SAMoD: Shared Autonomous Mobility-on-Demand using Decentralized Reinforcement Learning

Maxime Guériaud and Ivana Dusparic

Enable - CONNECT Research Centre
School of Computer Science and Statistics,
Trinity College Dublin
maxime.gueriau@scss.tcd.ie, ivana.dusparic@scss.tcd.ie

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Context and objectives

MoD with SAVs
Challenges
Approaches

SAMoD

Agents
System

Simulation

Requests
Scenarios
Demonstration

Results

Evaluation
Rebalancing and Ride-Sharing
Demand patterns

Conclusions

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## Context and objectives

### Mobility-on-Demand with Shared Autonomous Vehicles

<table>
<thead>
<tr>
<th></th>
<th>Taxi</th>
<th>Car-Sharing</th>
<th>SAV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pick-up</strong></td>
<td>Anywhere covered</td>
<td>Stations or where available</td>
<td>Anywhere possible</td>
</tr>
<tr>
<td><strong>Drop-off</strong></td>
<td>Anywhere covered</td>
<td>Same station or where authorized</td>
<td>Anywhere possible</td>
</tr>
<tr>
<td><strong>Parking</strong></td>
<td>Station or private parking</td>
<td>Stations or on-street</td>
<td>Dynamic and adaptive</td>
</tr>
</tbody>
</table>

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Context and objectives

✓ Advantages and ★ challenges for Mobility-on-Demand with SAV

✓ fully flexible fleet size
✓ robots (almost) never need to take a break
✓ can be summoned everywhere
✓ can be very efficient if ride sharing enabled [5, 6]
★ can save parking space?
★ can improve traffic in cities?
★ dynamic adaptation to demand (and/or anticipation [3])
★ limit empty mileage [7]?
★ optimize SAV-rider assignment (especially when ride sharing)
## Context and objectives

### Approaches

<table>
<thead>
<tr>
<th></th>
<th>Centralized</th>
<th>Decentralized</th>
<th>Learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Several SAV companies</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Dynamic fleet size</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Optimized assignment</td>
<td>✓ limited scalability</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Dynamic ride-sharing</td>
<td>✓ requires full knowledge [5]</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Used data</td>
<td>Full network knowledge [3, 5]</td>
<td>Local knowledge</td>
<td>Local knowledge</td>
</tr>
</tbody>
</table>
SAMoD agents

Perception:
- Requests and vehicles in current zone
- Built historical data per zone

Decision making:
- Reinforcement learning (Q-learning [11])
- Reward: to have passengers

Actions:
- Pick-up (inc. ride sharing)
- Rebalance to zone
- Do nothing
SAMoD system architecture

**SAMoD environment**
- Map of the area & zones
- Vehicles update (joining/leaving)

**Real-time requests**

<table>
<thead>
<tr>
<th>id</th>
<th>GPS cords.</th>
<th># of passengers</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>8784</td>
<td>-73.97942352; 40.74461365</td>
<td>1</td>
</tr>
<tr>
<td>8785</td>
<td>-73.98999023; 40.75730515</td>
<td>4</td>
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<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

**Raise events**
- Check for new requests in current zone:
  - At zone border crossed
  - At last passenger drop-off
  - At finished rebalancing
- At pick-up:
  - Calculate route to destination
  - Re-calculate route (if ride-sharing)

**SAMoD agents**
- Initialization of the learning process
  - RL States $S$
  - RL Actions $A$
  - Relocation zones

**RL Reward $R$**
- Built historical data per zone

**RL process**
- Decision making $S_{t+1}$, $R_{t+1}$, $A_{t+1}$

**Action**
- With passenger(s)
  - Ride-sharing
  - Drop-off
  - Travel
- Empty
  - Rebalancing
  - Pick-up
  - Idle

**Vehicles update**
- (joining/leaving)

**Requests**
- Vehicles
Simulation

From NYC taxi data trips to requests

Trips from 50 consecutive Tuesdays (07/2015 – 06/2016):
- 659,579 trips (1,074,690 passengers)

Four time periods:
- night (2-5am)
- morning rush hour (7-10am)
- midday (11am-2pm)
- afternoon rush hour (6-9pm)

One request:
- $t_R$: time the user requested the trip
- $n_R$: number of passengers (1–4)
- $l_{PU}$: waiting user/pick-up location (coordinates)
- $l_{DO}$: drop-off location (coordinates)
- $z_{PU}$: pick-up zone (id)
- $z_{DO}$: drop-off zone (id)

Example of trips origin position recorded on February 2nd 2016 and mapped to the zones describing the studied network.
### Simulation

#### Scenarios

<table>
<thead>
<tr>
<th>Baselines</th>
<th>Summary</th>
<th>Assignment</th>
<th>Rebalancing</th>
<th>Ride sharing</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Centralized</td>
<td>No</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>D</td>
<td>Decentralized</td>
<td>No</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>C_RB</td>
<td>Centralized</td>
<td>Yes</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>D_RB</td>
<td>Decentralized</td>
<td>Yes</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>C_RS</td>
<td>Centralized</td>
<td>No</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>D_RS</td>
<td>Decentralized</td>
<td>No</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>C_RB_RS</td>
<td>Centralized</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>D_RB_RS</td>
<td>Decentralized</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
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</table>

<table>
<thead>
<tr>
<th>SAMoD</th>
<th>Summary</th>
<th>Assignment</th>
<th>Rebalancing</th>
<th>Ride sharing</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_RB</td>
<td>Learnt</td>
<td>Learnt</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>S_RB_RS</td>
<td>Learnt</td>
<td>Learnt</td>
<td></td>
<td>Learnt</td>
</tr>
<tr>
<td>S_RB_RS+1</td>
<td>Learnt</td>
<td>Learnt</td>
<td></td>
<td>Learnt</td>
</tr>
<tr>
<td>S_RB2_RS+1</td>
<td>Learnt</td>
<td>Learnt</td>
<td></td>
<td>Learnt</td>
</tr>
</tbody>
</table>
Simulation

Demonstration
Results
Evaluation

We evaluated the impact of the different strategies on:

- **The system:**
  - served requests
  - not served/timed-out requests (10 min)

- **Riders:**
  - waiting time $t_w$
  - detour time $t_d$
  - travel time $TT$

- **Vehicles:**
  - total Vehicle Miles Travelled (VMT)
  - empty VMT
  - engaged VMT
  - shared VMT
  - occupancy
## Results: Rebalancing (7–10am)

<table>
<thead>
<tr>
<th>System</th>
<th>No RB, No RS</th>
<th>Rebalancing</th>
<th>Ride-sharing</th>
<th>RB and RS</th>
<th>SAMoD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>D</td>
<td>C_RB</td>
<td>D_RB</td>
<td>C_RS</td>
</tr>
<tr>
<td>Satisfied requests</td>
<td>29667</td>
<td>35388</td>
<td>30191</td>
<td>36913</td>
<td>38327</td>
</tr>
<tr>
<td>% of total requests</td>
<td>76.4</td>
<td>91.13</td>
<td>77.75</td>
<td>95.06</td>
<td>98.7</td>
</tr>
<tr>
<td>Not served requests</td>
<td>8675</td>
<td>3098</td>
<td>8150</td>
<td>1590</td>
<td>0</td>
</tr>
<tr>
<td>% of total requests</td>
<td>22.34</td>
<td>7.98</td>
<td>20.99</td>
<td>4.09</td>
<td>0</td>
</tr>
<tr>
<td>Avg $t_w$ (min)</td>
<td>11.63</td>
<td>5.48</td>
<td>11.07</td>
<td>4.57</td>
<td>2.41</td>
</tr>
<tr>
<td>Avg $TT$ (min)</td>
<td>5.8</td>
<td>5.69</td>
<td>5.79</td>
<td>5.72</td>
<td>10.31</td>
</tr>
<tr>
<td>Avg $t_d$ (min)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.57</td>
</tr>
<tr>
<td>Avg VMT</td>
<td>863.8</td>
<td>735.79</td>
<td>884.71</td>
<td>861.4</td>
<td>690.28</td>
</tr>
<tr>
<td>Avg empty VMT</td>
<td>428.48</td>
<td>228.29</td>
<td>442.24</td>
<td>330.04</td>
<td>117.02</td>
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<tr>
<td>Avg engaged VMT</td>
<td>435.32</td>
<td>507.5</td>
<td>442.47</td>
<td>531.36</td>
<td>573.26</td>
</tr>
<tr>
<td>Avg shared VMT</td>
<td>103</td>
<td>120.55</td>
<td>103.78</td>
<td>125.54</td>
<td>382.75</td>
</tr>
<tr>
<td>Avg occupancy</td>
<td>1.47</td>
<td>1.48</td>
<td>1.47</td>
<td>1.48</td>
<td>2.67</td>
</tr>
</tbody>
</table>
## Results: Ride sharing (7–10am)

<table>
<thead>
<tr>
<th>System</th>
<th>Satisfied requests</th>
<th>% of total requests</th>
<th>Not served requests</th>
<th>% of total requests</th>
<th>Avg ( t_w ) (min)</th>
<th>Avg ( TT ) (min)</th>
<th>Avg ( t_d ) (min)</th>
<th>Avg VMT</th>
<th>Avg empty VMT</th>
<th>Avg engaged VMT</th>
<th>Avg shared VMT</th>
<th>Avg occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>No RB, No RS</td>
<td>29667 35388</td>
<td>76.4 91.13</td>
<td>8675 3098</td>
<td>22.34 7.98</td>
<td>11.63 5.48</td>
<td>5.8 5.69</td>
<td>0 0</td>
<td>863.8 735.79</td>
<td>428.48 228.29</td>
<td>435.32 507.5</td>
<td>103 120.55</td>
<td>1.47 1.48</td>
</tr>
<tr>
<td>Rebalancing</td>
<td>C D</td>
<td>C_RB D_RB</td>
<td>C_RS D_RS</td>
<td>RB and RS</td>
<td>SAMoD</td>
<td>S_RB S_RB_RS S_RB_RS+1 S_RB2_RS+1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_RB</td>
<td>D_RB</td>
<td>C_RS</td>
<td>D_RS</td>
<td>C_RB_RS</td>
<td>D_RB_RS</td>
<td>S_RB</td>
<td>S_RB_RS</td>
<td>S_RB_RS+1</td>
<td>S_RB2_RS+1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30191 36913</td>
<td>98.7 98.81</td>
<td>0 54</td>
<td>98.75 98.91</td>
<td>7.48 1.78</td>
<td>0</td>
<td>11</td>
<td>2903 693</td>
<td>2242</td>
<td></td>
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<tr>
<td>38327 38368</td>
<td>2.1 2.6</td>
<td>0 0.14</td>
<td>98.75 98.91</td>
<td>7.48 1.78</td>
<td>0</td>
<td>0.03</td>
<td>7.48 1.78</td>
<td>2242</td>
<td></td>
<td></td>
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<tr>
<td>38346 38407</td>
<td>4.44 2.99</td>
<td>0</td>
<td>11</td>
<td>7.48 1.78</td>
<td>0</td>
<td>0.39</td>
<td>6.31 6.49</td>
<td>2242</td>
<td></td>
<td></td>
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<tr>
<td>35691 37790</td>
<td>0.03</td>
<td>3.39</td>
<td>7.48 1.78</td>
<td>2242</td>
<td>12.03 12.12</td>
<td>6.49</td>
<td>6.49</td>
<td>12.12</td>
<td>2242</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| No RB, No RS | 35388 | 91.13 | 8675 | 7.98 | 5.48 | 5.69 | 0 | 735.79 | 228.29 | 507.5 | 120.55 | 1.48 |
| Rebalancing | C D | C_RB D_RB | C_RS D_RS | RB and RS | SAMoD | S_RB S_RB_RS S_RB_RS+1 S_RB2_RS+1 |
| C_RB | D_RB | C_RS | D_RS | C_RB_RS | D_RB_RS | S_RB | S_RB_RS | S_RB_RS+1 | S_RB2_RS+1 |
| 36913 | 98.81 | 54 | 98.91 | 1.78 | 0.14 | 11 | 693 | 2242 |
| 38368 | 2.6 | 0.03 | 98.91 | 1.78 | 0 | 3.39 | 7.48 | 2242 |
| 38407 | 2.99 | 0 | 7.48 | 2242 | 12.12 | 6.49 | 6.49 | 2242 |
| 37790 | 0.39 | 3.39 | 98.91 | 2242 | 12.03 | 6.31 | 6.49 | 2242 |
| 38346 | 0.03 | 3.39 | 98.91 | 2242 | 12.03 | 6.31 | 6.49 | 2242 |
| 38397 | 0.39 | 3.39 | 98.91 | 2242 | 12.03 | 6.31 | 6.49 | 2242 |
Results

Demand patterns

- Average waiting time (min)
  - 2-5am
  - 7-10am

- Average travel time (min)
  - 2-5am
  - 7-10am

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Results
Demand patterns

Occupancy

Average # of passengers per trip
2-5am

Average # of passengers per trip
7-10am

S_RB  S_RB_RS  S_RB_RS+1  S_RB2_RS+1
0  1  2  3  4
Vehicle objective is selfish but learnt policy enables improvements:

- At the system scale
- From riders perspective

Vehicle fleet learns an effective rebalancing strategy using historical data

Results highlight a complex trade-off

Impact of/on traffic is not considered
Conclusions

Future work
Conclusions

Future work

Model a SAV system with enabled ride sharing in Dublin:

- generate trips from a survey
- create different adoption rate scenarios (from the survey)

Evaluate the impact of this system on:

- traffic conditions
- parking space use
References I


