Estimating Energy Efficiency of Connected and Autonomous Vehicles in a Mixed Fleet

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Introduction

- Driver behavior could affect the fuel economy of vehicles by 10~40%.
- CAVs and manually driven vehicles are likely to share the road.
- The fuel saving benefit of eco-adaptive cruise control may vary with the position and penetration of CAV in the string of mixed traffic.
- Battery electric vehicles (BEV)
  - Ability to recover energy while braking using a regenerative braking system.
Research Overview

Lead vehicle → Car-following models → Energy consumption models → Velocity & Acceleration → Energy efficiency → On-road fuel economy data
Energy Consumption Models

- **ICEV fuel consumption**
  - speed & acceleration as predictors
  - there is an optimal speed range for fuel consumption

- **BEV energy consumption**
  - optimal ambient temperature: 60~70°F
  - 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) using speed, acceleration, and fuel consumption rate, collected from a gasoline vehicle for a year

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

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

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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

- BEV energy consumption is sensitive to ambient temperature (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 vehicle specific power (VSP) and auxiliary power ($P_{aux}$) to estimate energy consumption rate ($ECR$)

$$ECR = h_0 + h_1 VSP + h_2 P_{aux}$$

$$VSP = v(1.1a + C_{rr}) + C_{aero}v^3$$

$$\ln P_{aux} = \begin{cases} 
  c_0 + c_1 t, & \text{if } -17 \leq t \leq 23 \\ 
  c_0 + c_1 (46 - t), & \text{if } 23 < t \leq 40 
\end{cases}$$

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<th>Energy Consumption Models</th>
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<tr>
<td>Proposed model</td>
<td>13.3%</td>
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<td>Yao et al. (2014) Model</td>
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<td>Yang et al. (2014) Model</td>
<td>16.7%</td>
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Simulation: Traffic Stream with Mixed Manually-Driven Vehicles and CAVs

- A single lane
- 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
Car-Following Models

- Manually-Driven Vehicles
  - Intelligent Driver Model (IDM)

- (Cooperative) Adaptive Cruise Control
  - IDM-ACC
  - Nissan Model
  - Ecological Smart Driver Model (Eco-SDM)
  - Energy-Efficient Electric Driving Model (E³DM)
Accelerations

Nissan

IDM-ACC

Eco-SDM

$E^3DM$
Scenario 1: All ICE-CAVs

Position of the following vehicles

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

Fuel consumption (L)
Scenario 2: One ICE-CAV at different position

![Graph showing total fuel consumption change for IDM-ACC, Nissan-ACC, and Eco-SDM as the location of the CAV changes.](image)
Scenario 3: Different % of ICE-CAVs

![Graph showing total fuel consumption change vs market penetration of CAVs for Eco-SDM, Nissan-ACC, and IDM-ACC]
Scenario 4: All e-CAVs

Energy consumption (kWh)

Position of the following vehicles:
- Manual
- IDM-ACC
- Nissan-ACC
- E³DM
Scenario 5: One e-CAV at different position

![Graph showing total energy consumption change with position of the CAV for different systems: IDM-ACC, Nissan-ACC, and E³DM.](image)
Scenario 6: Different % of e-CAVs

The graph shows the total energy consumption change (%) against the market penetration of e-CAVs. The lines represent different scenarios:

- IDM-ACC
- Nissan-ACC
- E³DM

The x-axis represents the market penetration of e-CAVs ranging from 0% to 100%, and the y-axis represents the total energy consumption change ranging from -8% to 1%. The graph illustrates how the energy consumption changes as the percentage of e-CAVs increases in the market.
Conclusion

- ICE CAV with Eco-SDM
  - a CAV platoon consumes less fuel than a manual vehicle platoon;
  - One CAV towards the front of a mixed platoon 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 CAV with $E^3$DM
  - a CAV platoon consumes less energy than a manual vehicle platoon;
  - One e-CAV towards the front of a mixed platoon improves the energy efficiency;
  - One e-CAV towards the end of a mixed platoon increase the energy consumption;
  - The highest energy efficiency is achieved when the market penetration of e-CAVs is 20%.
Thank you!
Questions?

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