Overview of VTTI’s Environmental Connected Vehicle Research Activities

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Presentation Outline

- Eco-routing
  - Field and modeling results
- Eco-drive systems
- Eco-cooperative adaptive cruise control systems in the vicinity of signalized intersections
- Autonomous vehicle control
- On-going and future research initiatives
Connected Vehicle Eco-Routing Research
## Trip Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Highway</th>
<th>Arterial</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Travel Time (min)</td>
<td>25.63</td>
<td>29.9</td>
<td>4.27 (14%)</td>
</tr>
<tr>
<td>95 percentile of Travel time</td>
<td>36.25</td>
<td>37.86</td>
<td></td>
</tr>
<tr>
<td>5 percentile of Travel time</td>
<td>23.32</td>
<td>26.23</td>
<td></td>
</tr>
<tr>
<td>Std.Dev. of Travel Time (min)</td>
<td>4.17</td>
<td>5.08</td>
<td>0.91</td>
</tr>
<tr>
<td>Average Speed (mi/h)</td>
<td>53.39</td>
<td>35.39</td>
<td>18</td>
</tr>
<tr>
<td>Std. Deviation of Speed</td>
<td>6.39</td>
<td>4.94</td>
<td></td>
</tr>
<tr>
<td>95 percentile of Speed</td>
<td>58.85</td>
<td>39.44</td>
<td></td>
</tr>
<tr>
<td>5 percentile of Speed</td>
<td>37.04</td>
<td>27.46</td>
<td></td>
</tr>
<tr>
<td>Distance (mi)</td>
<td>22.44</td>
<td>17.25</td>
<td>5.19</td>
</tr>
</tbody>
</table>

HC Emissions

<table>
<thead>
<tr>
<th>Highway</th>
<th>Arterial</th>
<th>Highway</th>
<th>Arterial</th>
<th>Highway</th>
<th>Arterial</th>
<th>Highway</th>
<th>Arterial</th>
</tr>
</thead>
<tbody>
<tr>
<td>VT-Micro</td>
<td>MOBILE6</td>
<td>MOVES2010</td>
<td>CMEM24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HC (g)
# Contribution of High Engine Loads

<table>
<thead>
<tr>
<th></th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
<th>CO2</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>
System-wide Eco-Routing Impacts: The INTEGRATION Connected Vehicle Framework


Connected Vehicle Eco-routing Logic

- **Model initialization:**
  - Routes selected based on fuel consumption levels for travel at the facility’s free-flow speed

- **Feedback system:**
  - Vehicles report their fuel consumption experiences prior to exiting a link
  - Moving average fuel consumption estimate is recorded for each link for each of the five vehicle classes
  - Re-routing frequency defined by user
  - Independent white noise errors can also be introduced
    - Vehicle class dependent
Network-wide Testing

Columbus Network
Network Characteristics

- Cleveland network
  - Four interstate highways (I-90, I-71, I-77, and I-490)
  - 65,000 vehicles in the morning peak hour.
  - 1,397 nodes, 2,985 links, 209 traffic signals, and 8,269 origin-destination (O-D) demand pairs using 2010 demand data.

- The Columbus network
  - Three interstate highways (I-70, I-71, and I-670)
  - Grid configuration.
  - Downtown area is a bottleneck during peak hours.
  - Network provides more opportunities for re-routing compared to the Cleveland network.
  - 2,056 nodes, 4,202 links, 254 traffic signals, and 21,435 O-D demand pairs.
Network-wide Impacts

- Eco-routing consistently reduces network-wide fuel consumption levels
  - Reductions of 3.3 and 9.3 percent, respectively
  - 4.8 and 3.2 percent increase in the average travel time
# Network-wide Impacts

## Impact of Traffic Demand

<table>
<thead>
<tr>
<th>MOEs</th>
<th>Routing Method</th>
<th>Cleveland</th>
<th>Columbus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50%</td>
<td>75%</td>
</tr>
<tr>
<td>Distance (Km)</td>
<td>ECO</td>
<td>4.57</td>
<td>4.57</td>
</tr>
<tr>
<td></td>
<td>TT</td>
<td>4.81</td>
<td>4.81</td>
</tr>
<tr>
<td></td>
<td>Rel. Diff</td>
<td>5.0%</td>
<td>5.1%</td>
</tr>
<tr>
<td>Time (s)</td>
<td>ECO</td>
<td>312</td>
<td>315</td>
</tr>
<tr>
<td></td>
<td>TT</td>
<td>299</td>
<td>301</td>
</tr>
<tr>
<td></td>
<td>Rel. Diff</td>
<td>-4.3%</td>
<td>-4.5%</td>
</tr>
<tr>
<td>Fuel (l)</td>
<td>ECO</td>
<td>0.537</td>
<td>0.540</td>
</tr>
<tr>
<td></td>
<td>TT</td>
<td>0.556</td>
<td>0.560</td>
</tr>
<tr>
<td></td>
<td>Rel. Diff</td>
<td>3.37%</td>
<td>3.59%</td>
</tr>
<tr>
<td>HC (g)</td>
<td>ECO</td>
<td>1.77</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td>TT</td>
<td>1.99</td>
<td>2.06</td>
</tr>
<tr>
<td></td>
<td>Rel. Diff</td>
<td>11.1%</td>
<td>11.9%</td>
</tr>
<tr>
<td>CO (g)</td>
<td>ECO</td>
<td>44.59</td>
<td>45.80</td>
</tr>
<tr>
<td></td>
<td>TT</td>
<td>50.52</td>
<td>52.34</td>
</tr>
<tr>
<td></td>
<td>Rel. Diff</td>
<td>11.7%</td>
<td>12.5%</td>
</tr>
<tr>
<td>NOx (g)</td>
<td>ECO</td>
<td>1.54</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>TT</td>
<td>1.66</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td>Rel. Diff</td>
<td>7.2%</td>
<td>7.6%</td>
</tr>
<tr>
<td>CO₂ (g)</td>
<td>ECO</td>
<td>1184</td>
<td>1188</td>
</tr>
<tr>
<td></td>
<td>TT</td>
<td>1220</td>
<td>1226</td>
</tr>
<tr>
<td></td>
<td>Rel. Diff</td>
<td>2.9%</td>
<td>3.1%</td>
</tr>
</tbody>
</table>
Eco-Drive Systems
Eco-Cruise Control
Overview

- **Objective:**
  - Develop a predictive fuel-optimum control system

- **Input:**
  - Desired speed and speed bounds (min/max speed)

- **Building blocks:**
  - Powertrain and fuel consumption model

---


Eco-Cruise Control
Powertrain Model

- 2007 Chevy Malibu: I-81 southbound
  - 65 mph cruise control operation
  - Measured: 13,297 kW vs. Estimated: 13,871 kW (4.3% Error)
Eco-Cruise Control
VT-CPFM Model

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

\[
FC(t) = \frac{a_0 + a_1 P(t) + a_2 P(t)^2}{a_0} \\
\tag{1}
\]

- 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 CO₂ emissions \((R^2=95\%)\)

Where:
- \(a_0, a_1, a_2\) 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 \(t\).
Eco-Cruise Control

Publications


Eco-Cruise Control
Model Logic

- Upper Boundary
- Target Speed
- Lower Boundary

Stage Length ($d_s$)

Optimization Distance ($d_o$)

Optimization Frequency ($d_f$)
Eco-Cruise Control
Model Logic

- Three step optimization:
  - Prune search space using powertrain model
  - Speed and gear space that the vehicle is physically able to achieve for the given topography and vehicle characteristics
  - Discretize continuous search space
  - Use speed and gear levels to construct a graph
  - Compute optimum control (minimum path)
    - The vehicle speed and gear changes over each stage considering a cost function at stage transitions

\[
Cost = w_1 \times FC(v_0, v_1) + w_2 \times \left| \frac{v_1}{v_{ref}} - 1 \right| \times FC(v_{ref}) + w_3 \times \left| g_1 - g_0 \right| \times FC(v_{ref})
\]
Eco-Cruise Control
Model Testing (NYC to LA)

- 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-Cruise Control Model Testing (NYC to LA)

<table>
<thead>
<tr>
<th>Toyota Camry</th>
<th>Fuel (L)</th>
<th>MPG</th>
<th>Fuel Saving</th>
<th>TT (hr)</th>
<th>Avg. Spd (mph)</th>
<th>$\sigma_s$ (mph)</th>
<th>$\Delta$TT (%)</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 : 60.7 mph)</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 (hr)</th>
<th>Avg. Spd (mph)</th>
<th>$\sigma_s$ (mph)</th>
<th>$\Delta$TT (%)</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: 60.3 mph)</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-Drive System
Model Overview

- Predictive Eco-Cruise Control (ECC) and car-following

Eco-Cooperative Adaptive Cruise Control in the Vicinity of Signalized Intersections


ECACC
Formulation

- Problem solved using DP
  - Initial state: When SPaT information is received.
  - Intermediate state: When vehicle should reach stop line.
  - Final state: Location when vehicle reaches its desired speed for lowest acceleration level.

- Use A* algorithm to speed computation of minimum path

\[
\min J_u + J_d
\]

Where:
\[
J_u = \int_{t_0}^{t_s} FC(t) dt \quad J_a = \int_{t_s}^{t_f} FC(t) dt
\]
ECACC Results

![Bar chart showing fuel consumption for ECACC Profile and Uninformed Driver.](image)
Intersection Cooperative Adaptive Cruise Control System


**iCACC Formulation**

**Objective:**
\[
\text{Min} \sum_{i=1}^{\Omega^1} \text{Delay}_{D_i}
\]

**Subject to:**

1. Ensure that the FIFO rule is applied to all vehicles in the same lane;

2. The arrival of two intersecting vehicles at the same conflict point is separated by a minimum safe time gap;

3. The arrival time of each vehicle at the conflict point is greater than any arrival time computed in the previous simulation step;

\[
\text{min} (\alpha_{ij} + \beta_{ij} + \gamma_{ij} - \delta_{ij})
\]

\[
\text{max} (\alpha_{jk} + \beta_{jk} + \gamma_{jk} - \delta_{jk})
\]

\[
\text{max} (\alpha_{mp} + \beta_{mp} + \gamma_{mp} - \delta_{mp})
\]
iCACC
Example Demonstration

Sample Control Output
iCACC
System Evaluation

Average Fuel Consumption (mL)

Case Number

iCACC
Signal
Roundabout
AWSC
iCACC
Roundabout System Enhancement

- Average Delay per Vehicle (sec)
- Level of Penetration (%)

- v/c=0.2
- v/c=0.4
- v/c=0.6
- v/c=0.8
- v/c=1.0

Graph showing the relationship between average delay per vehicle and level of penetration at different values of v/c.
iCACC
Bi-level Optimization

- Upper level
  - Delay optimization to schedule arrivals of vehicles
- Lower level
  - Fuel consumption optimization s.t. upper level constraints
On-going and Future Work

- Eco-traffic signal control:
  - Designing of traffic signal timings to reduce vehicle fuel consumption levels
  - Field testing a prototype system
- Real-time eco-scheduling and routing of buses
- Developing a prototype in-vehicle eco-routing system
- Integrating speed harmonization algorithms with eco-drive systems