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Performance/cost comparison of induction-motor & permanent-magnet-motor in a hybrid electric car

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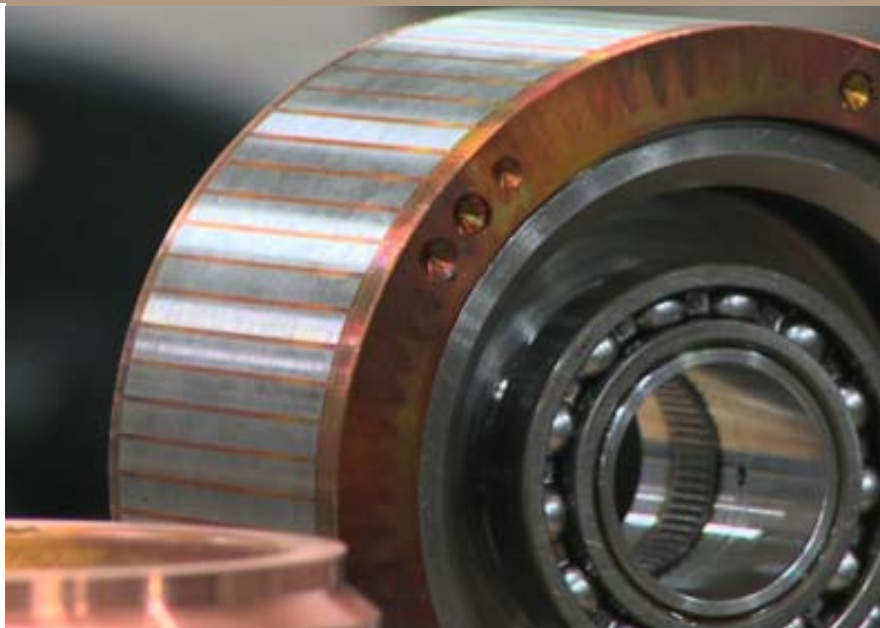
James Goss, Mircea Popescu - Motor Design Ltd

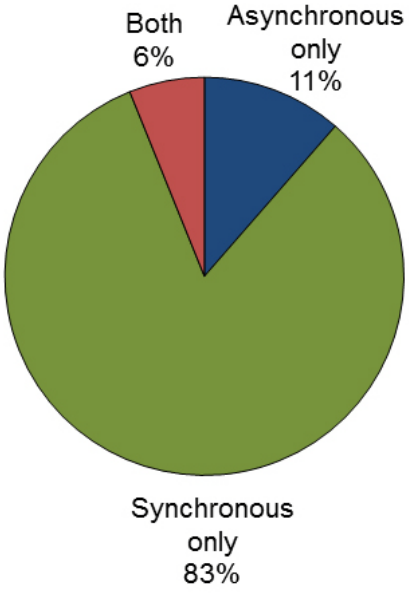
July 2013 - Tokyo



Is it time for change in the traction motor supply industry?

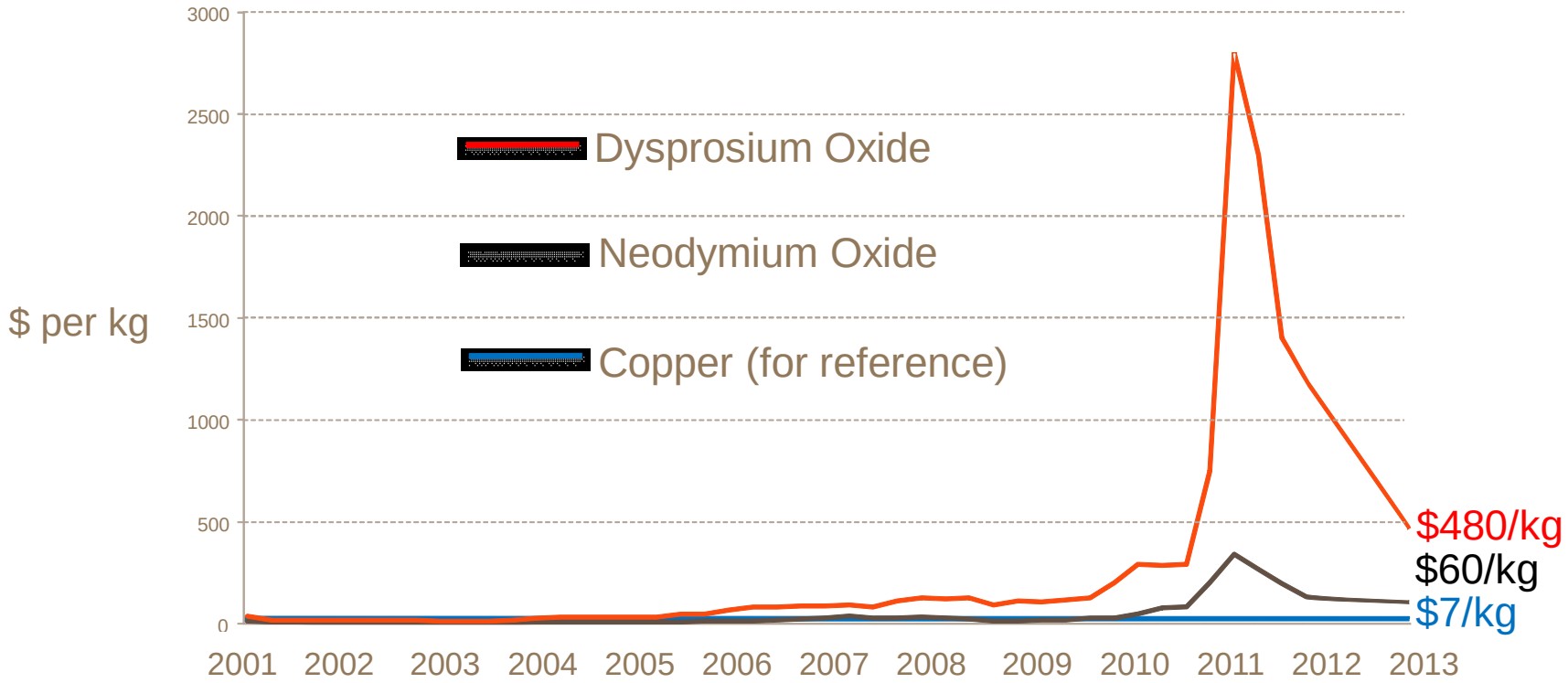
"[Our] survey of 123 manufacturers shows far too few making asynchronous or switched reluctance synchronous motors... ***this is an industry structured for the past that is going to have a very nasty surprise when the future comes****." **

Motor-types sold by suppliers of vehicle traction motors *



* Source: IDTechEx research report "Electric Motors for Electric Vehicles 2013-2023: Forecasts, Technologies, Players"
www.IDTechEx.com/emotors

The challenge for electric traction motors: rare earth cost-levels and cost-volatility



Source: metal-pages.com, Kidela Capital

Background to this work

Today, the permanent magnet motor is the leading choice for traction drives in hybrid vehicles

But permanent magnet motors have challenges:

- High costs
- Volatile costs
- Uncertain long term availability of rare earth permanent magnets

This makes alternative magnet-free motor architectures of great interest

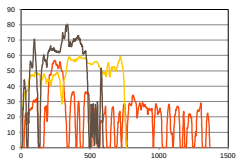
The induction motor is one such magnet-free architecture

This presentation

The work presented here compares two equivalent 50kW tractions motors for use in hybrid electric vehicles: a permanent magnet motor and an equivalent induction motor

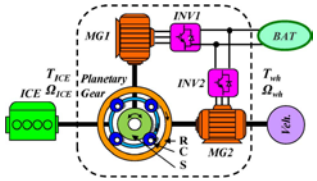
- The main analysis has copper as the rotor cage material of an induction motor
- Motoring and generating modes are modelled using standard drive cycles
- Important outputs of the work, for each motor type, are:
  - Lifetime energy losses and costs
  - Relative component performance parameters, weights and costs
- Top-level comments on aluminium cages are presented at the end

Overview of the analysis covered in this presentation

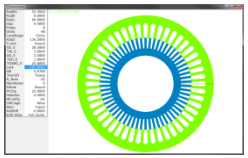


1. Driving cycles

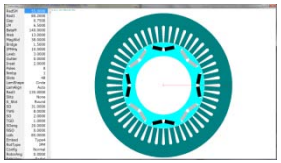
2. Vehicle Model



3. Powertrain Model

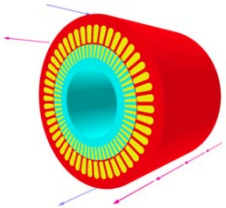


Induction Motor



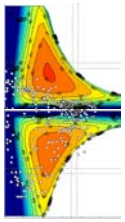
Permanent Magnet Motor

Magnetics



Heat Flows

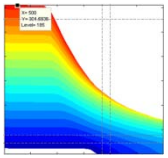
4. Motor Models



5. Motor Performance

Total losses in the motor	Permanent magnet motor	Copper rotor induction motor
City driving over 120,000 miles (UDDS)	1270 kWh	2240 kWh
Highway driving over 120,000 miles (HWFET)	610 kWh	1250 kWh
Aggressive driving over 120,000 miles (US06)	1430 kWh	2510 kWh
Combined average losses over 120,000 miles	1100 kWh	2000 kWh
Extra energy cost (grid price of $0.25/kWh)	0	$220
Extra energy cost (internal combustion engine cost of $0.294/kWh)	0	$260

6. Energy Losses & Costs



7. Inverter Currents

Materials per motor	Permanent magnet motor		Copper rotor induction motor	
	Weight	Cost	Weight	Cost
Stator Copper	4.5 kg	$31	9.1 kg	$64
Steel	24 kg	$24	24 kg	$24
Permanent magnets (2011/2013 prices)	1.3 kg	$200-540	0	0
Rotor cage	0	0	8.4 kg	$59
Increased inverter cost	-	0	-	$50
Total	29.8 kg (100%)	$260-590	41.5 kg (140%)	$200
Reduction of consumer purchase price*	-	0	-	$150-980

8. Motor Weights & Costs

9. Battery Capacities

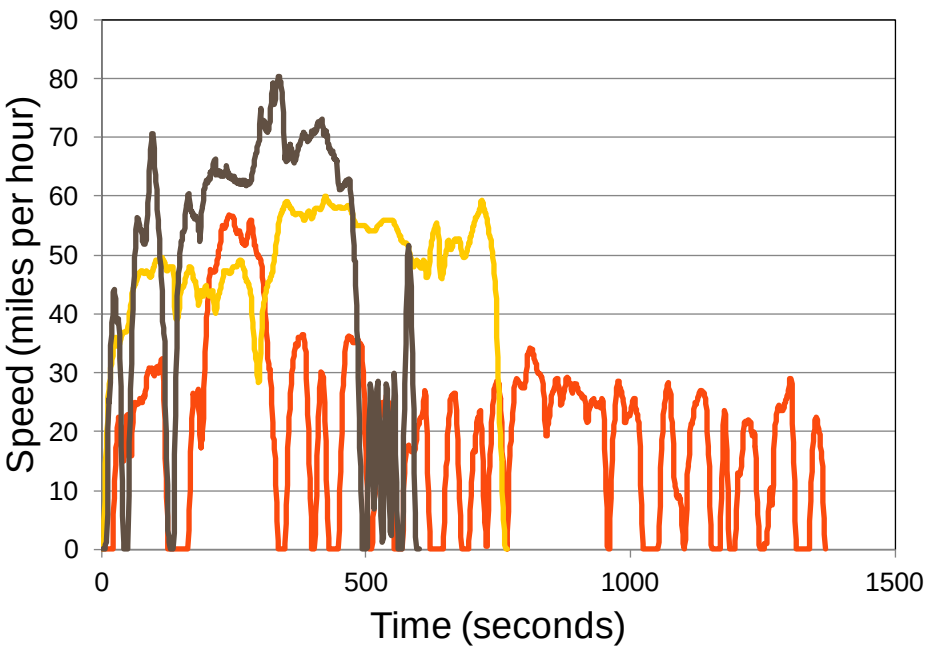
10. Breakeven Analysis

Main conclusions from this work

- Comparing a 50kW copper-rotor induction motor to a 50kW permanent magnet motor:
  - No rare earth metals used
  - +40% weight
  - -25% torque density
  - +10-15% peak inverter current
- However, the induction motor is a good alternative because:
  - Total motor+inverter unit costs are $60-$390 less (=$150-980 lower sticker price)
  - It uses only $260 in extra energy over 120,000 miles
  - Increased inverter costs are modest at ~$50/vehicle
- Battery size:
  - Can optionally be increased to match increased motor losses
  - Unit cost savings are larger than increased battery costs up to 27kWh battery size
- Using aluminum instead of copper in the rotor of a 50kW induction motor for an HEV:
  - Increases losses by 4%
  - Lowers torque density by 5%

1. Vehicle drive cycles

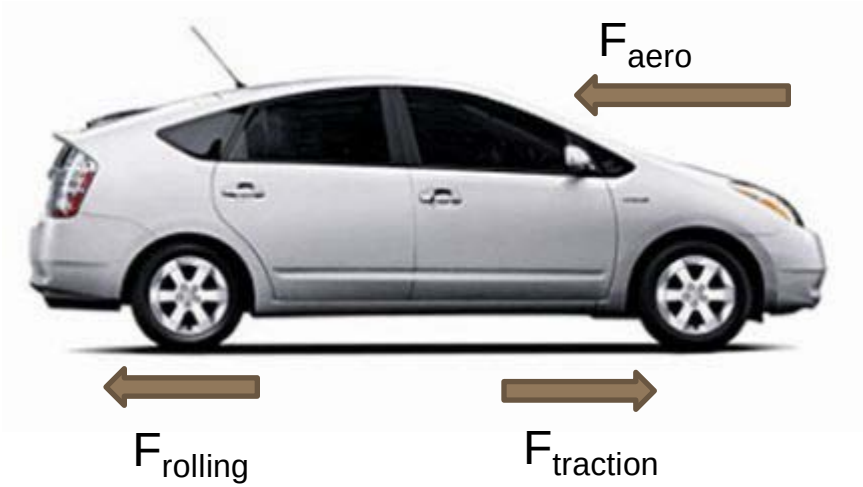
Three standard drive cycles are used for the comparison of two traction motors: a permanent magnet motor and a copper rotor induction motor. The 120,000/10year vehicle life is assumed to be composed equally of these three types of driving



Driving cycle	Distance	Average speed
City (UDDS)	7.5 miles	20 mph
Highway (HWFET)	10.3 miles	48 mph
Aggressive (US06)	8.0 miles	48 mph

2. Vehicle Model

A standard vehicle model is used to convert drive cycle information into powertrain torque/speed requirements.



$$F_{rolling} = k_r m g$$

$$F_{aero} = \frac{1}{2} p v^2 C_d A_f$$

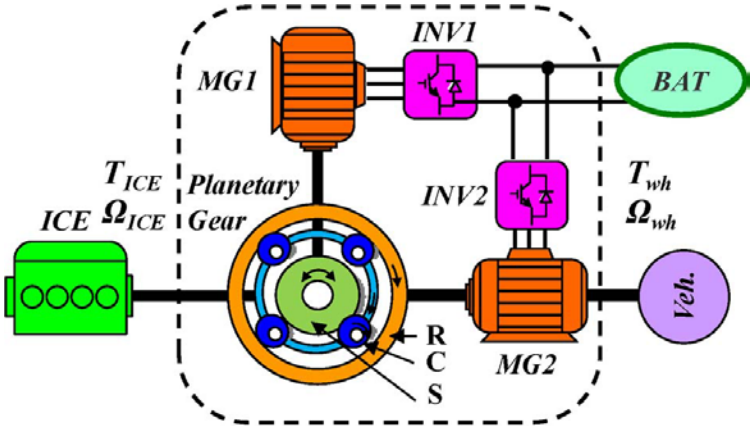
$$T_{motor} = k_{dem} \frac{F_{traction} \cdot r_\omega}{n_d}$$

$$Acceleration\ of\ Vehicle = \frac{(F_{traction} - F_{aero} - F_{rolling})}{m}$$

3.1 Powertrain model

A standard two motor/generator hybrid powertrain architecture is used

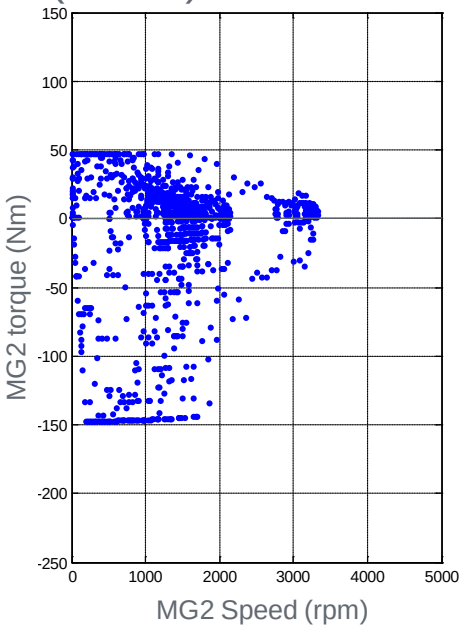
- Consists of two electrical motor/generators, MG1 and MG2 and an internal combustion engine, all connected through a planetary gear set
- Rotational speed of the internal combustion engine (ICE) is decoupled from the vehicle speed to maximise efficiency
- We analyze MG2 for performance/cost
- We assume that MG2:
  - Has a rated power of 50kW
  - Couples to the drive wheels through a fixed gear ratio
  - Provides 30% of motoring torque
  - Recovers up to 250Nm braking torque
  - The ICE and brakes supply the rest



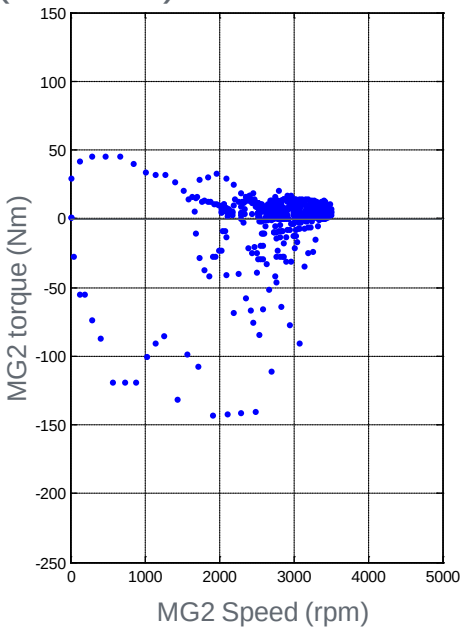
3.2 Motor torques/speeds produced during driving cycles

By applying the vehicle and powertrain models we convert the driving cycle data into motor torque/speed data points. One data point is produced for each one second of driving cycle

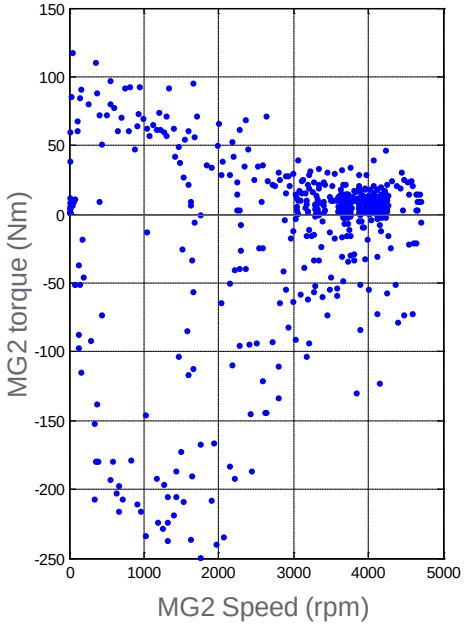
City cycle MG2 loads (UDDS)



Highway cycle MG2 loads (HWFET)

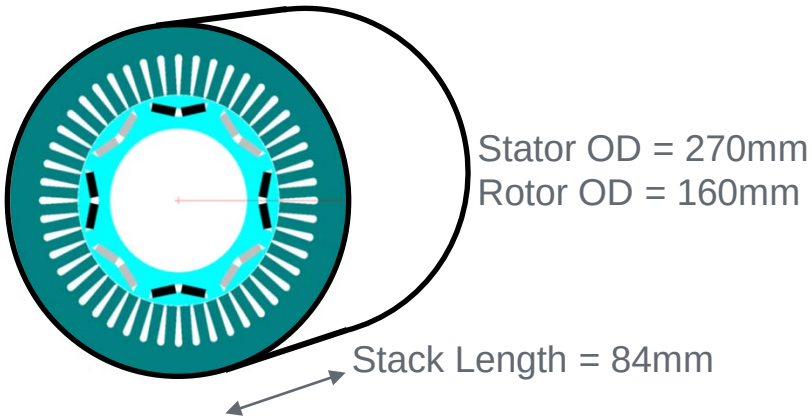


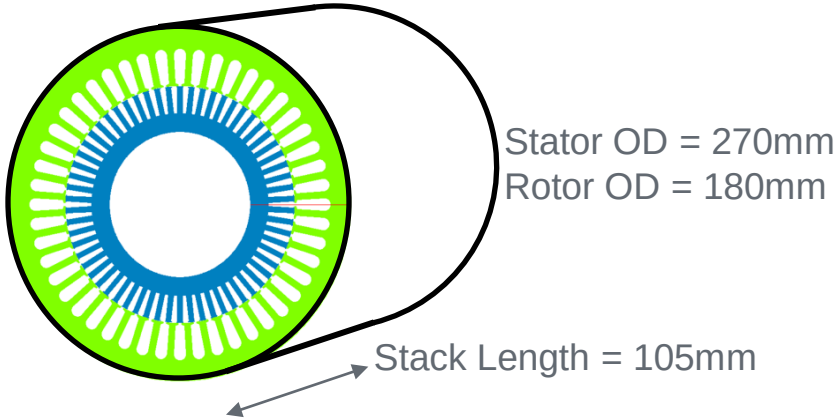
Aggressive cycle MG2 loads (US06)



4.1 Magnetic models of permanent magnet motor and induction motor

The two motor types were modeled for similar torque/speed performance: same stator outside diameters, same cooling requirements but different stack lengths

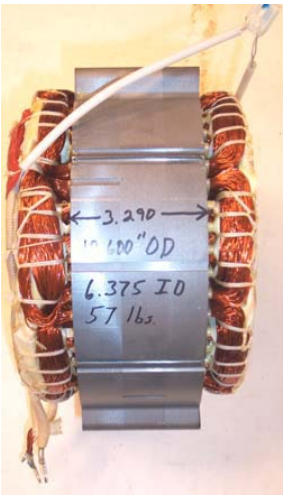


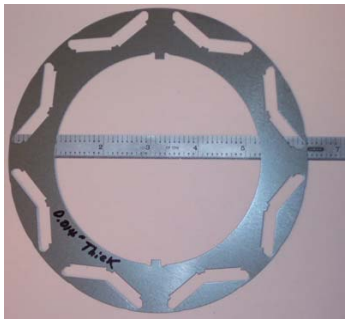


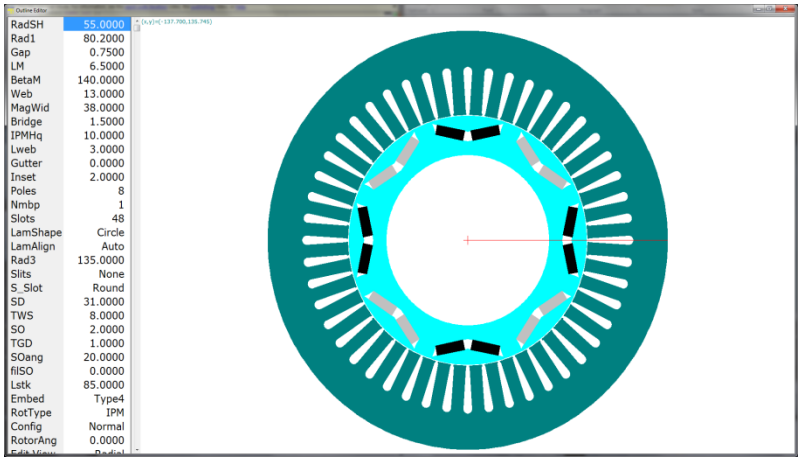
Permanent Magnet Motor		Copper Rotor Induction Motor
8	Poles	8
48	Stator Slots	48
-	Rotor Bars	62

4.2 Reference permanent magnet motor model

The modelled permanent magnet motor is a well-documented actual motor used in a production hybrid vehicle.



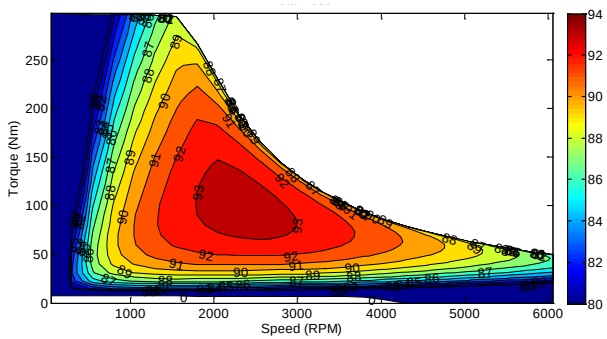




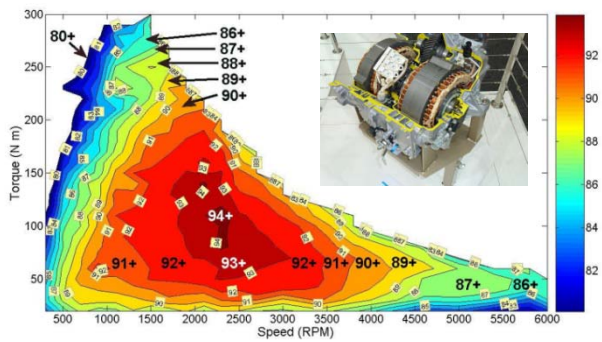
4.3 Validation of the motor performance model

The model of the permanent magnet motor was validated against test data from the actual motor

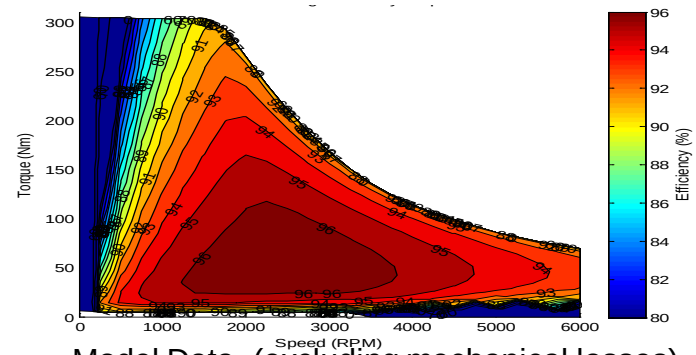
Model and actual data correspond well



Model data (including mechanical losses)



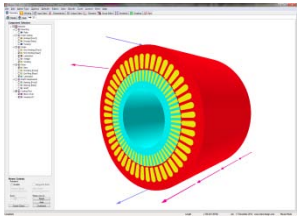
Test data from actual motor (including mechanical losses)



Model Data (excluding mechanical losses)

Our analysis continues using motor performance which excludes mechanical losses

4.4 Thermal Performance Comparison

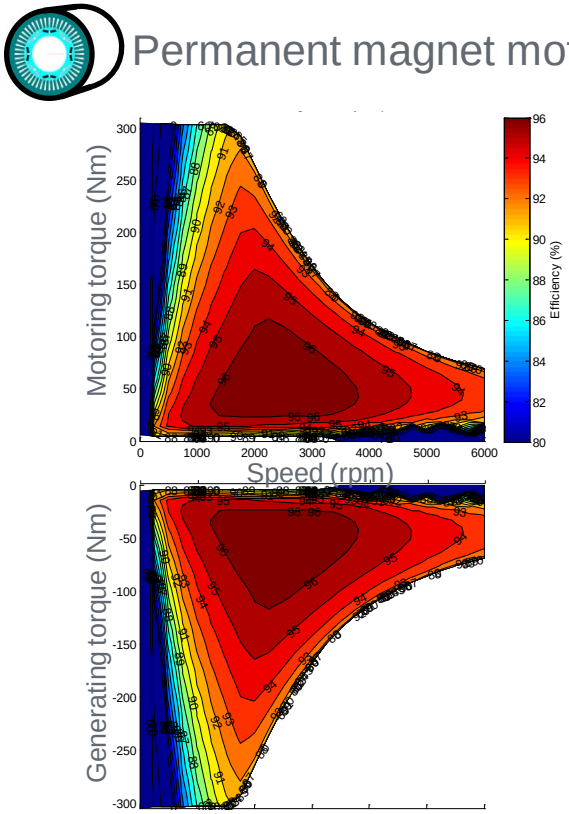


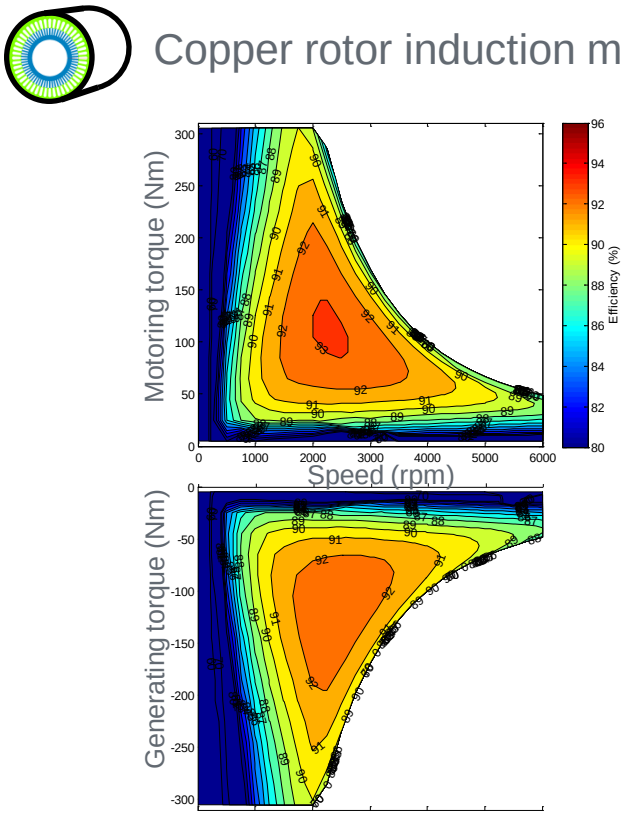
Steady-state thermal analysis was used to equalize cooling system requirements for both motors at a 118 Nm/900 rpm operating point

Permanent Magnet Motor		Copper Rotor Induction Motor
92%	Efficiency	88%
780 W	Stator Copper Loss	940 W
0 W	Rotor Loss	230 W
0 W	Stray Load Loss	140 W
100 W	Iron Loss	180 W
880 W	Total Loss	1490 W
105°C	Coolant Temperature	105°C
2.4 gallons/min	Coolant Flow Rate	2.4 gallons/min
156°C	Maximum Winding Temp	156°C

5.1 Torque/speed/efficiency maps of the permanent magnet motor and induction motor

The two motors have similar torque/speed performance, with the induction motor having ~5% lower efficiencies



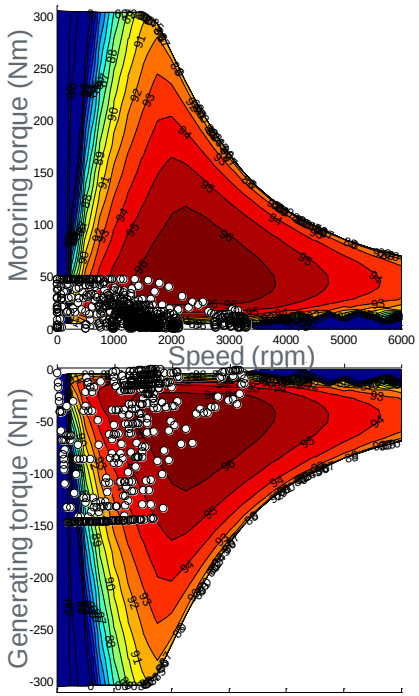


5.2 Torque/speed loads during drive cycles: permanent magnet motor

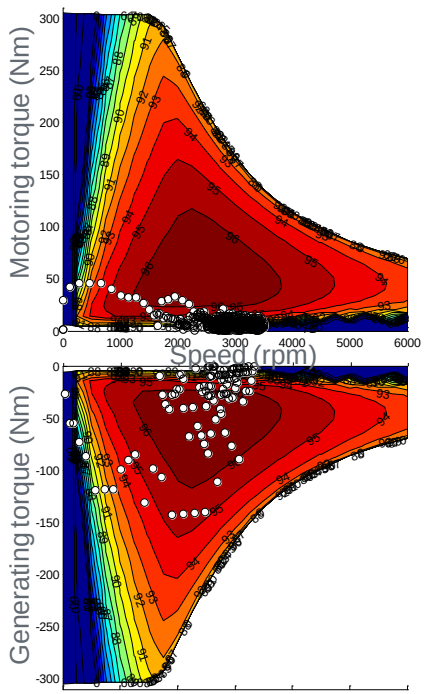
Torque/speed points from the vehicle/powertrain model of the driving cycles are applied to the performance map of the permanent magnet motor to determine total motor losses during driving:

Permanent magnet motor

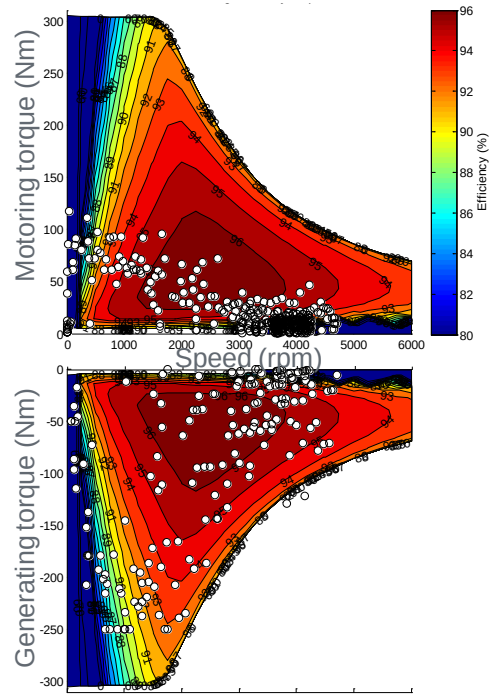
City driving cycle loads (UDDS)



Highway driving cycle loads (HWFET)



Aggressive driving cycle loads (US06)

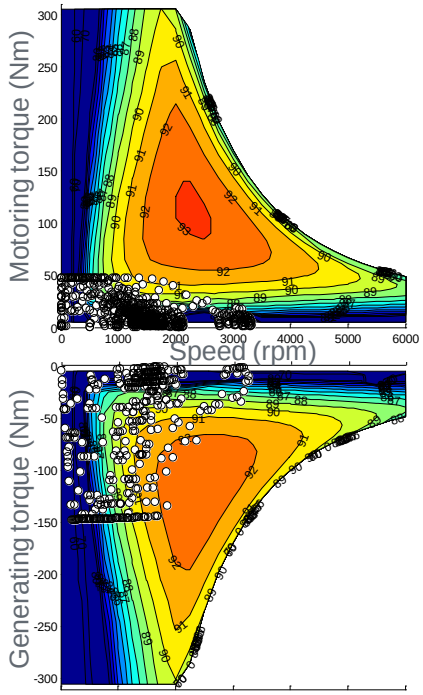


5.3 Torque/speed loads during drive cycles: copper rotor induction motor

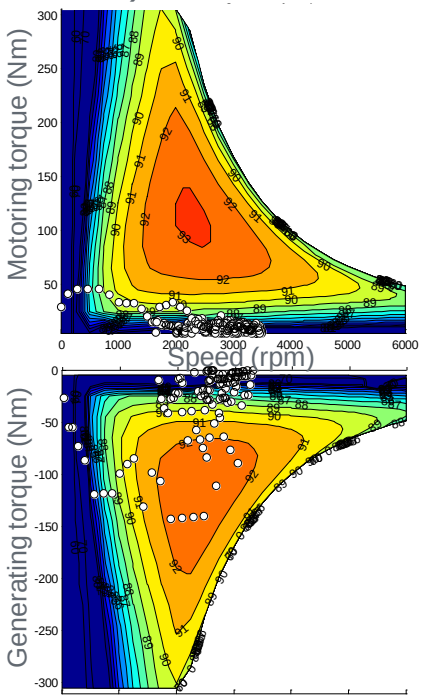
Torque/speed points from the vehicle/powertrain model of the driving cycles are applied to the performance map of the copper rotor induction motor to determine total motor losses during driving:

Copper rotor induction motor

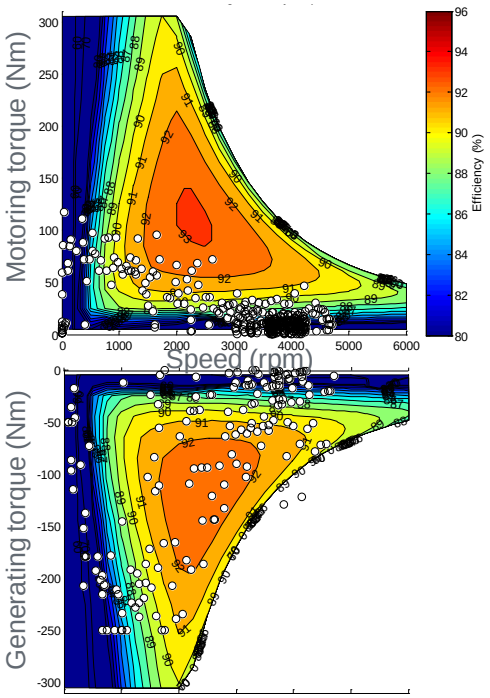
City driving cycle loads (UDDS)



Highway driving cycle loads (HWFET)



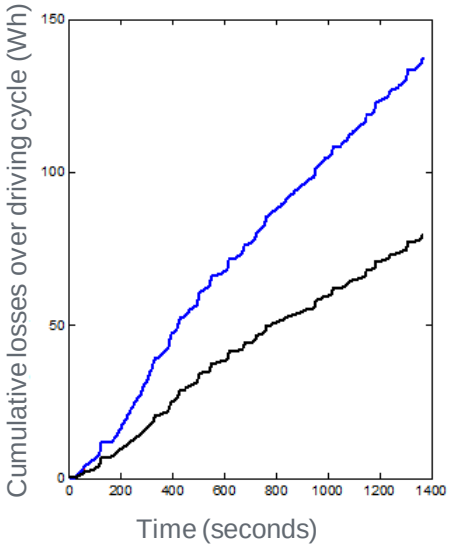
Aggressive driving cycle loads (US06)



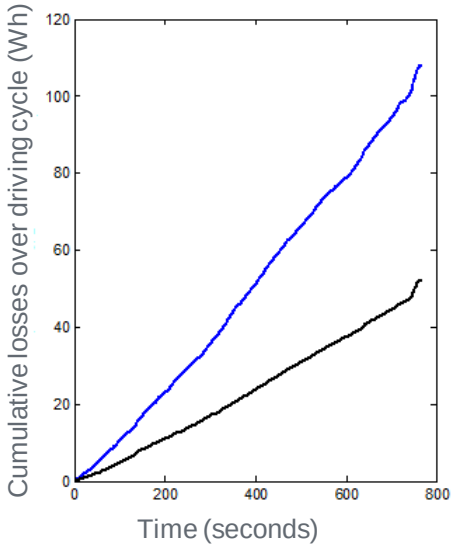
6.1 Motor losses during driving cycles

From the motor models, cumulative losses during each driving cycle can be calculated:

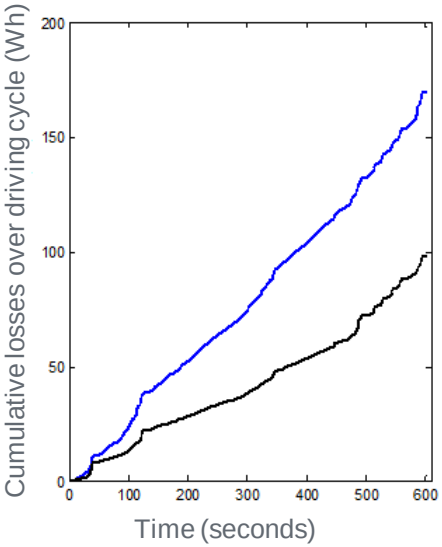
City driving cycle losses (UDDS)



Highway driving cycle losses (HWFET)

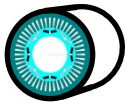


Aggressive driving cycle losses (US06)



6.2 Combined losses over life of the motor

The total difference in electrical running costs between the permanent magnet motor and the copper rotor induction motor are $220-$260. Over a typical lifetime of 120,000miles and 10 years, this is an insignificant cost.



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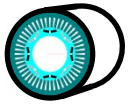
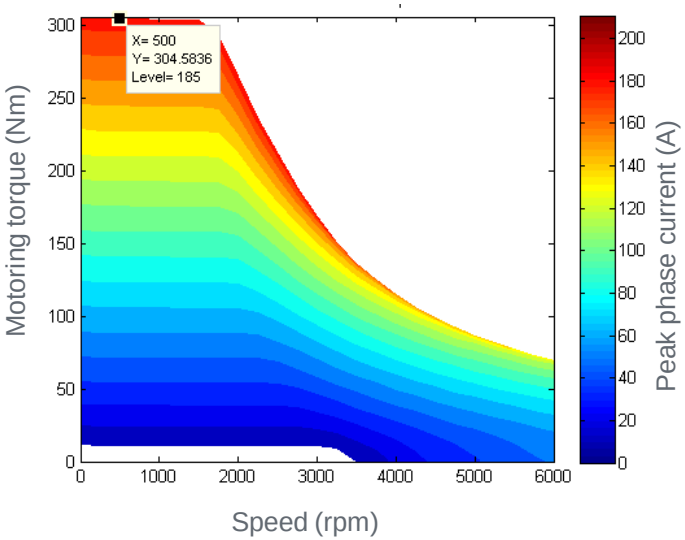
Combined average losses over 120,000 miles	1100 kWh	2000 kWh
Extra energy cost (grid price of $0.25/kWh)	0	$220
Extra energy cost (internal combustion engine cost of $0.294/kWh)	0	$260

7. Cost of increased inverter for copper motor induction motor

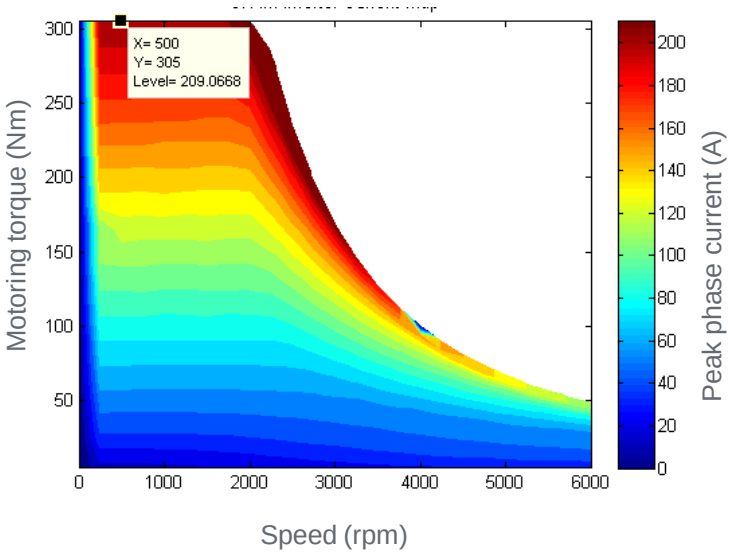
The copper rotor induction motor/generator requires 10-15% more current to achieve maximum torque. This requires that the power electronics cost ~$50 more than for a permanent magnet motor.



Permanent magnet motor

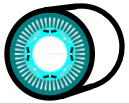


Copper rotor induction motor



8. Component cost comparison

The copper rotor induction motor saves between $60 (at 2013 magnet prices) and $390 (at 2011 magnet prices) costs per vehicle. This translates into $150-980 purchase price savings for the consumer



Materials per motor	Permanent magnet motor		Copper rotor induction motor	
	Weight	Cost	Weight	Cost
Stator Copper	4.5 kg	$31	9.1 kg	$64
Steel	24 kg	$24	24 kg	$24
Permanent magnets (2011/2013 prices)	1.3 kg	$200-540	0	0
Rotor cage	0	0	8.4 kg	$59
Increased inverter cost	-	0	-	$50
Total	29.8 kg (100%)	**$260-590**	41.5 kg (140%)	**$200**
Reduction in consumer purchase price*	-	**0**	-	**$150-980**

* Assumes materials-cost/consumer-price ratio = 40%

9. Cost of increased battery capacity to cover increased motor losses

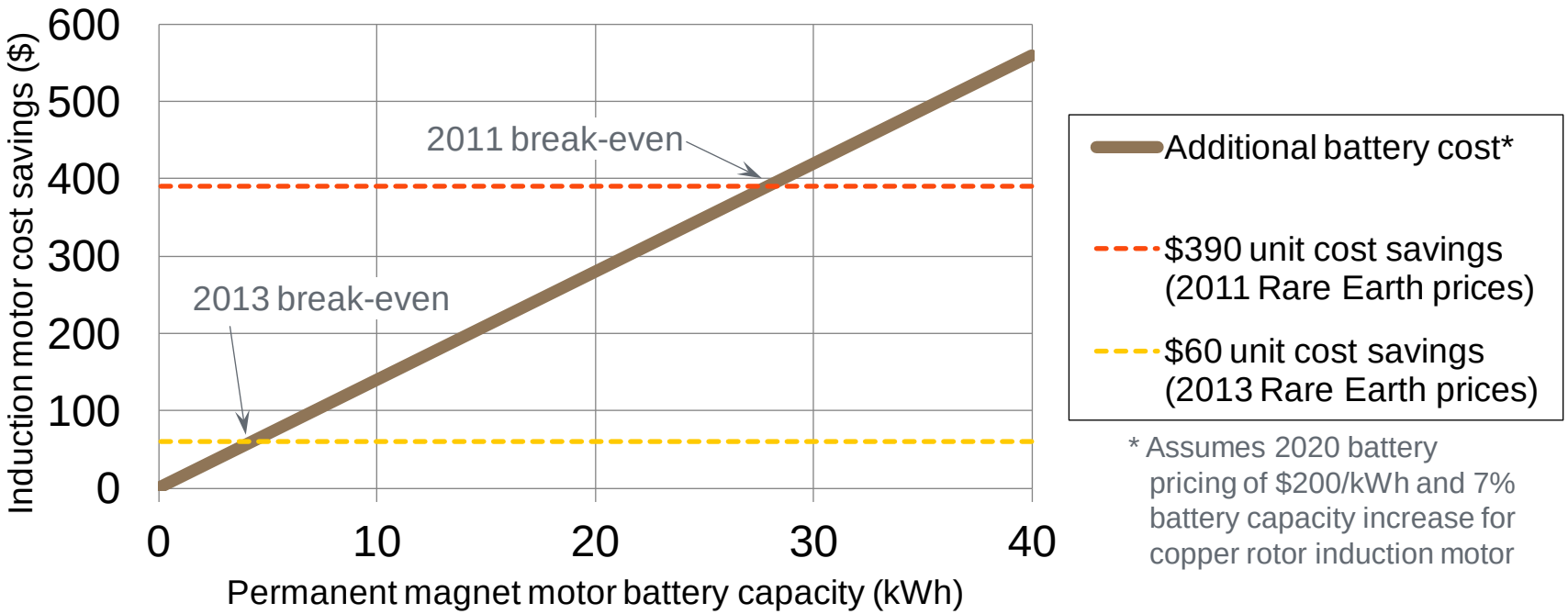
Using a copper rotor induction motor can require the vehicle designer to increase the battery size by ~7%. This would allow a customer to perceive no difference in overall vehicle performance.

Key assumptions used in costing the required increase in battery capacity:

- Motor must at some time provide all motoring and braking torque in the highway driving cycle (like a plug-in hybrid electric vehicle)
- Induction motor uses 7% more motoring energy than a permanent magnet motor
- Induction motor recovers 6% less braking energy than the permanent magnet motor
- Total braking energy is 20% of the motoring energy over the driving cycle
- 75% of battery energy is used for motoring, 25% for auxiliary systems (cabin conditioning, lights, radio, electronics)

10. Break-even for using copper motor induction motor

If the designer chooses to increase battery size for a 50kW system, a copper rotor induction motor saves total vehicle costs when the battery size for a permanent magnet motor system is less than 27kWh

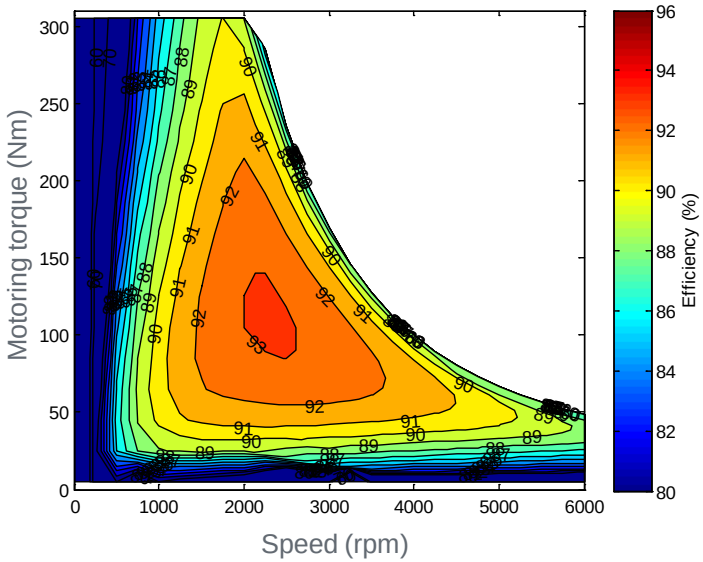


* Assumes 2020 battery pricing of $200/kWh and 7% battery capacity increase for copper rotor induction motor

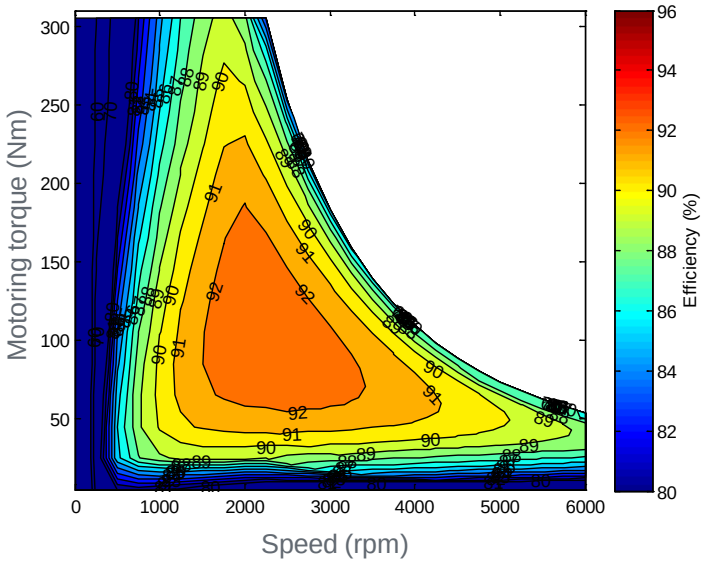
Possible use of aluminum in the rotor of an induction motor

Aluminum has only 56% of the conductivity of copper, which leads to an inferior performance when used in the rotor of an induction motor. In a first-pass analysis of a 50kW aluminum rotor induction motor, losses were 4% higher and power/torque densities 5% lower than the equivalent copper rotor motor.

Copper rotor induction motor



Aluminum rotor induction motor



Main conclusions from this work

- Comparing a 50kW copper-rotor induction motor to a 50kW permanent magnet motor:
  - No rare earth metals used
  - +40% weight
  - -25% torque density
  - +10-15% peak inverter current
- However, the induction motor is a good alternative because:
  - Total motor+inverter unit costs are $60-$390 less (=$150-980 lower sticker price)
  - It uses only $260 in extra energy over 120,000 miles
  - Increased inverter costs are modest at ~$50/vehicle
- Battery size:
  - Can optionally be increased to match increased motor losses
  - Unit cost savings are larger than increased battery costs up to 27kWh battery size
- Using aluminum instead of copper in the rotor of a 50kW induction motor for an HEV:
  - Increases losses by 4%
  - Lowers torque density by 5%

Thank you

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Copper Alliance