PHEV Component
Requirements
Summary

November 2008

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Sponsored by Lee Slezak
Outline

- Development of Current Requirements
- Impact of Standard Drive Cycles
- Impact of Real World Drive Cycles
Define PHEVs Component Requirements

Component Data from R&D Teams

- Battery
- Electric Machine
- Accessories

Vehicle Classes

Vehicle Requirements

PSAT Simulations

Sizing & Simulation

Results Shared with R&D Teams

Validation

Battery RCP

Vehicle Testing

Component Model

Vehicles

Simulations

Requirements

Battery RCP

Vehicle Testing

JCS VL41M

Prius A/C Power

Camry A/C Power

2004 Prius
PHEV Battery Modeling is More Complex than for Conventional HEVs

- Discharge requirements for long periods resulting in considerable diffusion over-voltage.
- Available data from large capacity SAFT cells applied to SAFT VL41 M cell.
- These data were modeled and are the basis of the impedance equations used in the PHEV vehicle simulation study.

Test data

PHEV Model

Scaling Algorithm for Power & Energy

Scaled

Energy
Optimum Battery Power and Energy Defined for Several Vehicle Platforms and AER

Final values selected by the ESS Tech Team
- Short term 10 miles AER (3.4 kWh, 50 kW)
- Long term 40 miles AER (11.6 kWh, 46 kW)
# Current PHEV Battery Requirements

<table>
<thead>
<tr>
<th>Characteristics at EOL (End of Life)</th>
<th>Short-Term Commercialization</th>
<th>Long-Term Commercialization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercialization Target Year</td>
<td>2012</td>
<td>2016</td>
</tr>
<tr>
<td>Peak Pulse Discharge Power (10 sec) kW</td>
<td>45</td>
<td>38</td>
</tr>
<tr>
<td>Peak Regen Pulse Power (10 sec) kW</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Available Energy for CD (Charge Depleting) Mode, 10 kW Rate kWh</td>
<td>3.4</td>
<td>11.6</td>
</tr>
<tr>
<td>Available Energy for CS (Charge Sustaining) Mode kWh</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Minimum Round-trip Energy Efficiency (USABC HEV Cycle) %</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Cold cranking power at -30°C, 2 sec - 3 Pulses kW</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>CD Life / Discharge Throughput Cycles/MWh</td>
<td>5,000 / 17</td>
<td>5,000 / 58</td>
</tr>
<tr>
<td>CS HEV Cycle Life, 50 Wh Profile Cycles</td>
<td>300,000</td>
<td>300,000</td>
</tr>
<tr>
<td>Calendar Life, 40°C year</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Maximum System Weight kg</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>Maximum System Volume Liter</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Maximum Operating Voltage Vdc</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Minimum Operating Voltage Vdc</td>
<td>&gt;0.55 x Vmax</td>
<td>&gt;0.55 x Vmax</td>
</tr>
<tr>
<td>Maximum Self-discharge Wh/day</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>System Recharge Rate at 30°C kW</td>
<td>1.4 (120V/15A)</td>
<td>1.4 (120V/15A)</td>
</tr>
<tr>
<td>Unassisted Operating &amp; Charging Temperature Range °C</td>
<td>-30 to +52</td>
<td>-30 to +52</td>
</tr>
<tr>
<td>Survival Temperature Range °C</td>
<td>-46 to +66</td>
<td>-46 to +66</td>
</tr>
<tr>
<td>Maximum System Production Price @ 100k units/yr</td>
<td>$1,700</td>
<td>$3,400</td>
</tr>
</tbody>
</table>
Electric Machine Power Required within FreedomCAR Target

<table>
<thead>
<tr>
<th>End of Life All Electric Range (miles)</th>
<th>Peak Electric Machine Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>Midsize SUV</td>
</tr>
<tr>
<td>10</td>
<td>Midsize car</td>
</tr>
<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

Midsize SUV
- Power (kW): 40, 45, 50, 55, 60

Midsize car
- Power (kW): 30, 35, 40, 45, 50, 55

UDDS Cycle
Outline

- Development of Current Requirements

- Impact of Standard Drive Cycles
  - PHEV Sizing Based on UDDS for 10, 20, 40 AER.
  - Control Strategy Options when Engine is ON
  - What is the Maximum Share of the Standard Drive Cycle than can be Run in EV?
  - What is the Share of the Standard Drive Cycle than can be Run in EV when Engine is Used at Best Efficiency?
  - PHEV Sizing Based on Various Driving Cycles.

- Impact of Real World Drive Cycles
PSAT Modeling Assumptions

Pre-transmission parallel HEV configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glider Mass</td>
<td>kg</td>
<td>990</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>m²</td>
<td>2.1</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td></td>
<td>0.31</td>
</tr>
<tr>
<td>Wheel Radius</td>
<td>m</td>
<td>0.317</td>
</tr>
<tr>
<td>Rolling Resistance</td>
<td></td>
<td>0.008</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–60mph</td>
<td>s</td>
<td>9 +/- 0.1</td>
</tr>
<tr>
<td>0–30mph</td>
<td>s</td>
<td>3</td>
</tr>
<tr>
<td>Grade at 60 mph</td>
<td>%</td>
<td>6</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>mph</td>
<td>&gt; 100</td>
</tr>
</tbody>
</table>
Vehicle Sized to Meet Requirements

Vehicle Assumptions

Motor Power

Battery Power

Engine Power

Battery Energy

No

Convergence

Yes

Associated Requirements

Drive Cycle in EV Mode

Perfo:
IVM-60 mph

Grade:
60 mph 6% grade

Range
- Battery power slightly increases due to vehicle mass
- Battery capacity changed to maintain acceptable battery pack voltage (~200V)
Cycle Characteristics: SC03, LA92, and US06 are More Aggressive

**Max & Ave Speed**

**Max Accel & Decel**
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  - PHEV Sizing Based on Various Driving Cycles.
- Impact of Real World Drive Cycles
Two PHEV Controls Were Considered

- **Engine Minimum Assist**: Engine is turned on when Motor torque reaches its maximum power curve. Engine provides the delta power between required power at the gearbox input and maximum motor power.

- **Engine Assist at Best Efficiency**: Engine is turned on when Motor power reaches its maximum power curve. The engine operates at the best efficiency region. The surplus power from the engine is used to charge the battery.
Outline

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- Impact of Real World Drive Cycles
Charge Depleting (CD) Capability Decreases as Drive Cycle Aggressiveness Increases

Range

Aggressiveness Decreases  Aggressiveness Increases

CD Increases  CD Decreases

Engine Minimum Assist
Engine Used Only When Electric Machine Reaches its Limit

Maximum Power Required at Gearbox Input for UDDS (~67.4kW)

Engine Minimum Assist
Energy Consumption of Engine Increases as the Aggressiveness of Cycle Increases

- Japan1015: 309.6, 100%
- HWFET: 301.8, 100%
- NEDC: 313.2, 100%
- LA92: 406.0, 99%
- SC03: 400.7, 95%
- US06: 465.6, 85%

Engine Usage increases as the aggressive increases

Avg. Engine Efficiency ~ 24.6%

Engine Minimum Assist
Outline

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  - What is the Share of the Standard Drive Cycle than can be Run in EV when Engine is Used at Best Efficiency?
  - PHEV Sizing Based on Various Driving Cycles.
- Impact of Real World Drive Cycles
How does Engine Assist at Best Efficiency Control Strategy Affects Energy Consumption?
Engine Assist at Best Efficiency Increases AER for Aggressive Cycles
Energy Consumption of Engine Increases as the Aggressiveness of Cycle Increases

Engine Usage increases as the aggressive increases

Avg. Engine Efficiency ~ 29.0%

Engine Assist at Best Efficiency
Outline

- Development of Current Requirements
- Impact of Standard Drive Cycles
  - PHEV Sizing Based on UDDS for 10, 20 40 AER.
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  - What is the Share of the Standard Drive Cycle than can be Run in EV when Engine is Used at Best Efficiency?
  - PHEV Sizing Based on Various Driving Cycles.
- Impact of Real World Drive Cycles
When Battery Sized for Each Cycle, its Power Increases With Cycle Aggressiveness
Sizing based on Each Driving Cycle Decreases Energy Consumption for Aggressive Cycles

The greater impacts are shown on more aggressive cycles, such as SC03, LA92, and US06.
Conclusion

- The choice of driving cycles influences PHEV design decisions.
- All standard drive cycles considered are less aggressive than real-world driving conditions.
- All electric operation can be achieved on aggressive drive cycles with small additional battery power (10 to 15 kW) compared to the UDDS. However, considering Li-ion technology, available power might not be an issue.
- Should the batteries be designed on UDDS to satisfy CARB requirements when it is not representative of real-world driving conditions?
Outline

- Development of Current Requirements
- Impact of Standard Drive Cycles
- Impact of Real World Drive Cycles
Objective: Impact of Real World Drive Cycles on Power and Energy Requirements

Real World Drive Cycles

Automated Sizing

Analysis (Distribution)

Vehicle Assumptions

Motor Power for Cycle

Battery Power

Engine Power

Battery Energy

>110 Trips
One day in Kansas City

Power Split
Midsize Vehicle

Only Hot Conditions Assumed!
Analysis of Vehicle Speed Traces at Different Levels

A hill is the portion of a cycle between two stops
Daily Driving Characteristics

■ 111 different drivers – All based on Conventional Vehicles

Distribution of Distance for Daily Drives

- Result from EPA Daily Drive
- Results from NHTS

Mean = 37.3 mile
Median = 37.5 mile
Std = 17.4 mile

Number of Daily Drive = 111
Trips Characteristics

- 364 trips (trip = get in and out of the car)

**Distribution of Distance for Trips**

- Mean = 11.4 mile
- Median = 9.9 mile
- Std = 9.7 mile
- Number of Trip = 363
50% of the Daily Trips Require >100 kW

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

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

DOE Requirement (50 kW) => 3.5%
DOE Requirement (46 kW) => 2.9%
Distribution of Discharging Peak Power Per Trip

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

- Mean = 74.6 kW
- Median = 68.6 kW
- Std = 32.4 kW
- Number of Trips = 363

If we size on the UDDS, only 22% of the cycles can be completed due to Power Limitation.
Distribution of Discharging Power (All Points)

If we size on the UDDS, 97.1% of the cycles can be completed.

Mean = 14.4 kW
Median = 10.5 kW
Std = 15.2 kW

Number of Trip = 363
Distribution of Charging Peak Power Per Daily Driving

- **Mean**: -57.2 kW
- **Median**: -53.4 kW
- **Std**: 17 kW

Number of Daily Drives = 111

DOE Requirement (30 kW) => 3.6%

DOE Requirement (25 kW) => 1.8%
Distribution of Charging Power (All Points)

- **Mean** = -10.9 kW
- **Median** = -8.9 kW
- **Std** = 8.9 kW
- **Number of Trip** = 363

If we size on the UDDS, 92% of the cycles can be completed.
12 kWh Usable is Required to Complete 50% of the Daily Drives

Distribution of Batter Energy out for Daily drives

DOE Requirement (11.6 kWh) => 51.8%  
Mean=11.6 kWh  
Median=11.1 kWh  
Std=6.1 kWh  
Number of Daily Drive =111

DOE Requirement (3.4 kWh) => 10.0%
UDDS Represents only 10% of the Electrical Consumption

Mean=0.3 kW/mile
Median=0.3 kW/mile
Std=0.1 kW/mile
Number of Trip =363
Maximum UDDS Power Reached Shortly After Departure

Distribution of time until the power demand first exceeds 50 kW for Trips

Mean = 3.5 minutes
Median = 2.8 minutes
Std = 3.4 minutes
Number of Trips = 279
Power Demand >50 kW Occurs for Short Periods of Time

Distribution of total time where power demand is greater than 50 kW for all cycles

Mean = 2.3 Minutes
Median = 2 Minutes
Std = 1.1 Minutes
Number of Trips = 279
Maximum Power Demand Occurs at Highway Speeds

Distribution of vehicle speed while power demand is greater than 50kW

Mean = 58.6 mph  
Median = 63.8 mph  
Std = 14.6 mph

Number of Trips = 279
EV Distance Greatly Varies Depending Upon Cycles Aggressiveness

For 10kWh Usable, the range varies from 24 to 42 miles.

UDDS represents lowest bound while LA92 is more representative of the real world sample.
Conclusion

- The PHEV requirements analysis is only valid for the set of drive cycles considered and should not be generalized to the US market.

- Aggressive driving will put limits on all EV range, which in turn favors a blended mode operational strategy.

- When the battery is sized for the UDDS,
  - 3% of the daily driving and 20% of the trips can be completed in EV due to power limitation. However, the power requirements are sufficient 97% of the time.
  - 1.5% (short term goal) and 50% (long term goal) of the daily driving can be completed in EV due to energy limitation.

- The real world drive cycles are more aggressive than the UDDS, resulting in larger energy requirements to drive the same distance.

- LA92 better represents current drive cycle aggressiveness.