Developing and Testing Eco-Drive Systems

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What is Eco-Driving and its Impacts?

- A way of driving that reduces fuel consumption and greenhouse gas emissions – Ecodriving.org
- Teaching eco-driving can improve actual fuel efficiency by an average of 17 percent - McKinsey & Company 2009
- 1% of the highway trip is responsible for 16, 19, 4, 3, and 4% of the trip’s total HC, CO, NO\textsubscript{X}, CO\textsubscript{2}, and fuel consumption – Ahn and Rakha 2008
Objectives

- Develop an Eco-drive system
  - Predictive Eco-Cruise Control (ECC) system
  - Eco-car-following
Presentation Overview

- Describe the building blocks of the Eco-drive system
  - Fuel Consumption Model
  - Powertrain Model
  - Predictive Eco-Cruise Model
  - Car-Following Model
- Overview of proposed algorithm
- Simulation results
- Study conclusions and recommendations
Fuel Consumption Modeling
Fuel Consumption Models

VT-CPFM

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

\[ FC(t) = \frac{\alpha_0 + \alpha_1 P(t) + \alpha_2 P(t)^2}{\alpha_0} \quad \forall P(t) \geq 0 \]

\[ FC(t) = \frac{\alpha_0 + \alpha_1 P(t) + \alpha_2 P(t)^2}{\alpha_0} \quad \forall P(t) < 0 \]

- Has the ability to produce a control system that does not result in bang-bang control and
- Easily calibrated using publicly available data without the need to gather detailed engine and fuel consumption data.
- Estimates CO₂ emissions (\(R^2=95\%\))
Vehicle Powertrain Modeling
Vehicle Powertrain Model

- Typical powertrain models:
  - Computationally intensive
    - Challenging to integrate within microscopic traffic simulation software
  - Require proprietary parameters
    - Require gathering field data for the entire envelope of operation of a vehicle.

- Simple vehicle powertrain model needed:
  - CSM developed a model used within the context of this approach
Vehicle Powertrain Model

- The proposed model
  - Uses driver throttle input to compute the engine speed and power and finally compute the vehicle acceleration, speed, and position
  - Can be calibrated using vehicle parameters that are publically available without the need for field data collection.
Vehicle 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)
Predictive Eco-Cruise Model
Predictive Eco-Cruise Model

- 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 (or stage length), the look-ahead distance, and the optimization frequency.
Predictive Eco-Cruise Model

- Three step optimization:
  - Define 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

\[
\text{Cost} = w_1 \times FC_{(v_0,v_1)} + w_2 \times |v_1 - v_{\text{ref}}| \times FC_{(v_{\text{ref}})} + w_3 \times |g_1 - g_0| \times FC_{(v_{\text{ref}})}
\]
Predictive Eco-Cruise Model

- Speed Profile
- Upper Boundary
- Target Speed
- Lower Boundary
- Stage 1
- Stage Length ($d_s$)
- Optimization Distance ($d_o$)
- Optimization Frequency ($d_f$)
- Optimization 1
- Optimization 2
- Optimization 3
- Optimization $m$
- Optimal Control
Car-Following Model
Car-Following Model

- Car-following models define relationships between a following and preceding vehicle in a range of inter-vehicle spacing.

- Modeled as
  - Equations of motion under steady-state conditions plus
  - Constraints that govern the behavior of vehicles while moving from one steady-state to another.

- The Rakha-Pasumarthy-Adjerid (RPA) model is used
  - Van Aerde steady-state car-following model
  - Vehicle dynamics acceleration and deceleration constraints
Car-Following Model

- Steady-State Modeling

\[
\tilde{s}_n(t + \Delta t) = c_1 + c_3 u_n(t + \Delta t) + \frac{c_2}{u_f - u_n(t + \Delta t)}
\]

\[
u_n(t + \Delta t) = \frac{-c_1 + c_3 u_f + \tilde{s}_n(t + \Delta t) - \sqrt{A}}{2c_3}
\]

\[
A = \left( c_1 - c_3 u_f - \tilde{s}_n(t + \Delta t) \right)^2 - 4c_3 \left( \tilde{s}_n(t + \Delta t)u_f - c_1 u_f - c_2 \right)
\]

where \( s_n(t) \) is vehicle spacing at time \( t \), \( u_n(t) \) is speed of vehicle \( n \) at time \( t \) (km/h), \( u_f \) is free-flow speed (km/h), \( \Delta t \) is length of time interval, \( c_1 \) is fixed vehicle spacing constant (km), \( c_2 \) is first variable vehicle spacing constant (km\(^2\)/h), and \( c_3 \) is second variable vehicle spacing constant (h).
Car-Following Model

- **Collision Avoidance Modeling**

\[
s_n(t) = \frac{1}{k_j} + \frac{u_n(t + \Delta t)^2 - u_{n-1}(t + \Delta t)^2}{25920 \mu f_b \eta_b g}
\]

\[
u_n(t + \Delta t) = \sqrt{u_{n-1}(t + \Delta t)^2 + 25920 \mu f_b \eta_b g \left(s_n(t) - \frac{1}{k_j}\right)}
\]

Where \(k_j\) is jam density (veh/km) and \(u_{n-1}(t)\) is speed of vehicle \(n-1\) at time \(t\) (km/h). This deceleration level is assumed to be equal to \(\mu f_b \eta_b g\), where \(\mu\) is the coefficient of roadway friction, \(f_b\) is the driver brake pedal input \([0, 1]\), \(\eta_b\) is the brake efficiency \([0, 1]\), and \(g\) is the gravitational acceleration \((9.8067 \, m/s^2)\).
Car-Following Model

- **Vehicle Acceleration Modeling**
  - Vehicle acceleration is governed by vehicle dynamics
  - Vehicle dynamics models compute the maximum vehicle acceleration levels from the resultant forces acting on a vehicle.

\[
u_n(t + \Delta t) = u_n(t) + 3.6 \frac{F_n(t) - R_n(t)}{m_n} \Delta t\]

\[
F_n(t) = \min \left\{ 3600 f_p \beta \eta_d \frac{P_n}{u_n(t)}, m' n g \mu \right\}
\]

\[
R_n(t) = \frac{\rho}{25.92} C_d C_h A_f u_n(t)^2 + m_n g \frac{c_{r0}}{1000} \left( c_{r1} u_n(t) + c_{r2} \right) + m_n g G(t)
\]

where \(F_n(t)\) is vehicle tractive force (N), \(R_n(t)\) is total resistance force (N), \(m_n\) is vehicle mass (kg), \(f_p\) is the driver throttle input \([0,1]\), \(\beta\) is the gear reduction factor (unitless), \(\eta_d\) is the driveline efficiency (unitless), \(P_n\) is the vehicle power (kW), \(m'\) is the mass of vehicle \(n\) on its tractive axle (kg), \(g\) is the gravitational acceleration (9.8067 m/s\(^2\)), \(\mu\) is the coefficient of friction (unitless), \(\rho\) is the air density at sea level (1.2256 kg/m\(^3\)), \(C_d\) is the vehicle drag coefficient (unitless), \(C_h\) is the altitude correction factor (unitless), \(A_f\) is the vehicle frontal area (m\(^2\)), \(c_{r0}\) is the rolling resistance constant (unitless), \(c_{r1}\) is the rolling resistance constant (h/km), \(c_{r2}\) is the rolling resistance constant (unitless), and \(G(t)\) is the roadway grade at instant \(t\) (unitless).
Proposed Algorithm
Proposed Algorithm

GPS Information  Digital Map  Radar Sensor

? Look Ahead Distance
Spacing

Entire Horizon

Road Topography
Proposed Algorithm

- **Step 1**: If the spacing between the subject and lead vehicle is beyond the car-following threshold proceed to step 3, otherwise proceed with step 2.
- **Step 2**: Estimate the vehicle at instant $t + \Delta t$ using the RPA car-following model and proceed to step 4.
- **Step 3**: Using DP, the optimum vehicle speed trajectory over the look-ahead distance $(d_o)$ is estimated considering a spatial discretization of length $d_s$ (stage length).
- **Step 4**: Move the vehicle and then go back to step 1 at the conclusion of the time step $\Delta t$; otherwise end the simulation at $t = T$. 
Simulation Results
Key Input Variables

- Car-following spacing threshold
- Car-following model parameters
  - Free-flow speed, Jam density, Speed-at-capacity, and capacity
- Vehicle data
  - Powertrain related data, fuel economy data
- Roadway topography
- Real-time GPS data
- Lead vehicle location data (or spacing data)
Simulation Overview

- Three Test Vehicles
  - 2011 Toyota Camry (22/33 mpg)
  - 2008 Chevy Tahoe (14/20 mpg), and
  - 2008 Chevy Malibu Hybrid (24/32 mpg)

- Tested Two Lead Vehicle Trajectories (14 miles)
  - I-81 SB Field Data (2007 Malibu Manual Driving)
  - I-81 SB Eco-Driving Speed Profile (2011 Camry)

- Tested different car-following parameters
  - Car-following threshold: 100m, 50m, and 30m
  - Throttle level: 100%, 60%, and 40%
  - Fixed vs. dynamic threshold
### Summary Results – I-81 Speed Profile

<table>
<thead>
<tr>
<th></th>
<th>2011 Camry</th>
<th>2008 Tahoe</th>
<th>2008 Malibu Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Car-following</strong></td>
<td>13.5 mpg</td>
<td>8.9 mpg</td>
<td>16.2 mpg</td>
</tr>
<tr>
<td><strong>Eco-cruise</strong></td>
<td>24.6 mpg (82%)</td>
<td>14.3 mpg (60%)</td>
<td>25.4 mpg (57%)</td>
</tr>
<tr>
<td><strong>Eco-Cruise</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(100m following threshold)</td>
<td>13.5 mpg (-0.6%)</td>
<td>8.7 mpg (-2%)</td>
<td>16.1 mpg (-0.1%)</td>
</tr>
<tr>
<td><strong>Eco-Cruise</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(50m following threshold)</td>
<td>16.0 mpg (18%)</td>
<td>9.6 mpg (8%)</td>
<td>19.2 mpg (19%)</td>
</tr>
<tr>
<td><strong>Eco-Cruise</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(30m following threshold)</td>
<td>20.5 mpg (51%)</td>
<td>10.8 mpg (21%)</td>
<td>21.2 mpg (31%)</td>
</tr>
</tbody>
</table>
### Summary Results – I-81 Speed Profile
#### 2011 Toyota Camry

<table>
<thead>
<tr>
<th></th>
<th>100% Throttle</th>
<th>60% Throttle</th>
<th>40% Throttle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car-following</td>
<td>13.5 mpg</td>
<td>15.8 mpg (16%)</td>
<td>20.2 mpg (49%)</td>
</tr>
<tr>
<td>Eco-cruise</td>
<td>24.6 mpg (82%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eco-Cruise (100m following threshold)</td>
<td>13.5 mpg (-0.6%)</td>
<td>15.8 mpg (16%)</td>
<td>20.2 mpg (49%)</td>
</tr>
<tr>
<td>Eco-Cruise (50m following threshold)</td>
<td>16.0 mpg (18%)</td>
<td>18.6 mpg (38%)</td>
<td>20.3 mpg (50%)</td>
</tr>
<tr>
<td>Eco-Cruise (30m following threshold)</td>
<td>20.5 mpg (51%)</td>
<td>20.9 mpg (55%)</td>
<td>20.8 mpg (53%)</td>
</tr>
</tbody>
</table>
Summary Results – I-81 Speed Profile
Car-following Threshold of 30m

- 20.5 mpg, average spacing=196m, maximum spacing= 457m
Summary Results – I-81 Speed Profile
Car-following Threshold 30m & Max Spacing 100m

- If Spacing > max. spacing (100m) then use car-following model
- 17.2 mpg, average spacing = 48m, maximum spacing = 133m
Summary Results – I-81 Speed Profile
2011 Toyota Camry

<table>
<thead>
<tr>
<th></th>
<th>Fixed Car-following Threshold</th>
<th>Dynamic Car-following Threshold</th>
<th>Dynamic Car-following Threshold with Max Spacing Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eco-cruise</td>
<td>24.6 mpg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eco-Cruise (100m following threshold)</td>
<td>13.5 mpg (50m, 60m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eco-Cruise (50m following threshold)</td>
<td>16.0 mpg (78m, 161m)</td>
<td>15.8 mpg (54m, 179m)</td>
<td>15.9 mpg (53m, 183m)</td>
</tr>
<tr>
<td>Eco-Cruise (30m following threshold)</td>
<td>20.5 mpg (196m, 457m)</td>
<td>18.3 mpg (80m, 289m)</td>
<td>17.2 mpg (48m, 133m)</td>
</tr>
</tbody>
</table>

- Fuel economy, average and maximum vehicle spacing
Following ECC Vehicle

- Car-following only - 23.7 mpg
- ECC mode – 24.6 mpg
Conclusions and Recommendations

- Study shows that the proposed system can save fuel significantly consumption maintaining reasonable vehicle spacing
  - Toyota Camry: 27% fuel saving and average spacing: 48m along I-81

- Vehicle operations at lower power demands significantly enhance vehicle fuel economy (up to 49%)
  - Not as significant as the use of the ECC (improved fuel economy up to 82%).

- ECC equipped vehicles benefit following vehicles
  - Following vehicles will benefit by just following the lead vehicle.

- There is a need to quantify the potential benefits of using the proposed system at a network-wide level.
Thank You!

Go Hokies!