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: ~ CHF 1'966M/year.
    - Societal harm of road accidents: ~ CHF 7'158M/year

- Cost of congestion:
  - BFE figures, ARE report 2010: ~ CHF 1'565M/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

Shared Mobility

Conventional public transport

One-way shared mobility schemes

One-way mobility-on-demand

Two-way shared mobility schemes

Autonomous mobility-on-demand

Shared bicycle schemes

Motorized individual traffic

Rebalancing expensive/impractical

Not enough drivers at low cost

Only Round Trips
The Technology Enabling Autonomous Vehicles
Velocity 0.00 [m/s⁻¹]
Turning Rate 0.00 [s⁻¹]
Velocity 0.00[m s^{-1}]
TurningRate 0.00[s^{-1}]

28.2 Hz 25.8 deg
(0.727 m/s^2, -1.917 m/s^2, -0.995 m/s^2)
[0.00(s^{-1}), 0.00(s^{-1}), 0.00(s^{-1})]
The new trend: deep learning vs. explicit coding

• Basic assumptions:
  • There are too many rules of the road, it is impossible to capture all of them in code
  • Instead, it is better to learn from experience

‘If’ statements kill.” They’re unreliable and imprecise in a real world full of vagaries and nuance. It’s better to teach the computer to be like a human, who constantly processes all kinds of visual clues and uses experience, to deal with the unexpected rather than teach it a hard-and-fast policy. [G. Hotz, bloomberg.com, 2015]
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.

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The Three Laws

A robot may not injure a human being or, through inaction, allow a human being to come to harm.

A robot must obey the orders given it by human beings, except where such orders would conflict with the First Law.

A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

— Asimov
# Product vs. Service

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

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.

What **size** should I choose my **fleet** for a given geographical area?
Theory: Minimum Fleet Sizing

- Customer origins distributed according to \( \varphi_O \)
- Customer destinations distributed according to \( \varphi_D \)
- Customers arriving at a rate \( \lambda \)
- Shortest tour connecting a set of requests: **Stacker Crane Tour** composed of and of \( O \rightarrow D \) and \( D \rightarrow O \) pieces.
- The average rate of additional distance that needs to be covered is: \( \lambda \cdot (\bar{d}_{O \rightarrow D} + \bar{d}_{D \rightarrow O}) \)
- 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:

\[
N \cdot \bar{v} \geq \lambda \cdot (\bar{d}_{O \rightarrow D} + \bar{d}_{D \rightarrow O})
\]

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 $\lambda$, $\bar{U}$ and the distribution of request origins $\varphi_O$ and the distribution of request destinations $\varphi_D$ we can very easily compute the number of needed vehicles:

$$N > \frac{\lambda}{\bar{U}} \cdot (\mathbb{E}_{\varphi_O, \varphi_D} ||X - Y|| + EMD(\varphi_O, \varphi_D))$$
Simulation: Minimum Fleet Sizing

Requests Served at End of Day

Theoretically computed minimum fleet size 46

Total of 9247 Requests during Day
Simulation: Minimum Fleet Sizing

5 vehicles

40 vehicles

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

- Dispatching
- Intelligent Dispatching
- Intelligent Dispatching and Rebalancing

Autonomous taxi

Waiting customer
124 with customer
120 pickup
9 dispatch
248 start
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.
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.

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

- High subsidies
- Small number of trips
- Insufficient acceptance in population of other forms of public transportation than train.

**Future operation as AMoD scheme:** Less expensive? Higher Service Level?

Mobility-on-demand operation with **conventional vehicles realizable today?**
Vorläufige Daten ohne Verifizierung (aktuell in Bearbeitung)
Preliminary Results: Waiting Times at 40 Vehicles

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

![Binned Waiting Times](chart.png)

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.