Evaluating Energy and Emissions Impacts of Cooperative Adaptive Cruise Control (CACC) Technology through Traffic Microsimulations

Andrew Eilbert, Lauren Jackson, George Noel, Brian O’Donnell (SGT), and Scott Smith
Automated Vehicles Symposium 2017
Breakout 9: Effects of Vehicle Automation on Energy-Usage and Emissions

July 11, 2017
Framework for Automated Vehicle Benefits

- “Big picture” of automated vehicle impacts
- Short-term direct impacts
- Longer-term indirect impacts

- Focus on the relationship between the vehicle operations and energy/emissions
- Connected a traffic microsimulation software (PTV Vissim) with EPA’s emission inventory model for highway vehicles (MOVES)
Modeling Approach

- Produce 15 random Vissim seeds from speed distribution
- Process Vissim output to create operating mode distributions
- Apply Vissim modeled roadway network in MOVES
- Run MOVES model and analyze emission results
Vehicle Automation Scenarios

- Modeled passenger cars on Interstate 91 northbound near Springfield, MA
- Speeds and traffic volumes from MassDOT
  - Speed data from sensor on I-91 north of Springfield, MA
  - Volume data from peak weekday morning hour by highway segment
- Modified CACC Driver Model DLL from Turner-Fairbank Highway Research Center (FHWA)
  - Does not include platooning, lane change, or designated lane
- Ran three different microsimulation scenarios in Vissim:
  1) Baseline with default Wiedemann 99 car-following algorithm
  2) All vehicles using CACC driver model
  3) Default Wiedemann 99 algorithm with traffic oscillations set to zero
- MOVES project-level emissions calculated on a per vehicle basis for each scenario (grams/vehicle/hour)
Map of I-91 Network
Input I-91 Traffic Speeds and Volumes

Cumulative Distribution Function of Speeds on I-91 Northbound in April 2017

Input Volumes for Northbound I91 Network

<table>
<thead>
<tr>
<th>Link ID</th>
<th>Link Description</th>
<th>Date</th>
<th>Day of Week</th>
<th>AM Peak Time</th>
<th>AM Peak Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1. I91 North</td>
<td>3/10/2017</td>
<td>Friday</td>
<td>7:00-8:00</td>
<td>2562</td>
</tr>
<tr>
<td>200</td>
<td>On Ramp (US-5, I91 North, Holyoke, Greenfield)</td>
<td>7/9/1997</td>
<td>Wednesday</td>
<td>7:00-8:00</td>
<td>714</td>
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<tr>
<td>205</td>
<td>On Ramp (US-5 to I91 North)</td>
<td>11/13/2001</td>
<td>Monday</td>
<td>7:00-8:00</td>
<td>1045</td>
</tr>
<tr>
<td>305</td>
<td>Off Ramp (Exit 3/North 5 to 57, Agawam)</td>
<td>4/17/2015</td>
<td>Friday</td>
<td>7:00-8:00</td>
<td>317</td>
</tr>
<tr>
<td>209</td>
<td>On Ramp (I91 North, Holyoke, Greenfield)</td>
<td>4/17/2015</td>
<td>Friday</td>
<td>7:00-8:00</td>
<td>351</td>
</tr>
<tr>
<td>210</td>
<td>On Ramp (I91 North, Holyoke, Greenfield)</td>
<td>4/17/2015</td>
<td>Friday</td>
<td>7:00-8:00</td>
<td>92</td>
</tr>
</tbody>
</table>

Input Cumulative Distribution

Normal Cumulative Distribution
Network Performance

- Box plots of speeds for each link
  - 25th percentile, median, 75th percentile, mean (red dot)

![Box plots of speeds for each link: Baseline and CACC](image-url)
Vehicle-specific power (VSP) and emissions are well correlated.

VSP is derived from instantaneous speed and acceleration along with other constants such as vehicle mass and aerodynamic drag.

- Microsimulations run at 10 Hz.

MOVES operating modes assigned according to VSP and speed bins.

- Separate op modes for braking (opModelID 0) and idling (opModelID 1).

Operating Mode Distributions

I-91 Springfield Link 101
Emission and Energy Impacts

AV Benefits I-91 Springfield Normalized Energy Ranges

AV Benefits I-91 Springfield PM2.5 Emissions Ranges
Conclusions and Future Work

- **Results**
  - Automated vehicles generally show less braking, leave less headway, and have less fluctuations in speed and acceleration than baseline
  - Results are more pronounced for congested links
    - CACC has less of an effect on energy and emissions in freely flowing traffic
  - Traffic smoothing through setting the Wiedemann oscillations to zero does not have much benefit over the default car-following algorithm
  - DLL needs to be thoroughly tested and validated

- **Next Steps**
  - Vary traffic volumes to simulate higher densities of vehicles
    - Expect automation to matter more for heavily congested scenarios
  - Experiment with different penetrations of CACC-enabled vehicles
  - Investigate lane changing capabilities to accommodate merging and weaving
For More Information

http://www.dot.gov/

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Sponsorship through US DOT Intelligent Transportation Systems Joint Program Office (ITS JPO)
Extra Slides
Network Energy and Emissions Impacts

AV Benefits I-91 Springfield Normalized Energy Ranges

AV Benefits I-91 Springfield PM2.5 Normalized Emission Ranges

factor(scenario)

- baseline
- smartcar_dll
- wiedemann

Energy Rate (MMBTU/veh/hr)

Emission Rate (g/veh/hr)
Road Test of CAV Eco-ACC on Rolling Terrain

Jia Hu, Ph.D.
Research Associate, Office of Operations R&D
Federal Highway Administration

Jiaqi Ma, Ph.D.
Research Scientist / Project Manager
Leidos, Inc

U.S. Department of Transportation
FEDERAL HIGHWAY ADMINISTRATION
This vehicle controller optimizes fuel consumption by giving speed and powertrain commends to CAVs.
Eco-drive Control Breakdown

- **Powertrain**
- **Transmission**
- **Battery Usage**

**Cruise Control**

**Power Request Optimization**
- 8-20% Savings

**Power Efficiency Optimization**
- 15-25% Savings
Formulation (Regular Vehicle)

• Cost Function is defined as:

\[ J = \psi(x_{tf}) + \int_{t_0}^{t_f} L(x, F) \, dt \]

• where \( \psi(x_v(T)) \) is the terminal cost and \( L(x_v, u_1) \) is the running cost

\[ \psi(x_{tf}) = \gamma_1(x_1(t_f) - v_i(t_f-t_0))^2 + \gamma_2(x_2(t_f) - v_i)^2 \]

\[ L(x, F) = w_1 \frac{\dot{m}_{fuel}}{\text{Cost}_{\text{fuel}}} + w_2 \frac{(x_2(t) - v_i)^2}{\text{Cost}_{\text{mobility}}} + w_3 \frac{(F - F_{\text{res}})^2}{\text{Cost}_{\text{comfort}}} \]

\[ \dot{m}_{fuel}(T_e, n, x_2) = \beta_0 T_e n x_2 + \beta_1 T_e + \beta_2 n x_2 + \beta_3 + \beta_4 (n x_2)^2 \]
\[ L = (1 - g_2)((1 - g_1)(1 - g_0)L_{00}(x, u) + g_0 L_{01}(x, u)) + g_1[(1 - g_0)L_{10}(x, u) + g_0 L_{11}(x, u)] + g_2 L_b(x, F_b) \]

\[ H = g_0 g_1 g_2 G_1 + g_0 g_1 G_2 + g_0 g_2 G_3 + g_1 g_2 G_4 + g_0 G_5 + g_1 G_6 + g_2 G_7 + G_8 \]

where

\[
\begin{align*}
G_1 &= -\{(L_{00} - L_{01} + L_{11} - L_{10}) + \lambda^T(f_{00} - f_{01} + f_{11} - f_{10})\} \\
G_2 &= (L_{00} - L_{01} + L_{11} - L_{10}) + \lambda^T(f_{00} - f_{01} + f_{11} - f_{10}) \\
G_3 &= -\{(L_{01} - L_{00}) + \lambda^T(f_{01} - f_{00})\} \\
G_4 &= -\{(L_{10} - L_{00}) + \lambda^T(f_{10} - f_{00})\} \\
G_5 &= (L_{01} - L_{00}) + \lambda^T(f_{01} - f_{00}) \\
G_6 &= (L_{10} - L_{00}) + \lambda^T(f_{10} - f_{00}) \\
G_7 &= (L_b - L_{00}) + \lambda^T(f_b - f_{00}) \\
G_8 &= L_{00} + \lambda^T f_{00}
\end{align*}
\]

• Control law:

\[ u(t) = (-m \cdot n \cdot \lambda_2(t) - w_1 \cdot m^2[\beta_0 \cdot n \cdot x_2(t) + \beta_1] + 2 \cdot n \cdot w_3 F_{res}) / (2n^2 \cdot w_3) \]
Eco-ACC on Rolling Terrain Results

![Bar chart showing fuel consumption and improvement results for Major Arterial (Long), Collector Road, and Collector Road (Long) for different optimization methods.]
Eco-drive Tests

Field Test

Hardware in the Loop Simulation

2016.12-2017.10

2017.4-2018.4
Connected Automation Platform

Features

Rugged development platform to support connected vehicle and automation research
Data Collection Flow Chart

PC

<table>
<thead>
<tr>
<th>ETHERNET</th>
</tr>
</thead>
<tbody>
<tr>
<td>PINPOINT GPS</td>
</tr>
<tr>
<td>IMU</td>
</tr>
</tbody>
</table>

| MICRO-AUTOBOX |
| FUEL RATE |
| MASS AIR FLOW |
| SPEED |

| CAN |
| CAN LOGGER |
| ODOMETER |
Control Implementation

P = 10
I = 0.01
D = 0.1
Upper Sat = 100%
Lower Sat = -5%
1. George Washington Pkwy between I-495 and Memorial Bridge (8*2=16mi)
2. River Road: town of Potomac – end (6.5*2=13 mi)
3. Georgetown Pike – test sites (2*2=4 mi)
4. Georgetown Pike (between VA-7 and VA-123) Beltway - Great Falls (4.5 *2=9 mi)
5. US-17 between I-66 and Warrenton (8*2)
### Field Test Results: Georgetown Pike

#### WESTBOUND WRENCH EFFORT, PID=10,0.01,0.1, PROFILE A10S45I1

<table>
<thead>
<tr>
<th>Filename</th>
<th>Total (l)</th>
<th>Max (ml/min)</th>
<th>Min (ml/min)</th>
<th>Average (ml/min)</th>
<th>Total (cut) (l)</th>
<th>Savings</th>
<th>Run Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp1_028*</td>
<td>0.193</td>
<td>200.7</td>
<td>14.09</td>
<td>59.8</td>
<td>0.160</td>
<td>21.2%</td>
<td>163.0</td>
</tr>
<tr>
<td>exp1_029</td>
<td>0.193</td>
<td>206.3</td>
<td>1.203</td>
<td>59.6</td>
<td>0.160</td>
<td>21.2%</td>
<td>163.3</td>
</tr>
<tr>
<td>exp1_030</td>
<td>0.228</td>
<td>357.3</td>
<td>1.003</td>
<td>68.7</td>
<td>0.175</td>
<td>13.8%</td>
<td>163.6</td>
</tr>
</tbody>
</table>

*Braking eliminated from this run

#### WESTBOUND WRENCH EFFORT, PID=10,0.01,0.1, PROFILE A10

<table>
<thead>
<tr>
<th>Filename</th>
<th>Total (l)</th>
<th>Max (ml/min)</th>
<th>Min (ml/min)</th>
<th>Average (ml/min)</th>
<th>Total (cut) (l)</th>
<th>Savings</th>
<th>Run Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp1_031</td>
<td>0.211</td>
<td>200.7</td>
<td>1.937</td>
<td>65.5</td>
<td>0.175</td>
<td>13.8%</td>
<td>163.3</td>
</tr>
<tr>
<td>exp1_032</td>
<td>0.214</td>
<td>222.0</td>
<td>2.115</td>
<td>66.3</td>
<td>0.177</td>
<td>12.8%</td>
<td>162.7</td>
</tr>
</tbody>
</table>

#### WESTBOUND WRENCH EFFORT, PID=10,0.01,0.1, PROFILE A10S45

<table>
<thead>
<tr>
<th>Filename</th>
<th>Total (l)</th>
<th>Max (ml/min)</th>
<th>Min (ml/min)</th>
<th>Average (ml/min)</th>
<th>Total (cut) (l)</th>
<th>Savings</th>
<th>Run Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp1_036</td>
<td>0.215</td>
<td>225.4</td>
<td>1.988</td>
<td>66.9</td>
<td>0.177</td>
<td>12.8%</td>
<td>162.5</td>
</tr>
<tr>
<td>exp1_037</td>
<td>0.217</td>
<td>225.4</td>
<td>1.296</td>
<td>67.3</td>
<td>0.180</td>
<td>11.3%</td>
<td>162.6</td>
</tr>
</tbody>
</table>

Road segment surrounding stoplight was cut from all datasets
Speed Profile: Georgetown Pike

River Rd Northbound Speeds for exp1_056 (2017-04-09)

River Rd Northbound Speeds for exp1_054 (2017-04-09)
More Data for Statistical Analysis
Contact

• Email: jh8dn@virginia.edu

• ResearchGate Link
  – https://www.researchgate.net/profile/Jia_Hu15
  – All my related papers are available through the link
Estimating Energy Efficiency of Connected and Autonomous Vehicles in a Mixed Fleet

Liang Hu, Chaoru Lu, Jing Dong, and Jie Yang

7/11/2017

AVS 2017, San Francisco, CA
Introduction

Car-following models

Lead vehicle

On-road fuel/energy economy data

Fuel/Energy consumption models

Energy efficiency

Velocity & Acceleration

Methods

Results

Summary
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

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Manual vehicle</th>
<th>CAV</th>
<th>Nissan</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired velocity $v_0$</td>
<td></td>
<td>33.3 m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free acceleration exponent $d$</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desired time gap $T$</td>
<td></td>
<td>1.5 sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standstill distance $s_0$</td>
<td></td>
<td>2 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration range $a$</td>
<td>-6 ~ 1.4 m/s²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desired deceleration $b$</td>
<td>2 m/s²</td>
<td>2 m/s²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coolness factor $c$</td>
<td></td>
<td>0.99</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^1$Kesting et al., 2010. $^2$Shladover et al., 2012.
The proposed car-following model

\[ a_{CAV} = a - \frac{a + \frac{V_n^2 - V_{n-1}^2}{2\Delta x}}{\exp\left(\frac{\Delta x}{s_0 + V_n \times T} - 1 - \alpha \times \frac{V_n}{V_{max}} \times \frac{(V_{max} - V_n)}{V_{max}}\right)} \]

\[ \alpha = \begin{cases} \frac{1}{\ln(position of the target CAV)} + 1, & \text{if lead vehicle is manual} \\ 1, & \text{else} \end{cases} \]
Fuel consumption model of GVs

- The VT-Micro fuel consumption model

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

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

*FC*: instantaneous fuel consumption, mL/s;
*v*: vehicle velocity, m/s;
*a*: vehicle acceleration, m/s²;
*L_{i,j}*: regression coefficients;
*M_{i,j}*: regression coefficients.
Fuel consumption model of GVs

- Calibrated and validated model using OBD-II data

<table>
<thead>
<tr>
<th></th>
<th>$a \geq 0$</th>
<th>$a &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted $R^2$</td>
<td>0.8245</td>
<td>0.6616</td>
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</table>

### Constants and Coefficients

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

<table>
<thead>
<tr>
<th></th>
<th>Constant</th>
<th>$v^1$</th>
<th>$v^2$</th>
<th>$v^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a &lt; 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-7.89E-01</td>
<td>-2.14E-02</td>
<td>5.61E-03</td>
<td>-9.16E-05</td>
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<tr>
<td>$a^1$</td>
<td>2.83E-01</td>
<td>-1.02E-01</td>
<td>2.01E-02</td>
<td>-4.43E-04</td>
</tr>
<tr>
<td>$a^2$</td>
<td>1.39E-01</td>
<td>-7.45E-02</td>
<td>1.40E-02</td>
<td>-3.44E-04</td>
</tr>
<tr>
<td>$a^3$</td>
<td>9.13E-03</td>
<td>-9.58E-03</td>
<td>2.16E-03</td>
<td>-5.77E-05</td>
</tr>
</tbody>
</table>
Energy consumption model of EVs

- Power-based model considering regenerative braking

\[ EC = b_0 + b_1 VSP + b_2 P_{aux} \]

\[ VSP = v(1.1a + C_{rr}) + C_{aero}v^3 \]

\[ \ln P_{aux} = c_0 + c_1 T \]

- \( EC \): instantaneous energy consumption (+/-), W;
- \( VSP \): vehicle specific power, W/kg;
- \( P_{aux} \): vehicle auxiliary load, W;
- \( v \): vehicle velocity, m/s;
- \( a \): vehicle acceleration, m/s²;
- \( C_{rr} \): rolling resistance coefficient, N/kg;
- \( C_{aero} \): aerodynamics drag coefficient, N s²/m² kg;
- \( T \): ambient temperature, °C;

\[ b, c \]: regression coefficients.

Introduction

Methods

Results

Summary
Energy consumption model of EVs

- Calibrated and validated model using OBD-II data.

![Graph showing actual vs. estimated trip energy consumption (kWh) with a linear model.](image)

<table>
<thead>
<tr>
<th>VSP</th>
<th>$v$</th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>$b_2$</th>
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</thead>
<tbody>
<tr>
<td>&gt;0</td>
<td>$&lt;12.5$</td>
<td>$3.22E+03$</td>
<td>$1.16E+03$</td>
<td>$2.15E+00$</td>
</tr>
<tr>
<td></td>
<td>$\geq 12.5$</td>
<td>$8.43E+03$</td>
<td>$7.57E+02$</td>
<td>$2.60E+00$</td>
</tr>
<tr>
<td>=0</td>
<td>$&lt;12.5$</td>
<td>$6.10E+02$</td>
<td>—</td>
<td>$1.19E+00$</td>
</tr>
<tr>
<td></td>
<td>$\geq 12.5$</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>&lt;0</td>
<td>$&lt;12.5$</td>
<td>$7.20E+02$</td>
<td>$5.58E+02$</td>
<td>$2.10E+00$</td>
</tr>
<tr>
<td></td>
<td>$\geq 12.5$</td>
<td>$8.12E+03$</td>
<td>$5.94E+02$</td>
<td>$2.57E+00$</td>
</tr>
</tbody>
</table>
All gasoline-CAVs in the fleet

<table>
<thead>
<tr>
<th>Position of CAVs</th>
<th>CAV_IDM</th>
<th>CAV_Nissan</th>
<th>CAV_Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1.6%</td>
<td>-4.0%</td>
<td>-9.0%</td>
</tr>
</tbody>
</table>

CAV fuel consumption (L)
One CAV at different position

Fleet fuel consumption change

Position of the CAV

CAV_IDM  CAV_Nissan  CAV_Proposed

Introduction  Methods  Results  Summary
Different market penetration of CAVs

![Graph showing fleet fuel consumption change vs. market penetration of CAVs for CAV_IDM, CAV_Nissan, and CAV_Proposed.](image)

**CAV_IDM**

- Fleet fuel consumption change:
  - 0% market penetration: -10%
  - 10% market penetration: -8%
  - 20% market penetration: -6%
  - 30% market penetration: -4%
  - 40% market penetration: -2%
  - 50% market penetration: 0%
  - 60% market penetration: 2%
  - 70% market penetration: 4%
  - 80% market penetration: 6%
  - 90% market penetration: 8%
  - 100% market penetration: 10%

**CAV_Nissan**

- Fleet fuel consumption change:
  - 0% market penetration: -10%
  - 10% market penetration: -9%
  - 20% market penetration: -8%
  - 30% market penetration: -7%
  - 40% market penetration: -6%
  - 50% market penetration: -5%
  - 60% market penetration: -4%
  - 70% market penetration: -3%
  - 80% market penetration: -2%
  - 90% market penetration: -1%
  - 100% market penetration: 0%

**CAV_Proposed**

- Fleet fuel consumption change:
  - 0% market penetration: -10%
  - 10% market penetration: -9%
  - 20% market penetration: -8%
  - 30% market penetration: -7%
  - 40% market penetration: -6%
  - 50% market penetration: -5%
  - 60% market penetration: -4%
  - 70% market penetration: -3%
  - 80% market penetration: -2%
  - 90% market penetration: -1%
  - 100% market penetration: 0%
All electric-CAVs in the fleet

CAV energy consumption (kWh)

Position of CAVs

<table>
<thead>
<tr>
<th>Position</th>
<th>Manual</th>
<th>CAV_IDM</th>
<th>CAV_Nissan</th>
<th>CAV_Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-13</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
</tbody>
</table>

CAV_IDM: 1.9%
CAV_Nissan: -2.8%
CAV_Proposed: 2.8%
Summary

- **Gasoline vehicles, UDDS**
  - 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%.

- **Electric vehicles, UDDS**
  - CAV did not show energy saving benefit under urban driving conditions.
Thank you

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Leveraging Shared Autonomous Electric Vehicles as First/Last-Mile Connections for Transit

Farhan Javed, PhD
Tony Zhang
T. Donna Chen, PE, PhD
Cul-de-sac design

People with disability

Lack of pedestrian infrastructure

Bad weather
Data requirements

- Transit Ridership Data
- P&R License Plate Data
- Network Characteristics
- Mode of First/Last Mile Connection

Legend

- Tukwila_Station_Access_Origins
- Tukwila_Station_Access_Dest
- Tukwila_Station_Egress_Origins
- Tukwila_Station_Egress_Dest
- License Plate Data

Access Mode

- Bicycled
- Walked
- Dropped-off
- Bus
- P&R

Sources: ESRI, HERE, Google, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia @OpenStreetMap contributors, and the GIS User Community.
Network Mapping/Simulation Visualization
Simulation Environment

- Real time update of vehicle status
- Edge Weighted Digraph for the use of the Dijkstra's Algorithm
- Vehicle capacity constraint (4 seats)
- Service constraint (10 min window)
Results

Fleet Size 200

Number of Vehicles in Use

Time (hours)

Percentage of Trips Served

Average: 92.43%
Results

Average VMT: 181 mi
Application

- Transit Operator
- Service Pricing
- Energy Consumption
- SAEV Policy