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Autonomy and the Future of Urban Mobility: *Beyond the Hype*

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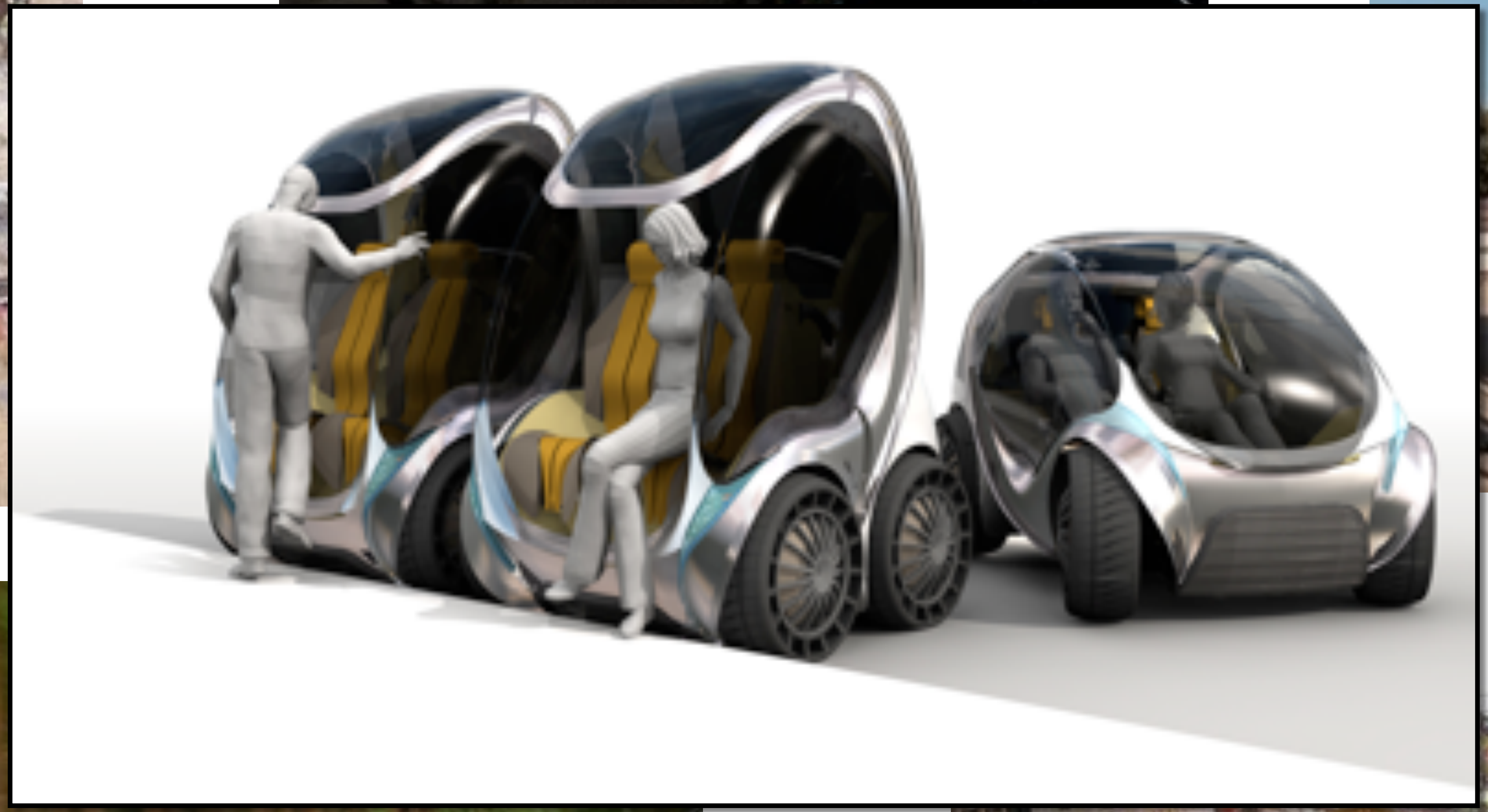
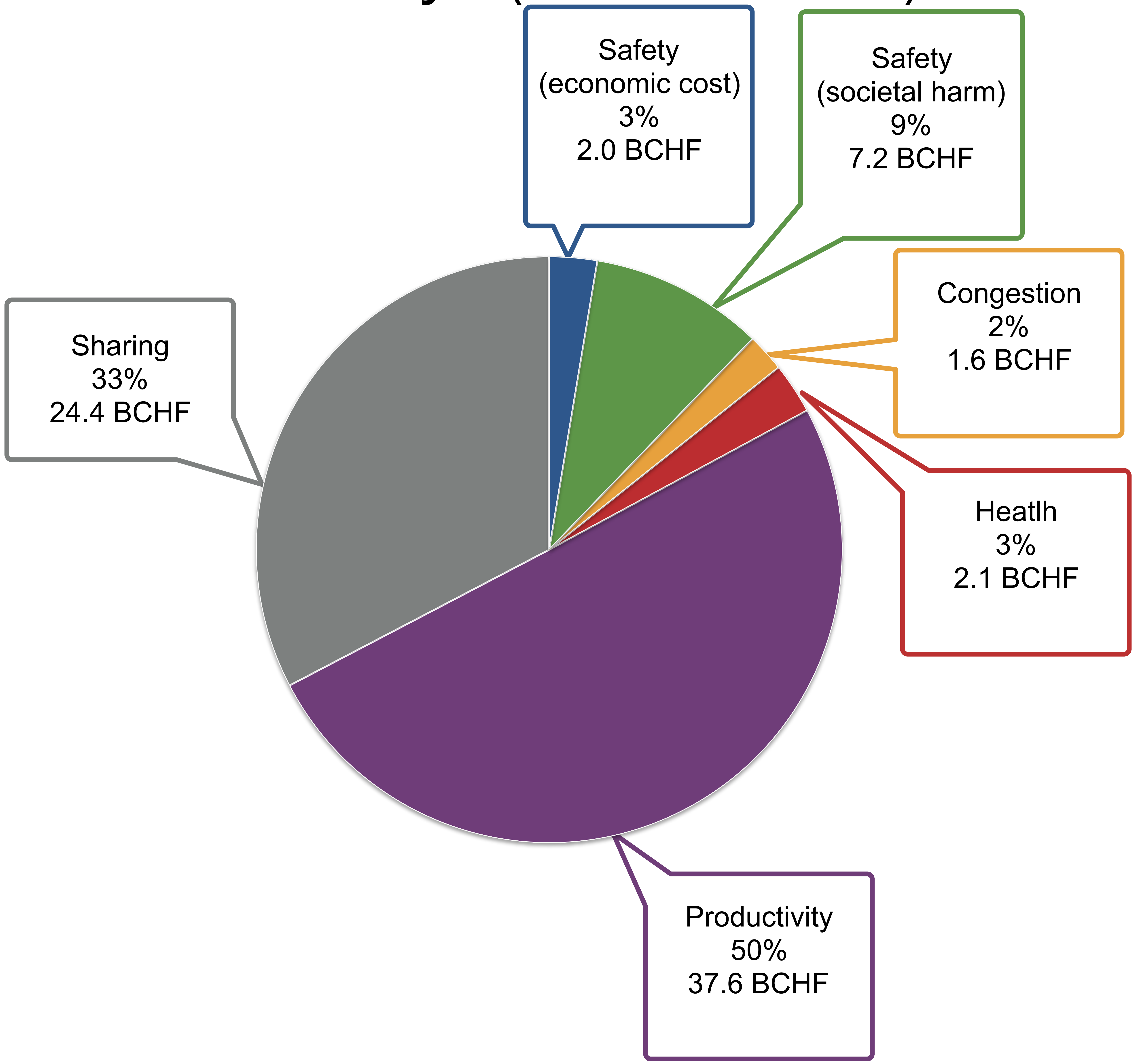
Autonomous Driving in 1994

Why Self-driving Vehicles?



A financial perspective on personal mobility (CH Market)

- Safety:
  - “Cost of a statistical life”: CHF 9M
  - Estimate based on 2010 ARE report and others:
    - Economic cost of road accidents: ~ CHF1'966M/year.
    - Societal harm of road accidents: ~ CHF 7’158M/year
- Cost of congestion:
  - BFE figures, ARE report 2010: ~ CHF1'565M/year
- Health costs of congestion:
  - Various reports, estimate: ~ CHF 2'097M/year
- Increased productivity/leisure:
  - Estimate ~ CHF 37'500 M/year
- Car sharing:
  - Assuming a “sharing factor” of 4, estimate CHF 24'400M/year of benefits to individuals.
  - Other studies [Burns et al., ’13, Fagnant, Kockelman ’14] suggest higher sharing factors, up to ~10.



Autonomous Mobility-on-Demand (AMoD) in Context

Transportation

Conventional public transport

Shared Mobility

Motorized individual traffic

One-way shared mobility schemes

Two-way shared mobility schemes

Only Round Trips

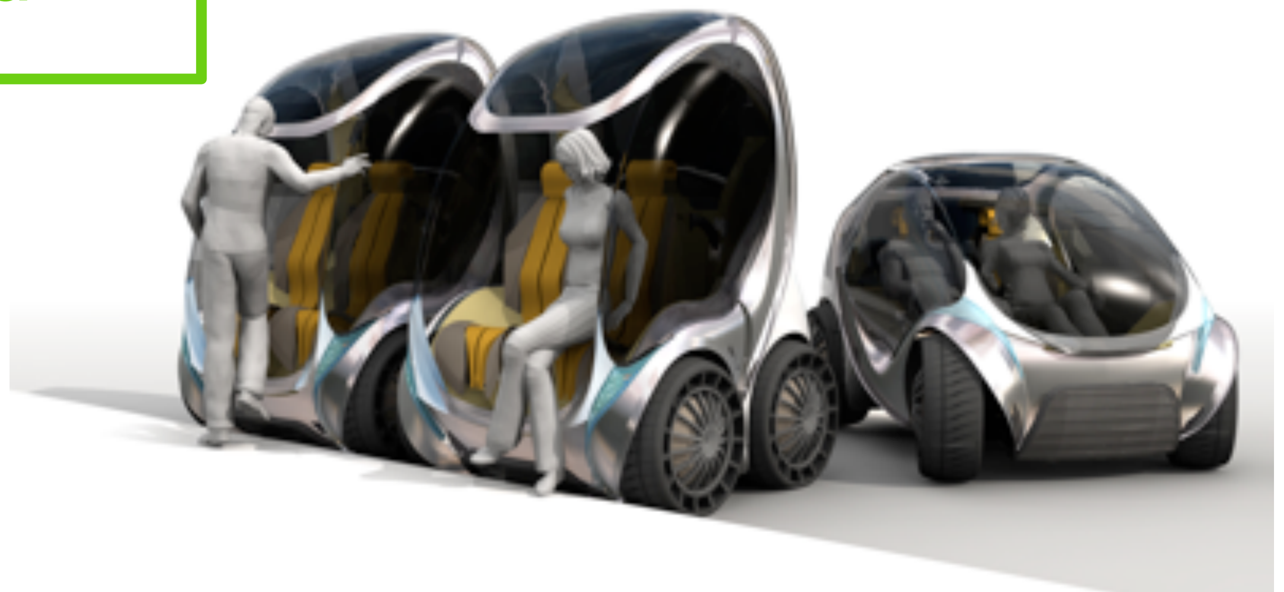
Shared bicycle schemes

One-way mobility-on-demand

Autonomous mobility-on-demand

Rebalancing expensive/impractical

Not enough drivers at low cost



The Technology Enabling Autonomous Vehicles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autobox.rimo.get
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Velocity 0.00[m*s^-1]
TurningRate 0.00[s^-1]


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autobox.rimo.put
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exp
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autobox.linmot.put BinaryBlob 5702
autobox.misc.get BinaryBlob 11454
autobox.misc.put BinaryBlob 5702
autobox.rimo.get BinaryBlob 28635
autobox.rimo.put BinaryBlob 5693
autobox.steer.get BinaryBlob 57274
autobox.steer.put BinaryBlob 5697
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davis240c.overview.... BinaryBlob 63646
gokart.pose.lidar BinaryBlob 5703
gokart.status.get BinaryBlob 11351
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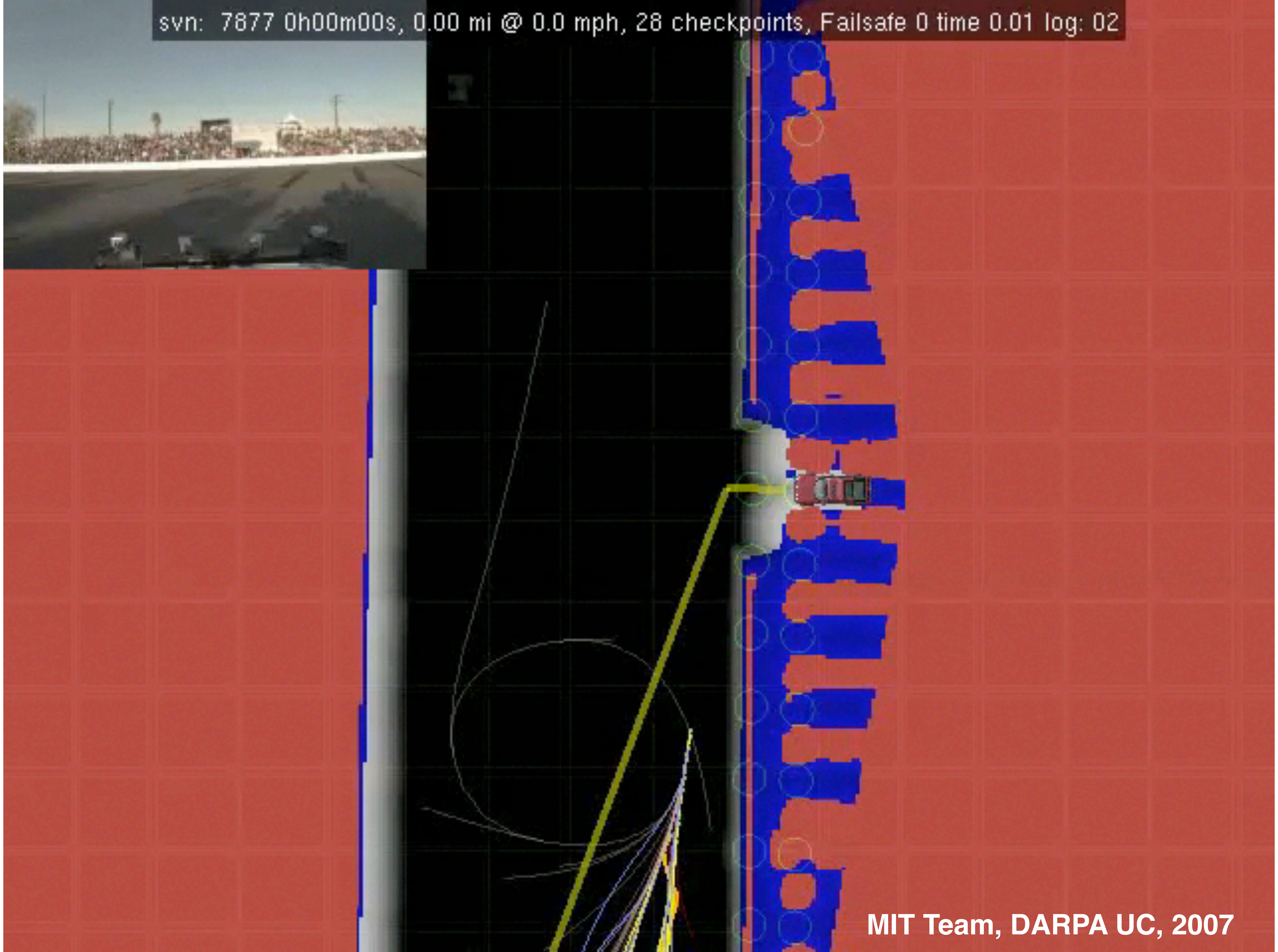
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MIT Team, DARPA UC, 2007

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File
View
Run
Help
[32.79 16.97 0.00 137.24]
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3m 15s 890msec [0.6]
rvizconfig.rviz* - RViz
Interact
Move Camera
Select
Focus Camera
Measure
2D Pose Estimate
2D Nav Goal
Publish Point
Reset
27 fps


In-vehicle camera
NVIDIA

The facts

- **The rules of the road are in fact not that many**
  - What can be driven, where, when
  - Who can drive, where, when
  - Accident prevention/ avoidance
  - Direction of travel
  - Speed limit
  - Right of way
  - Merging
  - Signals (passive)
  - Signals (active)
  - Parking/stopping

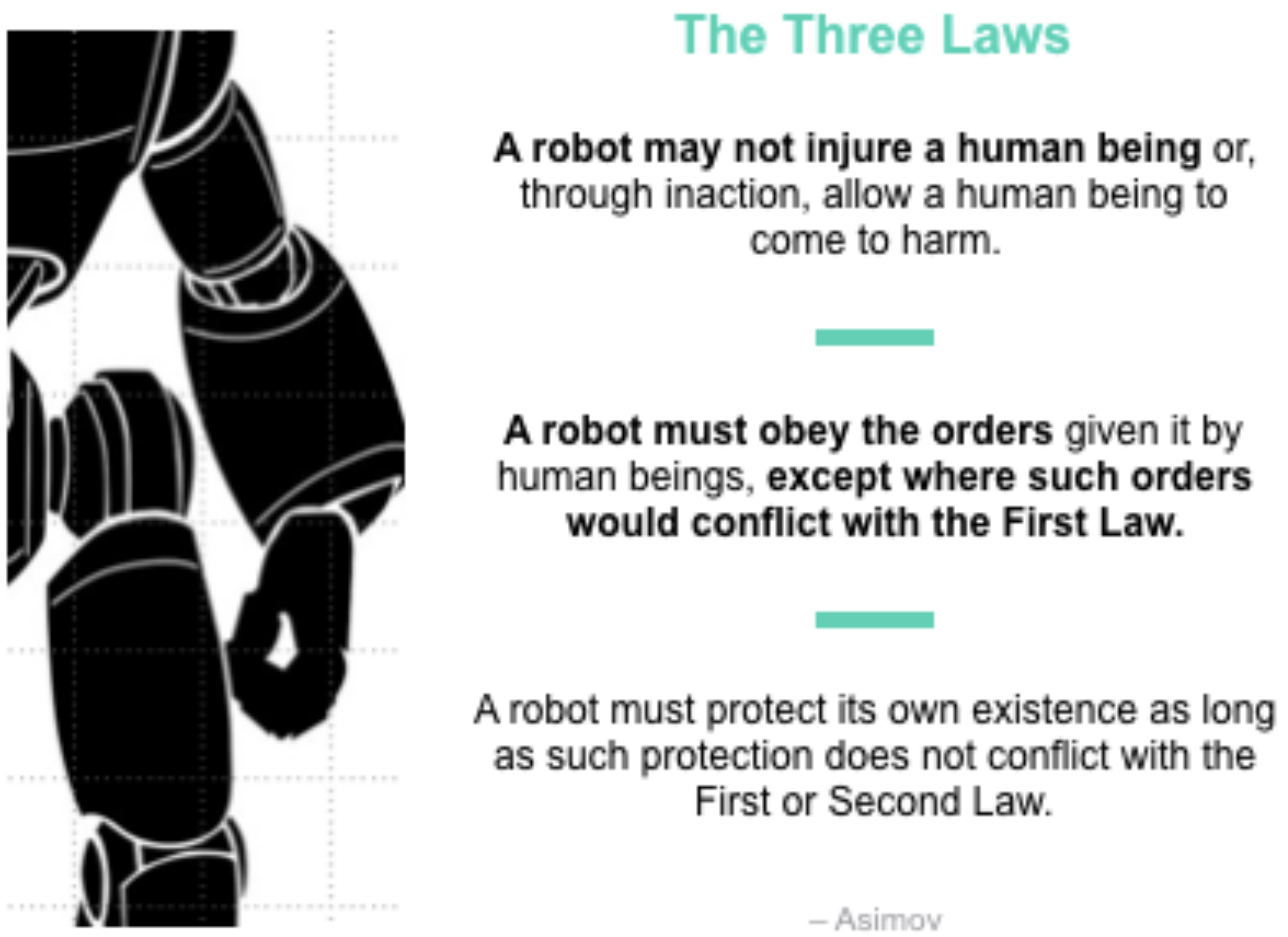
- However, the possible **combinations of rules,** and the way they are interpreted over different world instances, **are exceedingly many**

- **Hard to code** good behaviors
- **Hard to learn** good behaviors
- **Easy to recognize** good behaviors

But:
What if the rules are ambiguous?

The Achille's Heel for AVs

- The most fundamental problem in designing AVs is that we **don't really know how (human-driven) vehicles should behave**.
- Challenge for the AV R&D community: **Develop a sound theory of the "rules of the road"** for what are good vs. bad behaviors.



Product vs. Service

	AVs as a consumer product	AVs as a service (MaaS)
Scope Where and when the AV capabilities must function	Everywhere, all the time	Geo-, time-, weather-fenced operation
Financials Cost constraints	Comparable to the cost of the vehicle and/or driver's time. PV of the driver's time: ~23,000 USD for a 10-year lifetime	Comparable to the cost of hiring a driver > 100,000 USD per year
Infrastructure Maps, dealers, service	Global scale, immediately	Scale (sub)linearly with the user base
Servicing and Maintenance	Most high-tech sensors etc. not user serviceable yet	Servicing/maintenance crews already on roster.

Autonomous Mobility-on-Demand:
The Fleet Perspective


Wettingen
Boppelsen
Otelfingen
Buchs
Brütten
Oberwil
Sennhof
Kloten
Neuenhof
Dänikon
Würenlos
Bassersdorf
Regensdorf
Opfikon
Ottikon
Weisslingen
Effretikon
Spreitenbach
Seebach
Dietlikon
Wallisellen
Theilingen
Bisikon
Dietikon
Oberengstringen
Illnau
Höngg
Schlieren
Dübendorf
Stettbach
Künten
Urdorf
Volketswil
Gutenswil
Fehraltorf
Aussersihl
Zürich
Rudolfstetten
Enge
Binz
Bremgarten
Birmensdorf
Zufikon
Uster
Zollikon
Maur
Hermetschwil-Staffeln
Zumikon
Sulzbach
Kilchberg
Arni
Bonstetten
Küsnacht
Oberlunkhofen
Adliswil
Mönchaltorf
Gossau (ZH)

AMoDeus API

MATSim
Multi-Agent Transport Simulation

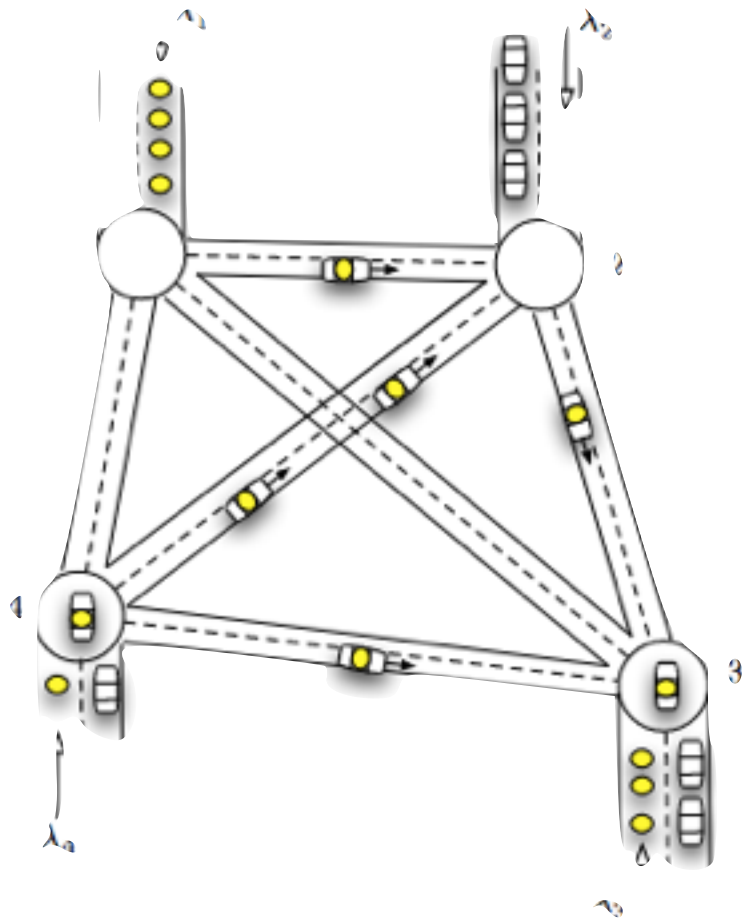
SIMMOBILITY

Simulation - Tools

✓Street-level detail.
✓Agent-based.
✓Extensive.
✓Effects such as dynamic demand, congestion etc. are taken into account.

- Hard to setup and calibrate.
- No AMoD specific performance metrics, adaptable visualizers.
- Limited AMoD support.

AMoDeus - API



e.g., Pavone, Marco, et al. "Robotic load balancing for mobility-on-demand systems." The International Journal of Robotics Research 31.7 (2012): 839-854.

Theoretical Results

✓Sound theories and proven limits.
✓Insights thanks to analytical formulas.

- Simplified models do not represent reality accurately enough.
- Often results have not been tested on high-fidelity simulations.

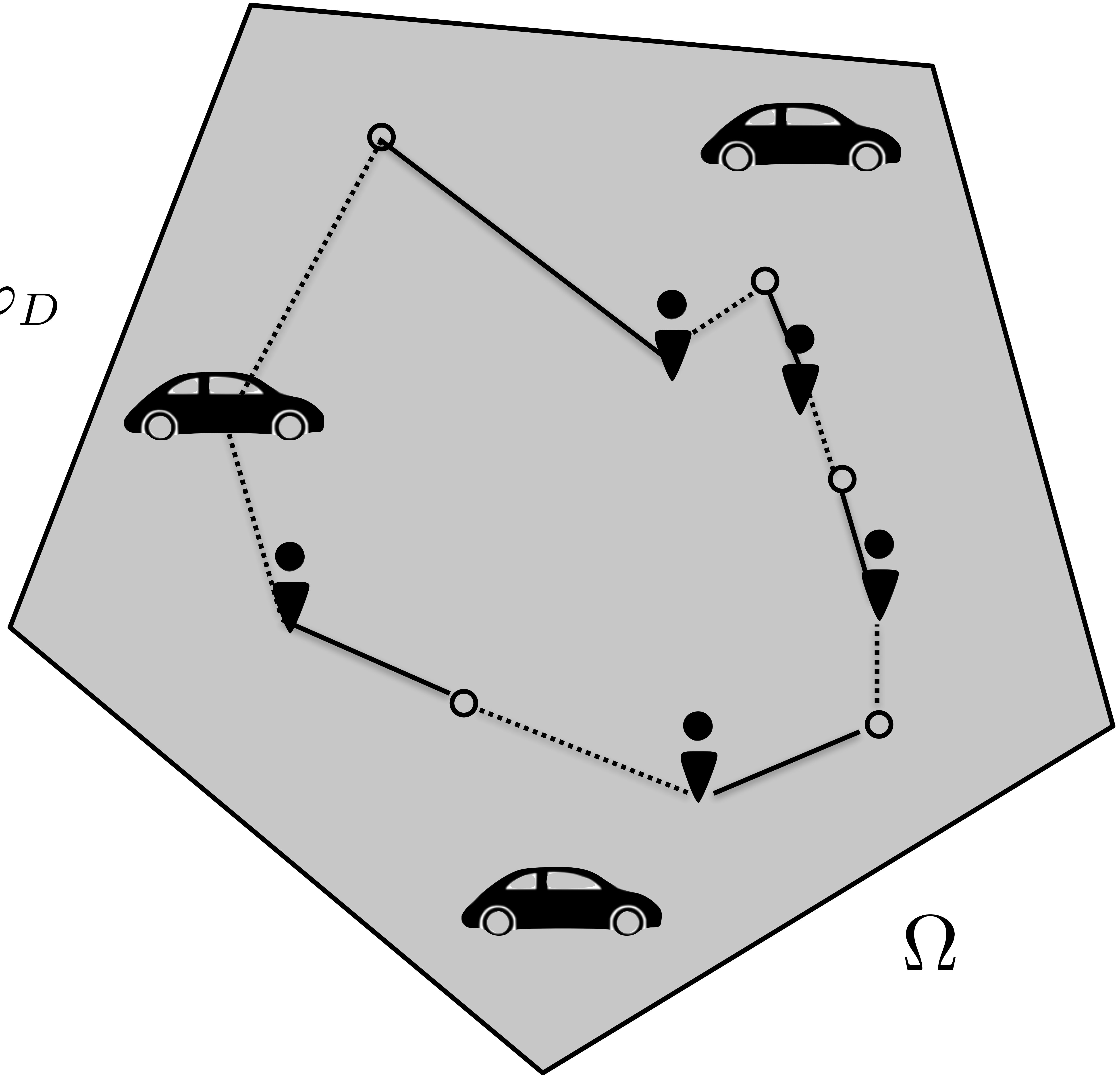
IDSC IVT

What **size** should I chose my **fleet** for a given geographical area?

Theory: Minimum Fleet Sizing

- Customer origins distributed according to φ_O
- Customer destinations distributed according to φ_D
- Customers arriving at a rate λ
- Shortest tour connecting a set of requests: **Stacker Crane Tour** composed of and of $O \to D$ and $D \to O$ pieces.
- The average rate of additional distance that needs to be covered is: $\lambda \cdot (\bar{d}_{O\to D} + \bar{d}_{D\to O})$
- The collective fleet of N vehicles cruising at average speed $\bar{v}$ needs to be able to cover at least the additional distance arriving with new requests:

$$N \cdot \bar{v} \geq \lambda \cdot (\bar{d}_{O\to D} + \bar{d}_{D\to O})$$

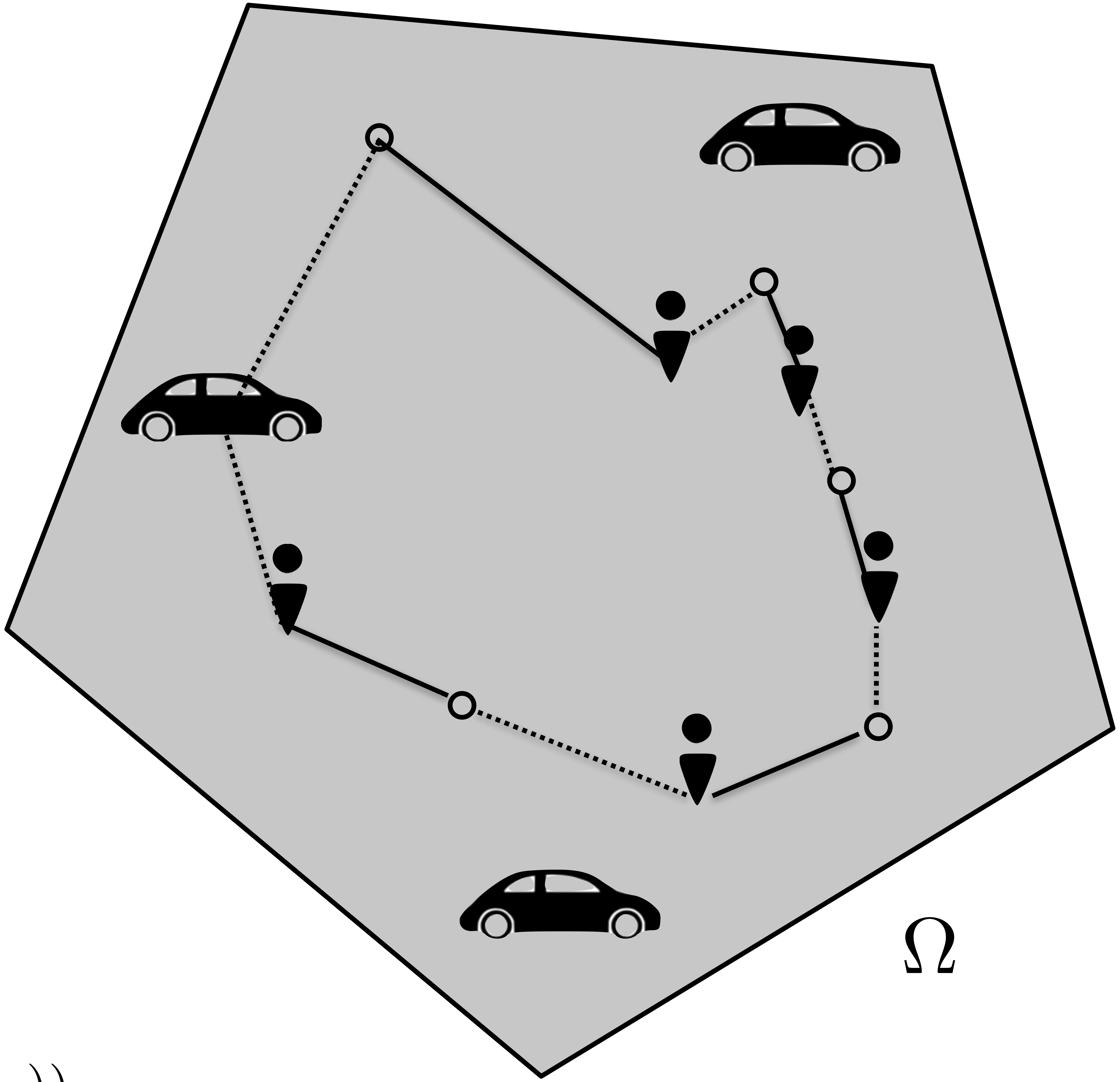


Treleaven, Kyle, Marco Pavone, and Emilio Frazzoli. "Asymptotically optimal algorithms for one-to-one pickup and delivery problems with applications to transportation systems." IEEE Transactions on Automatic Control 58.9 (2013): 2261-2276.

Theory: Minimum Fleet Sizing

- For a large number of requests the following properties hold:
  - $\bar{d}_{O \to D} \approx \mathbb{E}_{\varphi_O, \varphi_D} ||X - Y||$
  - $\bar{d}_{D \to O} \approx EMD(\varphi_O, \varphi_D)$
- EMD is the **Earth Mover's Distance**, a simple statistical quantity that can be obtained by solving a linear program.
- Knowing the rate of arrival of the requests λ, $\bar{v}$ and the distribution of request origins φ_O and the distribution of request destinations φ_D we can very easily compute the number of needed vehicles:

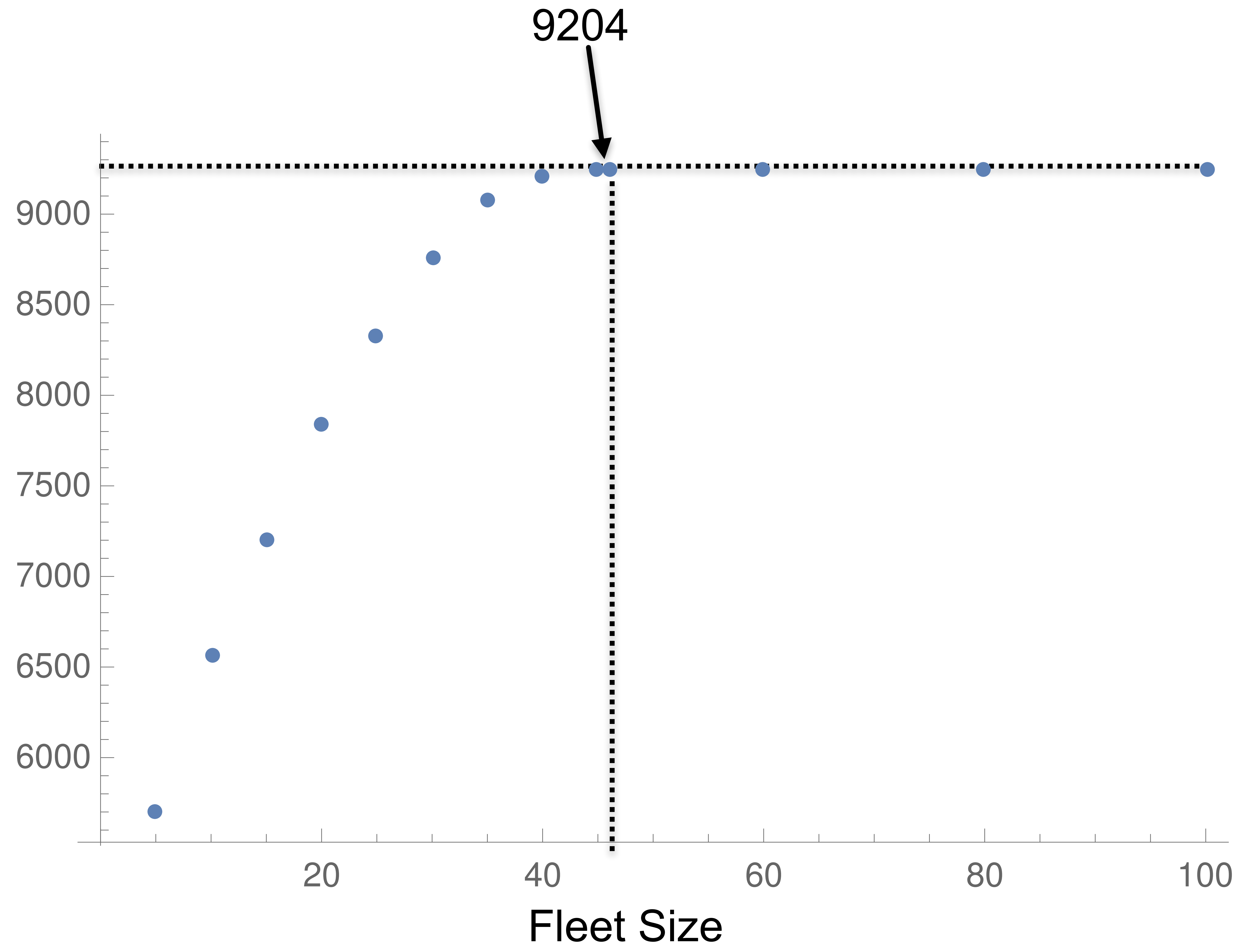
$$N > \frac{\lambda}{\bar{v}} \cdot (\mathbb{E}_{\varphi_O, \varphi_D} ||X - Y|| + EMD(\varphi_O, \varphi_D))$$



Treleaven, Kyle, Marco Pavone, and Emilio Frazzoli. "Asymptotically optimal algorithms for one-to-one pickup and delivery problems with applications to transportation systems." IEEE Transactions on Automatic Control 58.9 (2013): 2261-2276.

Simulation: Minimum Fleet Sizing

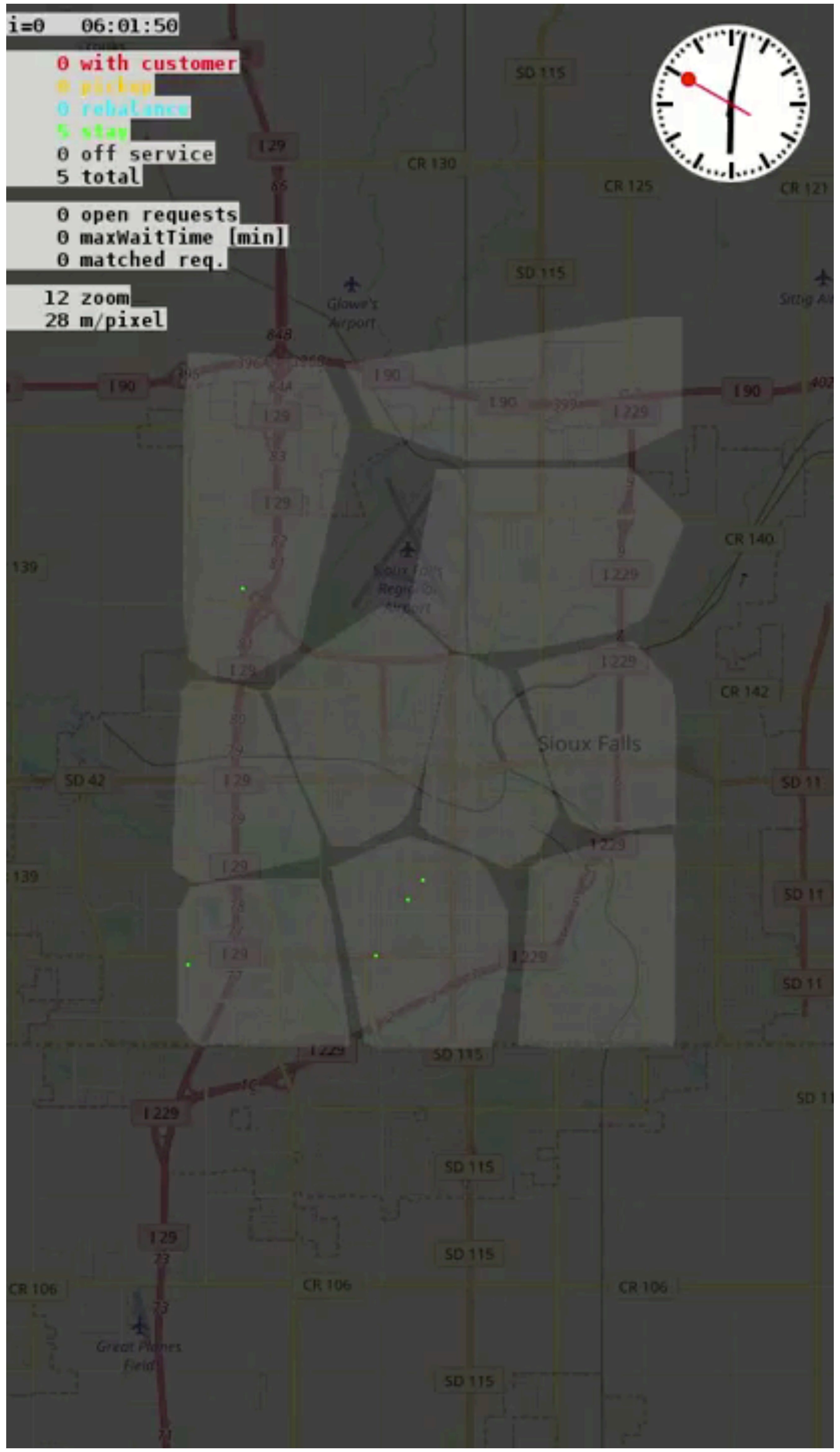
Requests Served
at End of Day



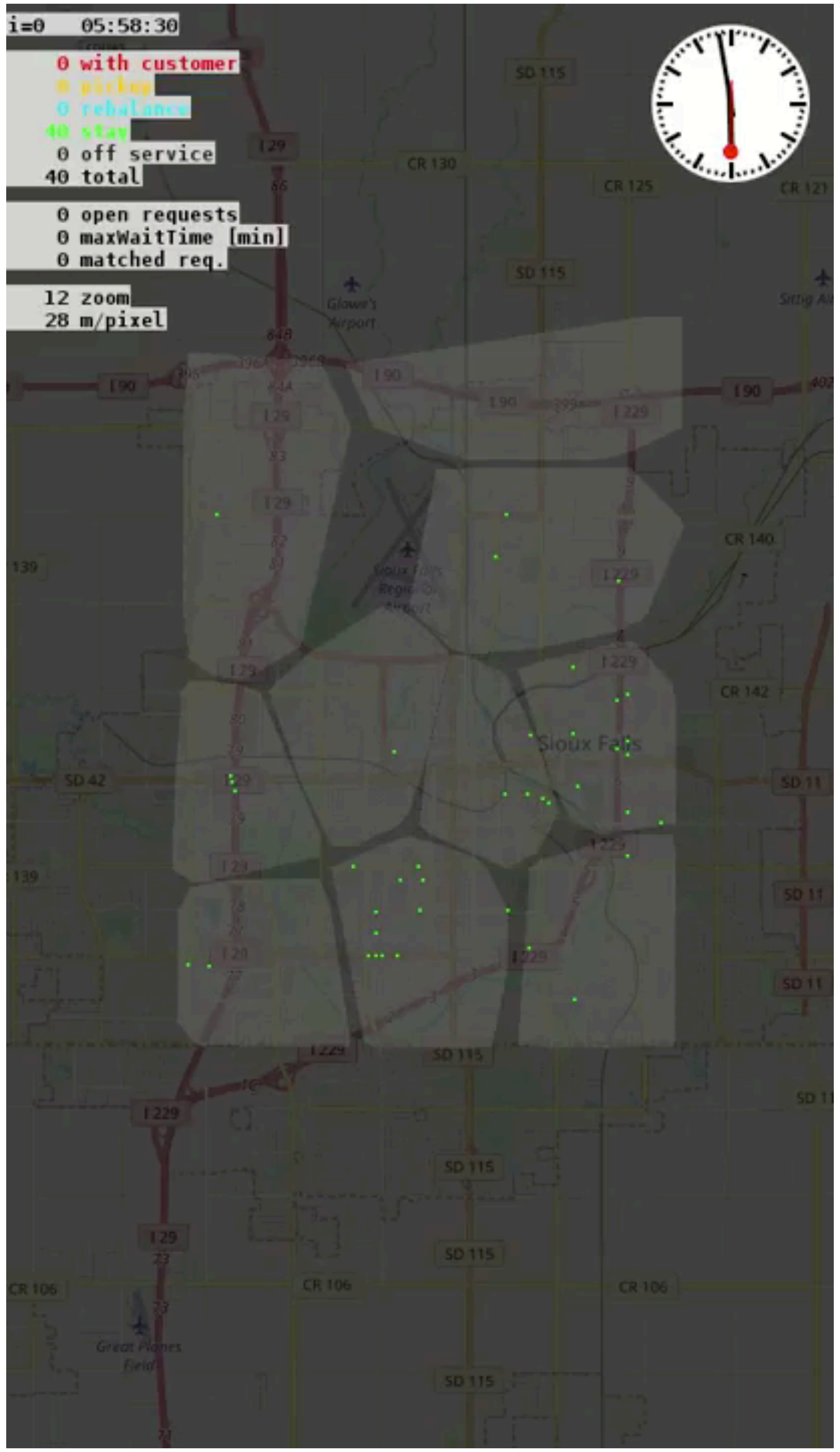
Total of **9247**
Requests
during Day

Theoretically computed
minimum fleet size **46**

Simulation: Minimum Fleet Sizing



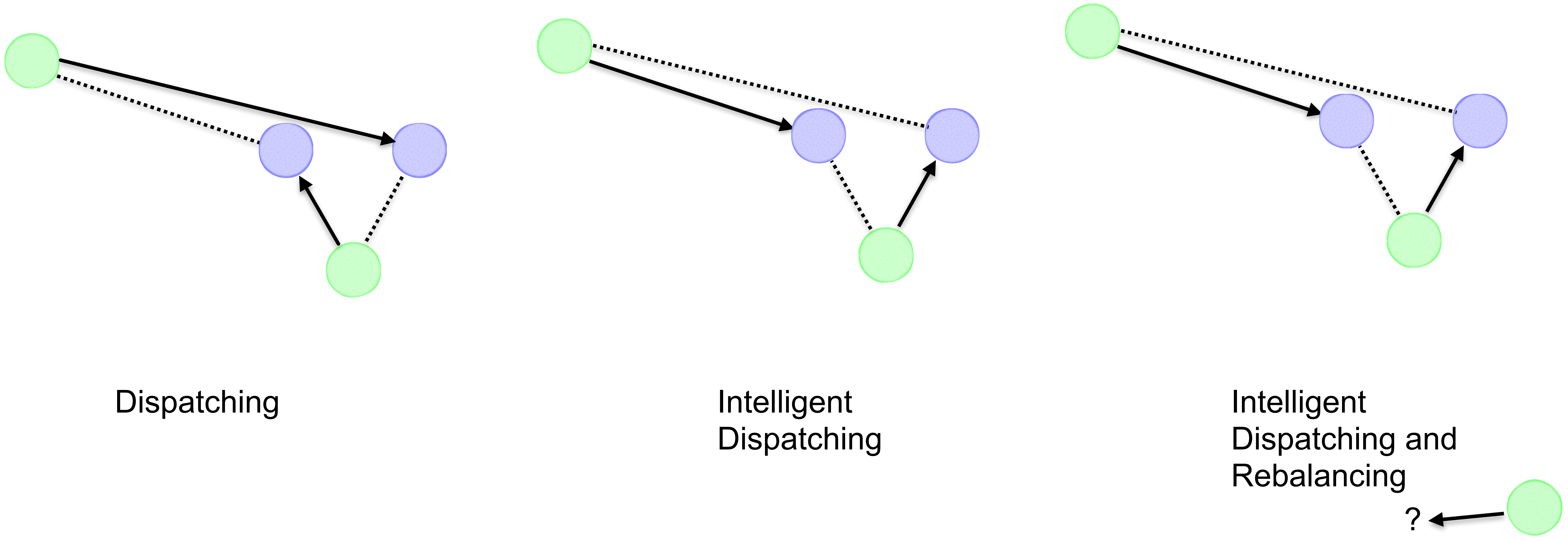
5 vehicles



40 vehicles

250 vehicles

Brief Introduction to the Autonomous Mobility-on-Demand Decision Space



Autonomous taxi

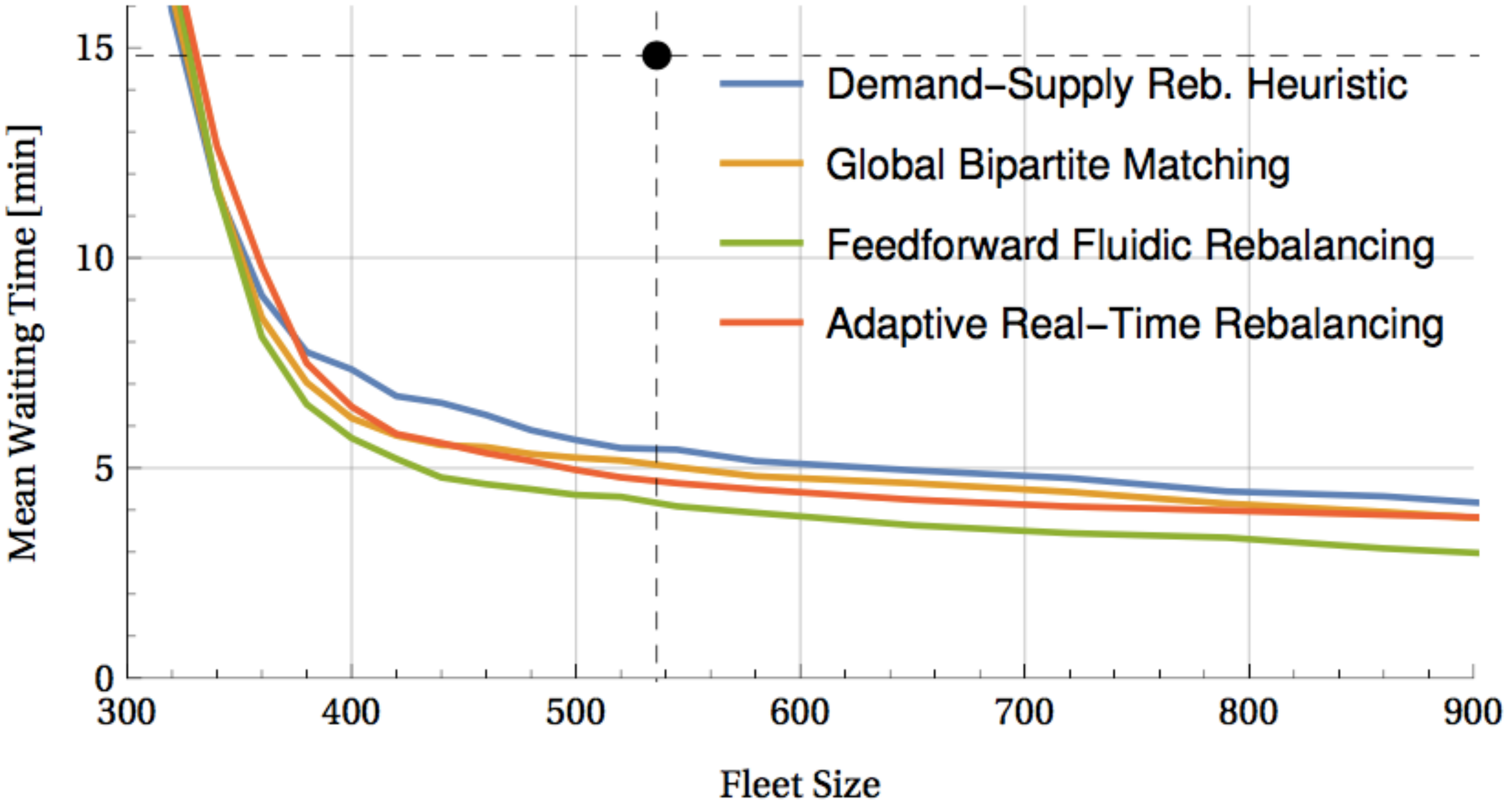
Waiting customer


i=0 08:02:30
124 with customer
120 pickup
0 rebalance
256 stay
0 off service
500 total
248 open requests
63 maxWaitTime [min]
2134 matched req.
too many streets
12 zoom
31 m/pixel

Preview: Performance Gains of Coordination

- Taxi Dataset:
  - 536 Taxis in San Francisco
  - May 17th to June 10th 2008
  - Totally 464,045 requests.

- **Waiting times** of coordinated fleet likely **smaller** than waiting times of taxi fleet.



● upper bound of waiting times in taxi dataset

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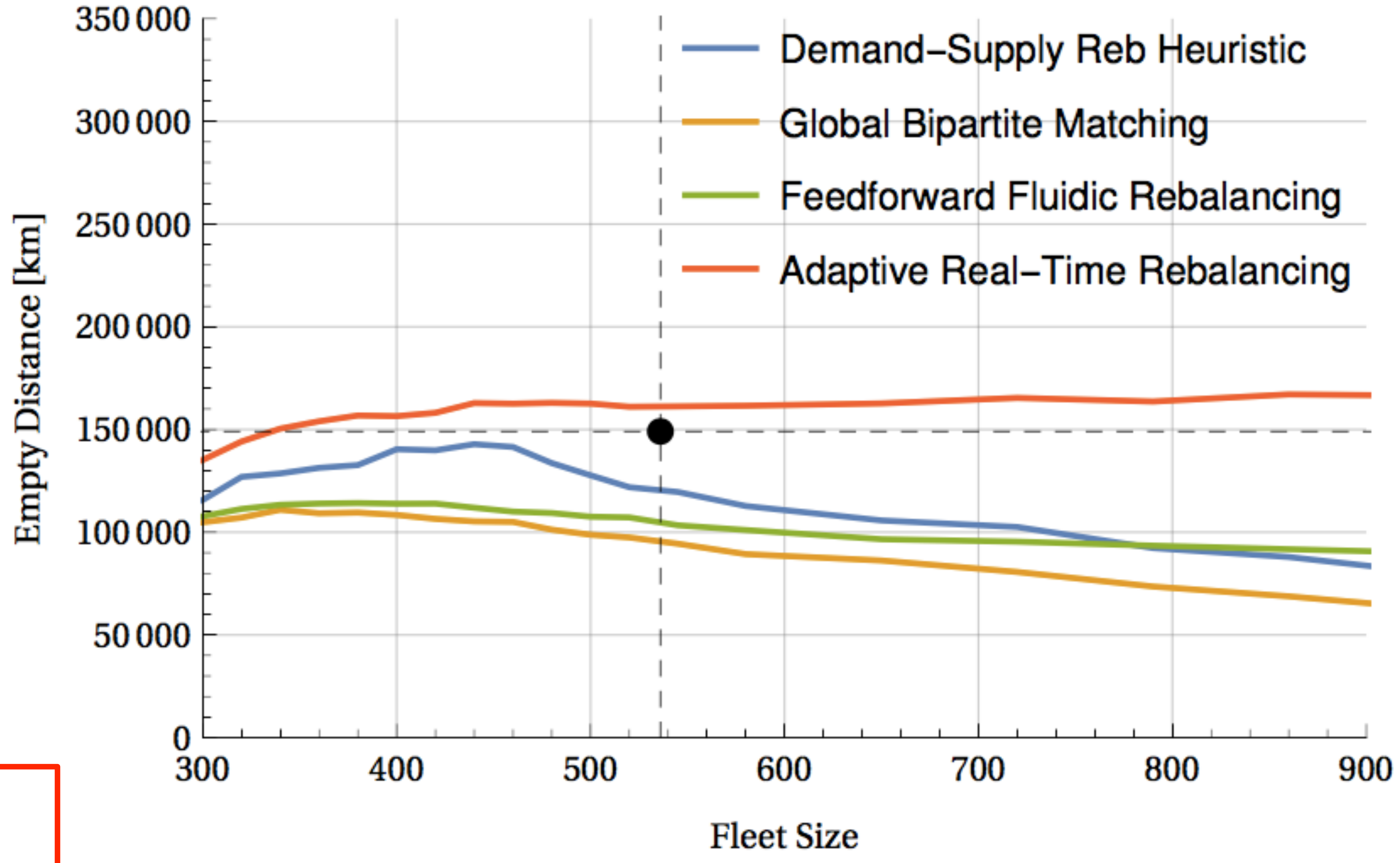
Preview: Efficiency Gains of Coordination

- Taxi Dataset:
  - 536 Taxis in San Francisco
  - Totally 464,045 requests.
  - May 17th to June 10th 2008

- **Empty distance** of coordinated fleet surely **smaller** than best case fleet distance of taxi fleet.

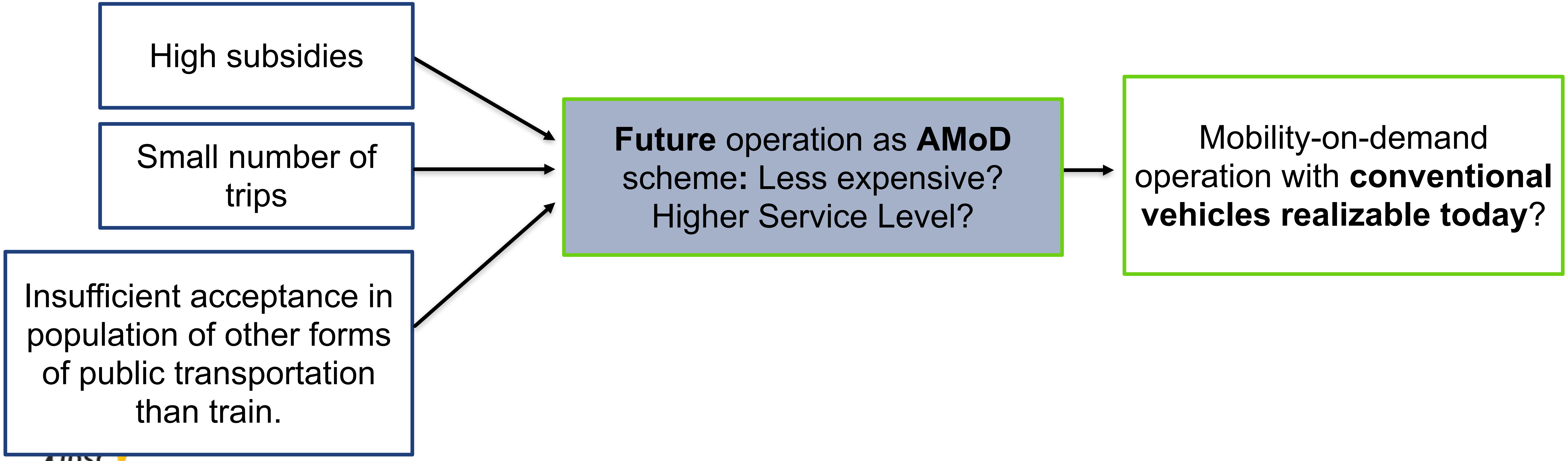


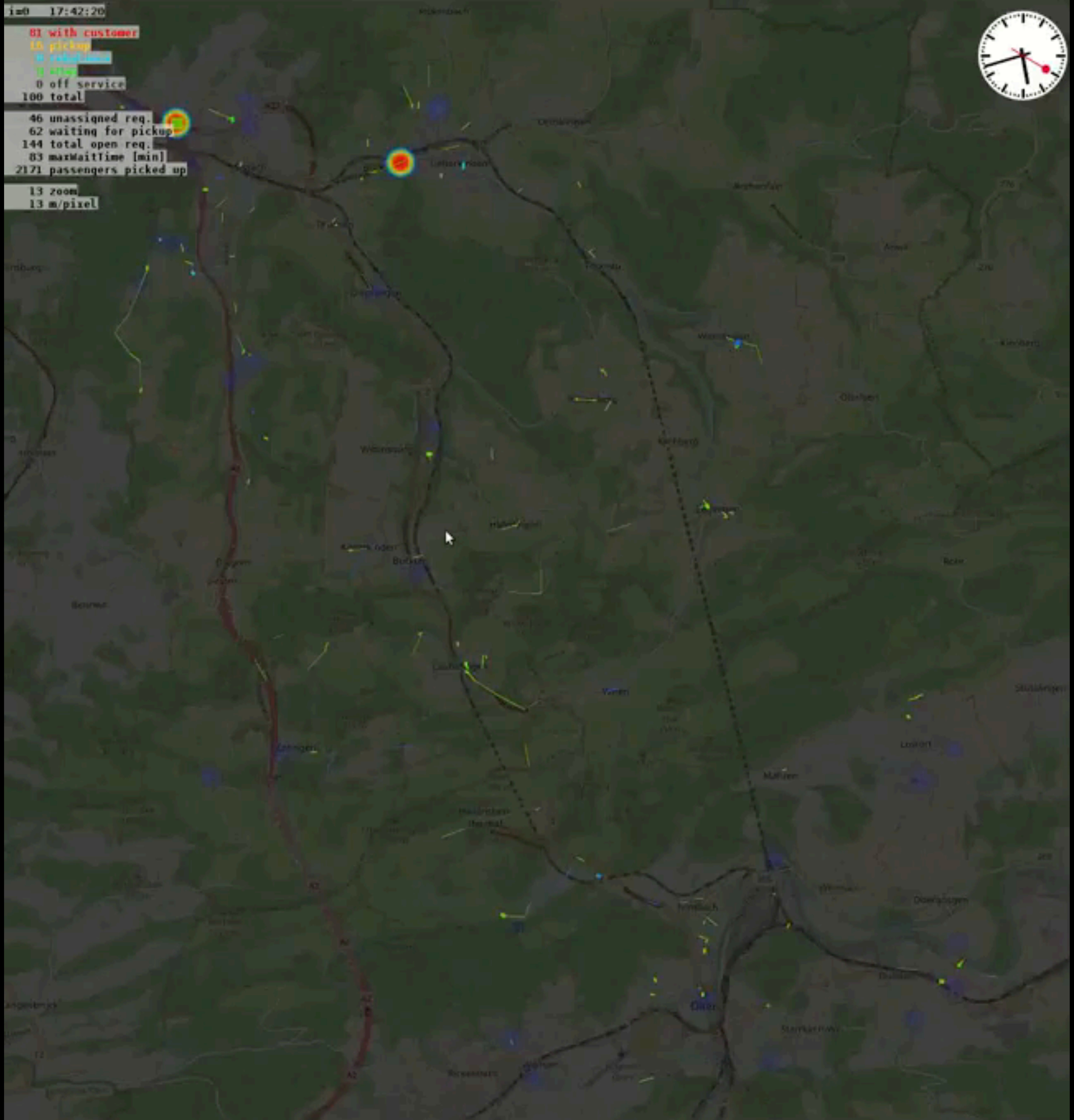
● lower bound on empty distance in taxi dataset

Coordinated control of fleets leading to **considerable gains in service level and efficiency** compared to exsting MoD schemes.

Preview: AMoD as a Form of Public Transportation in Cases of Low Utilization?

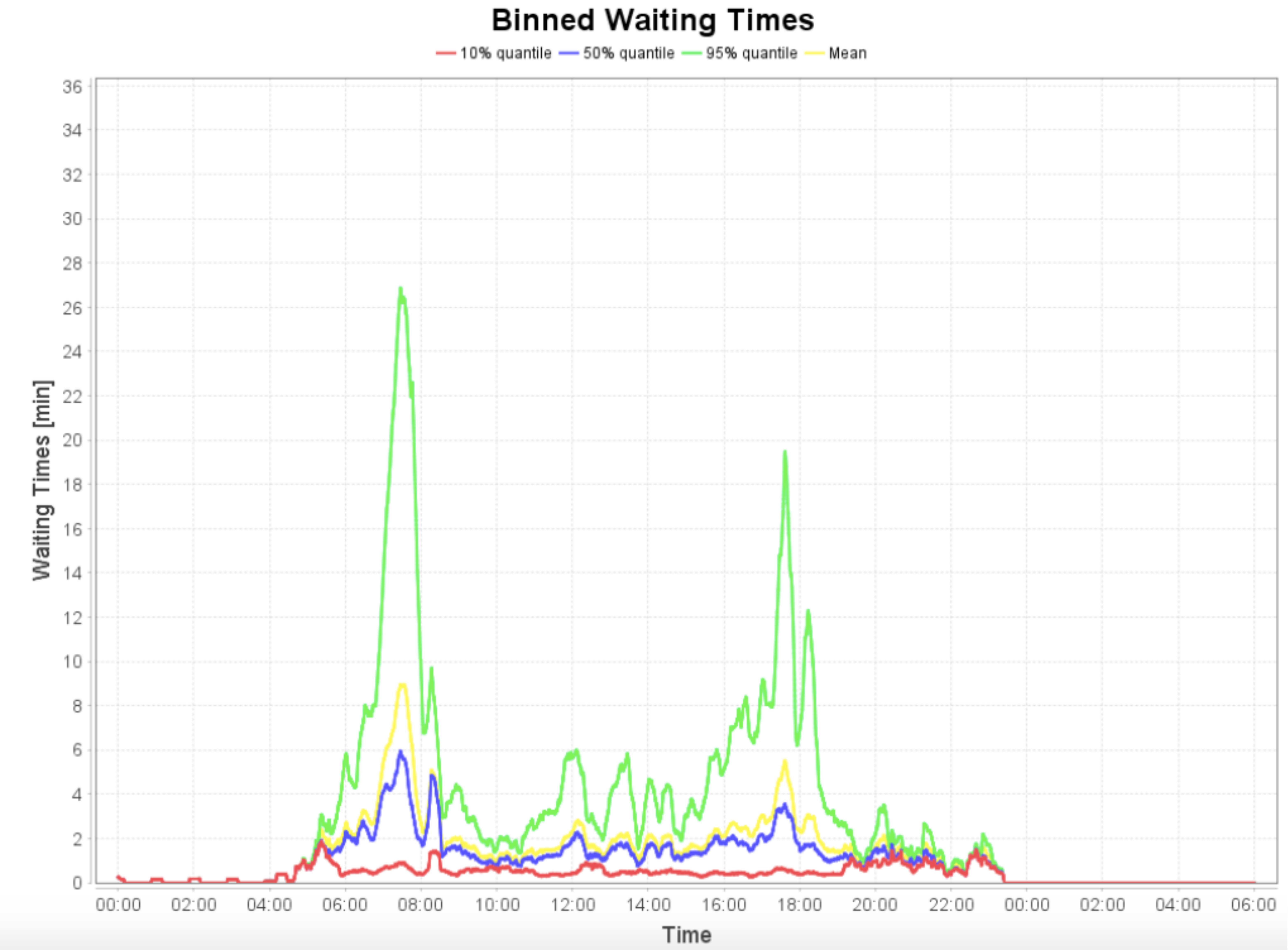
- Some train lines in Switzerland are financed less than 25% from ticket revenues..
- Train lines are not closed as population sees bus replacements as an inferior alternative.




i=0 17:42:20
81 with customer
0 off service
100 total
46 unassigned req.
62 waiting for pickup
144 total open req.
83 maxWaitTime [min]
2171 passengers picked up
13 zoom
13 m/pixel

Preliminary Results: Waiting Times at 40 Vehicles

- **Wait times**
  - 95% quantile
  - 50% quantile
  - 10% quantile
  - Mean



Preliminary unverified results (currently ongoing research)

Conclusions

1. The main benefit of **autonomous driving** in terms of economic value is that it allows sharing of cars and thus **enables one-way shared mobility on a large scale**.
2. The **technology** enabling autonomous driving **favours** its **application in a service scope**.
3. **Optimization** of AMoD fleet operations using **dispatching and rebalancing algorithms** results in significant improvements of operational efficiency and service level.

Thank you very much for your attention.