The Need for Transit-Centric Thinking in an Autonomous, Connected, and **Electrified** Future

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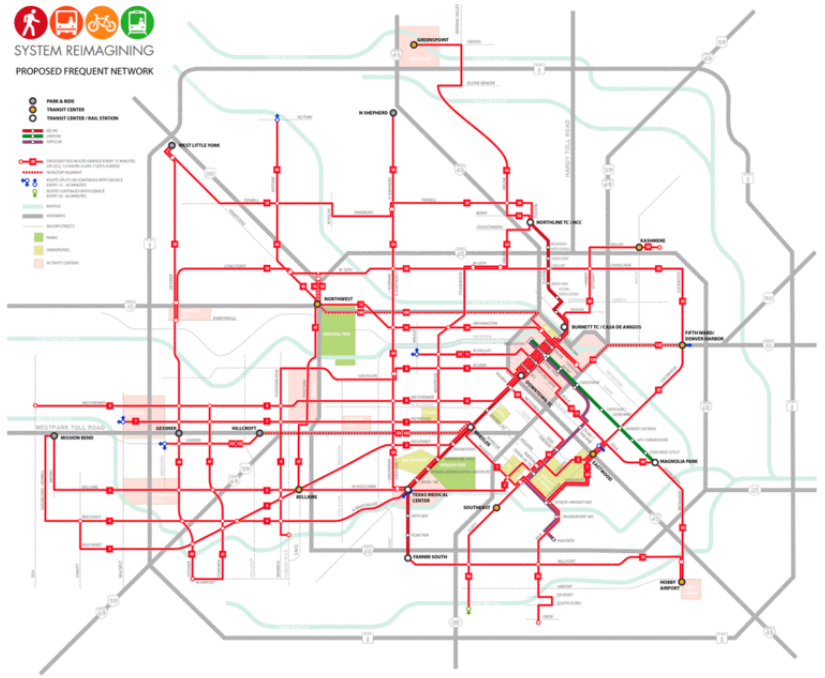
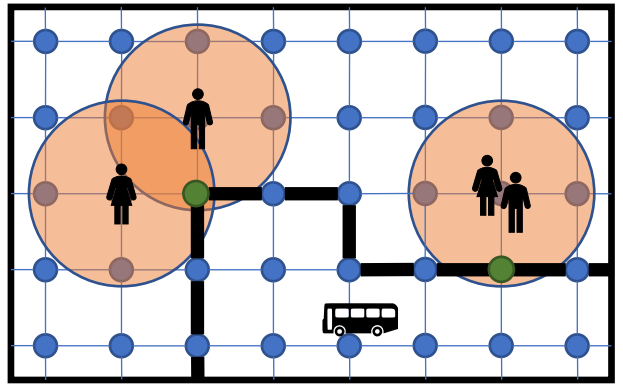
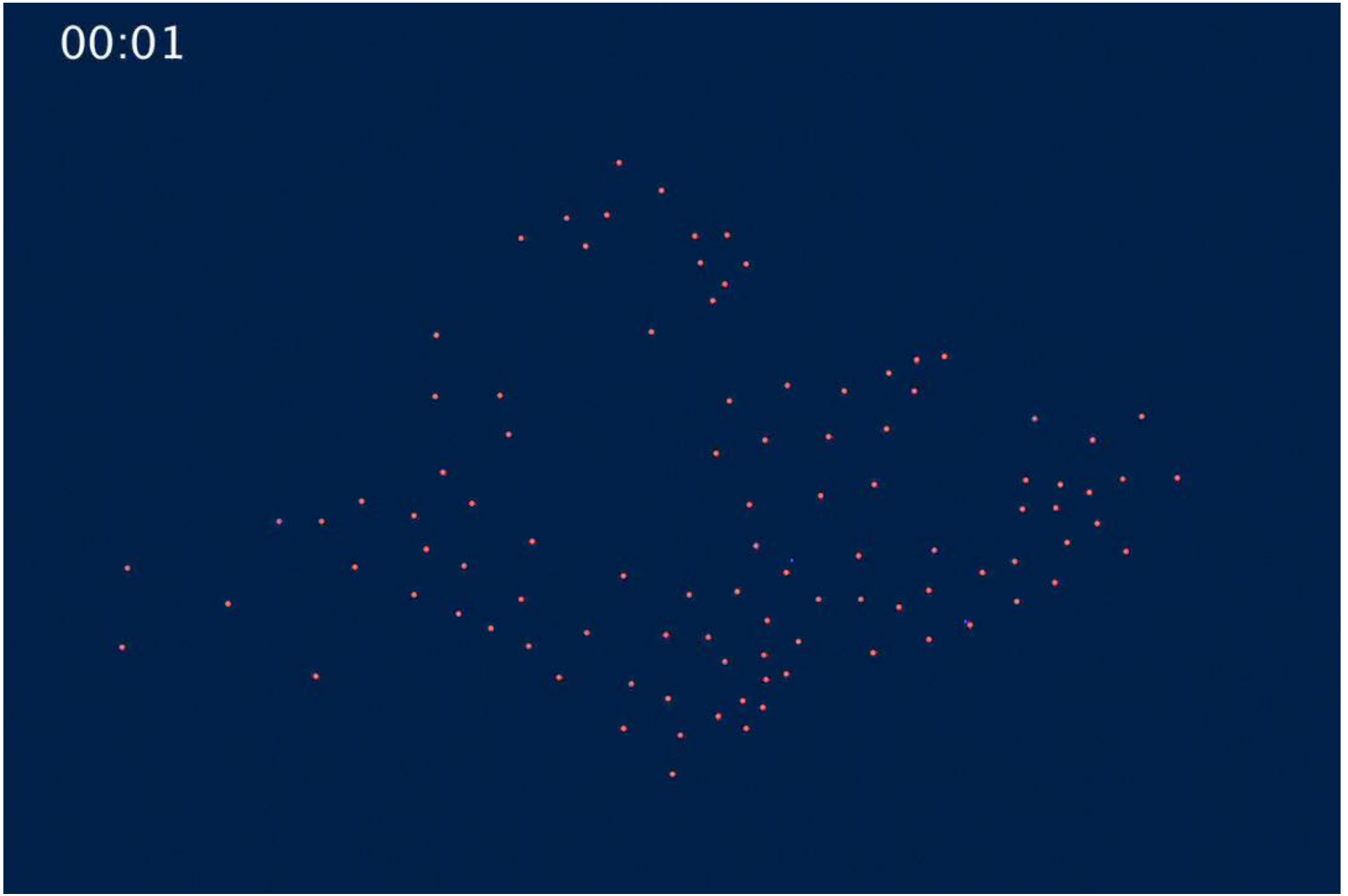


[Image from Houston Metro]



[Image by: Juan Carlos Martinez Mori]

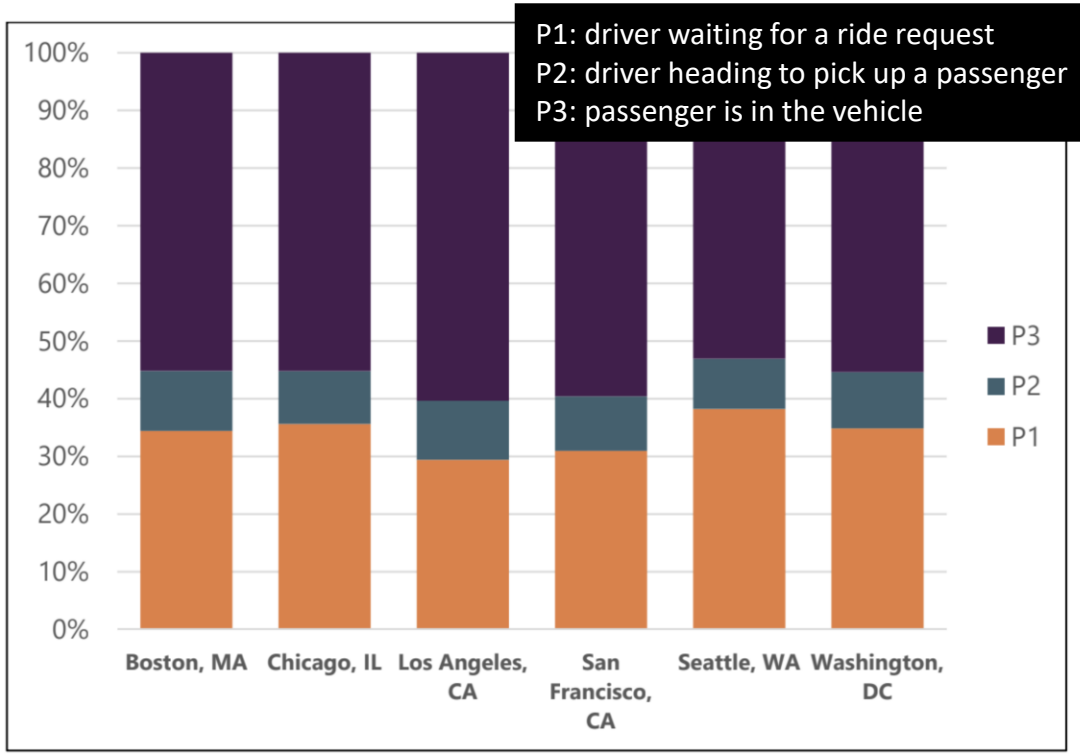


Approximately 300,000 shared autonomous cars (vs. ~800,000 passenger vehicles) could satisfy the mobility needs of the entire population, with waiting times within 15-20 minutes at peak hours.

[Spieser, Treleaven, et al. RVA'14]

Why focus on mass transit centric solutions?

[Spieser, Treleaven, et al. RVA'15]



FEHR PEERS 2019

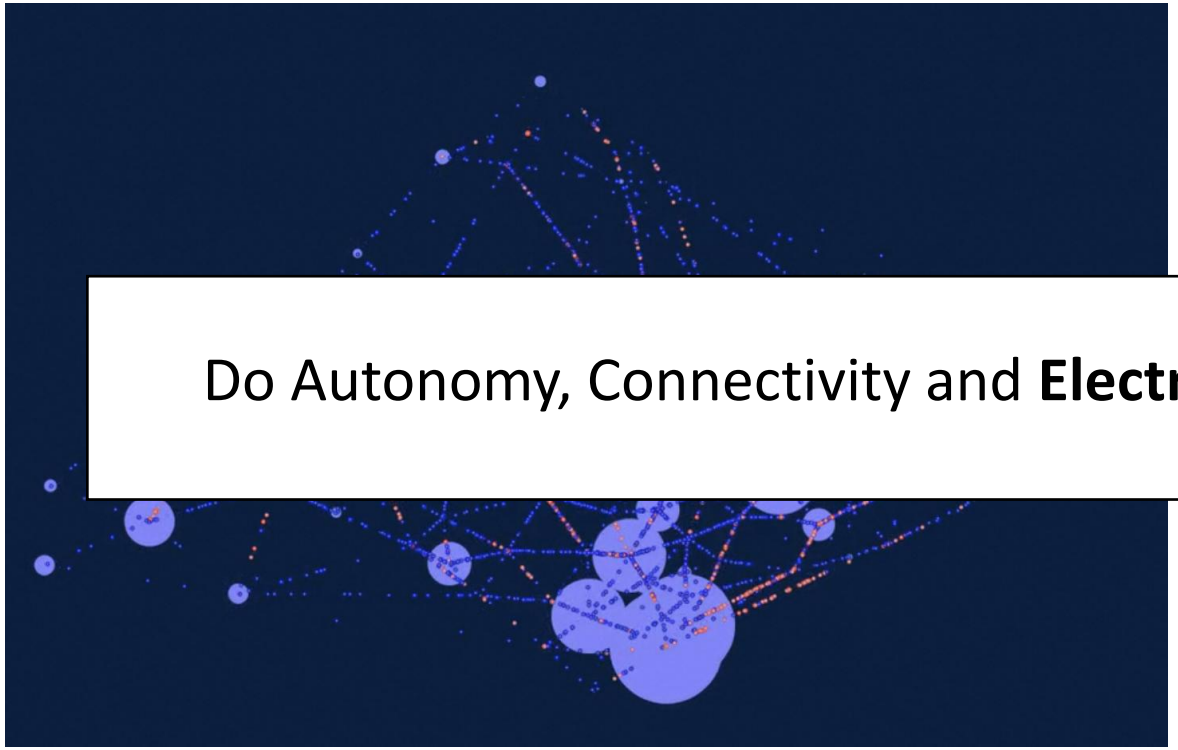
Ride-hailing systems can increase total vehicle miles traveled (VMT) compared to private vehicle ownership[1]

⇒ Increase in negative externalities (e.g., congestion, emissions, impact on mass transit, equity)

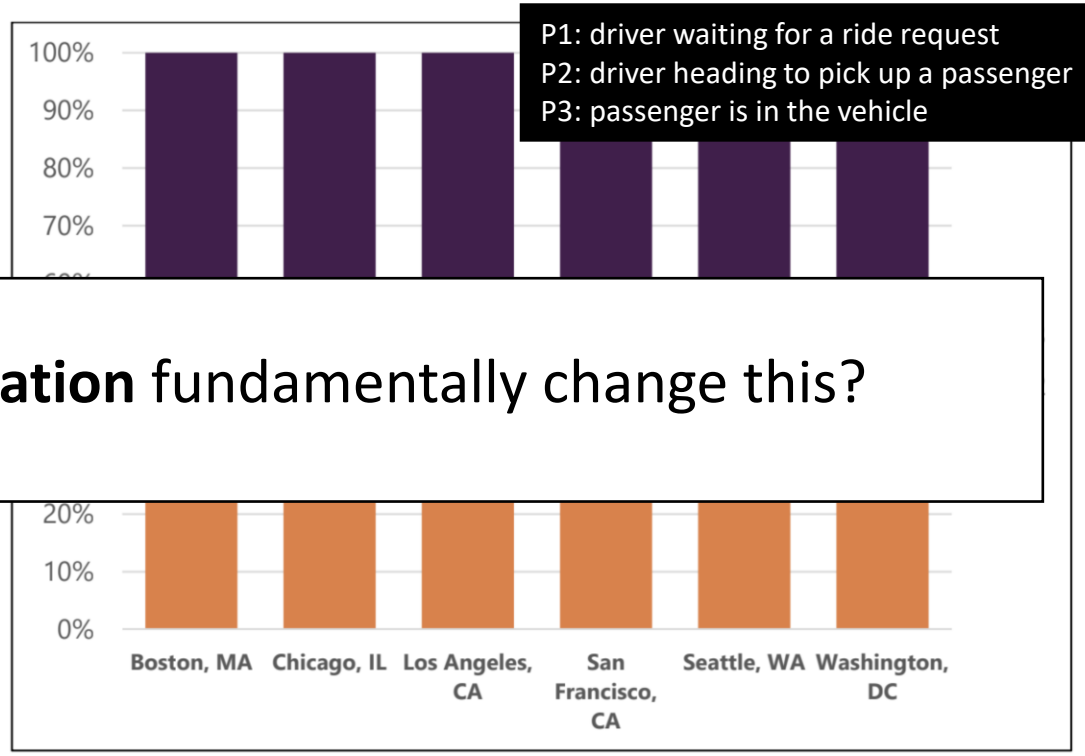
⇒ Competition can amplify this via the "Price of Fragmentation"
[Sejourne, Samaranayake, Banerjee; ACM SIGMETRICS '18]

1. Increases VMT per passenger mile travelled

Why focus on mass transit centric solutions?



[Spieser, Treleaven, et al. RVA'15]



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Do Autonomy, Connectivity and **Electrification** fundamentally change this?

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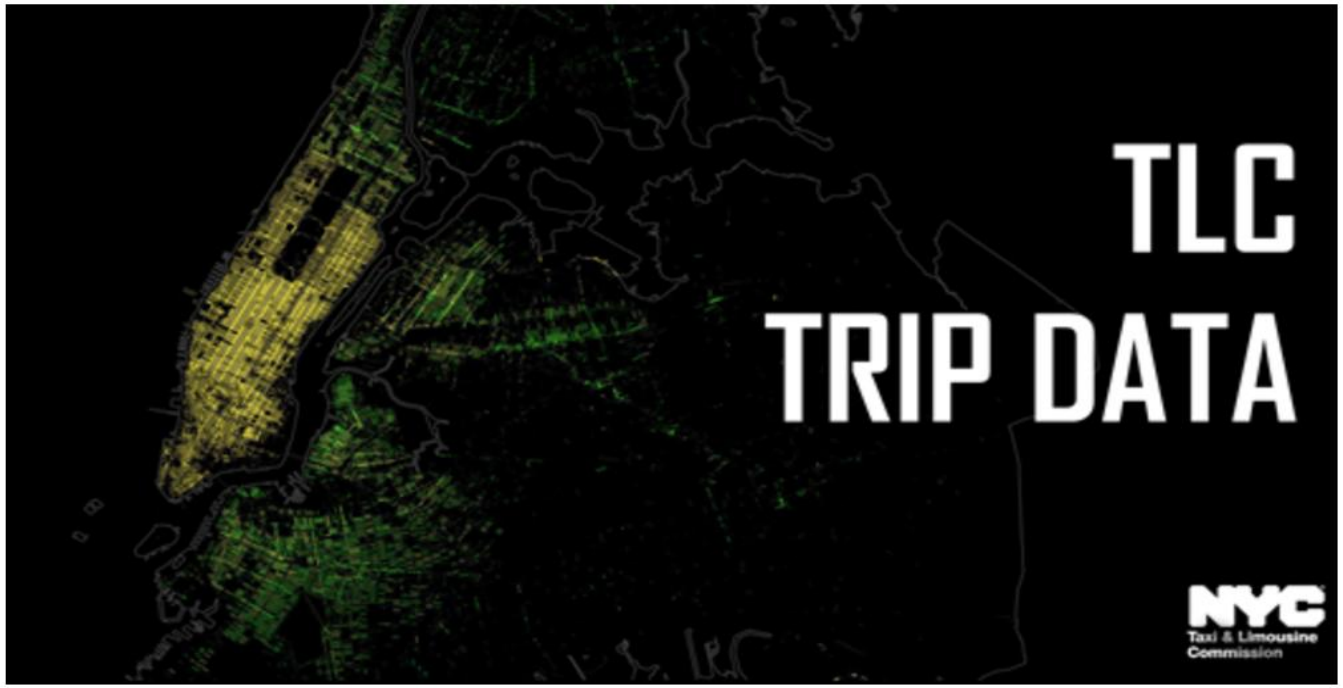
1. Increases VMT per passenger mile travelled

High capacity sharing at the scale of NYC in real-time



Sample week:
- May 5 - 11, 2013
- 380k (Sun) – 460k (Fri) trips/day
- 2000 active trips at anytime
- Served by 13,580 taxis

NYC Network: 4,092 nodes, 9,453 edges

[Alonso-Mora, Samaranayake, Waller, Frazzoli, Rus. PNAS ‘17]

Some observations from pilot deployments

DOE VTO: Micro-transit/public-transit for coordinated multimodal movement of people

NSF S&CC: Mobility for all - Harnessing Emerging Transit Solutions for Underserved Communities

- Many pilot deployments of various styles
- Small publicly funded short-term deployments
- Low occupancy, limited integration with transit infrastructure
- Not enough incentives for avoiding single occupancy trips
  - Labor costs not proportional to vehicle size
  - The economics needs to change, e.g., congestion pricing

Both innovation (AVs) and regulation (e.g., congestion pricing) can help

Multi-modal mass transit systems

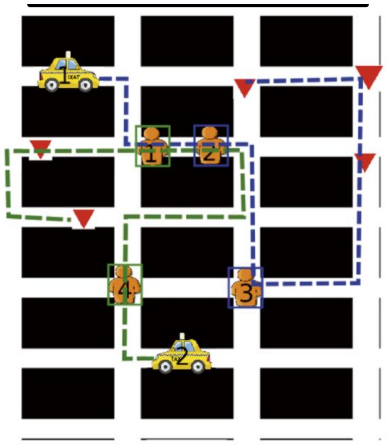
Multi-modal transit system

Fixed-line transit

+

Complimentary services

- Ride-hailing/ridepooling
- Bikesharing/micromobility
- Microtransit



Energy efficiency

Network externalities

Equity

Multi-modal (Bus) line planning

$x_{\ell p}$: Do I assign p to ℓ ?

$$\max_{x,y} \sum_{p} \sum_{\ell} v_{\ell p} x_{\ell p}$$

y_ℓ: Do I open line ℓ ?

$x_{\ell p} \in \{0,1\}$

$y_\ell \in \{0,1\}$

Subject to:

$$\sum_{\ell} c_\ell y_\ell \leq B$$

$$\sum_{\substack{p: \\ p \text{ uses edge } e \\ \text{on line } \ell}} x_{\ell p} \leq C\, f_\ell\, y_\ell \quad \text{for all lines } \ell, \text{ edges } e$$

$$\sum_{\ell} x_{\ell p} \leq 1$$

Choose the set of lines, and the assignment of passengers to lines, that maximizes ridership

Constraints:

1) Budget B to open lines
2) At most C passengers per edge, per line

No inter-bus transfers

Budget corresponds to Operational Expense (OpEx)

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This is a *really* hard problem.

Problem: Exponentially many lines to choose from!

"Solutions":

- Add lines iteratively via branch and price (column generation + branch and bound)
- Assume access to a candidate set of lines (can be large, just not exponential in number of nodes!)

[Borndörfer, Grötschel, Pfetsch; Transportation Science '07]
[Bertsimas, Ng, Yan; Operations Research '21]
[Ceder, Wilson; Transportation Research Part B '86]
[Schöbel; OR spectrum '12]

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This is a *really* hard problem.

Problem: Exponentially many lines to choose from!

"Solutions":
- Branch and price
- Use a candidate set of lines

This is still a hard problem.

- ILP with a bad LP relaxation
- More candidate lines → bigger ILP

Theoretical guarantees

(1) Solve an almost-equivalent, exponential-size optimization problem.

(2) Randomized rounding step:
- Flip a weighted coin according to solution of configuration LP.

(3) Flip thousands of coins and choose the best budget-respecting solution!

How well does this perform relative to optimum?

$$ALG \geq \left(1 - \frac{1}{e} - \epsilon\right) OPT$$

Budget-respecting with high probability

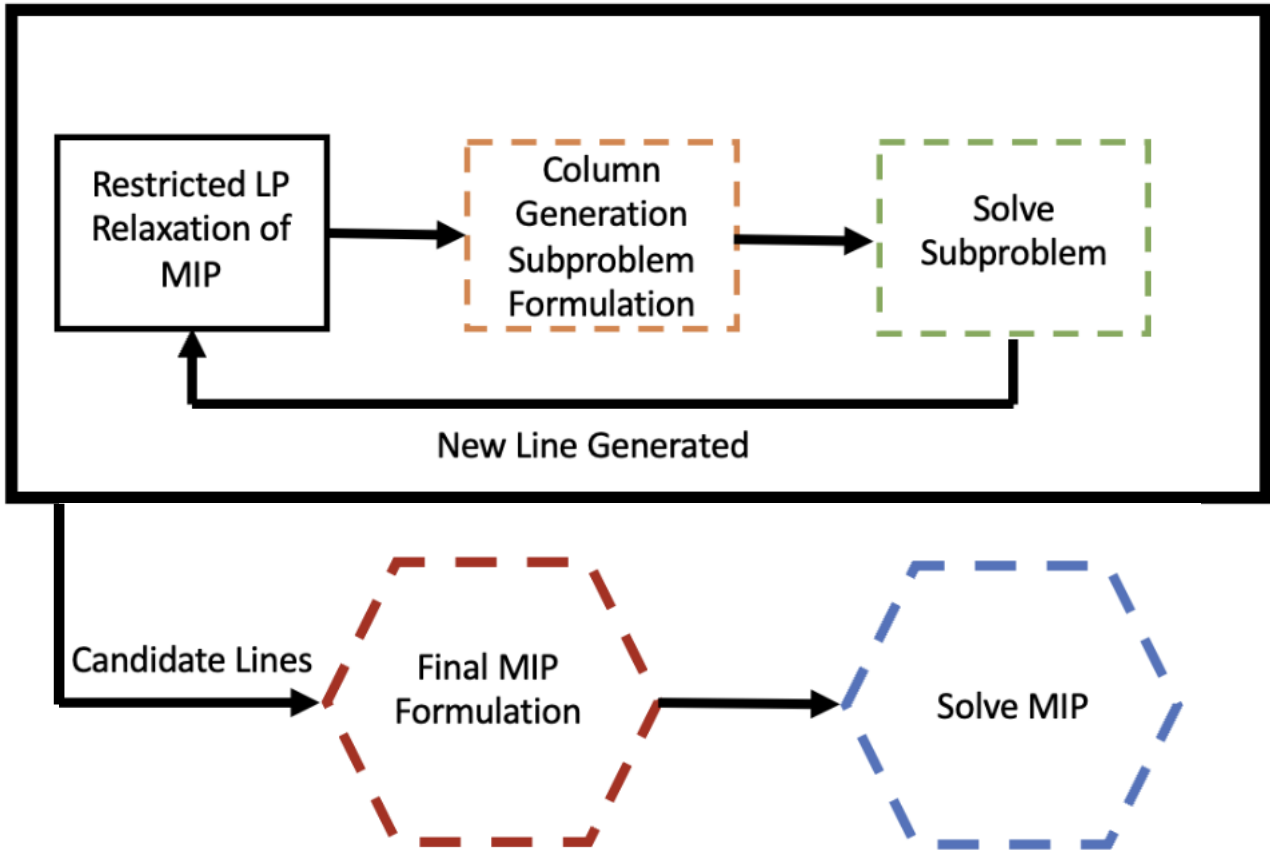
ϵ trades off between performance guarantee and fraction of time solution is budget-respecting

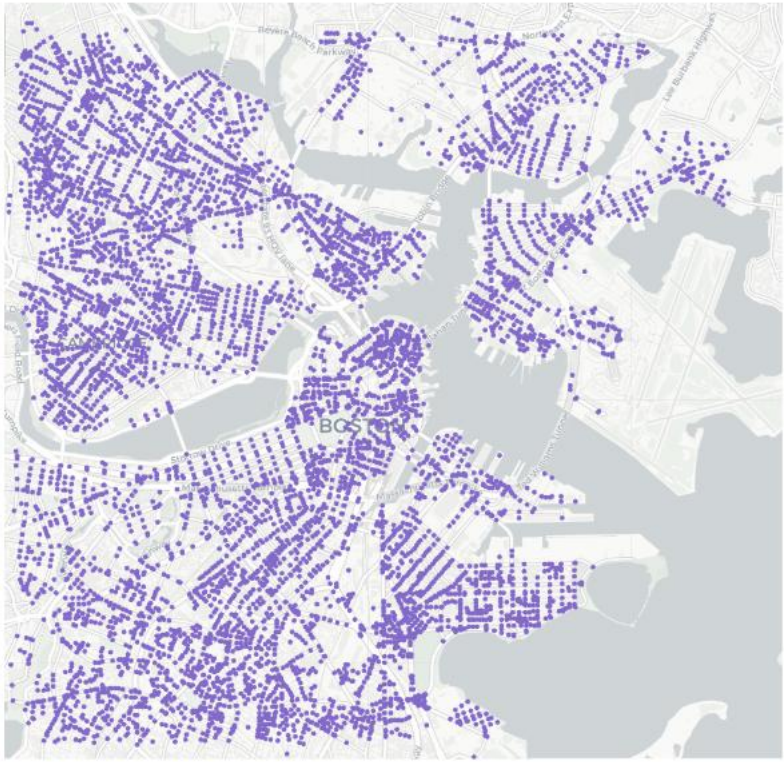
Real-Time Approximate Routing for Smart Transit Systems, with Sid Banerjee, Chamsi Hssaine and Noemie Perivier (ACM POMACS/SIGMETRICS '21)
Approximation Algorithms for Capacitated Assignment with Budget Constraints and Applications in Transportation Systems, with Hongyi Jiang (COCOON '23)

Scalable multi-modal line planning with line generation

Two major challenges:

- Finding the candidate lines
- Better integration of multi-modality

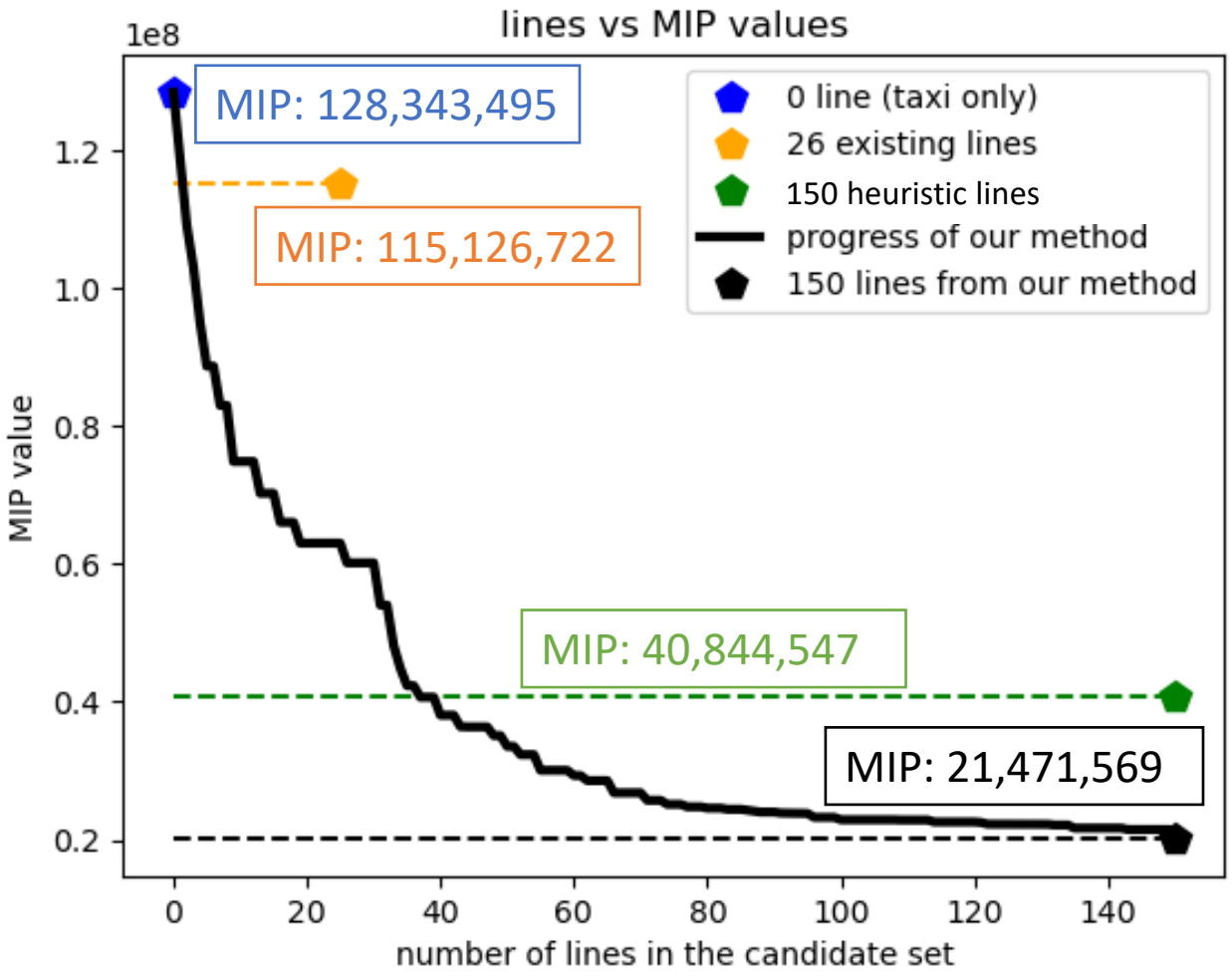




Case Study: Boston

[Large-scale multi-modal transit design, with Ning Duan and Oktay Gunluk]

Multi-modal (Bus) line planning with line generation



- Time limit of 5 minutes to generate each line via the pricing problem (in Gurobi)
- Cuts cost from 150 lines generated via a heuristic almost in half

Results shown for max ridership version of the problem

[Large-scale multi-modal transit design, with Ning Duan and Oktay Gunluk]

“*Buses will not be needed when Tesla rolls out unsupervised full self-driving, as they will take people point to point for a similar cost to a bus ticket*”

- Elon Musk

"*Buses will not be needed when Tesla rolls out unsupervised full self-driving, as they will take people point to point for a similar cost to a bus ticket*"
- Elon Musk

Regardless of the cost, we should not replace hundreds of buses with tens of thousands of robotaxis!

The Future of Mobility in Oslo

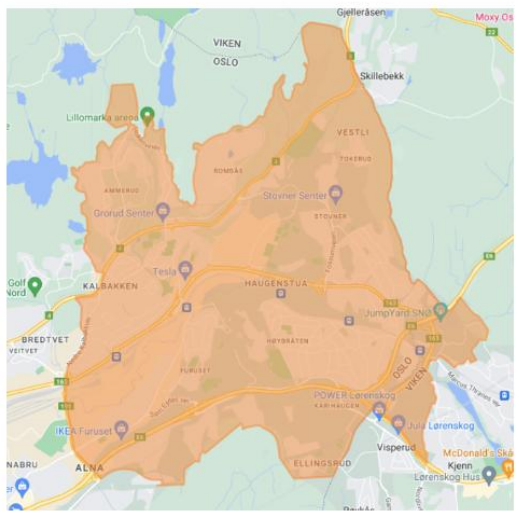
Technological demonstration
A pilot project to establish the technological capabilities and future possibilities.
Total AVs: 4-20
Total area: 22 km2

Business viability
An established use case and economic sustainability allow for expansion
Total AVs: 20-250.
Total area: 480 km2

Demonstrated scaling
Successful scaling in local municipalities will spread through the Oslo region.
Total AVs: 20.000
Total area: 6.920 km2

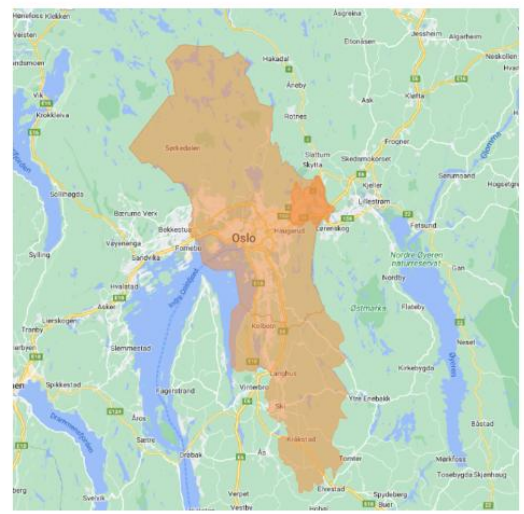
Future possibilities
From Oslo, the service could expand through greater Oslo and Norway.
Total AVs: 30.000+
Total area: 8.890 km2

2022-2024



2023-2025

2024-2030

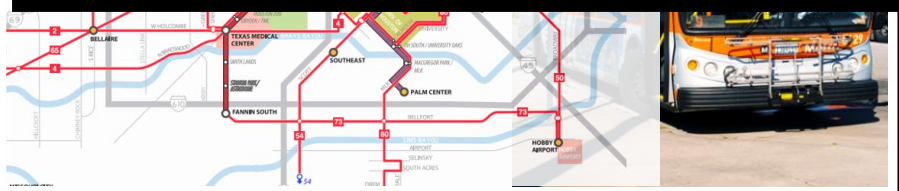


2030+

Multi-modal mass transit systems

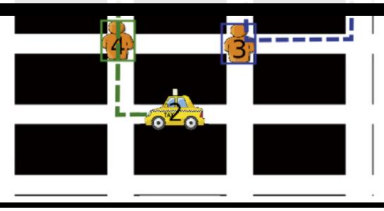
Multi-modal transit system

Fixed-line transit



Complimentary services

- Ride-hailing/ridepooling
- Bikesharing/micromobility



Sustainable, efficient and equitable personal mobility can not exist without a fundamental focus on mass-transit

Developing multi-modal transit systems that address this will require new technology, business models and public policy

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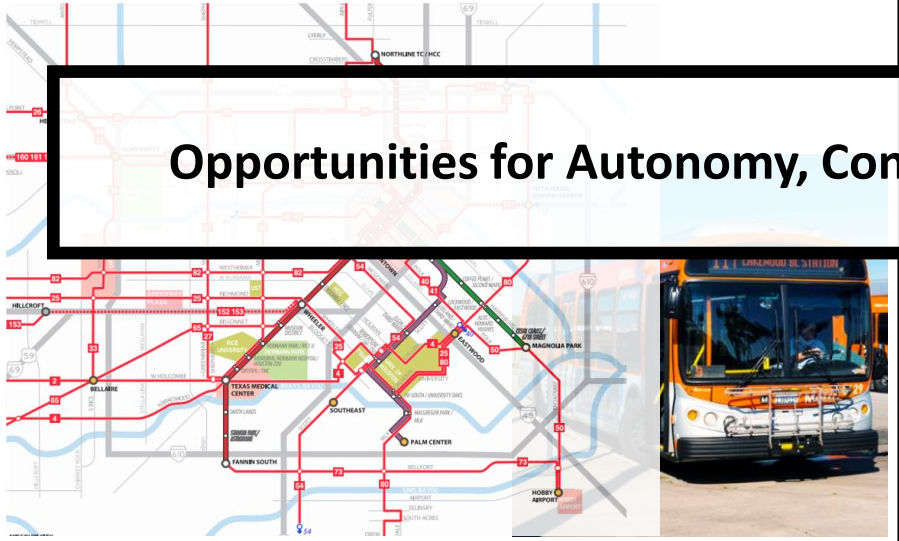

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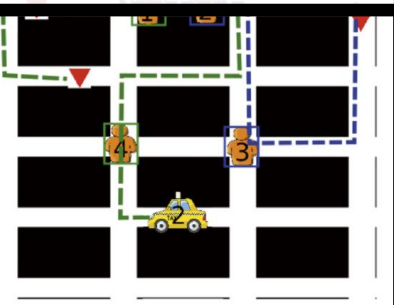

Opportunities for Autonomy, Connectivity and Electrification to play a greater role!

Energy efficiency

Network externalities

Equity