Turning Left at Urban Intersections: Turning Patterns and Gap Acceptance

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Background and Objective

• Turning left between oncoming traffic is one of the most safety-critical traffic manoeuvres (e.g. Sander, 2017)
• Knowledge about factors that influence a driver’s decision to turn can support the development of assistance systems and autonomous driving functions to promote safety (e.g. Hubmann et al., 2017; Zhou et al., 2017)

Objective
• Describe and understand the interaction behaviour between left-turning and oncoming traffic
• Identify factors that influence a driver’s gap acceptance

Available data
• Video and trajectory data collected at the Application Platform for Intelligent Mobility (AIM) research intersection in Braunschweig, Germany
Scenario: Turning Left with Oncoming Traffic
AIM Research Intersection in Braunschweig, Germany
Research Questions and Method

1. Which turning patterns can be observed?

2. Which time gaps in oncoming traffic are accepted/rejected?

3. Which characteristics of oncoming traffic and left-turning vehicles influence gap acceptance?
Research Questions and Method

1. Which turning patterns can be observed?
   - Classification of turning patterns based on video material

Left turns with PET ≤ 2 s with oncoming traffic
(13 days, n = 3584)

Random selection of 80 left turns per day
(n = 1040)
Identified Turning Patterns

- between oncoming traffic
- after oncoming traffic
- while oncoming traffic slowed down/stopped
- before oncoming traffic

Position of left-turning vehicle in queue:

- 1: 466
- 2: 303
- 3: 111
- 4: 47
- 5: 23
- 6: 15
- 7: 10
- 8: 9
- 9: 3
- 10: 1
- 11: 1
- 12: 1

Counts and Percentages:

- Between oncoming traffic: 466 (524; 50%)
- After oncoming traffic: 303 (143; 14%)
- While oncoming traffic slowed down/stopped: 111 (364; 35%)
- Before oncoming traffic: 52 (7; 1%)
Research Questions and Method

1. Which turning patterns can be observed?
   • Classification of turning patterns based on video material

2. Which time gaps in oncoming traffic are accepted/rejected?
   • Calculation of time gaps
   • Classification as accepted or rejected gap
   • Identifying critical gap by means of logistic regression

Left turns with PET ≤ 2 s with oncoming traffic (13 days, n = 3584)

Random selection of 80 left turns per day (n = 1040)

Left turns between oncoming traffic (n = 191)
   • left-turning vehicle on first position
   • of seven days
   • between 6 am and 20 pm
Time Gap, Gap Acceptance, Critical Gap and Logistic Regression

- **Time gap** = time that passes between departure of rear bumper of first oncoming traffic vehicle (O1) from the left-turn path and arrival of front bumper of following vehicle (O2) at the same point when left-turning vehicle (L) can be assumed to be ready to initiate the left turn (Ragland et al., 2006)

- **Gap acceptance** = probability of accepting a gap by length of gap (e.g. Ragland et al., 2006)
  - **Accepted gap** = gap chosen by left-turning vehicle to complete a left turn
  - Gap acceptance curve can be modeled by a logistic function
  - **Critical gap** = gap value that 50% of drivers would accept (e.g. Dissanayake et al., 2002)

- **Logistic models** can be used to relate factors to the drivers’ gap acceptance decision; model coefficients can be estimated by generalized linear models (e.g. Zhou et al., 2017)

\[
\text{time gap} = t_2 - t_1
\]
Gap Acceptance and Critical Gap

- Gaps larger than 8.03 s were accepted
- Gaps smaller than 2.74 s were rejected

\[ n_{\text{acc}} = 191 \]
\[ n_{\text{rej}} = 830 \]

Critical gap = 4.70 s

Hosmer and Lemeshow $R^2 = 0.81$
Cox and Snell $R^2 = 0.54$
Nagelkerke $R^2 = 0.88$
Research Questions and Method

1. Which turning patterns can be observed?
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2. Which time gaps in oncoming traffic are accepted/rejected?
   • Calculation of time gaps
   • Classification as accepted or rejected gap
   • Identifying critical gap by means of logistic regression

3. Which characteristics of oncoming traffic and left-turning vehicle influence gap acceptance?
   • Calculation of characteristics
   • Identification of significant factors by means of logistic regression
Factors Influencing Gap Acceptance

• Gap-related factors
  • Gap duration (e.g. Alexander et al., 2002)
  • Rejected and accepted gap number (e.g. Zhou et al., 2017)
  • Mean and total time of rejected/accepted gaps (e.g. Zhou et al., 2017)

• Driver-related factors
  • Driver age (e.g. Staplin & Lyles, 1991)
  • Gender (e.g. Yan et al., 2007)
  • Personality (e.g. Pollatschek et al., 2002)

• Traffic-related factors
  • Speed of oncoming traffic (e.g. Davis & Swenson, 2004)
  • Waiting time of left-turning vehicle (e.g. Devarasetty et al., 2012)
  • Lane number (e.g. Zhou et al., 2017)

• Environmental factors
  • Weather conditions (e.g. Zhody et al., 2010)
  • Visibility conditions (day/night) (e.g. Dissanayake et al., 2002)
## Does the Behaviour of Oncoming Vehicles Influence Drivers‘ Gap Acceptance?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-6.14* (2.64)</td>
</tr>
<tr>
<td>Time gap</td>
<td>1.08*** (0.20)</td>
</tr>
<tr>
<td>Average velocity O1</td>
<td>-0.16 (0.13)</td>
</tr>
<tr>
<td>Average acceleration O1</td>
<td>-2.82* (1.09)</td>
</tr>
<tr>
<td>Minimal acceleration O1</td>
<td>1.01 (0.62)</td>
</tr>
<tr>
<td>Maximal acceleration O1</td>
<td>0.54 (0.48)</td>
</tr>
<tr>
<td>Average velocity O2</td>
<td>0.27° (0.14)</td>
</tr>
<tr>
<td>Average acceleration O2</td>
<td>-2.83* (1.35)</td>
</tr>
<tr>
<td>Minimal acceleration O2</td>
<td>0.11 (0.49)</td>
</tr>
<tr>
<td>Maximal acceleration O2</td>
<td>0.51 (0.48)</td>
</tr>
</tbody>
</table>

*** p < .001, ** p < .01, * p < .05, ° p < .10
Accepted gaps are characterized by
- Larger time gaps
- Lower acceleration (O1 + O2)
- Higher velocity (O2)

→ oncoming traffic might adapt behaviour
→ left-turning drivers might underestimate velocity
(e.g. Davis & Swenson, 2004)
Does the „State“ of the Left-turning Vehicle Influence the Drivers‘ Gap Acceptance?

- Average velocity
- Average acceleration
- Minimal/maximal acceleration
- Average heading of left-turning vehicle in areas 1, 2 and 3
## Significant Predictor: Left-turning Vehicles’ Velocity in Area 2 and 3

<table>
<thead>
<tr>
<th></th>
<th>Area 1</th>
<th>Area 2</th>
<th>Area 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coeff.</td>
<td>Std. Error</td>
<td>Z value</td>
</tr>
<tr>
<td>Intercept</td>
<td>-0.12</td>
<td>1.58</td>
<td>-0.08</td>
</tr>
<tr>
<td></td>
<td>-2.33</td>
<td>1.63</td>
<td>-1.43</td>
</tr>
<tr>
<td></td>
<td>-1.00</td>
<td>1.23</td>
<td>-0.82</td>
</tr>
<tr>
<td>Average velocity</td>
<td>0.15</td>
<td>0.18</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>0.52</td>
<td>0.18</td>
<td>2.81**</td>
</tr>
<tr>
<td></td>
<td>0.71</td>
<td>0.24</td>
<td>2.96**</td>
</tr>
<tr>
<td>Average acceleration</td>
<td>0.45</td>
<td>0.90</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>-0.17</td>
<td>0.68</td>
<td>-0.24</td>
</tr>
<tr>
<td></td>
<td>-0.93</td>
<td>0.67</td>
<td>-1.36</td>
</tr>
<tr>
<td>Minimum acceleration</td>
<td>-0.46</td>
<td>0.49</td>
<td>-0.94</td>
</tr>
<tr>
<td></td>
<td>-0.27</td>
<td>0.38</td>
<td>-0.70</td>
</tr>
<tr>
<td></td>
<td>-0.21</td>
<td>0.37</td>
<td>-0.56</td>
</tr>
<tr>
<td>Maximum acceleration</td>
<td>0.03</td>
<td>0.52</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>0.46</td>
<td>0.35</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>0.32</td>
<td>0.40</td>
<td>0.80</td>
</tr>
<tr>
<td>Average heading</td>
<td>-0.05</td>
<td>0.08</td>
<td>-0.57</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>0.06</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>0.03</td>
<td>-0.77</td>
</tr>
</tbody>
</table>

*** <.001, ** <.01, *<.05, ° <.1

- Average velocity of left-turning vehicles in area 2 and 3 predicts gap acceptance
- Higher average velocity if gap is accepted
Does the „State“ of the Left-turning Vehicle in Relation to Oncoming Traffic Influence Drivers‘ Gap Acceptance?

Point in time: **O1 crosses future path of L**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.85 (3.12)</td>
</tr>
<tr>
<td>Distance to CP L</td>
<td>-0.73*** (0.18)</td>
</tr>
<tr>
<td>Velocity L</td>
<td>1.73*** (0.45)</td>
</tr>
<tr>
<td>Acceleration L</td>
<td>2.56** (0.88)</td>
</tr>
<tr>
<td>Waiting time L</td>
<td>0.19 (0.16)</td>
</tr>
<tr>
<td>Velocity O1</td>
<td>0.21 (0.19)</td>
</tr>
<tr>
<td>Acceleration O1</td>
<td>0.13 (0.78)</td>
</tr>
</tbody>
</table>

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131/140 O2s have not been detected at this time
Significant Predictors: Distance to CP, Velocity and Acceleration of L when O1 Crosses Future Path of L

Accepted gaps are characterized by
- Higher velocity
- Shorter distance to crossing point
- Higher acceleration
→ by the time O1 crosses path of left-turning vehicle, decision to turn seems to be made
Summary and Application of Results

Gap acceptance was predicted by the
- Behaviour of oncoming traffic (time gap, velocity, acceleration) → adaption, underestimation
- Behaviour and position of left-turning vehicle (velocity, acceleration, distance) → decision making

Predicting a left-turning vehicle’s behavior, i.e. gap acceptance, will help...

...oncoming traffic to
- prepare safety maneuvers
- adapt driving behavior to support left-turning vehicles

...left-turning vehicles by
- sending support messages at an appropriate time, e.g.
  - before the decision to turn is made
  - if a safety-critical decision was made
Thank you for your attention!

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