Benchmarking of Competitive Technologies

Tim Burress
Oak Ridge National Laboratory
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Project ID: APE006

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Overview

Timeline
• Start: FY04
• Finish: Ongoing

Budget
• Total project funding
  – DOE: 100%
• Funding received in FY09: $472K
• Funding received in FY10: $412K

Barriers
• Integrating ORNL developed controller with OEM components
• Adapting novel fixture to test cell

Partners
• Argonne National Laboratory
• Electric Transportation Applications
• Idaho National Laboratory
• National Renewable Energy Laboratory
• Oak Ridge National Laboratory, Materials Science and Technology Division
Objectives

• Benchmark on-the-road HEV or PEV vehicle technologies
  – Assess design, packaging, and fabrication characteristics from intensive disassembly of subsystems
    • Determine techniques used to improve specific power and/or power density
    • Reveal compositions and characteristics of key components
      – Trade-offs (magnet strength vs coercivity)
      – General cost analysis
  – Examine performance and operational characteristics during comprehensive test-cell evaluations
    • Establish realistic power rating (18 seconds)
    • Provide detailed information regarding time-dependent and condition-dependent operation
  – Develop conclusions from evaluations and assessments
    • Compare results with other HEV technologies
    • Identify new areas of interest
    • Evaluate advantages and disadvantages of design changes
      – Example: Complexity of LS 600h double sided cooling system

• FY10 objectives
  – Complete end-of-life (EOL) Prius benchmarking studies
  – Complete 2010 Prius benchmarking studies
# Milestones

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Milestone or Go/No-Go Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 2009</td>
<td>Milestone: Complete Lexus LS 600h benchmarking activity</td>
</tr>
<tr>
<td>September 2009</td>
<td>Go/No-Go decision: Determine if on-the-road HEV or PEV system is available and feasible to benchmark</td>
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<tr>
<td>September 2010</td>
<td>Milestone: Complete EOL Prius studies</td>
</tr>
<tr>
<td>September 2010</td>
<td>Milestone: Complete 2010 Prius testing</td>
</tr>
<tr>
<td>September 2010</td>
<td>Go/No-Go decision: Determine if on-the-road HEV or PEV system is available and feasible to benchmark</td>
</tr>
</tbody>
</table>
Approach

Choose subsystem

Teardown PCU and transaxle

Prepare secondary components

Determine volume, weight, SP and PD

Assess design-packaging improvements

Design, fabricate, and instrument

Develop interface-control algorithm

Test systems for performance, efficiency, and continuous operation
FY09 Technical Accomplishments (1)

- Lexus LS 600h PCU
  - Double-sided cooling
  - Despite much higher power capability, PE count reduced or maintained in comparison with Camry/Prius
FY09 Technical Accomplishments (2)

• Lexus LS 600h ECVT
  – Elongated rotor
  – Third magnet added to previous ‘V’ orientation
  – High-Low Ravigneaux planetary/clutch system

![Graph showing 2008 Lexus LS600h Combined Inverter-Motor Efficiency Contours with 93% efficiency.]
FY09 Technical Accomplishments (3)

- End of life tests conducted upon subcomponents from 2004 Prius with 160,000 miles of operation
  - Measured motor efficiency did not change more than 1% from original tests
  - Measured inverter efficiency did not change more than 0.5% from original tests
  - Behavior of capacitors show miniscule differences
  - No damage to stator windings found
  - Transmission oil which impacts rotational losses was found to have 40% lower viscosity for all temperatures
  - Slight wear due to gear meshing observed
  - No degradation of permanent magnet capabilities over vehicle lifetime

Transmission oil viscosity versus temperature

Locked rotor torque vs position
FY10 Technical Accomplishments (1)

- PCU design and packaging assessments
  - Smaller than 2nd generation Prius
  - Larger than 2007 Camry
  - 2010 Prius includes 200-12 V DC-DC converter for accessories
  - Direct cooling yields significant reduction of mass
FY10 Technical Accomplishments (2)

- Fundamental components and functionality similar, yet packaging is quite different from 2\textsuperscript{nd} generation Prius
  - Integrated cooling with power electronics module
  - Significant amount of gray thermal compound used between cooling substrate and bottom compartment
  - Inductor for boost converter has lower profile, yet larger footprint than Camry
  - Boost converter PEs larger
FY10 Technical Accomplishments (3)

- Use of ribbon bonds to connect to DC link and motor outputs
- Direct cooled method significantly reduces thermal conduction path from bottom of IGBT to coolant
  - ~9.0 mm (0.35”) for 2004 Prius
  - 3.8 mm (0.15”) for 2010 Prius
FY10 Technical Accomplishments (4)

- Wide, yet thin internal bus bars
- Capacitor cells cover full width (versus half or less in previous models)
- Main capacitor is not molded into housing like Camry and LS 600h
  - 750 V, 888 uF – inverter
  - 860 V, 0.562 uF – inverter
  - 470 V, 315 uF – battery
- Separate small capacitor fairly substantial in size
  - 900 V, 0.8 uF
  - 950 V, 0.562 uF
FY10 Technical Accomplishments (5)

• Transaxle design similar to Camry transaxle in many ways
  – High speed reduction planetary, power split planetary, & drive, final, differential gears housed within middle section of transaxle

• Unused coolant channels, as received
  – Parking mechanism mounted above cast aluminum coolant channels
Only the coolant channels adjacent to the generator/gear section are used.

Cast coolant channels on underside of transaxle are a new feature:
- This is where the transaxle fluid (lubricant and transfer medium) collects.
FY10 Technical Accomplishments (7)

• Comparison of motor leads
  – Drastic reduction of size for 2010 Prius, despite 55 → 60 kW increase
  – Perhaps due to voltage 500 → 650 Vdc, and speed 6,000 → 13,500 rpm – and/or less duty?
  – 12 ~ 20AWG wires in series for motor winding vs 13 for 2004 Prius, 18 for Camry, 18 for LS 600h

• Neutral brought out to terminal
  – For plug-in charging?

2004 2010 2007 2008
Prius Prius Camry Lexus
LS 600h

5.25mm 3.73mm 5.25mm 6.25 mm
Technical Accomplishments (8)

- Stack length: 2 inches – shortest motor stack length as of yet
- Laminations appear to be the same as Camry

### 2010 Prius Motor Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2008 LS 600h</th>
<th>2007 Camry</th>
<th>2004 Prius</th>
<th>2010 Prius</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td><strong>Lamination Dimensions</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Stator OD, cm</td>
<td>20</td>
<td>26.4</td>
<td>26.9</td>
<td>26.4</td>
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<tr>
<td>Stator stack length, cm</td>
<td>13.54 (5.33&quot;)</td>
<td>6.07 (2.4&quot;)</td>
<td>8.4 (3.3&quot;)</td>
<td>5.08 (2.0&quot;)</td>
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<tr>
<td>Rotor OD, cm</td>
<td>12.91</td>
<td>16.05</td>
<td>16.05</td>
<td>16.04</td>
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<tr>
<td>Rotor stack length, cm</td>
<td>13.59</td>
<td>6.2</td>
<td>8.36</td>
<td>5.0165</td>
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<tr>
<td>Air gap, mm</td>
<td>0.89</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
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<tr>
<td>Lamination thickness, mm</td>
<td>0.28</td>
<td>0.31</td>
<td>0.33</td>
<td>x</td>
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<tr>
<td><strong>Mass of Assemblies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Rotor mass, kg</td>
<td>11.93</td>
<td>9.03</td>
<td>10.2</td>
<td>6.7</td>
<td>Includes rotor shaft.</td>
</tr>
<tr>
<td>Stator mass, kg</td>
<td>18.75</td>
<td>18</td>
<td>25.9</td>
<td>15.99</td>
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<tr>
<td>Stator core mass, kg</td>
<td>15.15</td>
<td>12.38</td>
<td>19.05</td>
<td>10.36</td>
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<tr>
<td><strong>Stator Wiring</strong></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Copper mass, kg</td>
<td>3.59</td>
<td>5.6</td>
<td>6.8</td>
<td>5.63 est.</td>
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<tr>
<td>Number of stator slots</td>
<td>48</td>
<td>48</td>
<td>48</td>
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<tr>
<td>Wires per phase</td>
<td>18</td>
<td>18</td>
<td>13</td>
<td>12</td>
<td>~20 AWG</td>
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<tr>
<td>Configuration</td>
<td>Parallel</td>
<td>Parallel</td>
<td>Series</td>
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<tr>
<td><strong>Casing</strong></td>
<td></td>
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<tr>
<td>Motor casing mass, kg</td>
<td>14</td>
<td>9.5</td>
<td>8.9</td>
<td>15</td>
<td>Resolver, pump, etc</td>
</tr>
</tbody>
</table>
Technical Accomplishments (9)

- Rotor with PM in ‘V’ arrangement
- Segmented and potted winding
- 12 stator teeth (vs 48)
Collaborations

• Argonne National Laboratory
  – ANL provides vehicle level data obtained during extensive drive cycle testing which enables the observation of common operation conditions and trends observed on a system-wide basis
  – Converter, inverter, and motor characteristics such as efficiency and performance are supplied to ANL for use in system-wide vehicle modeling
• Electric Transportation Applications and Idaho National Laboratory
  – ETA and INL collaborate on a fleet vehicle testing program in which fleet vehicles undergo normal driving and maintenance schedules. The study of components from these vehicles provides information related to the reliability and operation long-term susceptibility of the designs.
• National Renewable Energy Laboratory
  – NREL utilizes temperature measurements observed during performance and efficiency tests to assess the characteristics of the thermal management system
  – NREL provides feedback and suggestions in regards to the measurements (such as thermocouple placement) useful to thermal management system assessments
• Oak Ridge National Laboratory, Materials Science & Technology Division
  – Provides detailed material analysis of components such as magnets and power electronics packages
Future Work

- Benchmarking efforts will focus on technologies of interest to DOE, the Electrical and Electronics Technical Team, and Vehicle Systems Analysis Technical Team
Summary

- Various drive systems sub-assemblies fully assessed (Prius, Accord, Camry, LS 600h)
  - Power density and specific power determined
  - Design specifications validated
  - *2010 Prius validations in progress

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2010 Prius (60 kW)*</th>
<th>Lexus (110 kW)</th>
<th>Camry (70 kW)</th>
<th>2004 Prius (50 kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Peak power density, kW/L</td>
<td>4.8</td>
<td>6.6</td>
<td>5.9</td>
<td>3.3</td>
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<tr>
<td>Peak specific power, kW/kg</td>
<td>1.6</td>
<td>2.5</td>
<td>1.7</td>
<td>1.11</td>
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<tr>
<td>Inverter (excluding generator inverter)</td>
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<td></td>
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<tr>
<td>Peak power density, kW/L</td>
<td>5.9</td>
<td>10.6</td>
<td>7.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Peak specific power, kW/kg</td>
<td>6.9</td>
<td>7.7</td>
<td>5</td>
<td>3.7</td>
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</table>

<table>
<thead>
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</thead>
<tbody>
<tr>
<td><strong>Motor-related Technology</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Motor peak power rating</td>
<td>60 kW</td>
<td>110 kW</td>
<td>70kW</td>
<td>12.4 kW</td>
<td>50 kW</td>
</tr>
<tr>
<td>Motor peak torque rating</td>
<td>207 Newton meters (Nm)</td>
<td>300 Nm</td>
<td>270 Nm</td>
<td>136 Nm</td>
<td>400 Nm</td>
</tr>
<tr>
<td>Rotational speed rating</td>
<td>13,500 rpm</td>
<td>10,230 rpm</td>
<td>14,000 rpm</td>
<td>6,000 rpm</td>
<td>6,000 rpm</td>
</tr>
<tr>
<td><strong>Power electronics-related Technology</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IPM Cooling</td>
<td>Direct cooled, single side water/glycol loop</td>
<td>Double-sided infrastructure, water/glycol loop</td>
<td>Heat sink with water/glycol loop</td>
<td>Air-cooled heat sink</td>
<td>Same as Camry</td>
</tr>
<tr>
<td>Bi-directional DC-DC converter output voltage</td>
<td>200-650 Vdc</td>
<td>~288-650 Vdc</td>
<td>250–650 Vdc</td>
<td>N/A</td>
<td>200–500 Vdc</td>
</tr>
<tr>
<td>High-voltage (HV) Ni-MH battery</td>
<td>201.6 V, 6.5 Ah, 27 kW</td>
<td>288 V, 6.5 Ah, 36.5 kW</td>
<td>244.8 V, 6.5 Ah, 30 kW</td>
<td>144V, 6.5 Ah, 13.8 kW</td>
<td>201.6 V, 6.5 Ah, 20 kW</td>
</tr>
</tbody>
</table>