Benchmarking EV and HEV Technologies

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U.S. DOE Vehicle Technologies Office
2015 Annual Merit Review and Peer Evaluation Meeting

June 9, 2015

Project ID: EDT006

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### Overview

<table>
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<tr>
<th>Timeline</th>
<th>Budget</th>
<th>Barriers</th>
<th>Partners</th>
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</thead>
<tbody>
<tr>
<td>• Start – FY04</td>
<td>• Total project funding</td>
<td>• Integrating custom ORNL inverter-motor-controller with OEM components.</td>
<td>• John Deere</td>
</tr>
<tr>
<td>• End – Ongoing</td>
<td>• DOE share – 100%</td>
<td>- Optimizing controls for non-linear motors throughout operation range.</td>
<td>• ANL</td>
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<td></td>
<td>• Funding received in FY14: $ 500K</td>
<td>• Intercepting, decoding, and overtaking OEM controller area network (CAN) signals.</td>
<td>• NREL</td>
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<td>• Funding for FY15: $ 540K</td>
<td>• Adapting non-standard motor shaft and assembly to dynamometer and test fixture.</td>
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<td></td>
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<td>• This project helps with program planning and the establishment and verification of all DOE 2020 targets.</td>
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Project Objective and Relevance

**Overall Objective:** The core function of this project is to confirm power electronics and electric motor technology status and identify barriers and gaps to prioritize/identify R&D opportunities

- Assess design, packaging, and fabrication innovations during teardown of sub-systems
  - Identify manufacturer techniques employed to improve specific power and/or power density
  - Perform compositional analysis of key components
    - Facilitates trade-off comparisons (e.g. magnet strength vs coercivity) and general cost analysis
- Examine performance and operational characteristics during comprehensive test-cell evaluations
  - Establish realistic peak power rating (18 seconds)
  - Identify detailed information regarding time-dependent and condition-dependent operation
- Compile information from evaluations and assessments
  - Identify new areas of interest
  - Evaluate advantages and disadvantages of design evolutions
  - Compare results with other EV/HEV technologies and DOE targets

**Objectives** (March 2014 through March 2015):

- Complete 2014 Honda Accord HEV teardown assessments.
- Conduct 2014 Honda Accord HEV dynamometer testing.
- Initiate teardown of BMW i3 inverter assembly and electric motor.
# Milestones

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestones and Go/No-Go Decisions</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>December 2014</td>
<td><strong>Go/No-Go decision:</strong> Identify and procure EV/HEV components.</td>
<td>Go.</td>
</tr>
<tr>
<td>March 2015</td>
<td><strong>Milestone:</strong> Determine core functionality and general design approach of HEV/EV subsystems.</td>
<td>Complete.</td>
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<tr>
<td>June 2015</td>
<td><strong>Milestone:</strong> Perform initial testing on HEV/EV subsystems.</td>
<td>On Track.</td>
</tr>
<tr>
<td>August 2015</td>
<td><strong>Milestone:</strong> Complete benchmarking tests of selected subsystem and assess design characteristics and operation with respect to 2020 DOE targets.</td>
<td>On Track.</td>
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Problem to be Addressed

• Without detailed knowledge of state-of-the-art technologies and their progression, vital feedback is lacking in many areas, including:
  – Design and functional assessments
    • Magnet and capacitor characteristics
    • Power control unit and electric motor design and packaging
    • Converter (e.g. boost, DC-DC, charger, etc.) design and packaging
    • Mass, volume, and power capabilities of various subsystems
    • Material quantities (e.g. copper mass, NdFeB mass and composition, etc)
    • Power density and specific power
  – Operational characteristics
    • Efficiency maps for motor, inverter, converter, and charger
    • Impact of temperature limits, speed, etc. upon capabilities
    • Continuous duration
      – Time-dependent and condition-dependent information especially important as technologies progress to long duration operation, such as electric vehicles EVs
      – 55 kW for 2 seconds, 2 minutes, or 2 hours?

Benchmarking Defines State-of-the-Art
Approach/Strategy

• Provide status of select EV and HEV technologies through assessment of design, packaging, fabrication, and performance during comprehensive testing
  – Compare results with other EV and HEV technologies
  – Confirm or provide feedback on VTO targets
  – Identify new areas of interest
  – Evaluate advantages and disadvantages of design changes, i.e., complexity of 3rd generation Prius PCU cooling system

• Foster collaborations with U.S. DRIVE Electrical and Electronics Tech Team (EETT) and Vehicle Systems Analysis Tech Team (VSATT)

• Publish test results and conclusions for open discussion
### FY15 Tasks to Achieve Key Deliverable

<table>
<thead>
<tr>
<th>2014</th>
<th>2015</th>
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<tbody>
<tr>
<td>Oct</td>
<td>Nov</td>
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<td></td>
<td>Feb</td>
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**Go No/Go Decision Point:** Determine if EDT components of interest are available.

**Key Deliverable:** Annual report with findings from benchmarking assessments.
Accomplishments – Previous FYs


<table>
<thead>
<tr>
<th>Component &amp; Parameter</th>
<th>2020 DOE Targets</th>
<th>2012 Leaf (80 kW)</th>
<th>2012 Sonata HSG 23 (8.5 kW)</th>
<th>2011 Sonata (30 kW)</th>
<th>2010 Prius (60 kW)</th>
<th>2008 LS600h Lexus (110 kW)</th>
<th>2007 Camry (70 kW)</th>
<th>2013 Camry (105 kW)</th>
<th>2004 Prius (50 kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td></td>
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<tr>
<td>Peak power density, kW/L</td>
<td>5.7</td>
<td>4.2</td>
<td>7.42 (2.7)</td>
<td>3.0</td>
<td>4.8</td>
<td>6.6</td>
<td>5.9</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Peak specific power, kW/kg</td>
<td>1.6</td>
<td>1.4</td>
<td>1.9 (0.7)</td>
<td>1.1</td>
<td>1.6</td>
<td>2.5</td>
<td>1.7</td>
<td>1.1</td>
<td></td>
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<tr>
<td>Inverter</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Peak power density, kW/L</td>
<td>13.4</td>
<td>5.7</td>
<td>5.6 (2.0)</td>
<td>7.3</td>
<td>5.9 (11.1)</td>
<td>10.6 (17.2)</td>
<td>7.4 (11.7)</td>
<td>12.7 (19.0)</td>
<td>4.5 (7.4)</td>
</tr>
<tr>
<td>Peak specific power, kW/kg</td>
<td>14.1</td>
<td>4.9</td>
<td>5.4 (2.0)</td>
<td>6.9</td>
<td>6.9 (16.7)</td>
<td>7.7 (14.9)</td>
<td>5.0 (9.3)</td>
<td>11.5 (17.2)</td>
<td>3.8 (6.2)</td>
</tr>
</tbody>
</table>

Note: All power density and specific power levels in table are not apples-to-apples. (e.g. LEAF and Sonata have continuous capability near their published rated power)
FY15 Accomplishments – 2014 Accord

- 2014 Accord is first mass produced ‘full’ hybrid by Honda offered in U.S.
- Power Converter Unit manufactured by Fuji Electric
FY15 Accomplishments – 2014 Accord

Various views of 2014 Accord Power Converter Unit

- Top compartment
- Bottom compartment
- Power Module
- Heatsink
FY15 Accomplishments – 2014 Accord

Converter/Inverter system similar to Toyota system

Electrical schematic of Accord hybrid system

Up to 700 VDC, depending on driving conditions

- Battery: PHEV (~320V), HEV (~259V)
- Bi-directional DC-DC Converter
  - Inductor
  - Filter Capacitor
- Motor Inverter
- Generator Inverter
- Up to 700 VDC, depending on driving conditions
FY15 Accomplishments – 2014 Accord

- Capacitor assembly:
  - 411 uF, 370Vdc (battery input)
  - 1,125 uF, 700 Vdc (boosted DC link)
  - Two small 0.047uF, 700 Vdc

Bottom Compartment of Accord Power Converter Unit

Thermal paste to mate inductor with heat exchanger

Bulk capacitors

Boost inductor
FY15 Accomplishments – 2014 Accord

2014 Accord Power Converter Unit – Top Compartment

• Same microcontroller used for motor and generator
  – D70F3507M1GJA2 – by Renesas,
  – V850 Family → V850E2/Px4
  – 32 bit, 512 kB Flash, 40 kB RAM, 32 kB data flash, 32 MHz, 100 pins, 22 ch x 12bit A/D, 8 channel DMA, 112 channel DTC, 11 external interrupts, 73 I/Os, 32 PWM outputs, 3-phase output function, 2 CAN channels, -40 to 125C

Control board

Bottom of control board
FY15 Accomplishments – 2014 Accord

- Motor inverter: 2 IGBTs per switch
- Generator inverter: 1 IGBT per switch
- Boost converter: 3 IGBTs lower switch, 2 IGBTs upper switch
FY15 Accomplishments – 2014 Accord

2014 Accord Power Converter Unit – Power Module

- EMI shield
- Bus bar infrastructure
- Power electronics devices and integrated cooling
FY15 Accomplishments – 2014 Accord

2014 Accord Power Converter Unit – Power Module

Generator Inverter  Motor Inverter  Boost Converter
Motor, generator, and boost converter IGBTs and diodes have the same dimensions:

- **Diode:**
  - 12.15mm x 11.06 mm
  - 134.38 mm²
- **IGBT:**
  - 12.18mm x 15.21 mm
  - 185.26 mm²
FY15 Accomplishments – 2014 Accord

Accord Power Converter Unit Heat Exchanger

- Close-up of fins on bottom of power module
- Boost inductor and bulk capacitor housing

Power Module
Accord Transmission Sections and External Components

- Transmission mates to engine with flywheel on splined shaft
- No torque converter
- Total Mass: 113.5 kg (249.5 lbs) - Camry hybrid transmission mass is 108 kg
FY15 Accomplishments – 2014 Accord

- Essentially series hybrid until engine locks in with a clutch, where the gear ratio from engine to drive-axles is: 65/19x49/61 = 2.748
  - The axle rpm is about 13 times the vehicle speed.
  - For engine speed of 4,000 rpm, this gives 112 mph.
  - 2,000 rpm correlates to 66 mph
- Fixed gear ratio from electric motor to drive-axles
  - 65/19x49/20 = 8.38
  - 14000 rpm → 128 mph
  - 6536 rpm → 60 mph
- Generator speed is 66/34 = 1.94 faster than engine speed
Accord Motor and Generator Cooling System

Two holes in each tube for generator end-turns

Two holes in each tube for motor end-turns
FY15 Accomplishments – 2014 Accord

- Generator and Motor stator and rotor laminations appear to be identical
  - Stator OD: 29.13 cm
  - Rotor OD: 19.5 cm

- Motor specifications
  - Stack length: 6.17 cm (1.64 times generator: 3.762 cm)
  - Rotor mass: 11.8 kg
  - Stator mass: 20.8 kg
  - Total magnet mass: 1.24 kg

2010 Prius rotor lamination 2014 Accord rotor lamination
Accord Hybrid Inverter and Motor on Dyno

- Power analyzers and other data acquisition equipment
- Accord Motor/Transmission
- ORNL Controller
- Accord Inverter
FY15 Accomplishments – 2014 Accord

ORN/ANL Collaboration (Vehicle testing)

• Obtained three-phase voltage and phase current at the following points at ANL:
  – 5 MPH, ~545 rpm
    • Coast, 100 Nm, 200 Nm, 264.8 Nm → 5.7 kW, 11.4 kW, 15.1 kW
  – 10 MPH, ~1089 rpm,
    • Coast, 100 Nm, 200 Nm, 252 Nm → 11.4 kW, 22.7 kW, 28.8 kW
  – 20 MPH, ~2179 rpm,
    • Coast, 100 Nm, 200 Nm, 254 Nm → 22.81 kW, 45.6 kW, 68.0 kW
  – 30 MPH, ~3268 rpm,
    • Coast, 100 Nm, 200 Nm, 254 Nm → 34.2 kW, 68.5 kW, 86.9 kW
  – 40 MPH, ~4358 rpm,
    • Coast, 100 Nm, 200 Nm, 254 Nm → 45.6 kW, 91.3 kW, 115.9 kW
  – 50 MPH, ~5447 rpm,
    • Coast, 100 Nm, 200 Nm → 57.0 kW, 114.1 kW (floored)
  – 60 MPH, ~6536 rpm,
    • Coast, 100 Nm, 172 Nm → 68.4 kW, 117.7 kW (floored)
  – 70 MPH, ~7626 rpm,
    • Coast, 100 Nm, 148 Nm → 79.9 kW, 118.2 kW (floored)
  – 80 MPH, ~8715 rpm,
    • Coast, 100 Nm, 126 Nm → 91.3 kW, 115.0 kW (floored)
FY15 Accomplishments – 2014 Accord

Preliminary Results: Motor Efficiencies at 300VDC

- Motor efficiency reaches above 95%

![Motor Efficiency Contours](chart.png)
FY15 Accomplishments – 2014 Accord

Preliminary Results: Inverter Efficiencies at 300VDC

• Inverter efficiency reaches 99%
FY15 Accomplishments – 2014 Accord

Preliminary Results: Combined Efficiencies at 300VDC

• Combined (motor and inverter) efficiency reaches above 93%
Responses to Previous Year Reviewers’ Comments

• One reviewer noted a good report on Toyota vehicles. To another, the analysis is well done, although several questions were raised, i.e., how can the work be more widely distributed, is any effort being made to understand and document the control algorithms used, and if Argonne is doing this work, can a link or contact be provided to get access to the information?
  – Response: Argonne performs analysis at the vehicle level, and collaborations with them have help established common operation conditions (e.g. speed, torque, etc) as well as maximum vehicle acceleration conditions.
  – A webpage dedicated to the benchmarking project will be developed for better dissemination of information.

• One reviewer said the results are not as fast as he would like, but considering the budget and resources, he is very satisfied. A different reviewer commented that a focus on quick turnaround will result in improved value.
  – Response: We are working on improving the turnaround on the work. Preliminary teardown information is available prior to the comprehensive benchmarking data, and we plan to present this information to EETT when available. Dynamometer test cell evaluations often require the design, fabrication, and assembly of complex interface hardware, and thus, there are uncontrollable delays in the process of preparation. Furthermore, the comprehensive data collected during the benchmarking efforts requires a significant amount of time for data processing, documentation, and formatting in the preparation of a final report.
## Partners/Collaborators

<table>
<thead>
<tr>
<th>Logo</th>
<th>Organization</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="John Deere Logo" /></td>
<td>John Deere</td>
<td>Provides input and general collaboration in the area of benchmarking.</td>
</tr>
</tbody>
</table>
| ![Argonne National Laboratory Logo](image) | ANL | • Provides system parameters to ORNL from on-the-road tests  
  – Includes extreme hot/cold temperature tests  
• Examples:  
  – Coolant temperature range and common operation conditions  
  – Battery voltage range and common operation conditions  
• ORNL provides component efficiency and operational characteristics for AUTONOMIE  
  – Also provides to EPA, automotive manufacturers, and public |
| ![National Renewable Energy Laboratory Logo](image) | NREL | ORNL provides component efficiency and operational characteristics to NREL for thermal studies. |
| ![Ames Laboratory Logo](image) | Ames Lab | Ames provides insight into magnet characterization and conducts quantitative analysis on samples from ORNL. |
Proposed Future Work

• Remainder of FY15
  – Finalize comprehensive benchmarking of Accord.
  – Complete destructive analysis of Accord.
  – Complete teardown assessments of BMW i3.
  – Design interfaces for and instrument i3 for testing.
  – Initiate benchmarking of 2nd generation LEAF charger, depending on availability.

• FY16
  – Select commercially available EV/HEV systems relevant to DOE’s VTO mission.
  – Perform standard benchmarking of selected system.
Summary

• **Relevance:** The core function of this project is to confirm power electronics and electric motor technology status and identify barriers and gaps to prioritize/identify R&D opportunities.

• **Approach:** The approach is to select leading EV/HEV technologies, disassemble them for design/packaging assessments, and test them over entire operation region.

• **Collaborations:** Interactions are ongoing with other national laboratories, industry, and other government agencies.

• **Technical Accomplishments:** Tested and reported on more than eight EV/HEV systems including recent efforts on the 2014 Honda Accord inverter and motor.

• **Future work:** Complete Accord HEV dynamometer testing and continue benchmarking BMW i3.