CAV Trajectory Optimization & Capacity Analysis
- Modeling Methods and Field Experiments

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Session 2B: Are We Ready for the AV Future?
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Hope for CAV: Capacity Booster

- People expect connected automated vehicles can significantly increase (or even multiple) highway capacity
- How to realize this potential?
Steps to Improve CAV Capacity

- Microscopic trajectory control
  - Reduce headway
  - Improve traffic smoothness

- Macroscopic capacity analysis
  - Understand the relationship between cav traffic characteristics (e.g., CAV penetration ratio) and macroscopic measures (e.g., traffic throughput)

- Validation
  - Field experiments
  - Data analysis
CAV Trajectory Optimization

- Signalized Intersections
  - Coordinate signal timing with vehicle trajectory control
Parsimonious Algorithms

- Shooting heuristic (SH)
  - A small number of analytical sections
# Benchmark vs. SH

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<th>$C'(s)$</th>
<th>$L(m)$</th>
<th>$f^s$</th>
<th>$\Delta T$</th>
<th>$\Delta E$</th>
<th>$\Delta S$</th>
<th>$\Delta M$</th>
<th>Solution Time</th>
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<td>1500</td>
<td>0.9</td>
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<td>32.78%</td>
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<td>67.06%</td>
<td>43.47%</td>
<td>10.2</td>
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</table>

Reference


CAV Trajectory Optimization

- Signalized Intersections
  - Mixed Traffic (CAVs + Human-driven vehicles (HVS))

Reference

CAV Trajectory Optimization

- Freeway Speed Harmonization

Reference:
Trajectory Control → Capacity Analysis

- CAV control → Heterogeneous headways in mixed traffic

CAV

Human-driven Vehicle (HV)

Freq. 0.3 2.0 h (s)
Freq. 0.5 2.6 h (s)
Freq. 0.6 2.6 h (s)
Freq. 0.7 2.4 h (s)
Capacity Analysis

- CAV technology uncertainties
  - Will CAV reduce headways?

Google car pulled over for being too slow
Capacity Analysis

- Different technology scenarios

![Diagram showing different technology scenarios with frequency and time intervals.]
Capacity Analysis

- CAV market penetration rate

Low CAV market penetration rate

High CAV market penetration rate
Capacity Analysis

- CAV platooning intensity

Low CAV platooning intensity

High CAV platooning intensity
Analytical Capacity Formulation

- Markov chain model

\[ t_{11}, h_{11}, t_{01}, h_{01}, t_{00}, h_{00}, t_{10}, h_{10} \]

n
n + 1
Analytical Capacity Formulation

- Markov chain model
  - $P_1 \in [0,1]$: CAV market penetration rate
  - $O \in [-1,1]$: CAV platooning intensity
  - $T := \begin{bmatrix} t_{11} & t_{10} \\ t_{01} & t_{00} \end{bmatrix}$

$$
t_{10} (P_1, O) := \begin{cases} P_0 (1 - O), & O \geq 0; \\
P_0 + O \left( P_0 - \min \left\{ 1, \frac{P_0}{P_1} \right\} \right), & O < 0, 
\end{cases}
$$

$$
t_{11} (P_1, O) := 1 - t_{10} (P_1, O),
$$

$$
t_{01} (P_1, O) := \begin{cases} P_1 (1 - O), & O \geq 0; \\
P_1 + O \left( P_1 - \min \left\{ 1, \frac{P_1}{P_0} \right\} \right), & O < 0, 
\end{cases}
$$

$$
t_{00} (P_1, O) := 1 - t_{01} (P_1, O).
$$
Analytical Capacity Formulation

• Approximate capacity

\[ \hat{c} := \frac{N-1}{\sum_{n=1}^{N-1} \mathbb{E}(h_n)} = \frac{N-1}{\sum_{n=1}^{N-1} h_{AnA_{n+1}}} = \frac{1}{\sum_{s \in S, r \in S} P_{tsr} h_{sr}} \]

- **Theorem 1:** \( \hat{c} \leq \bar{c} \) for any finite \( N \)
- **Theorem 2:** *When \( 0 < 1 \), \( \text{Pr}(\hat{c} \to \bar{c} \text{ as } N \to \infty) \)
Capacity analysis

- Numerical analysis

Optimistic Headway

Conservative Headway
Application – Lane Management

• Determine the optimal number of CAV lanes

\[ \hat{c}_A := \frac{1}{\hat{h}_{11}} \]
\[ q_A := \min(P_1 D, l_A \hat{c}_A) \]
\[ p_1 := \frac{\max(0, P_1 D - l_A \hat{c}_A)}{\max(1, D - q_A)} \]
\[ \hat{c}_{\text{mix}} := \frac{1}{\sum_{s \in S, r \in S} p_s t_{sr} \bar{h}_{sr}} \]

\[ Q := q_A + \min(D - q_A, (L - l_A) \hat{c}_{\text{mix}}) \]

\[ \text{ML} : \quad Q^* := \max_{l_A} Q(l_A, P_1, D, \alpha) \]

subject to \( l_A \in [0, 1, \ldots, L] \)

Reference:
CAV Fundamental Diagrams

- Ongoing Research

Field Experiments

- 10 HVs following tests in Harbin, China (collaborating with Harbin Institute of Technology)
Field Experiments

- HV following CAV/HV at the 2.4 km test track at Chang’an University, China
- Test different drivers, different CAV speed
Field Experiments

- HV following CAV/HV at the 2.4 km test track at Chang’an University, China
- Test different drivers, different CAV speed
Field Experiments

- Difference between HV-following-CAV and HV-following-AV
Acknowledgements

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Q & A?

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