PHEV Control Strategies

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Sponsored by Lee Slezak

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Project Overview

Timeline
- Start – September 2008
- End – September 2009
- 50% Complete

Barriers
- Develop optimum control strategies to maximize fuel displacement
- Take into account real world driving

Budget
- DOE
  - FY08 $ 400k
  - FY09 $ 200k

Partners
- U.S EPA
Main Objectives

- Understand the impact of different control strategy philosophies on fuel efficiency and component operating conditions.
- Analyze the most appropriate set of control parameters to maximize fuel efficiency while maintaining acceptable drive quality (e.g., engine starts) and maximizing battery life (e.g., low RMS current).
- Evaluate fuel efficiency obtained with different control strategies over Real World Driving Cycles (RWDC’s) and compare to the J1711 procedure.
Milestones

Develop Controls
Tune Parameters
Run Simulations on Real World Drive Cycles (RWDC)
Select “Best Control” per vehicle
Analyze Impact on Components Operation
Write report

Current Status
Approach - Vehicle Definition

Real World Drive Cycles

Automated Sizing

Control Strategy Analysis

Motor Power for Cycle
Battery Power
Engine Power
Battery Energy

Vehicle Assumptions

>110 Trips
One day in Kansas City

Midsize Vehicle

Only Hot Conditions Assumed, no Grade!
Approach - Control Strategies Considered

Study

Power Split

4kWh
- Load Following Engine Power
- Optimal Engine Power
- Differential Engine Power

8kWh
- Load Following Engine Power
- Optimal Engine Power
- Differential Engine Power

12kWh
- Thermostat
- Load Following Engine Power

16kWh
- Thermostat
- Load Following Engine Power

Each tuned for 10, 20, 30, 40 & 50 miles Charge Depleting (CD) range on the UDDS

All these options were simulated on the RWDCs (source EPA 2005 Kansas City Cycles – 110 trips)
Differential Engine Power Strategy

- The engine is started when wheel power demand exceeds a certain threshold.
- It then provides the difference between the wheel power demand and the power threshold.
Shouldn't the Power threshold be the available max torque of the EM?
Load Following Strategy

- The engine is started when *wheel power demand* exceeds a certain threshold.
- It then provides the **full wheel power**, i.e. it is load following
Constant Optimal Engine Strategy

- The engine is started when wheel power demand exceeds a certain threshold.
- Engine then operates at its optimal power.
- If engine power exceeds wheel power demand, the battery is charged.
Different Strategies Influence Energy Tradeoff - How Do We Select The “Best” Control?

Mean Values

Mean fuel consumption ranges from 2.5 to 5.5 l/100km depending on control alone for the 8kWh Split!
Kernel Density Will be Used to Compare Control Options

![Distribution Fuel Consumption]

Conventional Vehicle

- **Histogram**
- **Kernel density estimation**

**Fuel Consumption [liter/100km]**

- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35
- 40

**Number of Occurrences**

- 6
- 6.5
- 7
- 7.5
- 8
- 8.5
- 9
- 9.5
Best Fuel Economy with “Differential Engine Power” Strategy for the 4kWh Power Split

Differential engine power strategy (20 mi CD Range) achieves highest fuel efficiency

Preliminary results
All Controls Share Same Peak Density, Favoring Electrical Energy Leads to Lower Energy Consumption Maximum Values

Controls have similar operation for low wheel power requirements

Depleting faster leads to higher peak energy values

4kWh Split    Electrical Energy Consumption [Wh/mile]    Preliminary results
Number of Engine Starts Clearly Distinguishes Control Strategies

Preliminary results
Best Control Selected for Each Configuration Based on Criteria of Fuel Consumption & Number of Engine Start

Mean Values

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Fuel Consumption [l/100km]</th>
<th>Electrical Consumption [Wh/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>7.5</td>
<td>150</td>
</tr>
<tr>
<td>Split 4kWh</td>
<td>8.0</td>
<td>175</td>
</tr>
<tr>
<td>Split 8kWh</td>
<td>8.5</td>
<td>200</td>
</tr>
<tr>
<td>Series 12kWh</td>
<td>9.0</td>
<td>225</td>
</tr>
<tr>
<td>Series 16kWh</td>
<td>9.5</td>
<td>250</td>
</tr>
</tbody>
</table>

Preliminary results
Higher Average Engine Efficiency (at its maximum) for the Series Configuration

- Series 12kWh Thermostat
  (mean = 36.76 %, std = 0.696)
- Series 16kWh Thermostat
  (mean = 36.40 %, std = 1.254)
- Split 4kWh Load Following 10miles CD-range
  (mean = 35.48 %, std = 0.6720)
- Split 8kWh Only Optimal Engine Power
  (mean = 35.59 %, std = 0.5681)

Preliminary results
Future Activities

- Expand study to other Real World Drive Cycles (RWDC) – Source INL
- Develop and test control strategies with trip recognition
- Implement controls on hardware (if possible)
- Understand differences with J1711 fuel efficiency results
Summary

- The analysis is only valid for the specific set of RWDC.
- Several control strategies and set of parameters were evaluated on Real World Drive Cycles.
- Different controls were selected based on fuel efficiency and drive quality.
- Control selected varies depending on the battery energy.
  - Load Following for 4kWh battery
  - Optimum Engine for 8kWh battery
  - Thermostat for 12 and 16 kWh battery
- Impact of component operating conditions assessed
- Preliminary comparison with J1711 shows fuel economy under evaluated
References

- D. Karbowski, “Fair Comparison of Powertrain Configurations for Plug-In Hybrid Operation using Global Optimization”, SAE 2009-01-1334, SAE World Congress, April 2009
Additional Slides
Analysis of Vehicle Speed Traces at Different Levels

A hill is the portion of a cycle between two stops

Trips

Hills

Daily Driving
Daily Driving Characteristics

- 111 different drivers – All based on Conventional Vehicles
- An excel file references the different characteristics of the trips (distance, max speed, max acceleration, number of stop...)

**Distribution of Distance for Daily Drives**

- Mean = 37.3 mile
- Median = 37.5 mile
- Std = 17.4 mile
- Number of Daily Drive = 111

Number of daily drives based on distance:

- Result from EPA Daily Drive
- Results from NHTS

Number of occurrences (%):

- Distance (mile)
Additional Characteristics of the Daily Driving

Distribution of Max speed for Daily Drives

- Mean = 72.3 mile/h
- Median = 72 mile/h
- Std = 8.5 mile/h
- Number of Daily Drive = 111

Distribution of Mean acceleration positive for Daily Drives

- Mean = 0.7 m/s²
- Median = 0.7 m/s²
- Std = 0.1 m/s²
- Number of Daily Drive = 111

Distribution of Mean speed for Daily Drives

- Mean = 33.4 mile/h
- Median = 33.5 mile/h
- Std = 6.8 mile/h
- Number of Daily Drive = 111

Distribution of Mean deceleration for Daily Drives

- Mean = -0.8 m/s²
- Median = -0.8 m/s²
- Std = 0.1 m/s²
- Number of Daily Drive = 111
Trips Characteristics

- 364 trips (trip = get in and out of the car)
- An excel file references the different characteristics of the cycles (distance, max speed, max acceleration, number of stop...)

**Distribution of Distance for Trips**

- Mean = 11.4 mile
- Median = 9.9 mile
- Std = 9.7 mile
- Number of Trip = 363
Additional Characteristics of the Trips

- **Max Speed Distribution for Trips**
  - Mean: 57.9 mile/h
  - Median: 61.1 mile/h
  - Std: 16.1 mile/h
  - Number of Trips: 363

- **Mean Speed Distribution for Trips**
  - Mean: 28.5 mile/h
  - Median: 28.7 mile/h
  - Std: 10.9 mile/h
  - Number of Trips: 363

- **Mean Deceleration Distribution for Trips**
  - Mean: -0.5 m/s²
  - Median: -0.4 m/s²
  - Std: 0.1 m/s²
  - Number of Trips: 363
Cycles Cross correlation

Cross correlation
Battery Power Selection

Distribution of $P_{\text{ess}}$ max discharging for Daily Drives

- Mean = 107.3 kW
- Median = 99.1 kW
- Std = 33 kW
- Number of Daily Drive = 111

Series PHEV

PowerSplit PHEV
Battery Energy Selection Based on RWDC

Distribution of Battery Energy out for Daily drives

- **Series PHEV**
  - Mean = 11.6 kWh
  - Median = 11.1 kWh
  - Std = 6.1 kWh
  - Number of Daily Drive = 111

- **PowerSplit PHEV**

**DOE Requirement (11.6 kWh)** => 51.8%

**DOE Requirement (3.4 kWh)** => 10.0%

battery energy out (%)

Battery energy out (kWh)
## Vehicle Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Split 4 kWh</th>
<th>Split 8 kWh</th>
<th>Series 12 kWh</th>
<th>Series 16 kWh</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Engine</strong></td>
<td>76 kW</td>
<td>77 kW</td>
<td>70 kW</td>
<td>71 kW</td>
<td>123.8 kW</td>
</tr>
<tr>
<td><strong>Motor #1 Power</strong></td>
<td>69 kW (peak)</td>
<td>70 kW</td>
<td>117 kW</td>
<td>119 kW</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>34 kW (cont.)</td>
<td>59 kW</td>
<td></td>
<td></td>
<td>---</td>
</tr>
<tr>
<td><strong>Motor #2 / Generator Power</strong></td>
<td>44 kW (peak)</td>
<td>45 kW</td>
<td>70 kW</td>
<td>71 kW</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>29 kW (cont.)</td>
<td>30 kW</td>
<td>66 kW</td>
<td>66 kW</td>
<td>---</td>
</tr>
<tr>
<td><strong>Total Mass</strong></td>
<td>1715 kg</td>
<td>1749 kg</td>
<td>1780 kg</td>
<td>1814 kg</td>
<td>1618 kg</td>
</tr>
<tr>
<td><strong>Glider Mass</strong></td>
<td></td>
<td></td>
<td>990</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frontal Area</strong></td>
<td></td>
<td></td>
<td>2.2 m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Drag Coefficient</strong></td>
<td></td>
<td></td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electrical Accessory Power</strong></td>
<td></td>
<td></td>
<td>220 W</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak Motor Efficiency</strong></td>
<td></td>
<td></td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tire</strong></td>
<td></td>
<td></td>
<td></td>
<td>P195/65 R15, Wheel Radius = 0.317m</td>
<td></td>
</tr>
</tbody>
</table>