Power-trains for "More" Electric Road Vehicles

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Presentation overview :

1 Background to “more electric” vehicle concepts

2 Vehicle power-train power- and torque-speed requirements

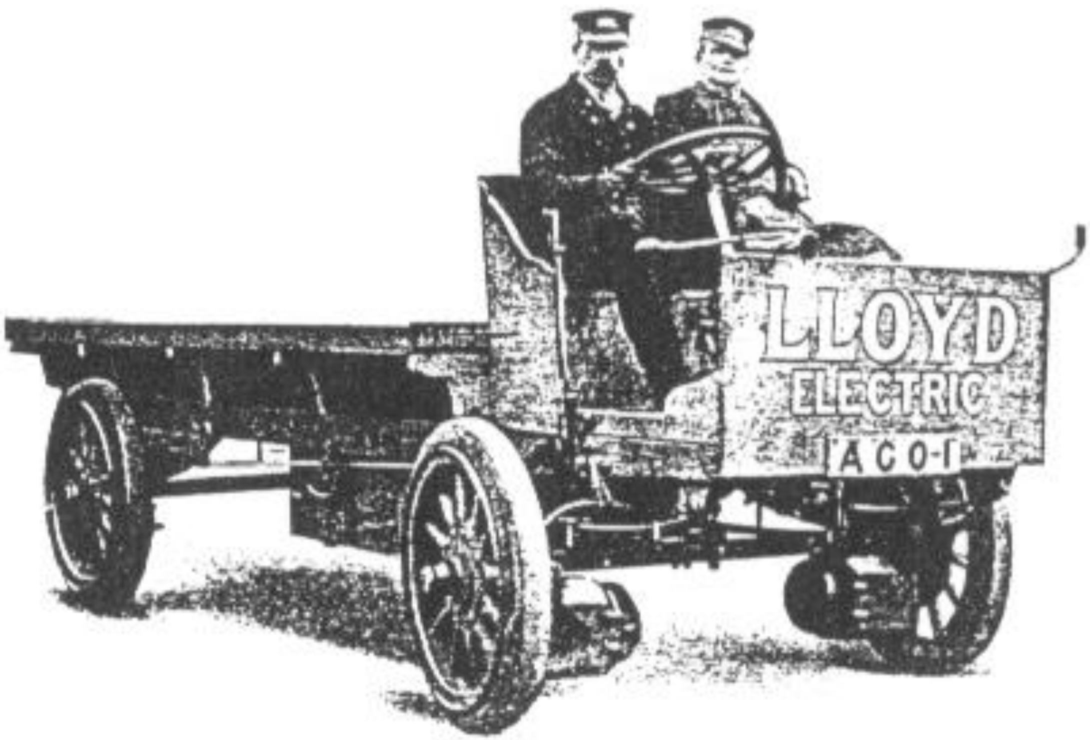
3 Machine and power electronics

4 Vehicle integration considerations

5 Energy sources

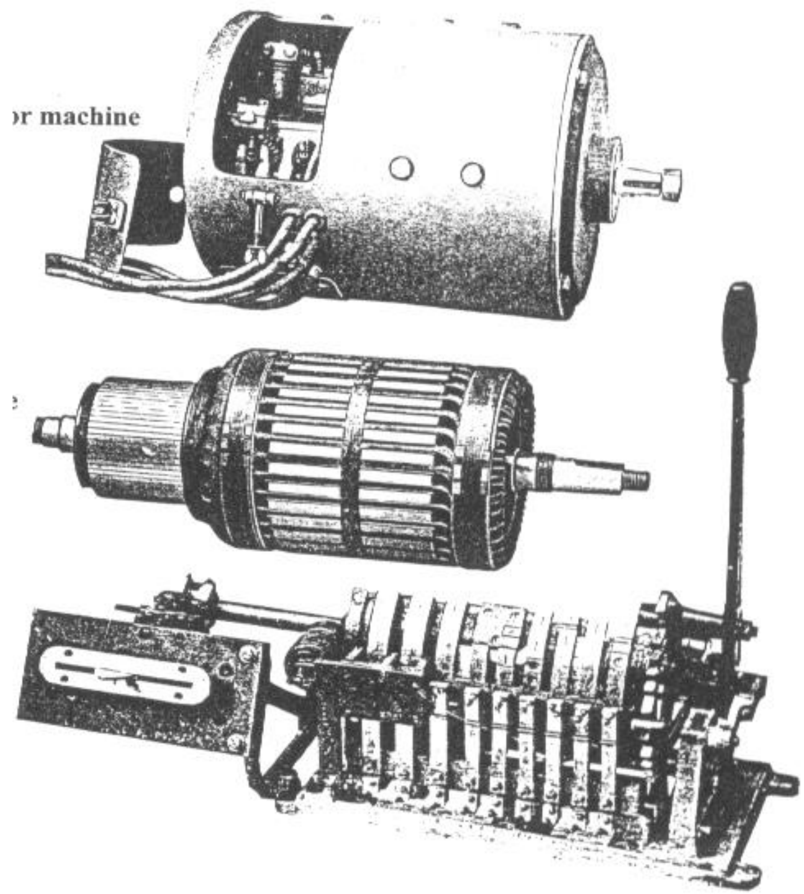
6 Summary

Early electric road vehicle

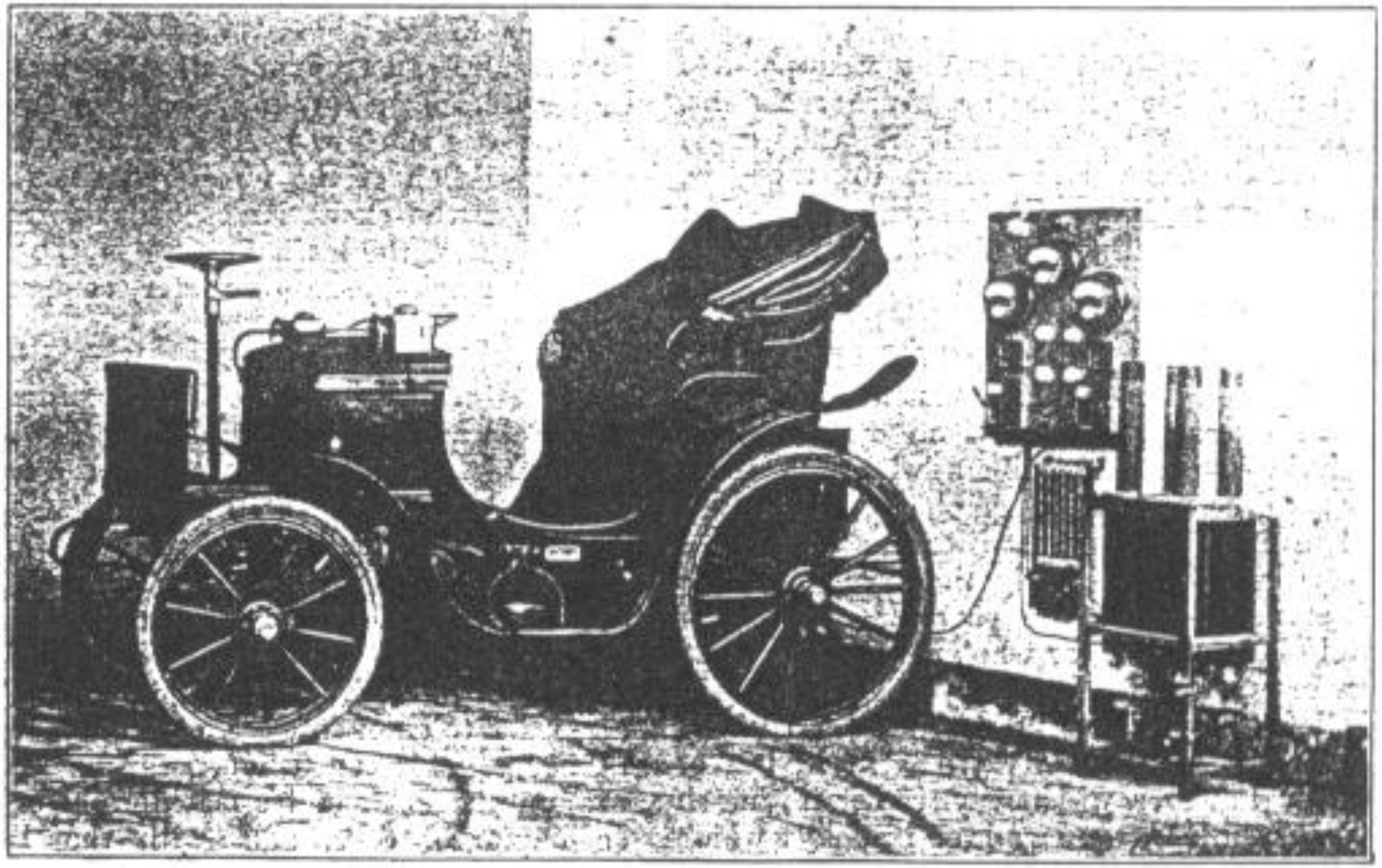


Lloyd Electric delivery vehicle

Brushed dc traction system

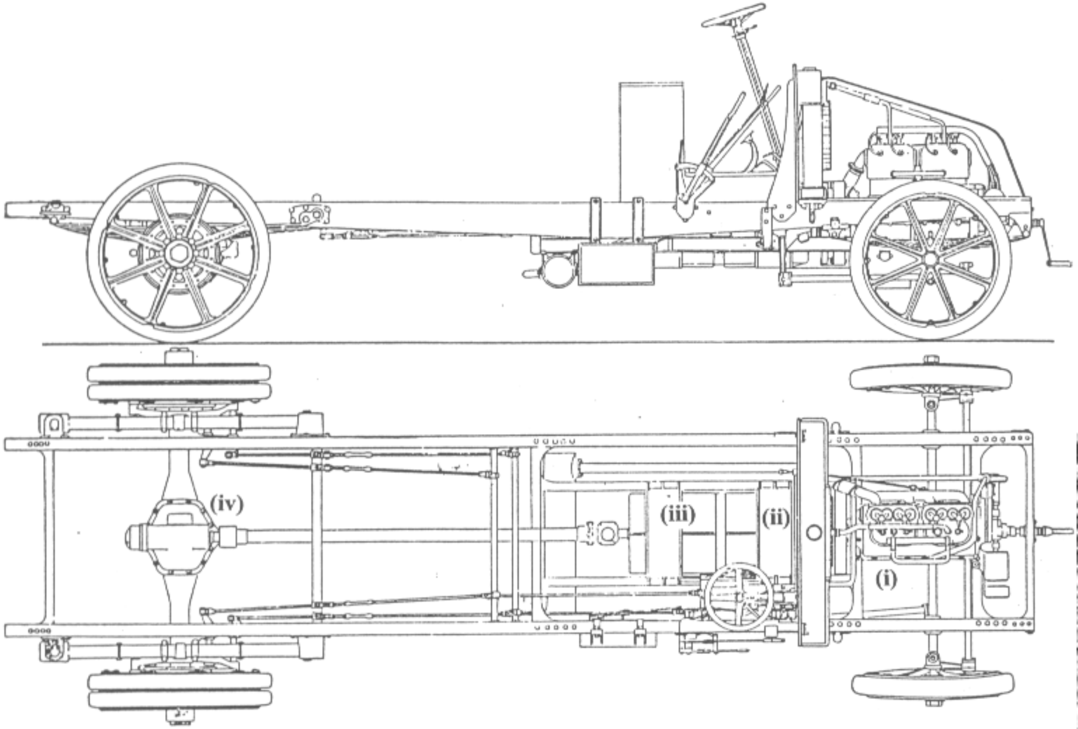


Electric road vehicle infrastructure

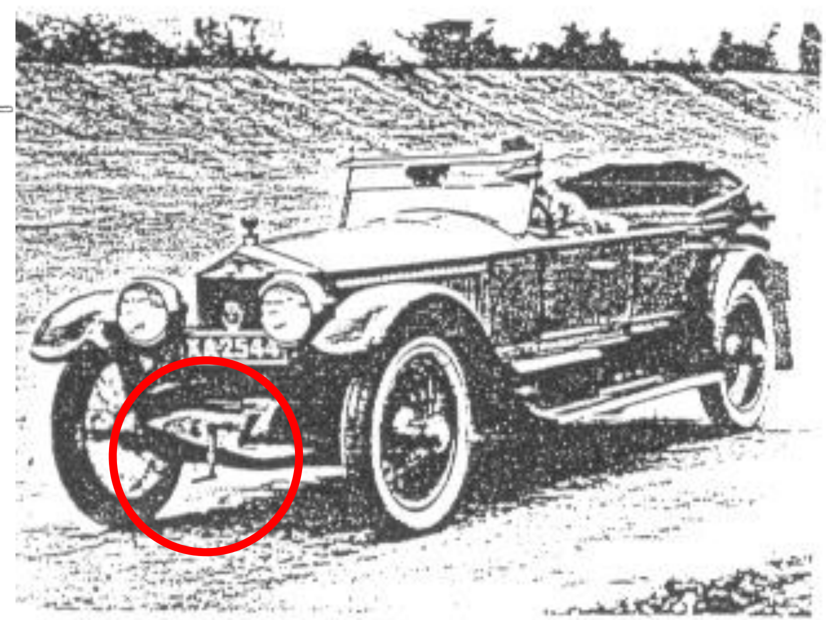


Electric vehicle and electrolytic rectifier charging station

Hybrid or 'More-electric' road vehicles

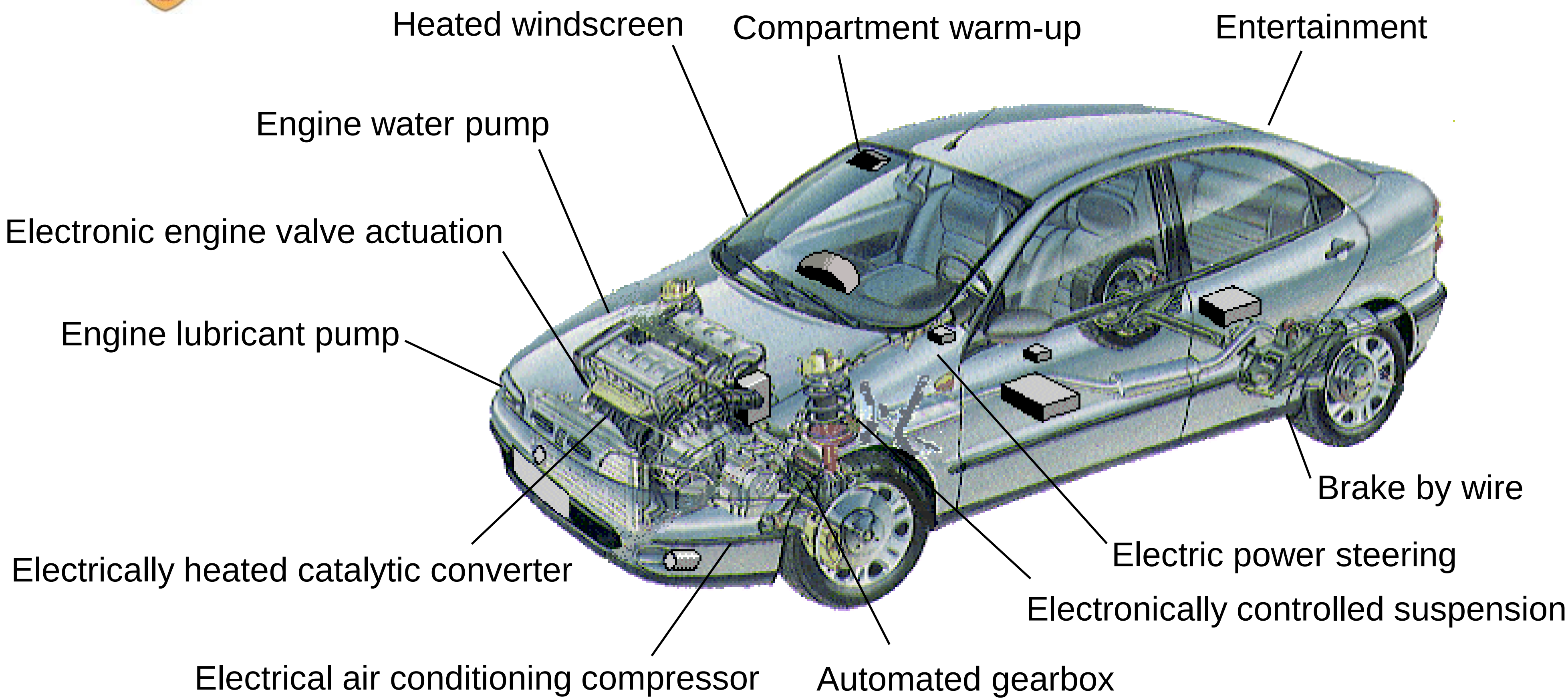


Tilling-Stevens motor-bus; 6864cc; 28.3kW engine



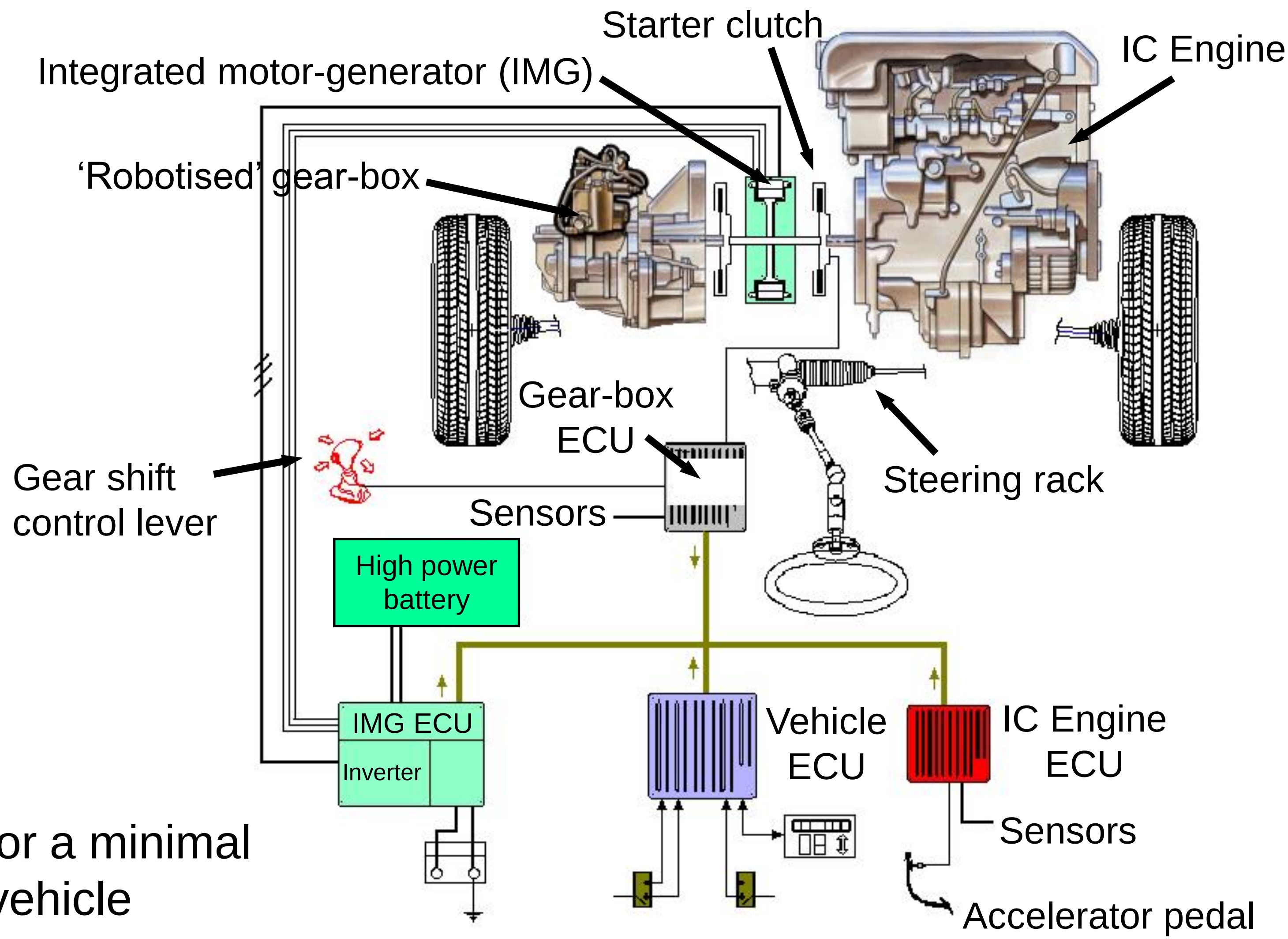
Hybrid-electric racing car, circa 1930's

Automotive applications of electrical machines and drives



Note: Installed electrical capacity projected to rise to 15kW over next 5 years (simple sum:- 15kW/12V = 1250A)

‘More electric’ automotive drive-trains



Example schematic for a minimal hybrid-electric vehicle

Fleet Conversions

3.5 tonne delivery vehicles

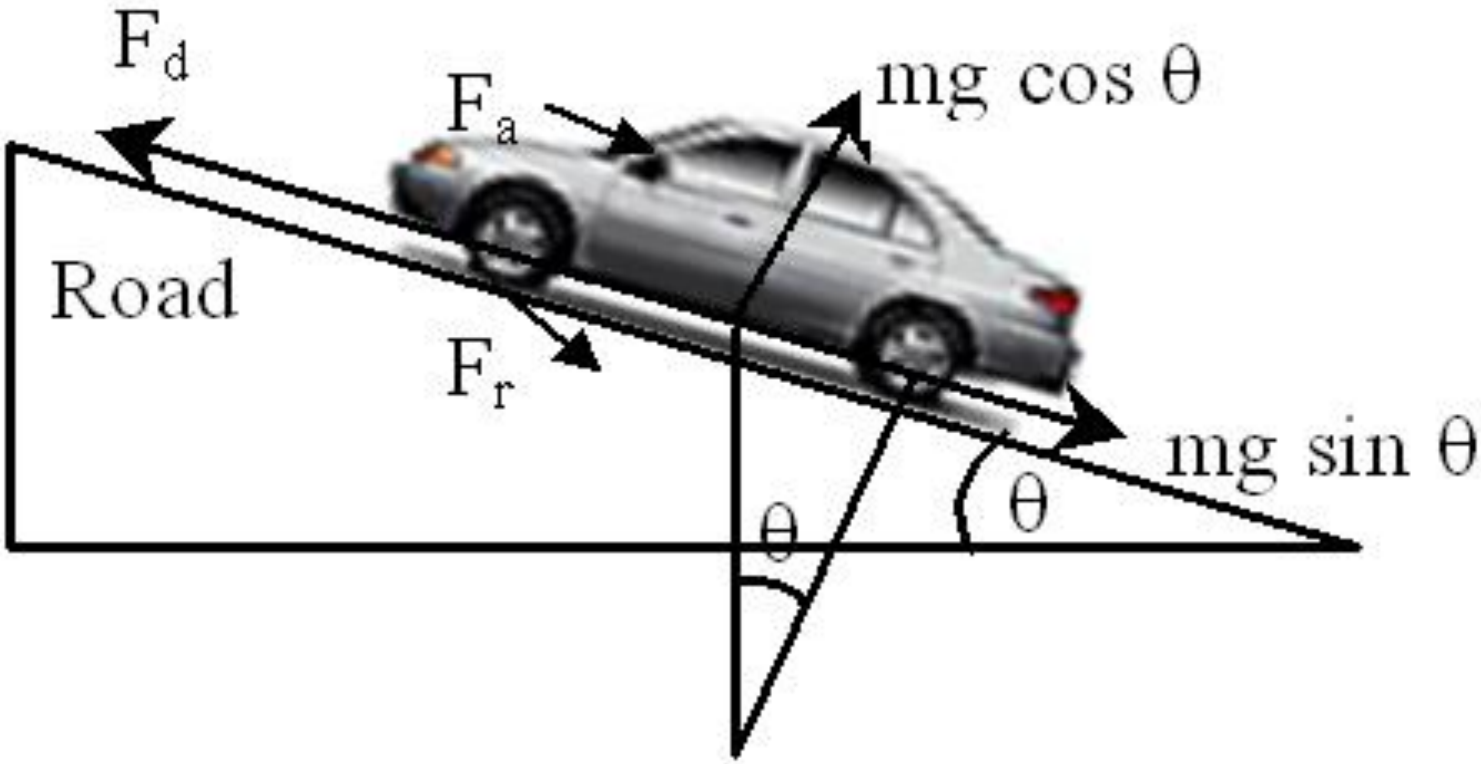
7.5 tonne delivery vehicles

Courtesy of Smith EV, Washington, UK

7.5 Tonne All-Electric Delivery Vehicle

Courtesy of Smith EV, Washington, UK

Vehicle kinematics and power-train rating



Expressing the wheel and traction machine angular velocities in terms of the vehicle linear velocity yields:

$$\omega_w = \frac{v}{r_w} \qquad (4) \qquad\qquad \omega_m = n_t \frac{v}{r_w} \qquad (5)$$

From which the machine torque equation can be expressed in terms of the vehicle linear velocity by substituting eqns.(1, 2, 4 and 5) into eqn.(3) :

$$T_m = \left[\left(\frac{n_t.J_m}{r_w} \right) + \left(\frac{J_w}{n_t \eta_t . r_w} \right) + \left(\frac{d_f r_w . m}{n_t \eta_t} \right) \right] \frac{dv}{dt} + \frac{d_f r_w}{n_t \eta_t} \left[\left(k_r \cos\theta + \sin\theta \right) mg + \frac{1}{2} \rho . C_d A_f v^2 \right] \qquad (6)$$

Mechanical power is torque multiplied by mechanical speed :

$$P_m = T_m \omega_m \qquad (7)$$

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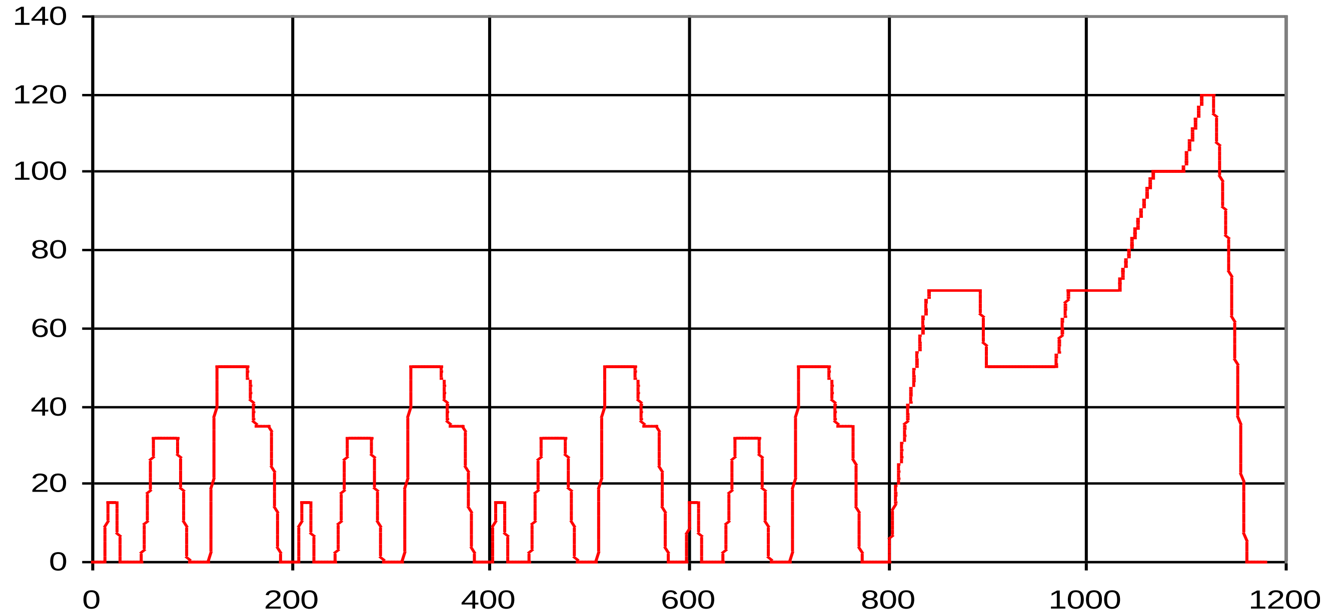
NEDC vehicle reference driving cycle

Vehicle speed (km/h)



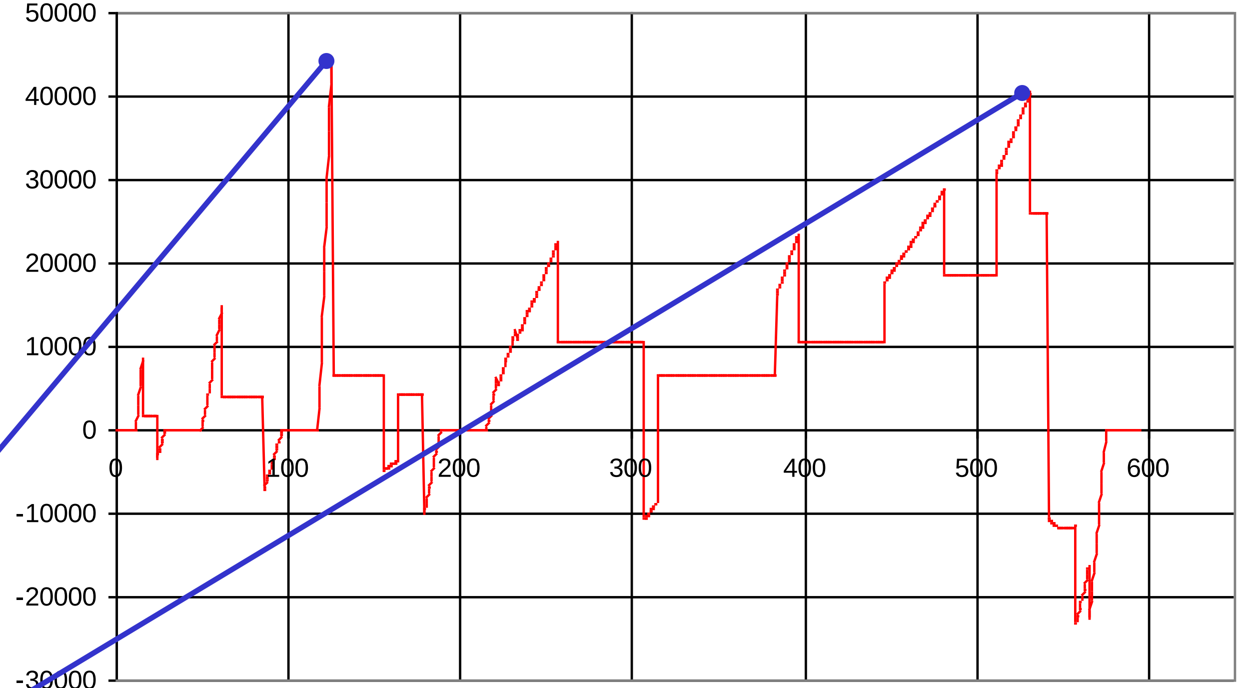
Cycle duration (s)

Cycle consists of :

- 4 x ECE15 standard driving cycles with enhanced acceleration
- 1 x ECE sub-urban cycle

Dynamic power over NEDC driving cycle

Mechanical power (W)



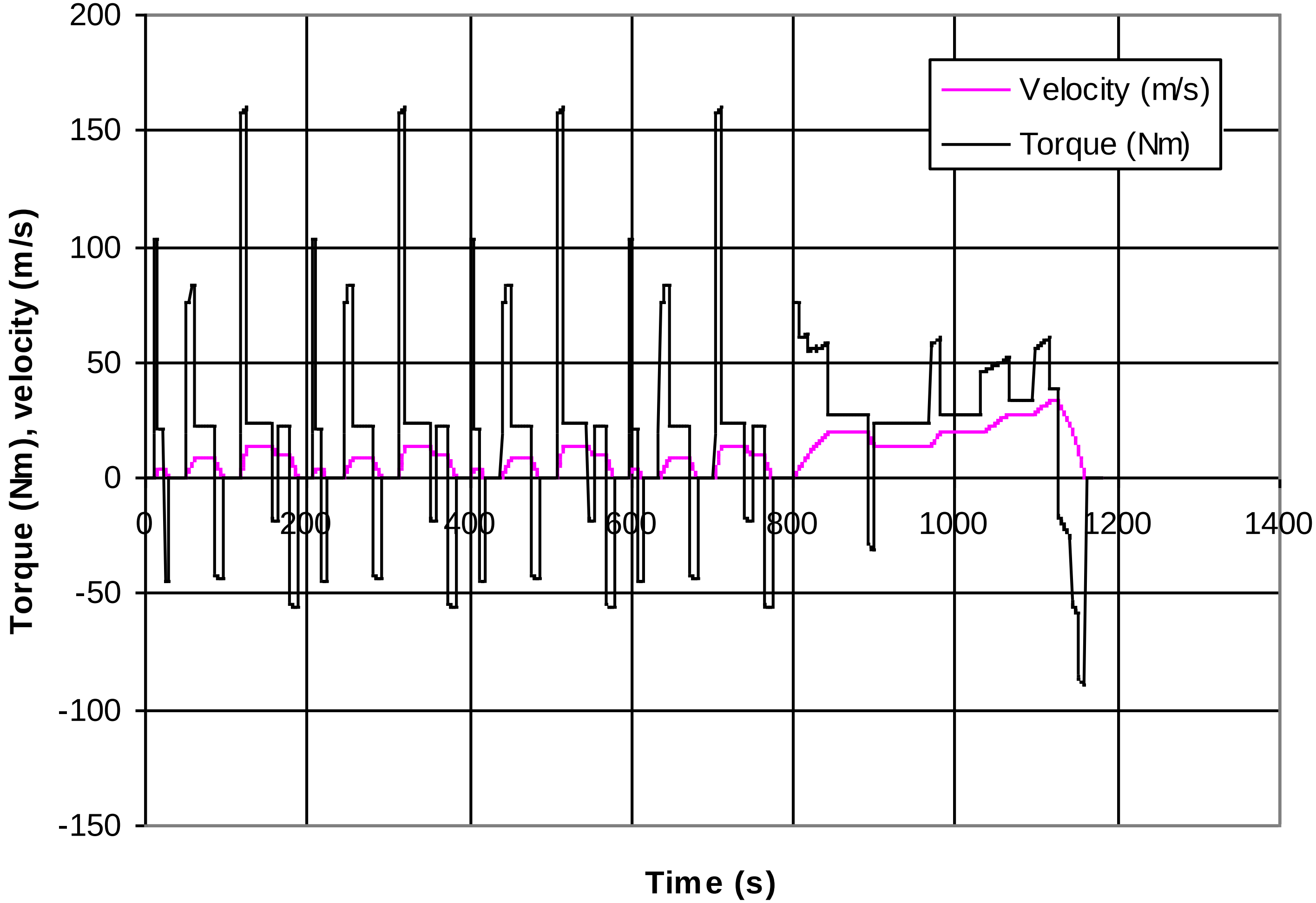
Machine speed (rpm)

Peak power at :

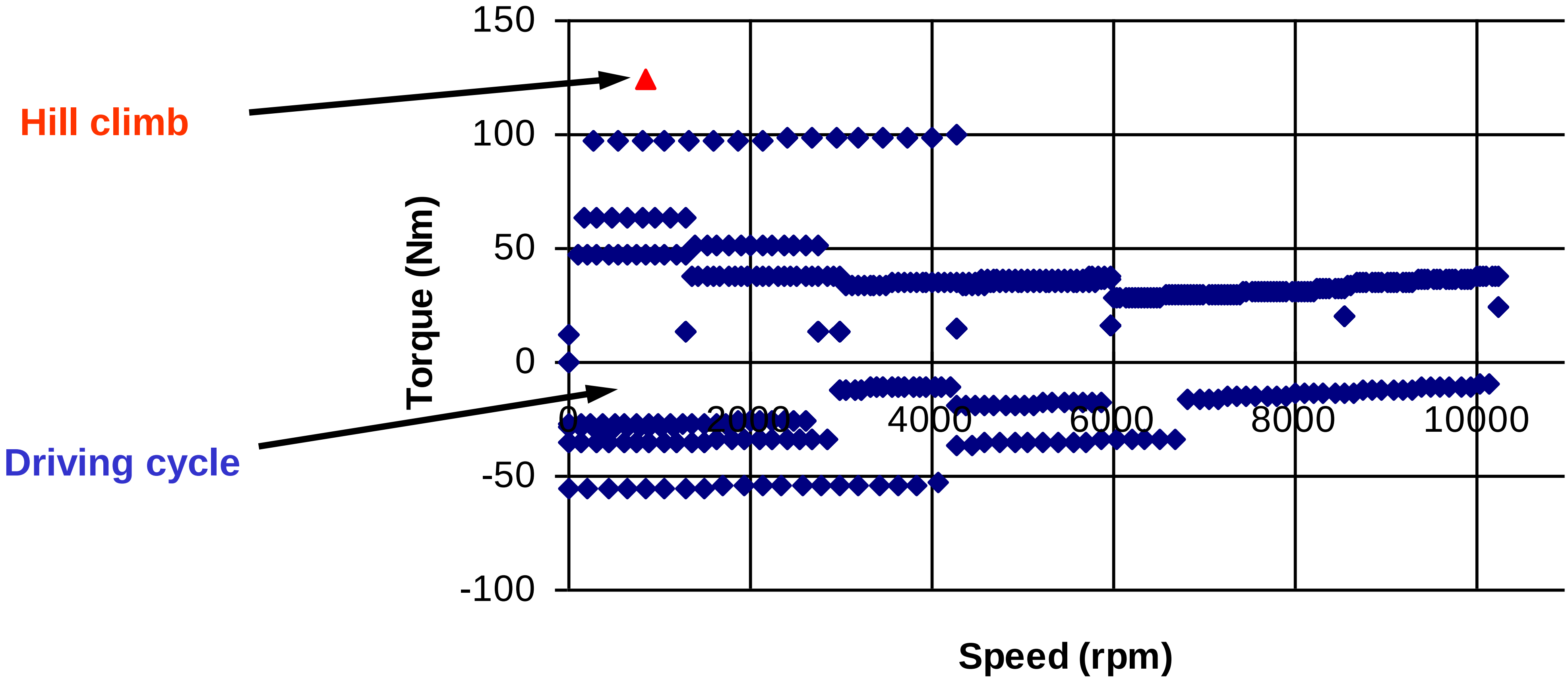
- max. acceleration, low speed.
- high speed, cruse

1.5 tonne vehicle on zero road gradient

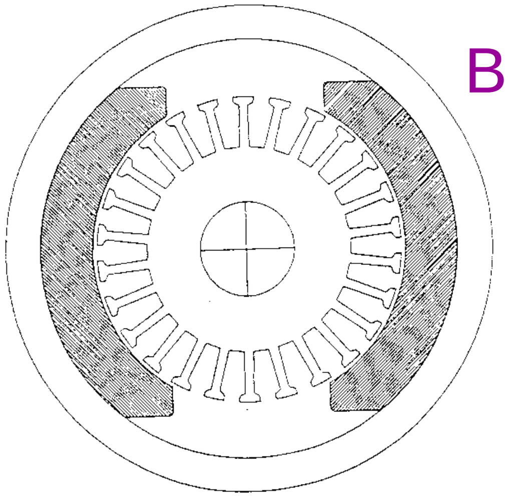
Traction machine torque vs. time



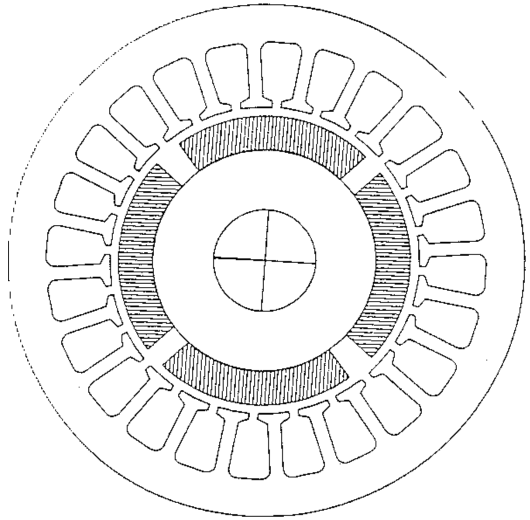
Traction machine torque - speed for a gear ratio of 8.83



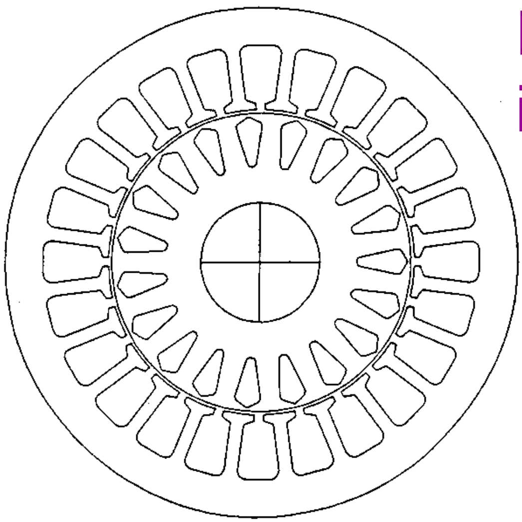
‘More electric’ vehicle machine technologies



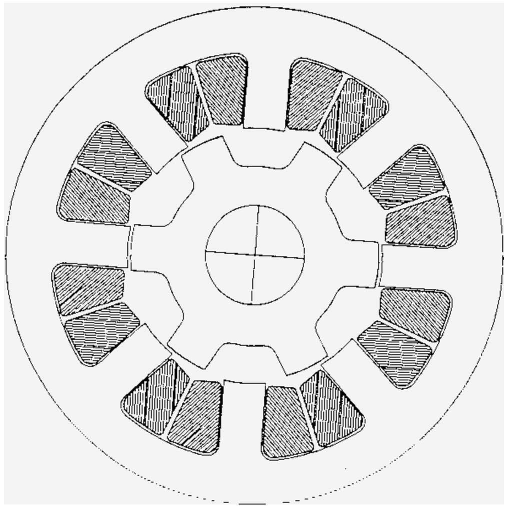
Brushed dc



Brushless - permanent magnet

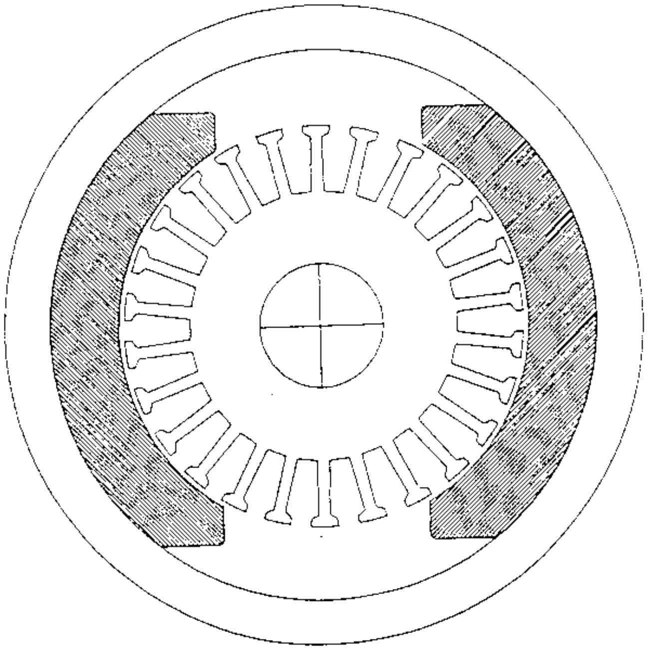


Brushless - induction

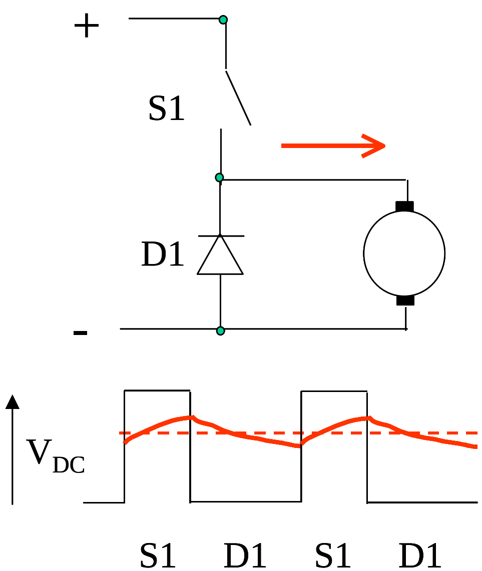


Brushless - switch reluctance

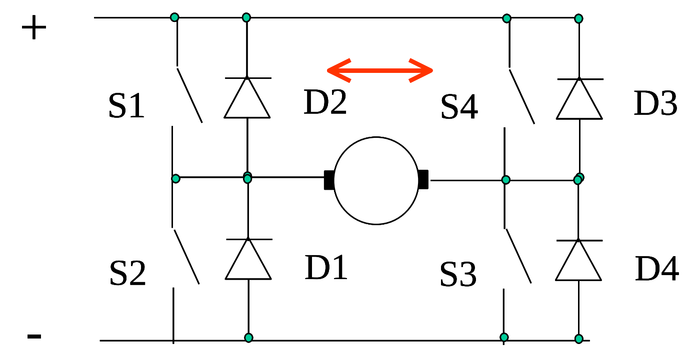
Brushed dc motor



1 Quadrant 'chopper'



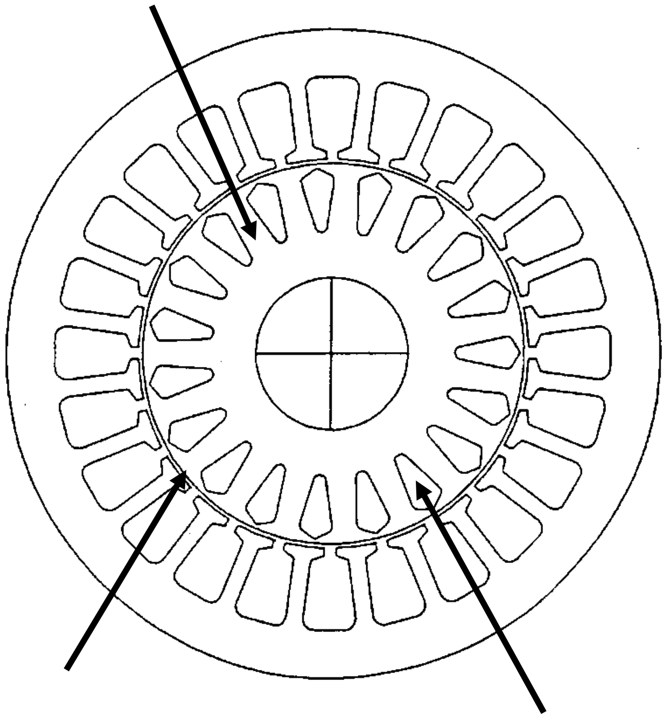
4 Quadrant drive



Motoring	S1,S3 and D1,D3
Braking	S2,S4 and D2,D4
Forward	duty >50%
Reverse	duty <50%

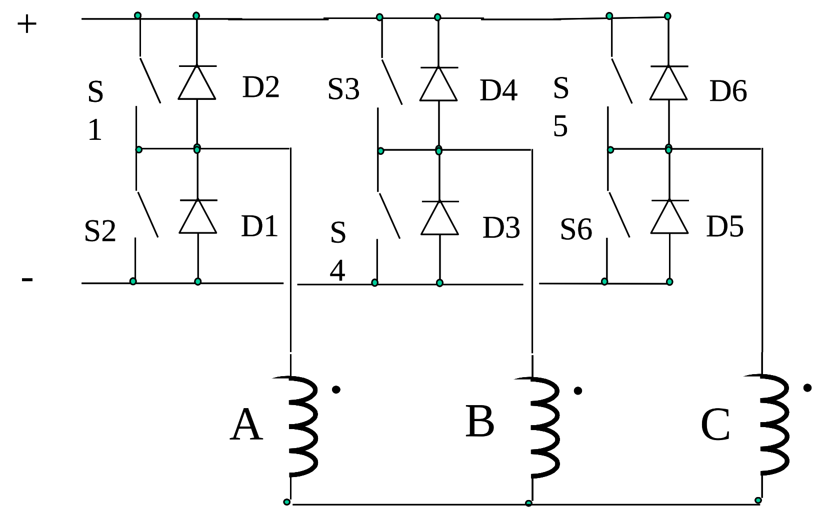
Induction motor

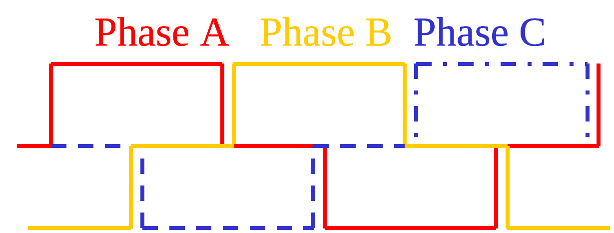
Rotor losses dissipated across airgap by convection

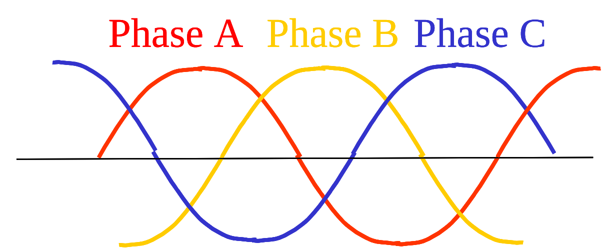


Narrow airgap for low reactive power

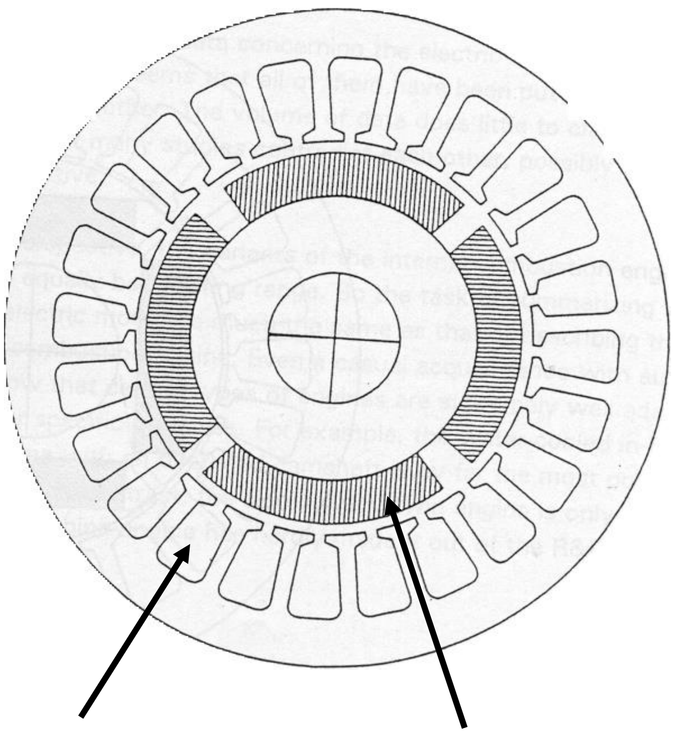
Cast aluminium or copper rotor bars

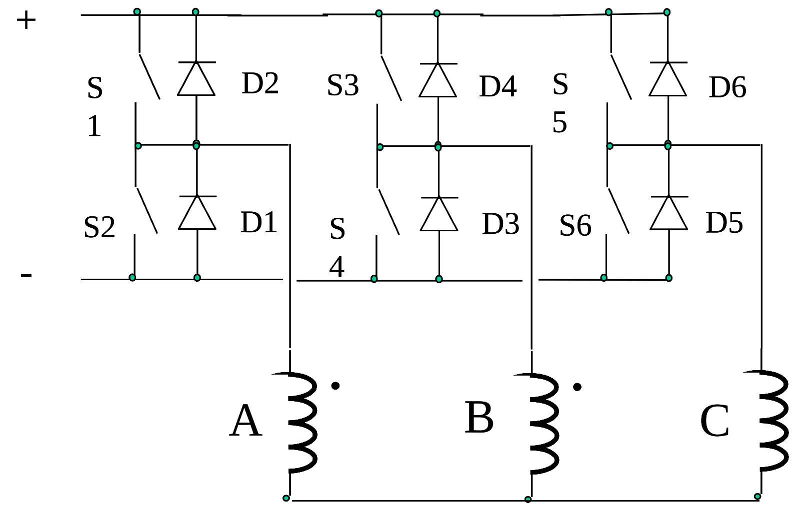


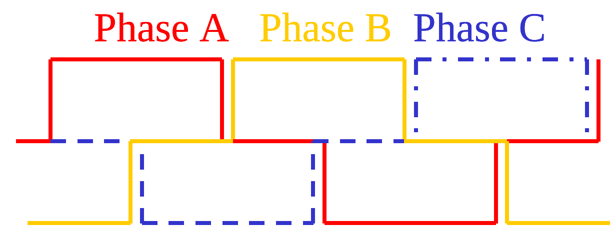


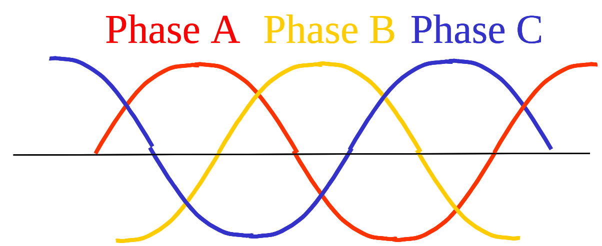


Brushless permanent magnet motor







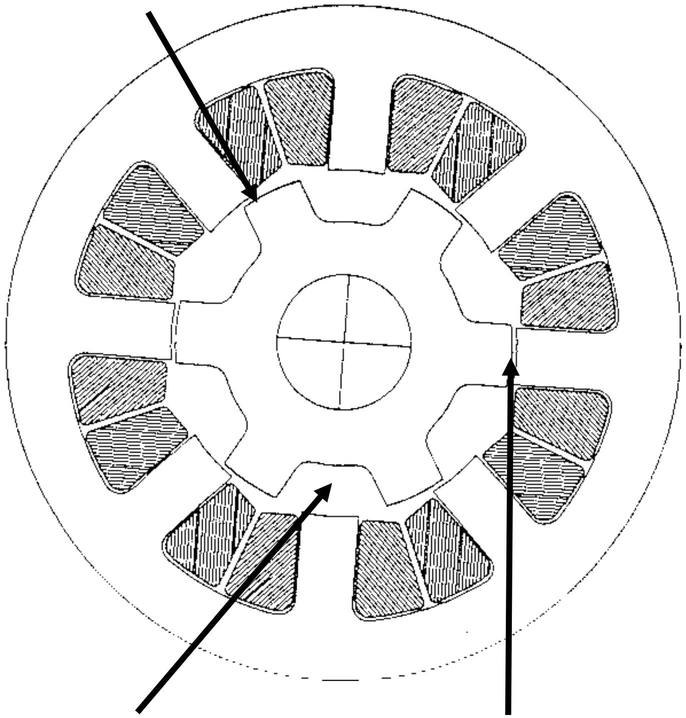


Concentrated or distributed multi-phase winding topologies

Permanent magnet rotor excitation

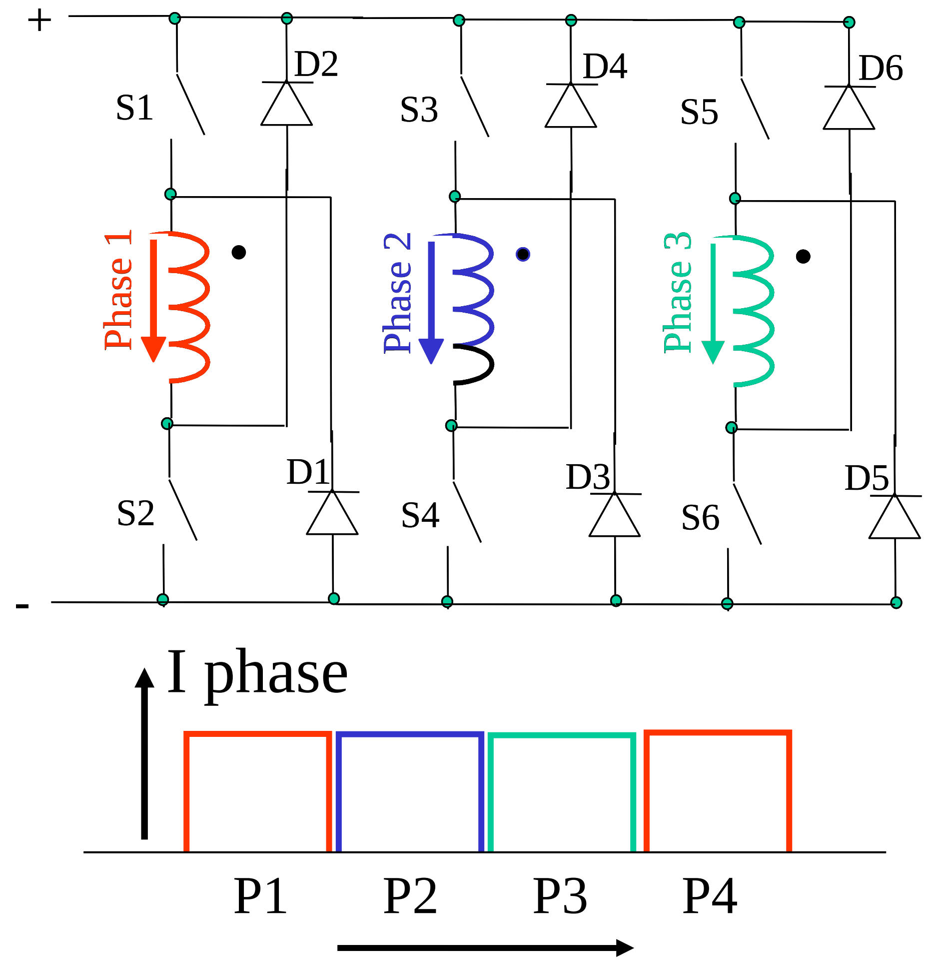
Switched reluctance motor

Torque produced in pulses from interaction of stator and rotor teeth

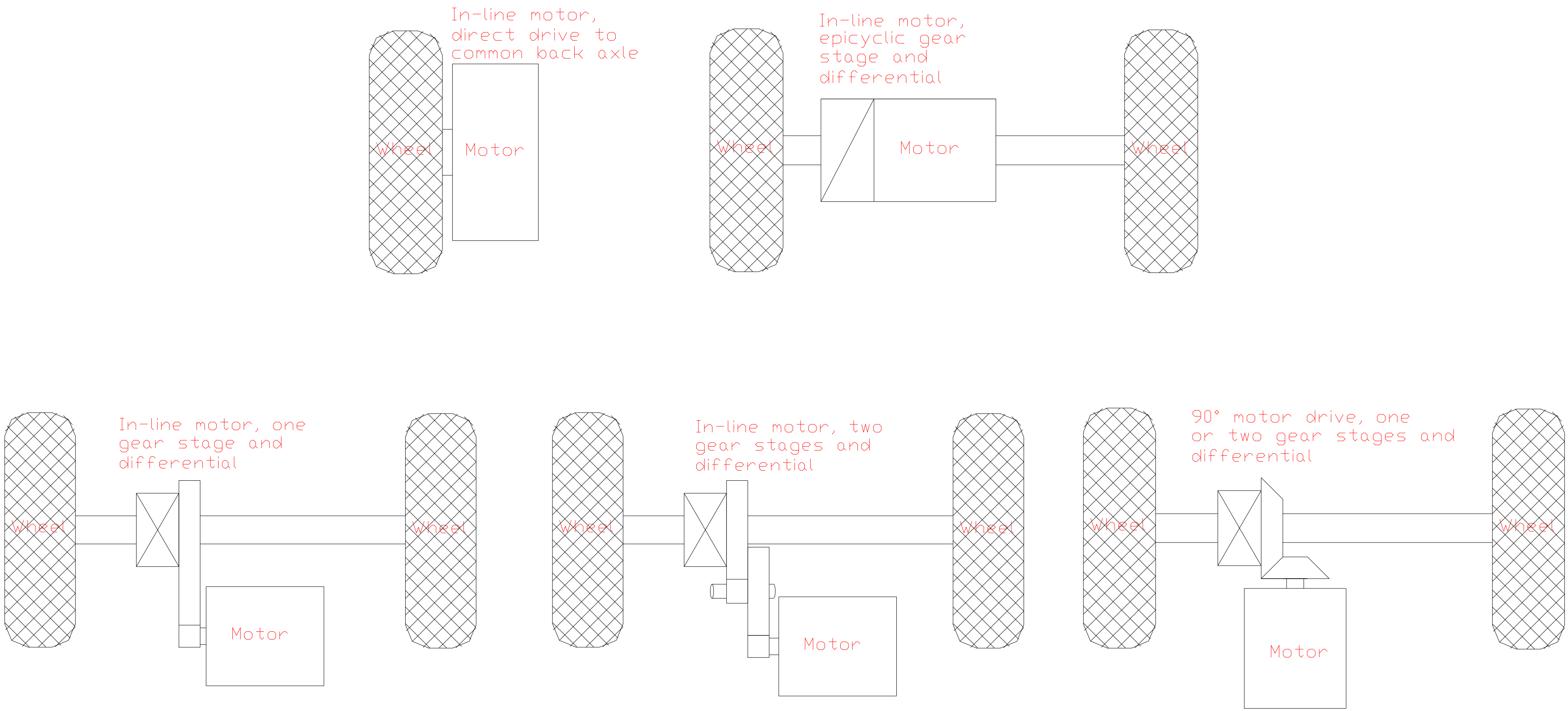


High windage loss and noise

Narrow high precision airgap

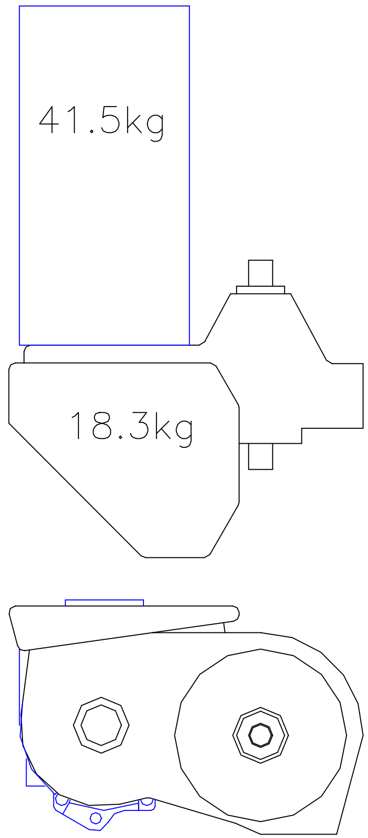


Traction motor, gear and differential configurations

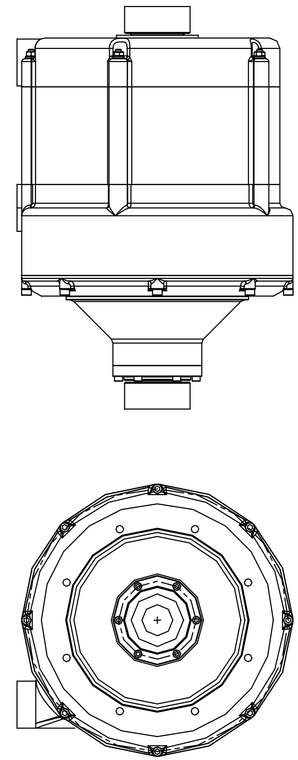


Prototype traction machine, gear-stage and differential

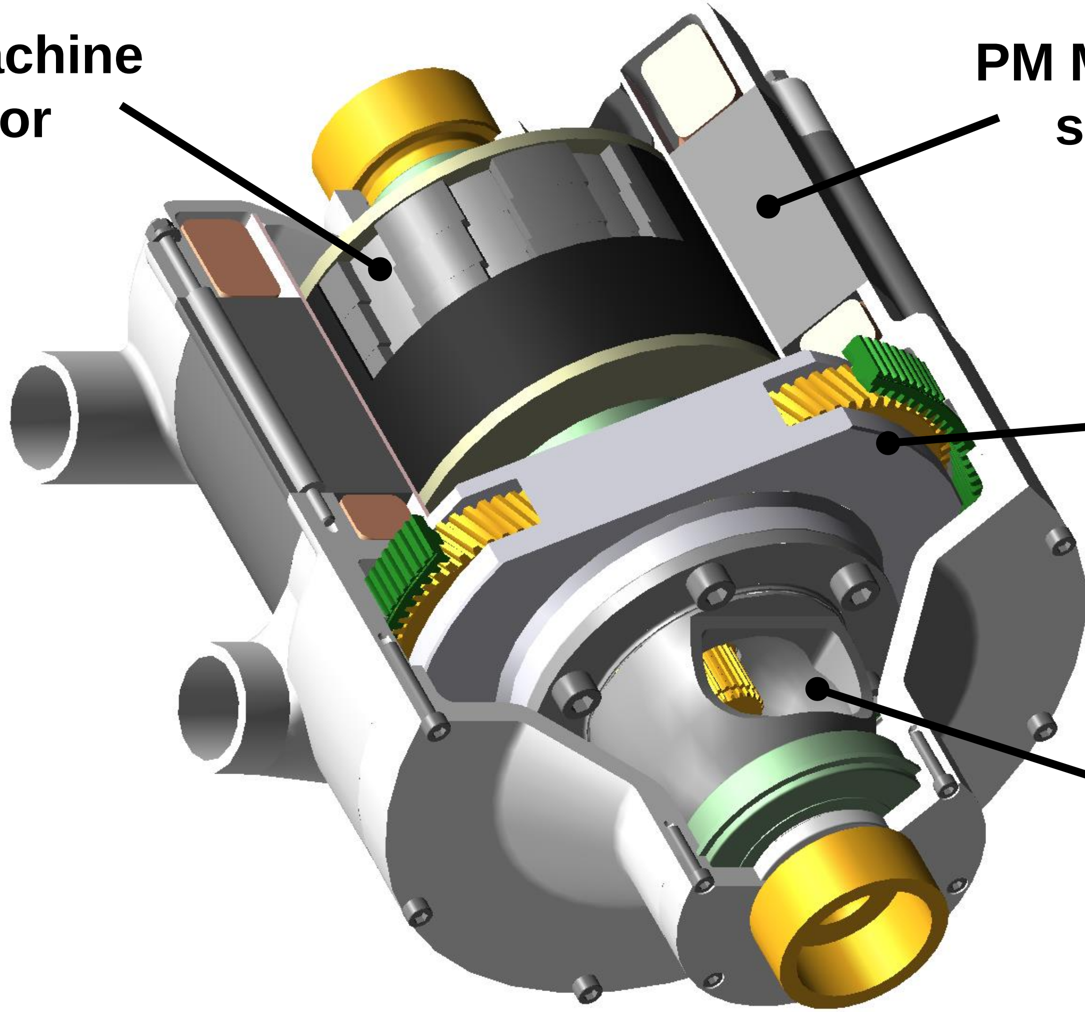
Total 59.8kg
Peak power = 0.51 kW/kg



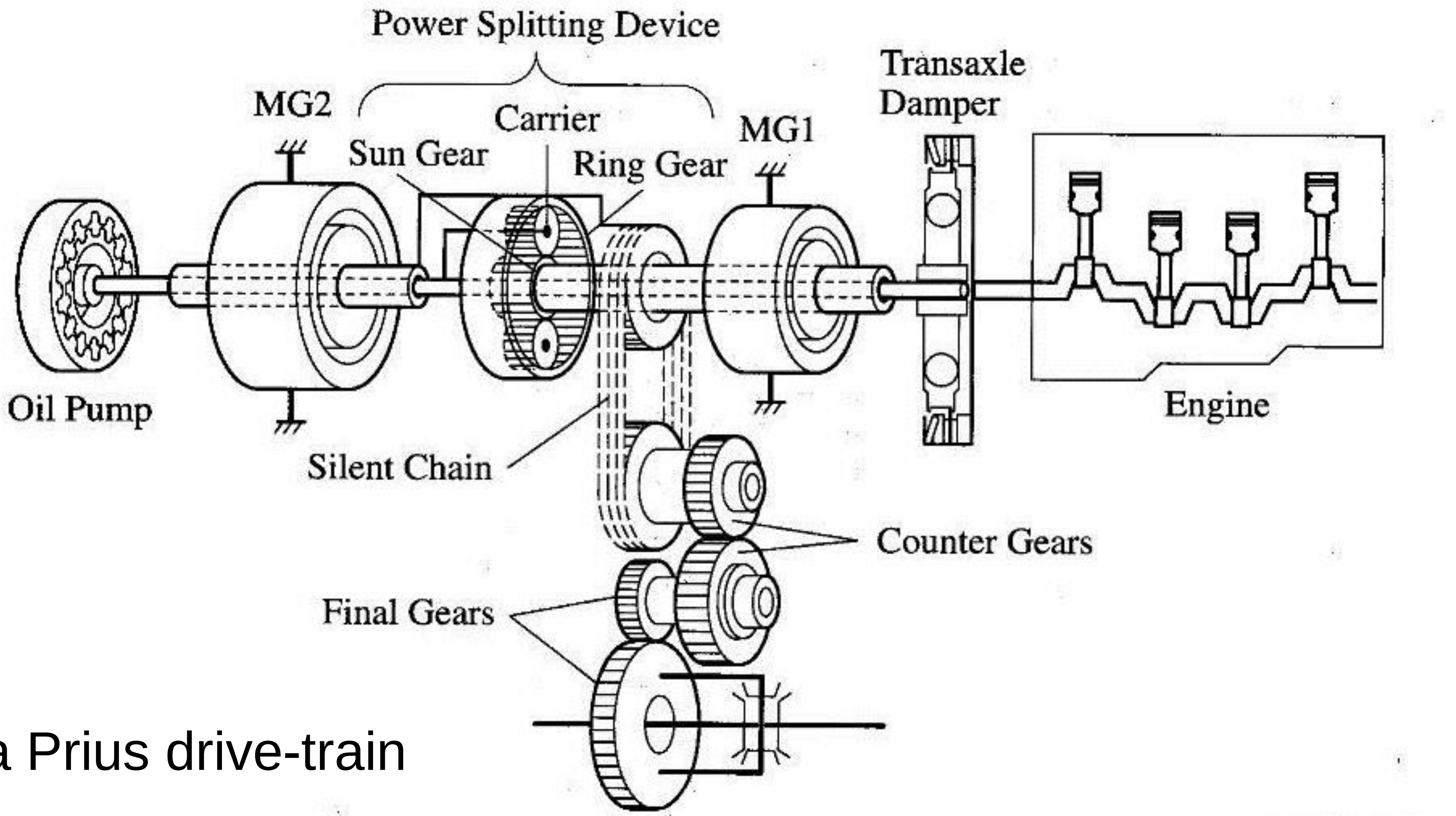
Total mass = 62.3kg
Peak power = 0.69 kW/kg



Traction motor, gear and differential integration



Toyota Prius drive-train



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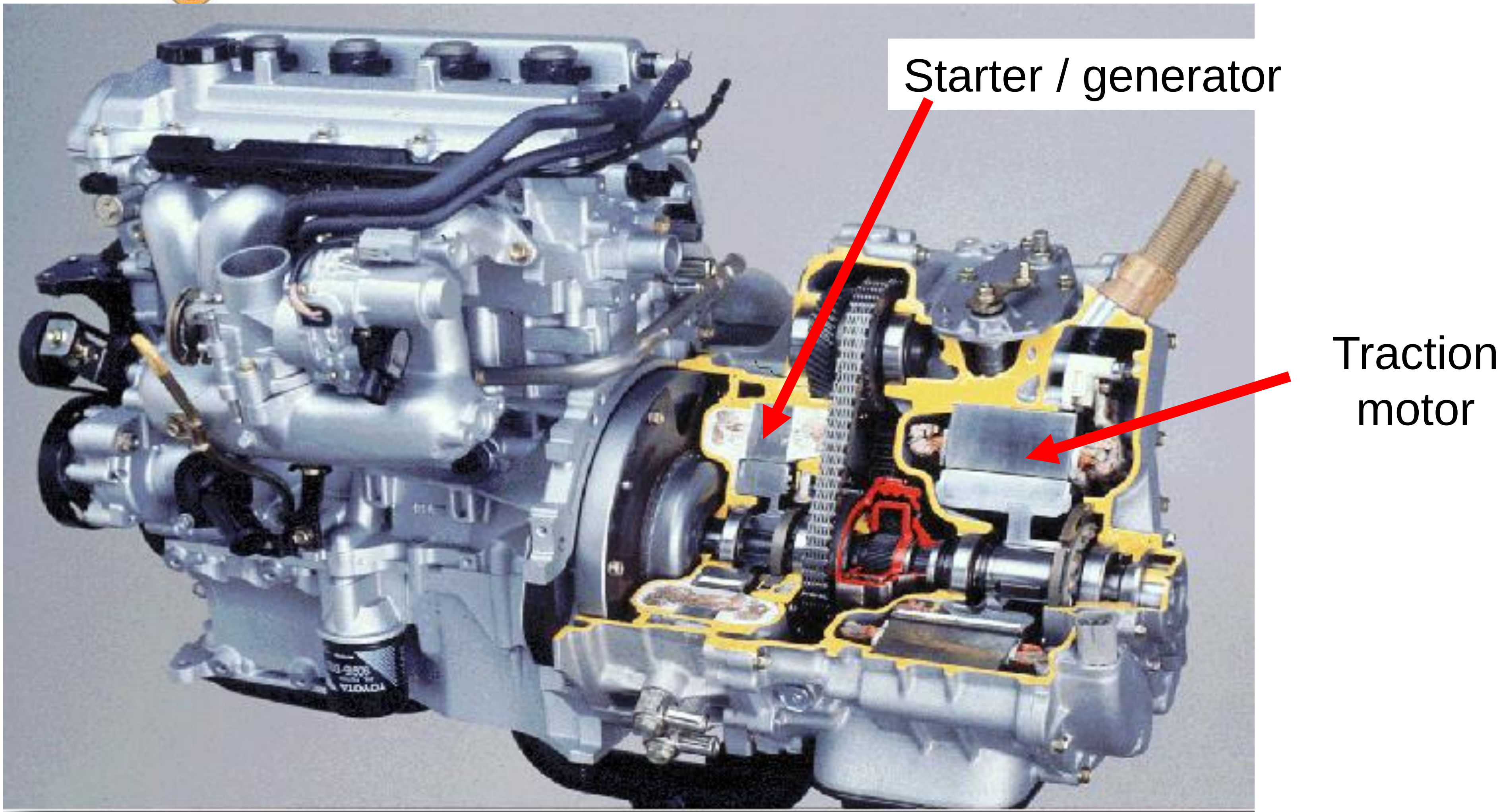
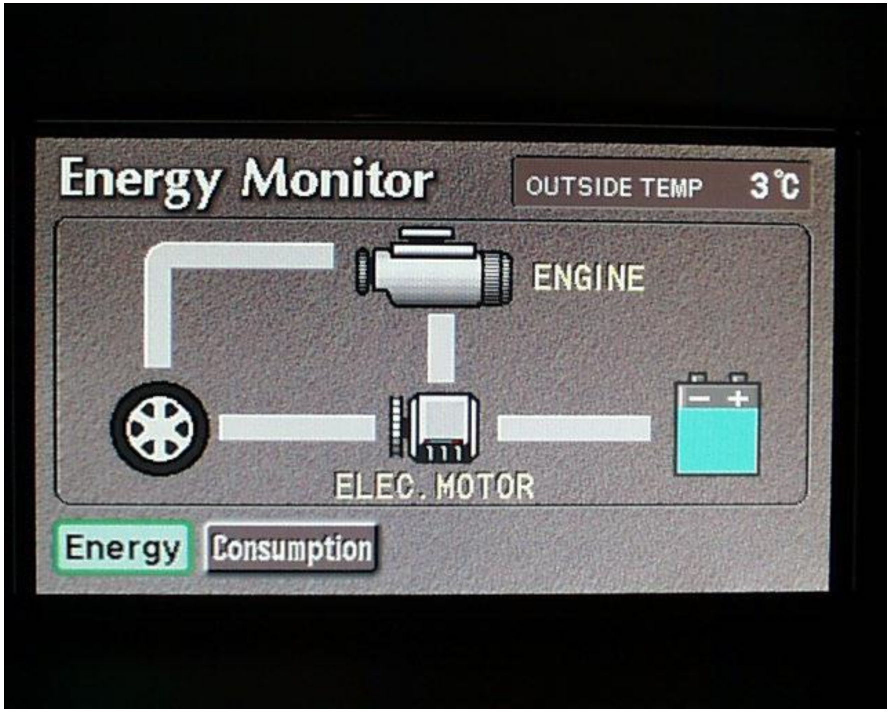
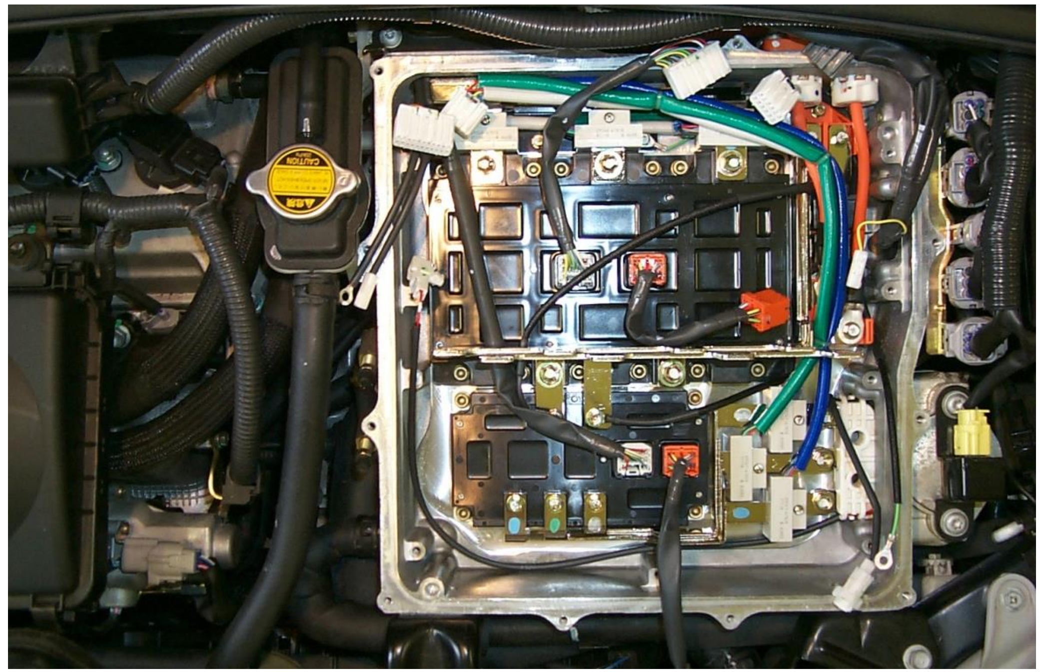


‘More electric’ vehicle power electronics and control



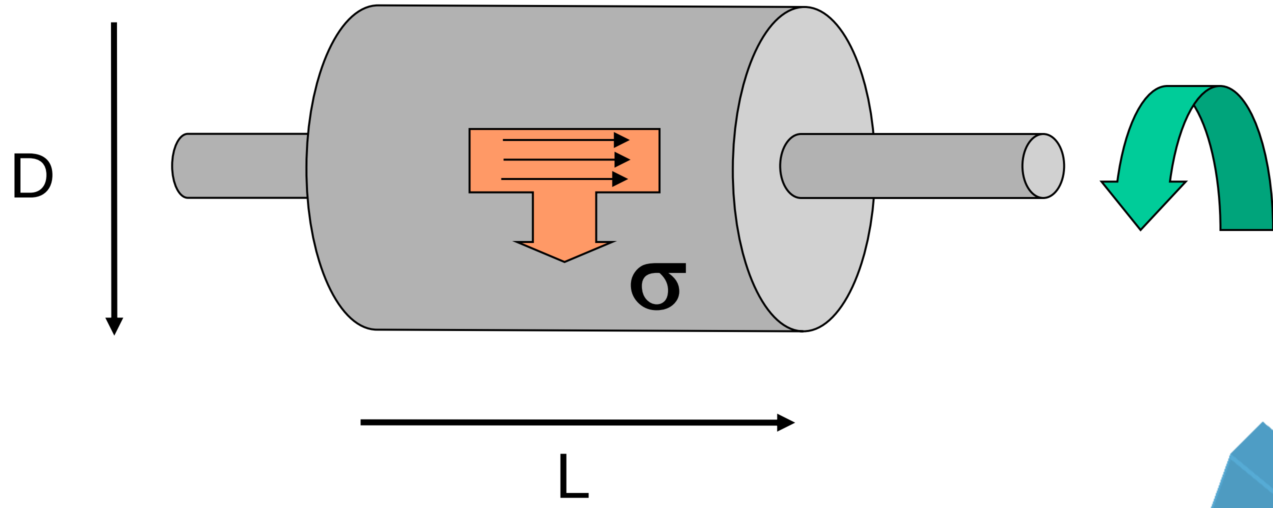
Toyota Prius :

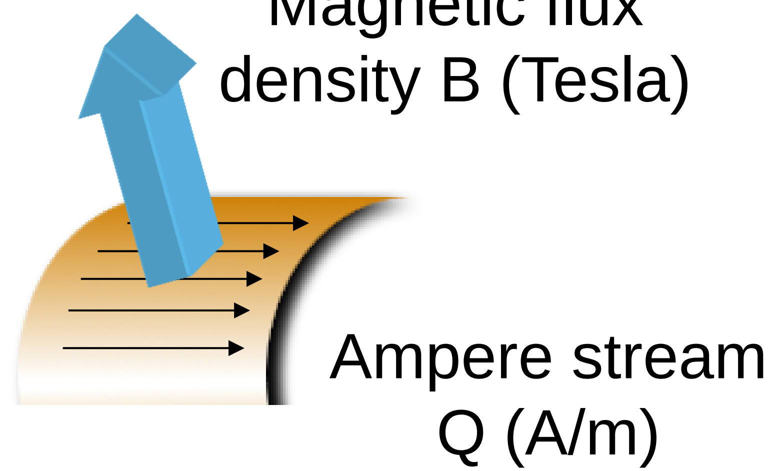
Integrated power electronics



Driver display screen

Torque generation in an electrical machine





Shear stress $\sigma = K_u B Q$

Torque generation in an electrical machine

Shear stress $\sigma = K_u B Q$

$\sigma \Rightarrow$ Output coefficient

Torque = $\pi/2 \, D^2 L \, K_u \, B \, Q$

Torque per unit rotor volume = 2σ

K_u factor which relates to the practical realisation of the magnetic field and current sheet

B average airgap flux density - limited by maximum working flux densities of stator/rotor iron and permanent magnets

Q electrical loading (total ampere stream per meter of airgap circumference) - limited thermally by ability to dissipate winding I^2R loss

Comparison of motor output coefficients

	K_U	B (T)	Q (A/m)	σ (kPa)
Brushed DC	1.0	0.7	20,000	14.0
Induction	0.81	0.57	32,000	14.7
Inverter fed IM	1.0	0.57	32,000	18.4
Synchronous	1.0	0.64	47,000	30.4
Brushless PM	0.94	0.9	50,000	42.3
Switched reluctance	1.29	0.3	50,000	19.4

Note: Q values assume forced air cooling of windings

Reference: J.G. West, IEE Power Division Colloquium on Motors and Drives for Battery Powered Propulsion, London, April 1993, Digest 1993/080

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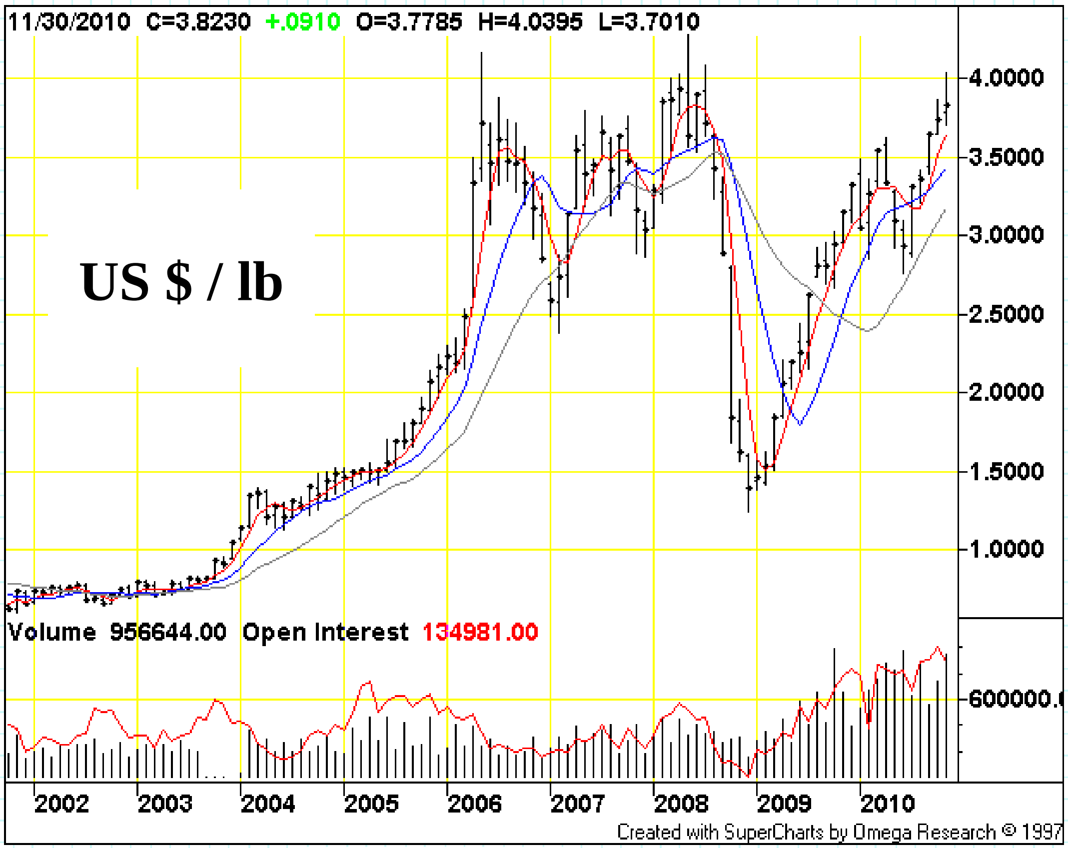
Research traction machine examples

Machine type	Induction		Brushless PM		Brushless PM
Cooling	Water jacket		Water jacket		Direct oil
Rated torque (Nm)	120		120		60
Max. Speed (rpm)	7,500		10,000		20,000
Rated power (kW)	25.8		46.2		75.4
Total mass (kg)	86		42		13
Specific output (kW/kg)	0.3		1.1		5.6
Specific torque (kNm/m^3)	12		30		81
Materials audit	kg	kg/kW	kg	kg/kW	
Silicon iron	59.24	2.296	32.31	0.70	
Copper	26.76	1.037	7.7	0.17	
NdFeB Magnets	-	-	2.7	0.06	

Other machine materials, copper :



Year

TFC Commodity Charts; http://tfc-charts.w2d.com/; 30-11-10

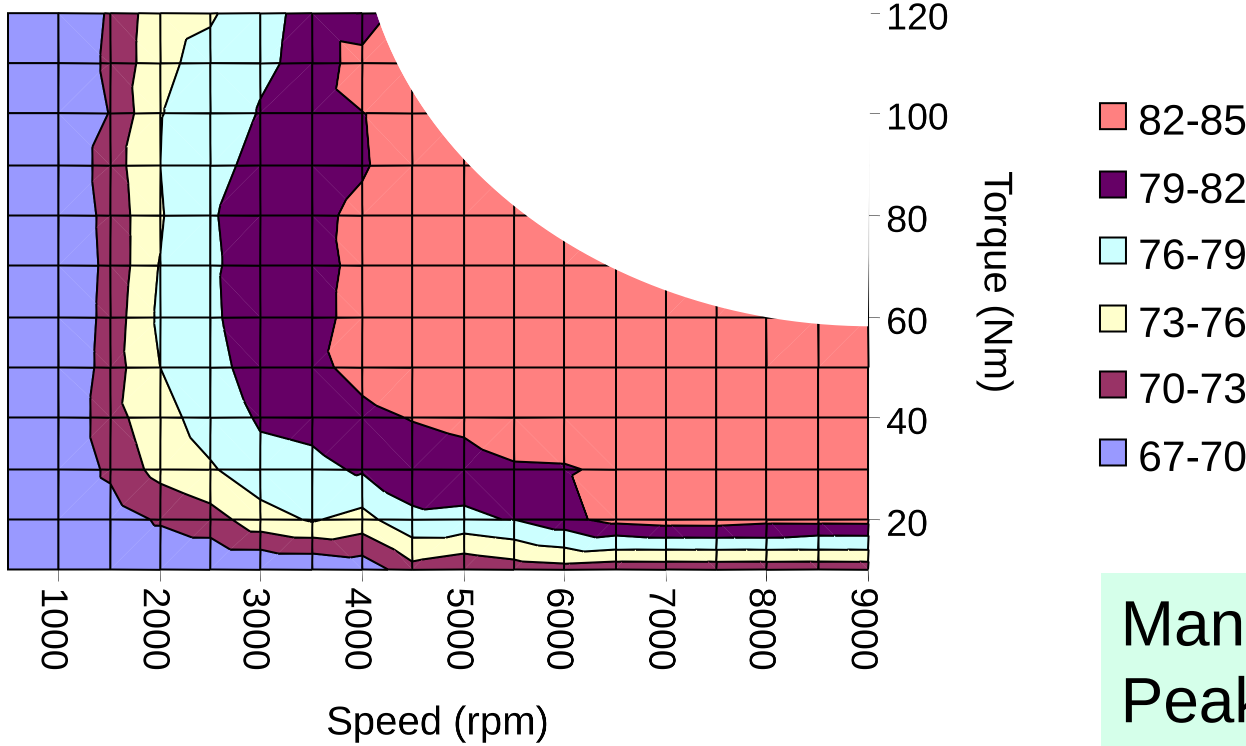
<u>Copper raw material cost</u>

1988 to 2002:

Average 1.0 $ / lb, (+1.4 / -0.72)

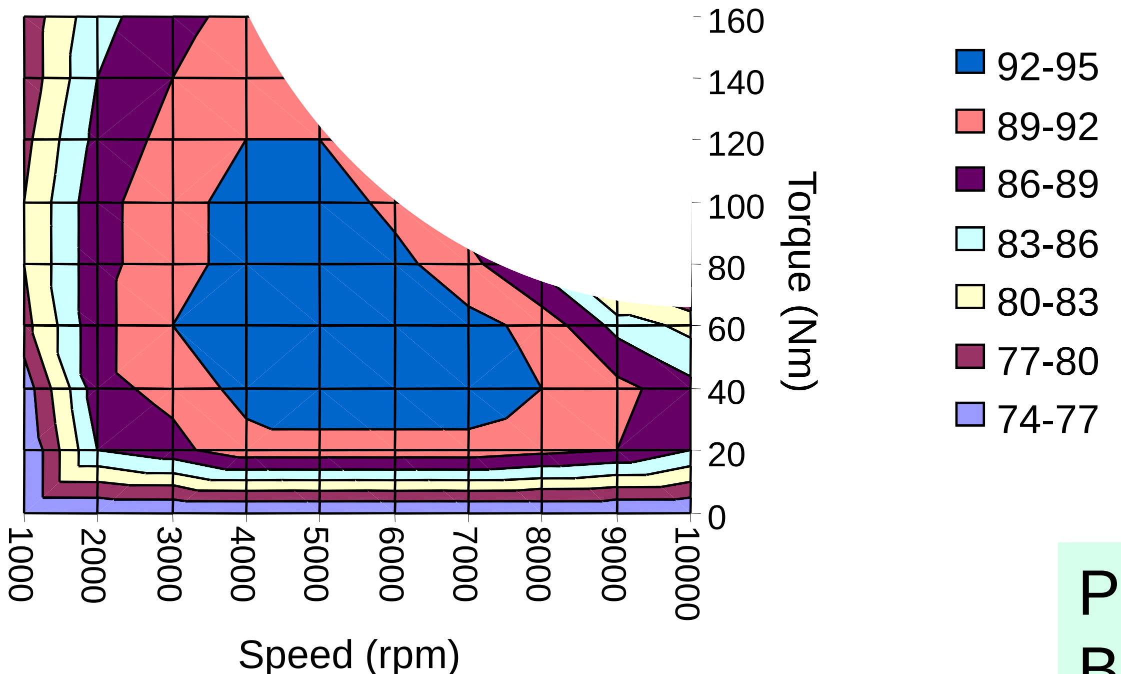
As well as machine mass and volume, material resource and cost impacted by move to lower grade PM's

Typical induction motor traction drive efficiency map



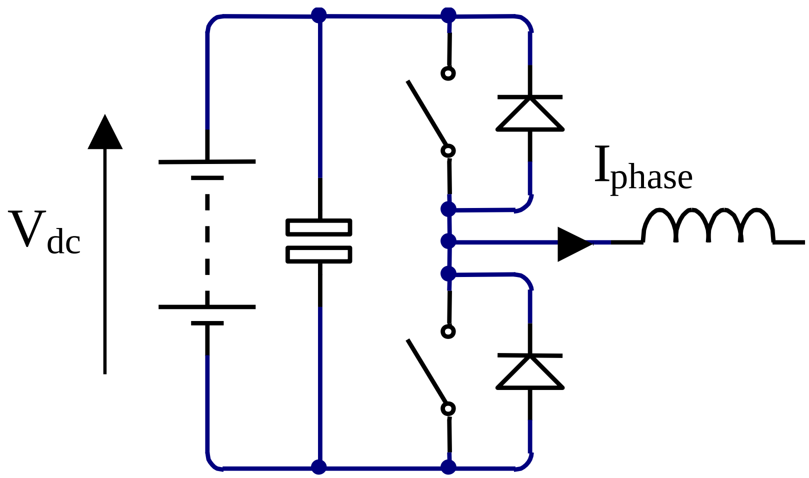
Manufacturer	Siemens
Peak torque	125 Nm
Base speed	4000 rpm
Max. speed	9000 rpm

Typical brushless PM traction drive efficiency map



Peak torque	180 Nm
Base speed	4000 rpm
Max. speed	10000 rpm

Terminal constraints on machine design imposed by the power electronic converter



Limited DC supply :
➔limitation of machine phase voltage

Converter components and thermal capability of the machine:
➔limitation of phase current during continuous operation (nominal current)
➔limitation of phase current during intermittent operation (peak current)

For traction machine design

2 operating points to satisfy:

- **Torque at peak acceleration, and**
- **Maximum power.**

But, within the converter supply constraints, there are only 2 variables that influence Torque and Power:

- **Phase rms emf coefficient (λ_o) or**
- **Phase inductance (L_d).**

Design considerations:

- **Supply constraints yield $P_{e(max)}$,**
- **Limit on rms phase voltage, V_s**
- **Limit on peak phase current, I_q**

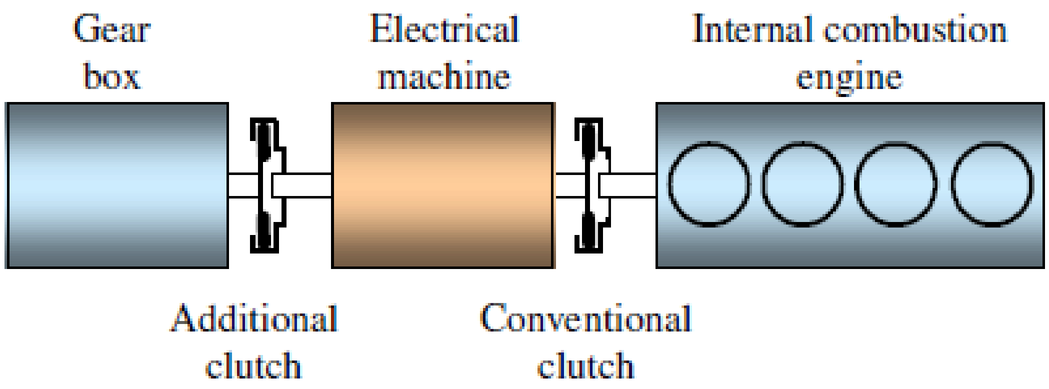
$$T_e = 3 p \lambda_o I_q$$

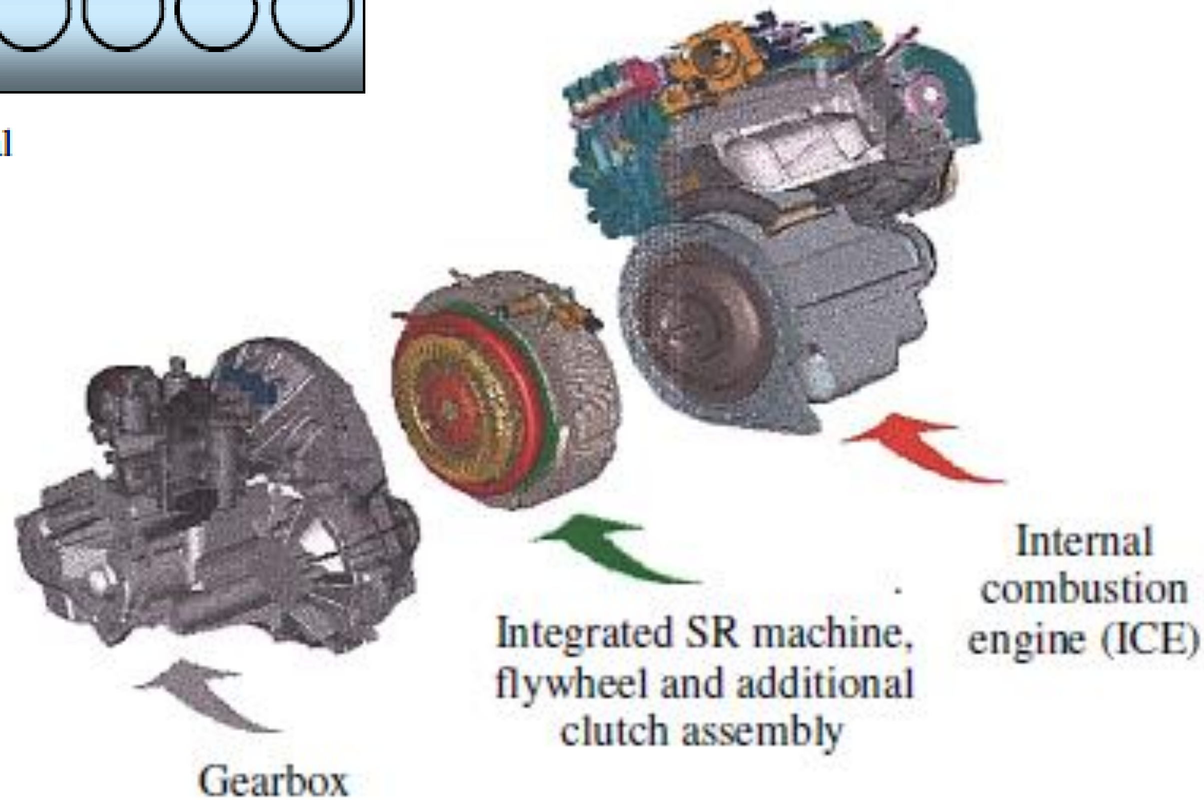
Torque consideration

$$P_e = \frac{V_s \lambda_o}{L_d} \sin(\delta)$$

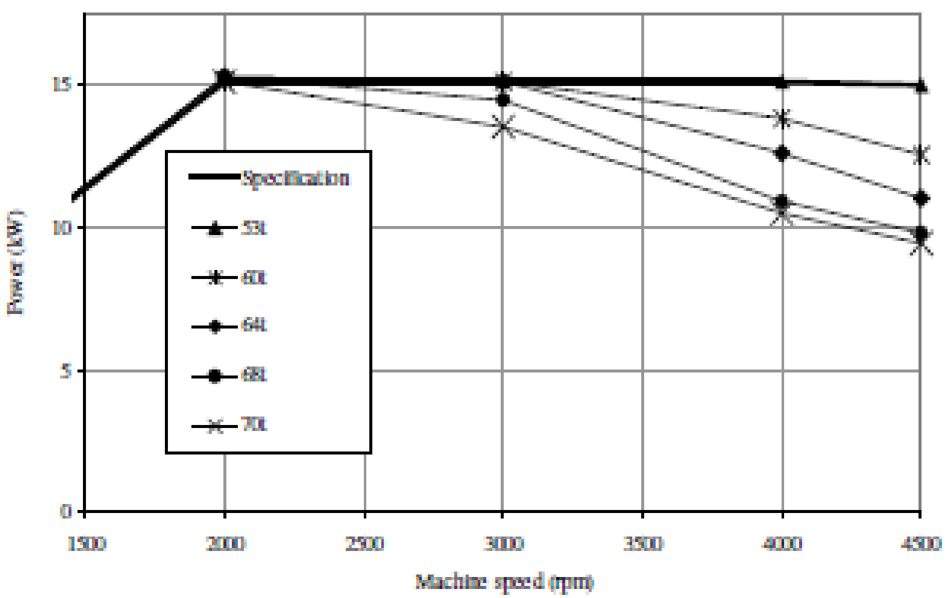
Power consideration

Minimal hybrid-electric power-train concept





Generator winding optimisation for extended speed



Power versus speed capability as a function of turns per stator pole

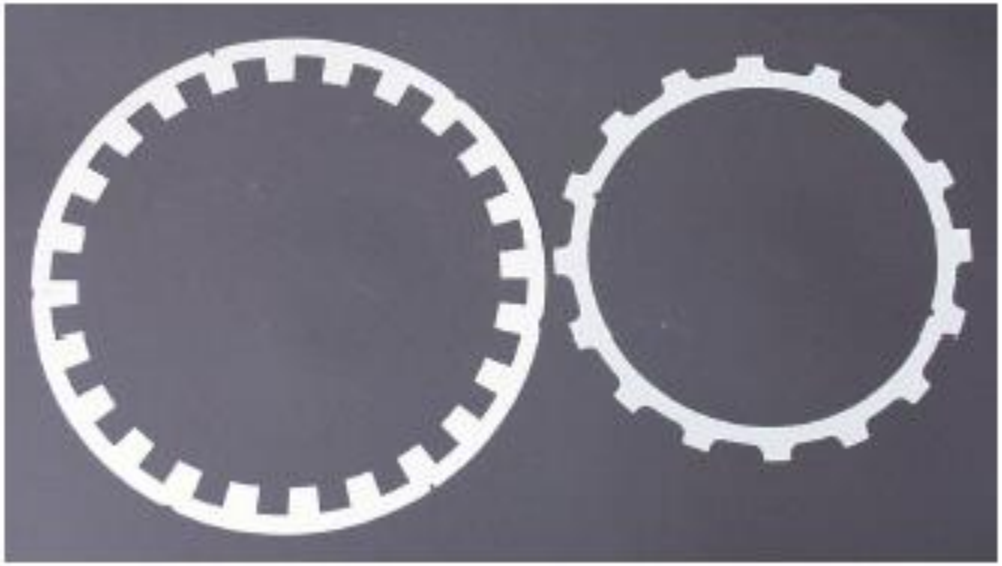
Table V. Summary of machine phase currents and system efficiency with speed for discontinuous and continuous current

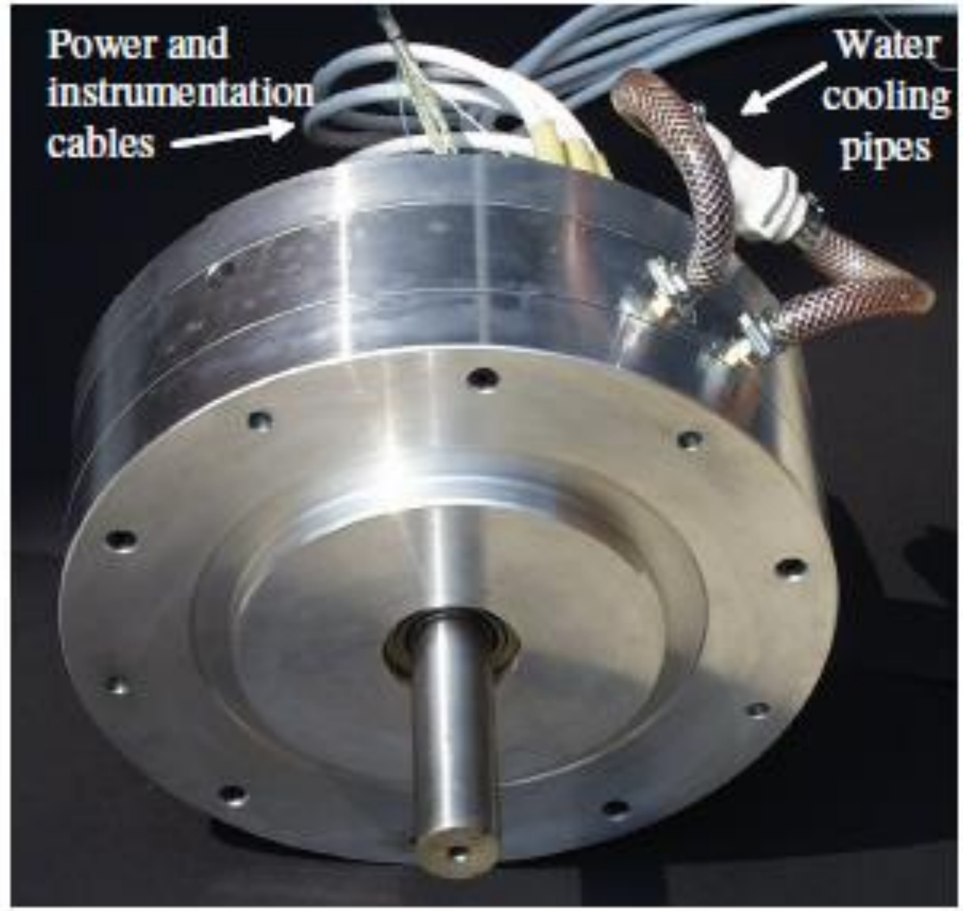
RPM		Turns per stator pole				
		53	60	64	68	70
2000	I_{pk} (A)	231.95	230.56	218.66	214.78	206.31
	I_{rms} (A)	130.16	122.1	117.44	115.12	111.65
	η_{sys} (%)	88.58	88.32	89.00	89.37	89.61
	η_{sys} (%)			89.4#		
3000	I_{pk} (A)	240.19	211.2	210.40	197.09*	194.25*
	I_{rms} (A)	119.62	109.22	109.45	104.85*	104.13*
	η_{sys} (%)	90.16	89.94	90.08	90.53*	90.60*
	η_{sys} (%)			89.9#		
4000	I_{pk} (A)	214.79	199.67*	191.88*	187.27*	186.77*
	I_{rms} (A)	109.37	104.8*	103.02*	102.28*	102.67*
	η_{sys} (%)	90.08	90.51*	90.68*	90.76*	90.82*
	η_{sys} (%)			88.8#		
4500	I_{pk} (A)	221.83	201.26*	192.8*	194.2*	154.24*
	I_{rms} (A)	113.54	106.79*	105.68*	109.47*	81.82*
	η_{sys} (%)	91.02	90.51*	90.08*	88.59*	92.00*
	η_{sys} (%)			89.0#		

*Achieved with continuous current operation

Measured data

Ref.: [1] Schofield et al.




Power and
instrumentation
cables
Water
cooling
pipes

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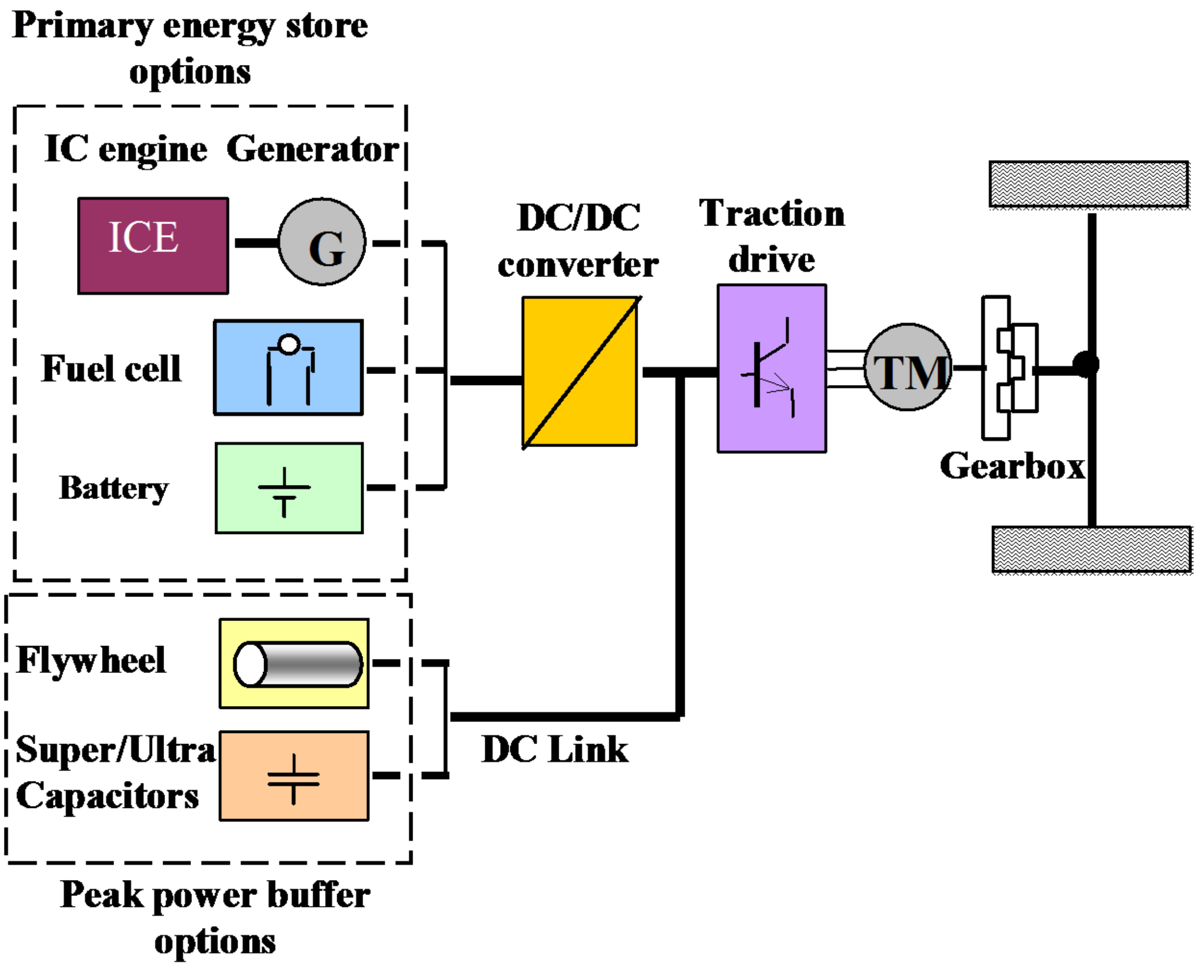
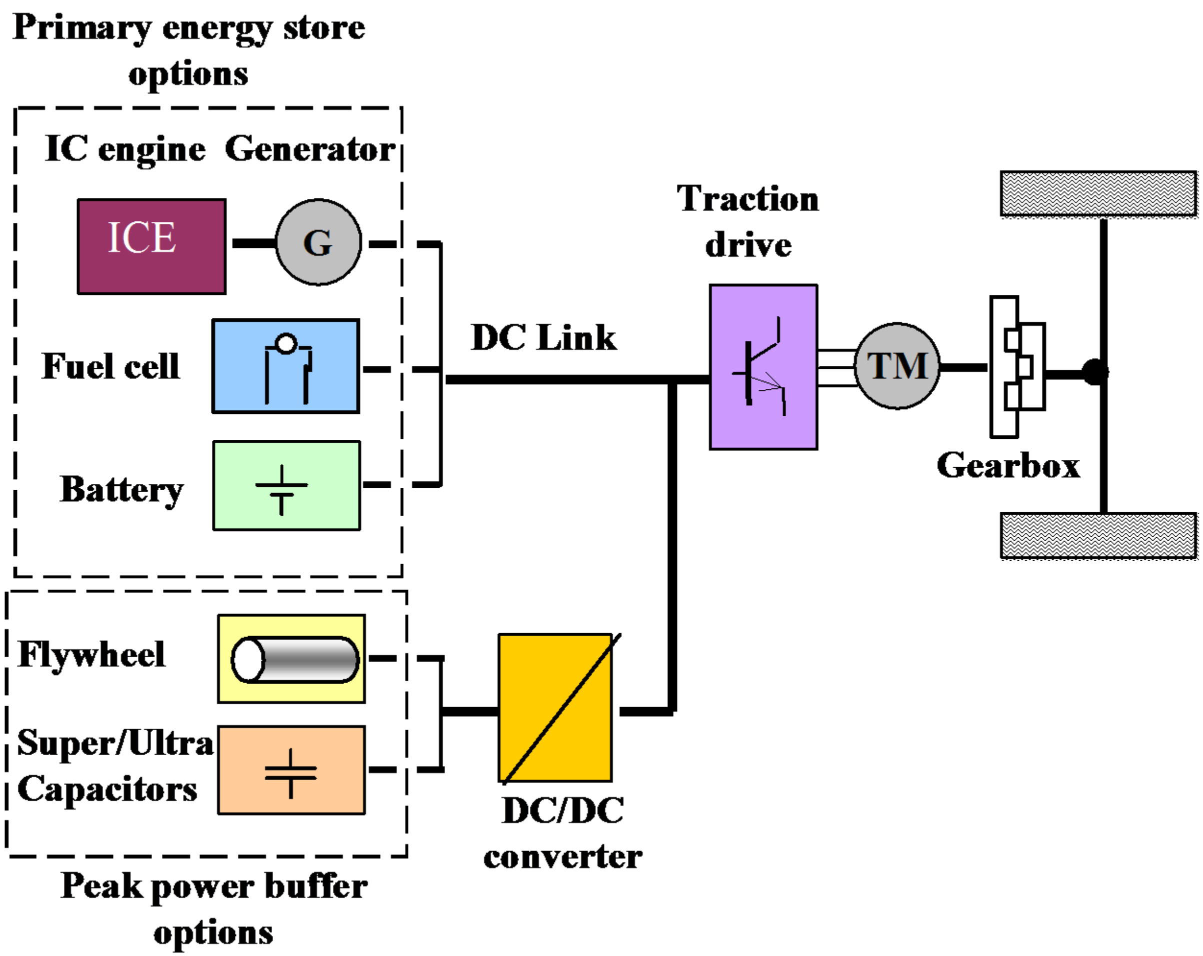
Power train connection schemes



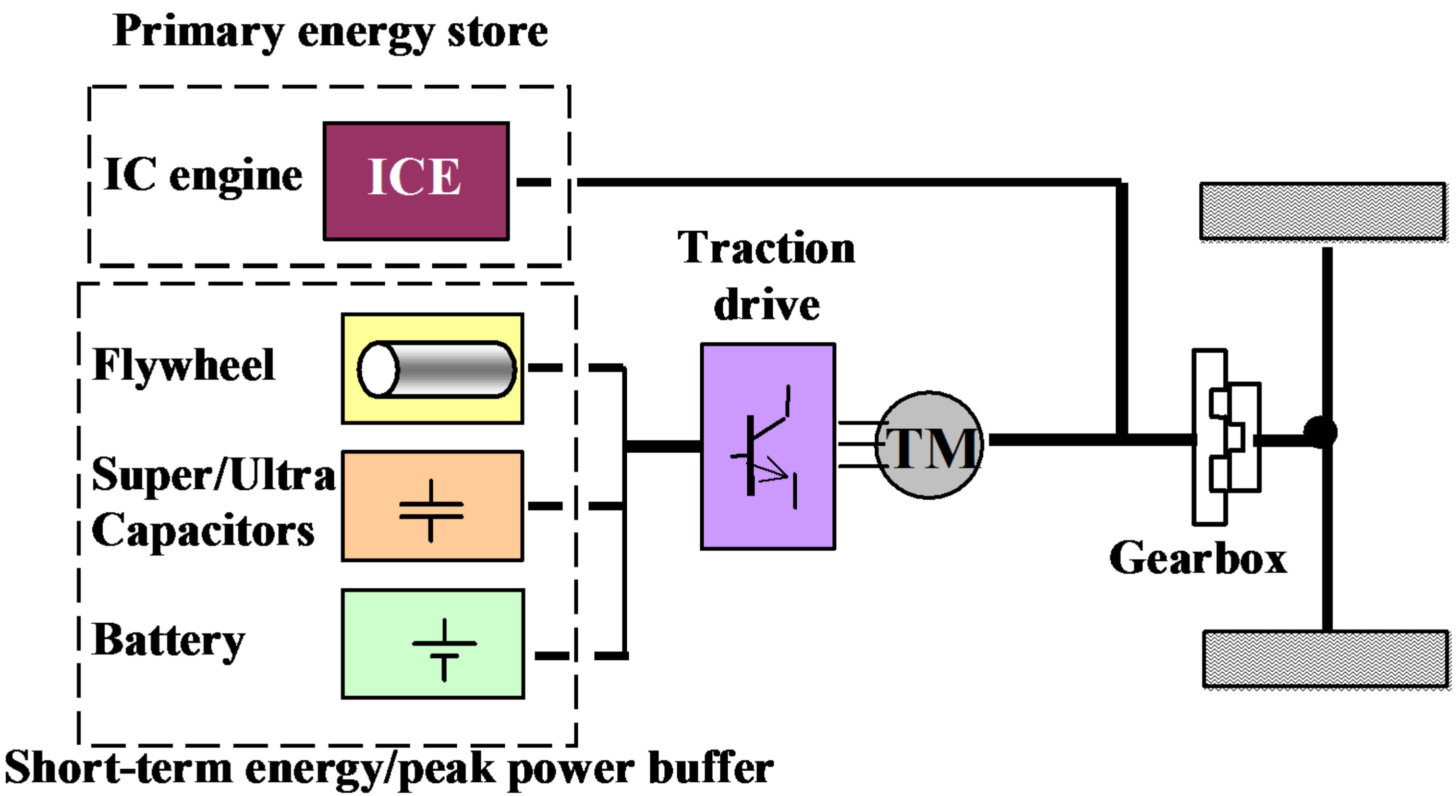
Series; dc-dc converter interfaces energy source to dc-link

Power train connection schemes



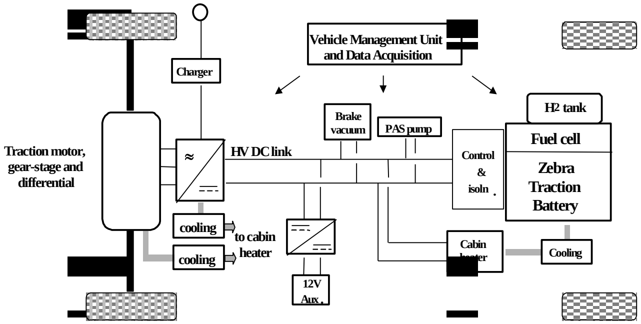
Series; dc-dc converter interfaces peak power buffer to dc-link

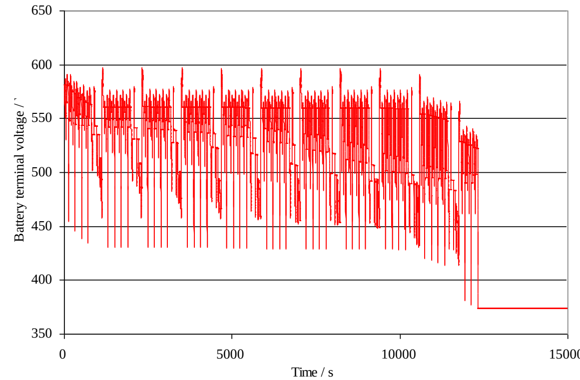
Power train connection schemes

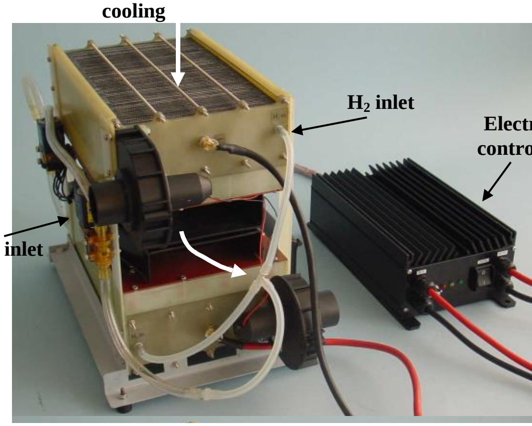


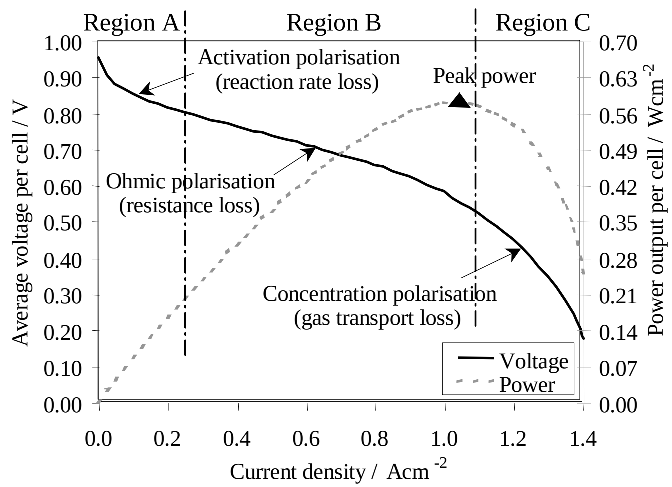
Parallel; electrical system facilitates power buffer

Example electric vehicle: 550-750Vdc traction system



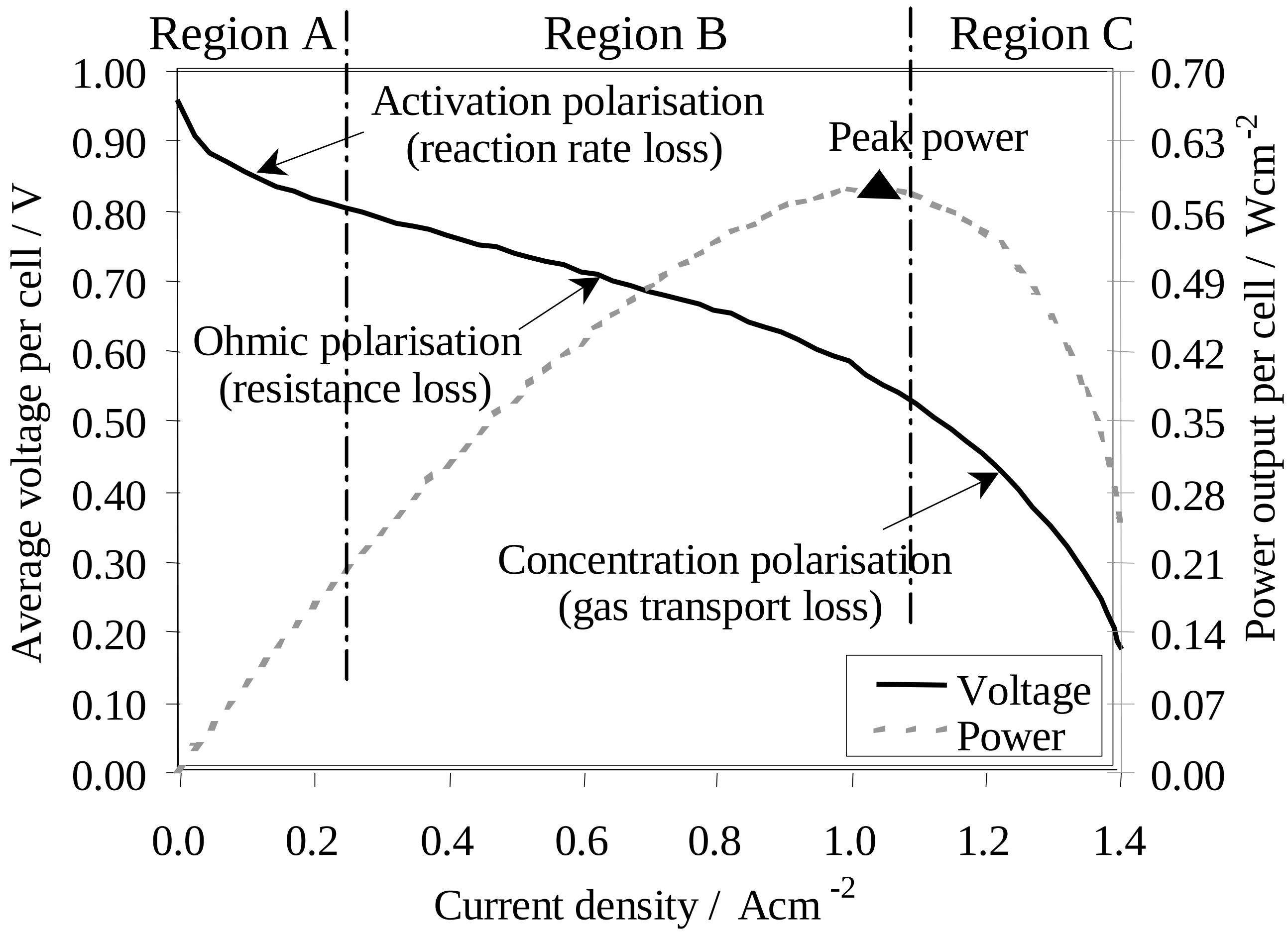






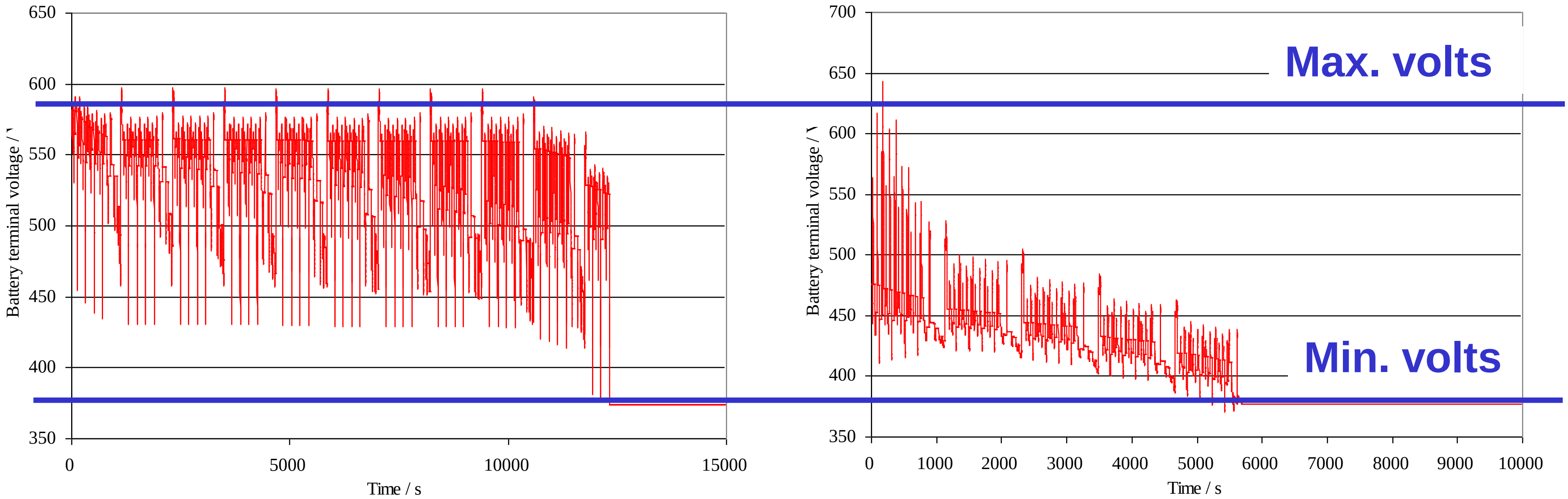
Ref.: [2] Schofield et al.

Fuel cell performance issues



Taxi performance evaluation

Battery terminal voltage with time :

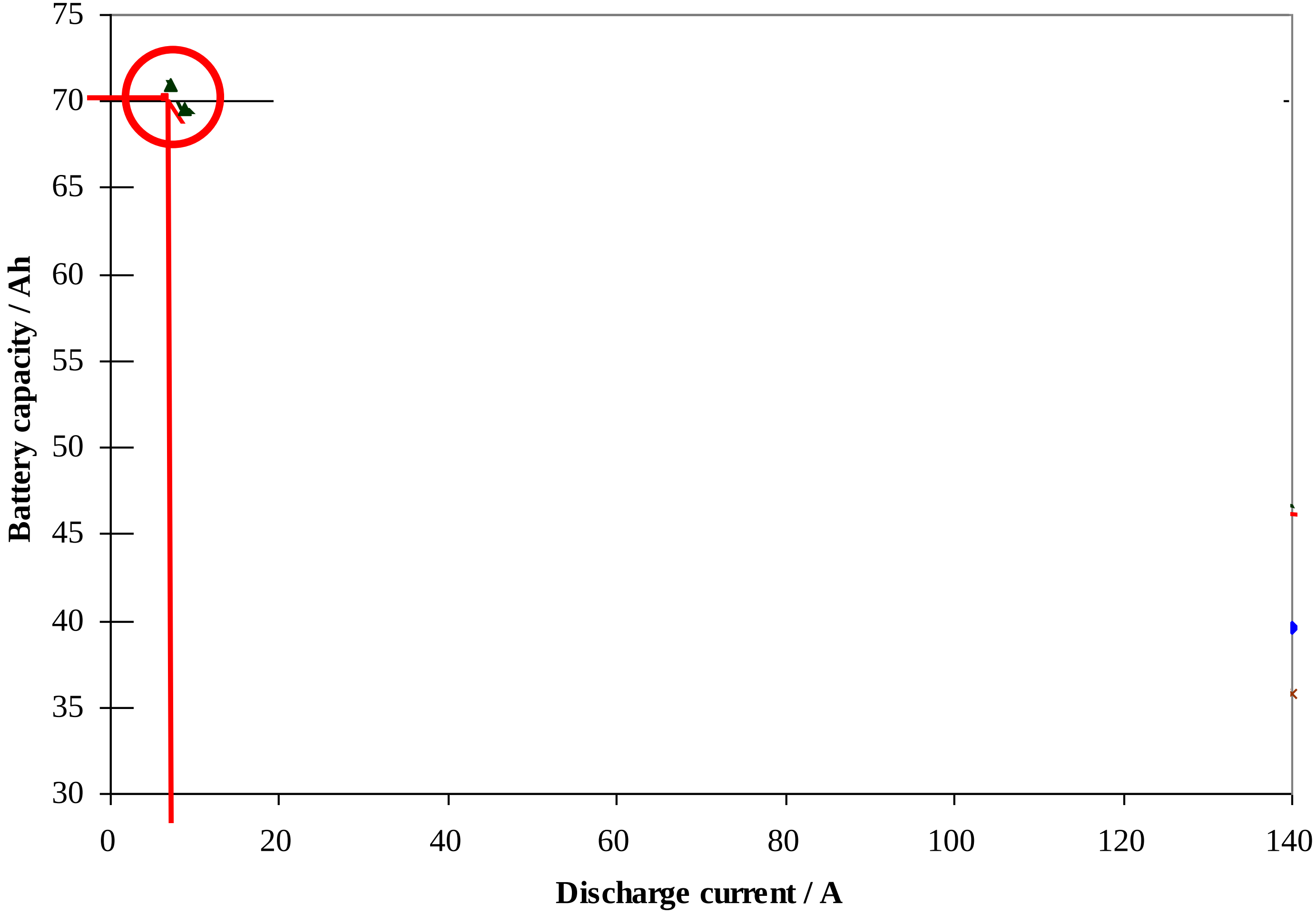


Zebra

Sealed lead-acid

Lead-acid battery performance issues

Peukert data for a Hawker 12V, 70Ah sealed lead-acid battery



Lead-acid battery performance issues

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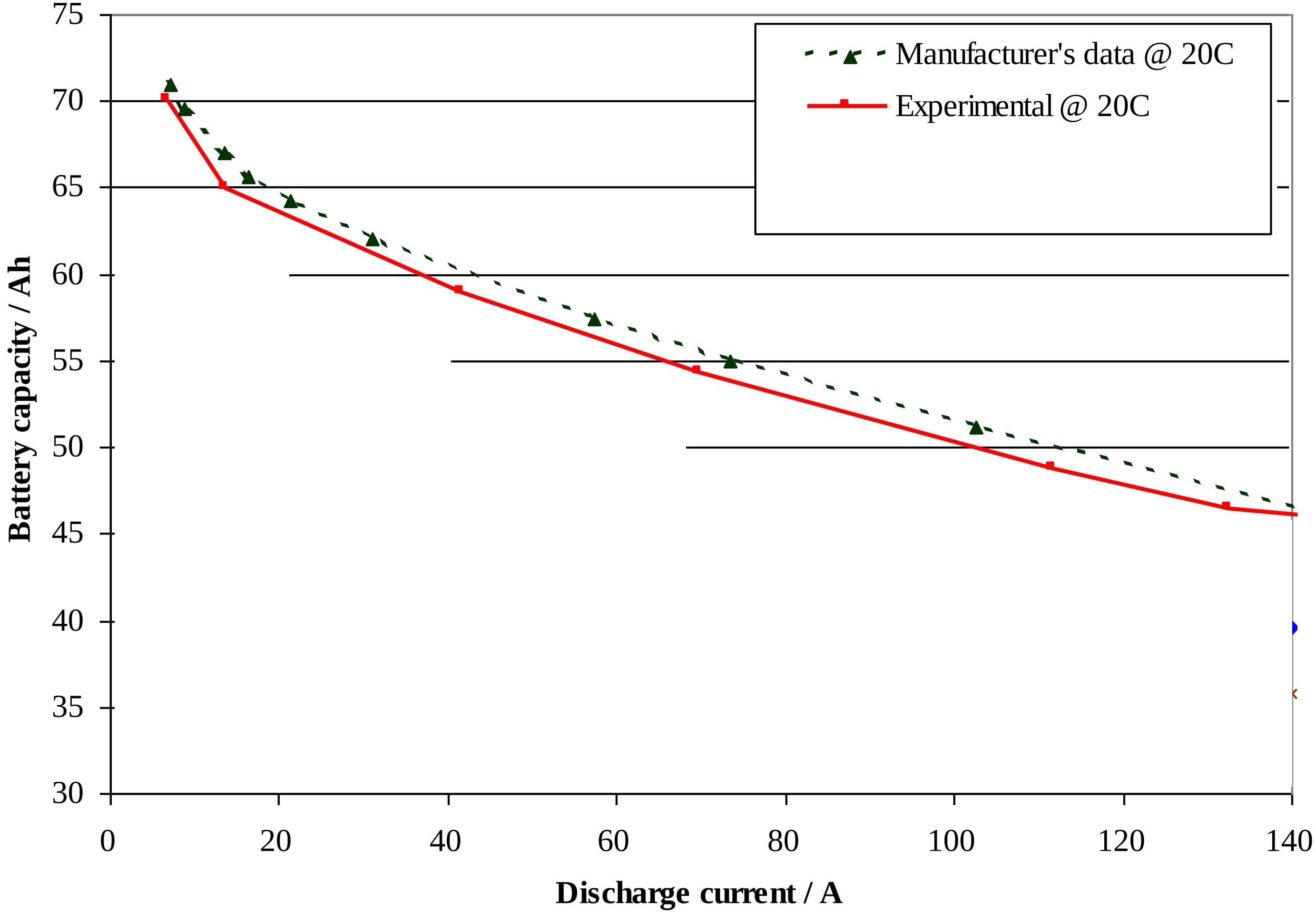
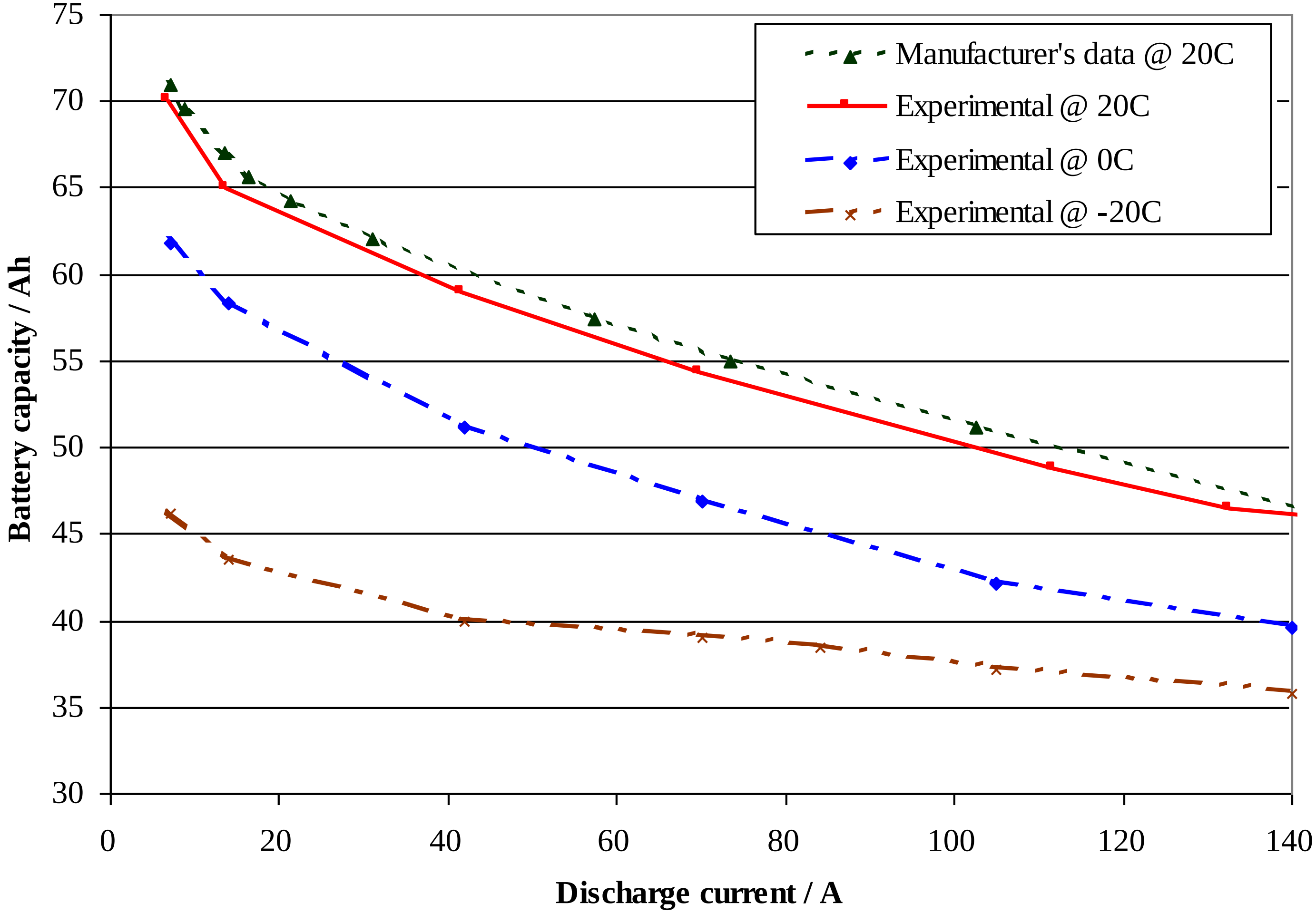


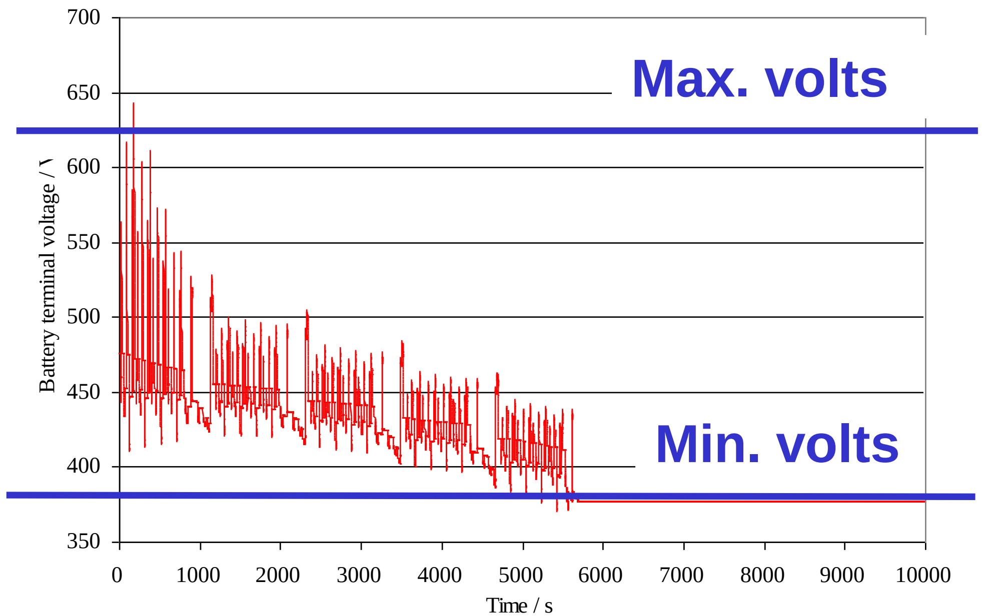
Lead-acid battery performance issues

Peukert data for a Hawker 12V, 70Ah sealed lead-acid battery



Battery State-of-Charge

Battery terminal voltage with time :



Sealed lead-acid

Traction battery

ZEBRA Z5C Traction battery

TABLE III ZEBRA Z5C BATTERY DATA

Type	Zebra Z5C
Capacity	66Ah
Rated energy	17.8kWh
Open circuit voltage	278.6V
Max. regen voltage	335V
Max. charging voltage	308V
Min. voltage	186V
Max. discharge current	224A
Weight	195kg
Specific energy	91.2Wh/kg
Specific power	164W/kg
Peak power	32kW
Thermal Loss	<120W
Cooling	Air
Battery internal temperature	270 to 350°C
Ambient temperature	-40 to +70°C
Dimensions (WxLxH)	533 x 833 x 300 mm
Number of cells per battery	216
Cell configuration	2 parallel strings of 108 series cells

ZEBRA Z5C Traction battery

Contactor and fuse unit

CAN 2b interface to vehicle management unit (VMU)

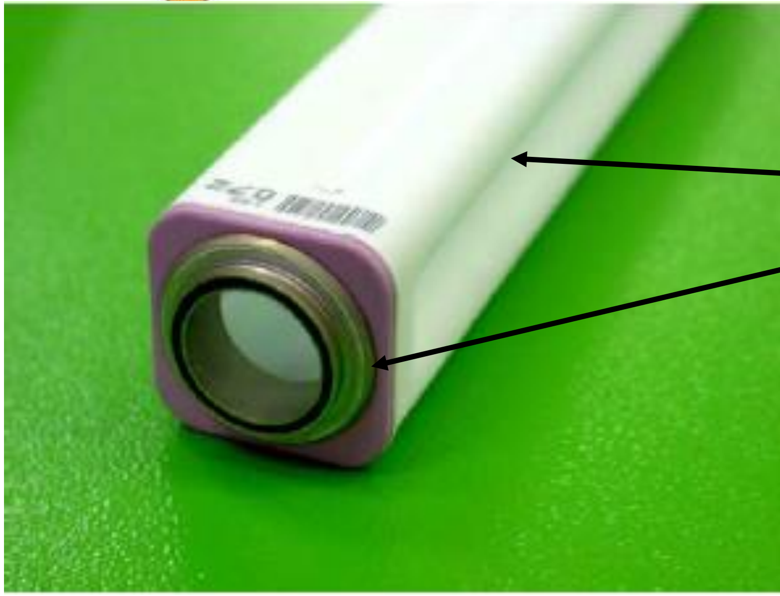
Battery management unit (BMU)

Forced air ventilation

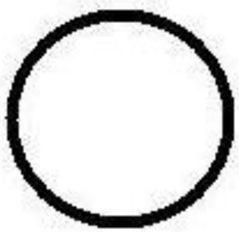
TABLE III ZEBRA Z5C BATTERY DATA

Type	Zebra Z5C
Capacity	66Ah
Rated energy	17.8kWh
Open circuit voltage	278.6V
Max. regen voltage	335V
Max. charging voltage	308V
Min. voltage	186V
Max. discharge current	224A
Weight	195kg
Specific energy	91.2Wh/kg
Specific power	164W/kg
Peak power	32kW
Thermal Loss	<120W
Cooling	Air
Battery internal temperature	270 to 350°C
Ambient temperature	-40 to +70°C
Dimensions (WxLxH)	533 x 833 x 300 mm
Number of cells per battery	216
Cell configuration	2 parallel strings of 108 series cells

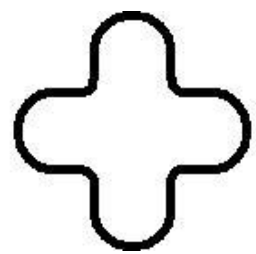
ZEBRA battery, Beta-alumina cells



Beta alumina ceramic tube with compression bond seal.



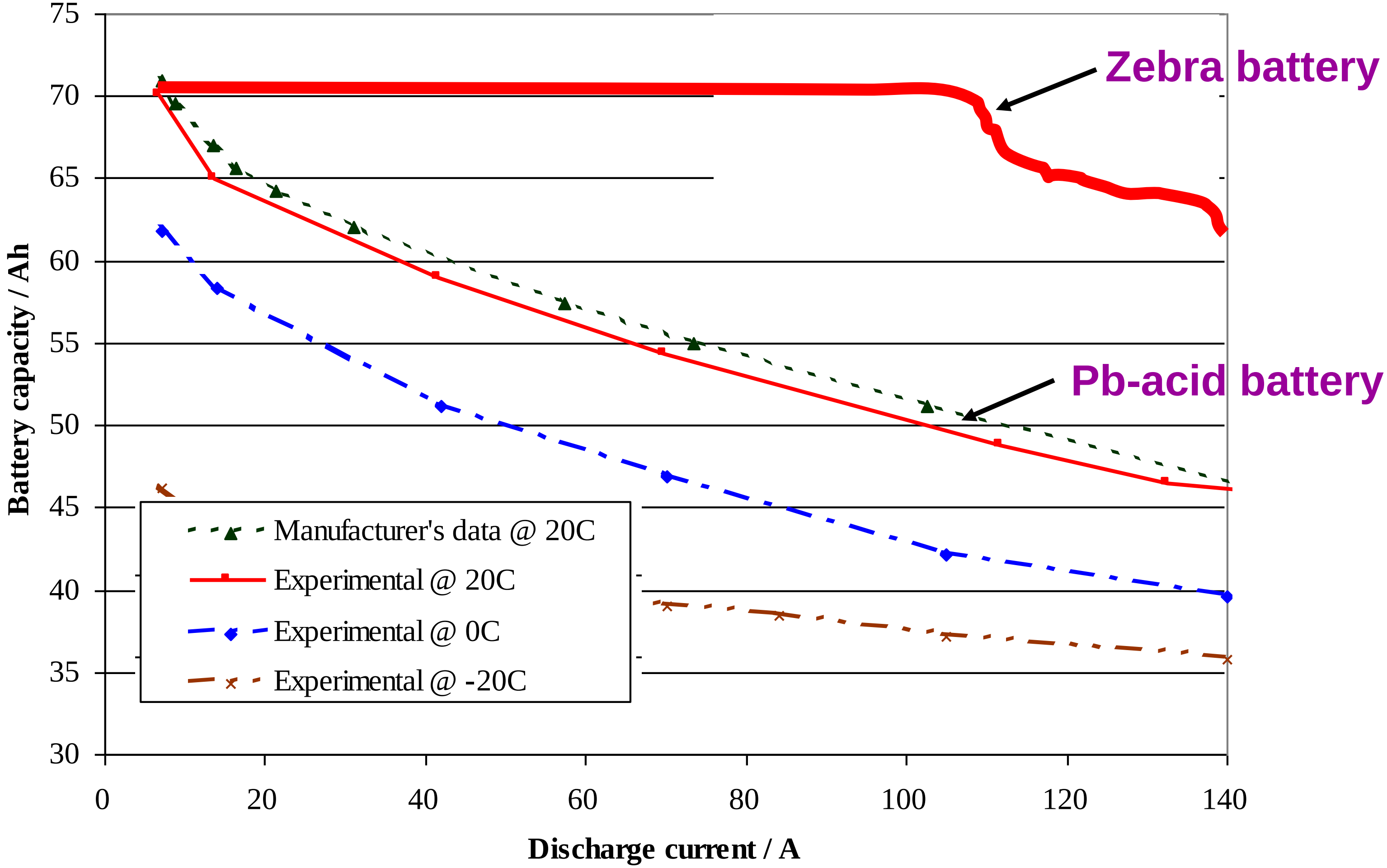
Circular or ‘slim line’ cross-section.



Cloverleaf or ‘monolith’ cross-section.

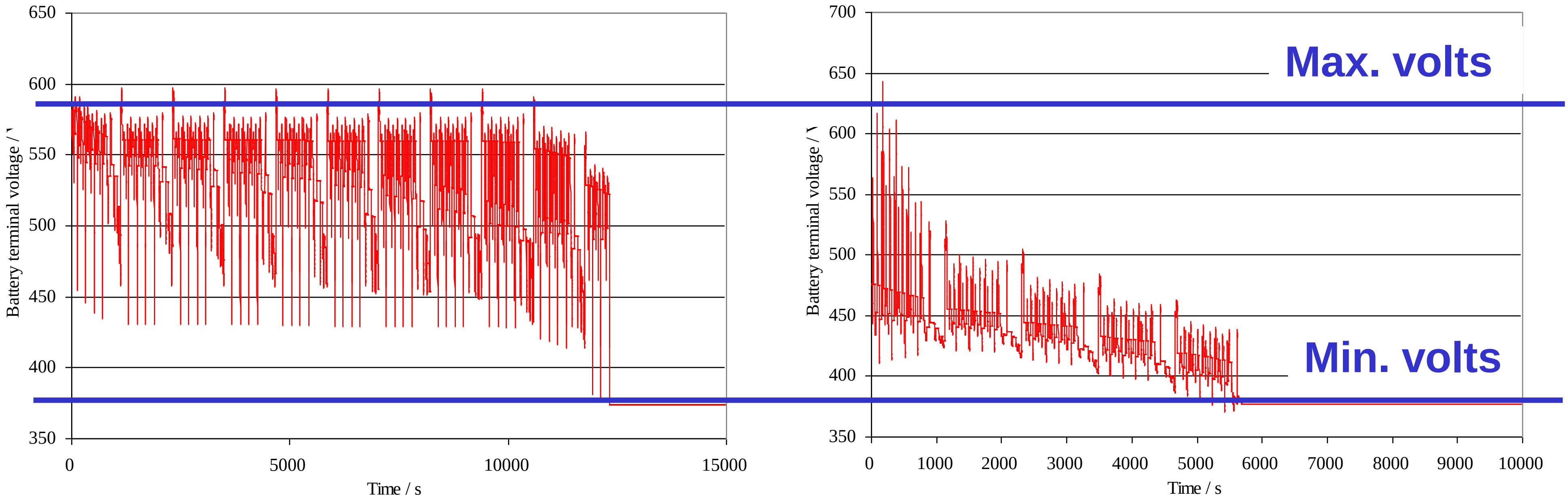
Battery performance issues

Peukert data for a Hawker and Zebra batteries



Taxi performance evaluation

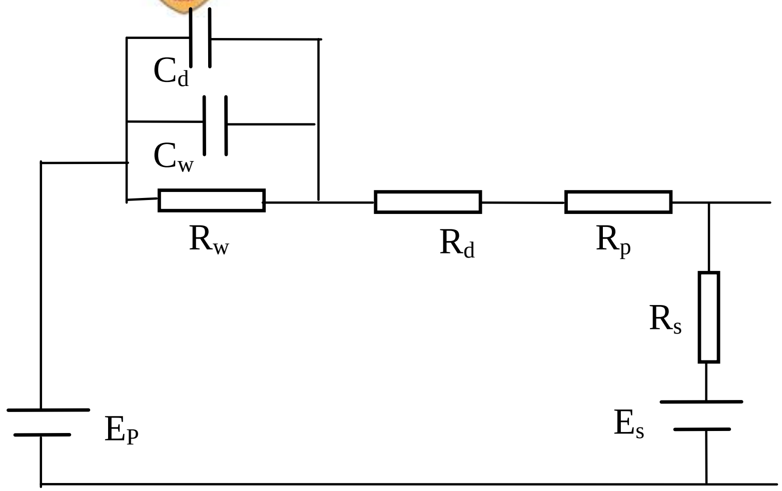
Battery terminal voltage with time :

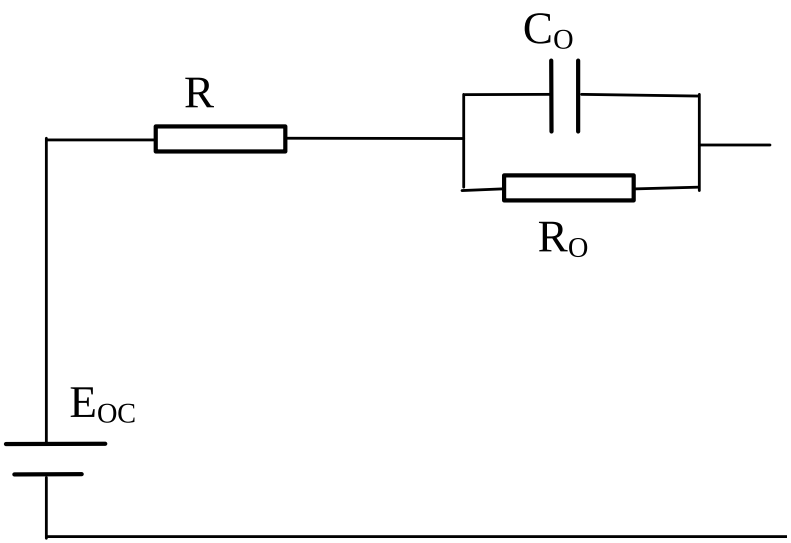


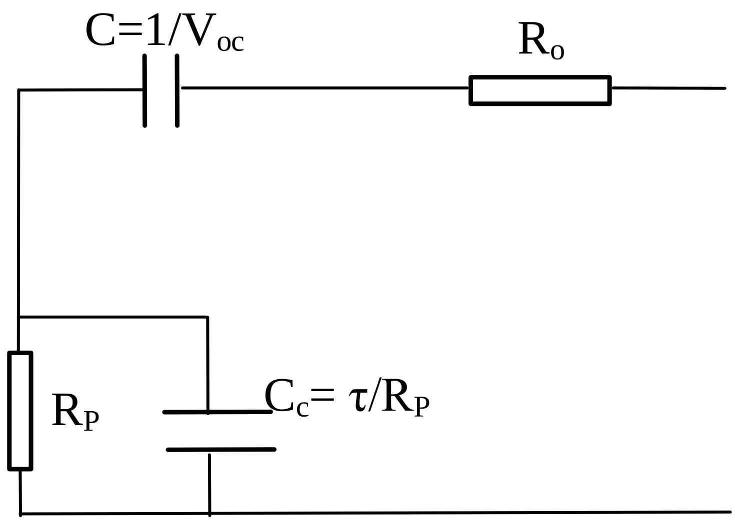
Zebra

Sealed lead-acid

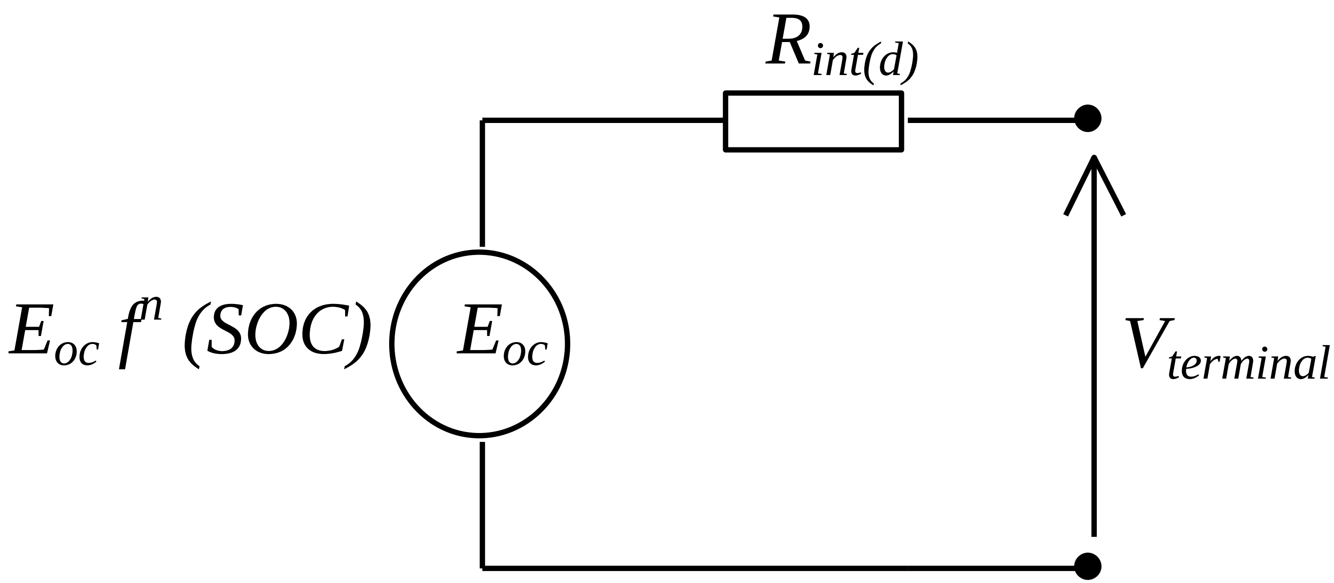
Battery models





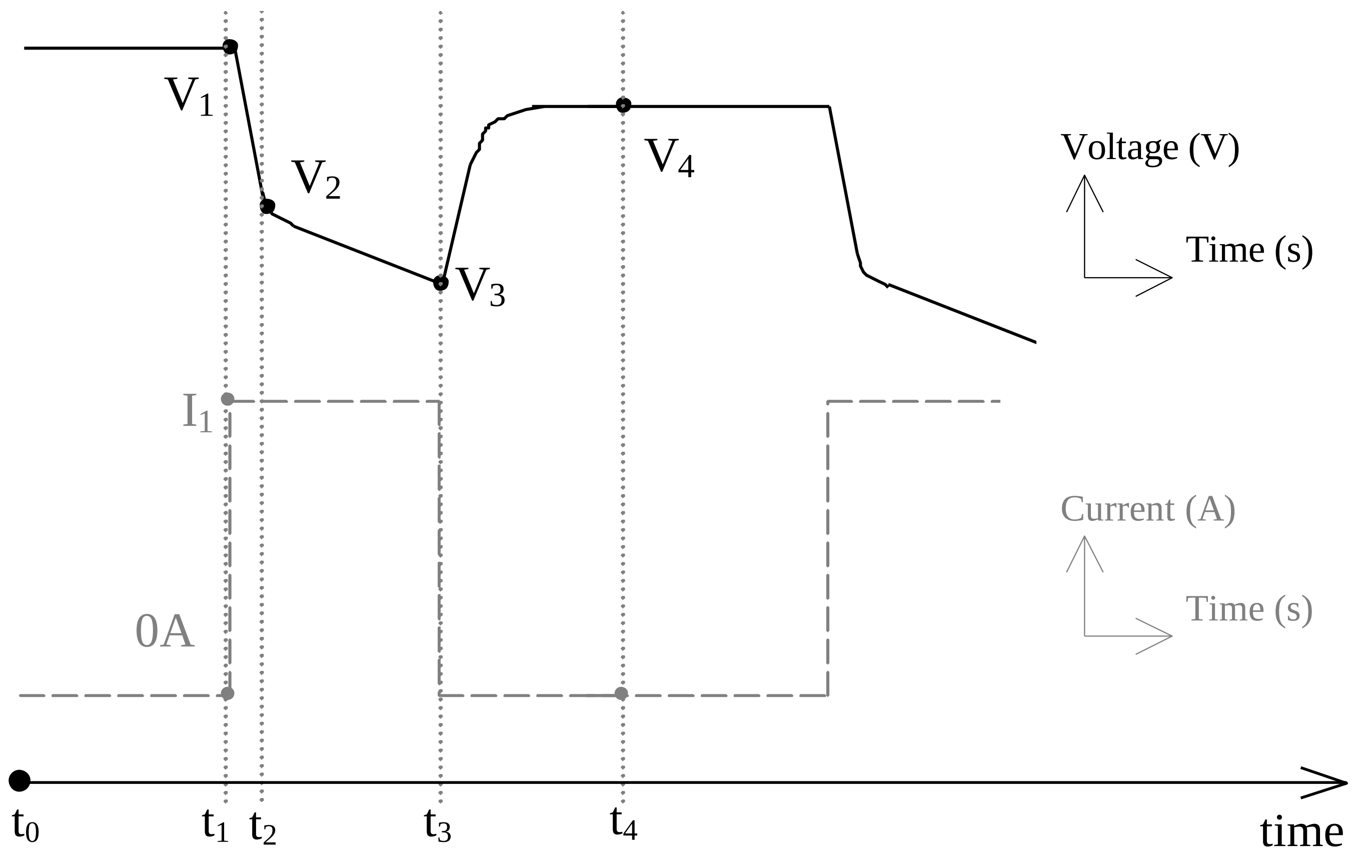


Lead-acid traction battery model



Battery test characterisation

Current and voltage waveforms for single-step pulse discharging.



Battery test characterisation

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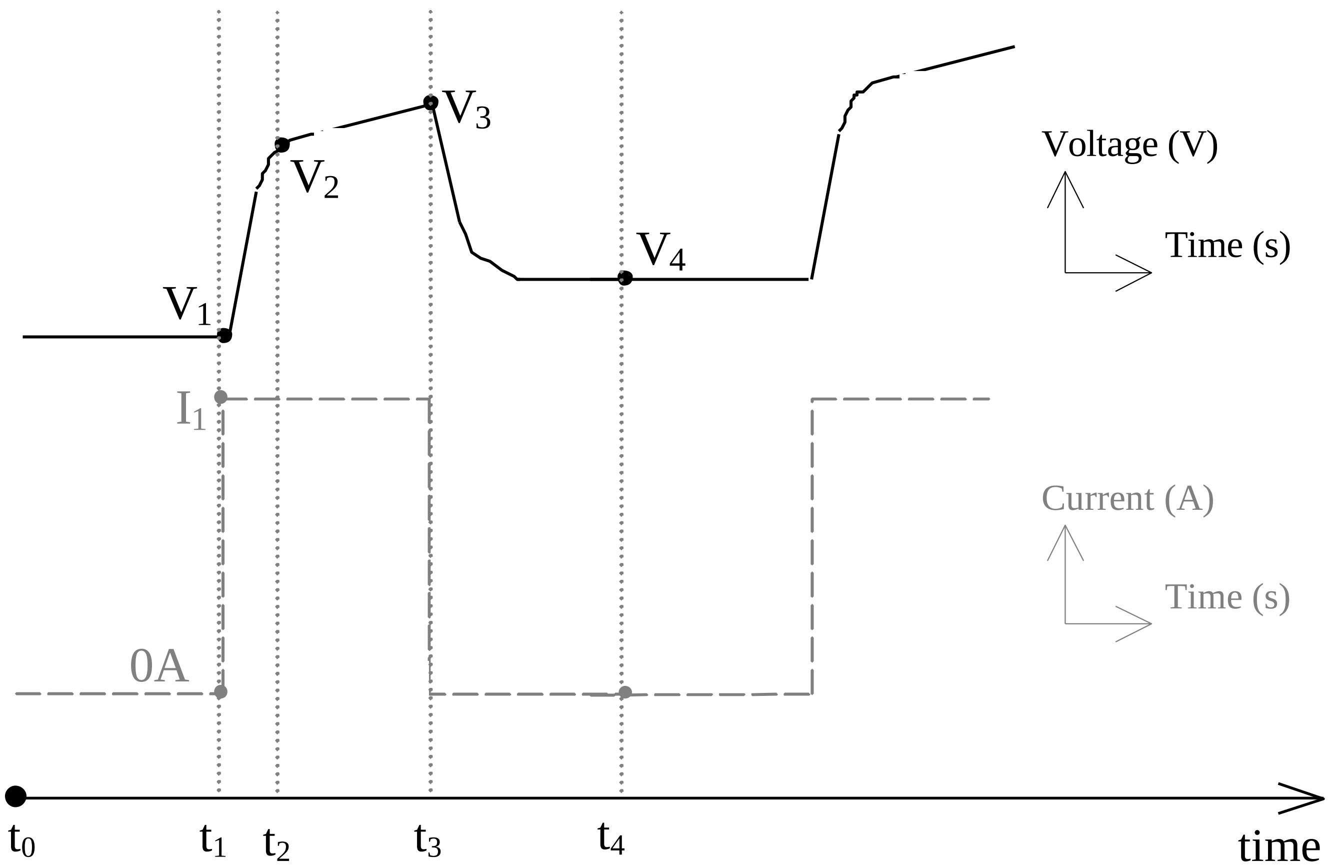
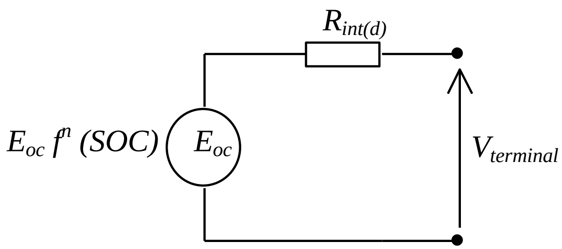
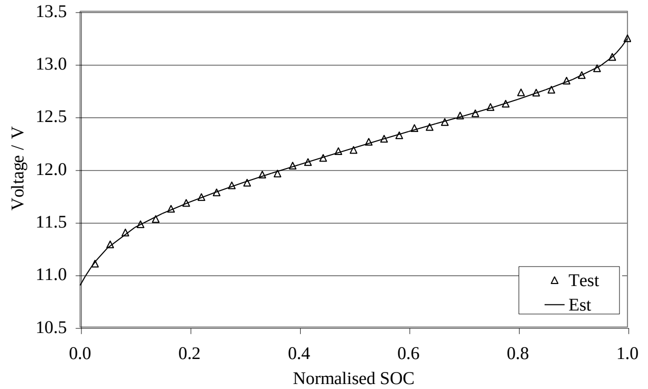
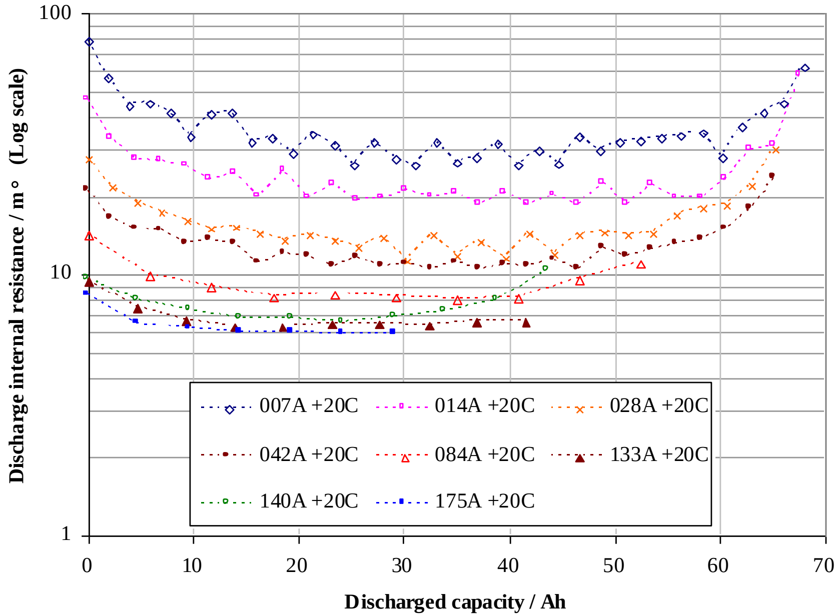
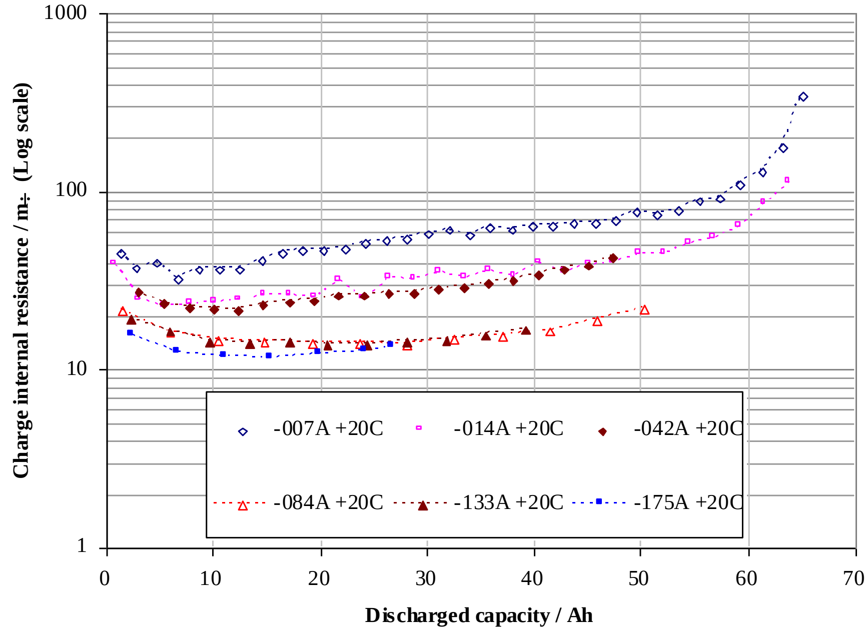


Lead-acid traction battery model



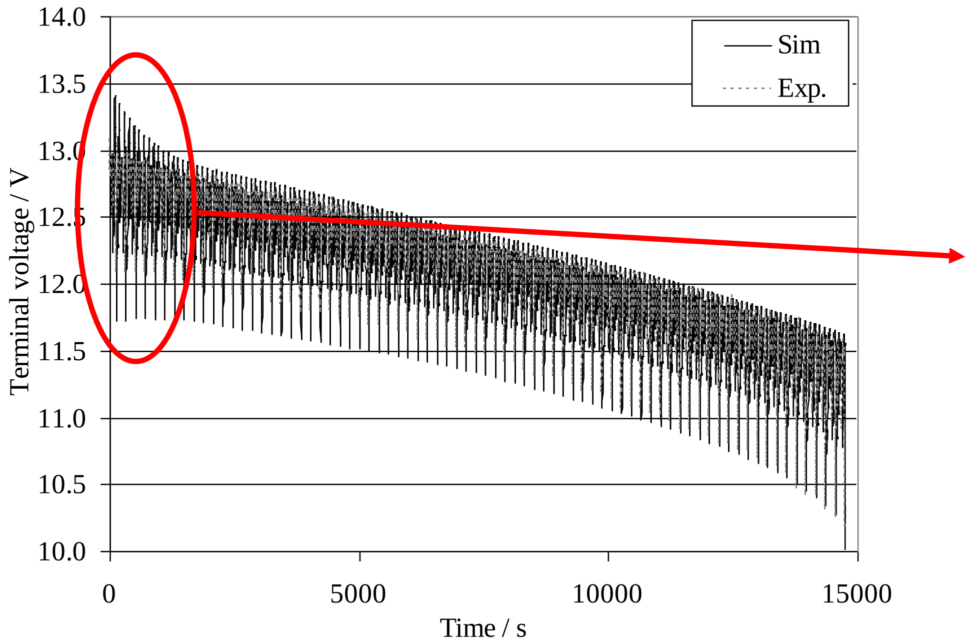




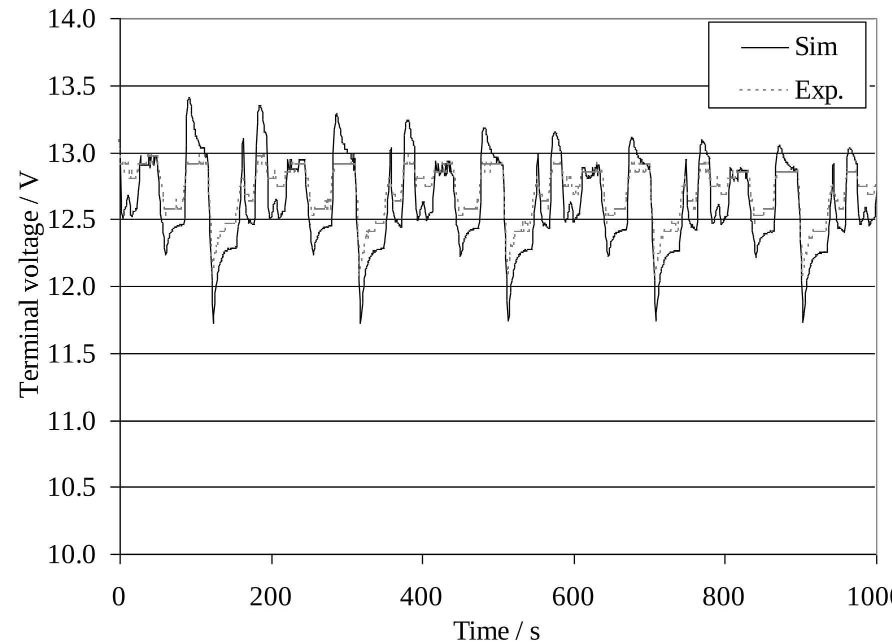


Variation in DC link supply to traction system

Simulated and measured battery terminal voltage for repetitive ECE15 driving

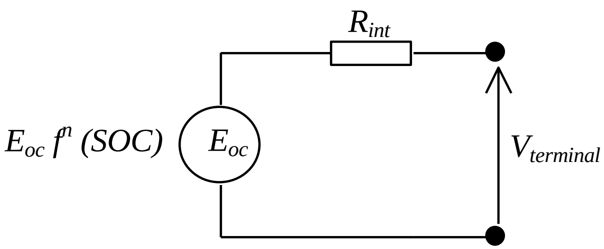


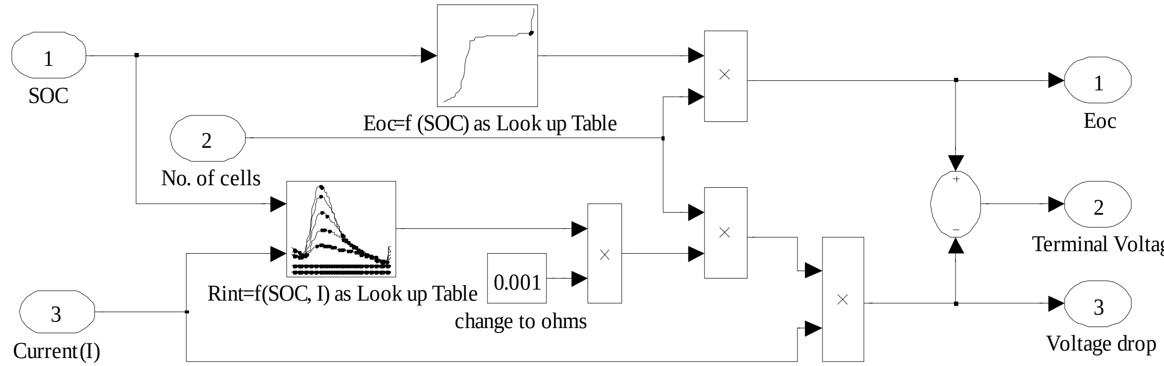
(a) Full data

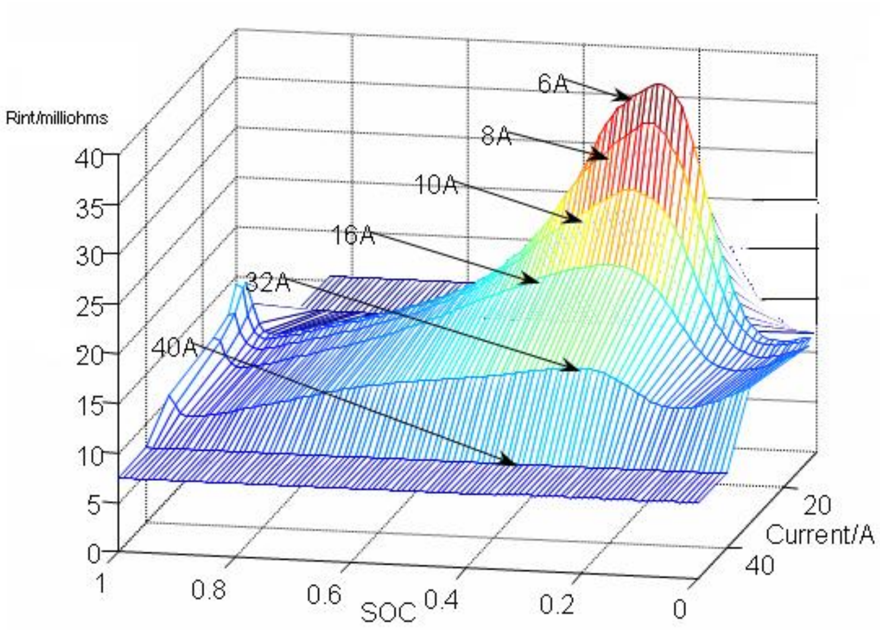


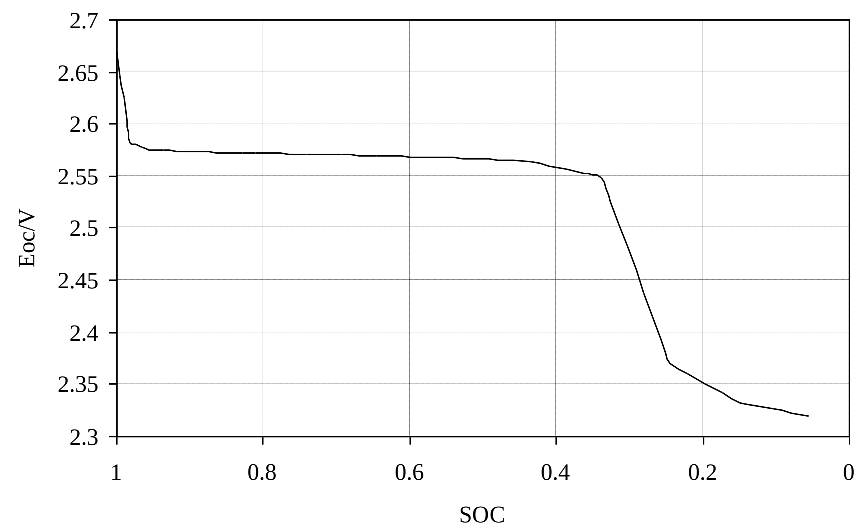
(b) First 1000s of data

Zebra traction battery model in Matlab/Simulink









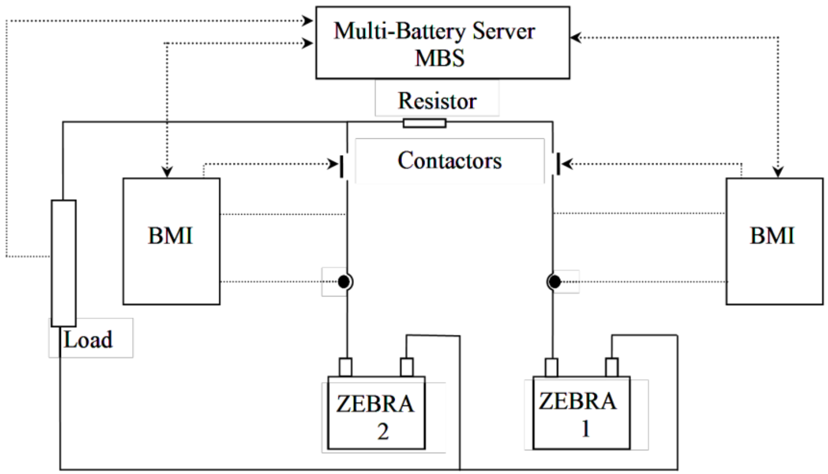
7.5 Tonne All-Electric Delivery Vehicle

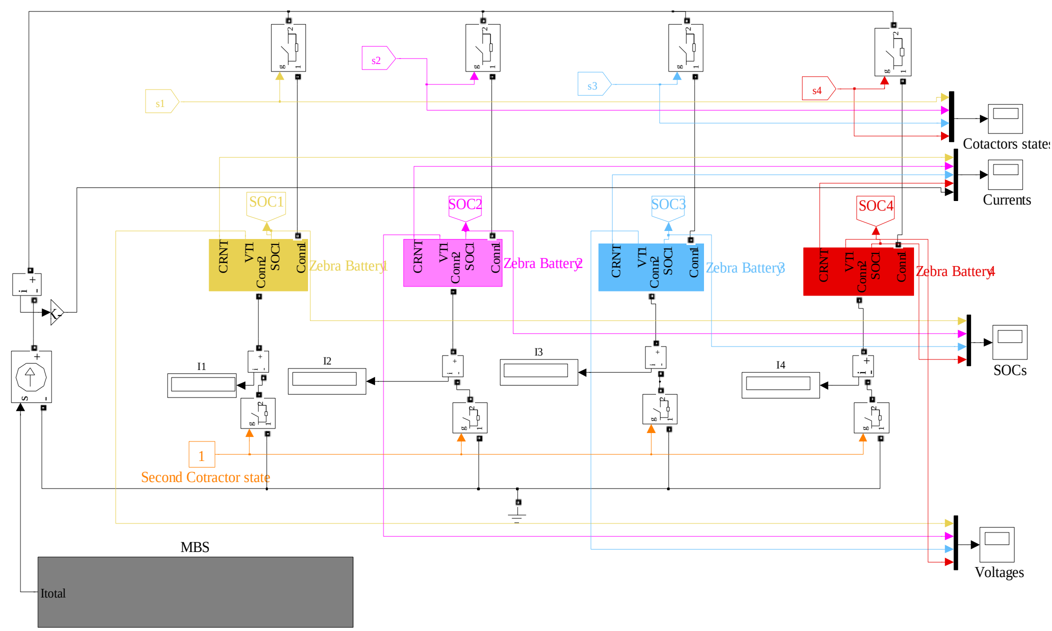
Courtesy of Smith EV, Washington, UK

7.5 Tonne All-Electric Delivery Vehicle

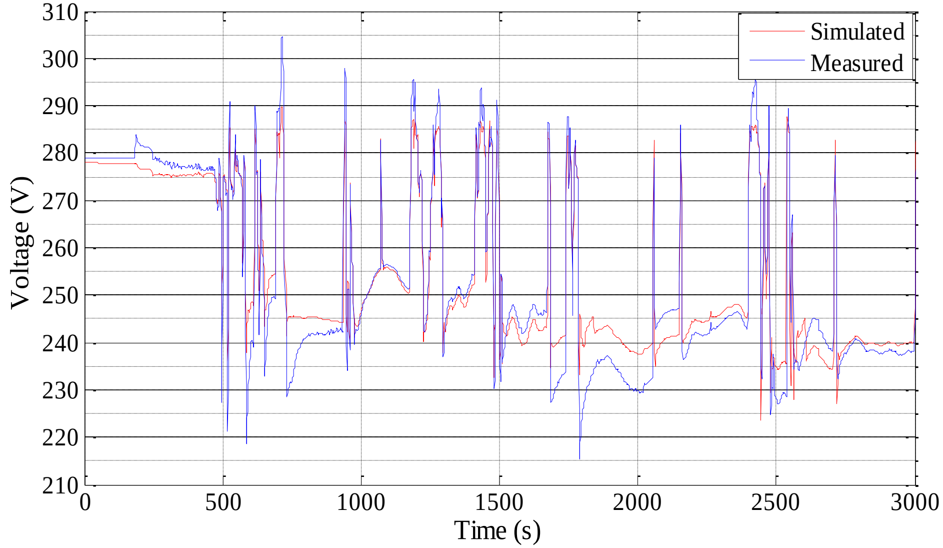
Courtesy of Smith EV, Washington, UK

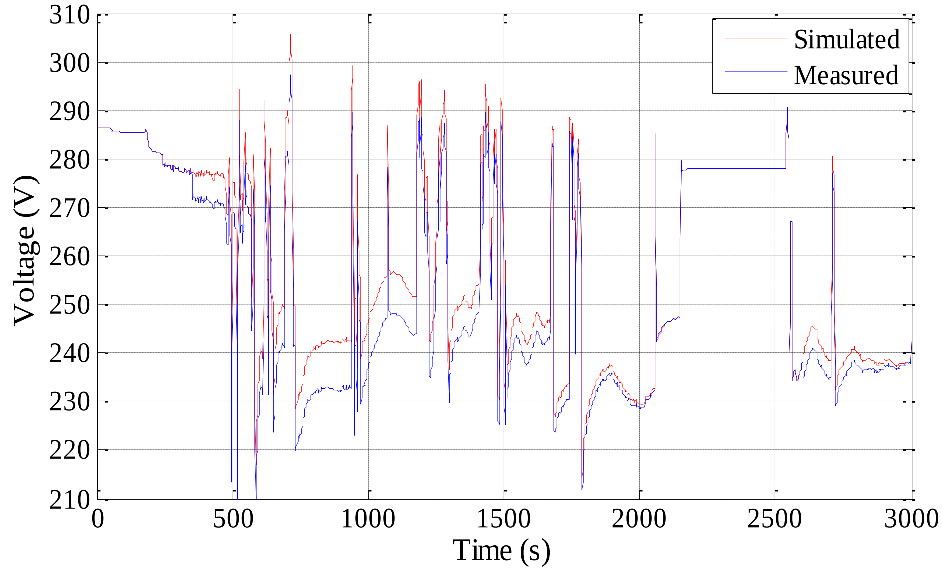
Multi-battery model in Matlab/Simulink



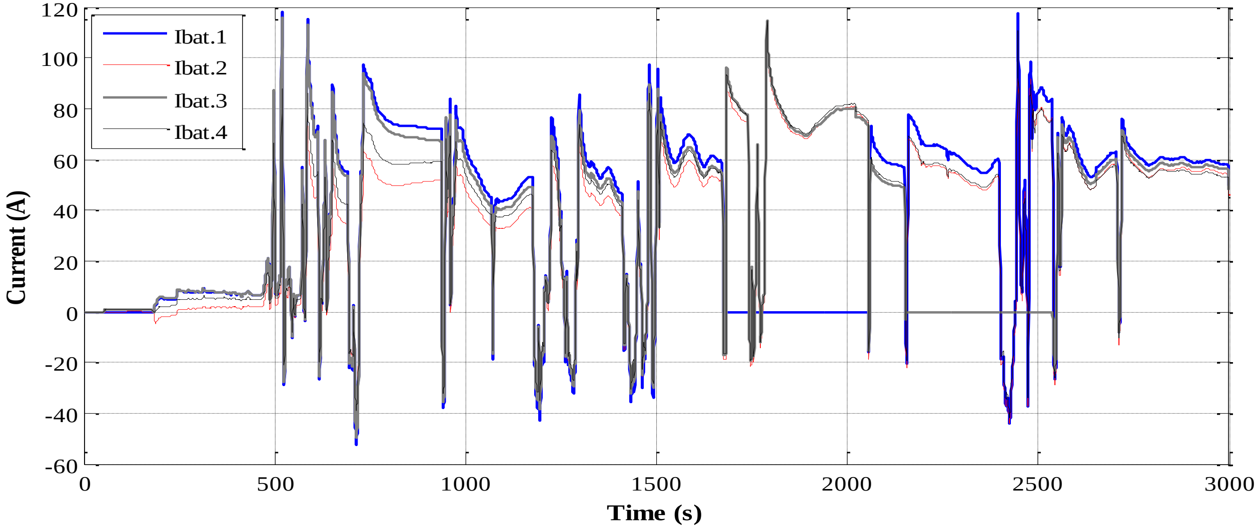


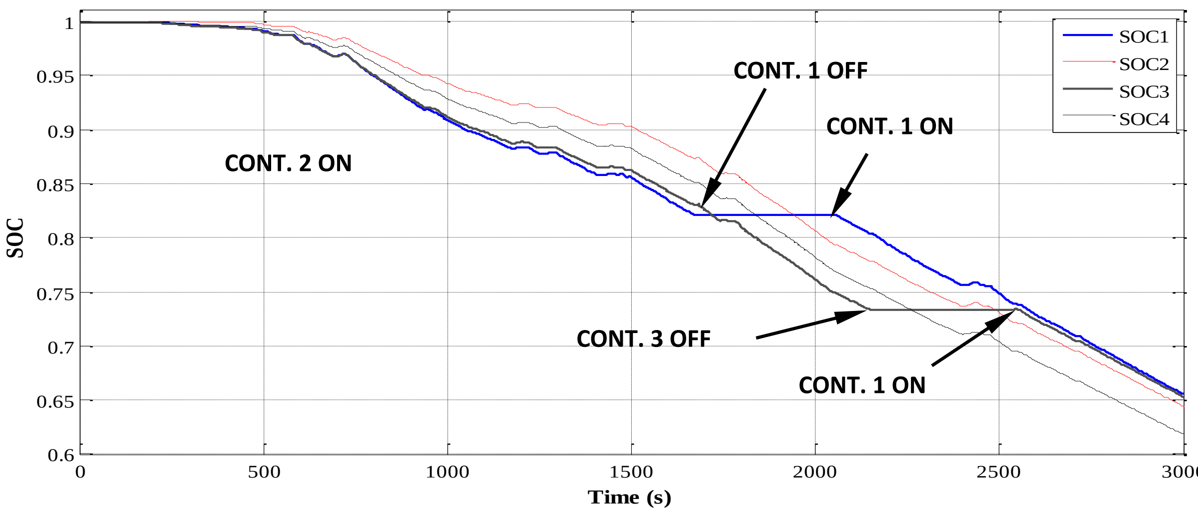
Multi-battery control



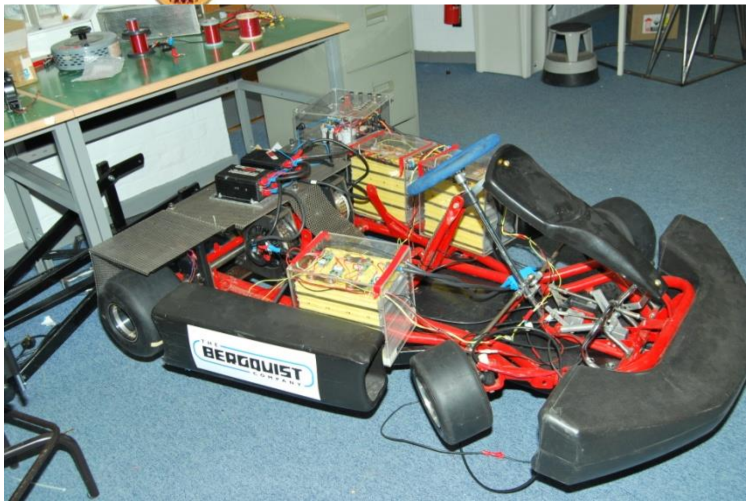


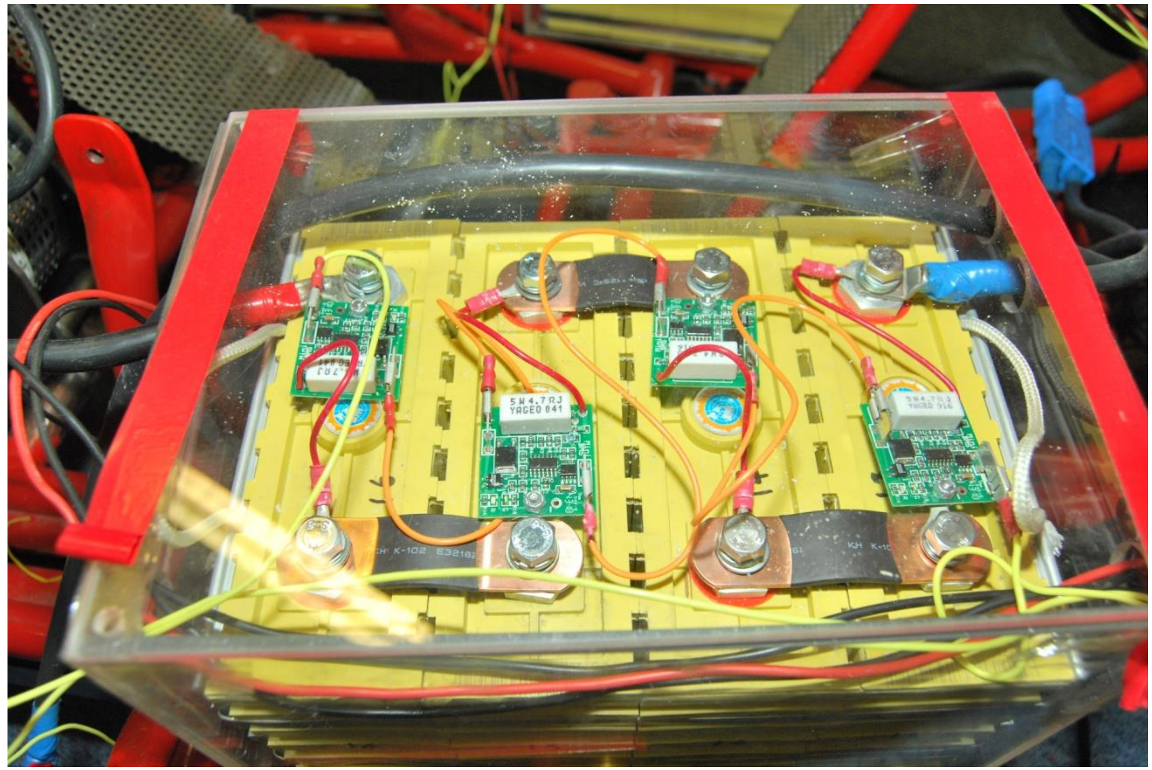
Multi-battery control





Rechargeable Lithium-Ion Traction Battery





McMaster University

Rechargeable Lithium-Ion Traction Battery

Specifications		U27-12XP
Voltage		12.8 V
Capacity (C/5)		130 Ah
Dimensions including terminals (L x W x H)		306x173x225 mm 12x6.8x8.6 in
BCI Group Number		Group 27
Weight (approximate)		19.5 kg / 42.9 lbs
Terminals, female-threaded		M8 x 1.25
Specific energy		85 Wh/kg
Energy density		140 Wh/l
Standard Discharge @ 23°C	Max. cont. current	150 A
	Max. 30 sec. pulse	300 A
	Cut-off voltage	10 V
Standard Charge	Charge voltage	14.6 V
	Float	13.8 V
	Recommended	65 A
	Charge time	2.5 hrs
DC internal resistance		5 mOhm

Do not expose to temperatures above 60°C

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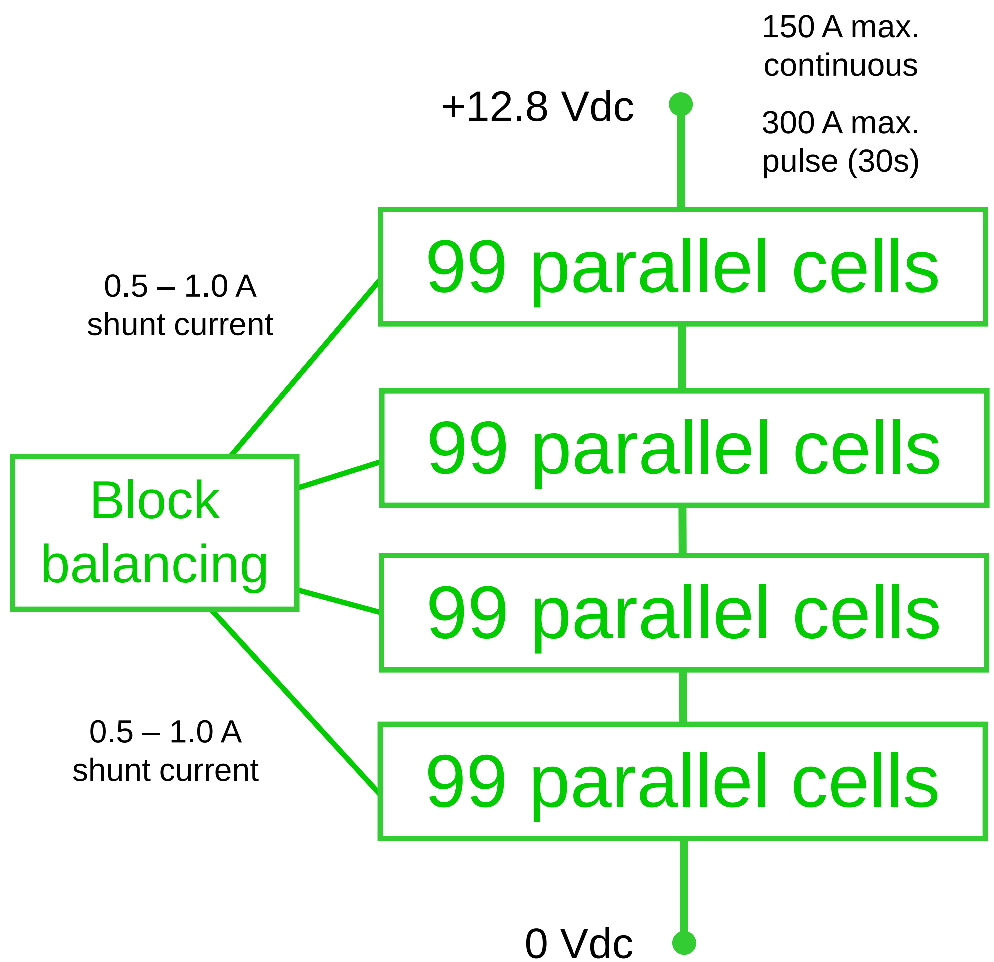
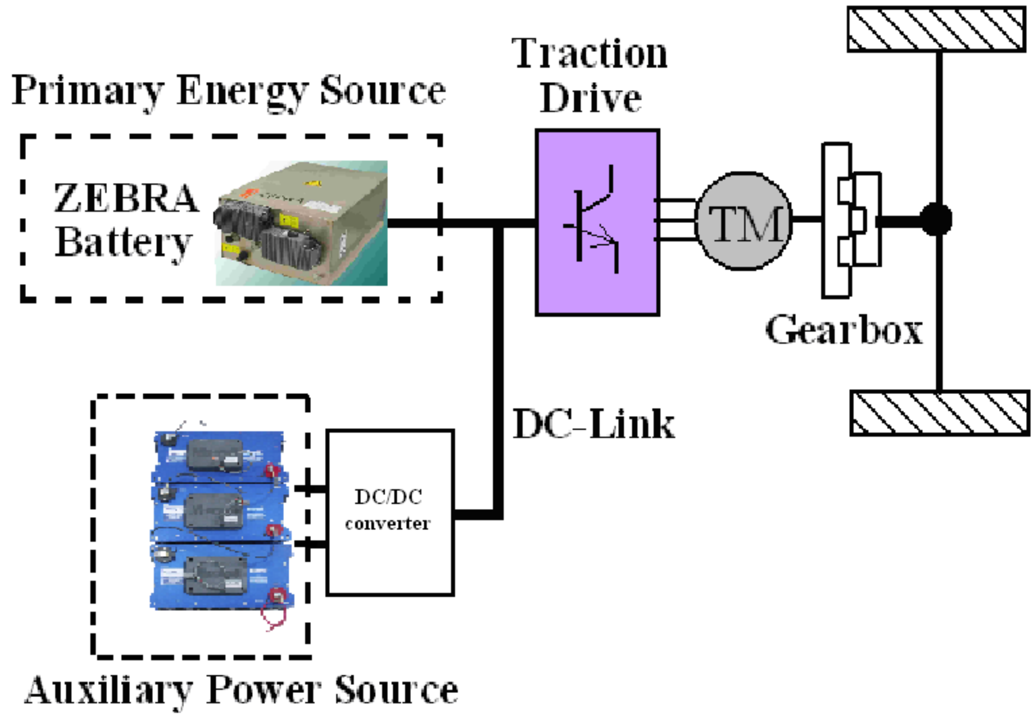


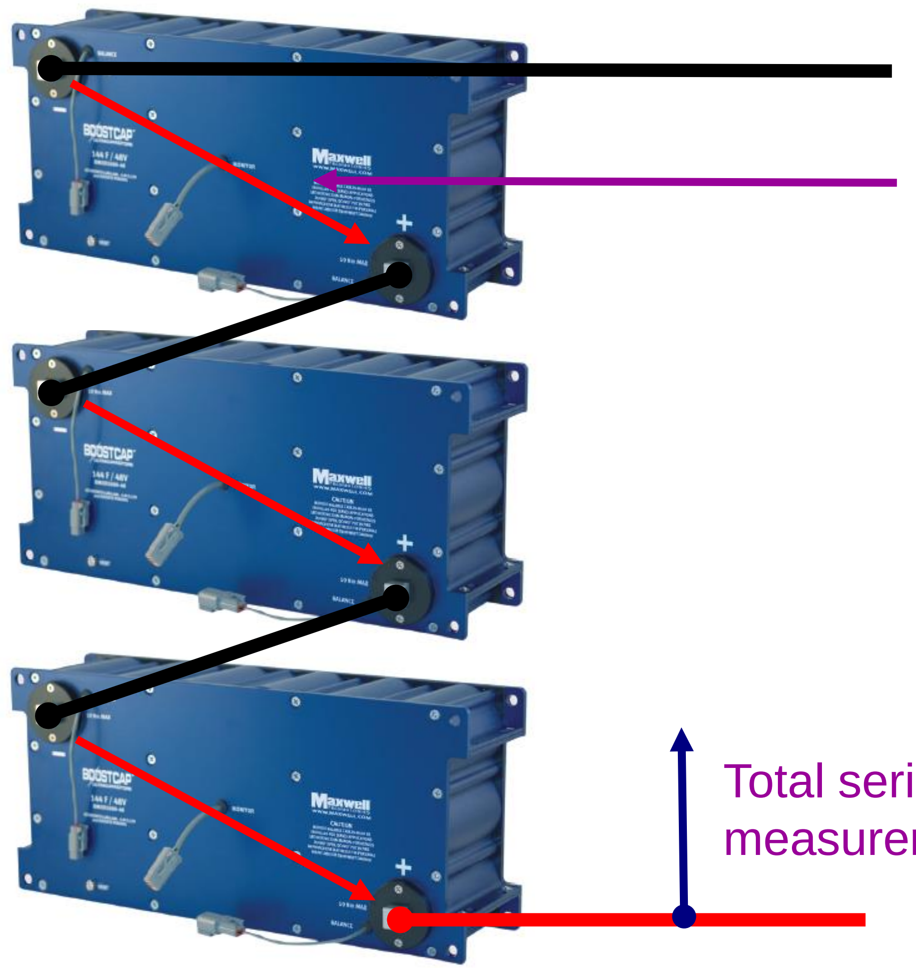
TSB “DESERVE” Power-train

Courtesy of Smith EV, Washington, UK

3.5 tonne delivery vehicle



Supercapacitor peak power buffer

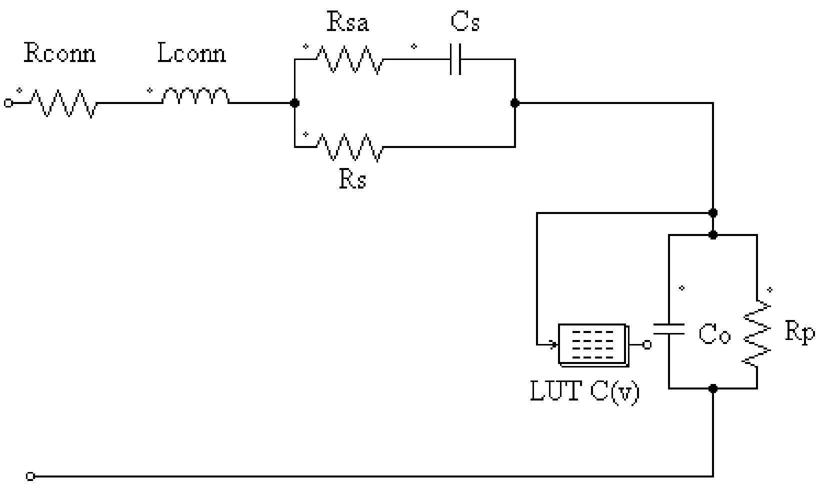


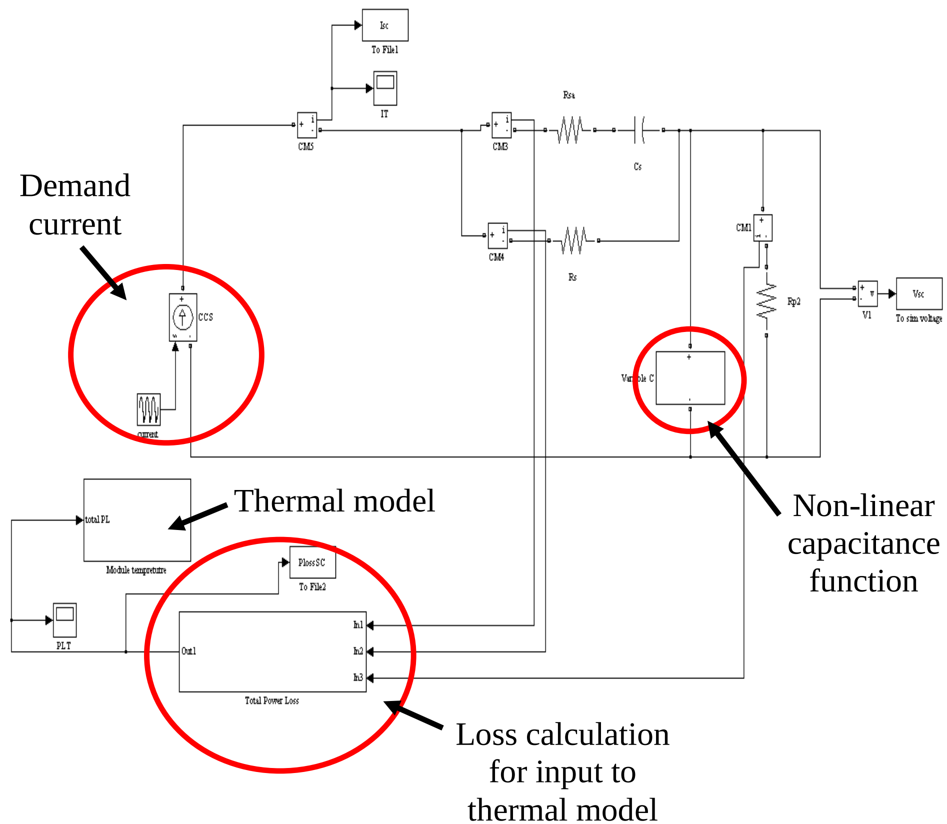
Individual unit voltage measurements (red)

3x 48V; 165F Units connected in series

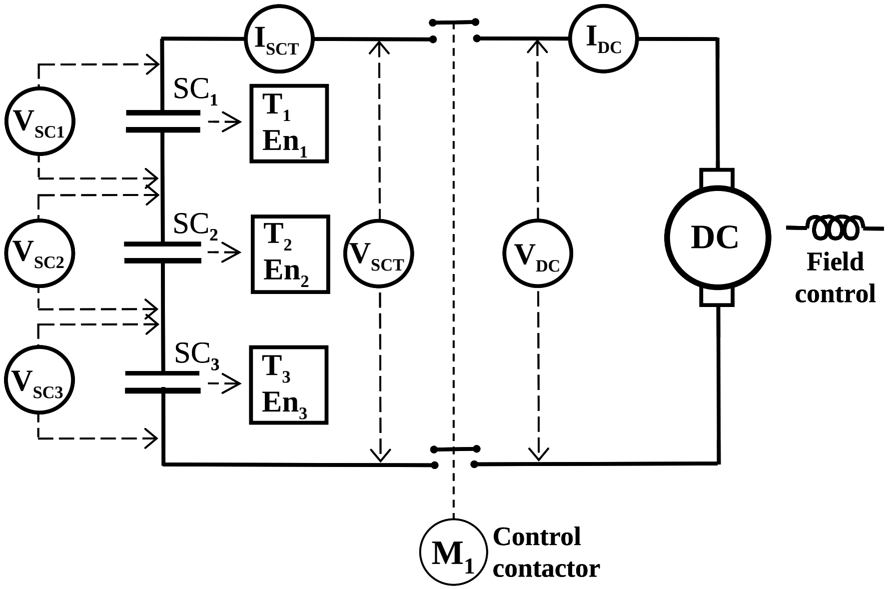
Total series current measurement (blue)

Supercapacitor model in Matlab/Simulink



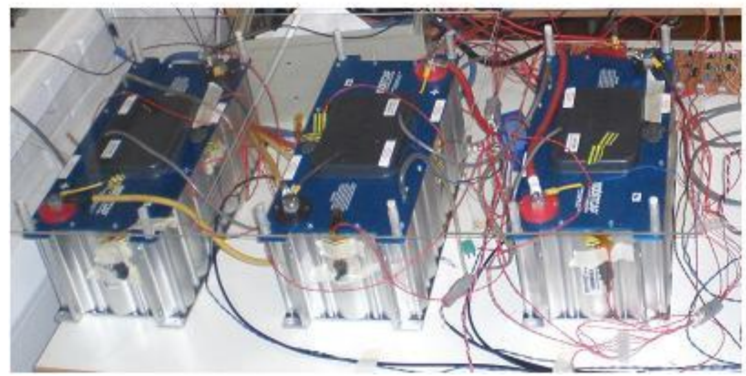


Supercapacitor load testing

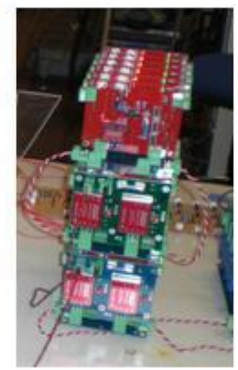


(a) PC for Labview control and data acquisition

(b) Ward-Leonard for controlled DC supply



(c) 3x 48 Volt, 165 F Maxwell supercapacitor units



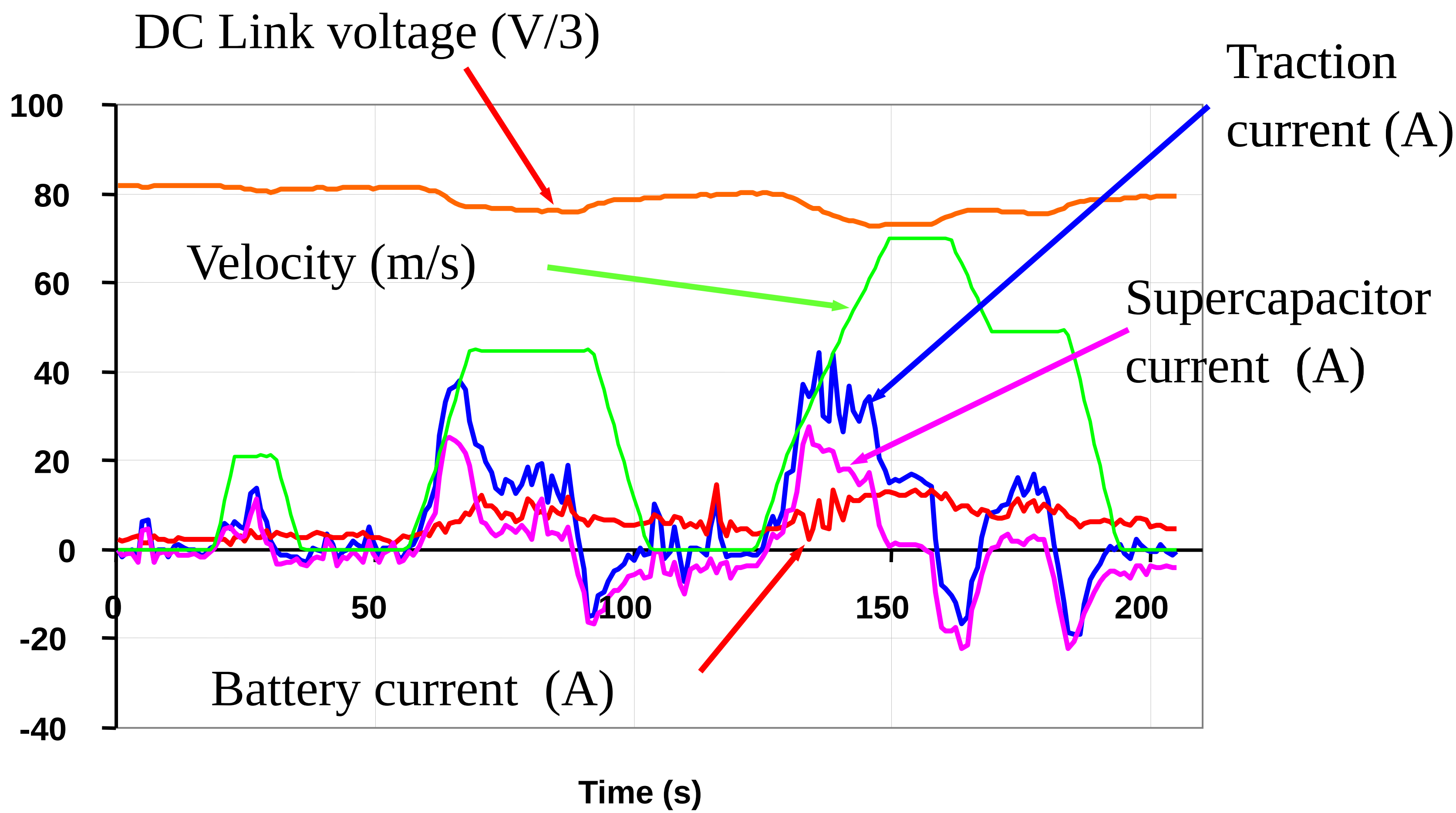
(d) Measurement PCBs

Testing at MIRA

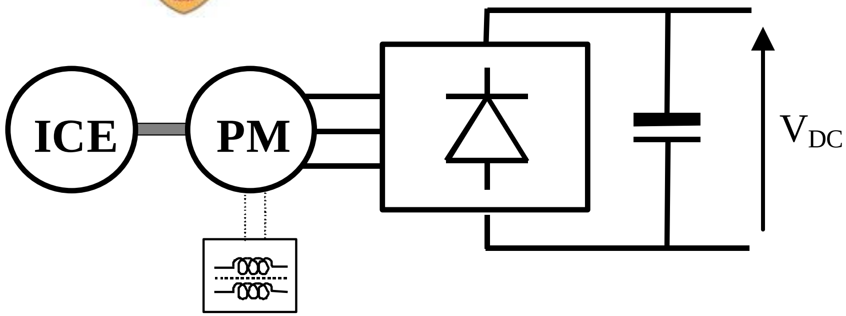
Dissemination of TSB DESERVE research project activities to UK Govt. Cabinet Minister

Electric vehicle energy management

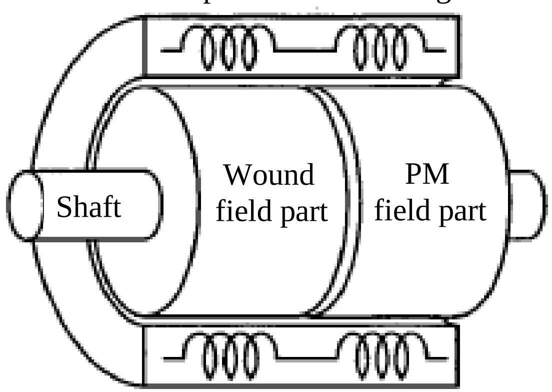
Test data over 1xECE15 driving cycle :



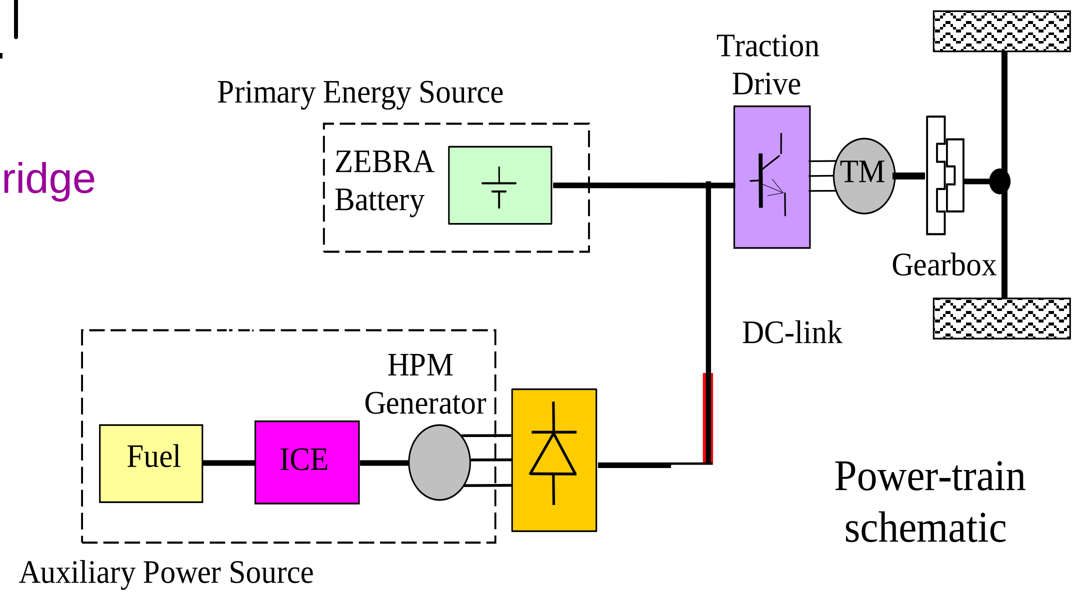
HPM Generator system components and machine concept



ICE/HPM machine and passive (full-bridge diode) rectification stage



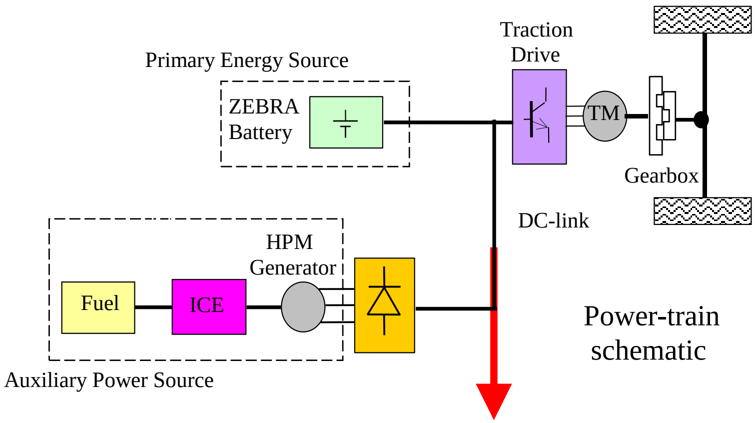
Schematic of HPM generator cross-section

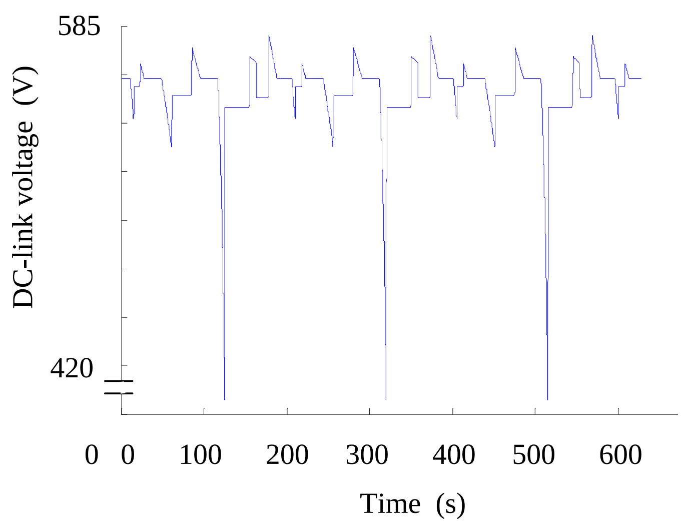


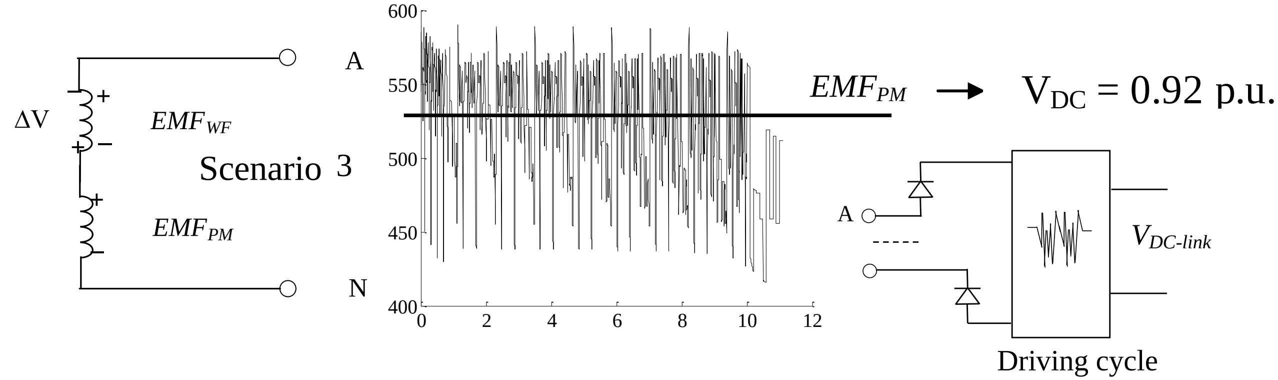
Power-train schematic

Ref.: [3] Schofield et al.

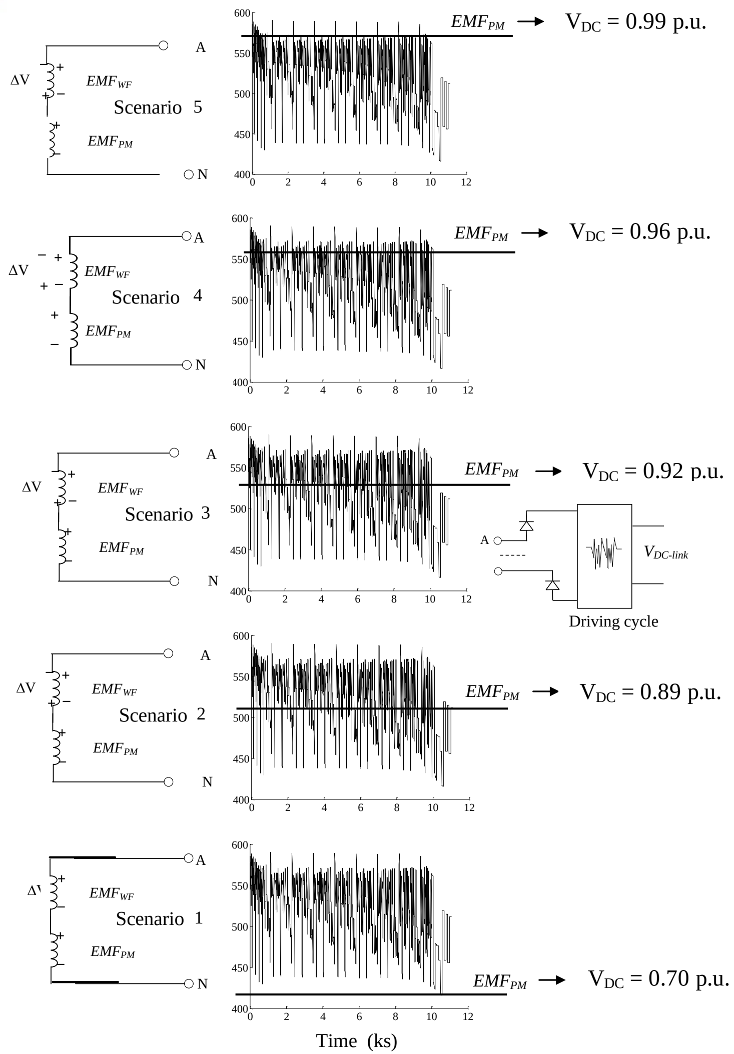
Generator interfacing issues – control philosophy



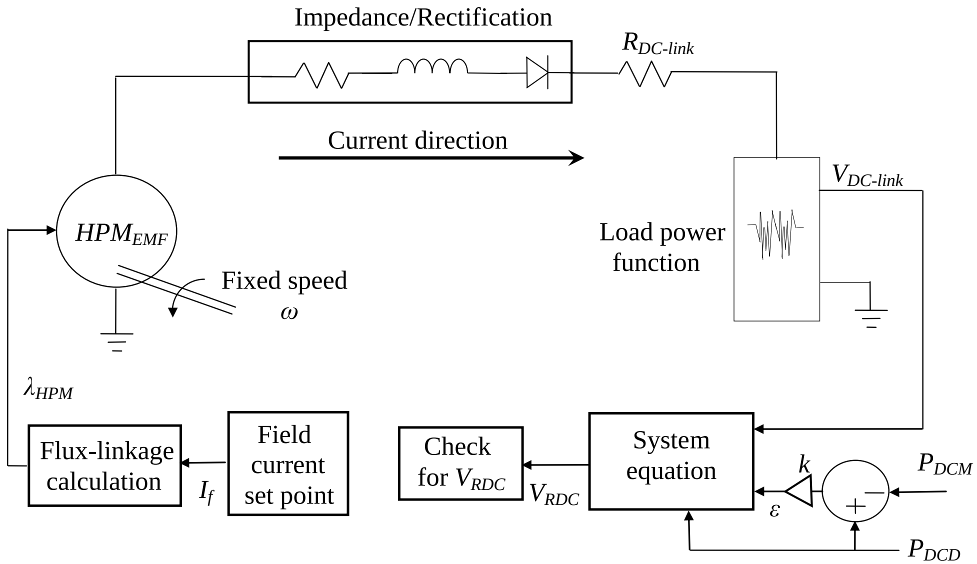




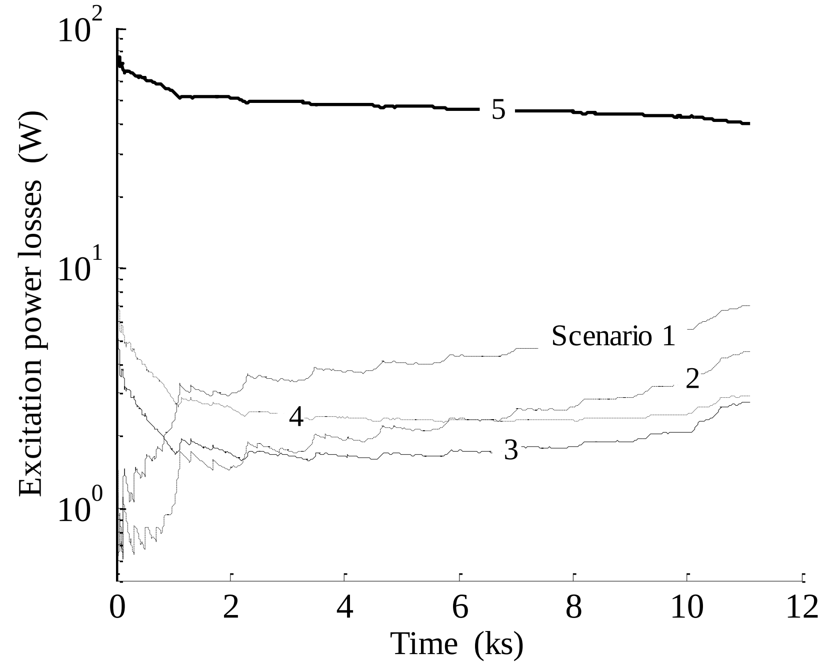
Generator interfacing issues – control philosophy



Generator interfacing issues – control philosophy



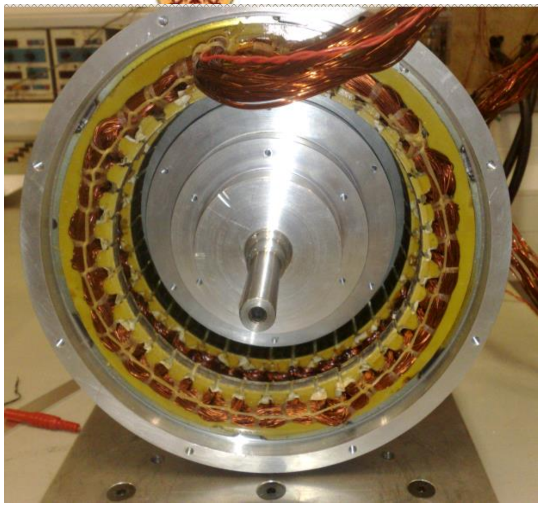
Wound field regulator

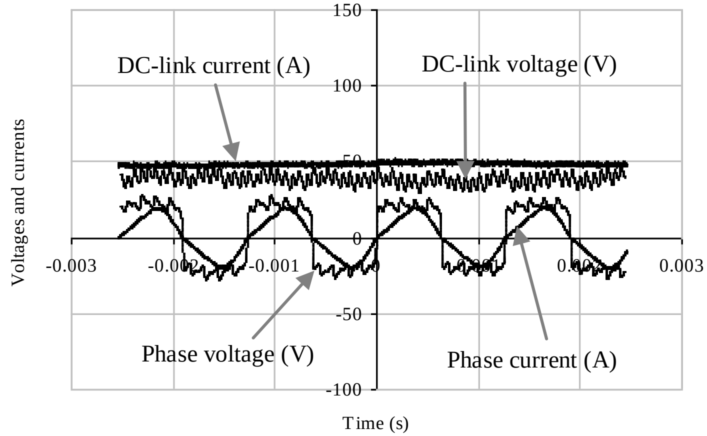


Wound field power loss during driving cycle and over battery SoC variation

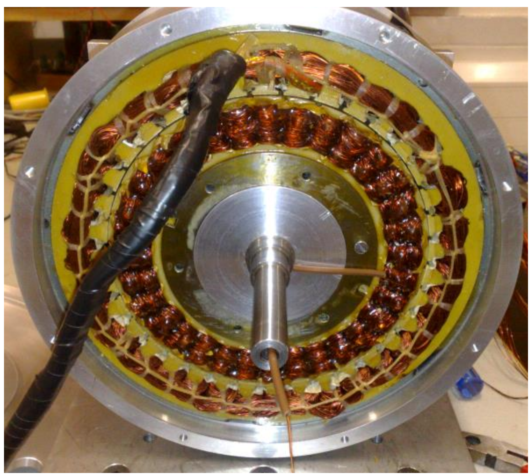
McMaster University

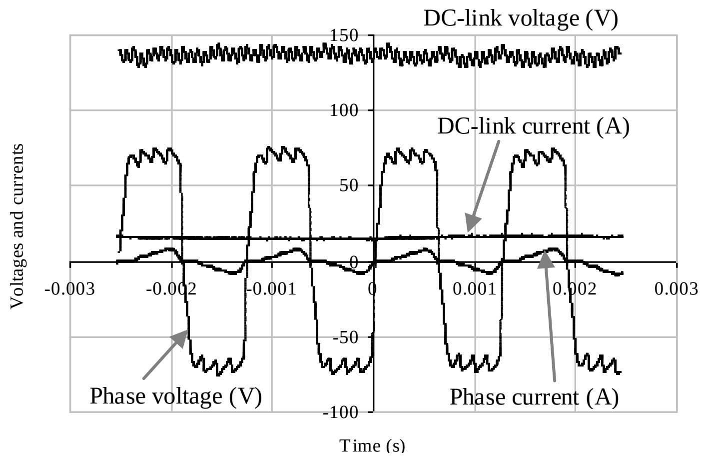
Generator design validation



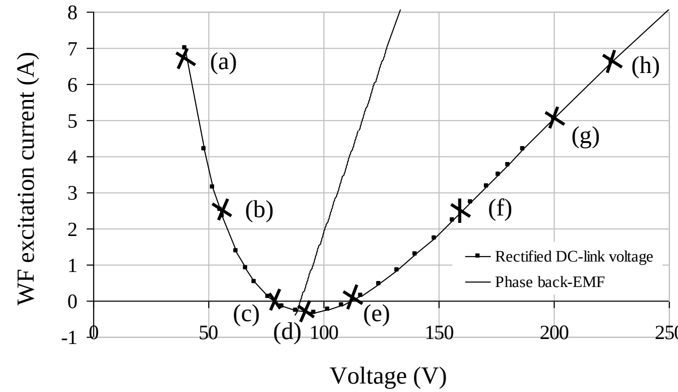


DC-Link voltage = 40V

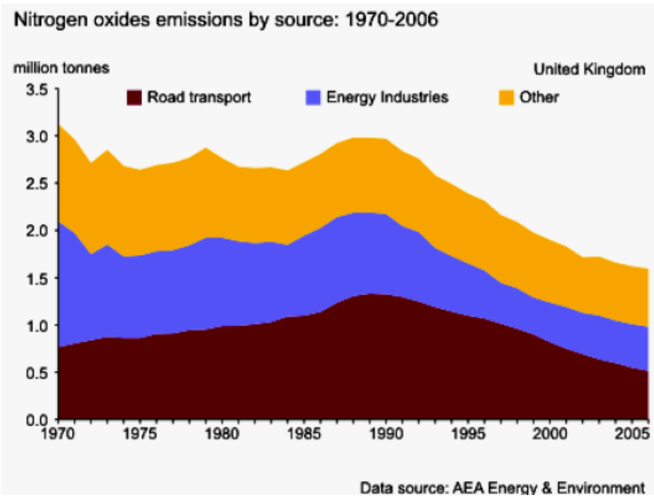


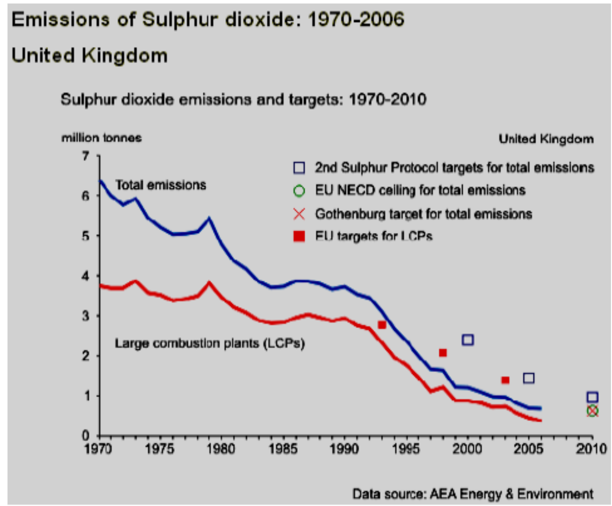


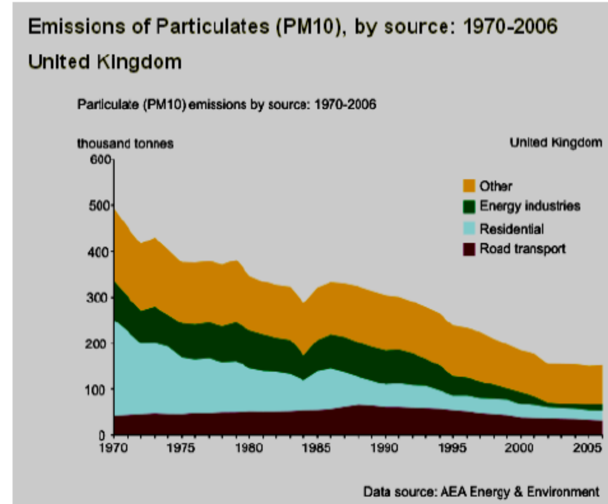
DC-Link voltage = 136V

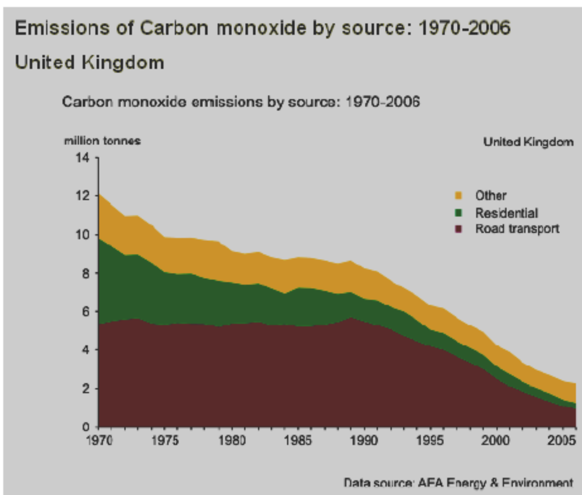


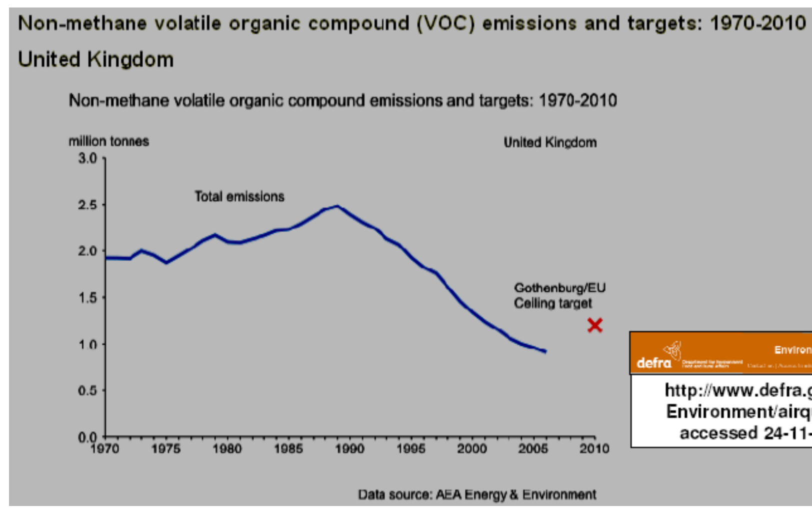
Motivating factors for new vehicle concepts











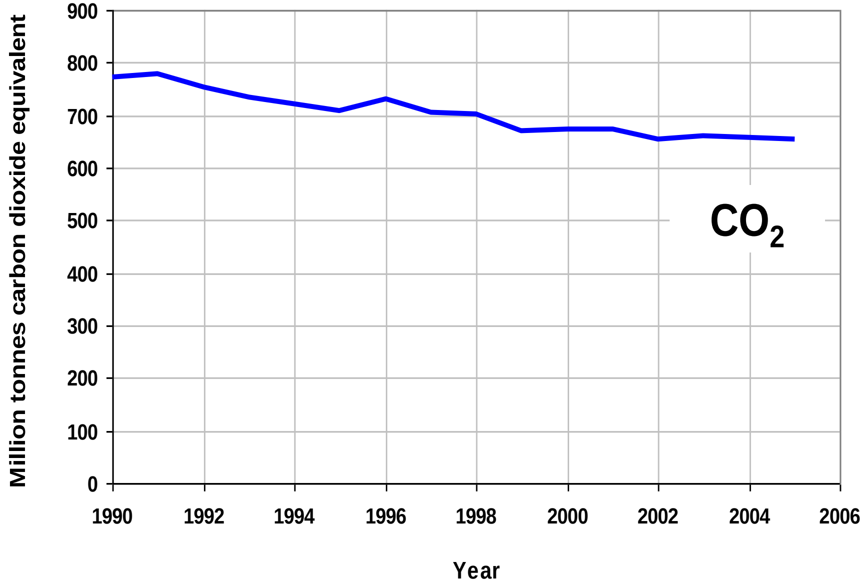
http://www.defra.gov.uk/Environment/airquality/; accessed 24-11-2008

Motivating factors for new vehicle concepts

All of the main vehicle related pollutants have reduced over the past 10 years due to emissions reduction legislation and improved engine technologies

– this against a background increase in vehicle numbers

– the exception is carbon (CO and CO_2) which is still increasing, hence the various LOW CARBON initiatives



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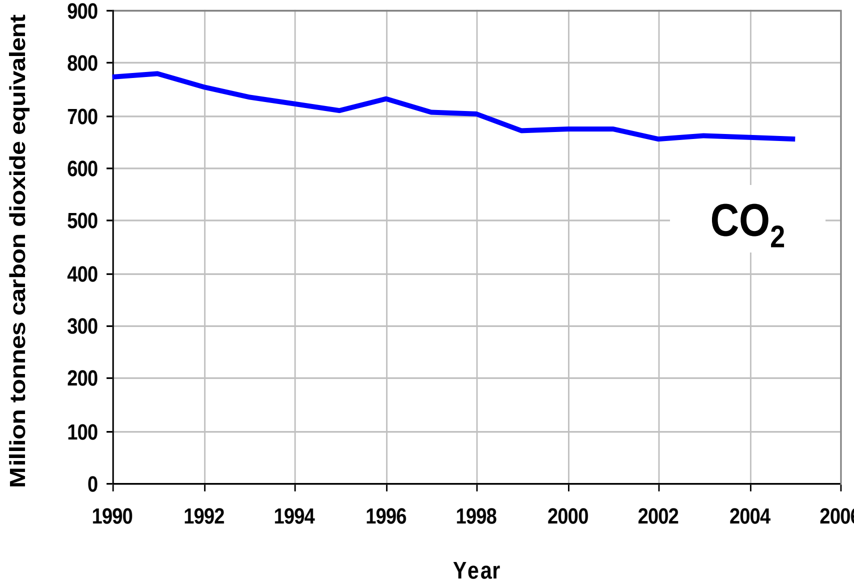

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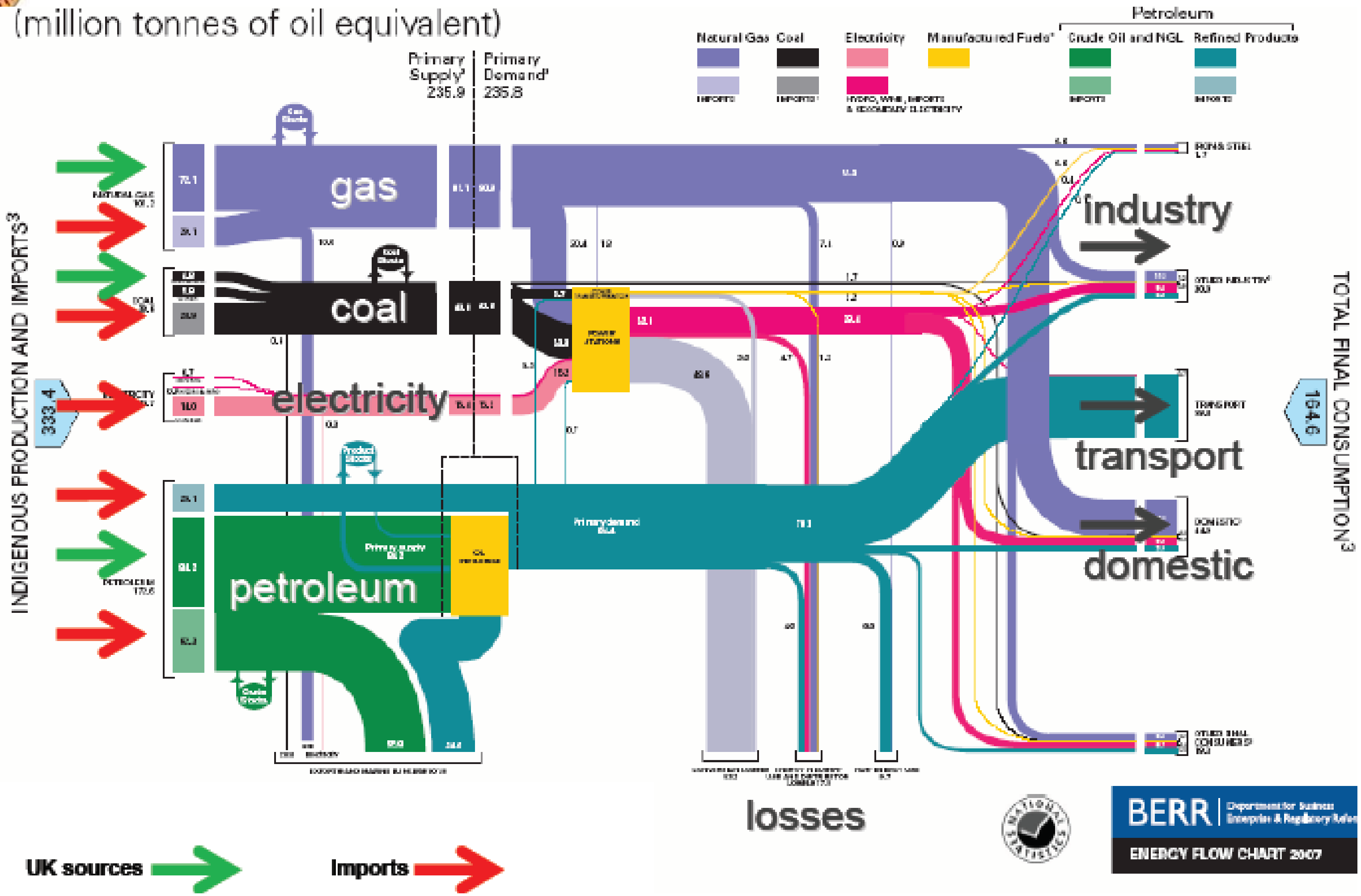
UK Energy Flow Chart 2007



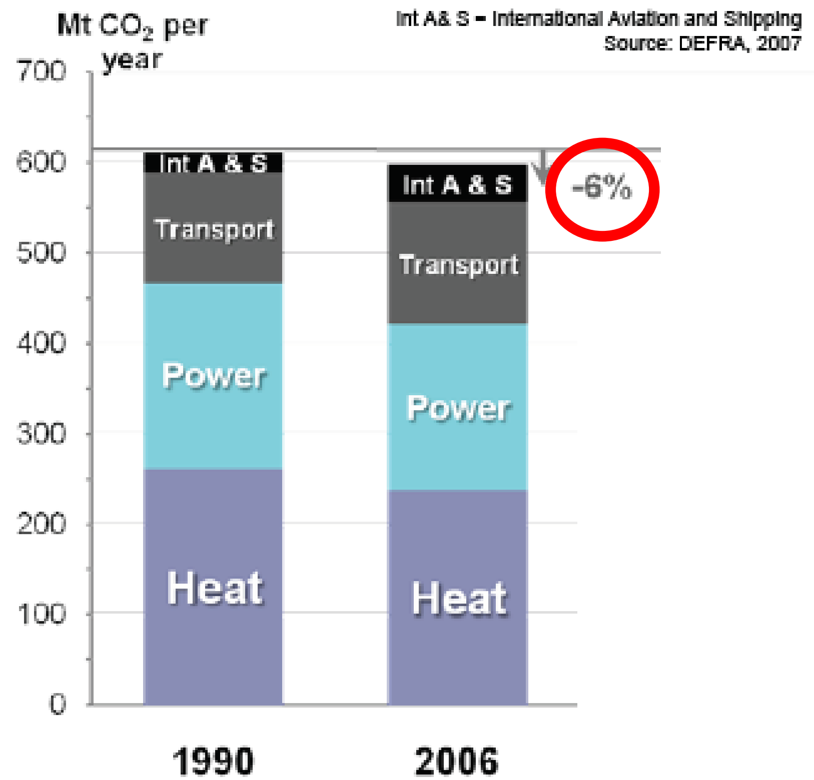
Source: IET Clerk-Maxwell Lecture, 19th February 2009, London, UK and BERR

2050 CO_2 target means change across all sectors

Transport - wide range of technology and applications

Heat - hard to treat in a centralised manner, and hindered by building stock issues

Power - sector is more centralised, but significant challenges remain



Source: IET Clerk-Maxwell Lecture, 19th February 2009, London, UK

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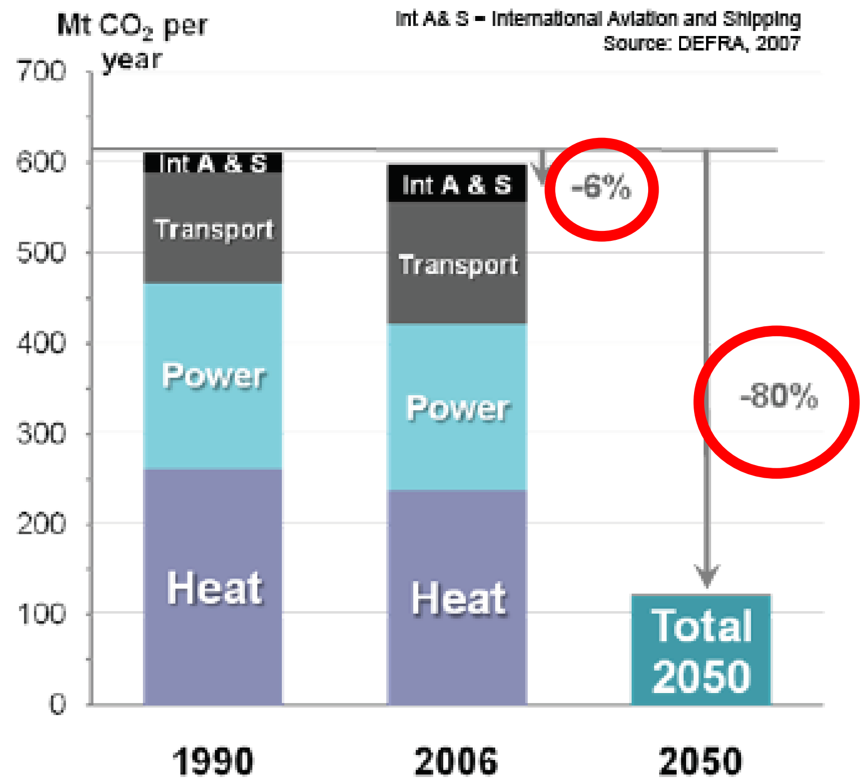
Achieving 2050 target may mean large scale **Infrastructure** shifts, eg:

⇨Countrywide electrification of heating and transport

⇨Wide-scale heat network coverage, CHP

⇨Hydrogen economy?



Source: IET Clerk-Maxwell Lecture, 19th February 2009, London, UK

Presentation review :

1 Background to “more electric” vehicle concepts

2 Vehicle power-train power- and torque-speed requirements

3 Machine and power electronics

4 Vehicle integration considerations

5 Energy sources

McMaster University

I would like to thank the many collaborators who have contributed and invite questions

References

[1] Schofield, N., Long, S.A., Howe, D. and McClelland, M.: 'Design of a Switched Reluctance Machine for Extended Speed Operation', IEEE Transactions on Industry Applications, Vol. 45, Issue 1, Jan.- Feb. 2009, pp. 116 – 122, DOI 10.1109/TIA.2008.2009506.

[2] UK Foresight Vehicle LINK Programme: 'Zero Emission Small vehicle with integrated high Temperature battery and FUel CelL (ZESTFUL)', N. Schofield (PI); REE1123/R012931. EPSRC Grant No. GR/S81971/01.

[3] Schofield, N., Al-Adsani, A.:' Operation of a Hybrid PM Generator in a Series Hybrid EV Power-Train', IEEE Vehicle Power and Propulsion Conference (VPPC '11), Chicago, USA, 6-9 Sept. 2011, pp. 1-6.