Autonomous car- and ridesharing systems

Simulation-based analysis of potential impacts on the mobility market

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Benjamin Kickhöfer
Agenda

1. Motivation

2. Methodology

3. Results
   a. Autonomous Car Sharing
   b. Sensitivity analysis (ETHZ cost calculator)
   c. Comparison of Autonomous Car and Ride Sharing

4. Conclusion and outlook
Motivation
Motivation

• Introduction of autonomous vehicles within next years/decades
  - Privately owned vehicles
  - Autonomous Carsharing Systems (ACS)
  - Autonomous Ridesharing Systems (ARS)

• Different interests of different stakeholders

• Uncertainty in the acceptance by users

• This study: sketch planning with a grid-search approach to get estimates of potential impacts on the mobility market
  - Operator profit
  - System costs
  - Modal split, total mileage
Methodology
Travel demand generation for Germany in 2035

- Based on German NHTS data (MiD 2008)
  - 60k persons
  - 190k reported trips
  - 35k vehicles

- Trip generation: socio-demographic projection to 2035
  - # individuals per area type (urban, suburban, rural)
  - # individuals per age group and gender
  - # driver licenses (cohort effect)

- Diffusion of AVs into the private fleet (rates depend on vehicle class)
  - Mobilisation of new user groups (impaired, no drivers license, teenagers)
  - Reduction of VTTS in AVs (−25%)
  - Reduction of access and egress times

For details, see Trommer et al. (2016)
Destination and mode choice

• Generation of attributes for non-chosen modes

• Gravity model for **distance class** choice

• Multinomial logit model for **mode** choice

• No network loading → distance based, mode-specific travel times

• Result: **reference scenario with private AVs**
  • Up to 20% AVs in the fleet by 2035
  • Up to 10% increase in VKT
  • Modal shift mainly from PT

For details, see Trommer et al. (2016)
New modes: Autonomous Car- or Ridesharing

<table>
<thead>
<tr>
<th>Feature</th>
<th>ACS</th>
<th>ARS</th>
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</thead>
<tbody>
<tr>
<td>Shared Vehicles</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Shared Rides</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Detours possible</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Empty rides possible</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Splitting of ride costs</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>
New modes: calculation of waiting times (in absence of a network)

\[ d_{nv} \approx \alpha \cdot \beta \cdot \sqrt{APV \cdot VUR} \]

\( d_{nv} \) Average access distance to the next empty vehicle

\( APV \) … Average serving area per vehicle \([km^2]\)

\( VUR \) … Vehicle usage rate: \( \frac{T_{user} + T_{empty}}{24 \, h} \)

\( \alpha, \beta \) … Scale factors

Based on Burns et al. (2013)
Results:

Autonomous Car Sharing (ACS)
Grid search

![Grid search diagram]

- Fleet density [AVs/1000 Inh.]
- User price [EUR/km]
- Vehicle usage rate $VUR$
- Demand $D^*$

++ (positive correlation)
-- (negative correlation)
ACS: operator profit landscape

- Zero Profit (ZP): 0.33 €/user-km; 4.50 veh/1000 inh
- Unregulated Monopoly (UM): 1.00 €/user-km; 1.55 veh/1000 inh
- System Optimum (SO): 0.23 €/user-km; 6.50 veh/1000 inh
ACS: system costs
(sum of operator profit and generalized user costs)

- Zero Profit (ZP): 0.33 €/user-km ; 4.50 veh/1000 inh
- Unregulated Monopoly (UM): 1.00 €/user-km ; 1.55 veh/1000 inh
- System Optimum (SO): 0.23 €/user-km ; 6.50 veh/1000 inh
Results:
Sensitivity analysis
(ETHZ cost calculator)
Sensitivity analysis for ACS: cost structure

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>DLR (Trommer et al. 2016)</th>
<th>ETHZ (based on Bösch et al. 2017)*</th>
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<tbody>
<tr>
<td>Depreciation, Capital Cost [€/veh-km]</td>
<td>0.12</td>
<td>0.092</td>
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<tr>
<td>Overhead, Vehicle Operations etc. [€/veh-km]</td>
<td>0.035</td>
<td>0.12</td>
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<tr>
<td>Cleaning, Maintenance, Insurance, Vehicle Tax, Parking [€/veh-km]</td>
<td>0.05</td>
<td>0.155</td>
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<tr>
<td>Fuel/Electricity [€/veh-km]</td>
<td>0.075</td>
<td>0.066</td>
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<tr>
<td>Profit Margin &amp; VAT [€/veh-km]</td>
<td>0.00</td>
<td>0.044</td>
</tr>
<tr>
<td><strong>Total Cost [€/veh-km]</strong></td>
<td><strong>0.28</strong></td>
<td><strong>0.48</strong></td>
</tr>
</tbody>
</table>

* 1 EUR = 1.07 CHF
Sensitivity analysis for ACS: cost structure (DLR)

- Zero Profit (ZP): 0.33 €/user-km; 4.50 veh/1000 inh
- Unregulated Monopoly (UM): 1.00 €/user-km; 1.55 veh/1000 inh
- System Optimum (SO): 0.23 €/user-km; 6.50 veh/1000 inh
- Rural areas break-even at ~0.40 €/km
Sensitivity analysis for ACS: cost structure (ETHZ)

- Zero Profit (ZP): 0.64 €/user-km; 2.25 veh/1000 inh
- Unregulated Monopoly (UM): 2.00 €/user-km; 1.00 veh/1000 inh
- System Optimum (SO): 0.32 €/user-km; 4.60 veh/1000 inh
- Rural areas break-even at ~1.50 €/km
Sensitivity analysis for ACS: cost structure

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>ZP: DLR cost</td>
<td>0.33</td>
<td>4.50</td>
<td>~0</td>
<td>10.6 %</td>
<td>+ 3.7 %</td>
<td>-402.9</td>
</tr>
<tr>
<td>ZP: ETHZ cost</td>
<td>0.64</td>
<td>2.25</td>
<td>~0</td>
<td>7.3 %</td>
<td>+ 2.0 %</td>
<td>-432.8</td>
</tr>
<tr>
<td>UM: DLR cost</td>
<td>1.00</td>
<td>1.55</td>
<td>13.0</td>
<td>5.4 %</td>
<td>+ 1.5 %</td>
<td>-434.3</td>
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<tr>
<td>UM: ETHZ cost</td>
<td>2.00</td>
<td>1.00</td>
<td>6.8</td>
<td>3.4 %</td>
<td>+ 0.9 %</td>
<td>-457.6</td>
</tr>
<tr>
<td>SO: DLR cost</td>
<td>0.23</td>
<td>6.50</td>
<td>-14.1</td>
<td>12.7 %</td>
<td>+ 5.5 %</td>
<td>-397.6</td>
</tr>
<tr>
<td>SO: ETHZ cost</td>
<td>0.32</td>
<td>4.60</td>
<td>-22.3</td>
<td>10.8 %</td>
<td>+ 3.9 %</td>
<td>-424.8</td>
</tr>
</tbody>
</table>

- Zero profit: **most likely case** in competitive situation
- System optimum: **subsidies needed** > likely to change if external effects are considered (see change in VKT!)
- Unregulated monopoly: **regulation needed** to avoid over-pricing
Results:
Comparison of ACS and ARS
Comparison of ACS and ARS

- **ARS:**
  - Simplistic pooling strategy based on demand (per 1x1km raster, 10 min time bins and rough direction).
  - Less attractive than ACS (vehicle waits for 10 min for other passengers).
  - However, splitting costs is possible and makes it cheaper than ACS.

- **So far:**
  - User price and fleet density fixed for all area types (urban, suburban, rural).
  - That is, urban areas subsidize rural areas.

- **Now:**
  - User price and fleet density varies for every area type.
  - Still: one operator can materialize economies of scale.
Zero profit supply parameters for different area types

- ARS can reach price levels comparable to PT in urban areas
- Spatial differences of prices are higher for ARS than for ACS
- Reason: high potential of pooling in urban areas yielding very low user prices
## Zero Profit (ZP) vs Unregulated Monopoly (UM)

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</thead>
<tbody>
<tr>
<td>ZP: ACS</td>
<td>0.30 – 0.35</td>
<td>3.0 – 5.0</td>
<td>~0</td>
<td>8.2 – 12.5 %</td>
<td>+3.0 to +5.7 %</td>
</tr>
<tr>
<td>ZP: ARS</td>
<td>0.12 – 0.38</td>
<td>2.5 – 3.5</td>
<td>~0</td>
<td>4.4 – 11.1%</td>
<td>-1.5 to +2.7 %</td>
</tr>
<tr>
<td>UM: ACS</td>
<td>0.95 – 1.05</td>
<td>1.4 - 1.6</td>
<td>13.2</td>
<td>4.2 – 6.2 %</td>
<td>+1.2 to +1.6 %</td>
</tr>
<tr>
<td>UM: ARS</td>
<td>0.45 – 0.80</td>
<td>1.3 – 1.5</td>
<td>6.2</td>
<td>2.5 – 6.0%</td>
<td>+1.1 to +1.8 %</td>
</tr>
</tbody>
</table>

- **UM**: High prices lower pooling probabilities > higher VKT
- **ZP**: Lower prices increase pooling probabilities in urban areas > lower VKT
- Regulatory measures needed!
Conclusion and outlook
Conclusion and outlook

- Sketch planning tool allows to get first estimates of country-wide/area type impacts on the mobility market through ACS/ARS

- Results are highly dependent on utility functions, vehicle operations, and operator cost structure > good test: under which circumstances exists a business case?

- Results hint towards regulatory measures (for the monopoly case) or even subsidies of ACS, ARS (for the system optimal case); however, externalities need to be considered/modelled

- Only ARS is able to reduce VKT in urban areas; all other schemes increase VKT

- Future research:
  - Use behavioral parameters by Steck et al. (2017 forthcoming)
  - Differentiation by time
  - Consideration of externalities
  - Implications on car ownership?
Thank you.
References


Backup methodology
Aspatial travel demand model
Distance based, mode-specific travel speed
Utility functions for ACS, ARS

<table>
<thead>
<tr>
<th>Constant</th>
<th>Price</th>
<th>Travel time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set in relation to car and PT mode</td>
<td>$p_{\text{user}} = p_{\text{user.km.area}} \times k_{\text{m-user}}$</td>
<td>$TT_{\text{ACS}} = \min\left(T_{\text{access}}, WT_{\text{ACS}}\left(distance \ to \ the \ next \ empty \ vehicle\right)\right) + DT_{\text{ACS}}(distance) + T_{\text{egress}}$</td>
</tr>
</tbody>
</table>

$TT_{\text{ARS}} = \min\left(T_{\text{access}}, WT_{\text{ARS}}\left(distance \ to \ the \ next \ empty \ vehicle, \ occupancy \ rate, maximum \ headway\right)\right) + DT_{\text{ACS}}(distance, detour \ factor) + T_{\text{egress}}$

$distance \ to \ the \ next \ empty \ vehicle_{\text{ACS/ARS}} = f(vehicles/inhabitants, area \ type, vehicle \ usage \ rate)$

$detour \ factor_{\text{ARS}} = f(occupancy \ rate, modal \ split_{\text{ARS}})$
Pooling strategy ARS

Iterative process:
Input: \(vehicles/inhabitants, p_{user.km.area}\)

ARS

- Occupancy-rate
- "Headways"
- Detour factors

Waiting Times, empty Vkm

Vehicle usage rate

ACS/ARS-demand
Operator cost structure

\[ C_{\text{operator}} = C_{\text{fix,operator}}(\text{fleet size}) + C_{\text{var,operator}}(\text{KM}_{\text{empty}}, \text{KM}_{\text{loaded}}) \]

\[ R_{\text{operator}} = \sum_{\text{area type}} (p_{\text{user,km,area type}} \times \text{KM}_{\text{user,area type}}) \]
Operator revenue and costs

- Operator revenue as product of user price per km and sum of vehicle-km in use
  \[ R_{\text{operator}} = p_{\text{user.km}} \times k_{\text{muser}} \]

  With:
  - \( p_{\text{user.km}} \) ... price per user km [€/km]
  - \( k_{\text{muser}} \) ... vehicle-km (loaded) [km]

- Operator costs as sum of fixed operator costs per vehicle and product of variable operator costs per km and sum of vehicle-km (empty and loaded)
  \[ C_{\text{operator}} = p_{\text{fix.operator.veh}} \times v_{\text{eh}} + p_{\text{var.operator.km}} \times (k_{\text{mempty}} + k_{\text{muser}}) \]

  With:
  - \( p_{\text{fix.operator.veh}} \) ... fix operator costs per vehicle [€/vehicle per year]
  - \( p_{\text{var.operator.km}} \) ... variable operator costs per vehicle-km [€/km]
  - \( v_{\text{eh}} \) ... number of vehicles
  - \( k_{\text{mempty}} \) ... vehicle-km (empty) [km]
Operator profit and social costs

• Operator profit as difference between operator revenues and operator costs
  \[ \Pi_{\text{operator}} = R_{\text{operator}} - C_{\text{operator}} \]
  
  With:  
  \( \pi_{\text{operator}} \) … Operator profit [€]
  \( R_{\text{operator}} \) … Operator revenue [€]
  \( C_{\text{operator}} \) … Operator costs [€]

• Social costs as difference between operator profit and generalized user costs
  \[ SC = \Pi_{\text{operator}} - GC_{\text{user}} \]
  
  With:  
  \( SC \) … Social costs (omitting external costs) [€]
  \( GC_{\text{user}} \) … Generalized user costs [€]
## Area type classification

<table>
<thead>
<tr>
<th>BIK</th>
<th>BIK-category</th>
<th>Population size of the associated central location</th>
<th>Core region</th>
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<td>X</td>
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<td>Suburban</td>
<td>50 - 100 k</td>
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<td>Suburban</td>
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<td>8</td>
<td>Urban</td>
<td>100 - 500 k</td>
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<tr>
<td>9</td>
<td>Suburban</td>
<td>&gt;= 500 k</td>
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<tr>
<td>10</td>
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### Estimated parameter values

<table>
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<tr>
<th>trip purpose</th>
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<th>mode</th>
<th>intercept</th>
<th>beta_gc</th>
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</tbody>
</table>
Backup results
Methodology: Assumptions on the setting of fleet-density/user-price-combinations

- Different fleet densities at a given user price for the assumptions of a zero-profit-case, a max-profit-case and a social-optimum-case
Methodology: Assumptions on the setting of fleet-density/user-price-combinations

\[ \Pi_{\text{operator,ZP}} \rightarrow \text{fd}^*(p) \]
\[ \Pi_{\text{operator,PM}} \rightarrow \text{fd}^*(p) \]
\[ \Pi_{\text{operator,WO}} \rightarrow \text{fd}^*(p) \]

\[ W = \text{max} \rightarrow \text{fd}^*(p) \]

- Operator profit in the social-optimum-case is less or equal to that one in the max-profit-case for all user prices
- Bigger differences when fleet density decreases (at a higher user price level)
Methodology: Assumptions on the setting of fleet-density/user-price-combinations

- Social welfare in the social-optimum-case is greater than or equal to that one in the max-profit-case for all user prices
- Bigger differences when fleet density decreases (at a higher user price level)
Methodology: Operator profit, generalized user costs and social welfare

\[ \Pi_{\text{operator}} \]

\[ WF \]

\[ GC_{\text{user}} \]

User price [EUR/km] (logarithmic)