Leveraging CAVs to Reduce Transportation System Energy/Fuel Consumption

Hesham A. Rakha, Ph.D., P.Eng.  
**Director**, Center for Sustainable Mobility

Samuel Reynolds Pritchard Professor of Engineering,  
Charles E. Via, Jr. Dept. of Civil & Environmental Engineering

**Courtesy Professor**, Bradley Dept. of Electrical and Computer Engineering
Proposed Eco-CAC System

Upper Level Strategic Controller
- Real-time Data Fusion
  - Strategic Speed Controller
  - Eco-router

Lower Level Controller
- Local Controller (Interrupted Flow): Eco-CACC-I
  - 1. SPaT Data
  - 2. MAP Data
  - 3. Topographical Data
  - Vehicle Dynamics Optimization
- Local Controller (Uninterrupted Flow): Eco-CACC-U
  - 1. User Input
  - 2. Topographical Data
  - Vehicle Dynamics Optimization
ENERGY/FUEL CONSUMPTION MODELING


VT-CPFM

• Virginia Tech Comprehensive Power-based Fuel consumption Model (VT-CPFM)

  \[ F(t) = \begin{cases} 
  \alpha_0 + \alpha_1 P(t) + \alpha_2 P(t)^2 & \forall P(t) > 0 \\
  \alpha_0 & \forall P(t) \leq 0 
  \end{cases} \]

  – Has the ability to produce a control system that does not result in bang-bang control and
  – Is easily calibrated using publicly available data without the need to gather detailed engine and fuel consumption data.
  – Estimates CO$_2$ emissions ($R^2=95\%$)

Where:
\( \alpha_0, \alpha_1, \alpha_2 \) are model constants that require calibration,
\( P(t) \) is the instantaneous total power in kilowatts (kW) at instant \( t \), and
\( w(t) \) is the engine speed at instant \( t \).
VT-CPEM

- Virginia Tech Comprehensive Power-based electric Energy consumption Model (VT-CPEM)
  - Energy consumption:
    
    \[ P(t) = \left( \frac{R(t)+(1+\lambda)ma(t)}{3600\eta_d} \right) \nu(t) \]

  - Energy regeneration:
    
    \[ \eta_{rb}(t) = \begin{cases} 
    \left[ e^{\frac{a}{|a(t)|}} \right]^{-1} & \forall a(t) < 0 \\
    0 & \forall a(t) \geq 0 
    \end{cases} \]

    \[ P_{re}(t) = P_{neg} \times \eta_{rb}(t) \]


Eco-routing

• Problem: Traditional energy calculation from mesoscopic modeling use single variable: average speed
Proposed CAV Eco-routing Algorithm

- Developed a vehicle-agnostic approach to collect transient vehicle data in real-time
  - Entire vehicle trajectory captured using 8 link-specific variables
- Data are sent to the cloud to be fused with existing data and then sent back to CAVs
  - Vehicle-specific link cost computed using the combination of vehicle parameters and the 8 link-specific variables
- Algorithm was implemented in INTEGRATION to generate
  - A dynamic stochastic incremental multi-class user-equilibrium traffic assignment
    - Minimum paths computed using the Dijkstra algorithm

### Proposed CAV Eco-routing Algorithm

<table>
<thead>
<tr>
<th></th>
<th>ICEV (ORNL)</th>
<th>BEV (Nissan Leaf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eco Routing</td>
<td>Eco Routing</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>50%</td>
</tr>
<tr>
<td>Cleveland</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy(kw)/Fuel(l)</td>
<td>0.57</td>
<td>0.56</td>
</tr>
<tr>
<td>Energy/Fuel saving</td>
<td>1.9%</td>
<td>4.8%</td>
</tr>
<tr>
<td>Travel time (s)</td>
<td>315</td>
<td>323</td>
</tr>
<tr>
<td>Delay (s)</td>
<td>76.2</td>
<td>81.5</td>
</tr>
<tr>
<td>Columbus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy(kw)/Fuel(l)</td>
<td>0.67</td>
<td>0.65</td>
</tr>
<tr>
<td>Energy/Fuel saving</td>
<td>2.27%</td>
<td>5.01%</td>
</tr>
<tr>
<td>Travel time (s)</td>
<td>314</td>
<td>323</td>
</tr>
<tr>
<td>Delay (s)</td>
<td>65.1</td>
<td>71.2</td>
</tr>
</tbody>
</table>
Dynamic Eco-routing Considering Communication System
Dynamic Eco-routing Considering Communication System

- Tested the model on downtown LA (demand of 530K vehicle trips)
  - The results show that in both the ideal and realistic communication cases, FB-ECO operates efficiently at technology market penetration rates between 20% and 30%
  - The VANET communication network performance (packet drop and delay) can have significant effects on the dynamic eco-routing system performance, especially in highly congested networks
  - At LMPs of 75% and higher delays were considerable resulting in network gridlock
STRATEGIC SPEED CONTROLLER


SPD-HARM Algorithm

- Developed a bang-bang feedback controller
  - Proactively regulate the flow of traffic approaching a freeway bottleneck
Algorithm Development, Modeling, Field Implementation and Testing

- Developed SPD-HARM algorithm
- I-66 test bed proof of concept and field testing
  - Supported Leidos and FHWA run three vehicles across all three lanes of I-66
- Conducted simulation testing considering different levels of market penetration
Study Conclusions

• The SH algorithm increases the discharge rate of the bottleneck.
  – Increases by up to 2% with reductions in vehicular delay by approximately 20%;
• The algorithm reduces vehicle emissions and fuel consumption levels.
  – At MPR=100%, CO₂ and fuel consumption can be reduced by approximately 3.5%;
• When CAV MPR is very low, benefits of the SH algorithm cannot be observed, as non-CAV vehicles do not follow the control algorithm;
  – An MPR=10% is sufficient for the SH algorithm to work successfully.
• For the study section, a CAV flow of 400 veh/h (167 veh/h/lane) is sufficient to obtain significant savings in trip delays, emissions and fuel consumption levels.
Strategic Speed Controller

- Developed a variable structure feedback controller
  - CAV-based algorithm regulates the flow of traffic approaching congested regions within a transportation system
Strategic Speed Controller

• Challenge:
  – In real networks we find it difficult to identify homogenous congested signalized regions

• Modified approach:
  – Use strategic speed controller on freeways to regulate the flow of traffic approaching congested regions
    • Dynamic CAV SPD-HARM algorithm
      – Bottlenecks and control links together with control strategy computed in real-time
    – Use data gathered by CAVs to operate a DNB traffic signal controller


Proposed System Overview

• We developed an Eco-CACC system to compute the optimum vehicle trajectory
  – Using I2V and V2V communication
  – Explicitly optimizing vehicle fuel consumption
Queue Prediction

• The model predicts the time at which the queue will be dissipated using kinematic wave theory.
Modeling Results

- Benefits increase with increased market penetration
- Multi-lane approaches more challenging to deal with
Field Implementation and Testing

- The system was implemented in an ACC-equipped vehicle and tested on the VDOT Smart Road
  - A total of 32 subjects were recruited
    - Equal male and female participants
  - Four scenarios:
    - S1: Uninformed driver
    - S2: In-vehicle indication count-down display
    - S3: In-vehicle audio speed recommendation every 2 seconds
    - S4: L2 automation from 250m upstream of the intersection to 180m downstream
Field Results

- The automated Eco-CACC system reduced fuel consumption levels and travel time by up to 39 and 9 percent, respectively.
- The manual Eco-CACC system reduced fuel consumption levels and travel time by nearly 13 and 9 percent, respectively.
## Results for EVs

<table>
<thead>
<tr>
<th>OD Demand</th>
<th>Test Scenario</th>
<th>Average Energy Consumption (KW)</th>
<th>Average Total Delay (sec)</th>
<th>Average Vehicle Stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>25% Demand</td>
<td>Without Eco-CACC-I</td>
<td>942.63</td>
<td>31.65</td>
<td>1.87</td>
</tr>
<tr>
<td></td>
<td>With Eco-CACC-I</td>
<td>854.93</td>
<td>30.41</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td>Reduction</td>
<td>9.3%</td>
<td>3.9%</td>
<td>23.0%</td>
</tr>
<tr>
<td>50% Demand</td>
<td>Without Eco-CACC-I</td>
<td>880.92</td>
<td>38.41</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>With Eco-CACC-I</td>
<td>815.6</td>
<td>36.98</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>Reduction</td>
<td>7.4%</td>
<td>3.7%</td>
<td>20.3%</td>
</tr>
<tr>
<td>75% Demand</td>
<td>Without Eco-CACC-I</td>
<td>851.13</td>
<td>55.67</td>
<td>2.12</td>
</tr>
<tr>
<td></td>
<td>With Eco-CACC-I</td>
<td>810.97</td>
<td>50.42</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>Reduction</td>
<td>4.7%</td>
<td>9.4%</td>
<td>20.3%</td>
</tr>
<tr>
<td>100% Demand</td>
<td>Without Eco-CACC-I</td>
<td>850.84</td>
<td>118.45</td>
<td>2.74</td>
</tr>
<tr>
<td></td>
<td>With Eco-CACC-I</td>
<td>832.95</td>
<td>112.43</td>
<td>1.98</td>
</tr>
<tr>
<td></td>
<td>Reduction</td>
<td>2.1%</td>
<td>5.1%</td>
<td>27.7%</td>
</tr>
</tbody>
</table>

### Comparison
- **EV**: Max. decel, Mid-range decel
- **ICEV**: Min. decel, Max. decel
Extension to Multiple Intersections

Control Region
ECO-CACC-U CONTROLLER


## Eco-CACC-U Controller
### Potential Benefits

<table>
<thead>
<tr>
<th></th>
<th>HC</th>
<th>CO</th>
<th>NO\textsubscript{x}</th>
<th>CO\textsubscript{2}</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VT-Micro Hwy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top 1 %</td>
<td>16 %</td>
<td>19 %</td>
<td>4 %</td>
<td>3 %</td>
<td>4 %</td>
</tr>
<tr>
<td>Top 2 %</td>
<td>24 %</td>
<td>30 %</td>
<td>7 %</td>
<td>6 %</td>
<td>7 %</td>
</tr>
<tr>
<td>Top 5 %</td>
<td>39 %</td>
<td>47 %</td>
<td>17 %</td>
<td>13 %</td>
<td>14 %</td>
</tr>
<tr>
<td>Top 10 %</td>
<td>54 %</td>
<td>64 %</td>
<td>32 %</td>
<td>23 %</td>
<td>25 %</td>
</tr>
<tr>
<td><strong>CMEM24 Hwy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top 1 %</td>
<td>20 %</td>
<td>38 %</td>
<td>30 %</td>
<td>3 %</td>
<td>5 %</td>
</tr>
<tr>
<td>Top 2 %</td>
<td>32 %</td>
<td>63 %</td>
<td>50 %</td>
<td>6 %</td>
<td>9 %</td>
</tr>
<tr>
<td>Top 5 %</td>
<td>52 %</td>
<td>80 %</td>
<td>73 %</td>
<td>14 %</td>
<td>17 %</td>
</tr>
<tr>
<td>Top 10 %</td>
<td>81 %</td>
<td>84 %</td>
<td>90 %</td>
<td>25 %</td>
<td>28 %</td>
</tr>
</tbody>
</table>
Eco-CACC-U Controller
Lead Vehicle Control

• The proposed predictive eco-cruise control system
  – Generates optimal vehicle controls using topographic data.
  – Optimizes the vehicle controls in advance using a dynamic programming (DP) implementation of Dijkstra’s shortest path algorithm.
  – Requires three system parameters:
    • Discretization distance (stage length), look-ahead distance, and optimization frequency.

• Three step optimization:
  – Discretize continuous search space
    • Use speed and gear levels to construct a graph
  – Prune search space using powertrain model
    • Speed and gear space within vehicle physical abilities for given topography
  – Compute optimum control (minimum path)
    • The vehicle speed and gear changes over each stage considering a penalty at transitions
Eco-CACC-U Controller
Lead Vehicle Control

- 2790 miles with mostly highway sections
  - Use I-80, I-76, I-70, I-15, and I-10 route
- Assumed no interaction with other vehicles
## Eco-CACC-U Controller
### Lead Vehicle Control

<table>
<thead>
<tr>
<th>Toyota Camry</th>
<th>Fuel (L)</th>
<th>MPG</th>
<th>Fuel Saving</th>
<th>TT (h)</th>
<th>Avg. Spd (mph)</th>
<th>σᵥ (mph)</th>
<th>ΔTT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>252.8</td>
<td>41.9</td>
<td></td>
<td>43.0</td>
<td>64.9</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Predictive (+5 &amp;-1 mph)</td>
<td>239.6</td>
<td>44.3</td>
<td>5.2%</td>
<td>43.3</td>
<td>64.4</td>
<td>1.2</td>
<td>0.8%</td>
</tr>
<tr>
<td>Conventional (Spd: 60.7mph)</td>
<td>239.2</td>
<td>44.3</td>
<td>5.4%</td>
<td>45.1</td>
<td>60.6</td>
<td>0.6</td>
<td>4.8%</td>
</tr>
<tr>
<td>Predictive (± 5 mph)</td>
<td>227.2</td>
<td>46.7</td>
<td>10.1%</td>
<td>46.0</td>
<td>60.7</td>
<td>2.0</td>
<td>7.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chevy Tahoe</th>
<th>Fuel (L)</th>
<th>MPG</th>
<th>Fuel Saving</th>
<th>TT (h)</th>
<th>Avg. Spd (mph)</th>
<th>σᵥ (mph)</th>
<th>ΔTT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>469.3</td>
<td>22.6</td>
<td></td>
<td>42.9</td>
<td>65.0</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Predictive (+5 &amp;-1 mph)</td>
<td>423.7</td>
<td>25.0</td>
<td>9.7%</td>
<td>43.5</td>
<td>64.1</td>
<td>0.7</td>
<td>1.4%</td>
</tr>
<tr>
<td>Conventional (Spd: 60.3mph)</td>
<td>431.4</td>
<td>24.6</td>
<td>8.1%</td>
<td>45.9</td>
<td>60.8</td>
<td>1.0</td>
<td>6.9%</td>
</tr>
<tr>
<td>Predictive (± 5 mph)</td>
<td>387.1</td>
<td>27.4</td>
<td>17.5%</td>
<td>46.3</td>
<td>60.3</td>
<td>1.2</td>
<td>7.9%</td>
</tr>
</tbody>
</table>
Eco-CACC-U Controller
Human Control

The vehicle dynamics model:

\[ a_n = f_a a_{\text{max}} \]

Throttle input function:

\[ f_a = e^{-g_1 X_n (1 - X_n^{g_2} e^{g_2 (1 - X_n)})^{g_3}} \]

Requires the calibration of 3 parameters \( g_1, g_2 \) and \( g_3 \)

Non-steady state Collision Avoidance:

\[ X_n = \frac{s_n}{\bar{s}_n} \cdot \frac{v_n}{\bar{v}_n} \]

Function of the actual and desired speed and distance gap.
Eco-CACC-U Controller
Human Control

- Noise signals:

\[
\begin{align*}
\overline{u_n}(t) &= u_n(t - \Delta t) - 0.01(s_{n+1} - s_j) \left( e^{-0.01} \cdot W_l(t - \Delta t) + \sqrt{0.02} \cdot N(0, 1) \right) \\
W_l(1) &= N(0, 1) \\
\overline{s_{n+1}}(t) &= s_{n+1}(t - \Delta t) \times e^{0.1 \left( e^{-0.01} \cdot W_s(t - \Delta t) + \sqrt{0.02} \cdot N(0, 1) \right)} \\
W_s(1) &= N(0, 1) \\
\ddot{a}_n(t) &= a_n(t) + N(0, 0.25)
\end{align*}
\]
Eco-CACC-U Controller
Automated Control

Accelerating

\[
d_{\text{max}}(t) = \frac{F(t) - R(t)}{m}
\]

\[
F = \min \left( \frac{3600 \eta_d P}{v}, m_{ta} g \mu \right)
\]

\[
R = \frac{\rho}{25.92} C_d C_h A_f v^2 + m g \frac{c_r^0}{1000} (c_r v + c_r^2) + mg G
\]

\[
m v = u [F - (R_a + R_r + R_g)]
\]

First order non-linear dynamical system in which the input is the signal \( u \) and the output is the car speed \( v \)

Decelerating

\[
d_{\text{max}}(t) = - \frac{F_{b, \text{max}}(t) + R(t)}{m}
\]

\[
F_{b, \text{max}} = mn_b g
\]

\[
R = \frac{\rho}{25.92} C_d C_h A_f v^2 + m g \frac{c_r^0}{1000} (c_r v + c_r^2) + mg G
\]

\[
m \frac{dv}{dt} = -u [F_{b, \text{max}} + R]
\]

Output signal \( u \) is capped at 1.0
Eco-CACC-U Controller
Automated Control

Immediate Leader

\[ e_{n1}(t) = (x_{n-1}(t) - x_n(t) - s_j) - h_{\text{desired}} \cdot v_n(t) \]

\[ v_n(t) = v_{i-1}(t) \]

\[ e_{n2}(t) = (x_1(t) - x_n(t) - s_j) - [(n - 1) \cdot h_{\text{desired}} \cdot v_n(t) + (n - 2) s_j] \]

Platoon Leader

Two PD controllers

\[ u_n(t) = u_{1n}(t) + u_{2n}(t) \]

\[ u_{1n}(t) = K_p e_{n1}(t) + K_d (v_{n-1} - v_n) \]

\[ u_{2n}(t) = \frac{K_p}{n} e_{n2}(t) + \frac{K_d}{n} (v_1 - v_n) \]
Eco-CACC-U Controller
Impact of Platooning on Drag Coefficient

![Graph of drag coefficient vs spacing and gap](image)

![Graph of percentage change in drag coefficient vs spacing and gap](image)
Questions?

Hesham A. Rakha
hrakha@vtti.vt.edu
540-231-1505