Motor Design Ltd

Implications of real-world drive cycles on efficiencies and life cycle costs of two solutions for HEV traction:

Synchronous PM motor vs Copper Rotor - IM

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Topics

- Aim: to compare the lifetime energy costs and material costs of a synchronous permanent magnet motor (SPM) and copper rotor induction motor (CR-IM) for a HEV traction application

- SPM Toyota Prius Motor/Generator THSII used for baseline comparison

Topics

- Our main conclusion is that CR-IM is an attractive architecture for HEV traction:
  - the increased efficiency of SPM do not justify the higher parts costs
  - lower parts cost for CR-IM make initial acquisition of HEV more attractive to the consumer by $300-450/vehicle even when increased battery capacity requirements for CR-IM are taken into account
  - the geopolitical sensitivity of RE's causes high PM price volatility, which is absent in CR-IM
- Supporting details:
  - Total ownership cost for HEV traction motor = motor parts cost + lifetime energy cost
  - CR-IM have a lower parts cost than SPM, but a higher lifetime energy cost due to their generally higher efficiencies (~4% higher in this study)
- This study quantifies motor parts costs, battery costs and lifetime energy costs so that they can be compared

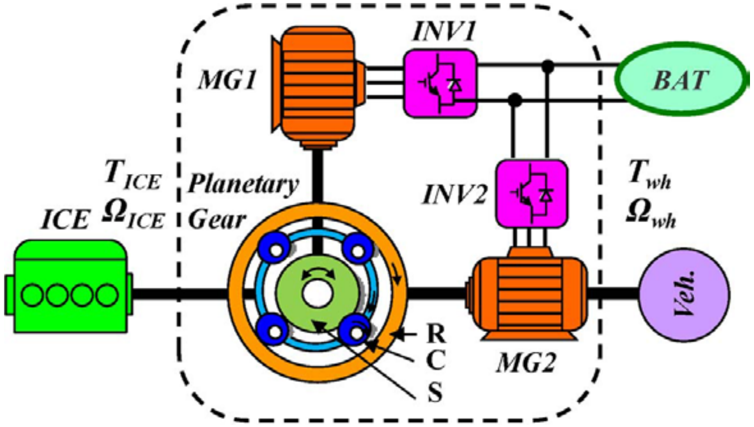
Topics

- Lifetime energy costs are assessed by analysing a comparable 50kW CR-IM and SPM run in three leading driving cycles (hard driving, highway, city)

- We conclude that for comparable 50kW motors:
  - CR-IM parts cost is lower than the SPM, $352 average.
  - The CR-IM requires a 7-8% larger battery capacity, $198 for a plug-in hybrid topology.
  - Resulting in an reduced consumer purchase price by $300-450 when a CR-IM is adopted.
  - CR-IM has a higher lifetime energy cost, $327 average over 120,000 miles.

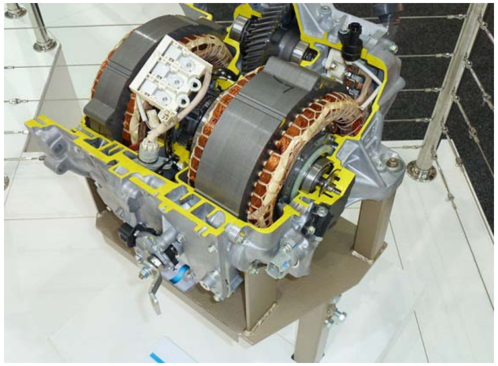
HEV Example: Toyota Prius

- Consists of two synchronous permanent magnet machines MG1 (Motor/Generator) and MG2 and an internal combustion engine connected through a planetary gear set.
- Rotational speed of the ICE decoupled from vehicle speed to maximise efficiency.
- By controlling MG1 and MG2 the hybrid powertrain acts as an electronically controlled continuously variable transmission.



HEV Example: SPM Toyota Prius THSII

- In this study a copper rotor induction motor replacement for MG2 will be analysed.
- Rotational speed of MG2 is directly coupled to the wheel speed through a gear ratio, max speed 6000rpm.
- MG2 torque dependant on vehicle control strategy or operating mode and battery SoC
- Here we assume:
  – MG2 contributes to 30% of the motoring torque.
  - Recovers up-to 250Nm of braking torque after which the frictional brakes supply the rest.

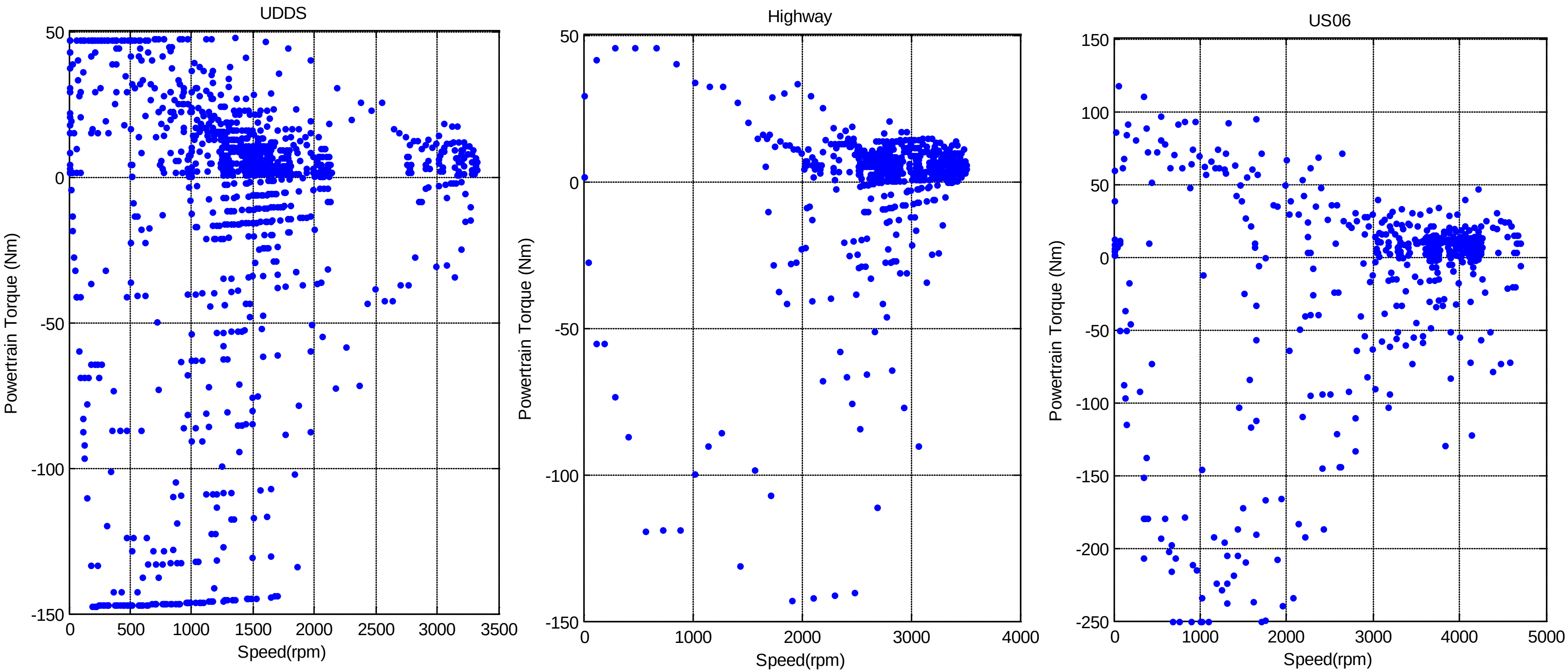


Driving Cycles

	UDDS	US06	HIGHWAY
Distance (miles)	7.45	8.01	10.26
Average Speed (mph)	19.59	48.37	48.3
Description	City Driving	Aggressive Driving	Typical Highway

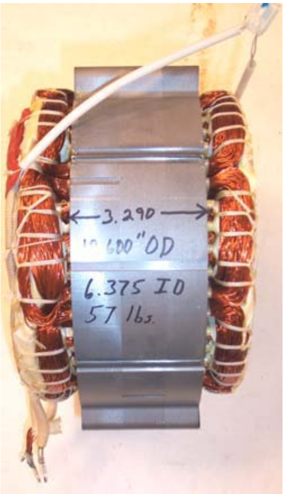
- Vehicle lifetime estimated as 120,000 miles
- Losses for the CR-IM and SPM calculated over lifetime for each driving cycle

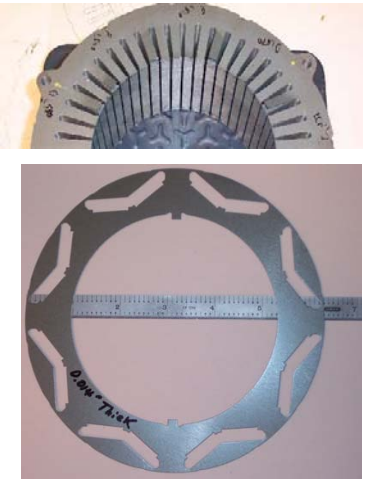
Driving Cycles – 30% Motoring Torque Contribution

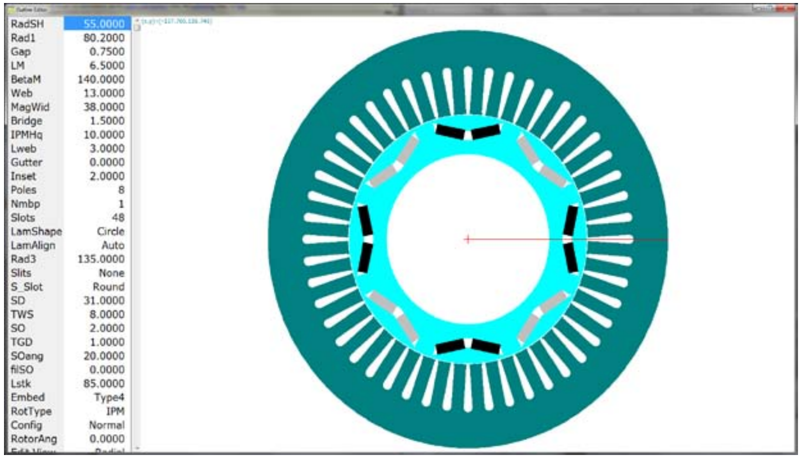


Synchronous Permanent Magnet Motor (SPM)

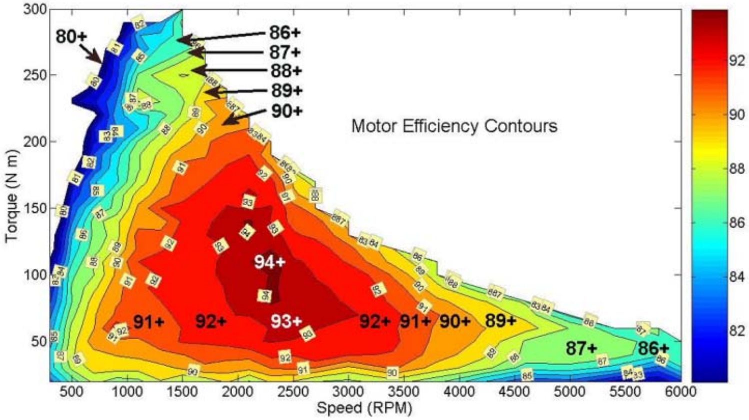
- Electromagnetic model and thermal model created using SPEED and Motor-CAD software
- Motor performance and losses calibrated using test data supplied in the Oak Ridge National Laboratory Reports.
- Losses calculated at each driving cycle operating point



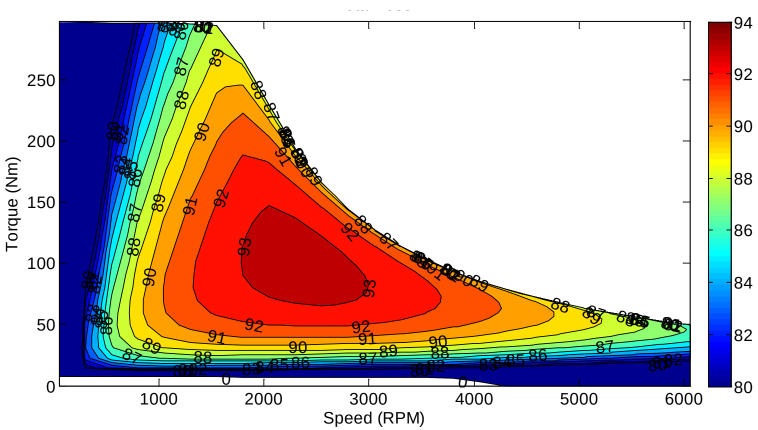




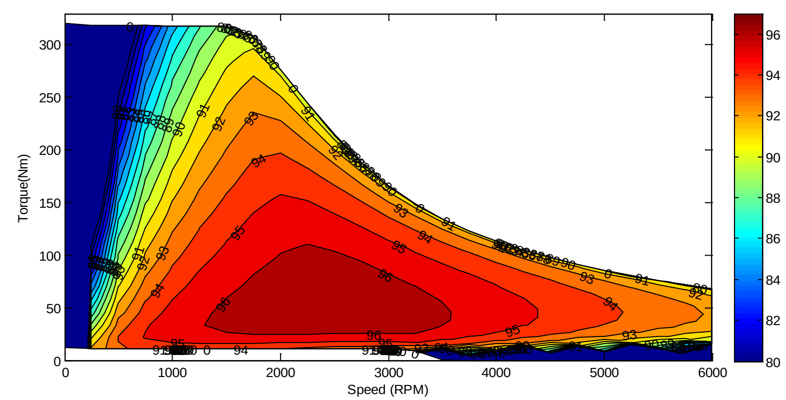
Efficiency map SPM



Test Data- including mechanical losses



Model Data- including mechanical losses

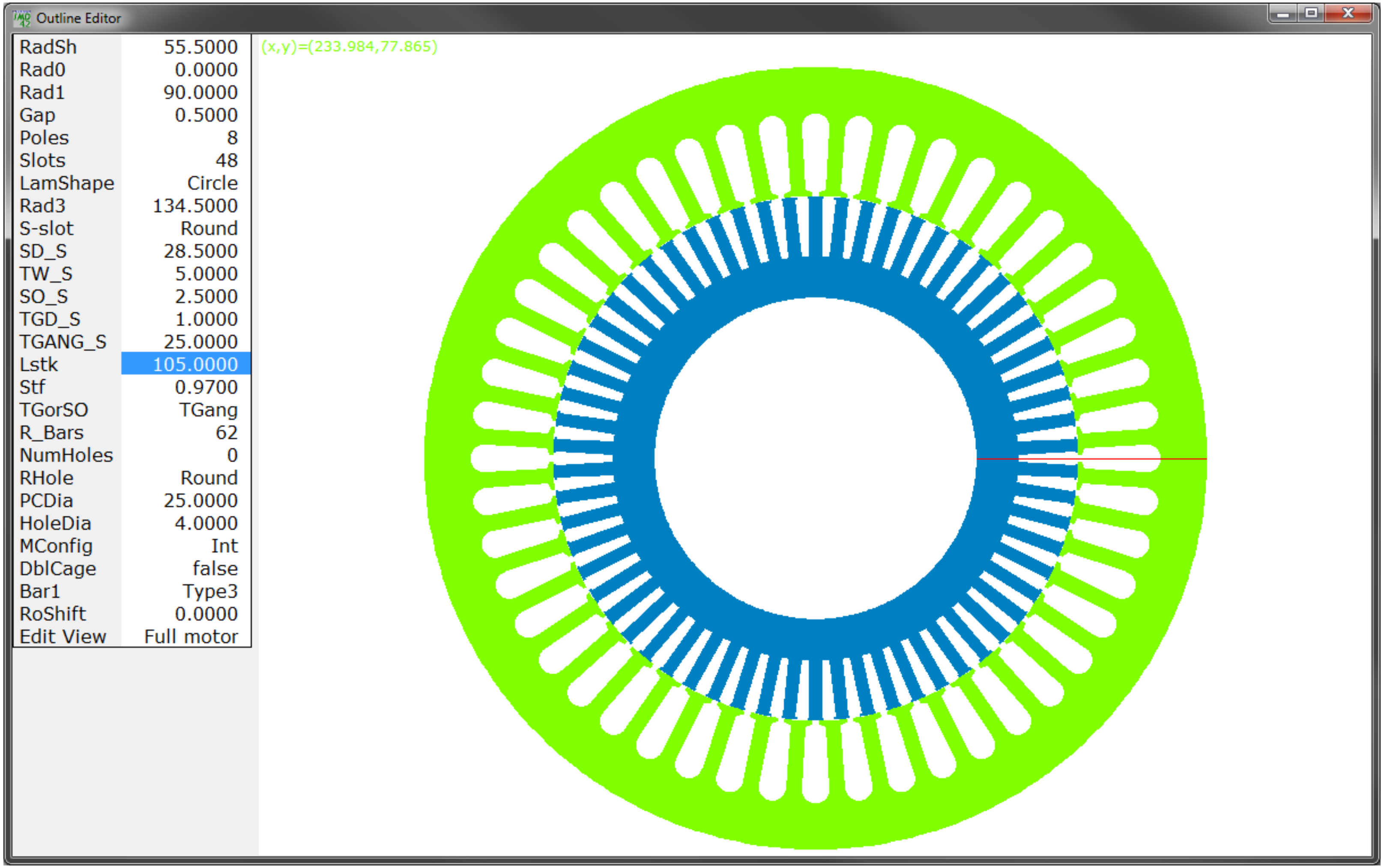


Model Data- excluding mechanical losses

Copper Rotor Induction Motor (CR-IM)

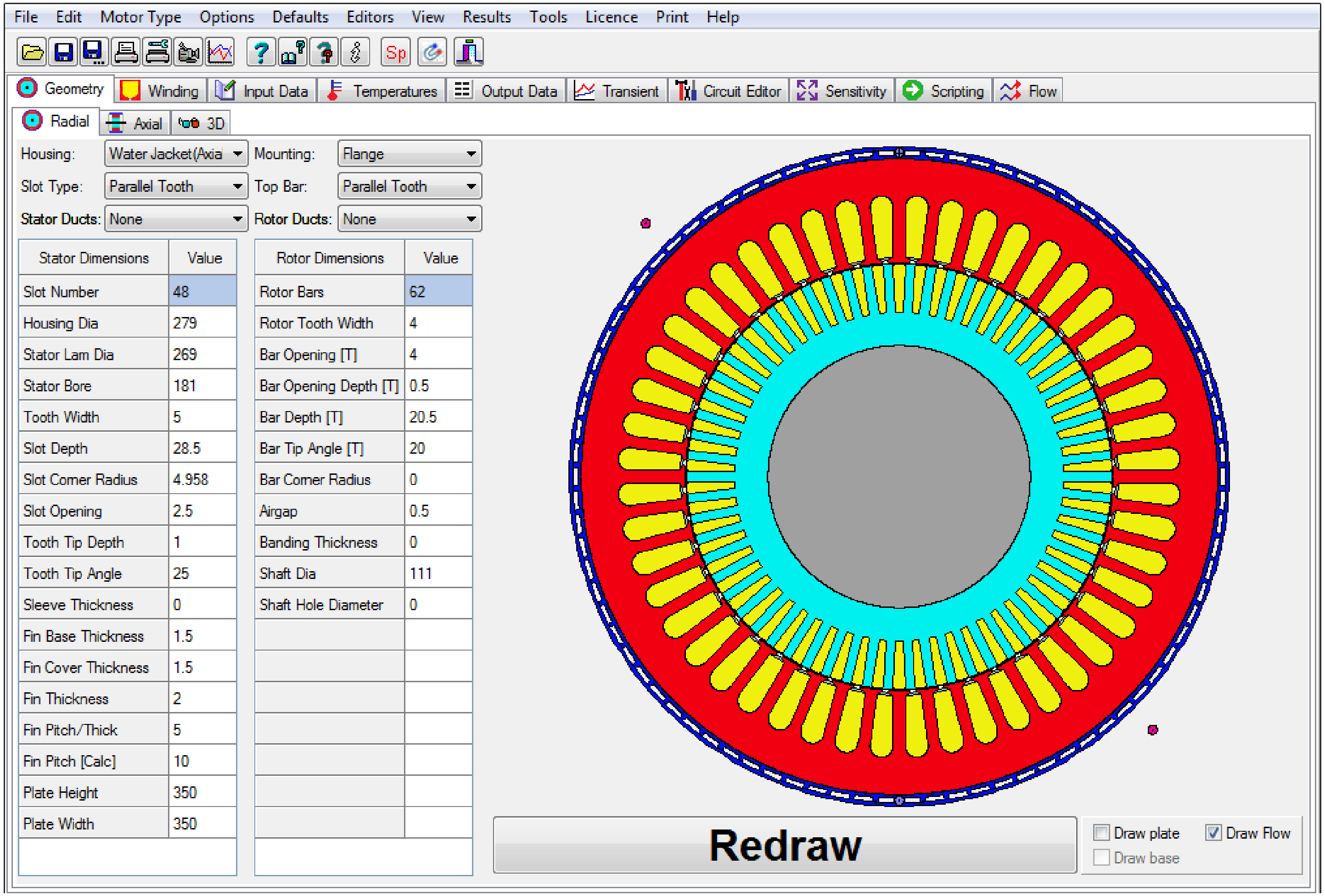
- CR-IM with equivalent performance has been designed
  - Similar OD with SPM motor
  - 48 slots
  - 62 bars
  - copper rotor cage
- CR-IM has inherently lower torque density than the BPM
- To achieve the same continuous and peak performance the possibilities are:
  - Increasing the active length gives a larger surface area to extract the loss through the cooling system and also reduces copper loss improving efficiency
  - Higher performance cooling system is required compared to the BPM motor

Copper Rotor Induction Motor (CR-IM)



CR-IM electromagnetic model in SPEED PC-IMD

Copper Rotor Induction Motor (CR-IM)



CR-IM thermal model in Motor-CAD

Thermal Performance Comparison

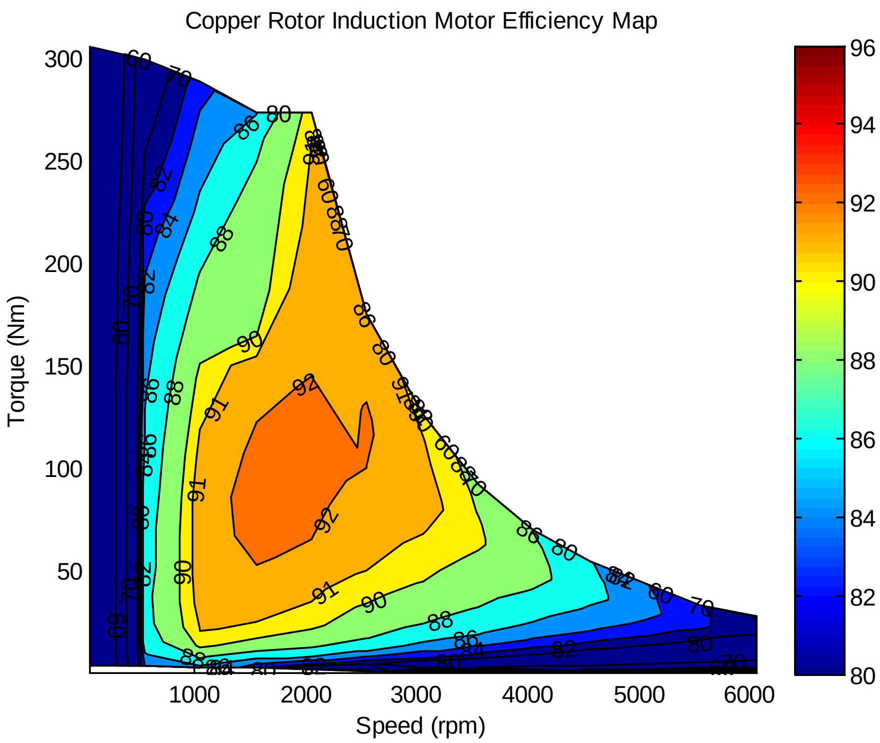
	SPM	CR-IM 1	CR-IM 2
Stack Length (mm)	**84mm**	**84mm**	**105mm**
Weight of Active Materials (kg)	**29.68**	**34.97**	**41.53**
Operating Point: 117.8Nm, 900rpm			
Efficiency (%)	92.5	86.5	88.2
Stator Copper Loss (W)	797	1163	935
Rotor Loss (W)	0	282	234
Stray Load Loss (W)	0	135	135
Iron Loss (W)	100	158	182
Total Loss (W)	897	1737	1485
Coolant Temperature	105	90	105
Coolant Flow Rate	2.4	2.4	2.4
Maximum Winding Temp	156	157	156

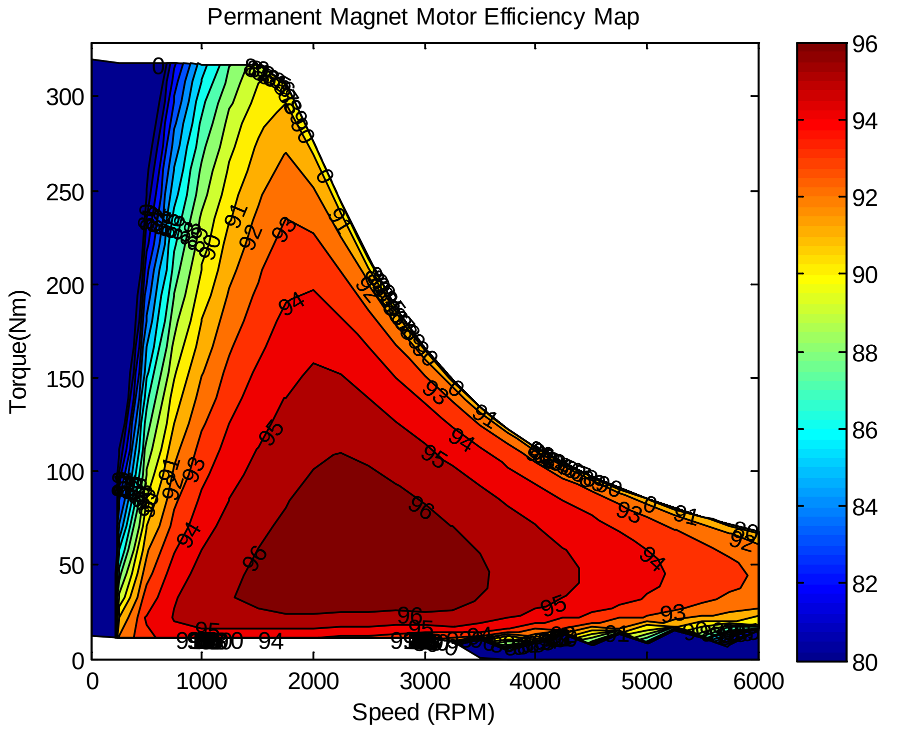
Assessed using Motor-CAD steady-state thermal analysis for each model

Active Material Weights Comparison

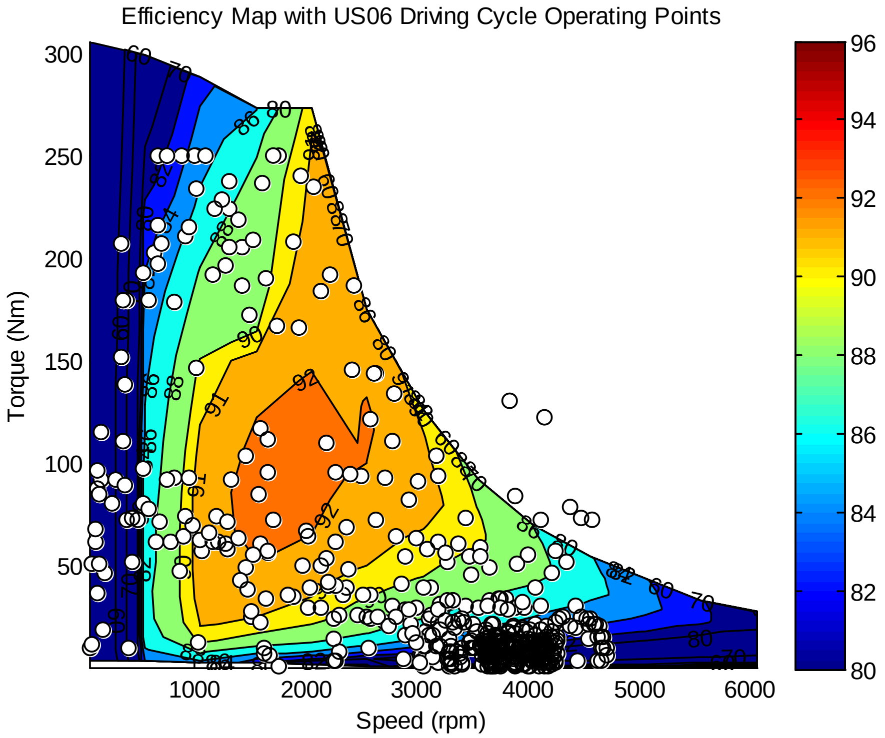
	SPM	CR-IM1 (84mm)	CR-IM2 (105mm)
Copper (kg)	4.47	8.33	9.12
Steel (kg)	23.87	19.23	24.03
Permanent Magnet/Rotor Cage (kg)	1.34	7.41	8.38
Total (kg)	29.68	34.97	41.53

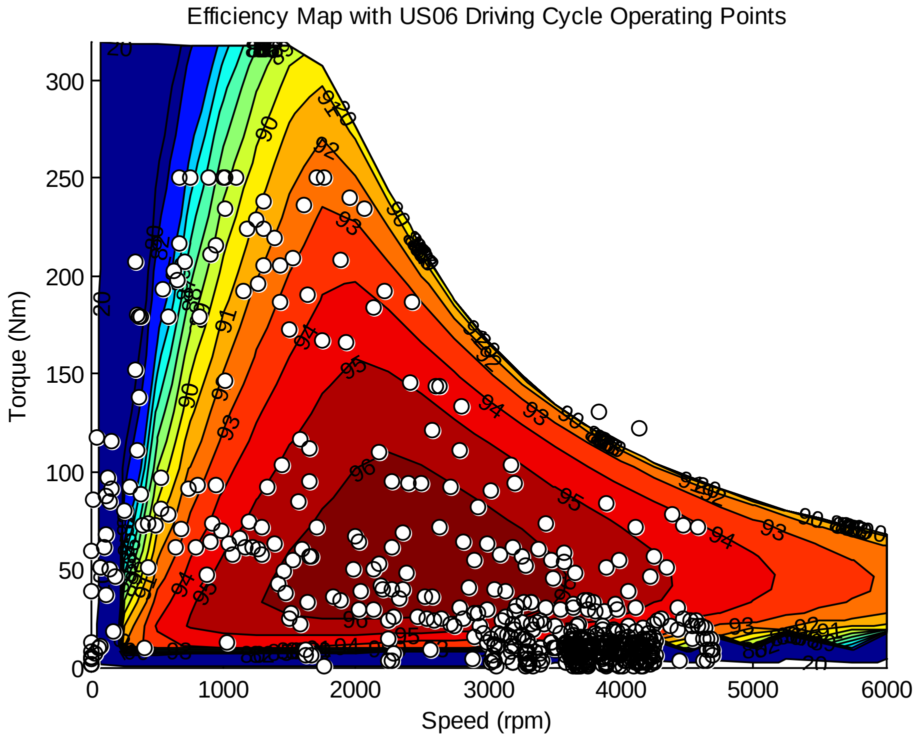
SPM and CR-IM efficiency comparison



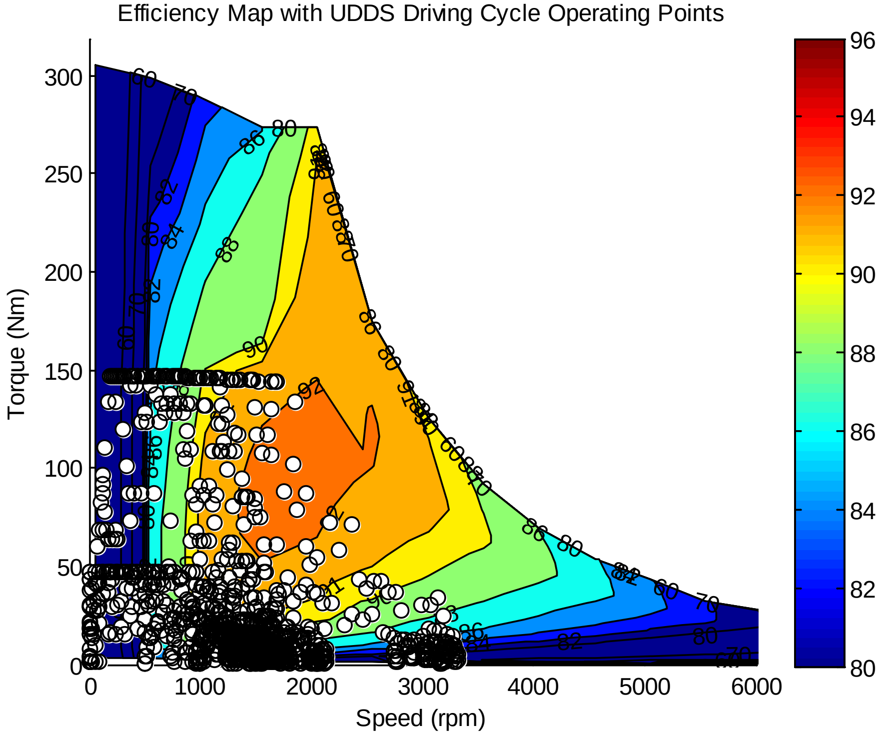


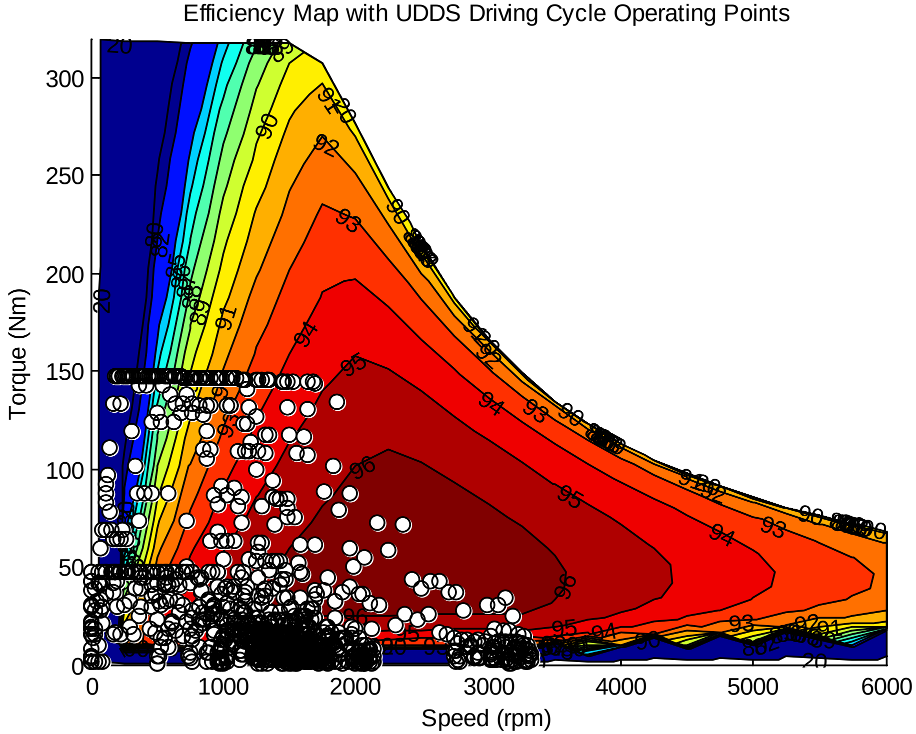
SPM and CR-IM efficiency comparison
US06 Driving Cycle Operation Points



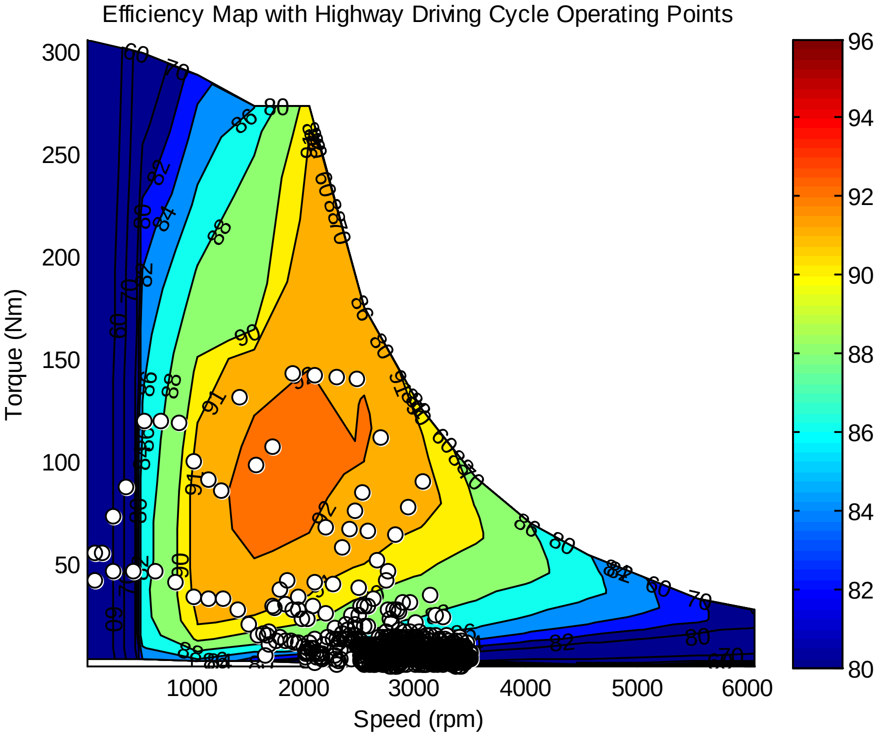


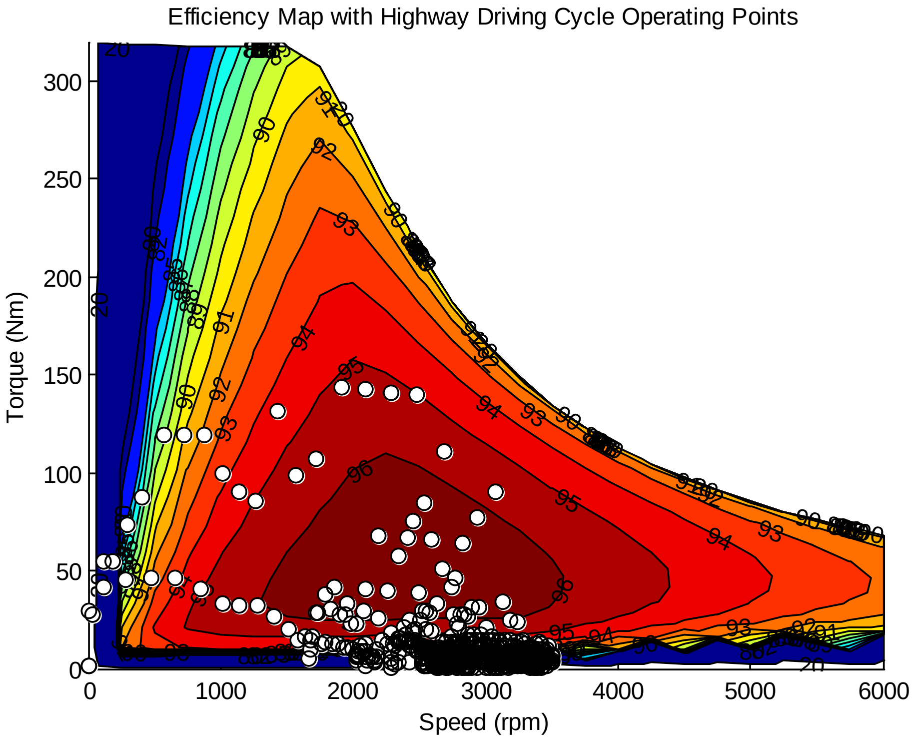
SPM and CR-IM efficiency comparison
UDDS Driving Cycle Operation Points



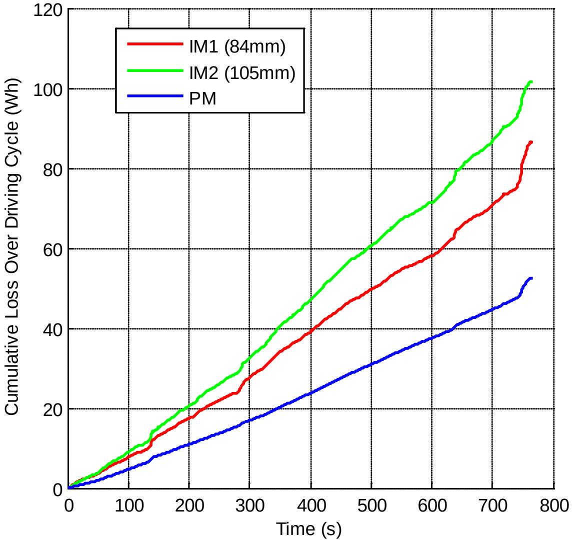


SPM and CR-IM efficiency comparison
Highway Driving Cycle Operation Points

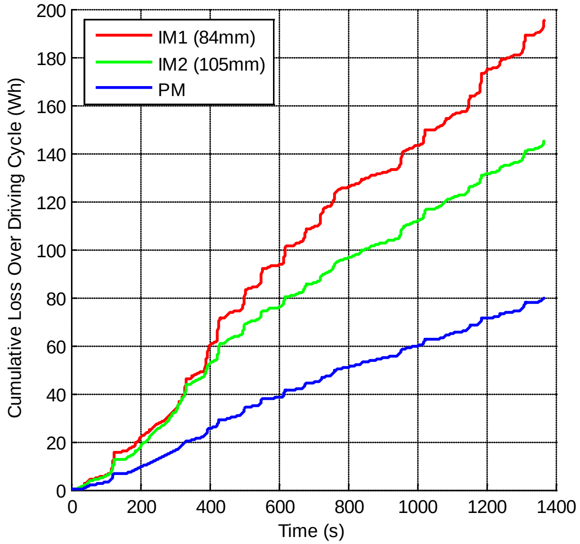




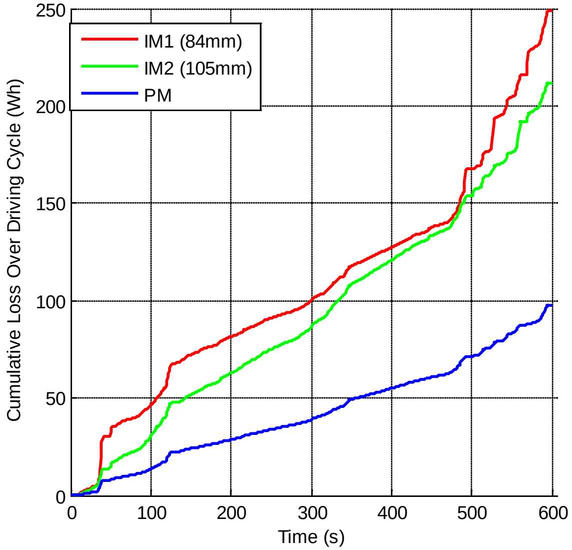
Driving Cycle Analysis



Highway



UDDS



US06

Lifetime Energy Cost

	SPM	CR-IM1 (84mm)	CR-IM2 (105mm)
UDDS (kWh)	1289	3148.7	2334
US06 (kWh)	1462	3729.3	3170
HWY (kWh)	613	1012.6	1188
Combined Average	1121	2630	2231
Extra Energy Cost from baseline @ $0.25/kWh	0	$377	$277
@$0.294/kWh (From petrol IC Engine)	0	$444.5	$326.34

Total losses over 120,000 mile lifetime

Material Cost Analysis

- Electric steel: $1.00/kg (source internet 2012)
- Copper: $7/kg (source ICA, 2012)
- Sintered rare-earth (NdFeB) magnets: $250-400/kg (source: Dave Murphy, Rare Earth Sourcing Challenges for PM, from the Perspective of the Miner and Processor, 2011)

	SPM	CR-IM1 (84mm)	CR-IM2 (105mm)
Copper ($/unit)	31.3	58.3	63.8
Steel ($/unit)	23.9	19.2	24.0
Permanent Magnet/Rotor Cage ($/unit)	335-536	51.9	58.6
Total ($/unit)	389.3-590.3	129.4	146.4

Battery Sizing

		Highway (10.25 miles)	UDDS (7.45 miles)	US06 (8 miles)
Motoring Energy Required from battery (kWh)	CR-IM 84mm	0.415	0.364	0.594
	CR-IM 105mm	0.430	0.363	0.600
	SPM	0.395	0.338	0.542
Braking Energy Recovered to battery (kWh)	CR-IM 84mm	0.205	0.578	0.625
	CR-IM 105mm	0.204	0.628	0.669
	SPM	0.219	0.668	0.724

- Battery capacity for 2012 Plug-in Prius = 4.4kWh
- Estimated required increase in battery back capacity for a CR-IM:
  - 7-8%, increase to 4.73kWh
- At $600/kWh (2012 battery price) increased cost $198
- At $200/kWh (est. 2020 price) increased cost $66

Other Considerations

- Security of supply for magnets material and volatility of prices
- Magnets can be permanently demagnetized through thermal and electric stress
- CR-IM require a simpler and cheaper open-loop control strategy, i.e. no rotor position information is necessary
- CR-IM tend to require a higher current to drive them which may have implications for the cost of the power electronics components (IGBTs) and the losses in the inverter

Conclusions

- Our main conclusion is that CR-IM are an attractive architecture for HEV traction:
  - the increased efficiency of SPM do not justify their higher parts costs
  - lower parts cost for CR-IM make initial acquisition of HEV more attractive to the consumer by $300-450/vehicle even when increased battery capacity requirements for CR-IM are taken into account
  - the geopolitical sensitivity of RE's causes high PM price volatility, which is absent in CR-IM

- Supporting details:
  - Total ownership cost for HEV traction motor = motor parts cost + lifetime energy cost
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Conclusions

- Lifetime energy costs are assessed by analysing a comparable 50kW CR-IM and SPM run in three leading driving cycles (hard driving, highway, city)

- We conclude that for comparable 50kW motors, the lower CR-IM parts cost ($352 average) is roughly the same as its higher lifetime energy cost ($327 average)

Acknowledgment

- European Copper Institute for technical support

Thank you for your attention!

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