Energy-Efficient Adaptive Cruise Control for Electric Connected and Autonomous Vehicles

USDOT T3e Webinar

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IOWA STATE UNIVERSITY
Institute for Transportation

- Focal point for transportation research
- 49 faculty, 257 students from 11 departments across ISU
- Collaborative culture and structure
- Innovation in streaming data, analytics, and decision support tools
Outline

- Introduction
- Fuel and Energy consumption model
- Adaptive cruise control
- Simulation
- Conclusion
Introduction

- In the United States, the fuel economy of personal vehicles is estimated as 24.7 miles per gallon (mpg) in 2016 and is projected to be 54.5 mpg in 2025.

- Battery electric vehicle
  - High energy efficiency
  - Zero tailpipe emissions

- Driver behavior could also affect the fuel economy of vehicles by 10~40%
Introduction

For ICEV

- Smoother deceleration and acceleration rate leads to better fuel efficiency \((Wu \ et \ al. \ 2015)\).
- ACC-equipped vehicle decreased the emissions \((Ioannou \ and \ Stefanovic \ 2005)\)

For BEV

- Ability to recover energy while braking using a regenerative braking system \((Fiori \ et \ al. \ 2016)\)
Introduction

Lead vehicle

Car-following models

On-road fuel/energy economy data

Fuel/Energy consumption models

Velocity & Acceleration

Energy efficiency
Energy Consumption Models

- ICEV fuel consumption model
  - a linear regression model, taking speed & acceleration as predictors
  - there is an optimal speed range for fuel consumption

- BEV energy consumption model
  - braking regenerates electricity
  - energy consumption increases with speed

- Different ACCs for ICEVs and BEVs are needed
ICEV Fuel Consumption Model

- Calibrated the VT-Micro model (Ahn et al., 2002), which uses speed ($v$) & acceleration ($a$) to estimate vehicle fuel consumption
- Used on-board diagnostics II (OBD-II) data, e.g. speed, acceleration, and fuel consumption rate, collected from a gasoline car for a year

\[
\ln FC = \sum_{i=0}^{3} \sum_{j=0}^{3} L_{i,j} v^i a^j, \quad \text{if } a \geq 0
\]

\[
\ln FC = \sum_{i=0}^{3} \sum_{j=0}^{3} M_{i,j} v^i a^j, \quad \text{if } a < 0
\]
ICEV Fuel Consumption Model

- Validated the model on the trip basis
- Compared the actual trip fuel consumption with the estimated trip fuel consumption
BEV Energy Consumption Model

- The regenerative braking feature of electric motors: kinetic energy converts to electricity during braking
- Vehicle specific power (VSP) < 0, when regenerative braking takes effect

If maintain the deceleration at high energy efficiency range for a long time period, BEVs are likely more energy efficient.

(Fiori et al., 2016)
BEV Energy Consumption Model

- EV energy consumption is more sensitive to ambient temperature \((\text{Dong and Hu, 2017; Greene et al., 2017})\)
- Ambient temperature influences auxiliaries, e.g. air conditioning; Auxiliaries consume considerable electricity
- There is an optimal temperature for energy consumption, e.g., 20 °C (or 68 F)
BEV Energy Consumption Model

- Use VSP and auxiliary power to estimate energy consumption rate (ECR)
  \[
  ECR = h_0 + h_1 VSP + h_2 P_{aux}
  \]
- Result in better estimation than other models, e.g. Yang et al., 2014 and Yao et al., 2014

<table>
<thead>
<tr>
<th>Energy Consumption Models</th>
<th>MAPE</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed model</td>
<td>13.3%</td>
<td>0.296 kWh</td>
</tr>
<tr>
<td>Yao’s model</td>
<td>19.5%</td>
<td>0.495 kWh</td>
</tr>
<tr>
<td>Yang et al.’s model</td>
<td>16.7%</td>
<td>0.511 kWh</td>
</tr>
</tbody>
</table>
Car-Following Models

- Human-driver models
  - Newell Model
  - Gipps Model
  - Optimal Velocity Model
  - Intelligent Driver Model

- Adaptive cruise control
  - Adaptive cruise control based on IDM (IDM-ACC)
  - Nissan Model
Adaptive Cruise Control

Source: https://res.cloudinary.com/engineering-com/image/upload/w_640,h_640,c_limit/Driverless_Car_Tech_2_zabzmt.jpg
Proposed Adaptive Cruise Control

Assumptions:

- Only CAVs are capable of communicating with other CAVs through V2V communication

- Ignore computational, sensor, and communication delays for CAVs
Platoon with Mixed CAV and Human-Driven Vehicles
Adaptive Cruise Control

- Gasoline-CAV
  Ecological Smart Driver Model (Eco-SDM)

- e-CAV
  Energy-Efficient Electric Driving Model ($E^3$DM)
String Stability (Acceleration profiles)

Comparison of ACCs

Nissan

Eco-SDM

IDM

E3DM
Simulation

- traffic stream with 1000 vehicles
- a single lane
- the platoon size ranges from 14 to 81 vehicles
Lead vehicle follows a driving cycle

- **Urban Dynamometer Driving Schedule (UDDS)**
  - city test
  - distance: 12 km
  - length: 1369 sec
  - average speed: 31.5 km/h
Scenario 1: All Gasoline-CAVs

The graph shows the fuel consumption (L) for different positions of the following vehicles:

- Manual
- IDM-ACC
- Nissan-ACC
- Eco-SDM

The y-axis represents fuel consumption (L) ranging from 0.92 to 1.16, and the x-axis represents the position of the vehicles from 2 to 16.
Scenario 2: One CAV at different position

![Graph showing fleet fuel consumption change with different CAV positions. The x-axis represents the location of the CAV (2 to 16), while the y-axis shows the fleet fuel consumption change from -2.5% to 0.5%. Three different lines represent IDM-ACC (orange), Nissan-ACC (gray), and Eco-SDM (blue).]
Scenario 3: Different % of CAVs

Eco-SDM  — Nissan-ACC  — IDM-ACC

Market penetration of CAVs

Fleet fuel consumption change

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Scenario 4: All e-CAVs

Energy consumption (kWh) vs. Position of the following vehicles

- Manual
- IDM-ACC
- Nissan-ACC
- E³DM
Scenario 5: One e-CAV at different position
Scenario 6: Different % of e-CAVs

![Graph showing energy consumption change vs market penetration of e-CAVs]

- IDM-ACC
- Nissan-ACC
- E³DM
Conclusion

- Gasoline vehicles
  - a CAV fleet consumes less fuel than a manual vehicle fleet;
  - 1 CAV at the front of a mixed fleet has larger impacts on the fleet fuel efficiency;
  - higher % of CAV leads to more fuel savings, but the marginal benefit diminishes after about 30%.
Conclusion

- Electric vehicles
  - a \( E^3 \)DM-equipped CAV fleet consumes less energy than a manual vehicle fleet;
  - 1 e-CAV at the front of a mixed fleet has larger impacts on the energy efficiency;
  - The higher % of e-CAVs may not result in better energy efficiency of the entire fleet.
  - With \( E^3 \)DM, the highest fleet-level energy efficiency is achieved when the market penetration of e-CAVs is 20%. 
Thank you

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Reference


