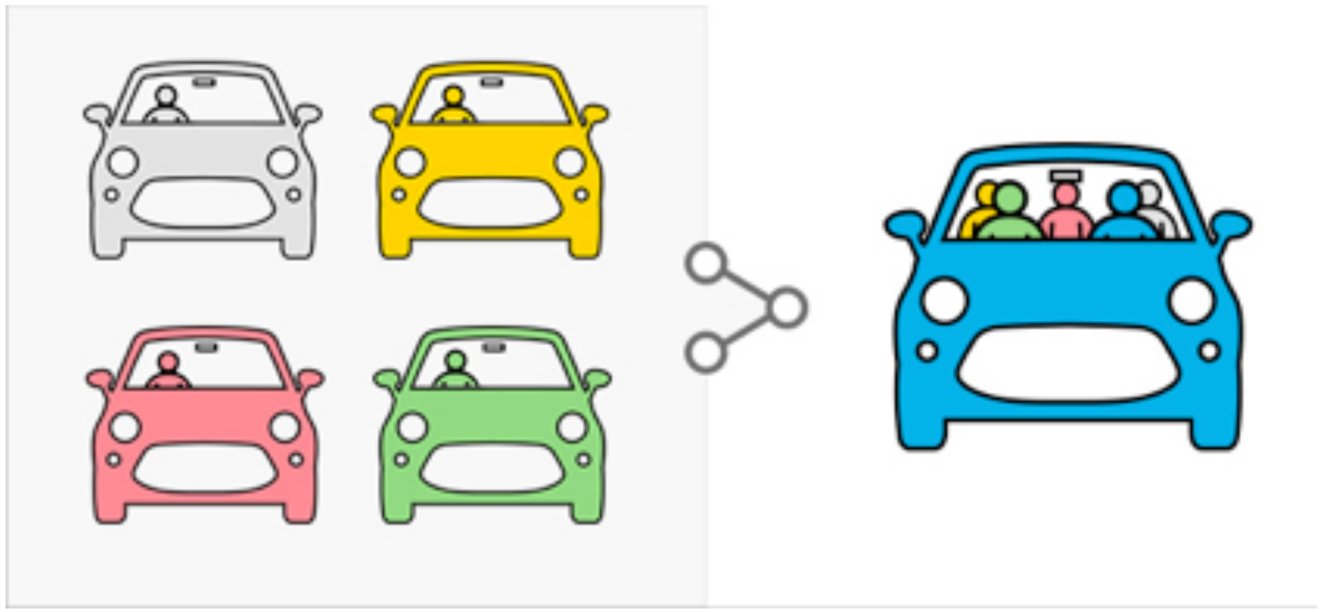
[**Zgraggen**, Tsao, Salazar, Schiffer, Pavone, **ITSC19**: Tuesday at 11:15, TuC-T9, Gallery Room 1]

Opportunities in AMoD

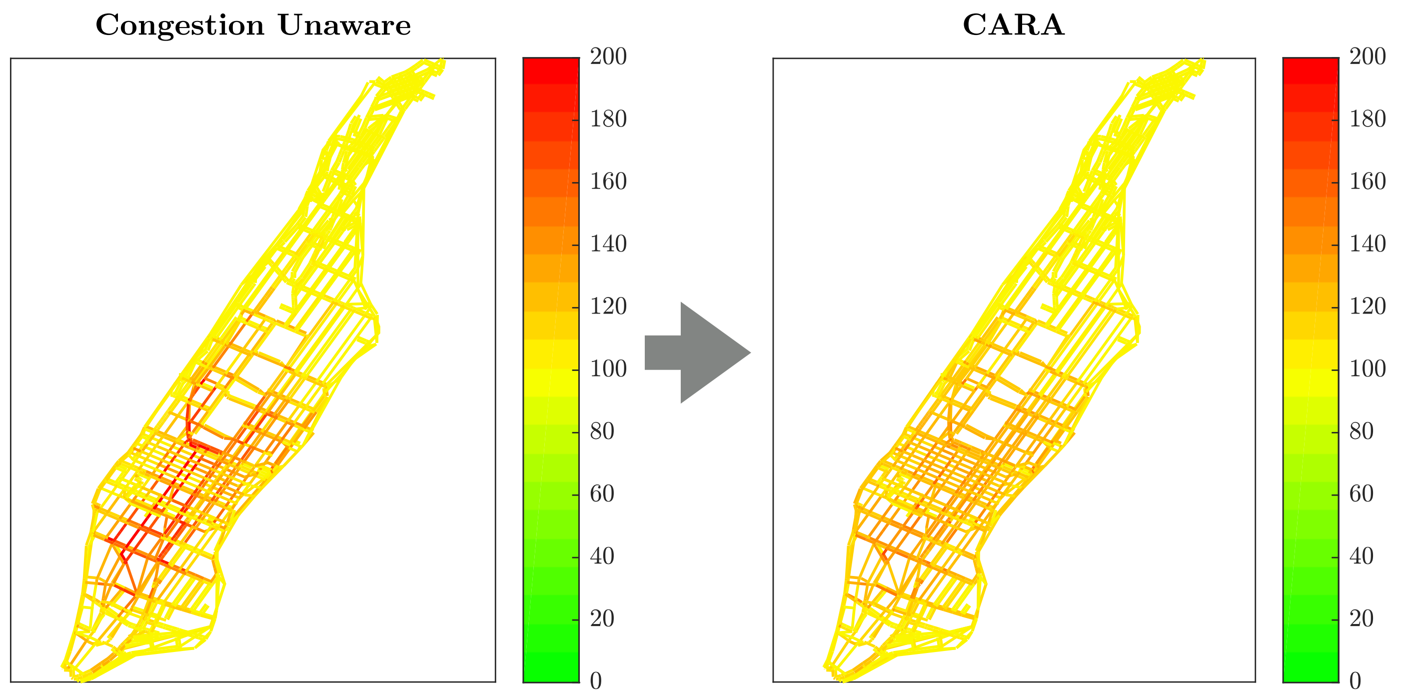
Interaction with Infrastructure



Ride-sharing



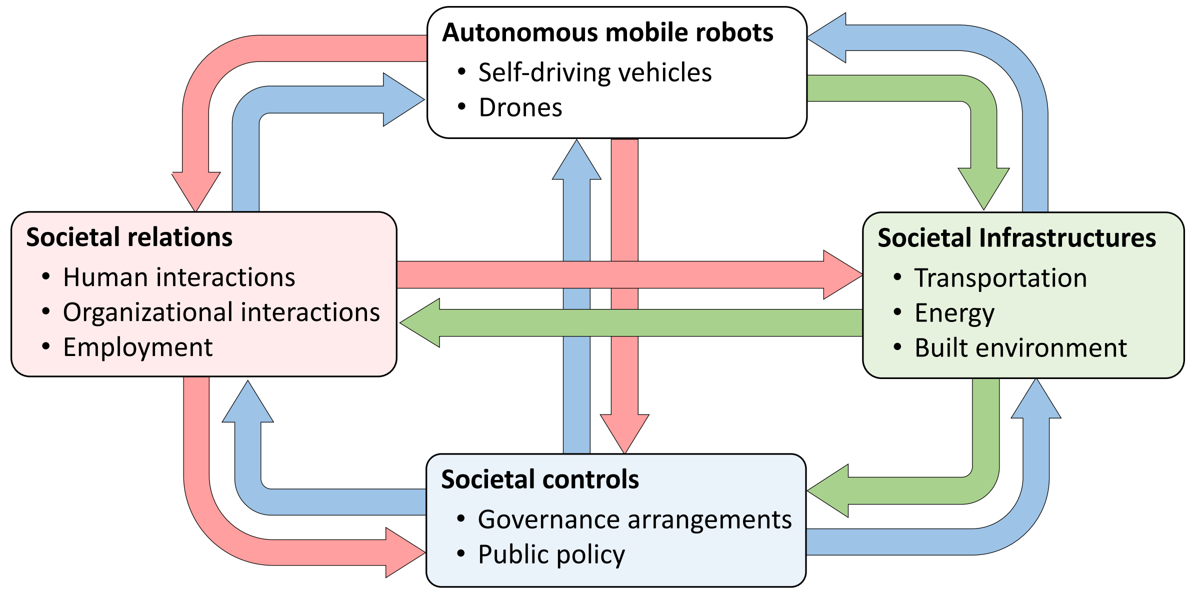
Real-time Routing Algorithms



Real-world Case Studies

Technology Infusion

Societal Implications



Conclusion

- Autonomous driving might lead to a **transformational** paradigm for personal urban mobility
- Integration of autonomous driving with the urban infrastructure gives rise to an entirely new class of problems (and opportunities)
- Solutions to these problems are key to enable AMoD and to carefully evaluate their value proposition

Acknowledgements: students at ASL, and sponsors

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Stanford University

Autonomous Systems Lab

TOYOTA RESEARCH INSTITUTE