U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Benchmarking of Competitive Technologies

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Project ID: APE006

Overview

Timeline

- Start: FY04
- Finish: Ongoing

Barriers

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

Budget

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

Partners

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

Objectives

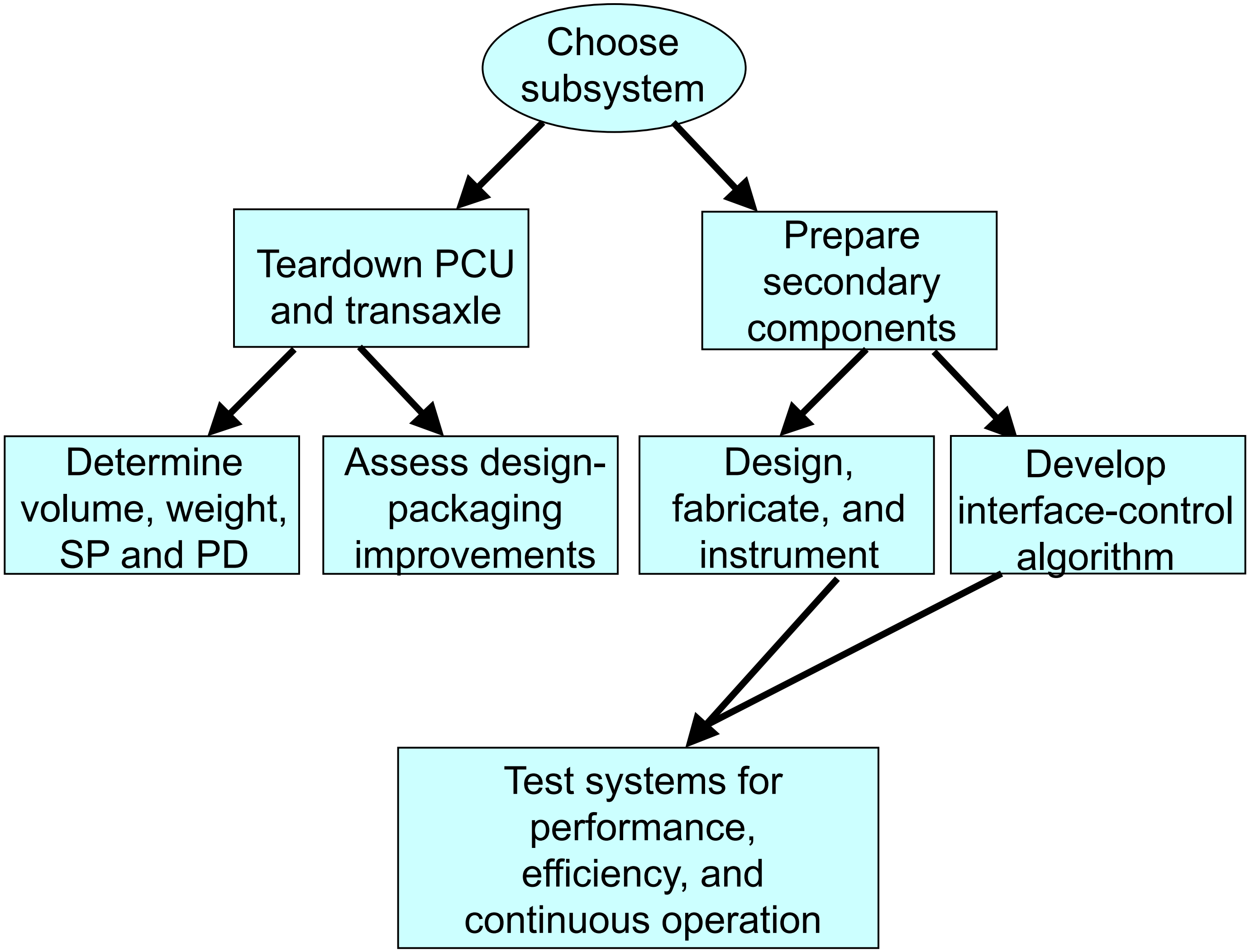
- Benchmark on-the-road HEV or PEV vehicle technologies
  - Assess design, packaging, and fabrication characteristics from intensive disassembly of subsystems
    - Determine techniques used to improve specific power and/or power density
    - Reveal compositions and characteristics of key components
      - 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

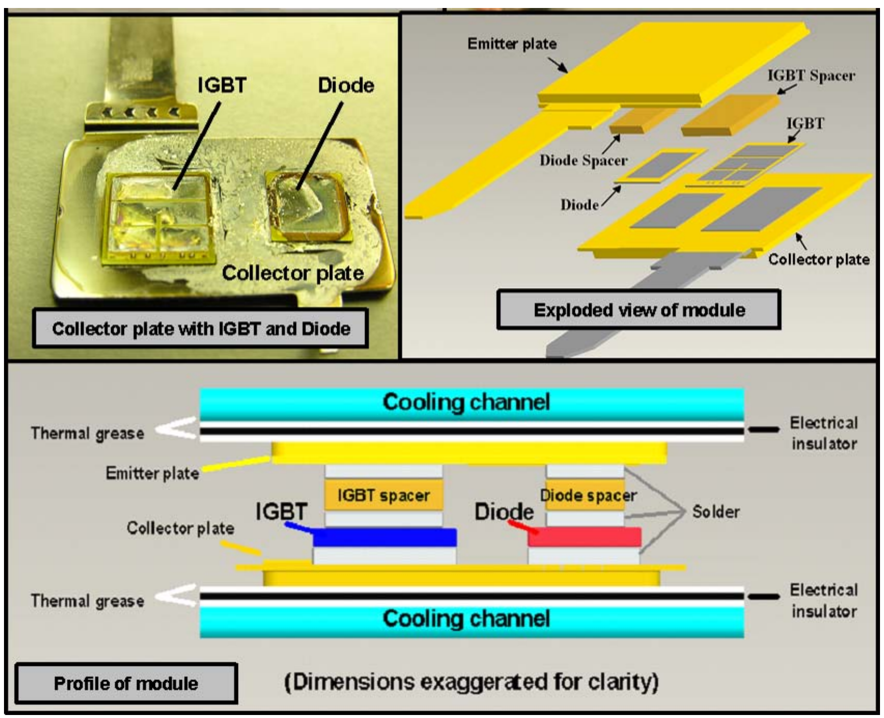
Month/Year	Milestone or Go/No-Go Decision
March 2009	Milestone: Complete Lexus LS 600h benchmarking activity
September 2009	Go/No-Go decision: Determine if on-the-road HEV or PEV system is available and feasible to benchmark
September 2010	Milestone: Complete EOL Prius studies
September 2010	Milestone: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

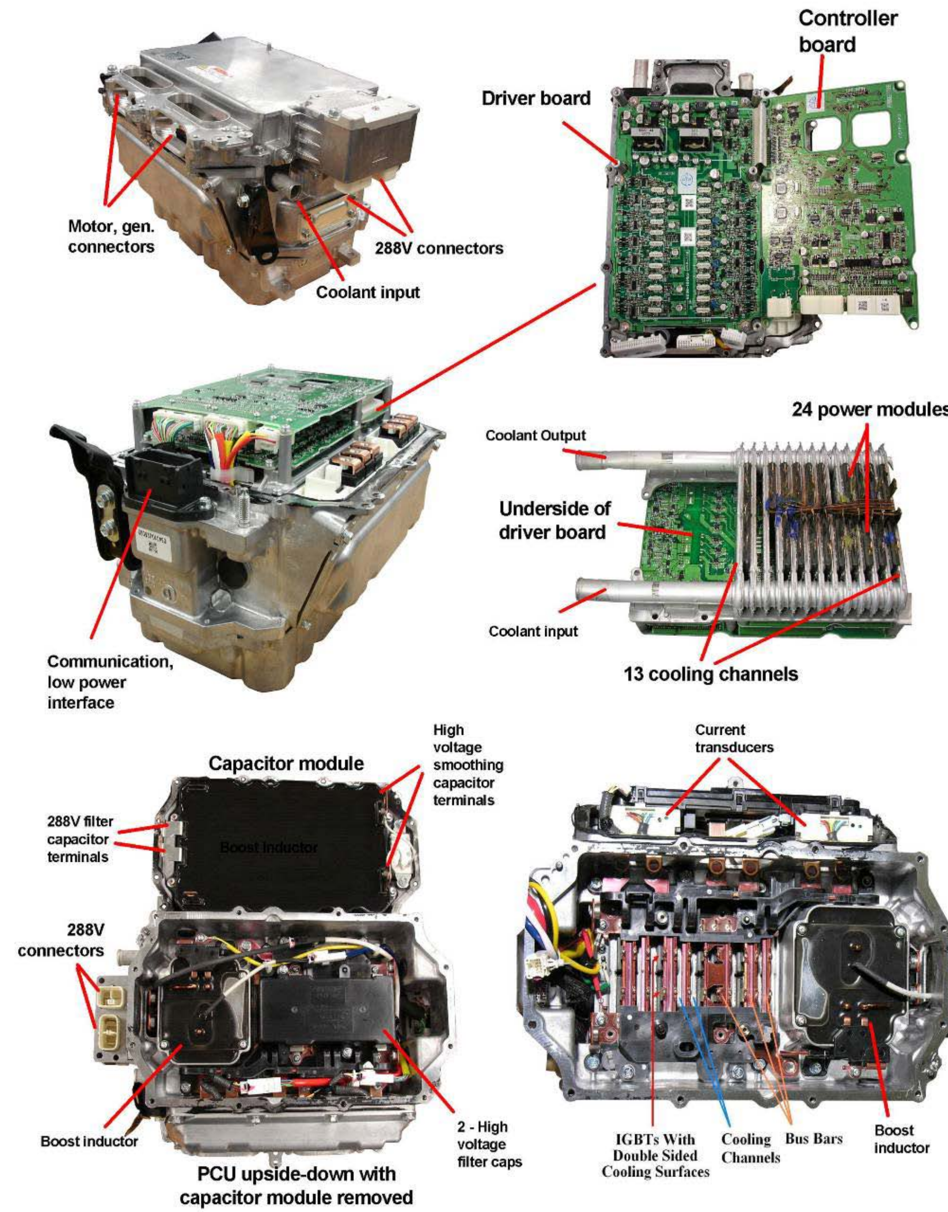
Approach


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)

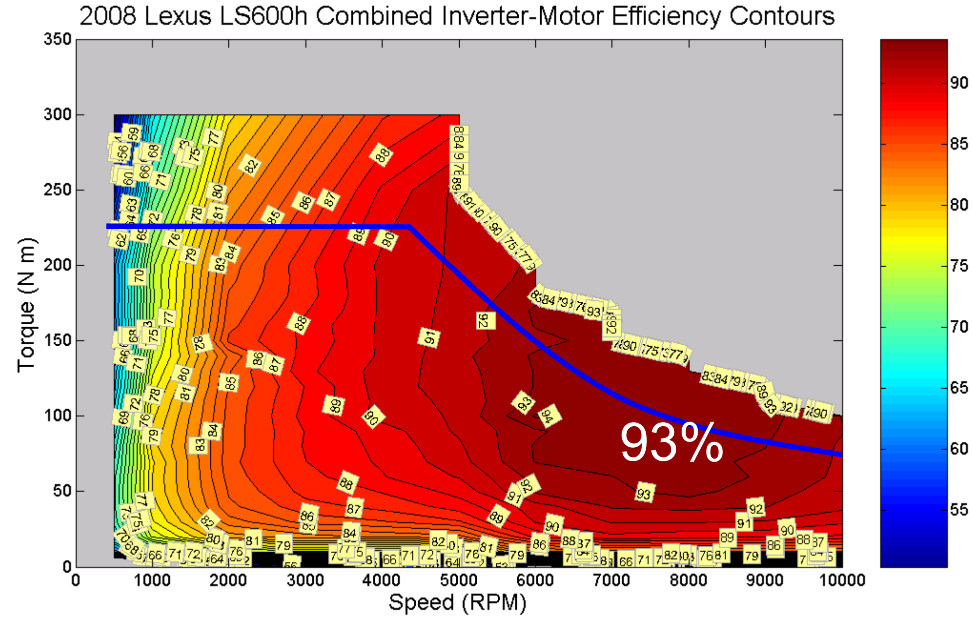
- Lexus LS 600h PCU
  - Double-sided cooling
  - Despite much higher power capability, PE count reduced or maintained in comparison with Camry/Prius

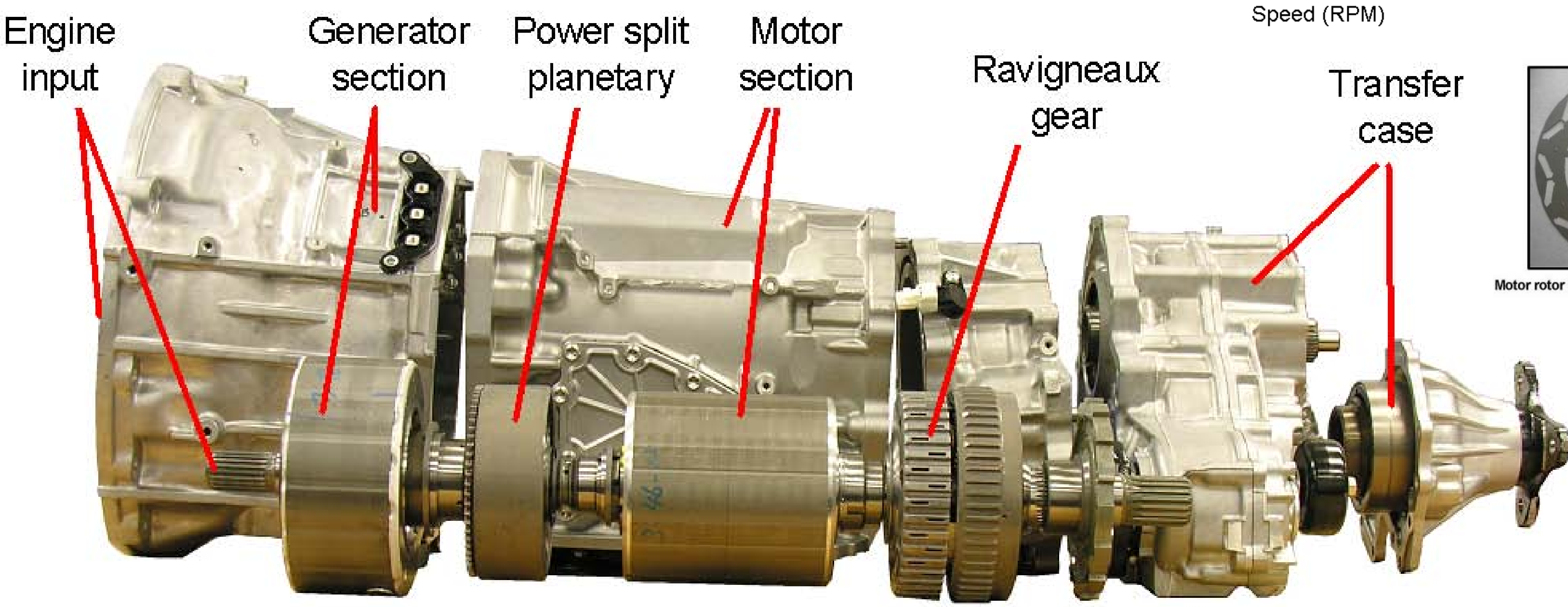




FY09 Technical Accomplishments (2)

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



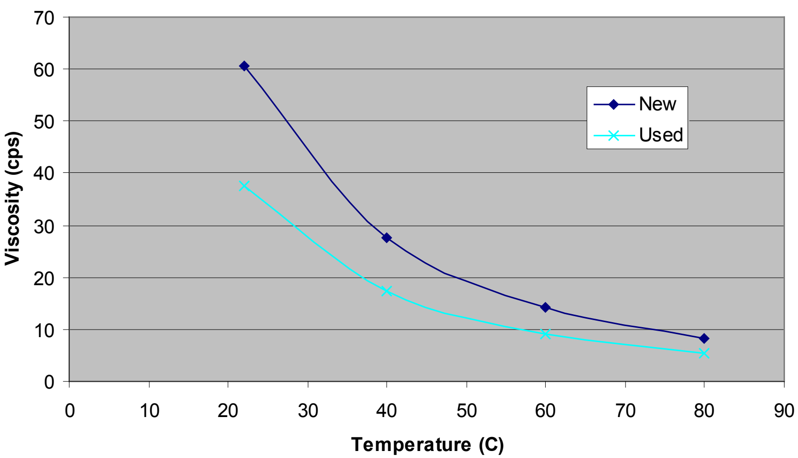


Motor rotor lamination: 2007 Camry vs 2008 LS600h

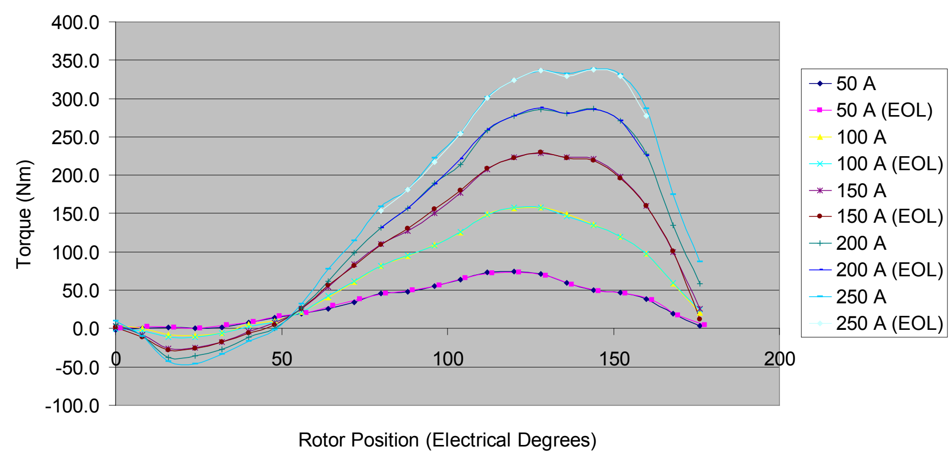
FY09 Technical Accomplishments (3)

- 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

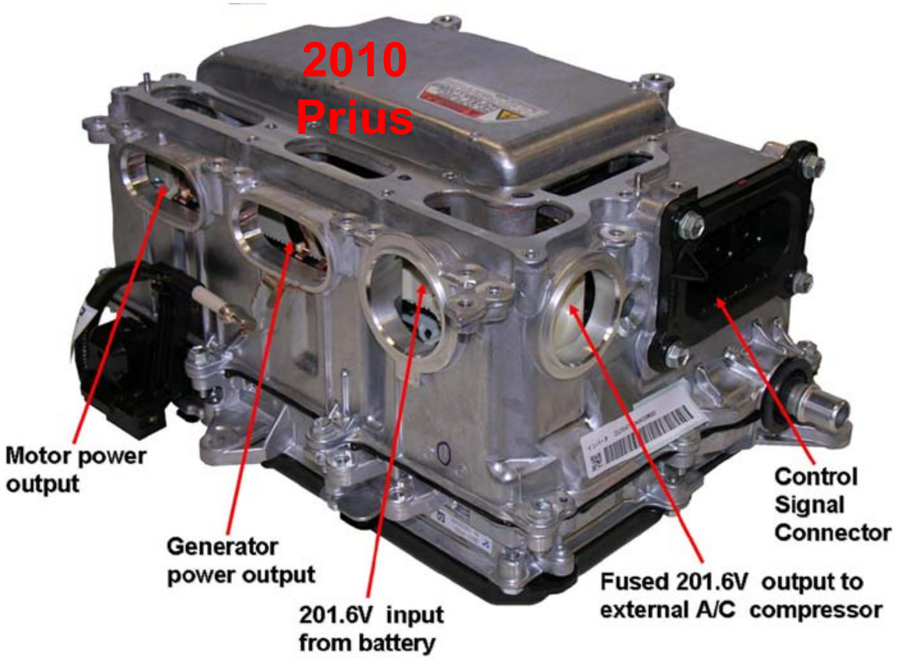


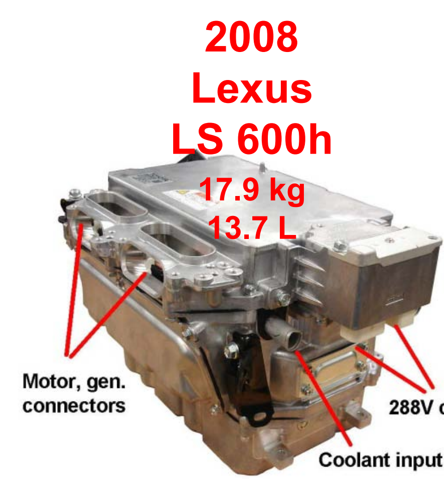
Locked rotor torque vs position



FY10 Technical Accomplishments (1)

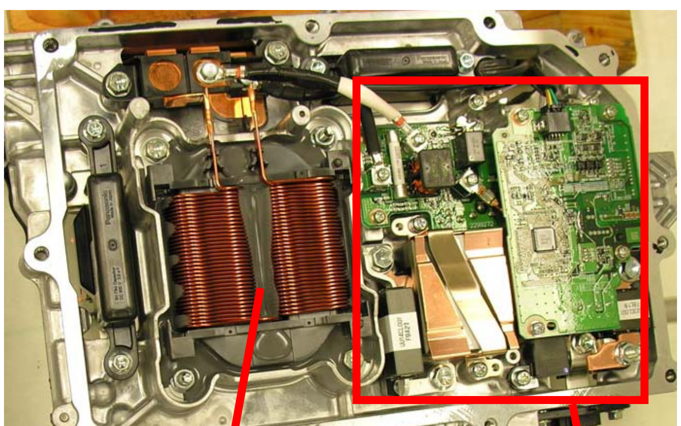
- PCU design and packaging assessments
  - Smaller than 2nd generation Prius
  - Larger than 2007 Camry
  - 2010 Prius includes 200-12 V DC-DC converter for accessories
  - Direct cooling yields significant reduction of mass

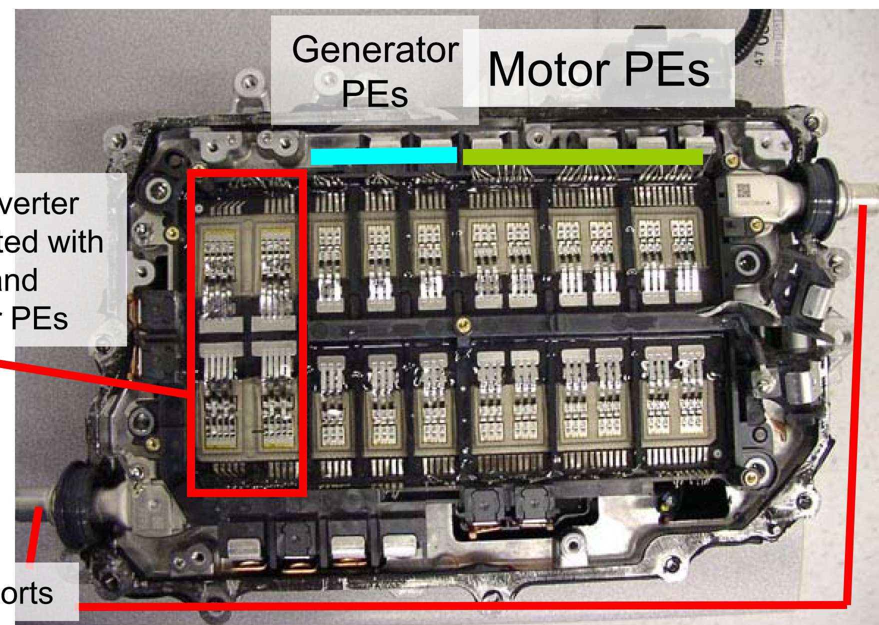




FY10 Technical Accomplishments (2)

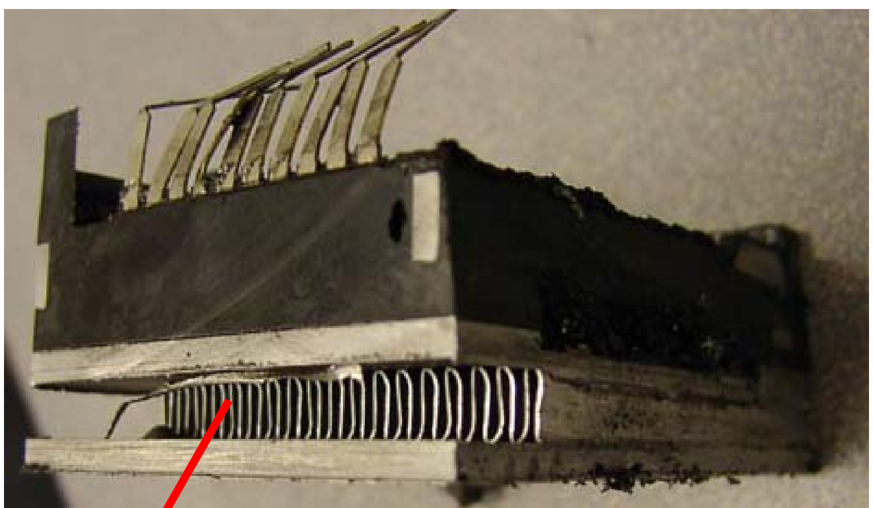
- Fundamental components and functionality similar, yet packaging is quite different from 2nd generation Prius
  - Integrated cooling with power electronics module
  - Significant amount of gray thermal compound used between cooling substrate and bottom compartment
  - Inductor for boost converter has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



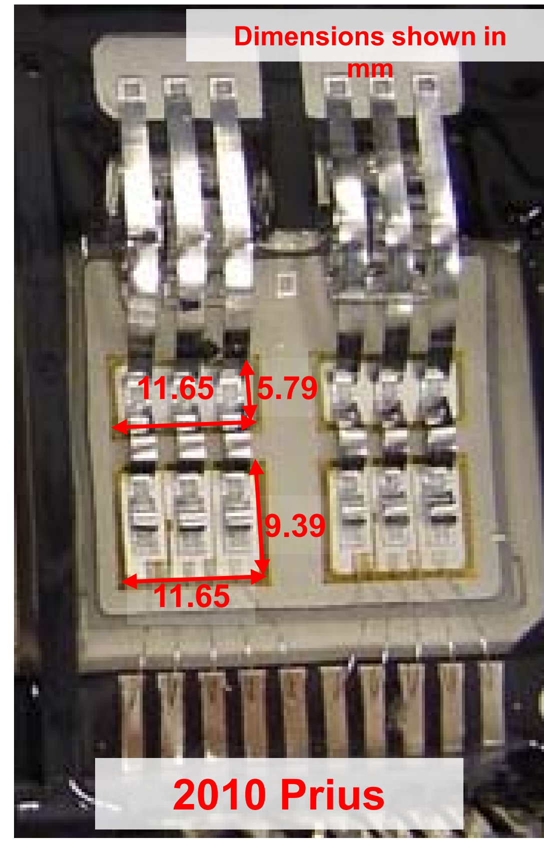


FY10 Technical Accomplishments (3)

- 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

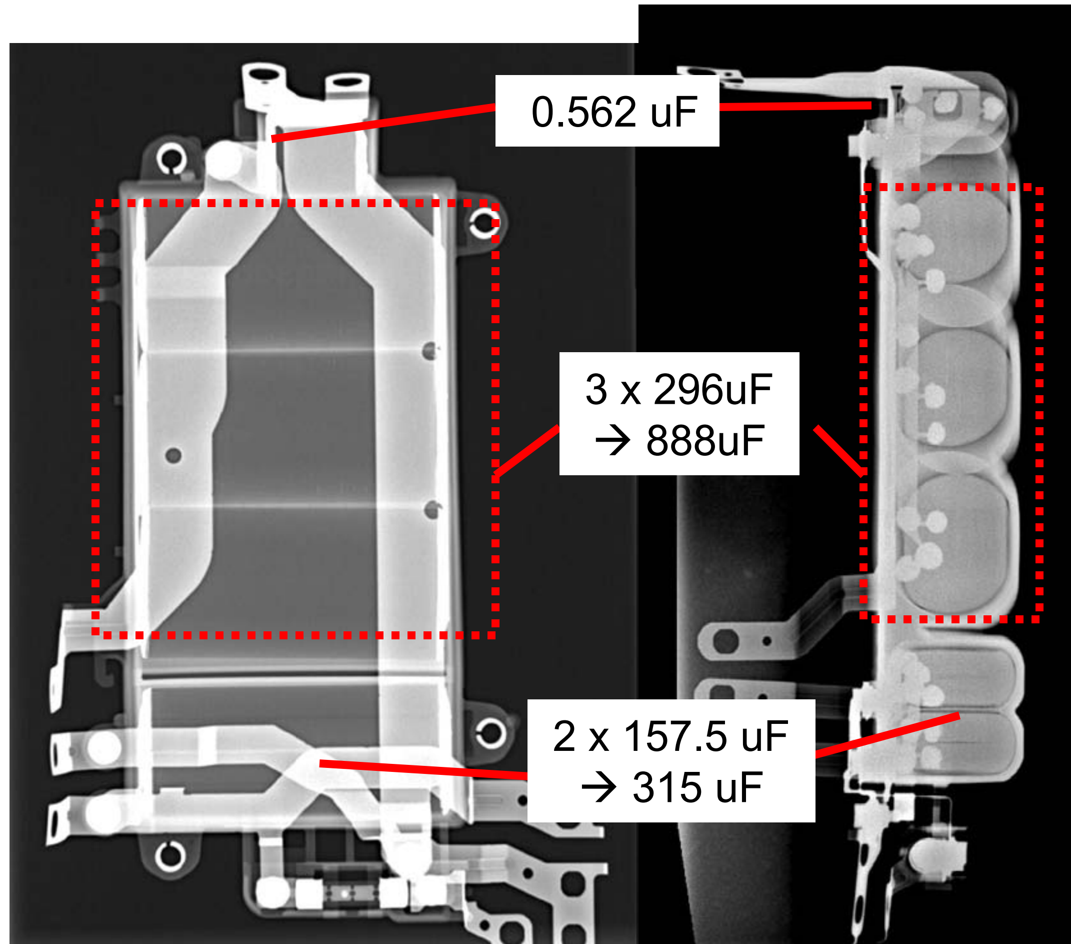


Channels for coolant



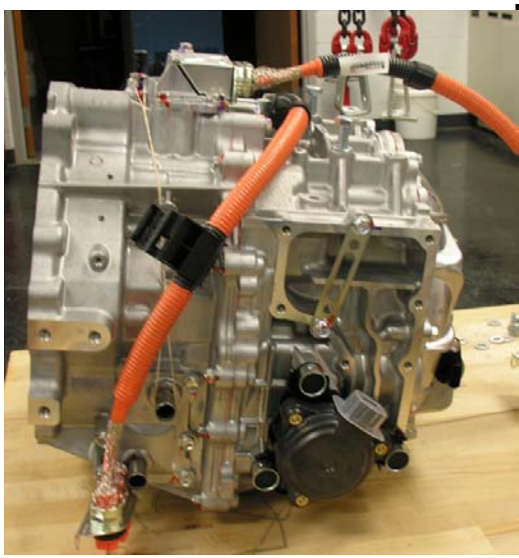
FY10 Technical Accomplishments (4)

- 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



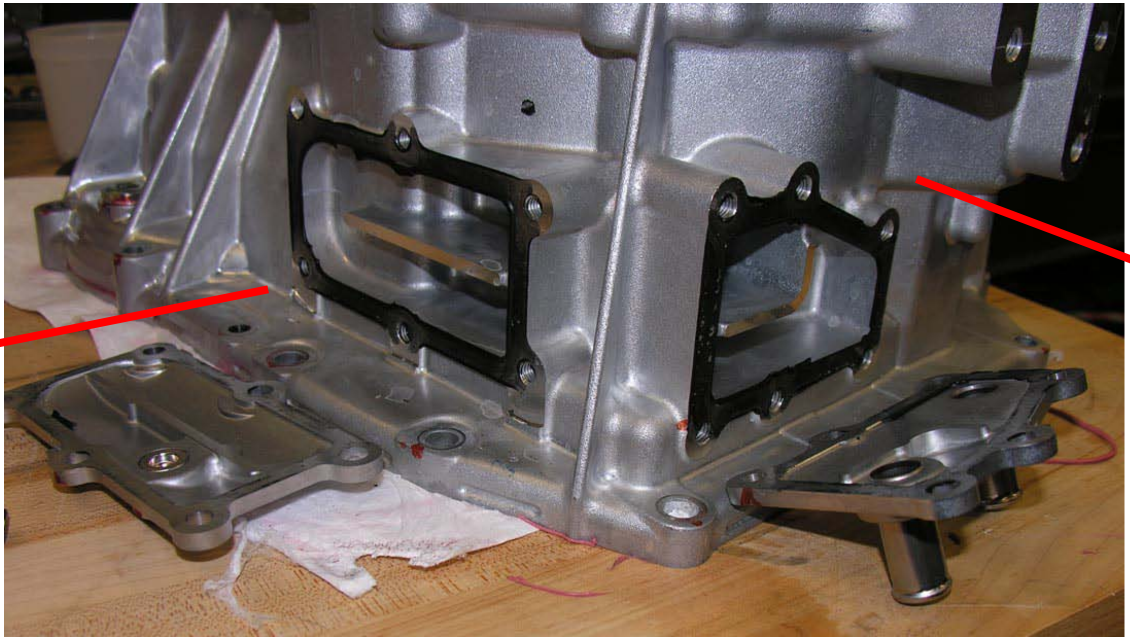
FY10 Technical Accomplishments (5)

- 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



FY10 Technical Accomplishments (6)

- 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

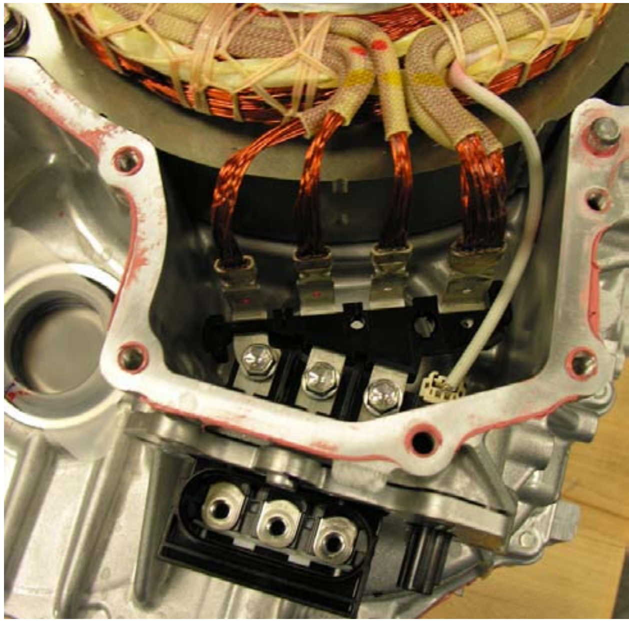


Underside of housing

Side of housing

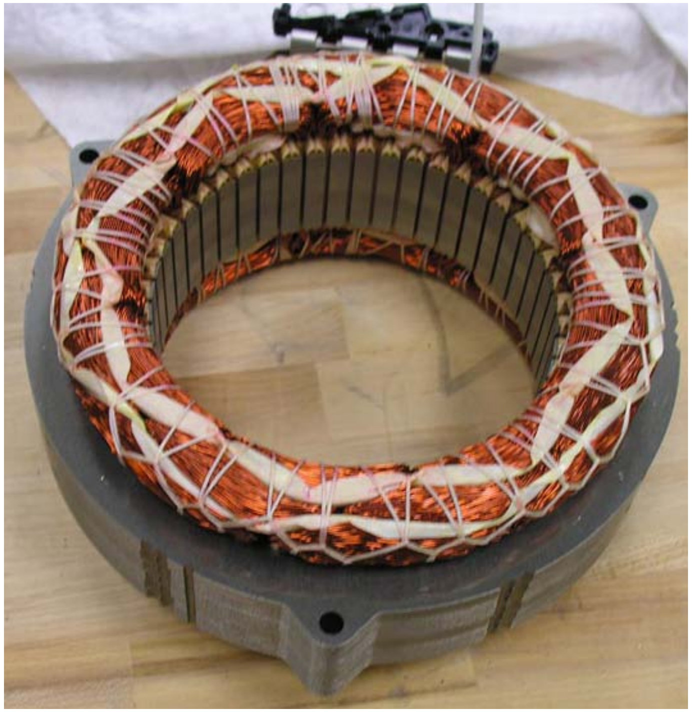
FY10 Technical Accomplishments (7)

- 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?



Technical Accomplishments (8)

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

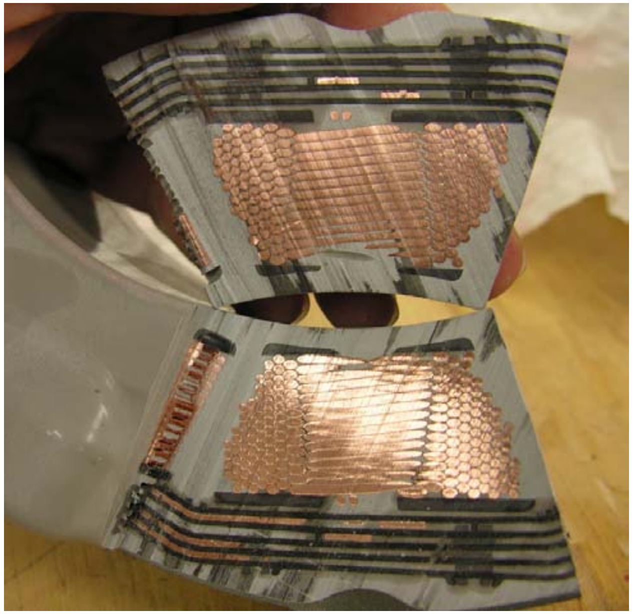


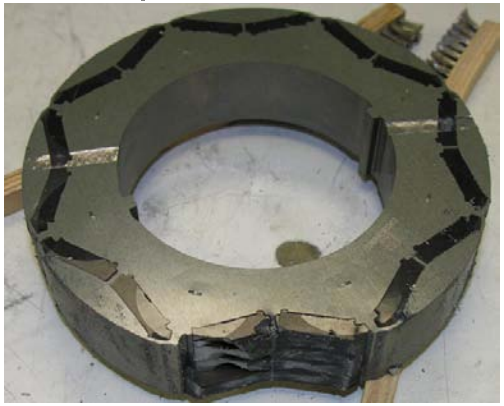
2010 Prius Motor Parameters

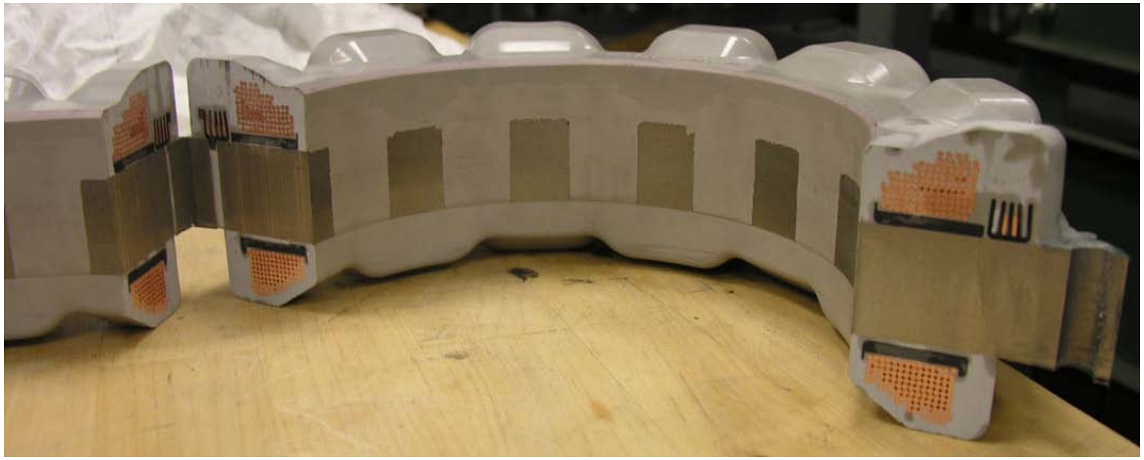
Parameter	2008 LS 600h	2007 Camry	2004 Prius	2010 Prius	Comments
Lamination Dimensions					
Stator OD, cm	**20**	**26.4**	**26.9**	**26.4**	
Stator inner diameter (ID), cm	**13.086**	**16.19**	**16.19**	**16.24**	
Stator stack length, cm	**13.54 (5.33")**	**6.07 (2.4")**	**8.4 (3.3")**	**5.08 (2.0")**	
Rotor OD, cm	**12.91**	**16.05**	**16.05**	**16.04**	
Rotor stack length, cm	**13.59**	**6.2**	**8.36**	**5.0165**	
Air gap, mm	**0.89**	**0.73**	**0.73**	**0.73**	
Lamination thickness, mm	**0.28**	**0.31**	**0.33**	**x**	
Mass of Assemblies					
Rotor mass, kg	**11.93**	**9.03**	**10.2**	**6.7**	**Includes rotor shaft.**
Stator mass, kg	**18.75**	**18**	**25.9**	**15.99**	
Stator core mass, kg	**15.15**	**12.38**	**19.05**	**10.36**	
Stator Wiring					
Copper mass, kg	**3.59**	**5.6**	**6.8**	**5.63 est.**	
Number of stator slots	**48**	**48**	**48**	**48**	
Wires per phase	**18**	**18**	**13**	**12**	**~20 AWG**
Configuration	**Parallel**	**Parallel**	**Series**	**Series**	
Casing					
Motor casing mass, kg	**14**	**9.5**	**8.9**	**15**	**Resolver, pump, etc**

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

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

Design Feature	2010 Prius*	2008 LS 600h	2007 Camry	2006 Accord	2004 Prius
Motor-related Technology					
Motor peak power rating	60 kW	110 kW	70kW	12.4 kW	50 kW
Motor peak torque rating	207 Newton meters (Nm)	300 Nm	270 Nm	136 Nm	400 Nm
Rotational speed rating	13,500 rpm	10,230 rpm	14,000 rpm	6,000 rpm	6,000 rpm
Power electronics-related Technology					
IPM Cooling	Direct cooled, single side water/glycol loop	Double-sided infrastructure, water/glycol loop	Heat sink with water/glycol loop	Air-cooled heat sink	Same as Camry
Bi-directional DC-DC converter output voltage	200-650 Vdc	~288-650 Vdc	250–650 Vdc	N/A	200–500 Vdc
High-voltage (HV) Ni-MH battery	201.6 V, 6.5 Ah	288 V, 6.5 Ah,	244.8 V, 6.5 Ah,	144V, 6.5 Ah	201.6 V, 6.5 Ah,
	27 kW	36.5 kW	30 kW	13.8 kW	20 kW