Goal Setting & Simulation Results

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Energy Storage Requirements Defined Using Systems-Level Approach

Component

Vehicle Simulation

Hardware Evaluation in System Context

Testing

Model

JCS VL41M
**Accurate Battery Modeling Used to Generate Requirements**

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

Pre-transmission parallel HEV configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Midsize Car</th>
<th>Crossover SUV</th>
<th>Midsize SUV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curb weight</td>
<td>kg</td>
<td>889</td>
<td>1100</td>
<td>1132</td>
</tr>
<tr>
<td>Vehicle Test Mass (Conventional)</td>
<td>kg</td>
<td>1629</td>
<td>1818</td>
<td>1893</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>m²</td>
<td>2.2</td>
<td>2.68</td>
<td>2.88</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td></td>
<td>0.3</td>
<td>0.41</td>
<td>0.41</td>
</tr>
<tr>
<td><strong>Components</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Machine Peak Efficiency</td>
<td>%</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>Electrical Power Accessory</td>
<td>W</td>
<td>800</td>
<td>1000</td>
<td>1200</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>Grade at 55 mph</td>
<td>%</td>
<td>6</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>mph</td>
<td>&gt; 100</td>
</tr>
</tbody>
</table>
Automated Sizing Process Implemented Including Oversizing

- **Motor Power for UDDS**
- **Battery Power**
- **Engine Power**
- **Battery Energy**
- **Oversize Battery**
- **Convergence**

**Associated Requirements**

- Satisfy CARB EV Range Definition
- 0-60 mph Grade (Safety 1.5 for thermal)
- Range
- 30% Power, 20% Energy to have same performance at EOL
Battery Power Fairly Constant With AER

Pulse Discharge Power (2 sec)

Midsize Car
Crossover SUV
Midsize SUV

All Electric Range Distance on UDDS
Usable Energy Linearly Increase with AER

[Graph showing the increase in usable energy (in kWh) with increasing all-electric range distance (in miles) for different vehicle types: Midsize Car, Crossover SUV, and Midsize SUV. The values in Wh/mile for each are marked at specific distances: 250 Wh/mile for 10 miles, 320 Wh/mile for 20 miles, 380 Wh/mile for 30 miles, and 400 Wh/mile for 40 miles.]
Power/Energy Ratio Decreases with AER
Vehicle Mass Has Little Impact on Usable Energy

Usable Energy (Wh/mile) vs. Vehicle Weight (kg)

- ~10 Wh/mile added for each 100kg

- midsize sedan
- crossover
- midsize SUV
Electrical Accessory Could Have Major Impact on Usable Energy

~5.5 Wh/mile added for each 100W

Accessory load (W)

Usable Energy (Wh/mile)

UDDS Test

midsize sedan

crossover

midsize SUV

A/C ON
### Energy Storage Requirements Summary

<table>
<thead>
<tr>
<th></th>
<th>Midsize Car</th>
<th>Crossover SUV</th>
<th>Midsize SUV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Value for the Uncertainty</td>
<td>230</td>
<td>280</td>
<td>330</td>
</tr>
<tr>
<td>Vehicle Mass Uncertainty</td>
<td>195&gt;X&gt;270</td>
<td>245&gt;X&gt;325</td>
<td>300&gt;X&gt;365</td>
</tr>
<tr>
<td>FA and Cd Uncertainty</td>
<td>220&gt;X&gt;240</td>
<td>270&gt;X&gt;300</td>
<td>320&gt;X&gt;345</td>
</tr>
<tr>
<td>Electrical Accessory Uncertainty</td>
<td>215&gt;X&gt;310</td>
<td>262&gt;X&gt;360</td>
<td>310&gt;X&gt;435</td>
</tr>
<tr>
<td>Representative Average Selected</td>
<td>250</td>
<td>320</td>
<td>380</td>
</tr>
</tbody>
</table>

Values in Wh/mile
PSAT Results Validated Through Hardware Characterization in a Virtual Vehicle Environment

Parameters:
Vehicle mass, drive cycle, Architecture, Component Power ratings, etc

PLANT

Feedback via CAN: voltage, current, temperature, SOC, available power, etc
Johnson-Control-Saft VL41M

- Main Li-ion VL41M Specifications
  - 41Ah @ C/3
  - 72 cells (194.4 – 288 V)
  - 61 kW for 30 sec. at 50% SOC
  - 10 kWh total
  - Water-cooled

- During testing, several key parameters were characterized
  - Voltage
  - Temperature
  - State of Charge
  - Available battery power
  - Other vehicle data
Midsize Vehicle Emulated on EV Mode on UDDS

Pre-transmission Parallel HEV Configuration
### PSAT Battery Model Validated Within <5% for Energy Requirements

<table>
<thead>
<tr>
<th>Units</th>
<th>HIL</th>
<th>PSAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>AER from 0.9 to 0.3 SOC</td>
<td>mi</td>
<td>24.79</td>
</tr>
<tr>
<td>Battery Ah Depleted</td>
<td>Ah</td>
<td>25</td>
</tr>
<tr>
<td>Battery Electrical Energy</td>
<td>kWh</td>
<td>6.29</td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>Wh/mi</td>
<td>253.7</td>
</tr>
</tbody>
</table>
Control Strategy Evaluation - Methodology

Global Optimization

Engine Torque, Motor Torque, SOC, Gear Ratio

Losses & Constraints
Control Strategy Evaluation - Methodology

When do we start/turn off the engine?
How do we split the torque?
How do we manage SOC?
Control Strategy Evaluation - Methodology

Global Optimization

Define Rules

Develop Control
Control Strategy Evaluation - Methodology

- Global Optimization
- Define Rules
- Develop Control
- Implement Control

MATT: Mobile Advanced Technology Test bed
Engine Should be Used Throughout the Trip When Distance > AER

Global optimization – Pre-transmission parallel midsize HEV
Optimum Control Depends on Distance

Different values for the same distance

Global optimization – Pre-transmission parallel midsize HEV
Simulation Studies Main Results

- PSAT used to define battery requirements for several vehicle classes and AER.
- For pre-transmission parallel HEVs:
  - Power requirement fairly independent of AER
  - Usable battery energy is linear function of AER
- Electrical accessory loads should be carefully considered when selecting the usable energy.
- Battery HIL demonstrated a 5% validation of the battery model for energy requirements.
- Vehicle testing demonstrated that, when implementing high capacity batteries in power split HEVs, the energy requirements could be lowered by as much as 40%.
PSAT Current/Future Activities

- **Goal setting**
  - Evaluate the impact of additional drivetrain configurations including series, other parallel and power splits.
  - Size the battery for different applications (not just for UDDS).

- Use battery HIL to define the thermal limitations of the VL41M and their implications on requirements.

- **Control strategy evaluation**
  - Global optimization
  - Real-time control development
  - Control parameters tuning using heuristic optimization (DIRECT, Genetic Algorithm…)

- Use MATT to define emission impact of control strategies
PSAT Current/Future Activities

- Impact of Component Technologies on Fuel Economy
  - Battery technology
  - Engine technology and fuel (gasoline, diesel, hydrogen, ethanol…)

- PHEV Fuel Economy Potential for Different Powertrain Configurations
  - Existing configurations
    - Power splits: Prius, Lexus RX400h, Ford Escape, GM 2 mode
    - Pre-transmission parallel (Sprinter PHEV)
    - Series engine (GM Volt)
  - Specific configurations (wheel motor, post-transmission…)

- Perform trade-off studies as ways to achieve some level of performance while easing requirements on one area or another.