Competitive Benchmarking Analysis:

Hybrid Vehicle Traction Motors

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Key Findings

- Recent studies have concluded that cast copper induction motors offer improved nominal efficiencies relative to permanent magnet motors, under normal vehicle operating conditions[1].
- Due to the reliance on rare earth oxide materials and other scattered minerals, permanent magnet motors are not cost effective at high (future) vehicle production volumes.
- Copper based induction motors are 20% less costly to manufacture than their permanent magnet based counterparts, and suffer no size (weight, volume) penalties.
- Cast copper induction motor manufacturing processes are more amenable to future high volume automotive demand than permanent magnet based motor designs.
- Permanent magnet based motors require a heat exchanger to protect the magnetic materials from demagnetization, adding cost, vehicle weight, and system reliability concerns.

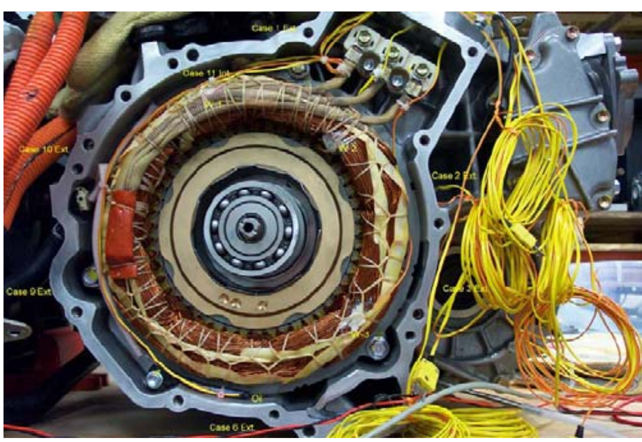

Figure 1a – 2004 Toyota Prius Motor[2]

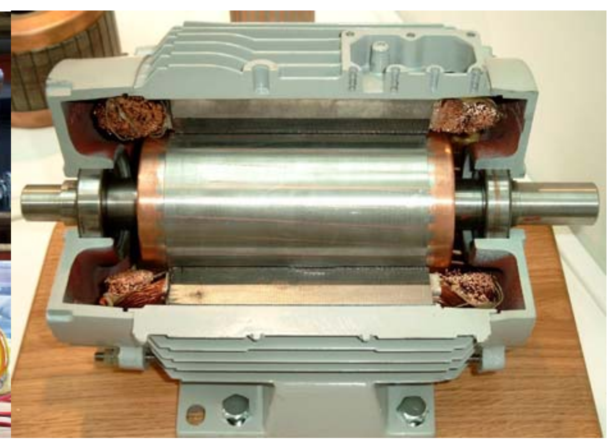

Figure 1b – Cast copper induction motor (Source: Siemens)

Introduction

This report summarizes the competitive position of three automotive torque motor designs: permanent magnet, mechanically assembled induction, and cast copper induction motors. Motor design and performance data was gathered from independent laboratory and academic publications. Manufacturing costs based on these functionally equivalent designs were calculated using Technical Cost Models developed by IBIS Associates, Inc.

Manufacturers of hybrid and hybrid electric vehicles should use cast copper induction motors in torque motor applications.

1. Recent studies have concluded that cast copper induction motors offer improved nominal efficiencies relative to permanent magnet motors, under normal vehicle operating conditions.

- Design and performance simulations conducted by independent laboratories (i.e. Department of Electrical Engineering at the Massachusetts Institute of Technology) have concluded that cast copper induction motors provide greater efficiency than permanent currently used (2004 Toyota Prius) magnet motors.

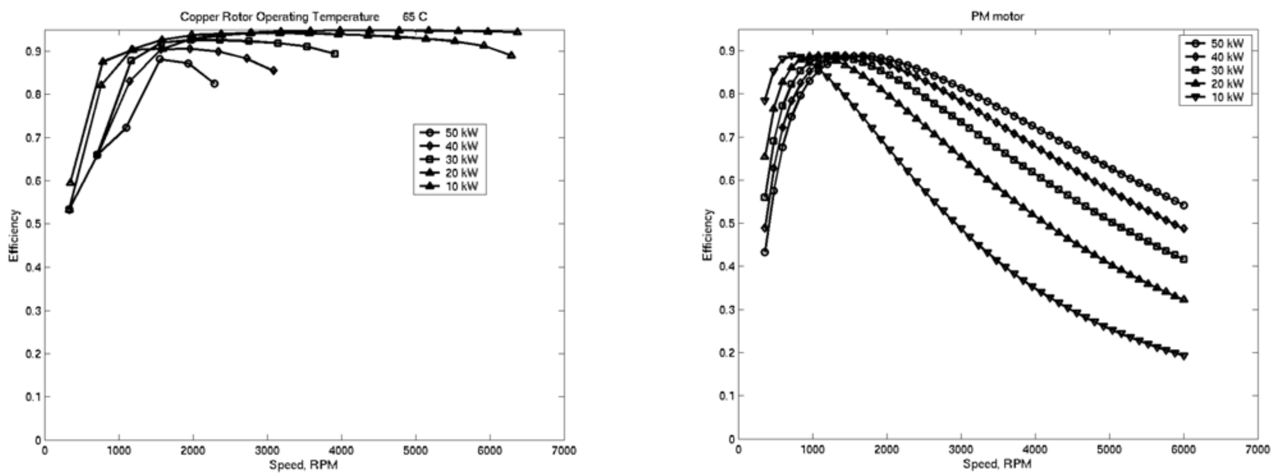

Figure 2 – Automotive (50kW) torque motor performance simulation results (Source: Kirtley et al [2])

- Under normal vehicle operating conditions[3], the effective operating efficiencies of the cast copper induction and permanent magnet motors are: 91% and 87%, respectively[1].

- Permanent Magnet Motors (PMMs) suffer a drag loss whenever the motor is turning. As a result, during high speed, low torque operating conditions PMMs suffer efficiency losses. Alternatively, cast copper induction motors are de-excited when not producing torque.

- The nominal efficiency advantage that induction motors provide occurs during vehicle operating conditions when the motor is not being used to produce torque. Since hybrid vehicles seek to rely on the electric powertrain for low speed, high torque acceleration, induction motors are particularly well suited for hybrid and plug-in hybrid applications.

2. Due to the reliance on rare earth oxide materials and other scattered minerals, permanent magnet motors are not cost effective at high (future) vehicle production volumes.

- Hybrid vehicles, including plug-in hybrids are a burgeoning market. JD Power Associates predicts there will be as many as sixty five (65) hybrid models for sale in the US by 2010. Technology selection decisions should consider immediate and future production

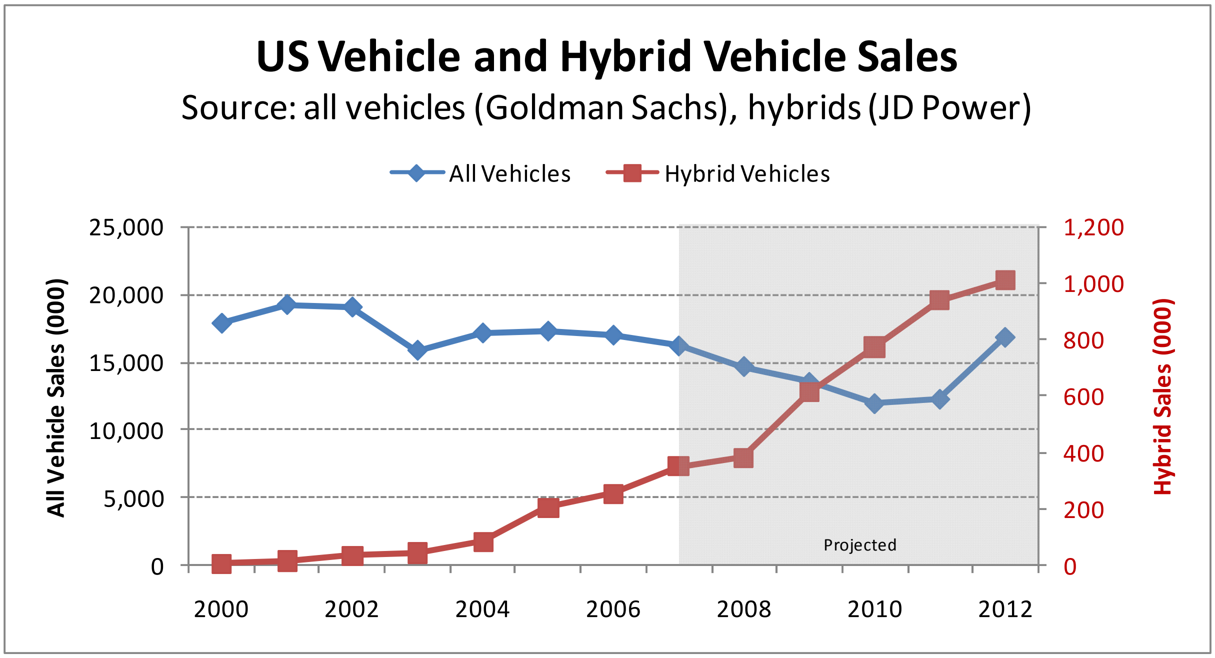

Figure 3 – US Vehicle and hybrid vehicle sales projections (Source: IBIS, Goldman Sachs, JD Power)

- Rare Earth Oxides (REOs) are used in permanent magnet torque motors to improve corrosion resistance (2 wgt-% cobalt) and coercivity (6 wgt-% dysprosium).

- Heavy REOs, such as dysprosium primarily come from the Jianzxi province of China. In addition to concerns over the demand for these materials outpacing supply, manufacturers also ought to be concerned with China's recent supply management strategies. While demand for REOs has risen, China has limited the supply and number of supplier companies allowed to export. China also imposed export tariffs of 15-25% on these materials.

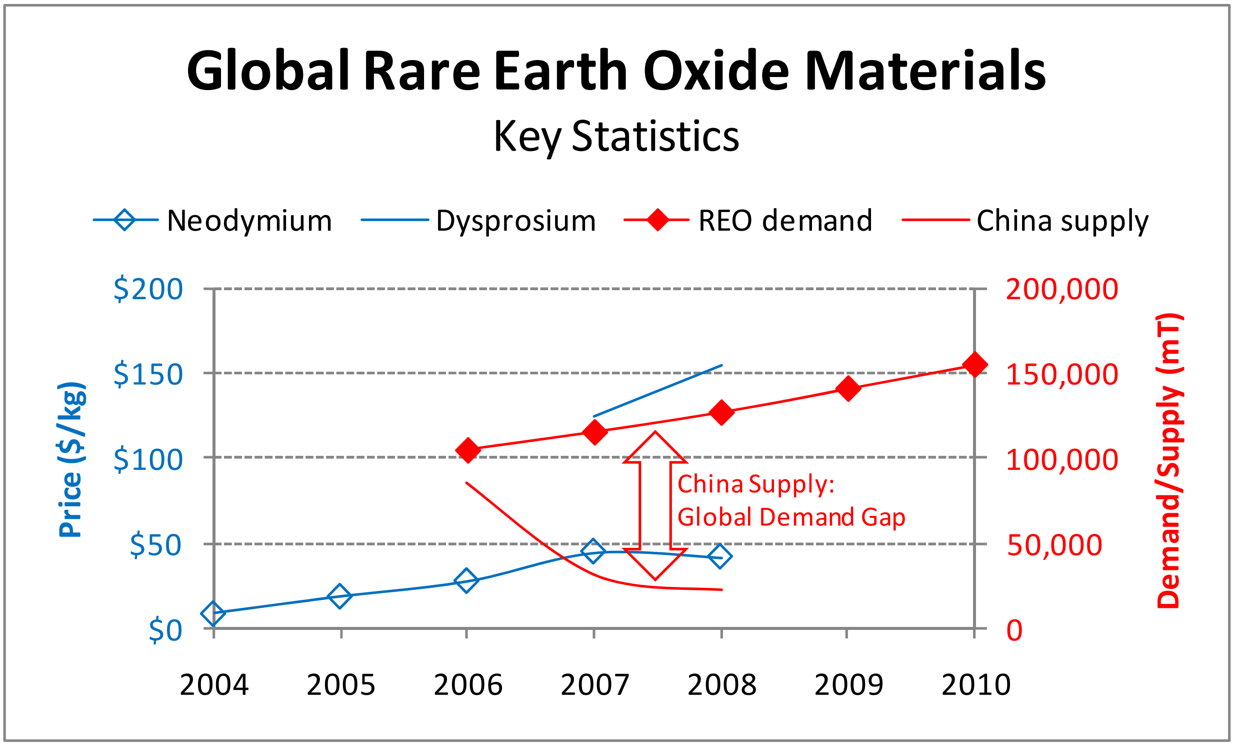

Figure 4 – Rare Earth Oxide material prices (Source: P. Campbell [5])

- Future price projections for these materials must consider the current supply constraints and projected surge in demand for hybrid vehicle motors (18% AGR through 2012).

- Electric bicycle motors are currently the largest application for REO magnet materials (permanent magnet motors). In Asia, growing economic prosperity will continue to fuel the demand for this competing permanent magnet motor application.

3. Copper based induction motors are 20% less costly to manufacture than their permanent magnet based counterparts, and suffer no motor size (weight, volume) penalties.

- Permanent Magnet Motors (PMMs) used in the Toyota Prius utilize hand winding techniques to achieve high stator winding fill factor efficiencies. A very narrow stator slot is used to keep the flux density low to obtain the maximum air-gap flux produced by the PMs.

- The assembly process that is required for permanent magnet motors requires more steps, and is less automation friendly than the high pressure die casting process used to produce the copper induction motor. The Toyota Prius PMM requires eight (8) permanent magnets to be inserted into the rotor core (see Figure 5 below), followed by compression and "securing the location of the clamping piece"[4].

Figure 5 – Toyota Prius permanent magnets (Source: ORNL [4])

- The high pressure die casting process that is used to produce the copper based induction motor requires fewer steps (no magnet assembly).
- Cast copper induction motors are more cost effective to manufacture than permanent magnet motors, and likely to be more so in the future. The future high volume demand for permanent magnet motor materials (principal motor cost element) is projected to contribute to further price escalation.

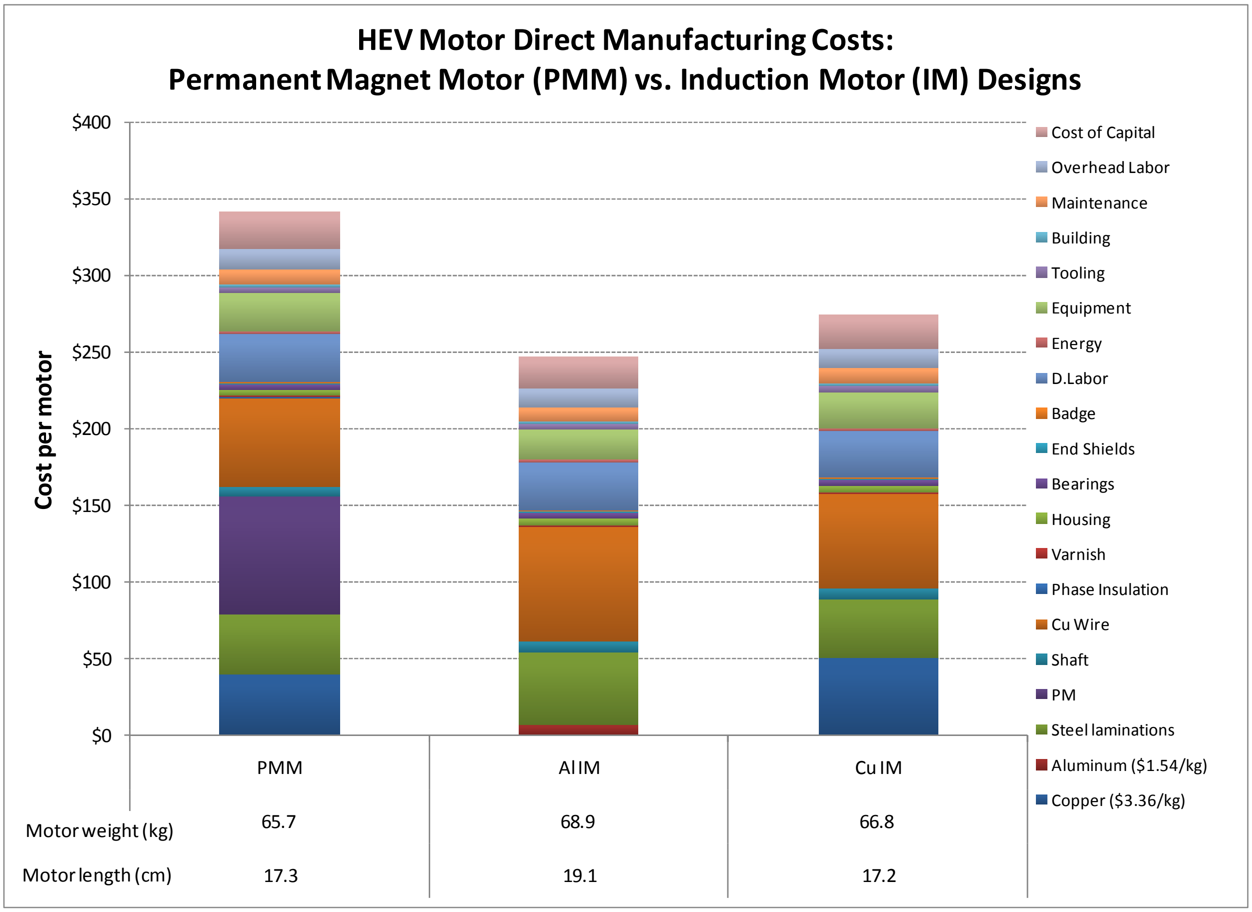

Figure 6 – Alternative HEV Traction Motor Designs: Cost summary (Source: IBIS Associates)

4. Cast copper induction motor manufacturing processes are more amenable to future high volume automotive demand than permanent magnet based motor designs.

- In addition to motor manufacturing costs, the applied cost of implementing induction motors is also less expensive. Permanent Magnet Motors (PMMs) require power and temperature conditioning components to optimize performance; resulting in higher costs, additional vehicle weight, and inherently less reliability than an induction motor based design that does not require such ancillary components.

- The Toyota Prius utilizes a series winding to boost torque without increasing motor size. For a given current, doubling the turns of the winding that interact with the fixed flux of the permanent magnets (PMs) double the torque. However, "a series winding requires twice the voltage of a parallel winding. In the low-speed region of operation, the back electromotive force is low and the 200-V bus voltage is quite sufficient to drive the motor. For high-speed operation, a boost converter" is required[4].

5. Permanent magnet motors require a heat exchanger to protect the magnetic materials from demagnetization, adding cost, vehicle weight, and reliability concerns.

- Permanent magnet materials may be demagnetized if motor operating temperatures exceed ~200°C (depending on their composition); a mere 42°C from the estimated maximum operating temperature. The Toyota Prius (2004), for example requires a water-ethylene-glycol heat exchanger, adding cost, vehicle weight, and consuming valuable engine compartment volume.

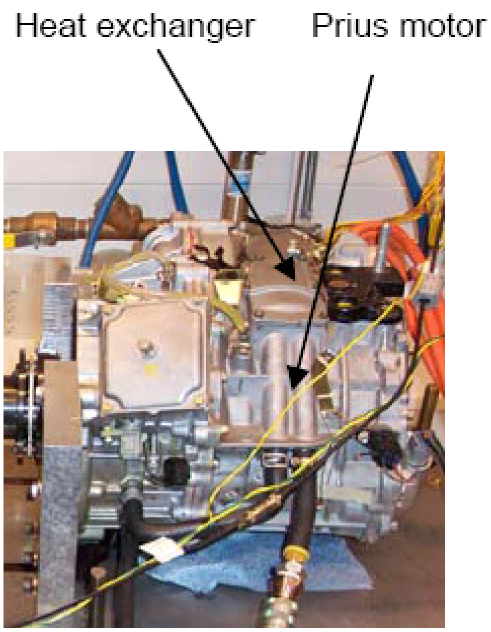

Figure 7 – Prius motor heat exchanger (Source: ORNL [2])

- The cost and weight of these additional components (boost converter, heat exchanger) is not known, but certainly a consideration when evaluating alternative motor designs which do not require these systems.

- The reliability of the Cast Copper Induction Motor (CCIM), which depends on fewer supporting components and subsystems is inherently greater than a Permanent Magnet Motor (PMM) which may suffer heat exchanger, or boost converter failure.

Summary

- Induction traction motors are less costly to manufacture than permanent magnet motors.

- Permanent Magnet Motors (PMMs) are burdened by limited global supplies and burgeoning demand in hybrid vehicles and electric bicycles, for example.

- Cast Copper Induction Motors (CCIMs) offer improved motor performance (efficiency) during automotive drive cycles.

- Copper induction motors provide performance advantages at a lower manufacturing cost, and lower applied (system) cost.

- Cast copper induction motors can be produced in and certainly lower than the sum of the PMMs and the subsystem components PMMs depend on.

	units	PM Motor	Al IM Rotor	Cu IM Rotor
Total Length	cm	17.3	19.1	17.2
Rotor Inner Radius	cm	5.8	5.8	5.8
Rotor Outer Radius	cm	8.0	7.8	7.8
Stack Height	cm	8.4	10.8	8.9
Rotor Weight	kg	5.3	5.2	5.2
PM Weight	kg	2.2	0.0	0.0
Stator Outer Radius	cm	15.0	15.0	15.0
Stator Weight	kg	39.0	42.5	42.5
Stator Windings	kg	6.0	7.7	6.4
Shaft Weight	kg	11.6	12.8	11.5
Housing Weight	kg	7.6	8.4	7.5
Bearings Weight	kg	n/a	n/a	n/a
Weight of Active Material	kg	46.5	47.7	47.7
Toral Motor Weight	kg	65.7	68.9	66.8
Efficiency		87%	91%	91%

Figure 8 – HEV Induction Motor (IM) and Permanent Magnet (PM) torque motors (Source: Kirtley [1], DOE [4], IBIS

Sources

[1] “Improved Hybrid Vehicle Traction Motors Using Cast Copper Rotor Induction Machines”, J.L. Kirtley, D.S. Peters, et al, 2008

[2] “Report on Toyota Prius Motor Thermal Management”, L.D. Marlino Program Manager, US Department of Energy, Freedom Car and Vehicle Technologies, EE-2G, 2005

[3] “Federal Test Procedure Review Project: Preliminary Technical Report’’ EPA 420-R-93-007, May 1993

[4] “Report on Toyota/Prius Motor Design and Manufacturing Assessment” ORNL/TM-2004/137, J.S. Hsu et al, Oak Ridge National Laboratory, 2004

[5] “High Coercivity”, Dr. Peter Campbell, Magnetics Business & Technology, January 2008

About the Author

Alan C. Goodrich is a graduate of Rensselaer Polytechnic Institute's School of Decision Sciences and Management Engineering, and a current MBA candidate at that Rensselaer's Lally School of Technology Management. Alan has worked at IBIS Associates for nearly a decade, providing research analyst and project management support to clients who have faced business development decisions in a broad range of industrial markets.

Mr. Goodrich specializes in providing business strategy recommendations that are based on rigorous quantitative analyses and first hand market intelligence. In addition to Techno Economic Analyses, Alan provides market forecasts and technology diffusion models based on the Bass Diffusion methodology.

Since joining IBIS Alan has had the opportunity to assist material suppliers and manufacturers in the Automotive, Specialty Chemical, Plastics, Building Materials, Appliance, and Alternative Energy markets. Mr. Goodrich leads IBIS' solar photovoltaic project activities.