Operations and Planning for Connected Autonomous Vehicles: From Trajectory Control to Capacity Analysis

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CUTR Webinar Series

Freeway Stop-and-Go Traffic
Arterial Operations

- Suboptimal timing – extra delay
- Stop-and-go waves – excessive fuel consumptions

Adverse Impacts

- Congestion
  - Exacerbate delay (3.7 billion hours/year) and congestion cost ($78 billion per year)
Adverse Impacts

- Increase fuel consumption & emission
  - 2.3 billion gallons of fuel /year
  - 70% U.S. petroleum fuel consumption
  - 30% U.S. greenhouse gas emission

Beijing, China | New York City, U.S

Adverse Impacts

- Safety hazards
  - 2,200,000 injuries
  - 33,000 fatalities
Connected and Automated Vehicles

- Information sharing
- Human drivers $\rightarrow$ robot drivers

CAV for operations

- Enable trajectory-level vehicle control and coordination
- Fundamentals of highway traffic operations
  - Past – accommodating human drivers
  - Future - designing robot drivers
CAV for Planning: 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-based Traffic Operations

CAV Trajectory Optimization

- Signalized Intersections
  - Coordinate signal timing with vehicle trajectory control

![Diagram showing human-driven traffic and CAV traffic](image)
Infrastructure

- Single lane highway segment \([0, L]\)
- Fixed signal timing \(G, R, G, \ldots\) at location \(L\)

![Diagram showing single lane highway segment with fixed signal timing.]

Entry Boundary Condition

- Indexed by \(n = 1, 2, \ldots, N\)
- Entry time \(t_n^-, \) speed \(v_n^-\), known a priori

![Diagram showing entry boundary condition with entry time and speed.]

\((t_n^-, v_n^-)\)
Physical Bounds

- Trajectory $p_n(t)$
- Speed $\dot{p}_n(t) \in [0, \bar{v}]$, acc. $\ddot{p}_n(t) \in [a, \bar{a}]$

Exit Boundary Constraint

- Exit during green time:
  $\text{mod}(p_n^{-1}(L), G + R) \leq G$
Vehicle Following Safety

- Two consecutive vehicles $n-1$ and $n$
- Shadow trajectory $p^S_{n-1}(t) = p_{n-1}(t + \tau) - s$
- Reaction time $\tau$
- Safety spacing $s$
- Safety constraint: $p_n(t) \leq p^S_{n-1}(t)$

Travel Time MOE

$$ T := \sum_{n \in \mathbb{N}} \left( p^{-1}_n(L) - t_n^- \right) / N, $$
**Fuel Consumption MOE**

- E.g., VT-micro, CMEM, MOVES

\[ E := \sum_{n=1}^{N} \int_{l_{n}}^{p_{n}^{-1}(L)} e\left(p_{n}(t), \dot{p}_{n}(t), \ddot{p}_{n}(t)\right) dt / N \]

**Safety MOE**

- Surrogate measure – Inverse Time-To-Collision (iTTC)

\[ S := \sum_{n=1}^{N} \int_{l_{n}}^{p_{n}^{-1}(L)} H\left( h^{iTTC} - \frac{\dot{p}_{n}(t) - \dot{p}_{n-1}(t)}{p_{n-1}(t) - p_{n}(t) - l} \right) dt / N \]
Trajectory Optimization (TO)

\[ \min_{\{p_n(t)\}} M\{p_n(t)\} := \alpha T + \beta E + \gamma S \]

subject to

- \( p_n(t^-) = 0; \forall n \) (entry)
- \( \dot{p}_n(t^-) = v_n^- \)
- \( 0 \leq \ddot{p}_n(t) \leq \ddot{v}; \forall n, t \) (kinematics)
- \( a \leq \dddot{p}_n(t) \leq \dddot{a}, \forall n, t \) (kinematics)
- \( \text{mod}(p_n^{-1}(L), G + R) \leq G, \forall n \) (exit)
- \( p_n(t) \leq p_{n-1}(t + \tau) - s, \forall n \neq 1 \) (safety)

TOO DIFFICULT TO SOLVE

Solution Parsimonious Algorithms

- Shooting heuristic (SH)
  - A small number of analytical sections

\[ \begin{array}{c}
\text{speed} \\
25 \\
20 \\
15 \\
10 \\
5 \\
0 \\
\end{array} \]

0

\[ \begin{array}{c}
\text{time} \\
0 \\
\end{array} \]
Benchmark vs. SH

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<td>67.06%</td>
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Reference

CAV Trajectory Optimization

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

Reference
CAV Trajectory Optimization

- Freeway Speed Harmonization

Reference:

Joint Trajectory and Signal Optimization

- Problem setting

Reference:
Joint Trajectory and Signal Optimization

- Signalized intersection

<table>
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Joint Trajectory and Signal Optimization

- Work-zone

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<td>$\tau$</td>
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Deep Learning Based Trajectory Control

- Using deep neural networks to design adaptive CAV controllers

Implication to Capacity Analysis & Planning
Trajectory Control → Capacity Analysis

• CAV control → Heterogeneous headways in mixed traffic
  - CAV
  - Human-driven Vehicle (HV)

<table>
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<tr>
<th>Frequency</th>
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<tr>
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<td>Frequency</td>
<td>0.5 2.6 h (s)</td>
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<tr>
<td>Frequency</td>
<td>0.6 2.6 h (s)</td>
</tr>
</tbody>
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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 distributions for various scenarios.]

Capacity Analysis

- CAV market penetration rate

![Diagram showing CAV market penetration rate with examples for low and high rates.]

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

\[ t_{11}, h_{11} \]

\[ t_{01}, h_{01} \]

\[ t_{10}, h_{10} \]

\[ t_{00}, h_{00} \]
Analytical Capacity Formulation

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

\[
\begin{align*}
t_{10}(P_1, O) &:= \begin{cases} P_0(1 - O), & O \geq 0; \\
P_0 + O \left( P_0 - \min\{1, P_0\} \right), & O < 0,
\end{cases} \\
t_{11}(P_1, O) &:= 1 - t_{10}(P_1, O), \\
t_{01}(P_1, O) &:= \begin{cases} P_1(1 - O), & O \geq 0; \\
P_1 + O \left( P_1 - \min\{1, P_1\} \right), & O < 0,
\end{cases} \\
t_{00}(P_1, O) &:= 1 - t_{01}(P_1, O).
\end{align*}
\]

Analytical Capacity Formulation

• Approximate capacity
  ▪ \( \hat{c} := \frac{N-1}{\sum_{n=1}^{N-1} E(h_n)} = \frac{N-1}{\sum_{n=1}^{N-1} h_{A_n A_{n+1}}} = \frac{1}{\sum_{s \in S, r \in S} P_3 t_{sr} h_{sr}} \)
  ▪ **Theorem 1:** \( \hat{c} \leq \bar{c} \) for any finite \( N \)
  ▪ **Theorem 2:** When \( O < 1 \), \( \Pr(\hat{c} \to \bar{c} \text{ as } N \to \infty) \)
Capacity analysis

- Numerical analysis

Optimistic Headway

Conservative Headway

Application – Lane Management

- Determine the optimal number of CAV lanes

\[
\hat{c}_A := \frac{1}{\bar{h}_{11}} \\
q_A := \min(P_1D, l_A \hat{c}_A) \\
p_1 := \frac{\max(0, P_1D - l_A \hat{c}_A)}{\max(1, D - q_A)} \\
\hat{c}_{\text{mix}} := \frac{1}{\sum_{s \in S, r \in S} p_s t_{sr} \bar{h}_{sr}} \\
Q := q_A + \min(D - q_A, (L - l_A) \hat{c}_{\text{mix}})
\]

ML : \[ Q^* := \max_{l_A} Q(l_A, P_1, D, \alpha) \]
subject to \[ l_A \in [0, 1, \ldots, L] \]

Reference:
Field Experiments – Pure HVs

- 15 HVs following tests in Harbin, China (collaborating with Harbin Institute of Technology)

Lead vehicle

Following vehicles
Data Collection on Public Roads

- Video-Based Intelligent Road Traffic Universal Analysis Tool (VIRTUAL) (Provisional Patent #: 62/701,978)

Table 1:

<table>
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<th>y(ft)</th>
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Fields Experiments – Pure CAVs

- Turner Fairbank Highway Research Center
- Level-1 Automated Cadillac

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 – Mixed Traffic

- Difference between HV → CAV and HV→HV
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  - Fang Zhou (Li’s student)
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Thank you!
Q & A?

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