ETH zürich

The Future of Mobility - a Chance for Public Transportation

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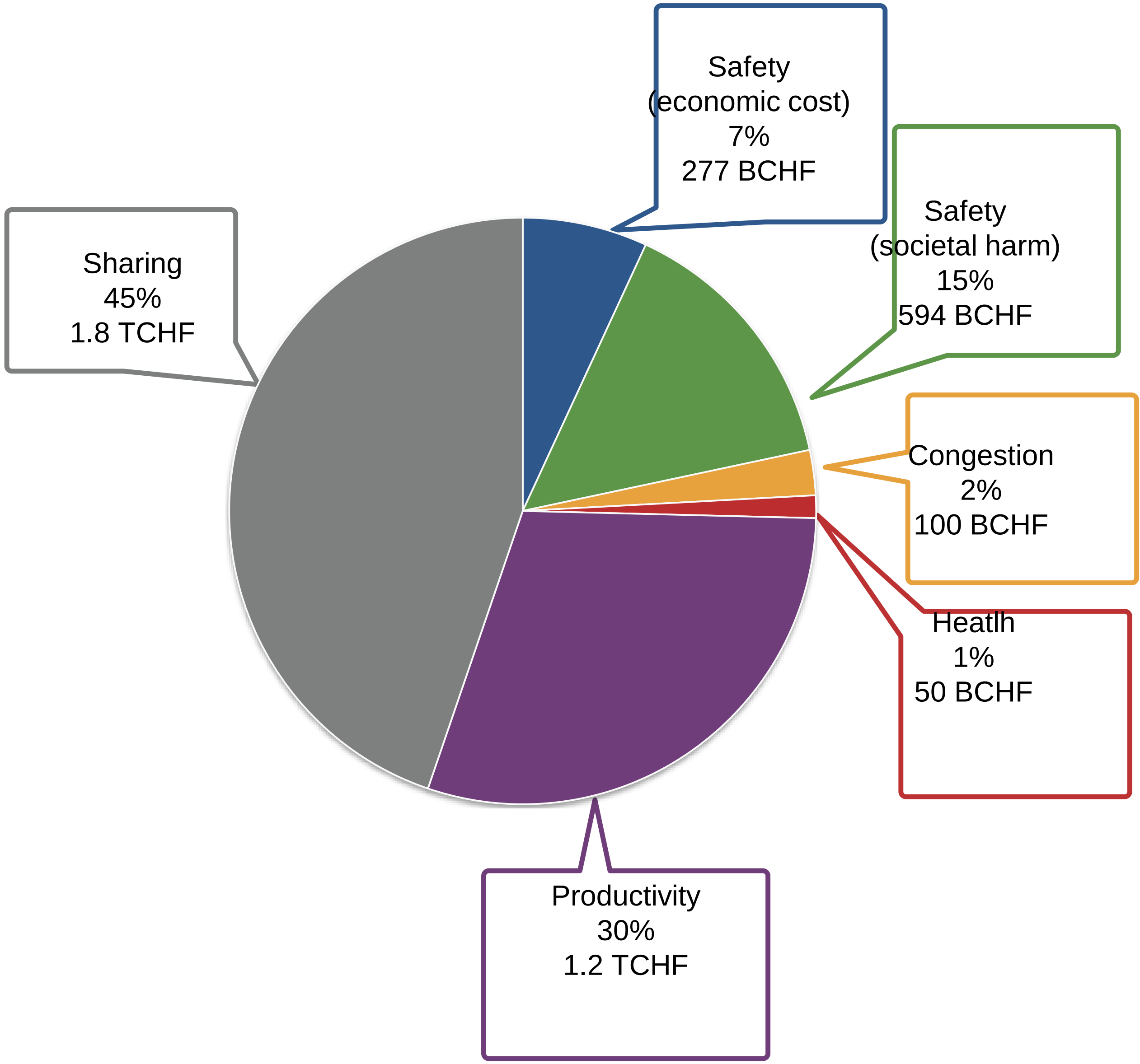
Why Self-driving Vehicles?

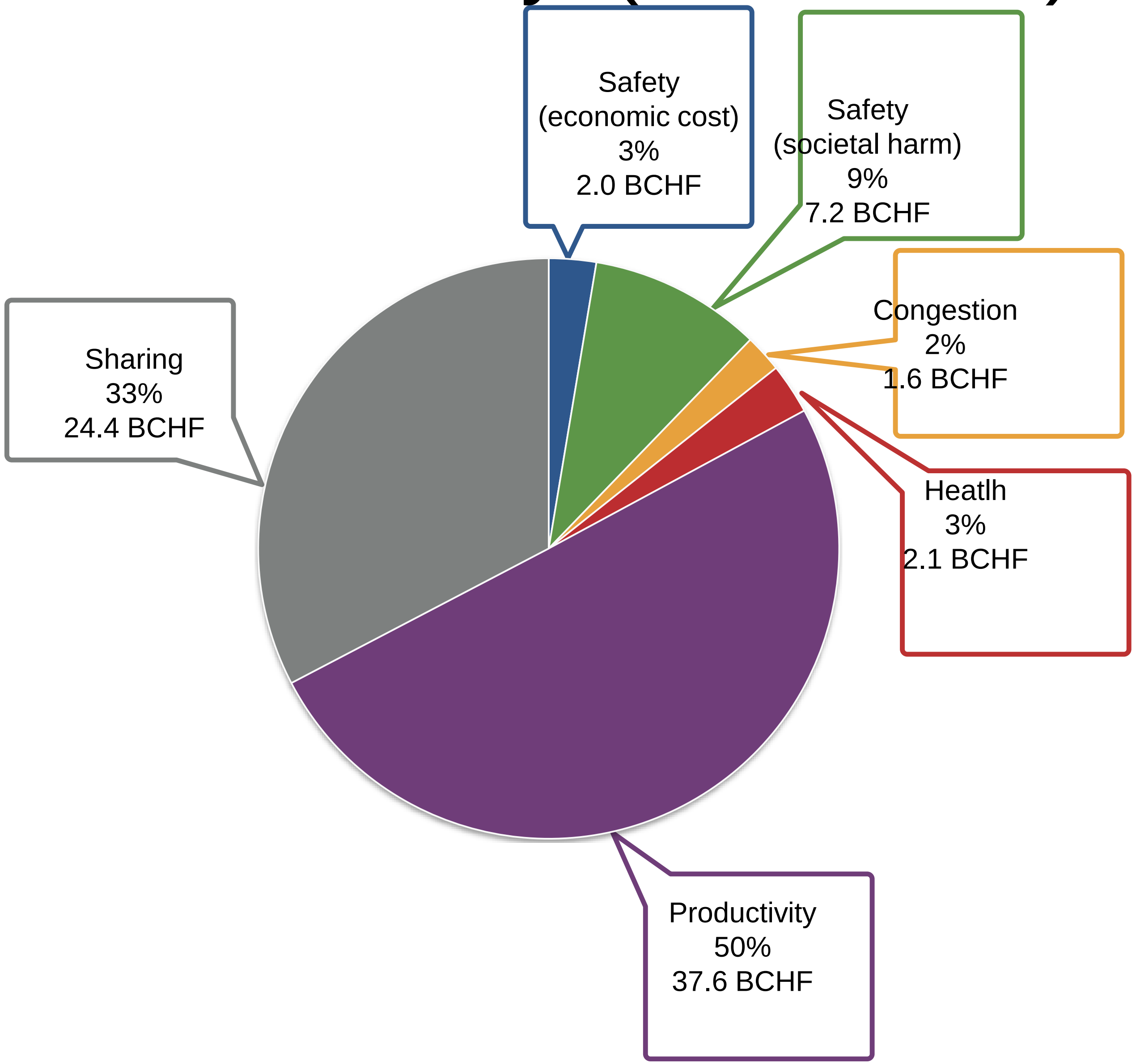
A financial perspective on personal mobility (US Market)

- Safety:
  - “Cost of a statistical life”: CHF 9.1M
  - 2014 NHTSA report:
    - Economic cost of road accidents: ~ CHF 277B/year.
    - Societal harm of road accidents: ~ CHF594B/year
- Cost of congestion:
  - Texas Transportation Institute, 2012: ~ CHF 100B/year
- Health costs of congestion:
  - Harvard School of Public Health, 2010: ~ CHF 50B/year
- Increased productivity/leisure:
  - Estimate CHF 1.2T/year
- Car sharing:
  - Assuming a “sharing factor” of 4, estimate CHF 1.8T/year of benefits to individuals.
  - Other studies [Burns et al., ’13, Fagnant, Kockelman ’14] suggest higher sharing factors, up to ~10.

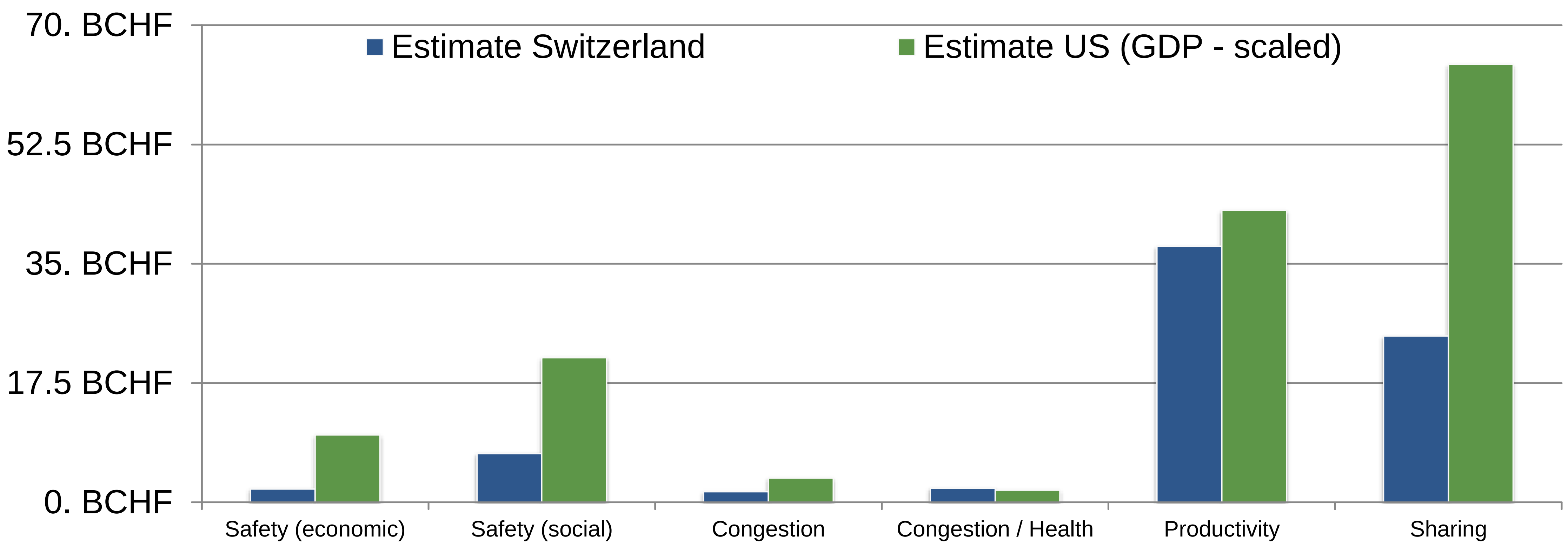


A financial perspective on personal mobility (CH Market)

- 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 7158M/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.



Financial Perspective: Differences



Fatalities per capita 4.6 times higher in the US (2016)

- Vehicles / Capita factor 1.41 higher in the US
- Higher mode share if individual motorized traffic in the US, .e.g., 57% in Chicago, 25%

“Autonomous Mobility on Demand (AMoD)” in Context

Conventional public transport

Transportation

Shared Mobility

Motorized individual traffic

One-way shared mobility schemes

Two-way shared mobility schemes

Shared bicycle schemes

One-way mobility-on-demand

Autonomous mobility-on-demand

Rebalancing expensive

Not enough drivers at low cost

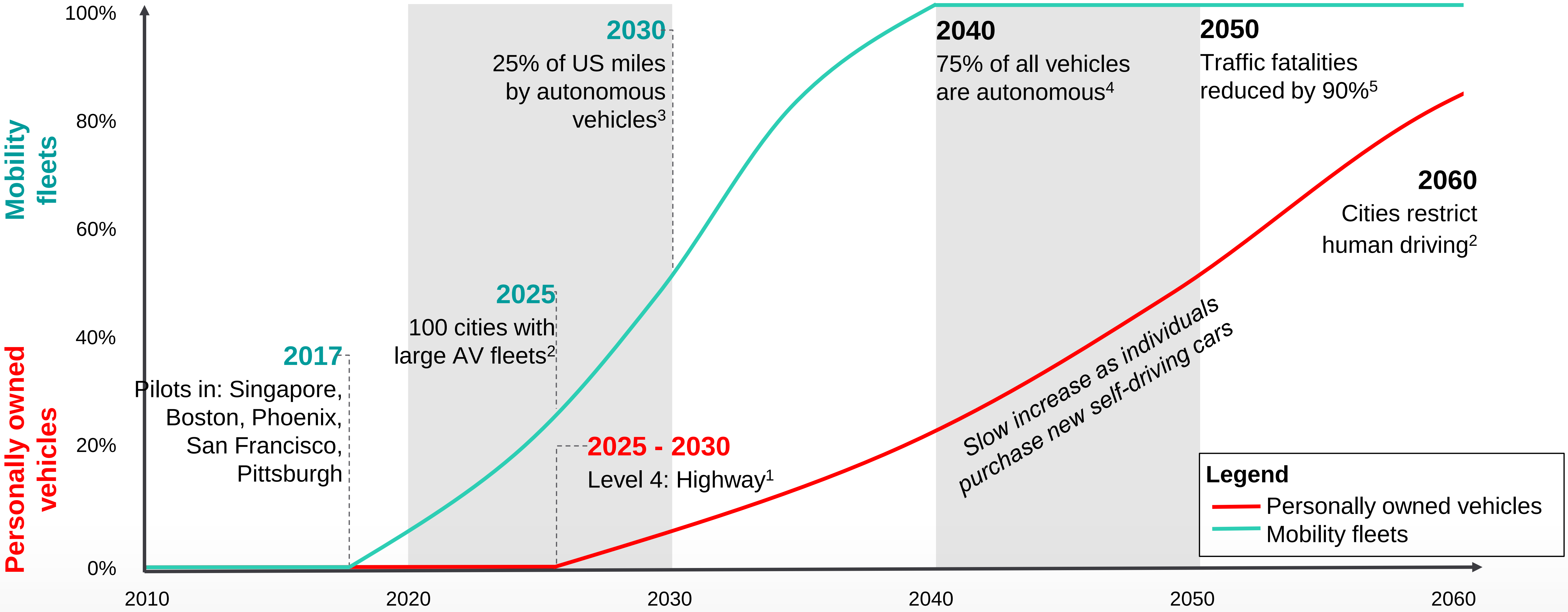
nuTonomy®

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. NPV 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.

WHEN WILL AUTONOMOUS VEHICLES ARRIVE?

Level 4/5 Autonomous Vehicle Penetration

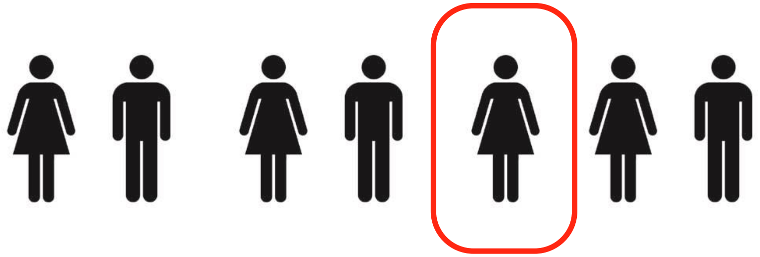


Sources: [1]Nissan, Toyota, Ford, BMW etc.; [2]nuTonomy estimates; [3]BCG; [4]IEEE; [5]McKinsey

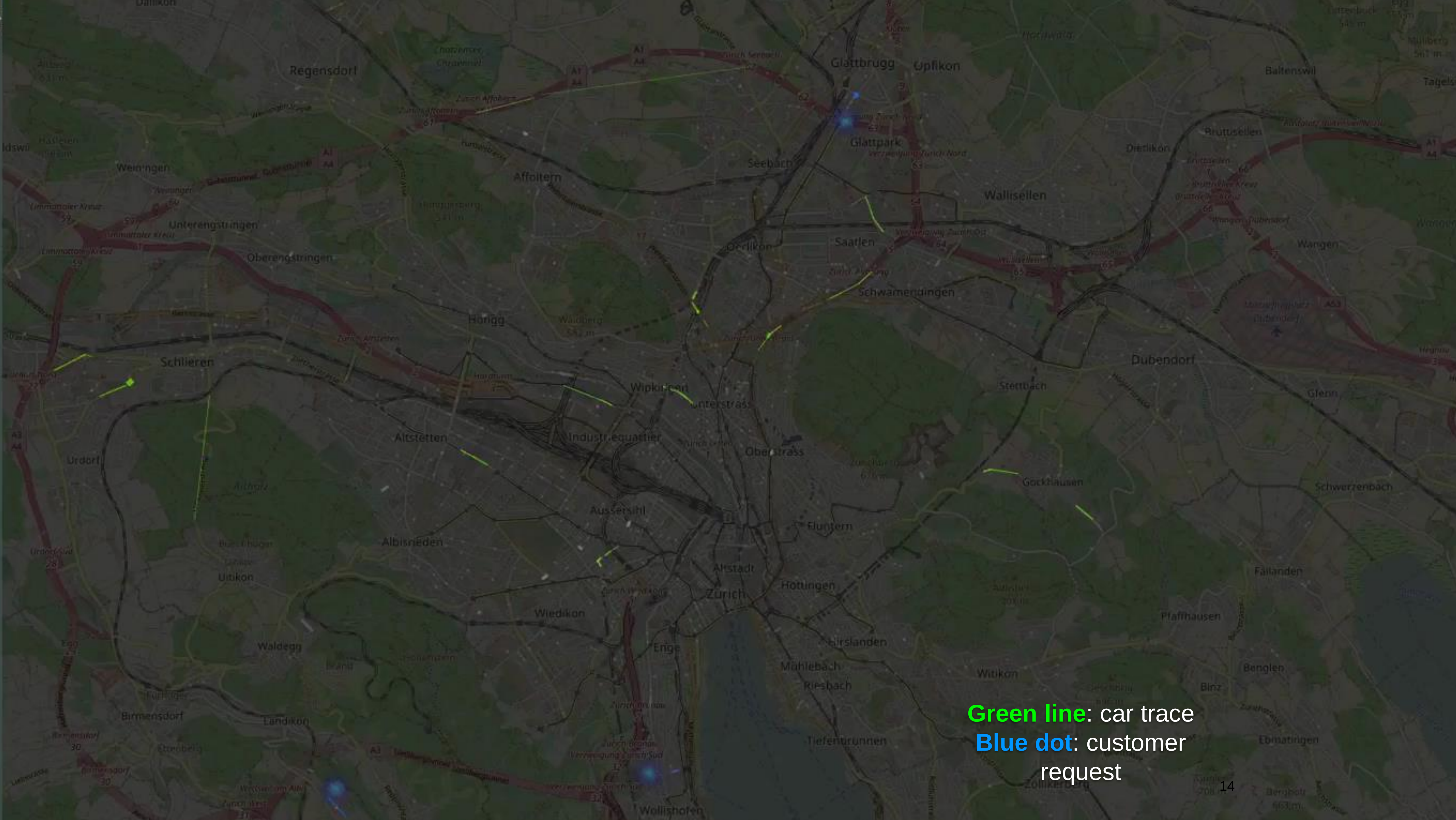
Labor Market

If Singapore would use only autonomous taxis

- [Spieser, Treleaven, Zhang, Frazzoli, Morton, Pavone]: transportation demand of Singapore could be met with a fleet of 300'000 Fahrzeugen vehicles.
- Considering a conservative estimate of 2.5 drivers per vehicle: 750'000 people out of a population of 5.399 Mio. people have to be drivers.
- One out of ~7 people would work as a driver.



Autonomous mobility does not destroy jobs but enables a novel form of transportation and the use of human resources for more productive tasks.


Regensdorf
Glattbrugg
Opfikon
Baltenswil
Glattpark
Seebach
Affoltern
Weiningen
Unterengstringen
Oberengstringen
Wallisellen
Dietlikon
Brüttisellen
Saatlen
Oerlikon
Schwamendingen
Wangen
Höngg
Schlieren
Dübendorf
Stettbach
Wipkingen
Unterstrass
Altstetten
Industriequartier
Oberstrass
Gockhausen
Schwerzenbach
Urdorf
Aussersihl
Fluntern
Albisrieden
Altstadt
Uitikon
Hottingen
Zürich
Fällanden
Wiedikon
Pfaffhausen
Waldegg
Enge
Hirslanden
Witikon
Mühlebach
Riesbach
Benglen
Birmensdorf
Landikon
Tiefenbrunnen
Ebmatingen
Wollishofen
Green line: car trace
Blue dot: customer request

IDSC - API: Theory Meets Reality

MATSim
Multi-Agent Transport Simulation

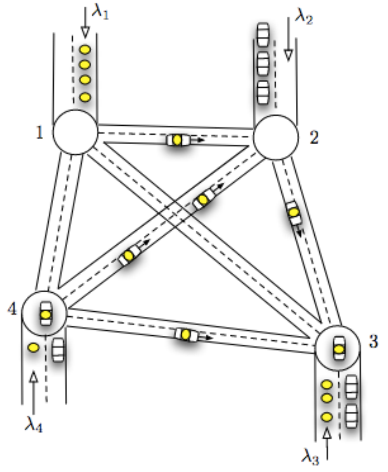
SIMMOBILITY

Simulation - Tools

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

- Hard to setup and calibrate.
- AMoD typically not integrated.
- No AMoD specific performance metrics, adaptable visualizers.

IDSC - 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 model reality accurately enough.
- Often results have not been tested on high-fidelity simulations.

IDSC

Case Study: Autonomous Mobility-on-Demand in Zürich

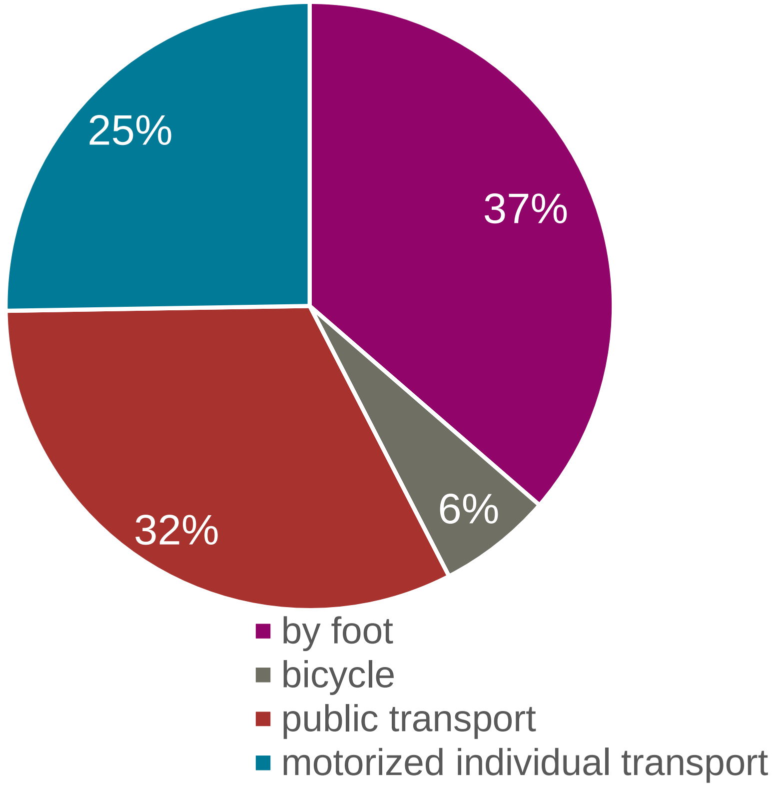
- City population: 372’857
- Metropolitan area: 1’830’000
- Fleet of 137’255 private vehicles in city alone [1].
- Travel behavior [1]:

Mean daily distance per capita	30.1 km
Mean number of daily trips per capita	3.4
Mean daily waytime capita	101 min

- Parking spaces in Zürich [1]:

Parking spaces in public streets	49’058
Parking spaces on private ground	210’300
Parking spaces in total	259’358
(of which parking spaces in car parks)	18’023

- Modal split of city population [1]:

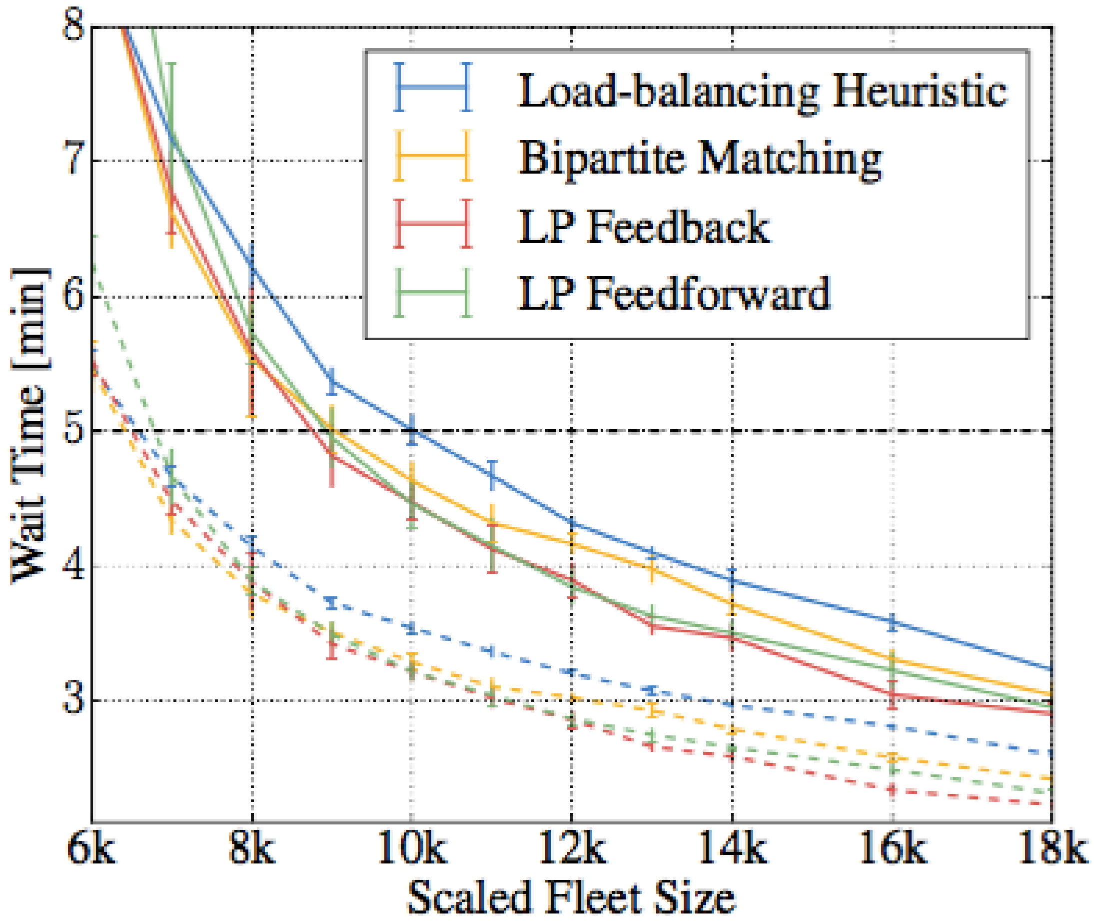


1: Stadt Zürich, Tiefbauamt, Städtevergleich, 2012

Case Study: Autonomous Mobility on Demand in Zürich

- Conclusions
  - Today: **2.71** inhabitants per car.
  - With AMoD: **9.7** inhabitants per car yields excellent service level.
  - The choice of the fleet control algorithm has large influence on the performance.

  - How will this new form of shared transportation compare in price?



Mean wait times at peak times (solid line) and for the entire day (dashed line).

Case Study: Autonomous Mobility on Demand in Zürich

- Current taxi price in Zurich:

  8 CHF base plus 5 CHF/km

- Full costs of a private vehicle (incl. value of time):

  ~**1.2 CHF/km**

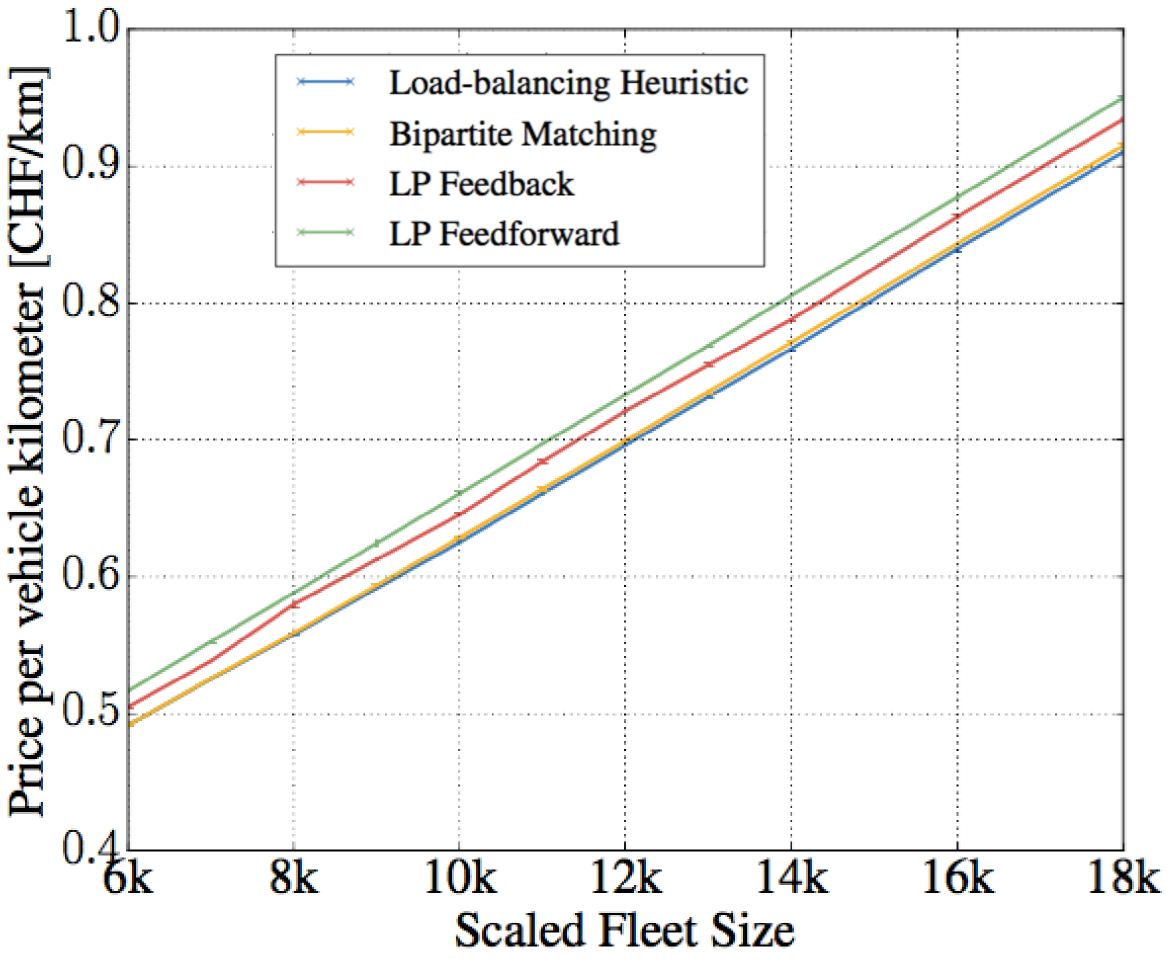
- Subsidized prices for mass transit:

  0.25

- Auto nd:

  ~ **0.**

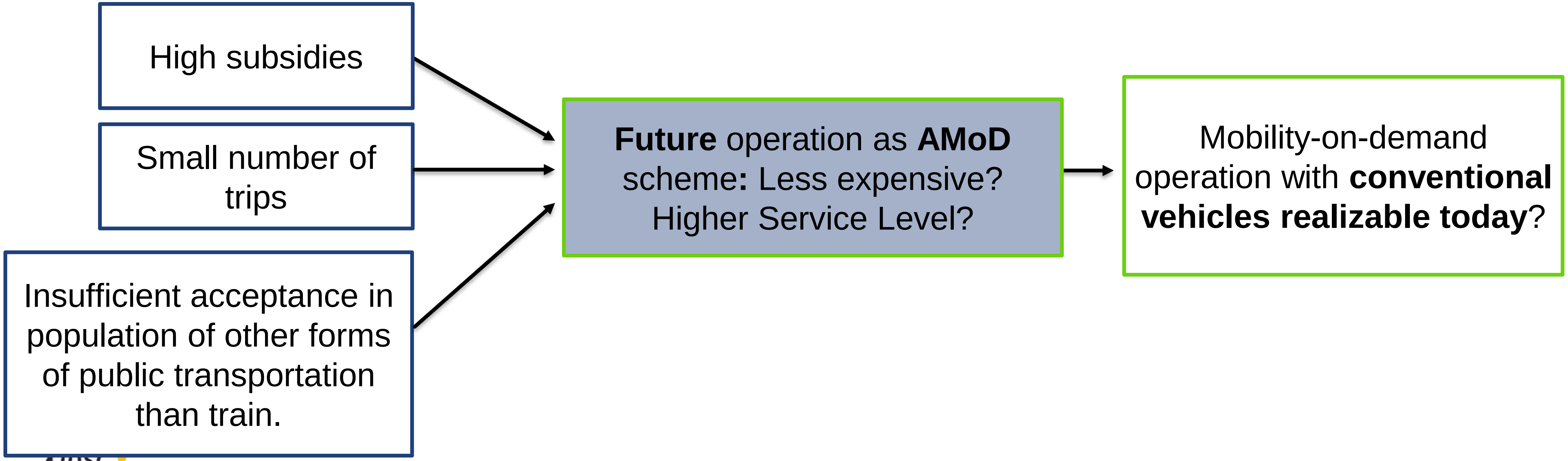
Convenience comparable to **private transporation, prices** similar to **conventional public tranportation.**
How would such a service change the transportation landscape?



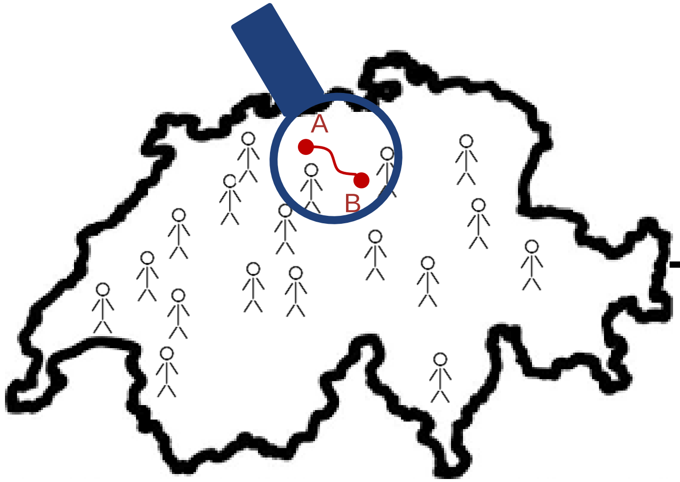
Minimal price per AMoD customer kilometre at 3% margin.

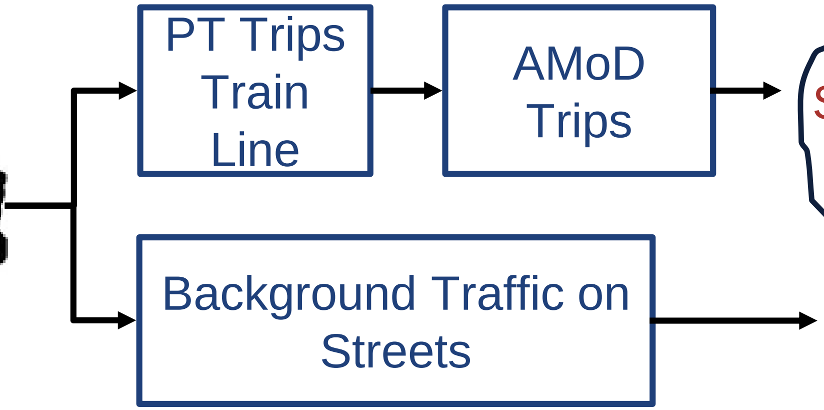
Ongoing Research: AMoD as a Form of Public Transportation in Cases of Low Utilization?

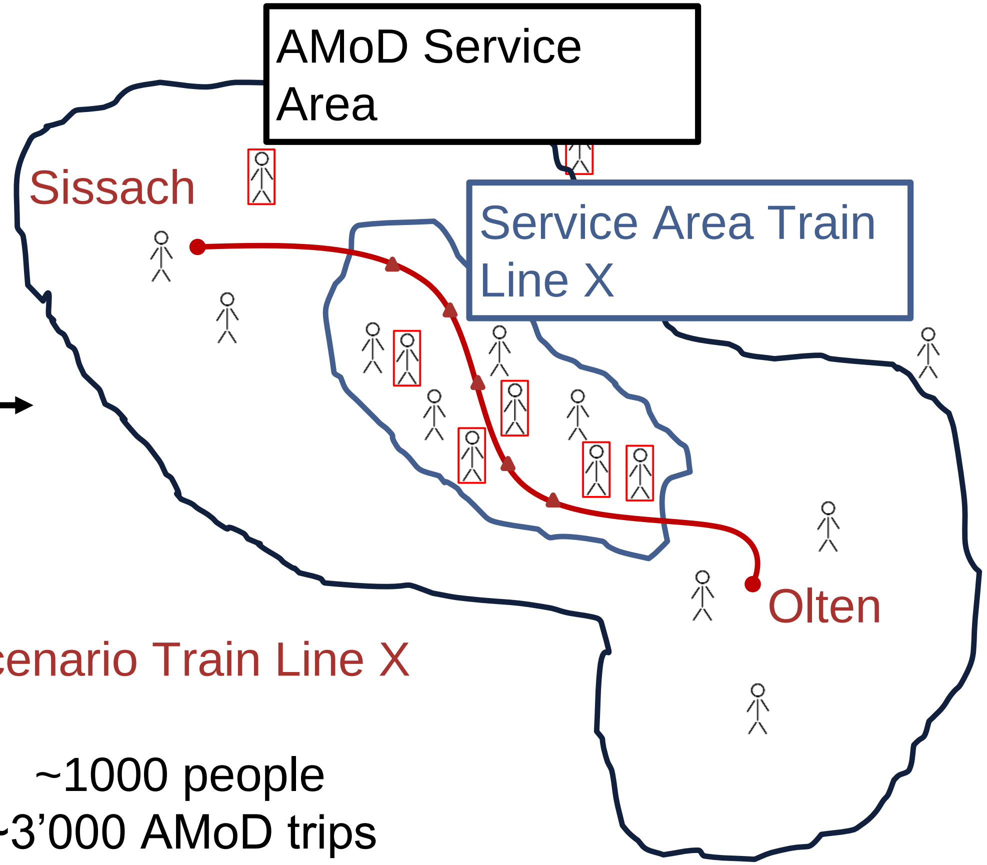
- Some train lines in Switzerland are financed less than 25% from ticket revenues..
- Train lines are not closed as population sees bus replacements as an inferior alternative.



Ongoing Research: Example «Läufelfingerli» S9 Olten-Sissach







Scenario Switzerland

~ 7 Mio people with daily plans

Institut für Verkehrsplanung
(basierend auf Mikrozensus
Mobilität 2010, BFS,
IVT ETH Zürich)

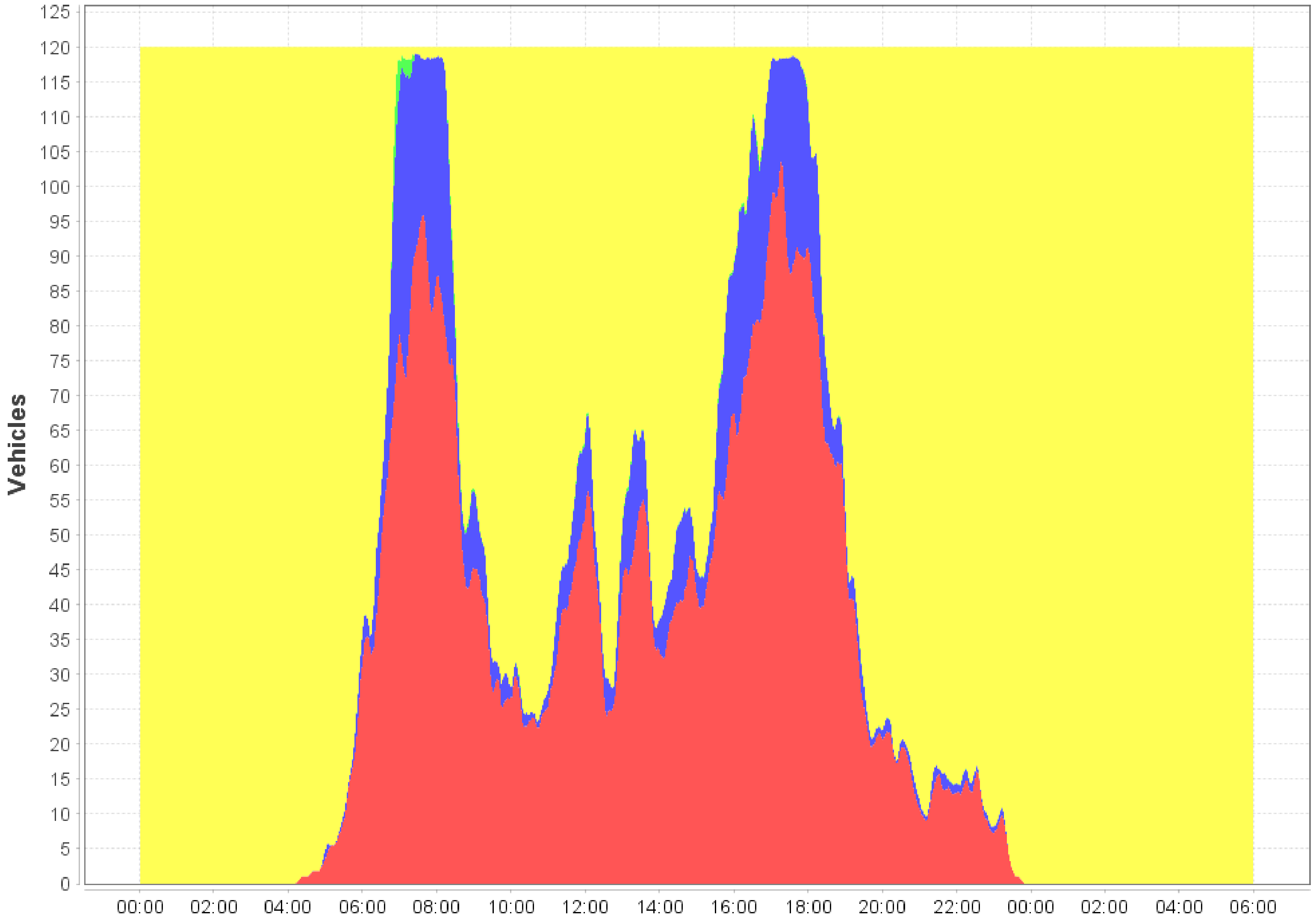
Scenario Train Line X

~1000 people
~3'000 AMoD trips
~ 50'000 car trips (background traffic)


17:42:20
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: Vehicle Status at 120 Vehicles

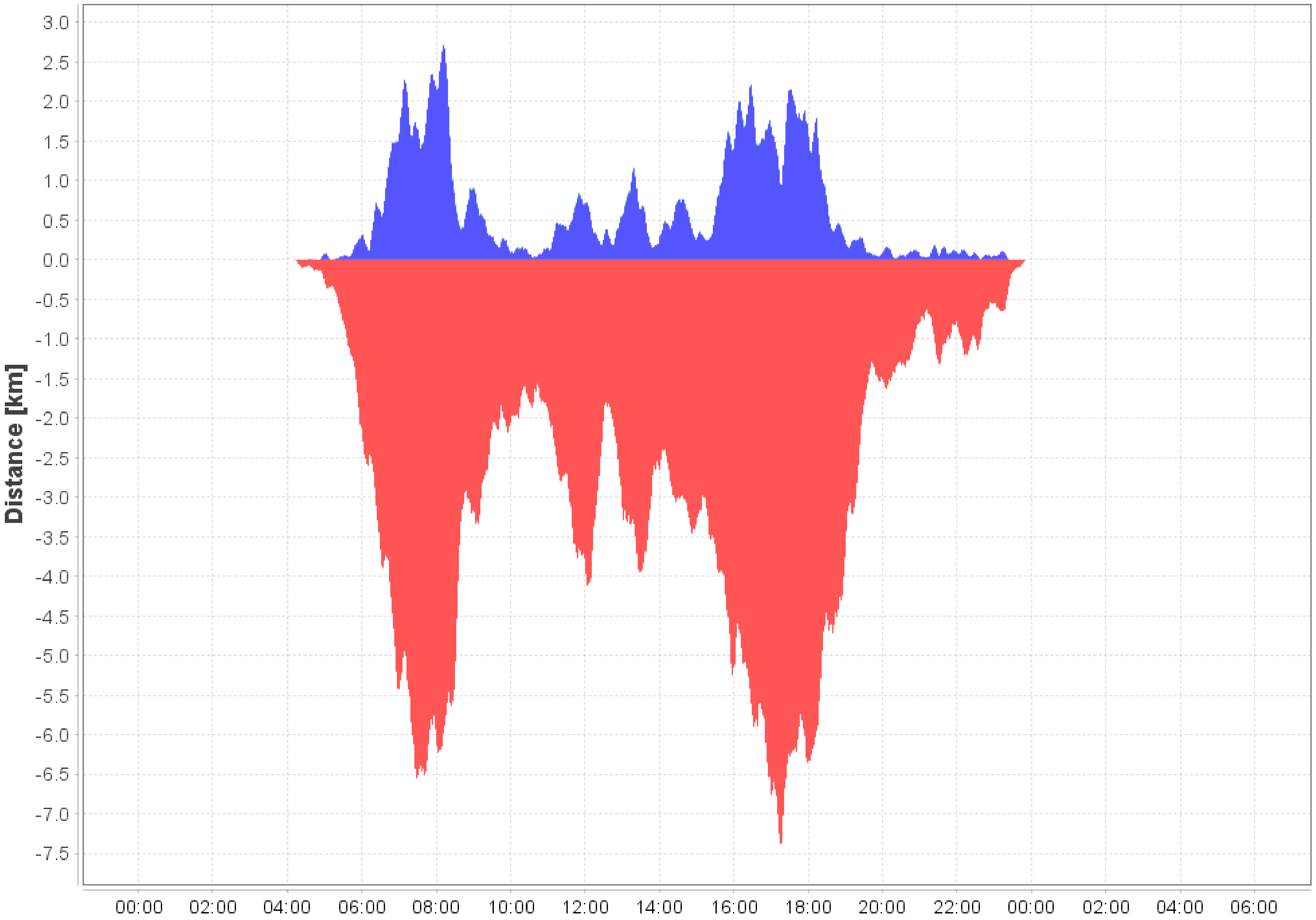
- **Vehicle Status**
  - Stay
  - Pickup of customer
  - Rebalancing
  - With customer
- **120** autonomous vehicles probably cover the demand very well..



Preliminary unverified results (currently ongoing research)

Preliminary Results: Fleet Distances for 120 Vehicles

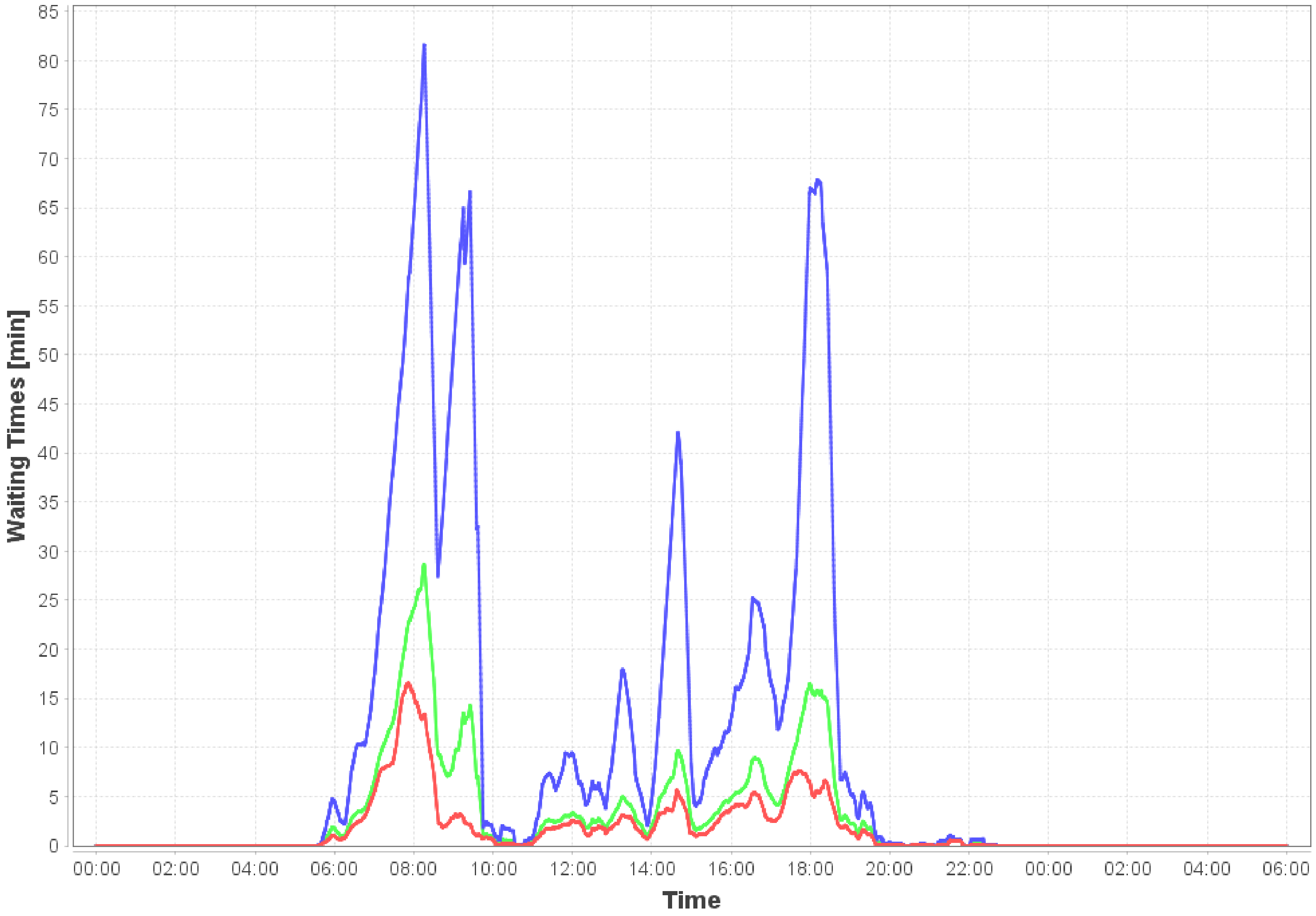
- **Fleet distances**
  - Pickup of customer
  - With customer
- **Unit-Capacity,** several customers per vehicle could further increase efficiency.



Preliminary unverified results (currently ongoing research)

Preliminary Results: Wait Times with 120 Vehicles

- **Wait times**
  - 95% quantile
  - 50% quantile
  - Mean
- Could **120** on-demand vehicles satisfy the demand at mean wait times < 15 min (peak) and 4-5 min during daytime?



Preliminary unverified results (currently ongoing research)

Conclusions

- Level-4 autonomous vehicles enable “one-way” mobility at a large scale.
- **Key tradeoff for mobility: throughput vs. delay as a function of space and time**
- Standard mass transit provides high throughput through high-capacity vehicles.
- AMoD can provide an additional operating point through higher availability and responsiveness, with lower-capacity vehicles.
  - First- and last-mile connections make mass transit more attractive;
  - Provide an attractive alternative to low-utilization routes.