Webinar: Modeling Freeway Traffic in a Mixed Environment: Connected and Human-Driven Vehicles

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Modeling Freeway Traffic in a Mixed Environment: Connected and Human-Driven Vehicles

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Automated Vehicles (AVs)

- Automated Vehicles (AVS) are operated with the support of various vehicle automation functions, which rely on real-time sensor data for making maneuver decisions, e.g., acceleration, deceleration, and lane changing.

- Six levels of vehicle automation

<table>
<thead>
<tr>
<th>SAE Level</th>
<th>SAE Name</th>
<th>Definition</th>
<th>Automation Controls...</th>
<th>Example(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Automation</td>
<td>Human performs entire driving task</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Driver Assistance</td>
<td>Automation controls one vehicle function (steering OR speed)</td>
<td>OR</td>
<td>Adaptive Cruise Control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lane Keep Assist</td>
</tr>
<tr>
<td>2</td>
<td>Partial Automation</td>
<td>Automation controls BOTH steering and speed; driver responsible for monitoring and immediate reengagement</td>
<td>AND</td>
<td>Tesla Autopilot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Audi Traffic Jam Assistant</td>
</tr>
<tr>
<td>3</td>
<td>Conditional Automation</td>
<td>Automation controls BOTH steering and speed and monitors environment; driver may be notified to reengage</td>
<td></td>
<td>Volvo DriveMe</td>
</tr>
<tr>
<td>4</td>
<td>High Automation</td>
<td>Automation performs all aspects of dynamic driving task in SOME driving modes; driver not required to reengage</td>
<td></td>
<td>Closed Campus Driverless Shuttle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Driverless Valet</td>
</tr>
<tr>
<td>5</td>
<td>Full Automation</td>
<td>Automation performs all aspects of dynamic driving task under ALL roadway and environmental conditions</td>
<td></td>
<td>Driverless Taxi</td>
</tr>
</tbody>
</table>
Autonomous vs. Automated?

**Definition:** "An autonomous car is a vehicle that is capable of sensing its environment and navigating without human input."

A Nissan engineer said: "A truly autonomous car would be one where you request it to take you to work and it decides to go to the beach instead."

To say it more plainly: "A truly autonomous car would decide on destination and route as well as control within the lanes. An automated car would follow orders about destination and route, and may only adopt some lane-keeping or car-following guidance."
Autonomous vs. Automated?

So, a car that can navigate lanes or traffic or mind speed limits is technically an "automated" car, not an "autonomous" car.
Self-Driving vs. Driverless?

• "Self-driving car" is a term Autotrader uses to encompass the entire idea of cars doing some or all the work of moving a car from point to point. It is a more general and inclusive term.

• All driverless cars are self-driving; all self-driving cars aren't driverless.
Automated Vehicle Example: Tesla

Two important control factors that can be set by drivers:

1. Desired Speed
2. Minimum Following Gap
Connected Vehicles

• Connectivity technologies
  • DSRC
  • C-V2X
  • 5G
  • DMB
  • V2X : V2V, V2I, V2P, V2B……
  • Etc.
The connectivity technology of CAVs allows the exchange of traffic information between vehicles and infrastructure.

The vehicle automation function will automatically adjust the speed in real time according to the desired travel speed and distance to the vehicle ahead.
Connected Automated Vehicle (CAV) are typically equipped with communication devices (e.g., DSRC) and on-board sensors (e.g., Radar, Lidar, Camera, etc.)
CAV Applications on Freeways

Cooperative Adaptive Cruise Control (CACC)

1. On a managed lane
2. Share the lanes with human-driven vehicles
CAV Applications on Freeways

Speed Harmonization

- Speed harmonization is a method to reduce congestion and improve traffic performance.

- This method is applied at points where lanes merge and form bottlenecks, the greatest cause of congestion nationwide.

- The strategy involves gradually lowering speeds before a heavily congested area in order to reduce the stop-and-go traffic that contributes to frustration and crashes.
Similar Concept: Variable Speed Limit
VSL Control Logic

The traffic flow model shall be able to produce results very quickly!

Macroscopic Traffic Flow Model
Macroscopic Traffic Flow Modeling

• Traffic state estimation has long been identified as an important task within a traffic control loop.

• A reliable traffic flow estimation is the foundation of good traffic management strategies.

• Under mixed traffic environment, CAVs can affect the whole freeway traffic state by changing their motion states, due to the speed control applied to CAVs.
Conventional Macroscopic Traffic Flow Model

\[
d_i(k + 1) = d_i(k) + \frac{\Delta T}{\lambda_i \Delta L} [q_{i-1}(k) - q_i(k) + r_i(k) - s_i(k)]
\]

\[
u_i(k + 1) = u_i(k) + \frac{\Delta T}{\tau_i} [V_i(d_i(k)) - u_i(k)] + \frac{\Delta T}{L_i} u_i(k) [u_{i-1}(k) - u_i(k)] - \frac{\gamma_i \Delta T}{\tau_i \Delta L} \frac{d_{i+1}(k) - d_i(k)}{[d_i(k) + \kappa]} \]

\[
V[d_i(k)] = u_f \exp \left[ -\frac{1}{a} \left( \frac{d_i(k)}{d_{cr}} \right)^a \right]
\]

\[
q_i(k) = d_i(k) u_i(k) \lambda_i
\]
Mix Traffic Flow Pattern

• CAVs will be operated with different speeds compared with HVs.

• The speed change/optimization of CAVs will inevitably affect the speed of HVs as they are sharing the roads.
CAV Impact

Ave speed of CAVs (case 1)
Ave speed of HVs (case 1)
Ave speed of HVs (case 2)
CAV Impact

• To fully account the CAV speed impact, we introduced an innovative modeling framework that categorizes vehicles into two groups (i.e., CAV and HV):

HV group:

\[ u_{1,i}(k + 1) = u(k) + \frac{\Delta T}{\tau_i} [V_{1,i}(k) - u_{1,i}(k)] + \frac{\Delta T}{L_i} u_{1,i}(k) [u_{1,i-1}(k) - u_{1,i}(k)] - \frac{\gamma_i \Delta T}{\tau_i L_i} \left[ \frac{d_{1,i+1}(k) + d_{2,i+1}(k) - d_{1,i}(k) - d_{2,i}(k)}{d_{1,i}(k) + d_{2,i}(k)} \right] \]

CAV group:

\[ u_{2,i}(k + 1) = u_{2,i}(k) + \frac{\Delta T}{\tau_i} [V_{2,i}(k) - u_{2,i}(k)] + \frac{\Delta T}{L_i} u_{2,i}(k) [u_{2,i-1}(k) - u_{2,i}(k)] - \frac{\gamma_i \Delta T}{\tau_i L_i} \left[ \frac{d_{1,i+1}(k) + d_{2,i+1}(k) - d_{1,i}(k) - d_{2,i}(k)}{d_{1,i}(k) + d_{2,i}(k)} \right] \]
CAV Impact

HV lane-changing from middle to left or right

Flow Direction

CAV:  
HV:  

HV lane-changing from left or right to middle

Flow Direction

CAV:  
HV:  

Estimating the initial value of beta

Event A:

HV behind a CAV on the lane.

Event B:

HV decide to make lane-changing to pass CAV.
CAV Impact Factor

\[ u_{1,i}(k+1) = u(k) + \frac{\Delta T}{\tau_i} + \frac{\Delta T}{L_i} u_{1,i}(k)[u_{1,i-1}(k) - u_{1,i}(k)] \]
\[ - \gamma_i \frac{\Delta T}{\tau_i L_i} \frac{[d_{1,i+1}(k) + d_{2,i+1}(k) - d_{1,i}(k) - d_{2,i}(k)]}{[d_{1,i}(k) + d_{2,i}(k) - d_{1,i}(k) - d_{2,i}(k)]} - \frac{\beta_i \Delta T}{\tau_i} [V_{1,i}(k) - V_{2,i}(k)] \]

\[ f(u) = u(k) + \frac{\Delta T}{\tau_i} + \frac{\Delta T}{L_i} u_{1,i}(k)[u_{1,i-1}(k) - u_{1,i}(k)] \]
\[ - \gamma_i \frac{\Delta T}{\tau_i L_i} \frac{[d_{1,i+1}(k) + d_{2,i+1}(k) - d_{1,i}(k) - d_{2,i}(k)]}{[d_{1,i}(k) + d_{2,i}(k)]} \]

\[ \beta_i = \frac{[f(u) - u_{1,i}(k+1)]}{\Delta T [V_{1,i}(k) - V_{2,i}(k)]} \times \tau_i \]

\[ u_{1,i}(k+1) = \frac{[(1 - \alpha) N (1 - P_{LC})] u_{2,i}(k+1) + (1 - \alpha) N P_{LC} f(u)}{N} \]

Event A:
HV behind a CAV on the lane.

Event B:
HV decide to make lane-changing to pass CAV.
Real-time learning and updating

Measurements (Ground Truth)

- Speed and flow rate at detection stations;
- CAV trajectory data.

\[
x(k) = f[x(k-1), u(k-1), 0]\]
\[
P^-(k) = AP(k-1)A^T + Q\]
\[
K(k) = P^-H^T(HP^-H^T + R)^{-1}\]
\[
x(k) = x^- + K[z(k) - h(x^-(k), 0)]\]
\[
P(k) = (I - KH)P^-(k)\]
Simulation Analysis

- To evaluate the proposed traffic state estimation model, our research team selects a 4 km long freeway stretch for case study.

![Simulation Diagram](image)

- Inflow detector:
- On-ramp
- Off-ramp
- 500m

Flow Rate (Veh/h) vs. Time (min)

- Inflow of Segment 1
- On-ramp Flow
Embedded CAV speed optimization model

• Objective: optimizing CAV’s desired speed profile in the simulation environment.

\[
\min \sum \sum \lambda_i [d_{1,i}(k) + d_{2,i}(k)] \Delta T
\]

\[
\begin{align*}
\{ u_{jam} & \leq u_{j,i}(k) \leq u_{f,ji}, & \text{segment i without CAV involved} \\
\{ u_{jam} & \leq u_{j,i}(k) \leq u_{f,ji} v_i(k), & \text{segment i with CAV}
\end{align*}
\]

\[0 < v_i(k) \leq 1\]

\[-\delta \leq u_{f,ji} v_i(k) - u_{f,ji} v_i(k - 1) \leq \delta\]
Models for Comparison

• In the simulations, the embedded optimization model functions to optimize the desired speed profile of CAVs.

• Two models are implemented to estimate the traffic state for comparison:
  - Model without EKF
  - The proposed model with EKF
Results Analysis (Speed Estimation)
Results Analysis (Flow Estimation)
## Results Analysis

### Table 1 Speed errors by the model without EKF

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>7.682</td>
<td>7.70</td>
<td>7.91</td>
<td>7.84</td>
<td>7.71</td>
<td>7.67</td>
<td>7.85</td>
<td>7.78</td>
</tr>
<tr>
<td>MAPE</td>
<td>7.86%</td>
<td>9.77%</td>
<td>10.95%</td>
<td>10.14%</td>
<td>9.43%</td>
<td>8.76%</td>
<td>8.49%</td>
<td>6.92%</td>
</tr>
<tr>
<td>MSPE</td>
<td>1.13%</td>
<td>1.89%</td>
<td>2.49%</td>
<td>1.96%</td>
<td>1.60%</td>
<td>1.33%</td>
<td>1.23%</td>
<td>0.84%</td>
</tr>
<tr>
<td>RMSPE</td>
<td>10.62%</td>
<td>13.77%</td>
<td>15.78%</td>
<td>13.99%</td>
<td>12.66%</td>
<td>11.55%</td>
<td>11.08%</td>
<td>9.17%</td>
</tr>
</tbody>
</table>

### Table 2 Speed errors by the model with EKF

<table>
<thead>
<tr>
<th>Flow</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>3.876</td>
<td>3.77</td>
<td>3.66</td>
<td>3.91</td>
<td>3.51</td>
<td>3.58</td>
<td>3.72</td>
<td>4.16</td>
</tr>
<tr>
<td>MAPE</td>
<td>3.97%</td>
<td>4.78%</td>
<td>5.06%</td>
<td>5.05%</td>
<td>4.29%</td>
<td>4.09%</td>
<td>4.03%</td>
<td>3.70%</td>
</tr>
<tr>
<td>MSPE</td>
<td>0.29%</td>
<td>0.45%</td>
<td>0.53%</td>
<td>0.48%</td>
<td>0.33%</td>
<td>0.29%</td>
<td>0.28%</td>
<td>0.24%</td>
</tr>
<tr>
<td>RMSPE</td>
<td>5.36%</td>
<td>6.74%</td>
<td>7.30%</td>
<td>6.96%</td>
<td>5.76%</td>
<td>5.40%</td>
<td>5.25%</td>
<td>4.90%</td>
</tr>
</tbody>
</table>
Sensitivity Analysis

• To further study the CAV impact under different scenarios

<table>
<thead>
<tr>
<th>Demand Level (two lanes)</th>
<th>CV Penetration Rate</th>
<th>CV Flows (two lanes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 veh/hr</td>
<td>5%-80% with 5% increment</td>
<td>75 – 1200 veh/hr</td>
</tr>
<tr>
<td>2000 veh/hr</td>
<td>5%-80% with 5% increment</td>
<td>100 – 1600 veh/hr</td>
</tr>
<tr>
<td>2500 veh/hr</td>
<td>5%-80% with 5% increment</td>
<td>125 – 2000 veh/hr</td>
</tr>
<tr>
<td>3000 veh/hr</td>
<td>5%-80% with 5% increment</td>
<td>150 – 2400 veh/hr</td>
</tr>
<tr>
<td>3500 veh/hr</td>
<td>5%-80% with 5% increment</td>
<td>175 – 2800 veh/hr</td>
</tr>
<tr>
<td>4000 veh/hr</td>
<td>5%-80% with 5% increment</td>
<td>200 – 3200 veh/hr</td>
</tr>
</tbody>
</table>
Critical CAV penetration rate
Conclusions

- The new macroscopic traffic flow model can better capture the operational differences between CAVs and HVs.

- The introduced factor (Beta) could model the CAV speed impact to HVs.

- Extended Kalman filter can help improve the traffic state estimation accuracy.

- The model can be used for producing optimal desired speed of CAVs.
Another application of the model

- Eco-Driving System for Connected Automated Vehicles

- Traffic Sensors Data
- CAV Data
- Computational Unit

Planning Level
- CAV Desired Speed Profile by Minimizing Travel Time
- CAV Optimal Trajectory by Minimizing Fuel Consumption

V2I

In-Vehicle System
- Speed Adaption to Ensure Operational Safety

Operation Level
- Powertrain Control Implementation
Acknowledgement

• NITC Small Start Project: “Vehicle Sensor Data (VSD) Based Traffic Control in Connected Automated Vehicle (CAV) Environment”

• Students: Zhehao Zhang (M.S.) and Alan Zhang (Ph.D.)
Thanks & Questions?

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