POWER MANAGEMENT STRATEGY FOR A PARALLEL HYBRID ELECTRIC TRUCK

Introduction and Motivation
Simulation model and preliminary rule-based control
Dynamic programming techniques
Improved rule-based control law
Simulation results
Dyno test results
Conclusions

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The University of Michigan

What is a Hybrid Vehicle?

• A HV has at least two sources of motive power
  - Prime: IC engines, fuel cells, gas turbines
  - Secondary: Batteries, flywheels, ultra-capacitors, hydraulics
• The most popular type: ICE + battery/motor (HEV)
• Bottom-line: “Better” than any single power source.
Potential Steps Towards Breakthrough in Fuel Efficiency

- **Light-weight**
  - 6 mpg

- **Aero-roll**
  - 4 mpg

- **Small engine**
  - 8 mpg

- **DI**
  - 10 mpg

- **HEV**
  - 15 mpg

**Description:**
- Current Taurus: 3200 lbs, 3.0 L, 2-valve
- Ultralite: 2000 lbs, Same
- Aero/Roll: 2000 lbs, Same
- Conv. P/T Match: 2000 lbs, 1.4 L, A/T
- Adv. P/T: 2000 lbs, 1.2L CIDI, Auto M/T
- Adv. Hybrid P/T: TBD

**Source:** Mike Schwarz, Ford Motor Company

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**HEV Configurations**

- **Series**
  - Simpler mechanical transmissions
  - Optimum engine efficiency and low emission
  - Both ICE and Electric drive rated to the maximum power requirement (main disadvantage)
  - Lower overall efficiency (main disadvantage)

- **Parallel (e.g. Chrysler MYBRID ESX2)**
  - More flexibility—sizing and control design more complicated
  - Lower power/weight/cost, and better efficiency.

- **Series-parallel combination (e.g. Toyota Prius)**
### Growing Market (Toyota)

<table>
<thead>
<tr>
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<td><strong>Prius</strong></td>
<td>323</td>
<td>17,653</td>
<td>15,243</td>
<td>19,011</td>
<td>29,459</td>
<td>7,402</td>
<td>89,091</td>
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<tr>
<td><strong>Estima Hybrid minivan</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5,886</td>
<td>5,840</td>
<td>11,726</td>
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<td><strong>Crown mild hybrid system</strong></td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>1,574</td>
<td>520</td>
<td>2,094</td>
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<td><strong>Coaster hybrid (bus)</strong></td>
<td>9</td>
<td>3</td>
<td>12</td>
<td>15</td>
<td>9</td>
<td>8</td>
<td>56</td>
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<tr>
<td><strong>Total by year/month</strong></td>
<td>332</td>
<td>17,656</td>
<td>15,255</td>
<td>19,026</td>
<td>36,928</td>
<td>13,770</td>
<td>102,967</td>
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<td><strong>Cumulative total</strong></td>
<td>332</td>
<td>17,988</td>
<td>33,243</td>
<td>52,269</td>
<td>89,197</td>
<td>102,967</td>
<td></td>
</tr>
</tbody>
</table>


---

### Advanced Powertrain

![Graph showing percent thermal efficiency and percent load for different powertrain systems]

- **Why hybrid vehicles?**
  - Load leveling
  - Regenerative braking

Source: Ricardo
Transportation Sector Contribution to Oil Gap

Ground Vehicle Energy Use

source: EIA Annual Energy Outlook, 1998
Federal Highway Administration, Highway Statistics
**Emission**

- Engine out vs. tail-pipe
- Temperature effect?

This presentation:

Engine out, hot engine only

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**Nox Emission**

Table 4.5

Emissions of Nitrogen Oxides from Highway Vehicles, 1970-99*

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Gasoline powered</strong></td>
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<td></td>
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<tr>
<td>Light vehicles &amp; motorcycles</td>
<td>4.16</td>
<td>4.73</td>
<td>4.42</td>
<td>3.81</td>
<td>3.01</td>
<td>3.04</td>
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<td>Light trucks&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.28</td>
<td>1.46</td>
<td>1.41</td>
<td>1.53</td>
<td>1.55</td>
<td>1.99</td>
<td>1.64</td>
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<tr>
<td>Heavy vehicles</td>
<td>0.28</td>
<td>0.32</td>
<td>0.30</td>
<td>0.33</td>
<td>0.31</td>
<td>0.33</td>
<td>0.46</td>
<td>5.3%</td>
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<tr>
<td><strong>Total</strong></td>
<td>5.71</td>
<td>6.51</td>
<td>6.11</td>
<td>5.67</td>
<td>4.87</td>
<td>5.36</td>
<td>4.96</td>
<td>57.7%</td>
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<tr>
<td><strong>Diesel powered</strong></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light vehicles&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.06</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.1%</td>
</tr>
<tr>
<td>Light trucks&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.68</td>
<td>2.12</td>
<td>2.46</td>
<td>2.39</td>
<td>2.25</td>
<td>2.54</td>
<td>3.02</td>
<td>42.1%</td>
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<tr>
<td>Heavy vehicles</td>
<td>1.68</td>
<td>2.14</td>
<td>2.49</td>
<td>2.42</td>
<td>2.34</td>
<td>2.59</td>
<td>3.63</td>
<td>42.3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1.68</td>
<td>2.14</td>
<td>2.49</td>
<td>2.42</td>
<td>2.34</td>
<td>2.59</td>
<td>3.63</td>
<td>42.3%</td>
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<tr>
<td><strong>Highway vehicle total</strong></td>
<td>7.39</td>
<td>8.65</td>
<td>8.62</td>
<td>8.09</td>
<td>7.21</td>
<td>7.96</td>
<td>8.59</td>
<td>100.0%</td>
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<tr>
<td><strong>Percent diesel</strong></td>
<td>22.7%</td>
<td>24.8%</td>
<td>28.9%</td>
<td>30.0%</td>
<td>32.4%</td>
<td>32.6%</td>
<td>32.3%</td>
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*Transportation Energy Data Book, Edition 21*
PM Emission

Table 4.9
Emissions of Particulate Matter (PM-10) from Highway Vehicles, 1970–99
(thousand short tons)

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Gasoline powered</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Light vehicles &amp; motorcycles</td>
<td>225</td>
<td>207</td>
<td>120</td>
<td>77</td>
<td>57</td>
<td>55</td>
<td>59</td>
<td>20.0%</td>
</tr>
<tr>
<td>Light trucks&lt;sup&gt;a&lt;/sup&gt;</td>
<td>70</td>
<td>72</td>
<td>55</td>
<td>43</td>
<td>37</td>
<td>41</td>
<td>36</td>
<td>12.2%</td>
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<tr>
<td>Heavy vehicles</td>
<td>13</td>
<td>15</td>
<td>15</td>
<td>14</td>
<td>10</td>
<td>9</td>
<td>12</td>
<td>4.1%</td>
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<tr>
<td>Total</td>
<td>308</td>
<td>294</td>
<td>190</td>
<td>134</td>
<td>104</td>
<td>105</td>
<td>107</td>
<td>36.3%</td>
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<tr>
<td><strong>Diesel powered</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Light vehicles</td>
<td>c</td>
<td>10</td>
<td>12</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td>0.3%</td>
</tr>
<tr>
<td>Light trucks&lt;sup&gt;b&lt;/sup&gt;</td>
<td>c</td>
<td>2</td>
<td>1</td>
<td>13</td>
<td>2</td>
<td>1</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td>Heavy vehicles</td>
<td>136</td>
<td>166</td>
<td>194</td>
<td>219</td>
<td>225</td>
<td>185</td>
<td>186</td>
<td>63.1%</td>
</tr>
<tr>
<td>Total</td>
<td>136</td>
<td>176</td>
<td>208</td>
<td>228</td>
<td>245</td>
<td>194</td>
<td>188</td>
<td>63.7%</td>
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<tr>
<td><strong>Highway vehicle total</strong></td>
<td>443</td>
<td>471</td>
<td>397</td>
<td>363</td>
<td>349</td>
<td>360</td>
<td>295</td>
<td>100.0%</td>
</tr>
<tr>
<td>Percent diesel</td>
<td>30.7%</td>
<td>37.4%</td>
<td>52.4%</td>
<td>62.8%</td>
<td>70.2%</td>
<td>64.7%</td>
<td>63.7%</td>
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</table>

Hybrid Vehicle Control Problems

<table>
<thead>
<tr>
<th></th>
<th>Main-loop</th>
<th>Servo-loop</th>
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<tbody>
<tr>
<td>Performance target</td>
<td>Fuel economy/</td>
<td>NVH/driveability/fuel</td>
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<tr>
<td>&quot;Control signal&quot;</td>
<td>emission</td>
<td>economy/emission</td>
</tr>
<tr>
<td>Horizon/dynamics</td>
<td>High level (Power)</td>
<td>Low level (throttle, current,</td>
</tr>
<tr>
<td>To satisfy</td>
<td></td>
<td>duty cycle)</td>
</tr>
<tr>
<td>Scenarios</td>
<td>Driving cycles</td>
<td>Test matrix</td>
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<tr>
<td>Algorithm</td>
<td>Optimal, intelligent</td>
<td>Robust, adaptive, ad-hoc</td>
</tr>
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</table>
Power Management Problem for Parallel HEV

- Goal: To develop a control strategy to minimize fuel consumption (and emission) while meeting the power demand from the driver
- Key problem: determine the total amount of power to be generated, and its split between the two power sources
- Maintain adequate battery energy (charge sustaining)

Preliminary Rule-Based Control Strategy

- Motor only mode
- Engine only mode
- Hybrid mode
- Engine provides additional power to charge the battery
- Regenerative braking
- Friction brake
**Problems of Existing (Main-loop) Control Approach**

- Based on simple concepts (e.g., load leveling) and mostly static maps.
- Tuning is done through trial-and-error.
- Don’t know the full potential (is 20% improvement good?)
- Not re-useable (fuel economy vs. fuel economy plus emission).

**2003 Fuel Economy Champions**

<table>
<thead>
<tr>
<th></th>
<th>Honda Civic (Manual)</th>
<th>Honda Insight (Automatic)</th>
<th>Toyota Prius (Automatic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Mileage (City/Highway)</td>
<td>46/51</td>
<td>57/56</td>
<td>52/45</td>
</tr>
</tbody>
</table>

Outline

- Introduction and Motivation
- Simulation model and preliminary rule-based control results
- Dynamic programming techniques
- Improved rule-based control law
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- Dyno test results
- Conclusions

Baseline Truck: Navistar International 4700 Series

**Engine**
- V8 DI Diesel
- Turbocharged, Intercooled
- 7.3 liters
- Bore: 10.44 cm
- Stroke: 10.62 cm
- Compression Ratio: 17.4
- Rated Power: 210 HP@2400 rpm

**Vehicle/Driveline**
- Total Mass: 7258 Kg
- Wheelbase: 3.7 m
- CG Location: 2.2 m from front
- Frontal Area: 5 m²
- Air Drag Coefficient (CD): 0.8
- 4 Speed Automatic Transmission
- Rear Wheel Drive - 4x2
Schematic of the Hybrid-Electric Truck

Parallel hybrid
Post-transmission type

Hybrid Truck Parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
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<tbody>
<tr>
<td>DI Diesel Engine</td>
<td>V6, 5.475L, 157HP/2400rpm</td>
</tr>
<tr>
<td>DC Motor</td>
<td>49kW</td>
</tr>
<tr>
<td>Lead-acid Battery</td>
<td>Capacity: 18Ah</td>
</tr>
<tr>
<td></td>
<td>Module number: 25</td>
</tr>
<tr>
<td></td>
<td>Energy density: 34 (Wh/kg)</td>
</tr>
<tr>
<td></td>
<td>Power density: 350 (W/kg)</td>
</tr>
<tr>
<td>Automatic Transmission</td>
<td>4 speed, GR: 3.45/2.24/1.41/1.0</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Curb weight: 7504 kg</td>
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</table>
Preliminary Rule-Based Control

- Braking rule
- Power split rule
- Recharge rule

<table>
<thead>
<tr>
<th></th>
<th>FE (mi/gal)</th>
<th>NOx (g/mi)</th>
<th>PM (g/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Truck</td>
<td>10.343</td>
<td>5.3466</td>
<td>0.5080</td>
</tr>
<tr>
<td>Hybrid Truck (Preliminary Rule-Base)</td>
<td>13.159</td>
<td>5.7395</td>
<td>0.4576</td>
</tr>
</tbody>
</table>
Outline

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Dynamic Optimization Based Algorithm

Objective
- To develop an optimal control policy that minimizes the fuel consumption over a given driving cycle

Advantage
- Explore the full potential of hybridization
- Benchmark for a better control strategy

Methodology
- A sequence of decisions applied to a dynamic system to minimize the total fuel costs — Multistage Decision Process
- Optimal control problem

\[
\begin{align*}
x(0) & \xrightarrow{f(0)} x(1) & \quad u(0) \\
x(1) & \xrightarrow{f(1)} x(2) & \quad u(1) \\
\vdots & \quad \vdots & \quad \vdots \\
x(N-1) & \xrightarrow{f(N-1)} x(N) & \quad u(N-1) \\
L(0) & \quad L(1) & \quad L(N-1)
\end{align*}
\]
Problem Formulation

• Discrete-time Nonlinear System
  \[ x(k + 1) = f(x(k), u(k)) \]

• Control Inputs
  Fuel injection rate and gear shift command to the transmission

• Constraints
  \[
  \omega_{e_{\text{min}}} \leq \omega_e(k) \leq \omega_{e_{\text{max}}},
  T_{e_{\text{min}}} \leq T_e(k) \leq T_{e_{\text{max}}},
  T_{m_{\text{min}}} \leq T_m(k) \leq T_{m_{\text{max}}},
  SOC_{\text{min}} \leq SOC(k) \leq SOC_{\text{max}}
  \]

• Minimize the Cost Function
  \[
  J = \sum_{k=0}^{N-1} \left[ L(x(k), u(k)) + G(x(N)) \right] = \sum_{k=0}^{N-1} \left[ \text{fuel}(k) + \mu \cdot \text{NOx}(k) + \nu \cdot \text{PM}(k) \right] + \alpha(SOC(N) - SOC) \]

Dynamic Programming (DP) Algorithm

• State and control values are quantized into finite grids

• Solve recursive equation backwards in time
  Step N-1:
  \[ J'_{N-1}(x(N-1)) = \min_{u(N-1)} \left[ L(x(N-1), u(N-1)) + G(x(N)) \right] \]
  Step k, for \( 0 \leq k < N-1 \)
  \[ J'(x(k)) = \min_{u(k)} \left[ L(x(k), u(k)) + J'_{k+1}(x(k+1)) \right] \]

• Obtain an optimal, time-varying, state-feedback control policy
  \[ u^*(x(k), k) \rightarrow \text{Stored in a table for each of the quantized states and time stages} \]

• DP creates a family of optimal paths for all possible initial conditions
Procedure of Dynamic Optimization

Dynamic Optimization Process

- Driving Cycle
- Dynamic Programming
- Optimal Control Law, \( u(x(k),k) \)
- Simulation (Complete HE-VESIM)
- Fuel Economy, Vehicle Response

EPA Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles (UDDSHDV) Cycle

- Initial SOC
- Final SOC
Fuel Economy Comparison

<table>
<thead>
<tr>
<th></th>
<th>FE (mi/gal)</th>
<th>NOx (g/mi)</th>
<th>PM (g/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Truck</td>
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<td>0.5080</td>
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<tr>
<td>Hybrid Truck (Preliminary Rule-Base)</td>
<td>13.159</td>
<td>5.7395</td>
<td>0.4576</td>
</tr>
<tr>
<td>DP $\mu = 0, \nu = 0$</td>
<td>13.705</td>
<td>5.627</td>
<td>0.446</td>
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</tbody>
</table>

$$J = \sum_{k=0}^{N-1} \left[ fuel(k) + \mu \cdot NOx(k) + \nu \cdot PM(k) \right] + \alpha (SOC(N) - SOC_j)^2$$

Fuel Economy and Emission Results

$$J = \sum_{k=0}^{N-1} \left[ fuel(k) + \mu \cdot NOx(k) + \nu \cdot PM(k) \right] + \alpha (SOC(N) - SOC_j)^2$$

$$\mu \in \{0, 5, 10, 20, 40\}$$

$$\nu \in \{0, 100, 200, 400, 600, 800\}$$
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Design Procedure by Dynamic Optimization

Preliminary Rule-based Controller

Improved Rule-based Controller

Dynamic Optimization Process

- Driving Cycle
- Dynamic Programming
- Optimal Control Law, \( u(x(k),k) \)
- Simulation (Complete HE-VESIM)
- Fuel Economy, Vehicle Response
Improved Rule-Based Control

- Braking rule
- Power split rule
- Recharge rule
- Transmission shift strategy

Improved Transmission Shift

The original optimal gear trajectory has frequent shifting which is undesirable.

\[ J = \sum_{k=0}^{N-1} \left[ \text{fuel}(k) + 40 \cdot NOx(k) + 800 \cdot PM(k) + \beta \cdot \left| g_s(k+1) - g_s(k) \right| \right] \\
+ 5 \cdot 10^6 \cdot (\text{SOC}(N) - \text{SOC}_f)^2 \]
Improved Transmission Shift

![Graph showing engine power demand vs transmission speed with different gear indicators.]

Improved Power Split Rule

\[ PSR = \frac{P_{\text{eng}}}{P_{\text{dem}}} \]

- \( PSR > 1 \) (Motor-only mode)
- \( 0 < PSR < 1 \) (Power-assist mode)
- \( PSR = 1 \) (Engine-only mode)
- \( PSR < 1 \) (Recharging mode)

\[ P_{\text{eng}} = PSR \times P_{\text{dem}} \]
\[ P_{\text{mot}} = P_{\text{dem}} - P_{\text{eng}} \]
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UDDSHDV Cycle Results

<table>
<thead>
<tr>
<th></th>
<th>FE (mi/gal)</th>
<th>NOx (g/mi)</th>
<th>PM (g/mi)</th>
<th>Performance Measure *</th>
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<tr>
<td>Baseline Rule-</td>
<td>13.159</td>
<td>5.7395</td>
<td>0.4576</td>
<td>840.63</td>
</tr>
<tr>
<td>Based</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>New Rule-Based</td>
<td>12.8738</td>
<td>4.8355</td>
<td>0.4292</td>
<td>787.0965</td>
</tr>
<tr>
<td>DP (FE &amp; Emis)</td>
<td>13.237</td>
<td>4.6422</td>
<td>0.3992</td>
<td>739.56</td>
</tr>
</tbody>
</table>

Performance Measure: \[ fuel + 40 \cdot NOx + 800 \cdot PM \]

Cycle beating?

<table>
<thead>
<tr>
<th></th>
<th>mpg</th>
<th>NOx (g/mi)</th>
<th>PM (g/mi)</th>
<th>Weighted Cost (Fuel+40<em>NOx+600</em>PM)</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>Pre Rule-Based</td>
<td>16.18</td>
<td>3.87</td>
<td>0.332</td>
<td>621.2</td>
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<tr>
<td>New Rule-Based</td>
<td>15.36</td>
<td>2.41</td>
<td>0.219</td>
<td>480.7 (-22.6%)</td>
</tr>
<tr>
<td>DP</td>
<td>16.63</td>
<td>2.04</td>
<td>0.161</td>
<td>403.6 (-35.0%)</td>
</tr>
<tr>
<td>WVUSUB (RDP 2)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Pre Rule-Based</td>
<td>15.31</td>
<td>4.43</td>
<td>0.355</td>
<td>671.225</td>
</tr>
<tr>
<td>New Rule-Based</td>
<td>14.58</td>
<td>2.927</td>
<td>0.296</td>
<td>574.63 (-14.4%)</td>
</tr>
<tr>
<td>DP</td>
<td>15.4</td>
<td>2.78</td>
<td>0.259</td>
<td>526.7 (21.5%)</td>
</tr>
<tr>
<td>WVUENTER (RDP 3)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pre Rule-Based</td>
<td>12.84</td>
<td>7.28</td>
<td>0.509</td>
<td>948.83</td>
</tr>
<tr>
<td>New Rule-Based</td>
<td>12.72</td>
<td>6.27</td>
<td>0.488</td>
<td>894 (-5.8%)</td>
</tr>
<tr>
<td>DP</td>
<td>12.97</td>
<td>6.17</td>
<td>0.44</td>
<td>847.7 (-10.7%)</td>
</tr>
<tr>
<td>UDDSHDV</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pre Rule-Based</td>
<td>13.159</td>
<td>5.74</td>
<td>0.4576</td>
<td>840.63</td>
</tr>
<tr>
<td>New Rule-Based</td>
<td>12.874</td>
<td>4.83</td>
<td>0.429</td>
<td>787.1 (-6.4%)</td>
</tr>
<tr>
<td>DP</td>
<td>13.237</td>
<td>4.64</td>
<td>0.3999</td>
<td>739.56 (-12.0%)</td>
</tr>
</tbody>
</table>
Outline

- Introduction and Motivation
- Simulation model and preliminary rule-based control results
- Dynamic programming technique
- Improved rule-based control law
- Simulation results
- Dyno test results (Fuel Economy Only)
- Conclusions

FedEx HEV Truck Proposal

- FedEx and the Alliance for Environmental Innovation proposed to develop an environmentally progressive truck that would reduce emission by 90% and improve fuel efficiency by 50%, while work as well as FedEx’s current (1999 W700) white delivery trucks and cost about the same over the vehicle’s lifetime.

- Winning design(s) that meet targets will get FedEx purchase (10-50 pre-production by mid 2003, production vehicles by 2004).
**Current FedEx Pickup/Delivery Vehicle Specification**

- Year 1999 baseline vehicle (W700 series)
- GVWR: 16,000 lbs
- Cargo capacity: approximately 670 cubic feet, 6000 lbs
- Cummins 138 kW 6-cylinder diesel engine
- Allison 4-speed automatic transmission (AT)

(http://www.environmentaldefense.org/realm)

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**Eaton Prototype Hybrid Electric Truck**

- Same chassis and body
- 125 kW 4-cylinder diesel engine
- 6-speed automated manual transmission (AMT)
- 44 kW AC motor
- Lithium-Ion battery
- PM trap

![Diagram of Eaton Prototype Hybrid Electric Truck](image)

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*COE Control Seminar-11/01-2002-43*
Test of Prototype Vehicle

- Modified FUDS cycle
- Tested at Southwest Research Institute (SwRI)
- Chassis dynamometer testing
- EPA standard procedure to determine fuel economy and exhaust emissions

Fuel Economy and Emission Results

- Hybrid Prototype #1: baseline prototype hybrid truck
- Hybrid Prototype #2: redesign control strategy (Our Dynamic Programming Design Technique) and add PM trap
**Fuel Saving**

**Rough Calculation**

50,000 miles/yr/truck  
50,000 trucks in the US  
Original: 10 miles/gallon

15,000,000 gallons/yr  
saved by  
Control algorithm improvement

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Weight Category (GWW)</th>
<th>Fuel</th>
<th>Count</th>
<th>Percent of Fleet</th>
<th>Vehicle Km Traveled</th>
<th>Fuel in Litres (000's)</th>
<th>Fuel Consumed in Litres/100 km</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cars and Station Wagons</strong></td>
<td>Less than 2,000 kg</td>
<td>Gas</td>
<td>95</td>
<td>1.5%</td>
<td>1,497</td>
<td>2.0%</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other</td>
<td>5</td>
<td>0.0%</td>
<td>46</td>
<td>0.1%</td>
<td>3</td>
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<tr>
<td><strong>Vans and Light Trucks</strong></td>
<td>Less than 2,000 kg</td>
<td>Gas</td>
<td>1,568</td>
<td>25.7%</td>
<td>14,111</td>
<td>18.8%</td>
<td>1,358</td>
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<tr>
<td></td>
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<td>Other</td>
<td>3</td>
<td>0.5%</td>
<td>240</td>
<td>0.3%</td>
<td>67</td>
</tr>
<tr>
<td><strong>RHD Vans (Light)</strong></td>
<td>Less than 2,000 kg</td>
<td>Gas</td>
<td>2,147</td>
<td>35.2%</td>
<td>17,474</td>
<td>23.3%</td>
<td>1,600</td>
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<tr>
<td></td>
<td></td>
<td>Other</td>
<td>6</td>
<td>1.0%</td>
<td>472</td>
<td>0.6%</td>
<td>105</td>
</tr>
<tr>
<td><strong>Step Vans (Medium)</strong></td>
<td>2,000 to 4,500 kg</td>
<td>Diesel</td>
<td>1,204</td>
<td>21.2%</td>
<td>19,331</td>
<td>25.8%</td>
<td>1,531</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gas</td>
<td>414</td>
<td>6.8%</td>
<td>6,189</td>
<td>8.2%</td>
<td>1,682</td>
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<tr>
<td></td>
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<td>Other</td>
<td>134</td>
<td>2.2%</td>
<td>2,003</td>
<td>2.7%</td>
<td>711</td>
</tr>
<tr>
<td><strong>Medium Vans</strong></td>
<td>4,500 to 15,870 kg</td>
<td>Diesel</td>
<td>310</td>
<td>5.2%</td>
<td>12,479</td>
<td>16.6%</td>
<td>1,436</td>
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<tr>
<td><strong>Tractors and Shunts</strong></td>
<td>Greater than 15,870 kg</td>
<td>Diesel</td>
<td>2</td>
<td>0.0%</td>
<td>1,199</td>
<td>1.6%</td>
<td>77</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>6,097</td>
<td>100.0%</td>
<td>75,046</td>
<td>100.0%</td>
<td>6,261</td>
</tr>
<tr>
<td><strong>Total Gasolina</strong></td>
<td></td>
<td></td>
<td>4,221</td>
<td>69.2%</td>
<td>39,271</td>
<td>52.3%</td>
<td>9,301</td>
</tr>
<tr>
<td><strong>Total Diesel</strong></td>
<td></td>
<td></td>
<td>1,655</td>
<td>27.1%</td>
<td>33,086</td>
<td>44.0%</td>
<td>10,174</td>
</tr>
</tbody>
</table>

http://www.sierralegal.org/reports/climtorfinal.pdf
Conclusions

✦ Designing the power management strategy for HEV by learning from the Dynamic Programming (DP) results has the clear advantage of being near-optimal, accommodates multiple objectives, and systematic.

✦ Improved rule-based control strategy can be developed by analyzing the DP results
  ✦ Significant reduction in NOx and PM emissions can be achieved at the price of a small increase in fuel consumption

✦ The new control strategy was found to be robust on different cycles