Iowa State University

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

Jing Dong-O'Brien (jingdong@iastate.edu)

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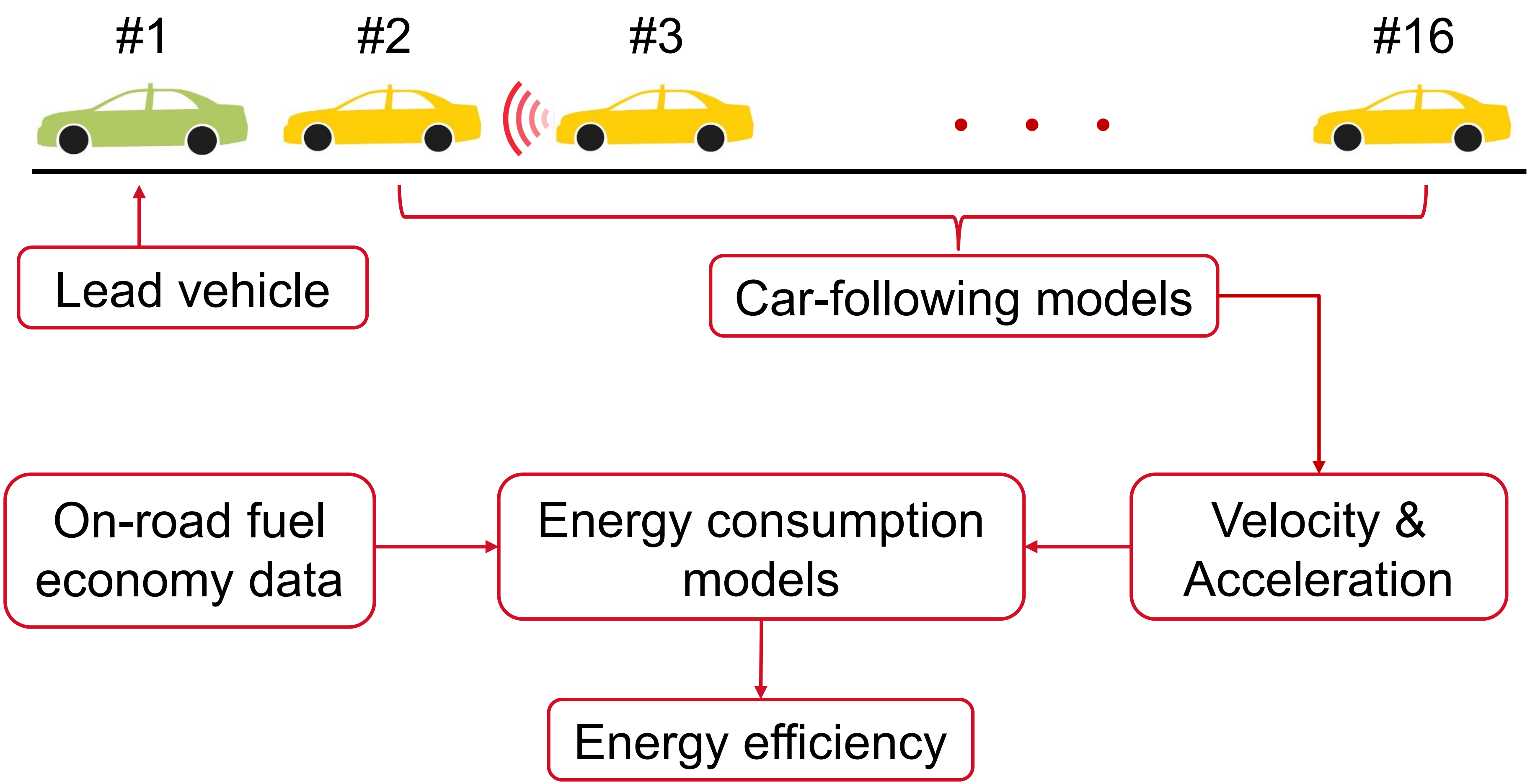
Introduction

- 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



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

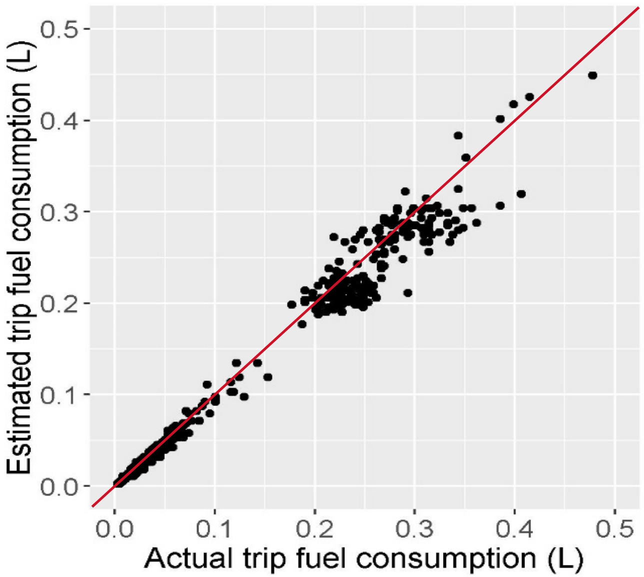
- Calibrated the VT-Micro model (*Ahn et al., 2002*) using speed, acceleration, and fuel consumption rate, collected from a gasoline vehicle for a year

$$\ln FC = \sum_{i=0}^{3} \sum_{j=0}^{3} L_{i,j} v^i a^j, \qquad if\ a \geq 0$$

$$\ln FC = \sum_{i=0}^{3} \sum_{j=0}^{3} M_{i,j} v^i a^j, \qquad if\ a < 0$$

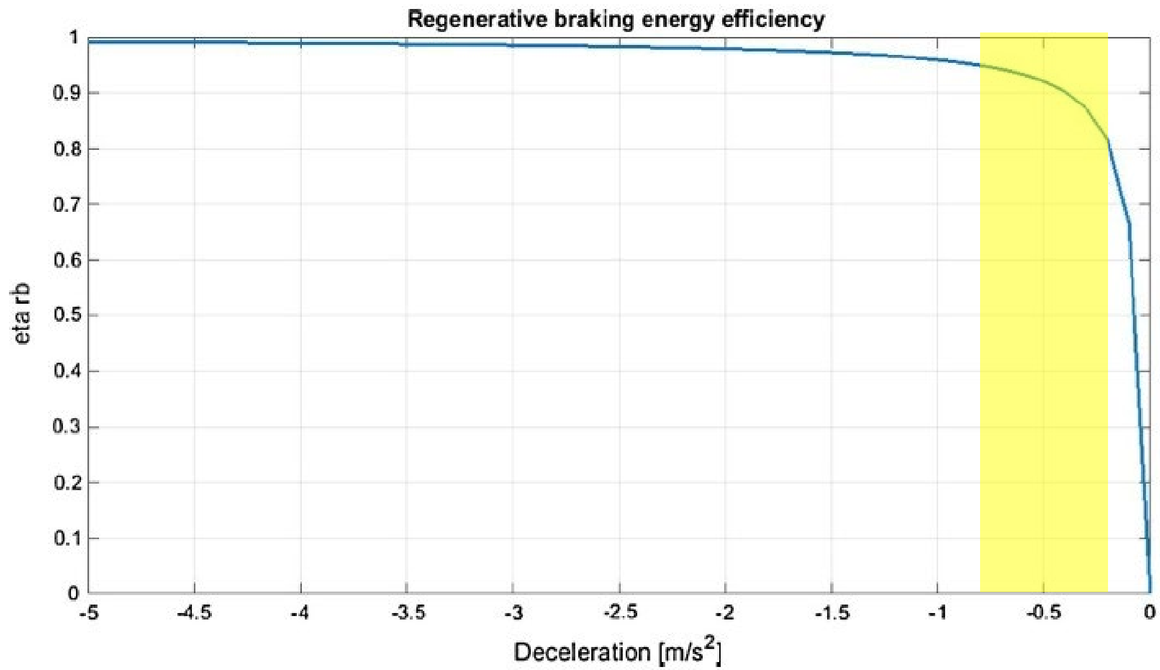
$a \geq 0$	Constant	v^1	v^2	v^3
Constant	-1.23E+00	6.05E-02	3.62E-04	-2.22E-06
a^1	4.69E-01	3.39E-01	-1.91E-02	2.56E-04
a^2	-4.54E-02	-1.33E-01	7.45E-03	-5.44E-05
a^3	1.34E-02	2.08E-02	-2.01E-03	3.19E-05

$a < 0$	Constant	v^1	v^2	v^3
Constant	-7.89E-01	-2.14E-02	5.61E-03	-9.16E-05
a^1	2.83E-01	-1.02E-01	2.01E-02	-4.43E-04
a^2	1.39E-01	-7.45E-02	1.40E-02	-3.44E-04
a^3	9.13E-03	-9.58E-03	2.16E-03	-5.77E-05



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

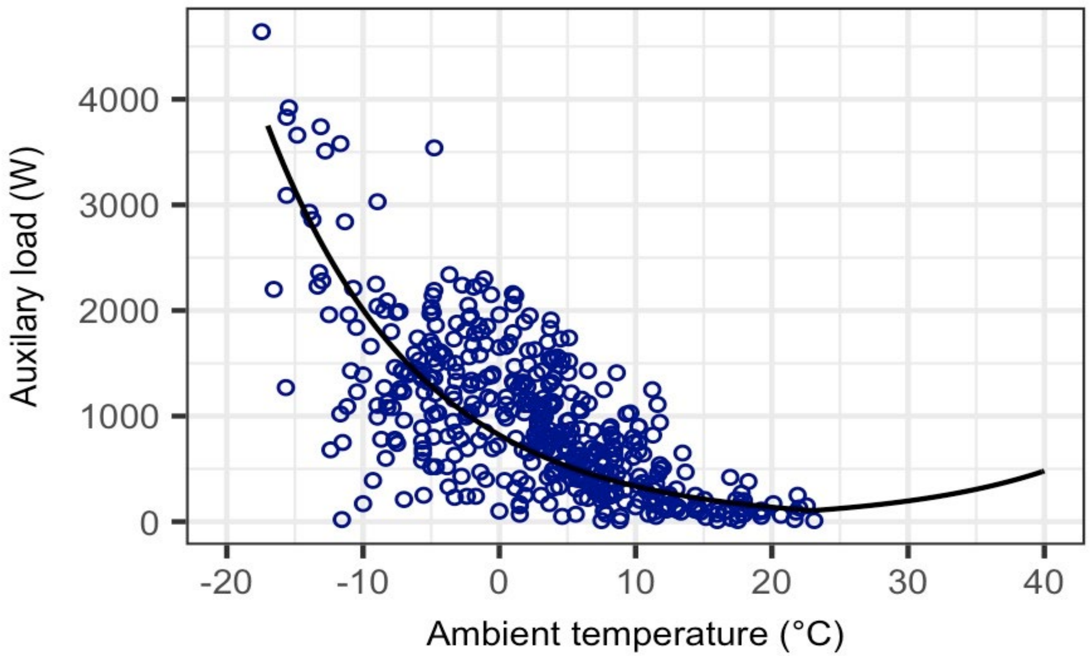


(Fiori et al., 2016)

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

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)



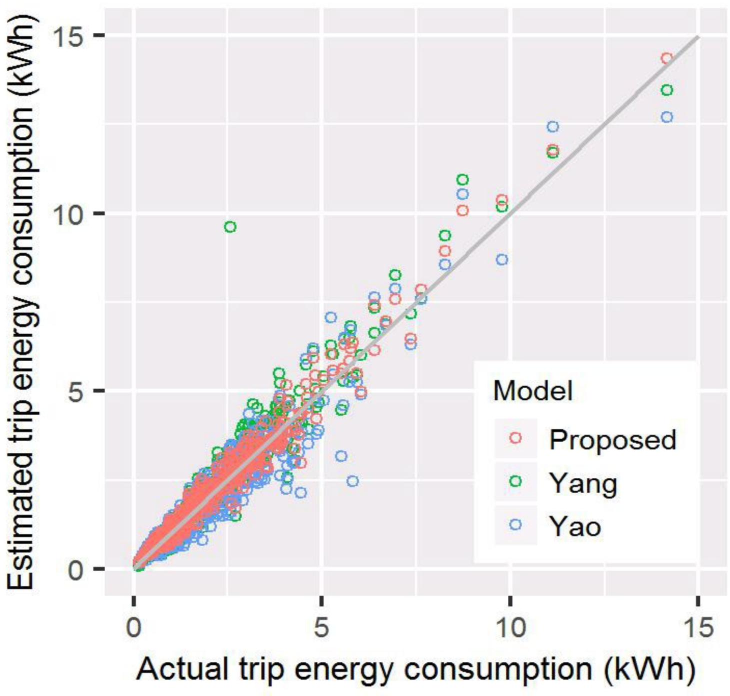
BEV Energy Consumption Model

- Use vehicle specific power (VSP) and auxiliary power (P_{aux}) to estimate energy consumption rate (*ECR*)

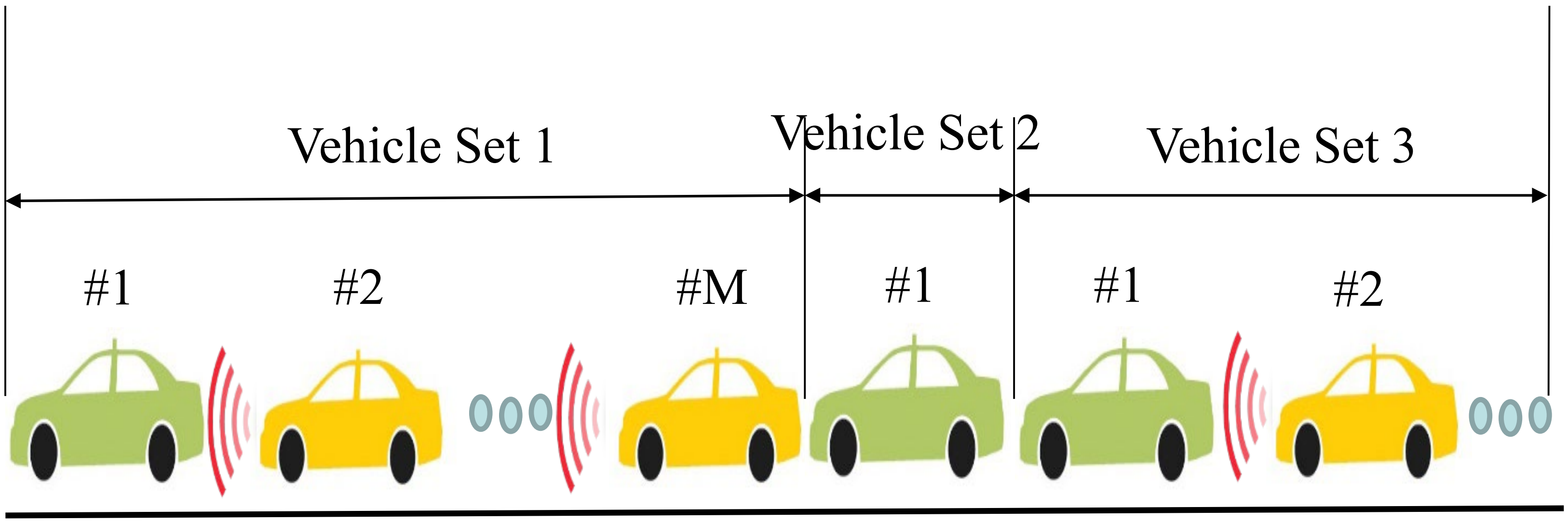
$$ECR = h_0 + h_1 VSP + h_2 P_{aux}$$
$$VSP = v(1.1a + C_{rr}) + C_{aero} v^3$$
$$\ln P_{aux} = \begin{cases} c_0 + c_1 t, & if -17 \le t \le 23 \\ c_0 + c_1(46 - t), & if\ 23 < t \le 40 \end{cases}$$

VSP	*v*	b_0	b_1	b_2
>0	<12.5	3.22E+03	1.16E+03	2.15E+00
	≥12.5	8.43E+03	7.57E+02	2.60E+00
=0	<12.5	6.10E+02	—	1.19E+00
	≥12.5	—	—	—
<0	<12.5	7.20E+02	5.58E+02	2.10E+00
	≥12.5	8.12E+03	5.94E+02	2.57E+00

Energy Consumption Models	MAPE	RMSE
Proposed model	13.3%	0.296 kWh
Yao et al. (2014) Model	19.5%	0.495 kWh
Yang et al. (2014) Model	16.7%	0.511 kWh



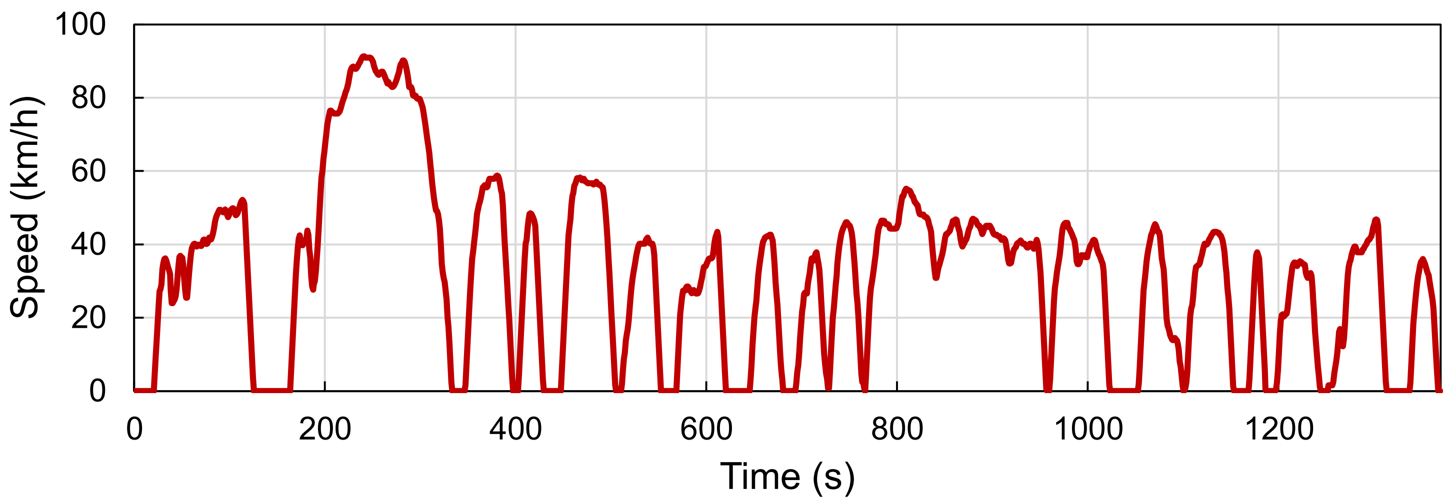
Simulation: Traffic Stream with Mixed Manually-Driven Vehicles and CAVs



- 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

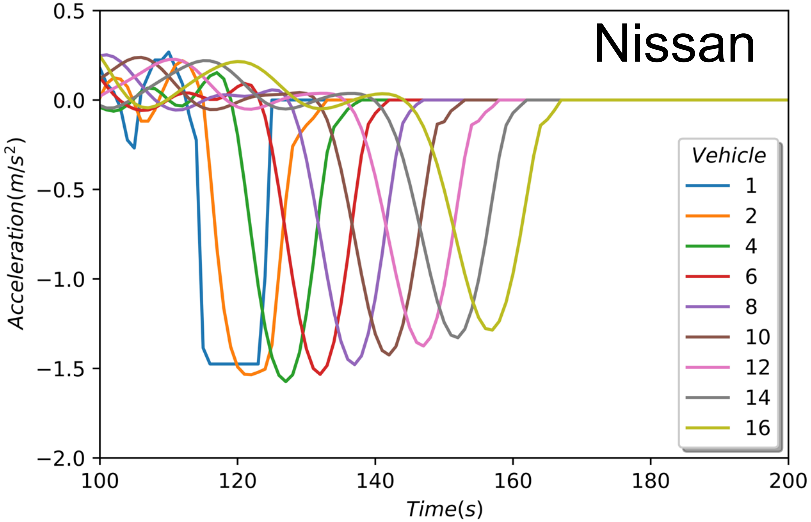


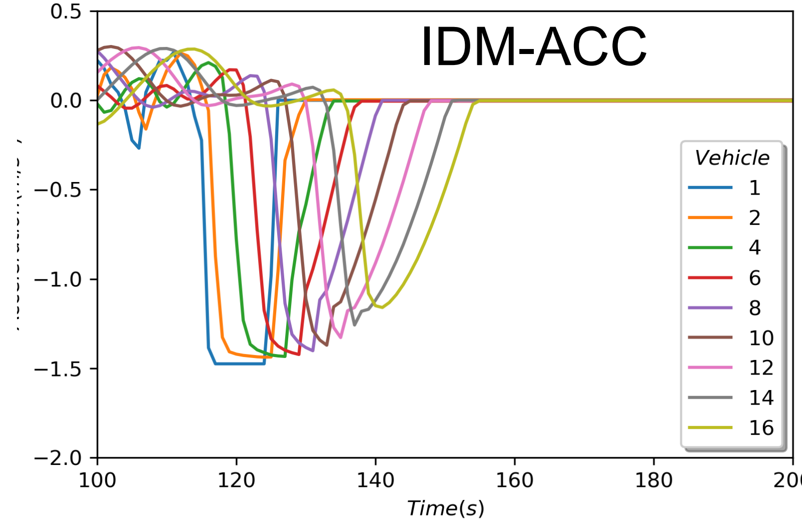
Car-Following Models

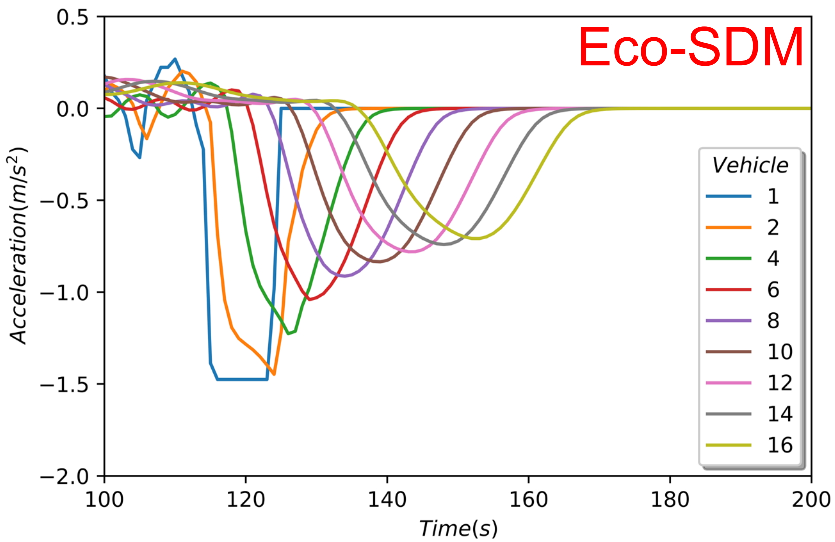
- Manually-Driven Vehichles
  - Intelligent Driver Model (IDM)

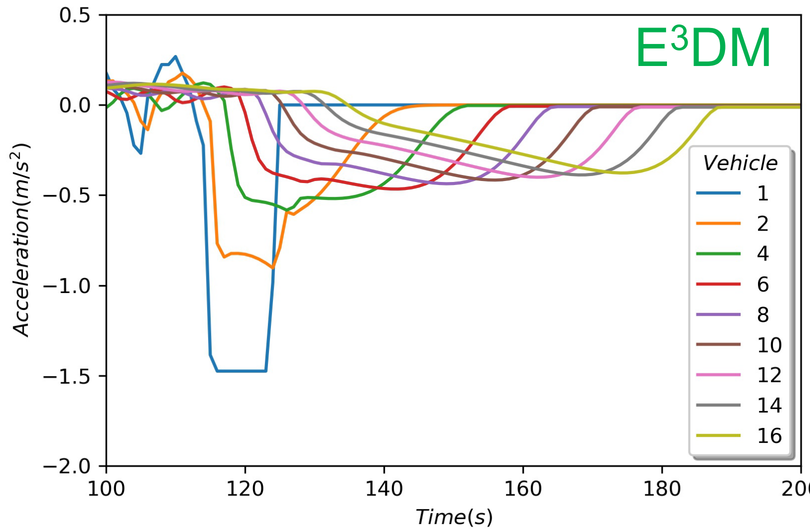
- (Cooperative) Adaptive Cruise Control
  - IDM-ACC
  - Nissan Model
  - Ecological Smart Driver Model (Eco-SDM)
  - Energy-Efficient Electric Driving Model (E^3DM)

Accelerations

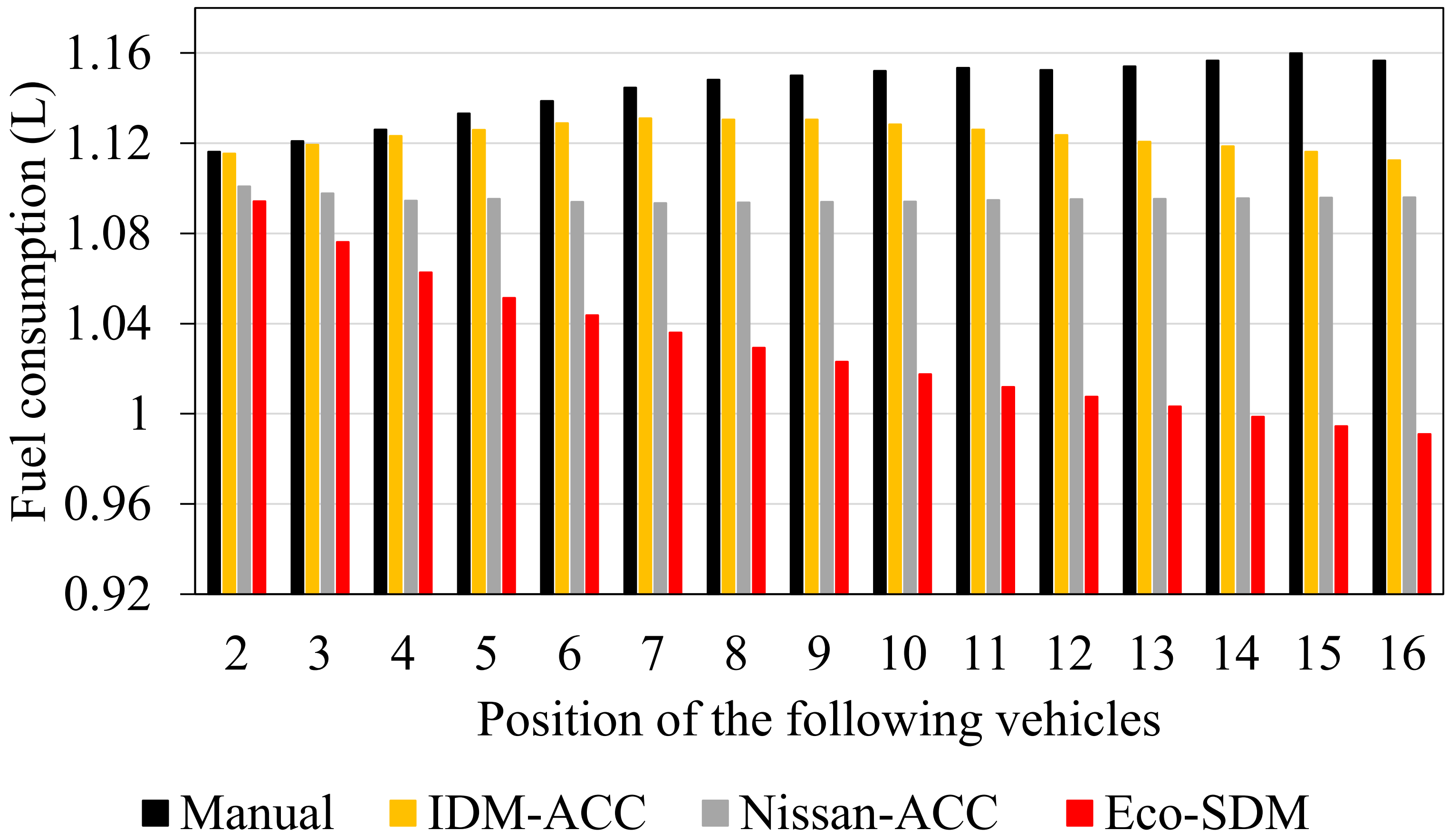




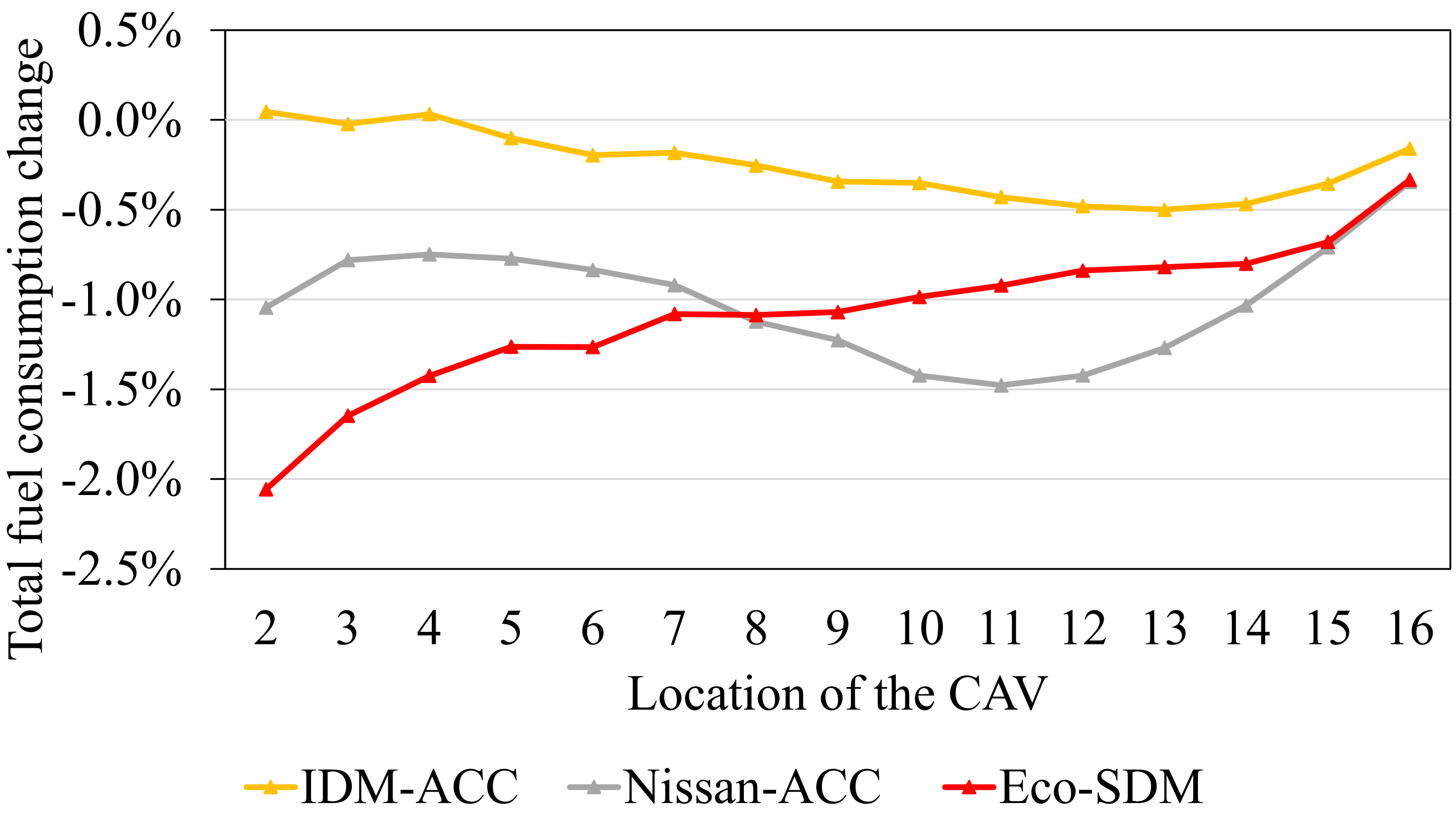




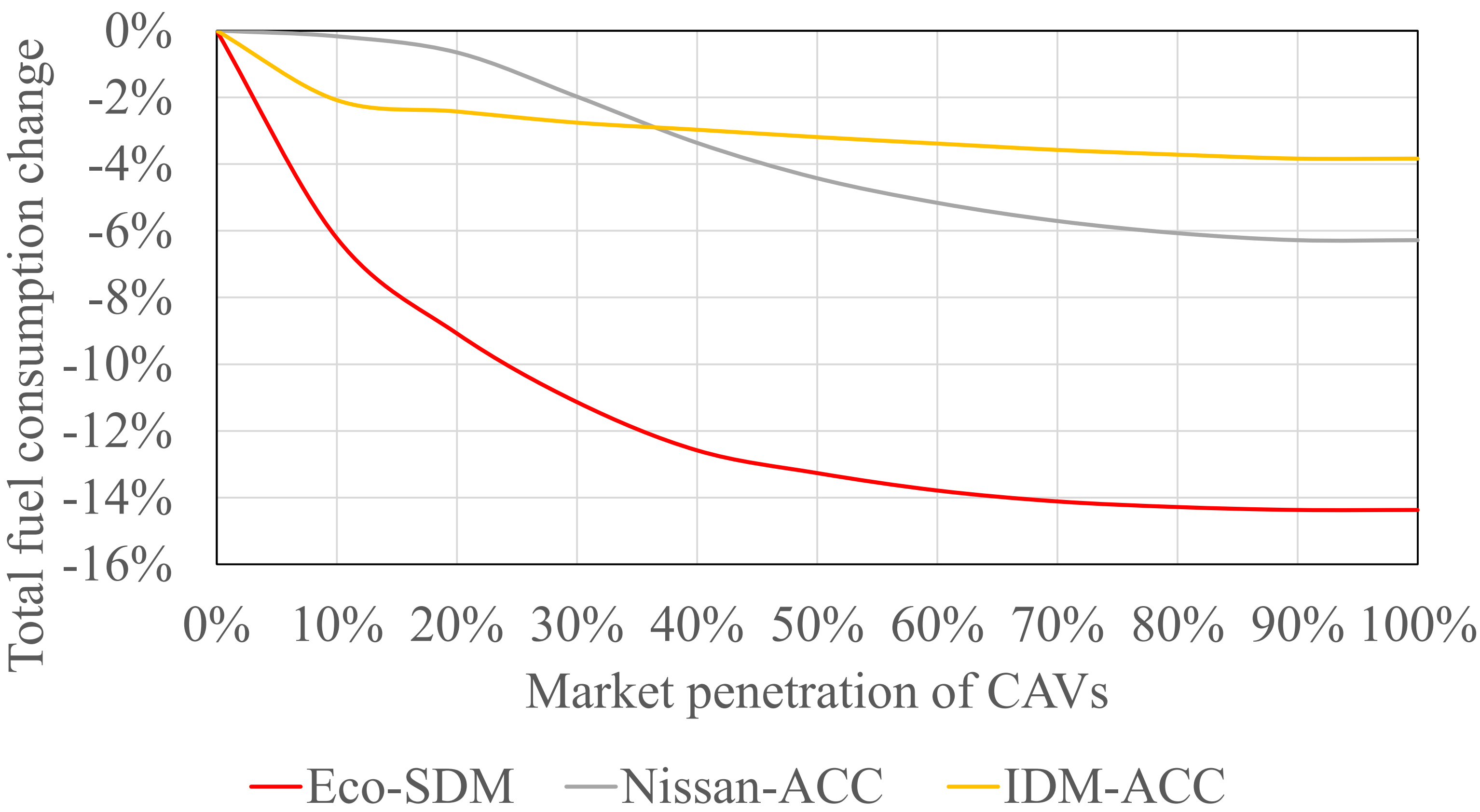
Scenario 1: All ICE-CAVs



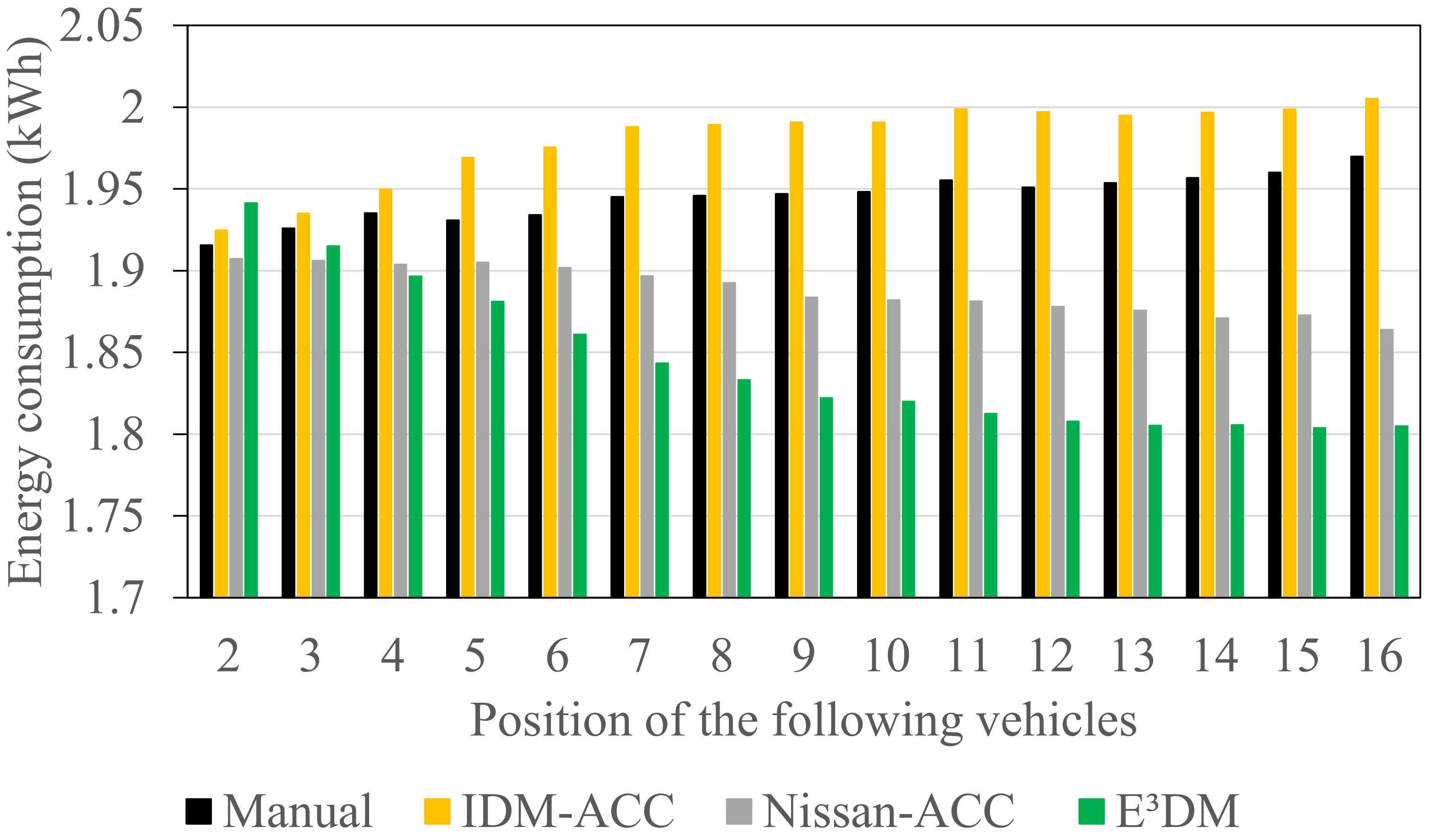
Scenario 2: One ICE-CAV at different position



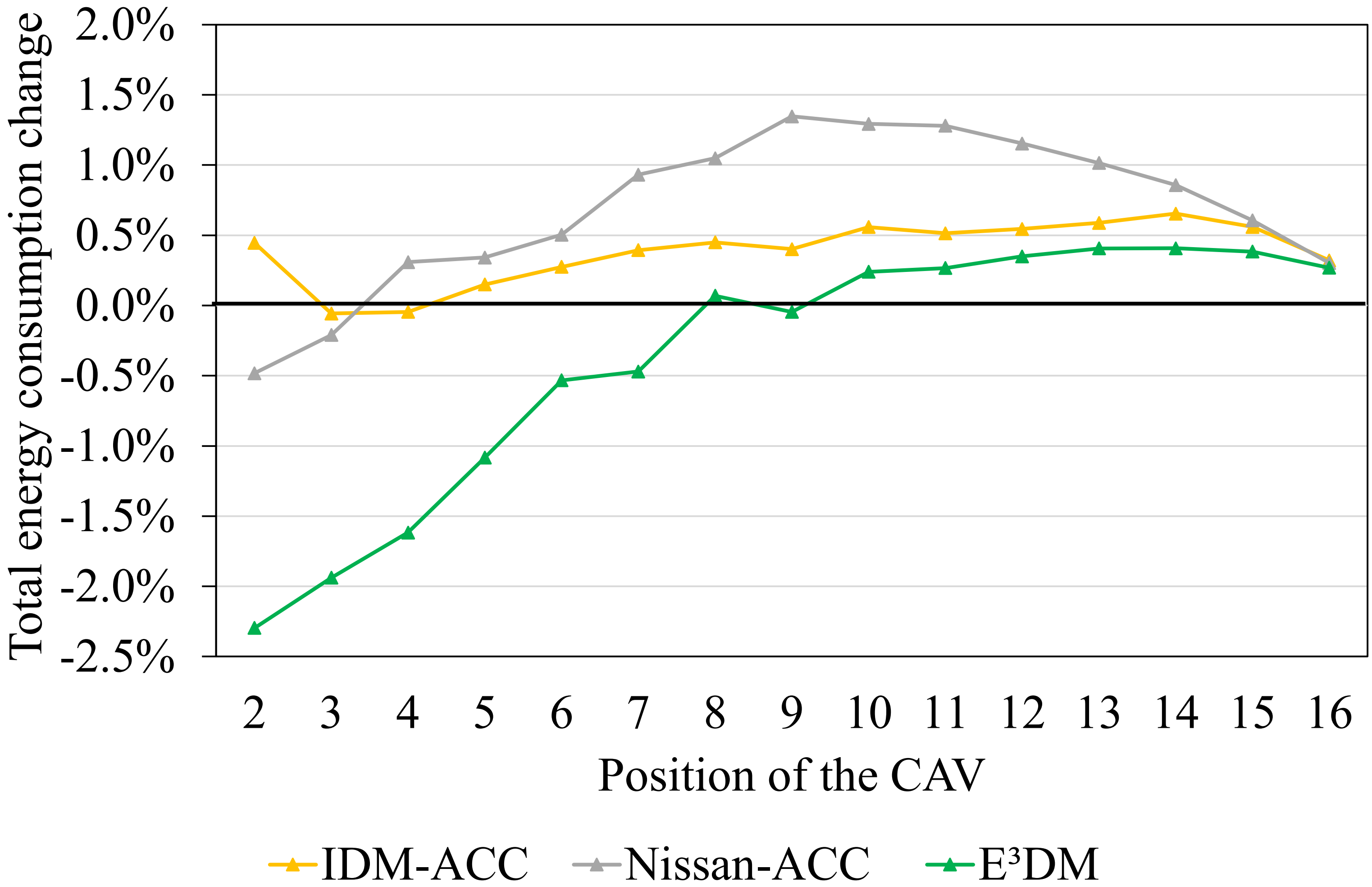
Scenario 3: Different % of ICE-CAVs



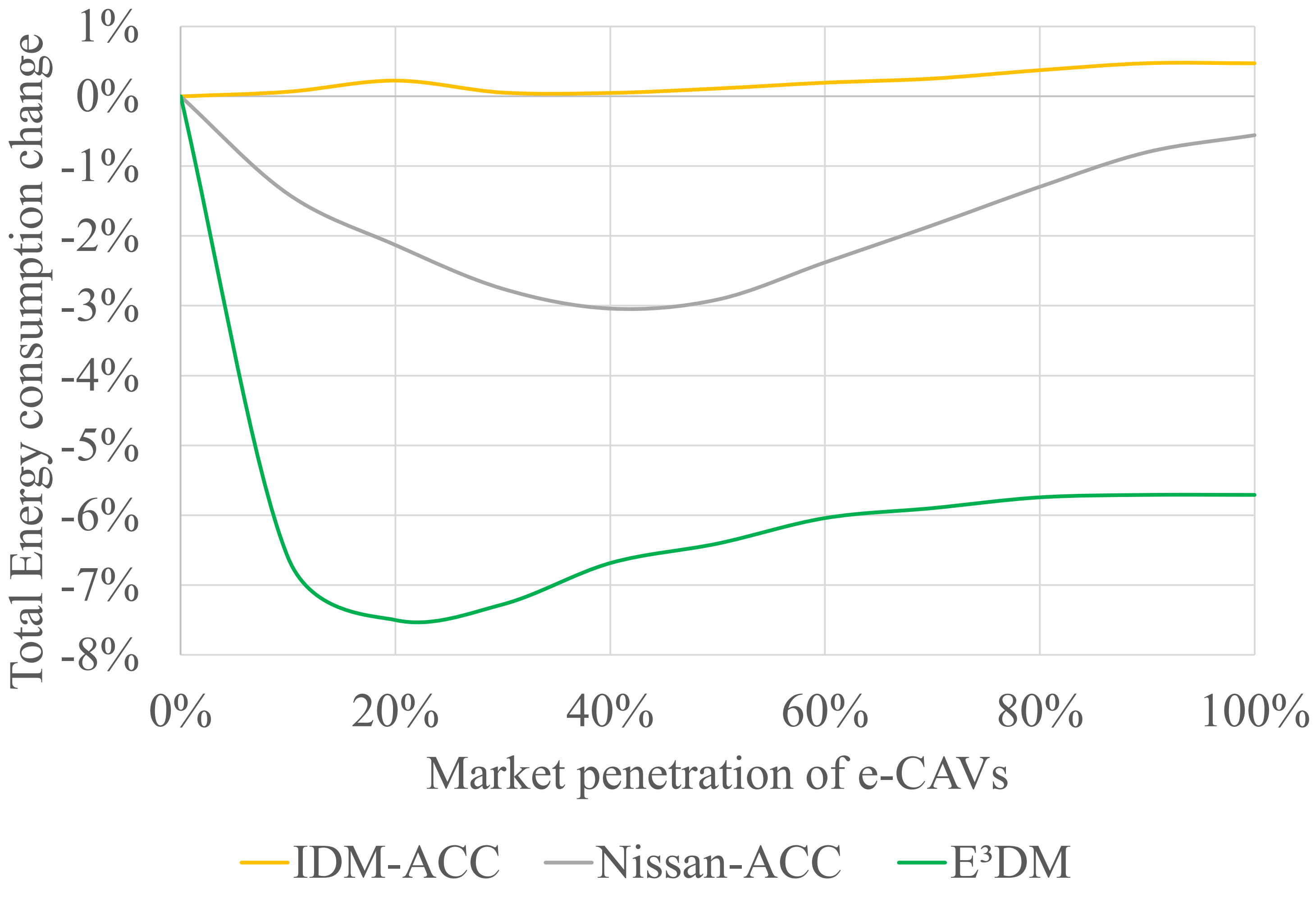
Scenario 4: All e-CAVs



Scenario 5: One e-CAV at different position



Scenario 6: Different % of e-CAVs



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^3DM
  - 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?

Corresponding author:
Dr. Jing Dong-O'Brien
jingdong@iastate.edu