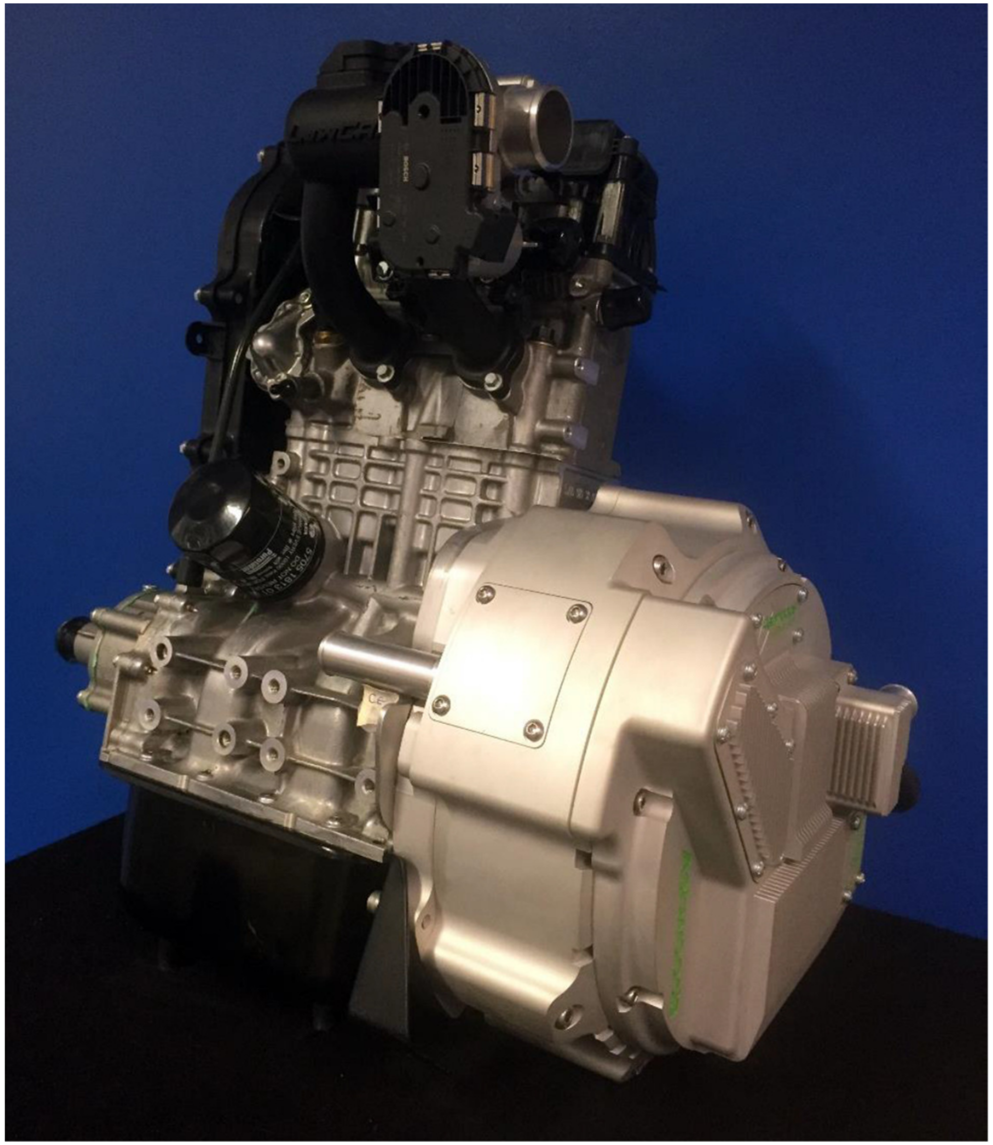
Department of Mechanical Engineering

UNIVERSITY OF BATH

Hybrid Electric Powertrains

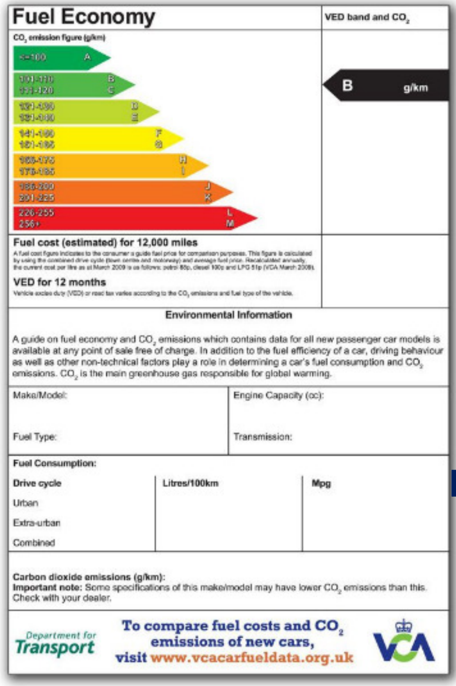
Chris Brace



Overview

- The hybrid – electric powertrain
- Impact on IC engine
- Some examples
- Case study - REEV
- Outlook

Air quality – a bigger driver than CO_2?



Fuel Economy

VED band and CO_2

CO_2 emission figure (g/km)

<=100	A
101-110	B
111-120	C
121-130	D
131-140	E
141-150	F
151-165	G
166-175	H
176-185	I
186-200	J
201-225	K
226-255	L
256+	M

B g/km

Fuel cost (estimated) for 12,000 miles

A fuel cost figure indicates to the consumer a guide fuel price for comparison purposes. This figure is calculated by using the combined drive cycle (town centre and motorway) and average fuel price. Recalculated annually, the current cost per litre as at March 2009 is as follows: petrol 88p, diesel 100p and LPG 51p (VCA March 2009).

VED for 12 months

Vehicle excise duty (VED) or road tax varies according to the CO_2 emissions and fuel type of the vehicle.

Environmental Information

A guide on fuel economy and CO_2 emissions which contains data for all new passenger car models is available at any point of sale free of charge. In addition to the fuel efficiency of a car, driving behaviour as well as other non-technical factors play a role in determining a car's fuel consumption and CO_2 emissions. CO_2 is the main greenhouse gas responsible for global warming.

Make/Model:	Engine Capacity (cc):
Fuel Type:	Transmission:

Fuel Consumption:

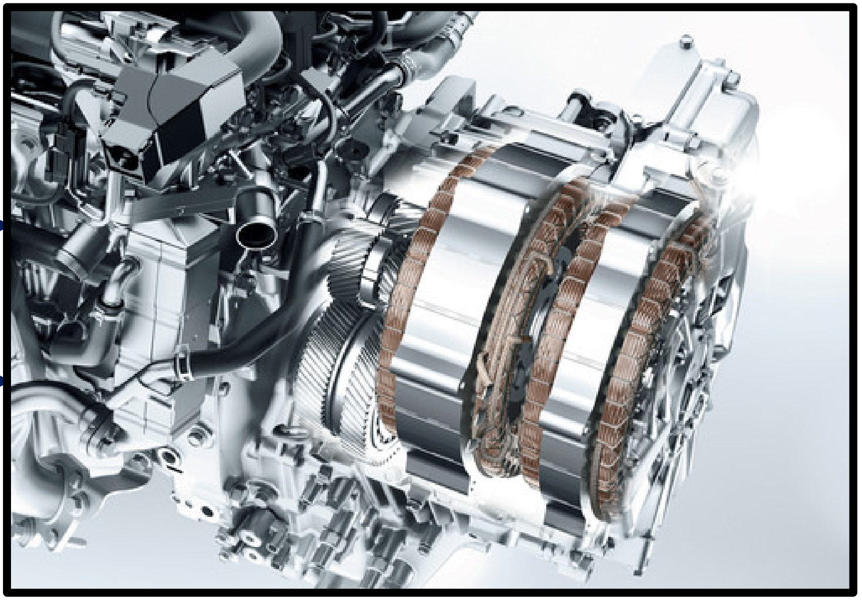
Drive cycle	Litres/100km	Mpg
Urban		
Extra-urban		
Combined		

Carbon dioxide emissions (g/km):
Important note: Some specifications of this make/model may have lower CO_2 emissions than this. Check with your dealer.

Department for Transport

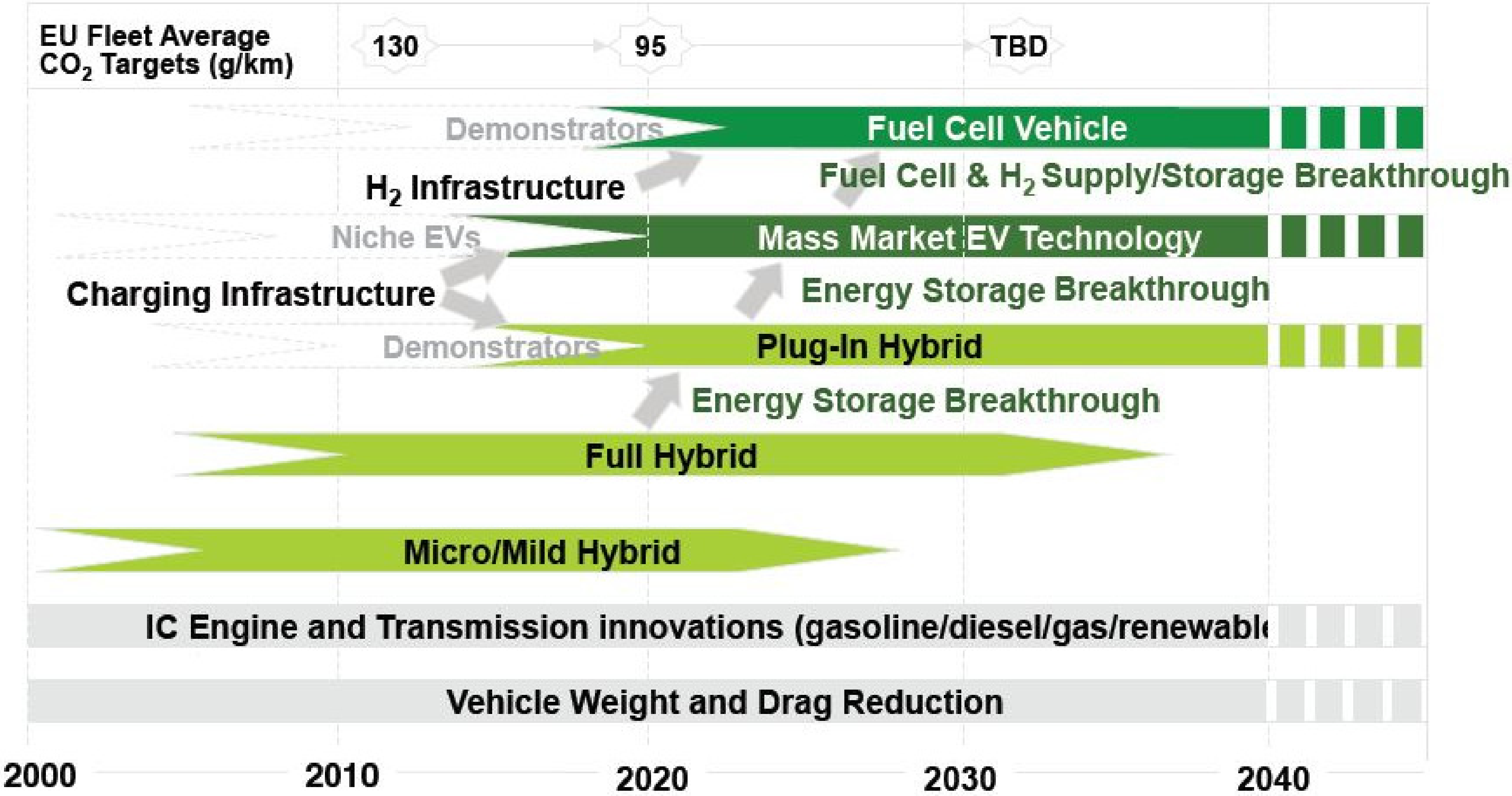
To compare fuel costs and CO_2 emissions of new cars, visit www.vcacarfueldata.org.uk

VCA



Passenger car low carbon technology roadmap

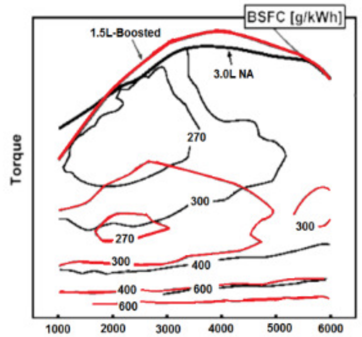
automotive council UK



Four Key Hybrid Advantages

ENGINE DOWNSIZING AND LOAD MANAGEMENT

- Electric torque assist to allow for smaller engine
- E-boosting to allow downsizing
- Engine can operate in efficient region
- Start/Stop



ENERGY RECOVERY, STORAGE AND RE-USE

- Regenerative braking: e-machine to battery or flywheel
- Exhaust energy recovery:
    - Turbine (pressure)
    - Bottoming cycle (heat)

REDUCED ANCILLARY LOADS

- Electrifying A/C compressors, pumps, and fans means reduced energy.
- High voltage systems more efficient

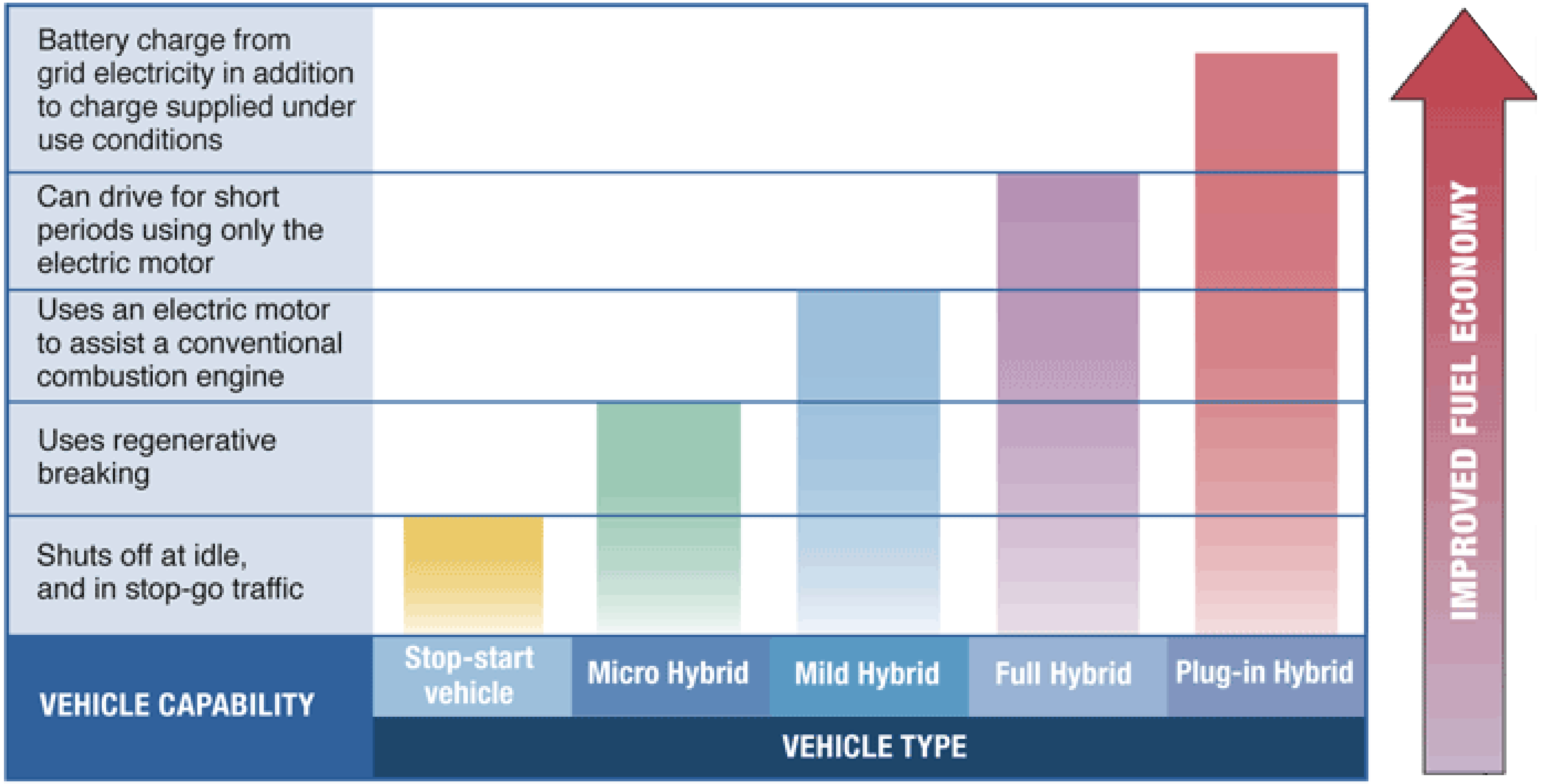
ZERO TAILPIPE EMISSIONS MODE

- Electric-only range helps improve city smog.
- Inexpensive short journeys

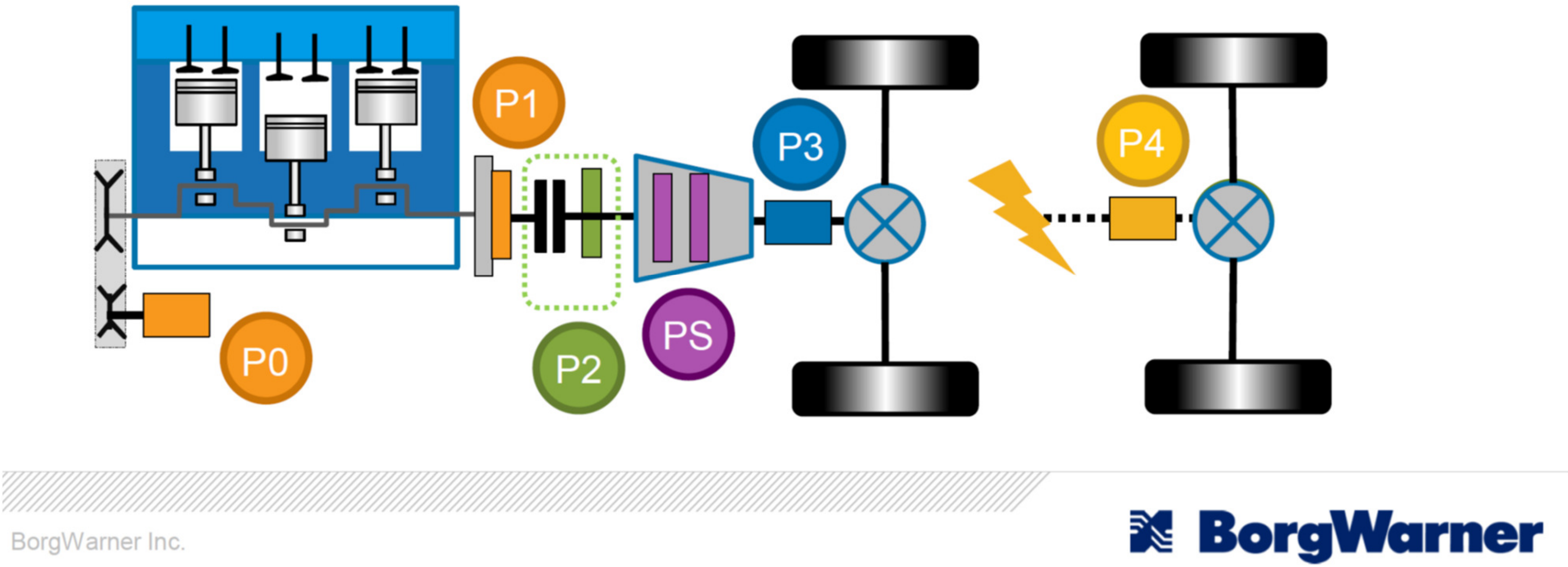
Hybrid definitions

- There is an effectively infinite range of possible configurations of hybrid electric powertrain
- Can be classified according to
  - Level of hybridisation
  - Motor position(s)
  - Arrangement of major components

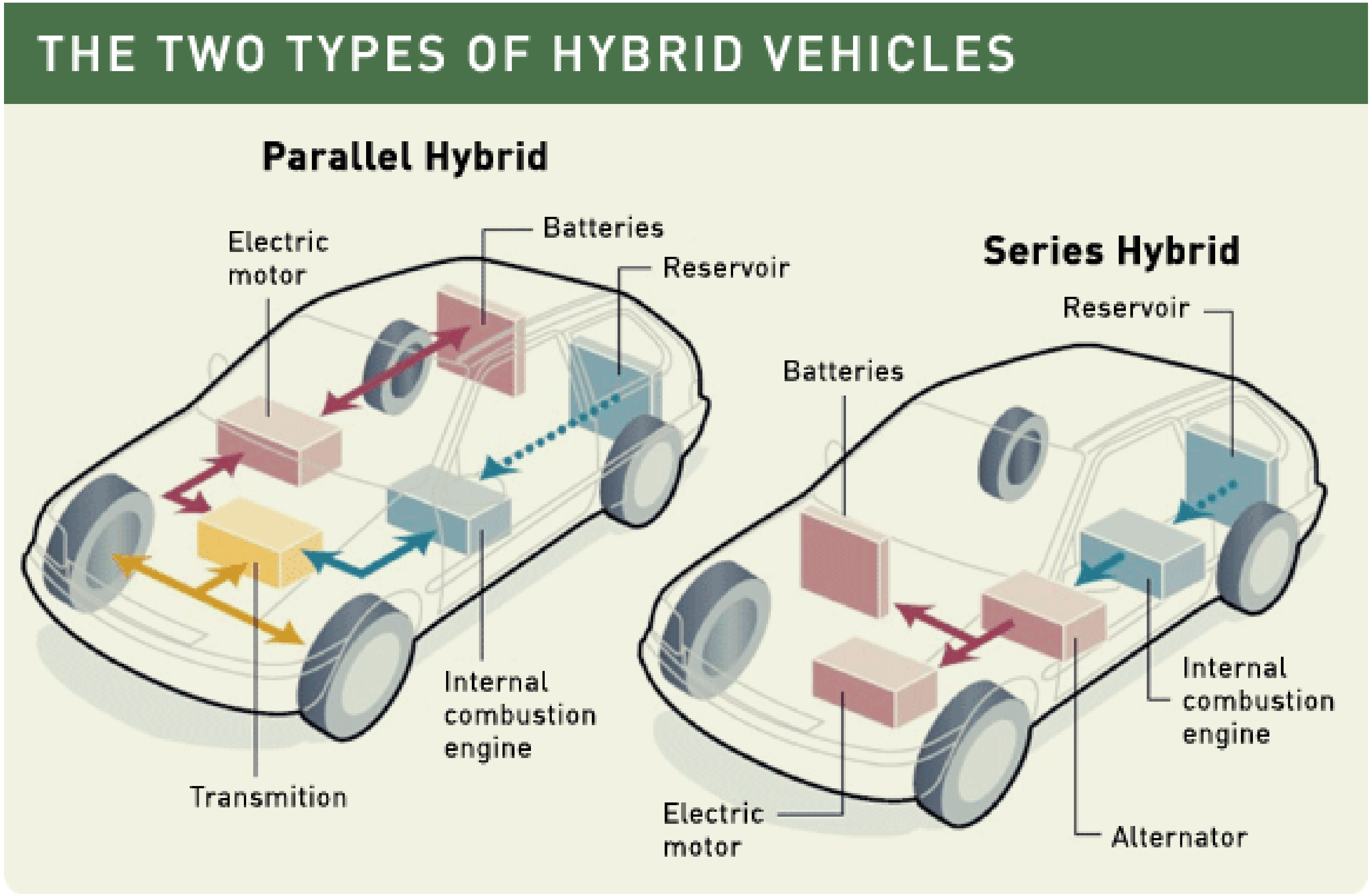
Levels of Hybridisation



Hybrid architecture - motor positon

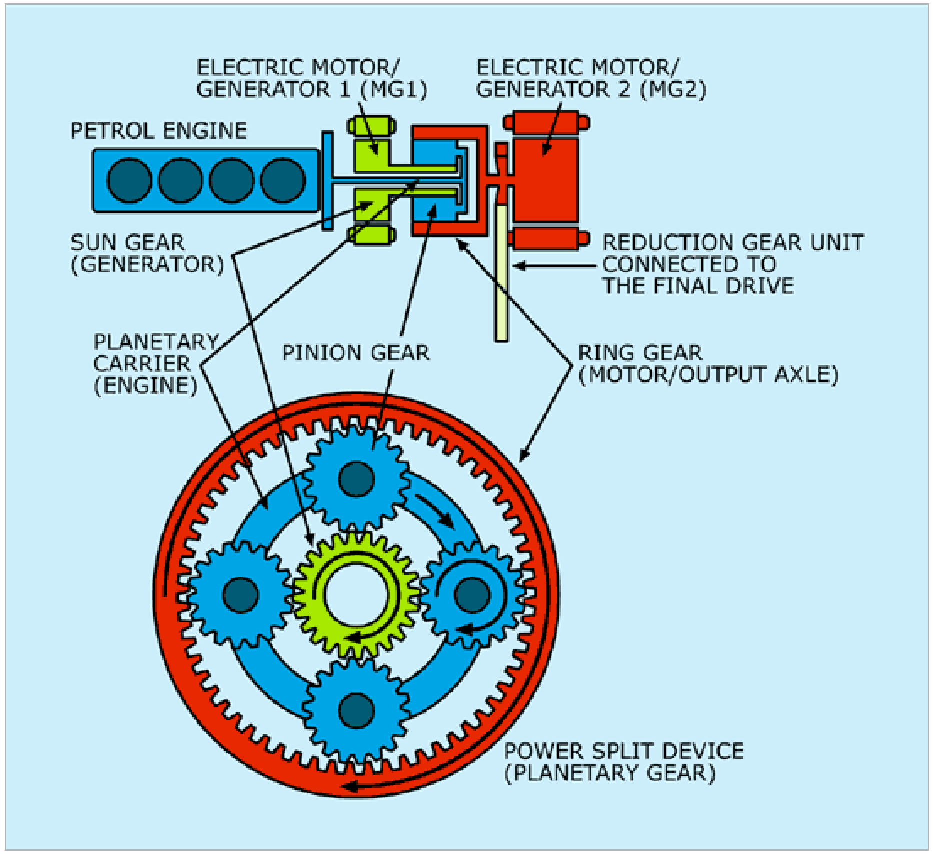


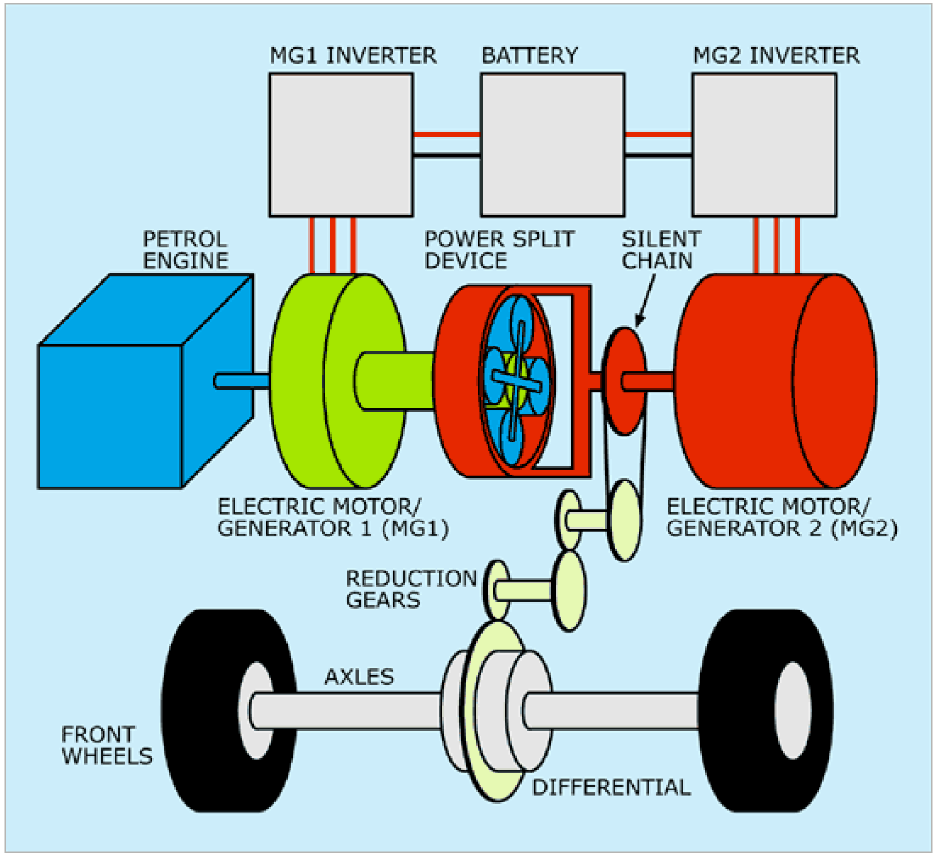
Arrangement of major components



Toyota Prius – setting the bar high

- Novel (then and now!) application of epicyclic transmission as a CVT in a hybrid powertrain

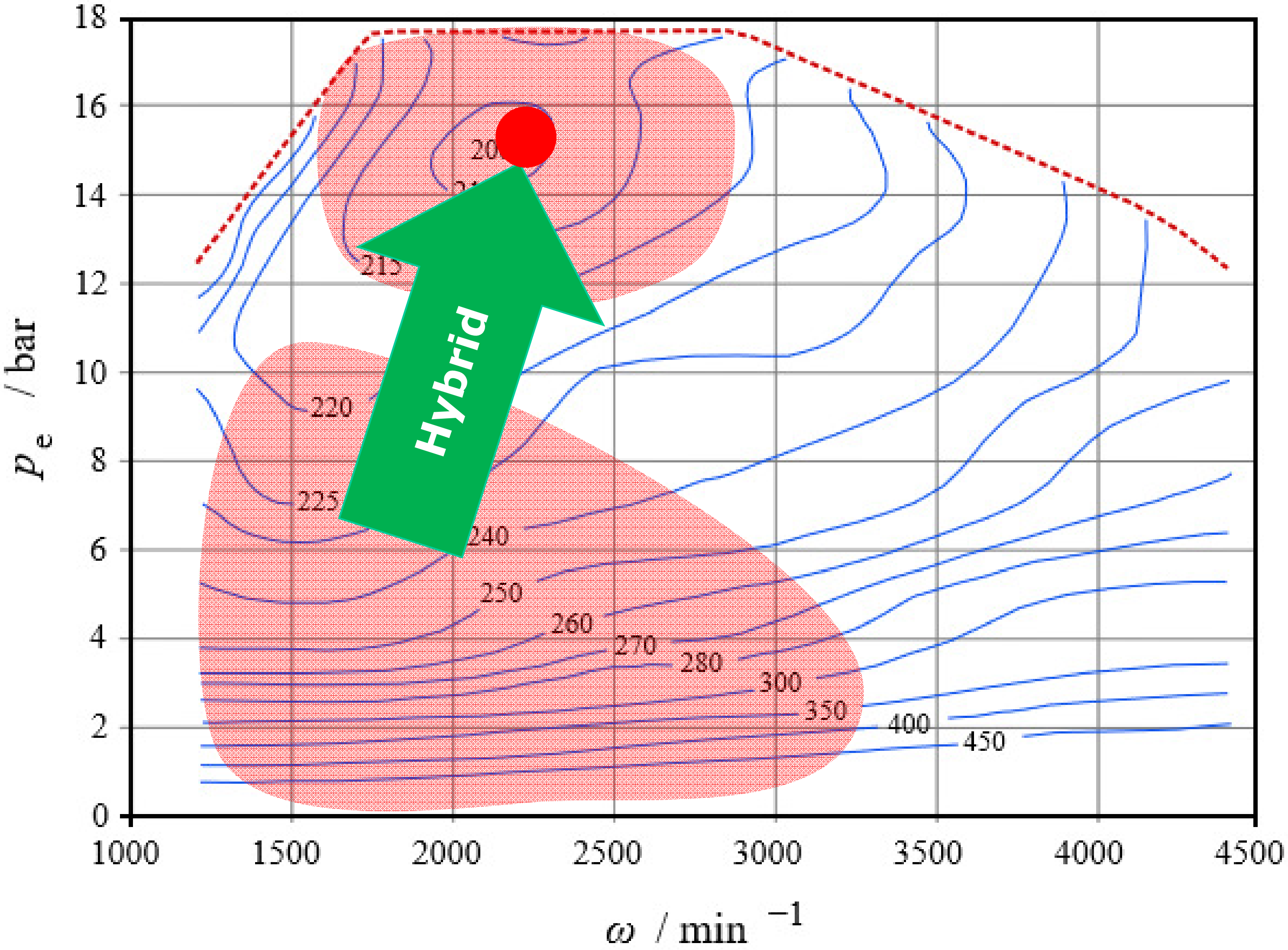




Impact on the IC engine

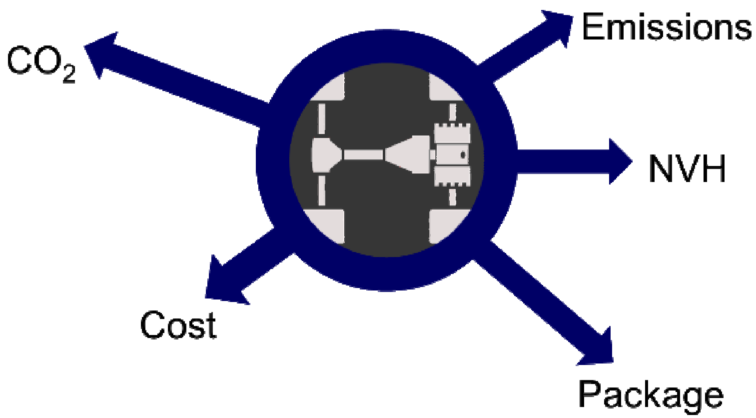
- IC Engine Duty cycle radically changes once the powertrain is hybridised
- Large influence on
  - Base engine design
  - Air path
  - Thermal management
  - Ancillaries
  - Optimisation

Hybrid impact on operating region

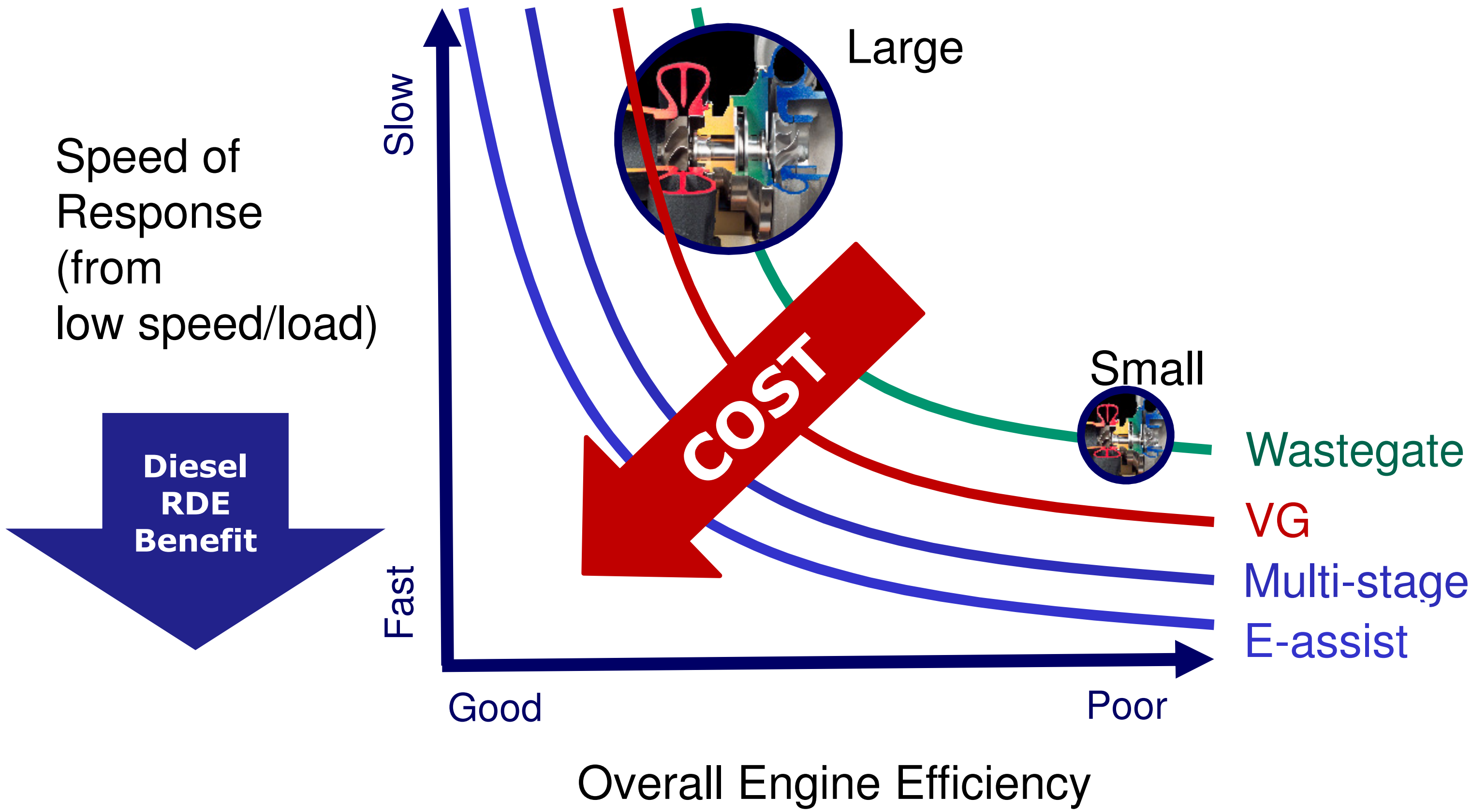


New base engine design freedom

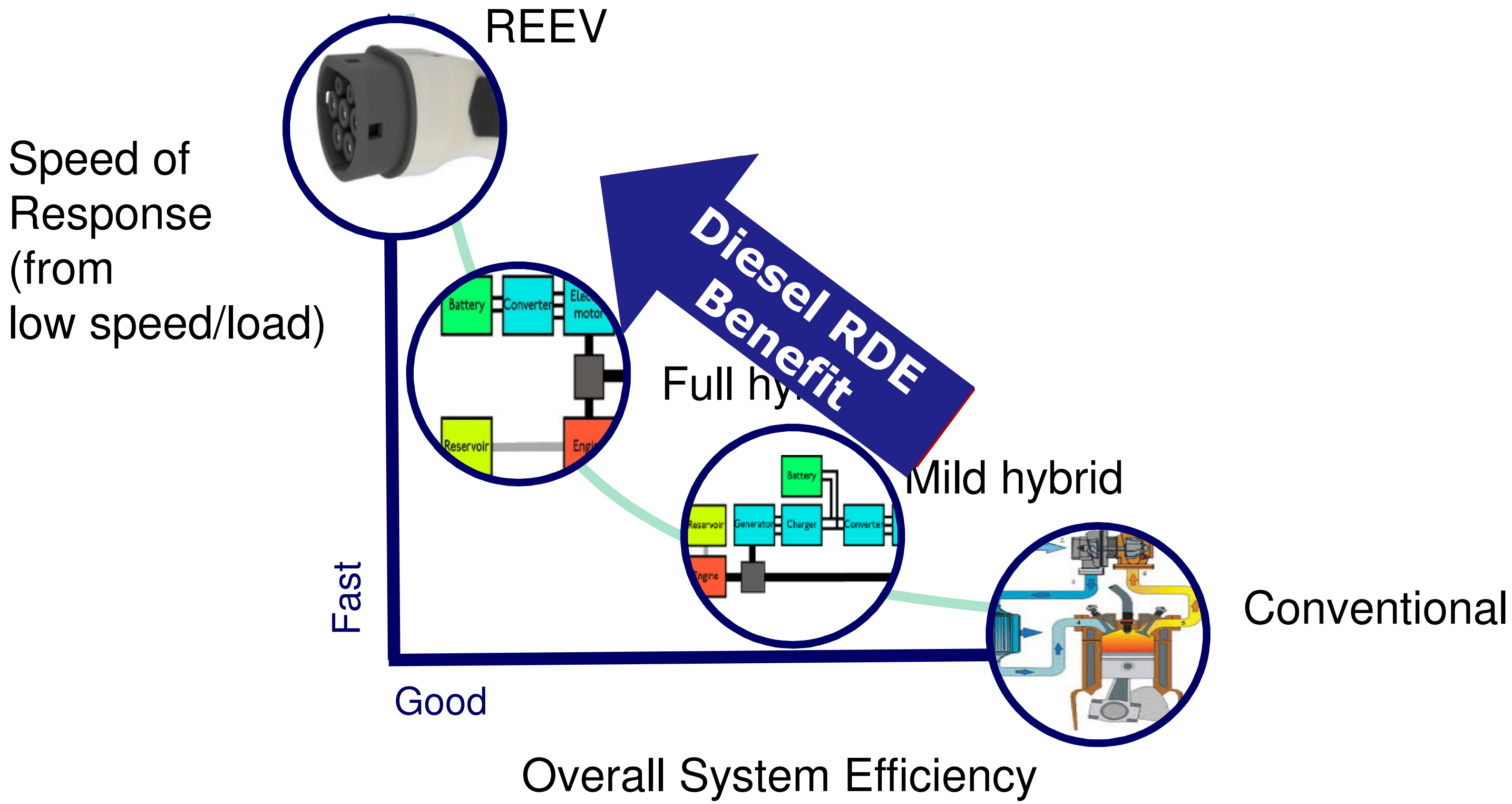
- Most modern engines are very flexible
  - Speed, load, temperature, transient
- Hybrids can reduce or remove this requirement for flexibility
- Reduced set of desirable attributes -
  - Efficiency
  - Cost
  - Clean
  - Sustainable
  - Package
  - NVH



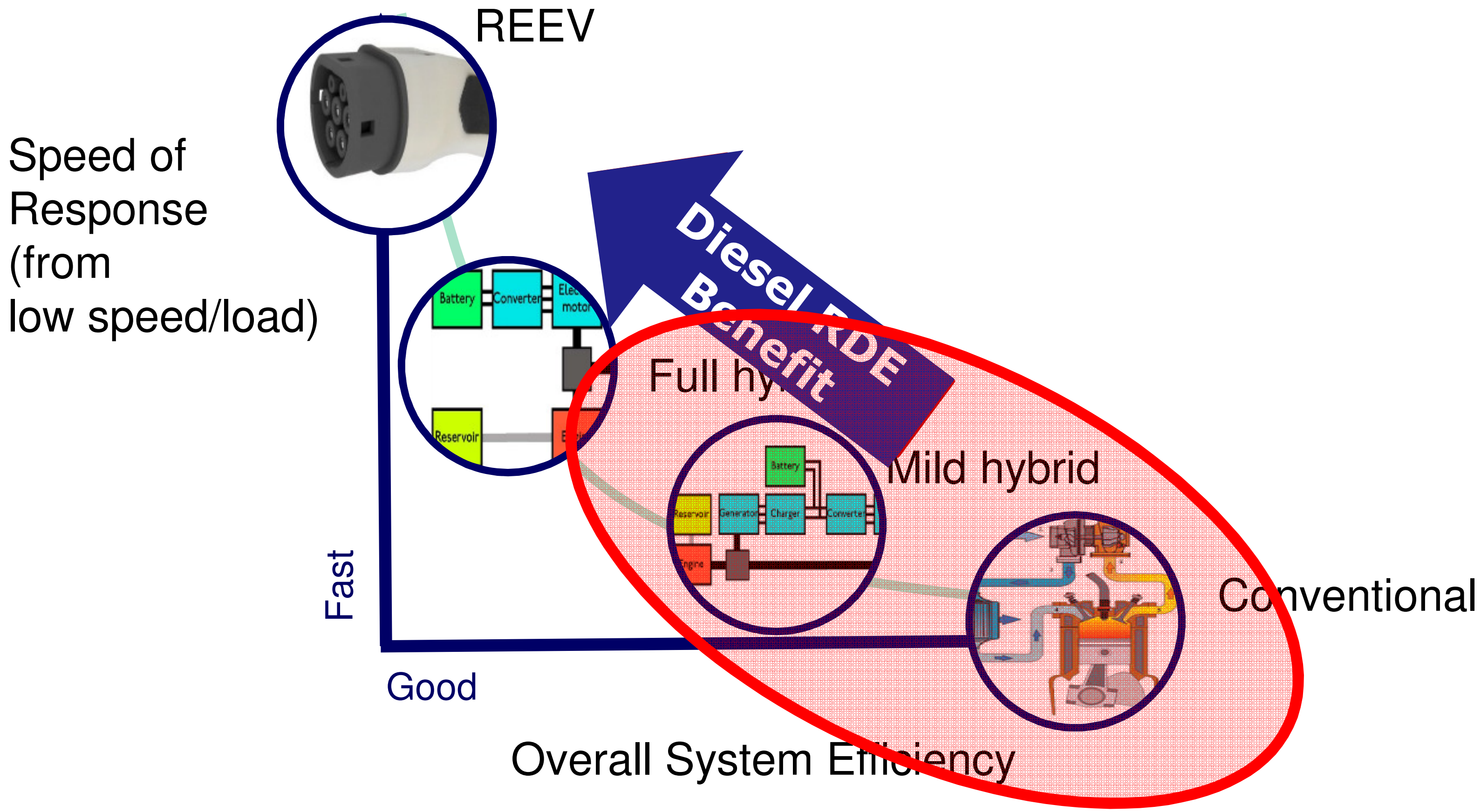
Historical trends - the tip-in/efficiency trade-off



Future dynamic response/efficiency trade-off



Future dynamic response/efficiency trade-off

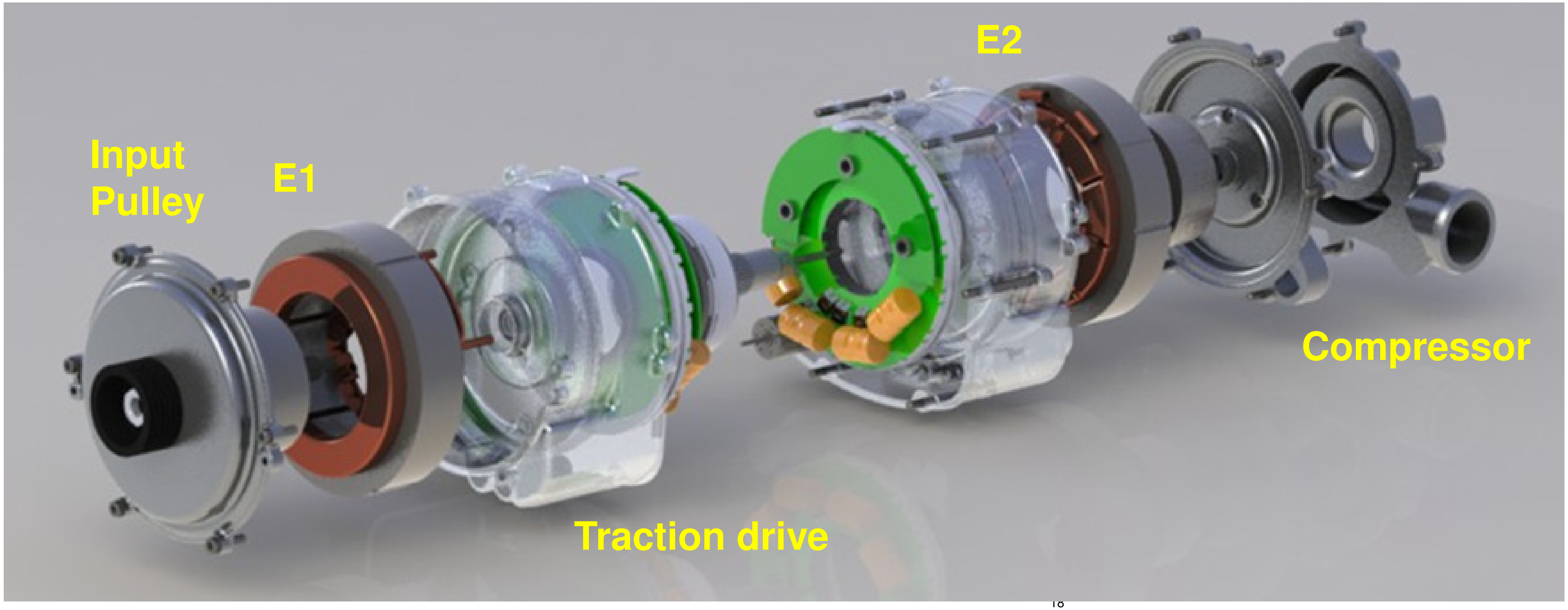


SuperGen

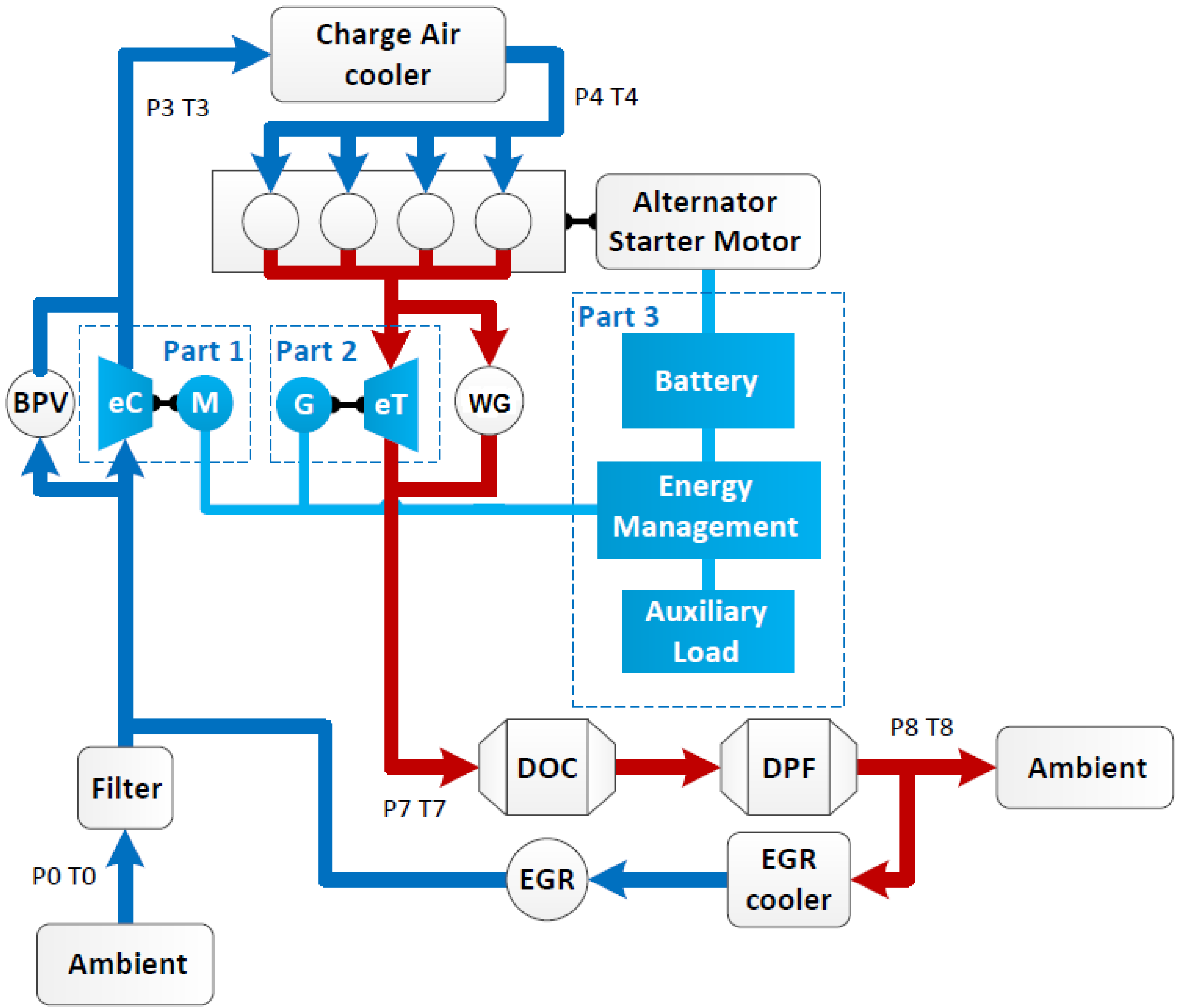
- Integrated starter-generator with hybridisation and supercharging functionality
- Mild-hybrid features including stop-start, recuperation and torque-assist functions
- Instead of one large ISG motor, uses two smaller e-machines which operate together in hybrid modes and independently for boosting functions
- Integrates power-splitting traction drive transmission with the two electric machines to provide a fully-variable, fast-response and efficient electro-mechanical transmission system
- Compressor speed completely decoupled from the crankshaft, >140:1 ratio at 1000rpm engine speed
- Conventional compressor technology based on turbocharger practice, compatible with EGR and multi-stage operation

For more details see SAE Paper Number 2015-01-1282

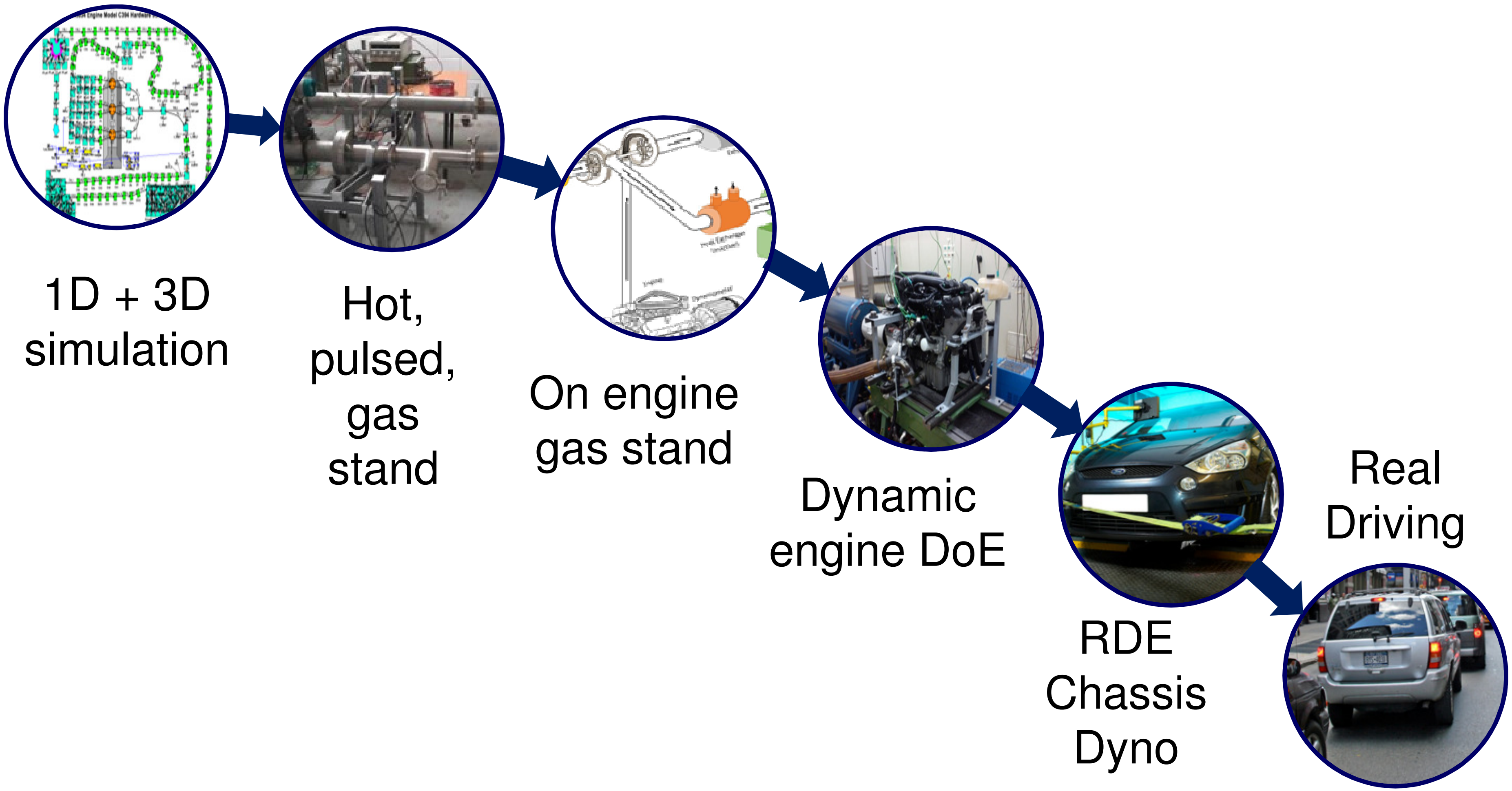
Supergen Arrangement



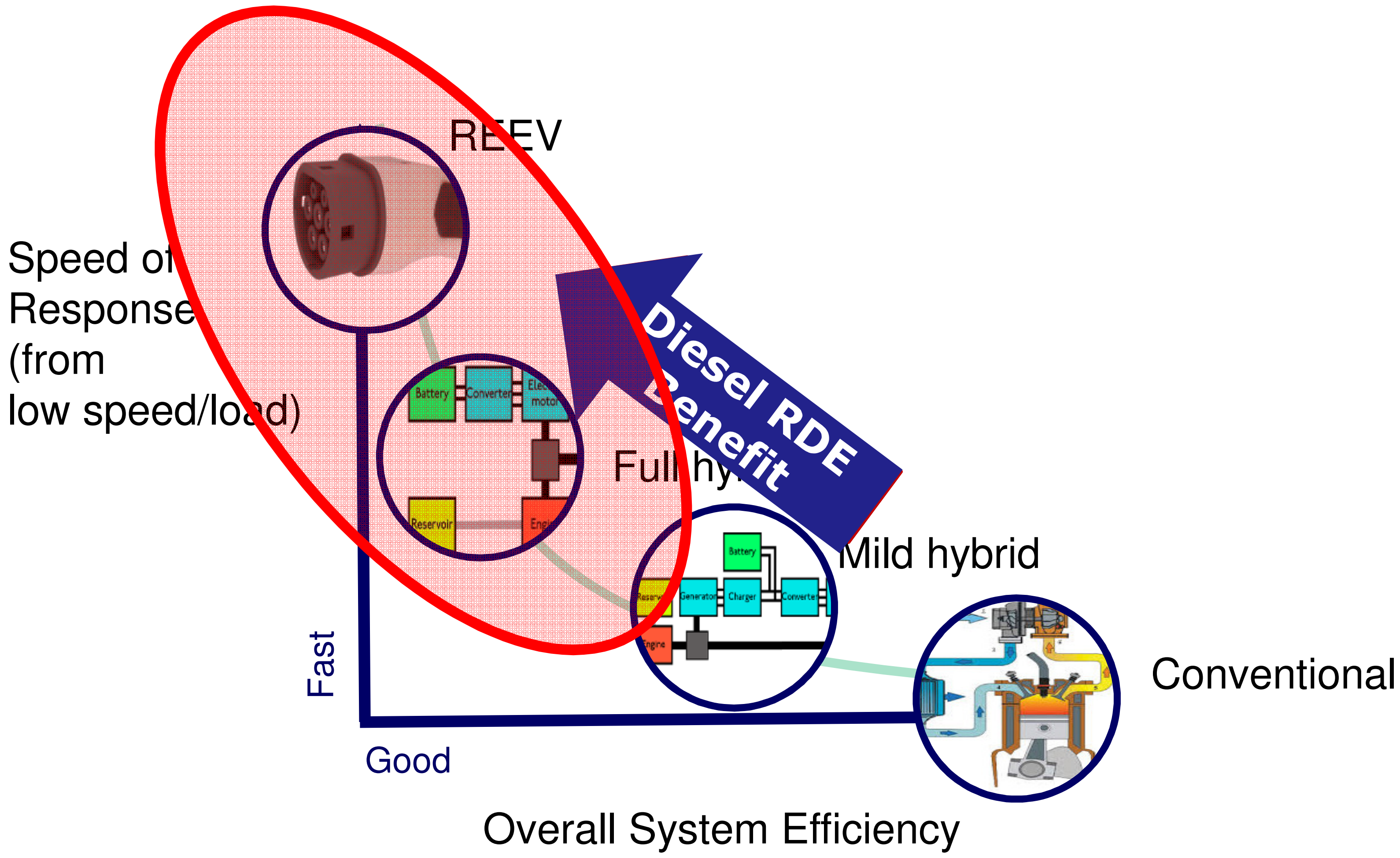
Fully Electric Turbocharger – Flexible Turbocompounding



Improving air path toolchain

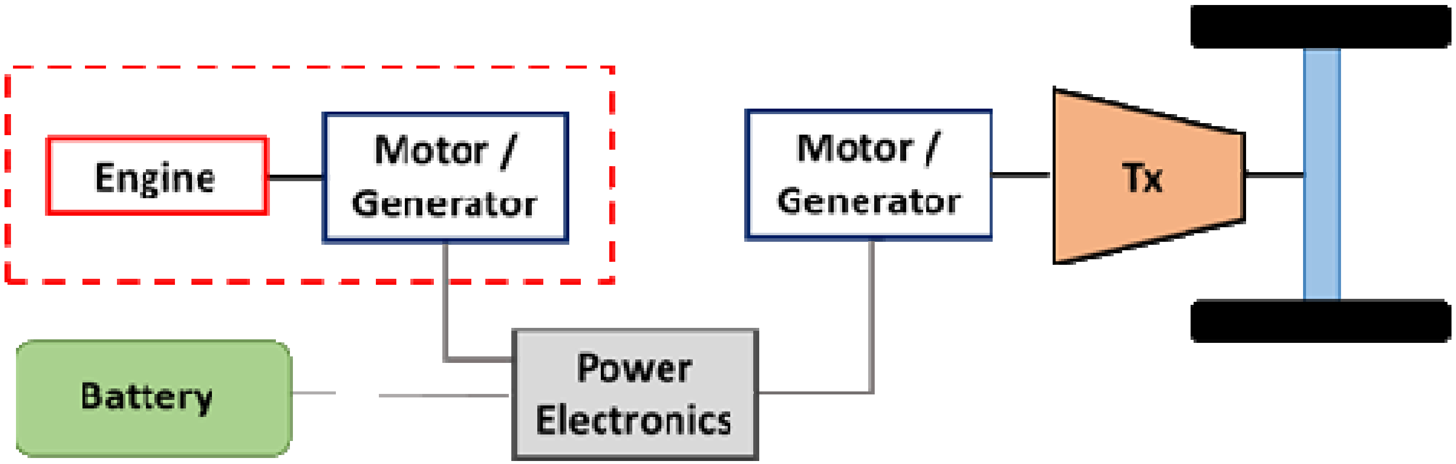


Future dynamic response/efficiency trade-off



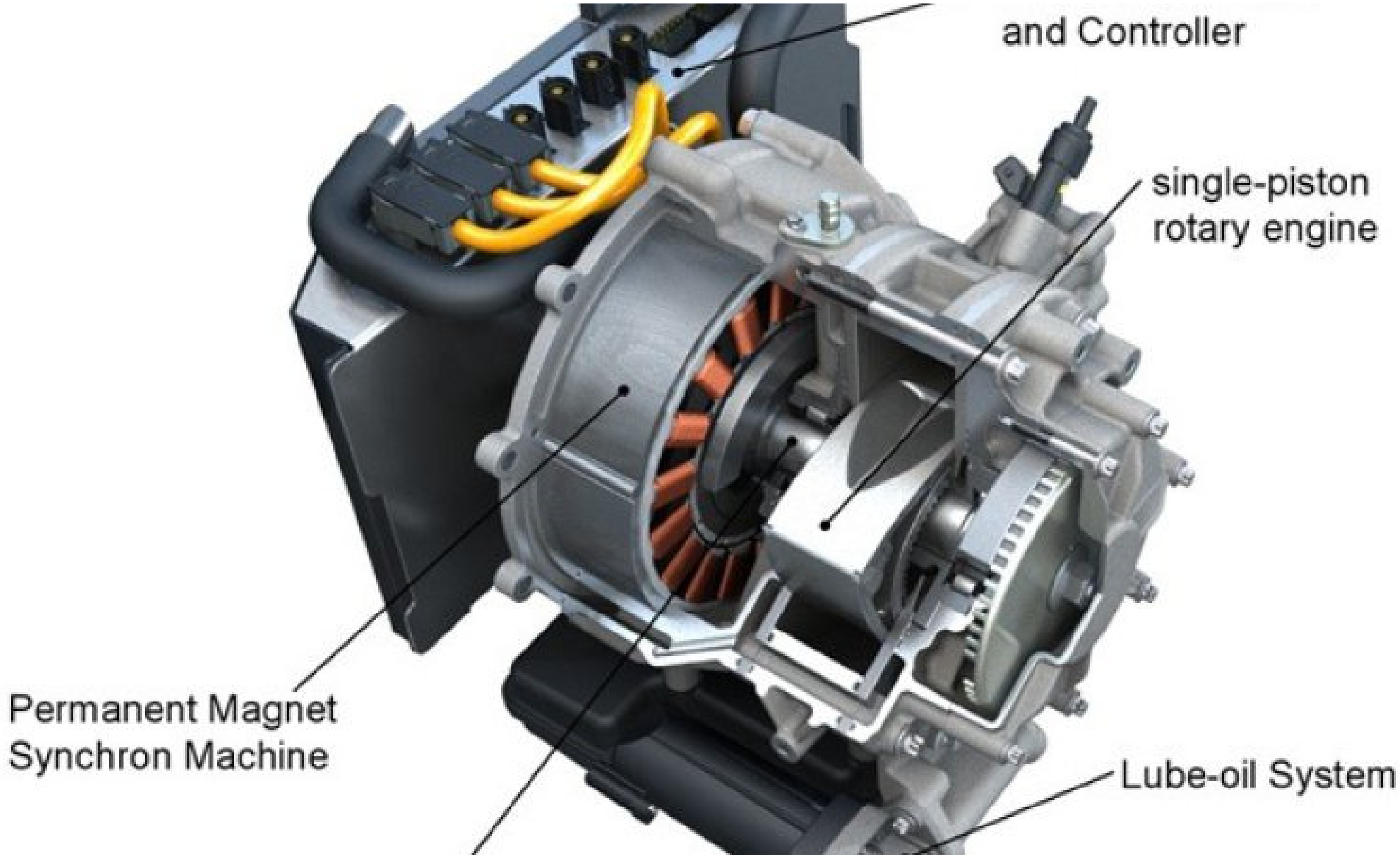
Range extended electric vehicle

- Smaller battery than pure EV
- Range extender of some form
  - IC Engine
  - Gas turbine
  - Rotary
  - Fuel cell



REEV Driveline Architecture

Other types of IC Engine?



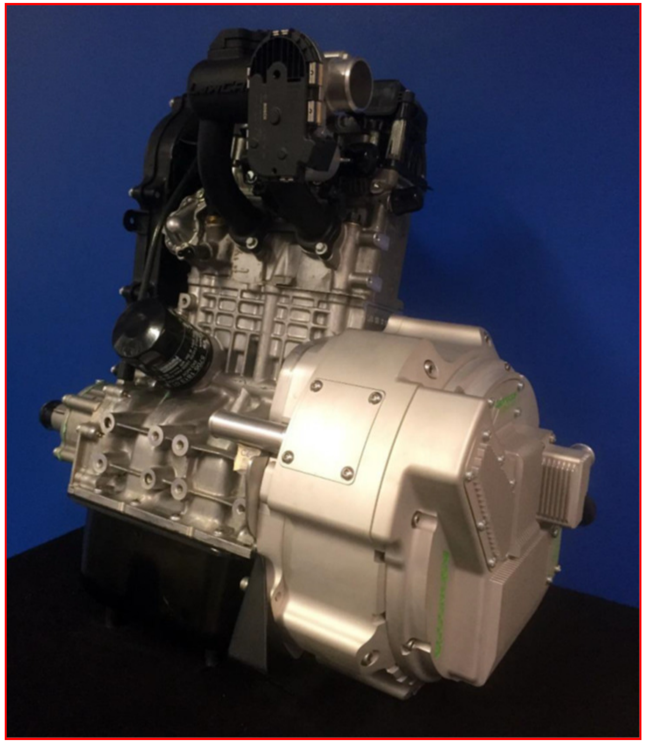
Low Cost Auxiliary Power Unit - LowCAP

- **Ashwoods Automotive Ltd**
- **Tata Motors European Technical Centre (TMETC)**
- **University of Bath**

Innovate UK funded CR&D project

Aim of the project

To design, model, develop and evaluate an industry first 'Low cost' auxiliary power unit for REEVs



The REEV landscape – some existing concepts

Mahle Powertrain

- 900cc 2-cylinder gasoline bespoke engine
- 30 kW at 4000 rpm

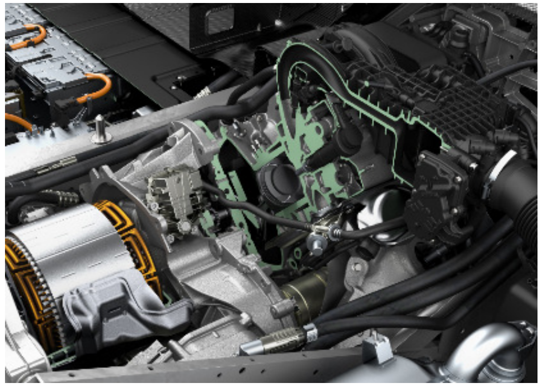
Lotus Engineering

- 1200cc, 3-cylinder gasoline bespoke engine
- 38 kW

Both were REEV demonstrators, yet to reach production stage

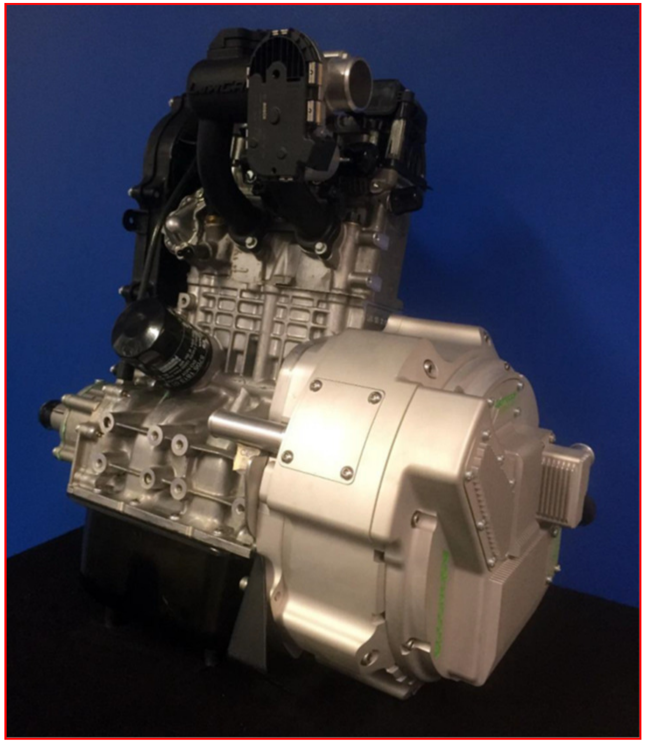
BMW i3

- 647 cc two-cylinder gasoline engine
- RE version costs additional US$3,850 over its fully electric version



LowCAP

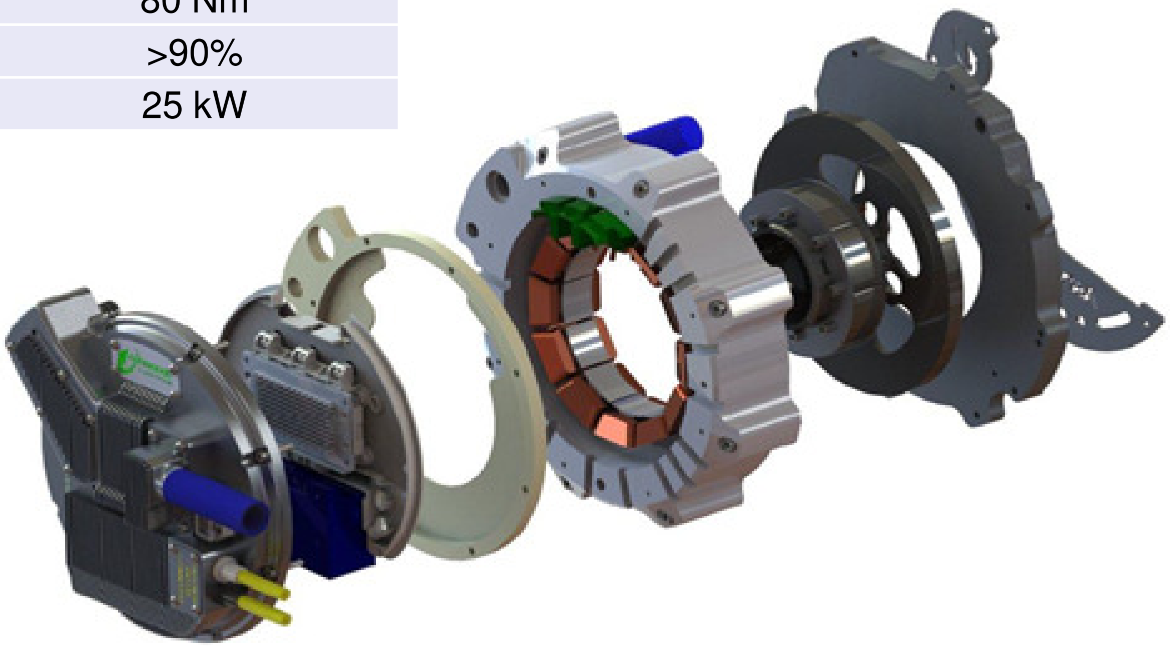
- Philosophy
  - Use a low cost, high volume, well optimised production gasoline engine
  - Innovative low cost motor and inverter by Ashwoods Automotive
- Low cost to maximise cost advantage over the proportion of the battery pack that it is effectively replacing
- 20 – 25 kW with lowest ESFC < 270 g/kWh
- Integrated engine, generator and power electronics cooling system
- Target vehicle – European ‘C’ segment



Prototype IPM machine with integrated inverter

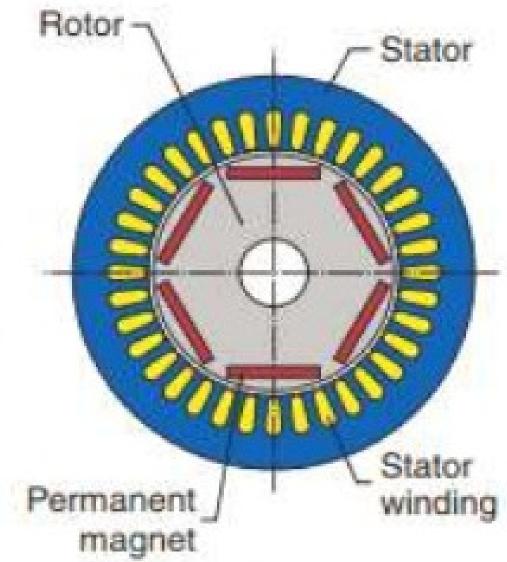
- Interior permanent magnet (IPM) machine with integrated inverter developed by Ashwoods Automotive Ltd
- Low cost motor and inverter solution

DC Voltage	350~450 V
Peak inverter DC current	100 A
Operating speed	4000 -5000 rpm
Cranking torque	80 Nm
Generator/Inverter efficiency	>90%
Continuous power	25 kW

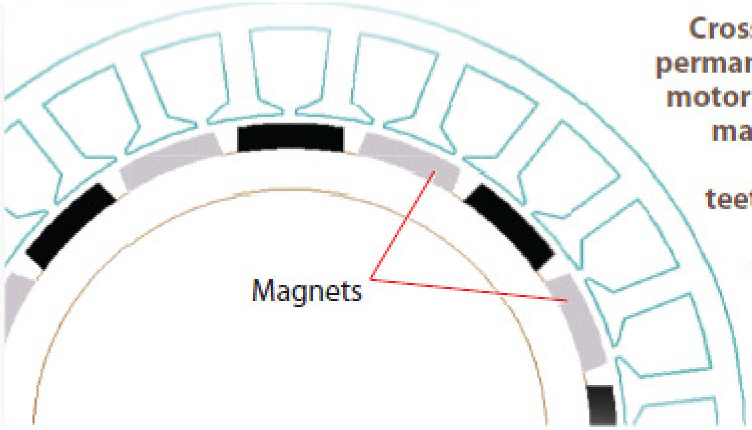


Interior Permanent Magnet Machine

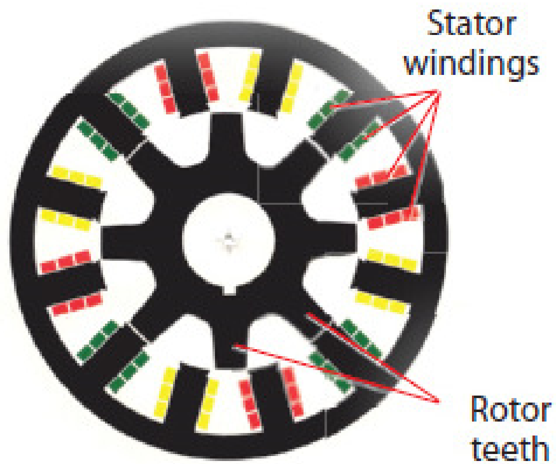
- Magnets buried inside rotor, not surface mounted
- Combines features of permanent magnet and switched reluctance machines
- Reduced magnet size relative to PM
- Some of the performance comes from reluctance torque



Interior permanent magnet motor (IPM).



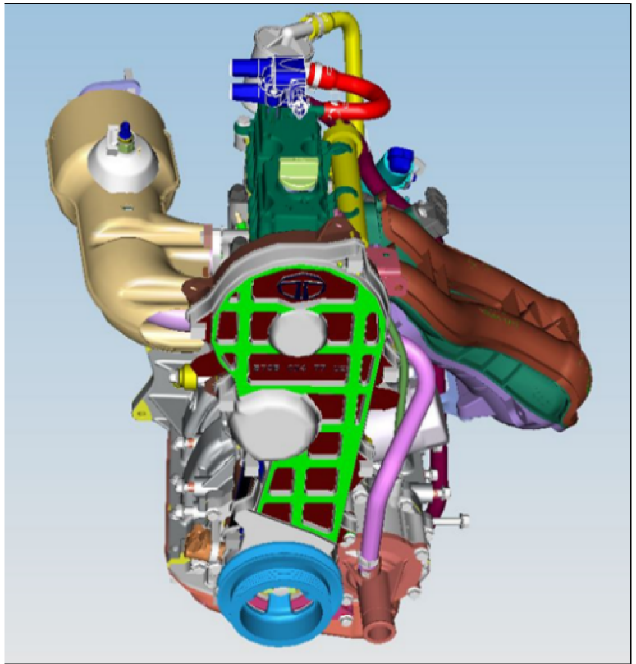
Cross section of a permanent-magnet motor with surface magnets on the rotor. Stator teeth are shown without windings for clarity.



Baseline Engine Specification and Performance

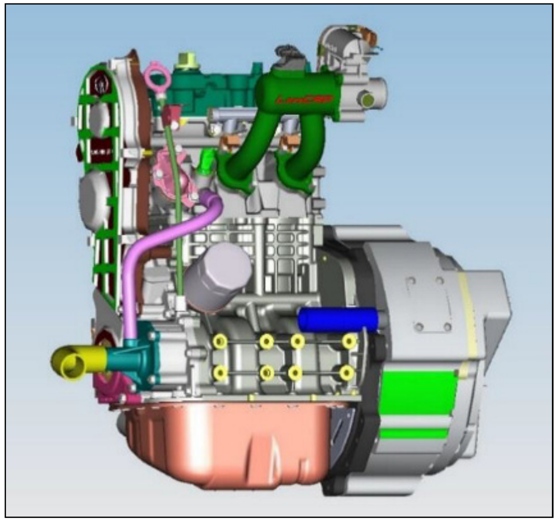
- Engine – Tata Motors 273 2-cylinder gasoline engine for Indian market application – Tata Nano
- High volume production, very low cost

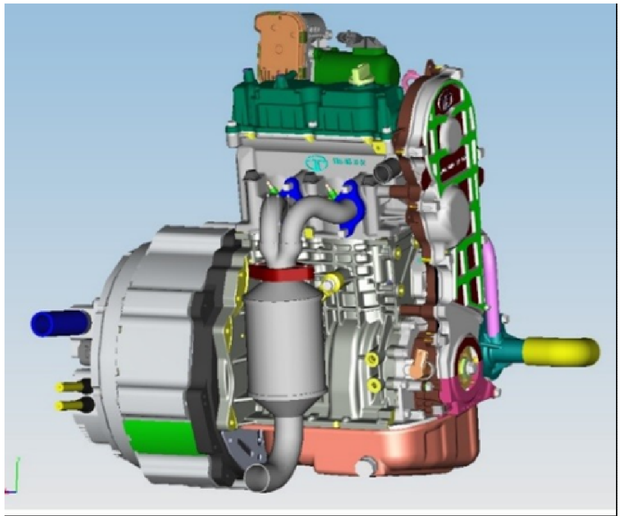
Displaced volume	**624 cc**
Bore / Stroke	**73.5 mm * 73.5 mm**
Compression ratio	**10.3:1**
Maximum power	**37 bhp @ 5500 RPM**
Maximum torque	**51 Nm @ 4000 RPM**
Firing order	**1 -2 (360˚ firing)**
Number of valves	**2 per cylinder, single fixed overhead camshaft**
Fuel System	**Sequential port fuel injection with closed loop A/F control**



Opportunities for improvement in REEV application

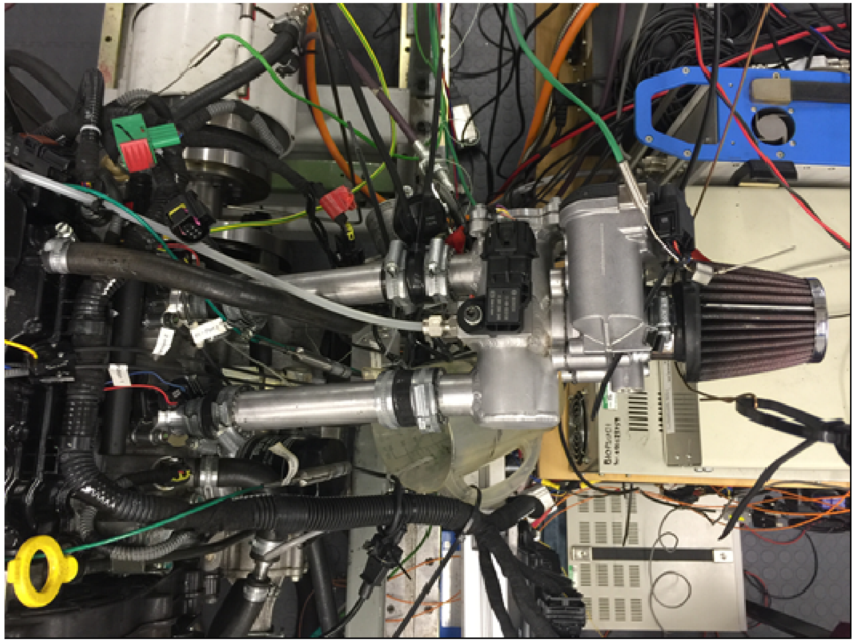
Sytem Efficiency	Volumetric Efficiency	Combustion Efficiency	Parasitic Losses	NVH
New EMS Electronic throttle System level optimisation	• Optimised Intake manifold • Optimised Exhaust manifold • 3 way Catalyst	• Operation at lambda 1 across a wider portion of the engine operating range • Spark timing optimisation	• Electric coolant pump • Common engine and generator coolant system • Optimised thermal management strategy	• Physical isolation • In cycle speed stabilisation

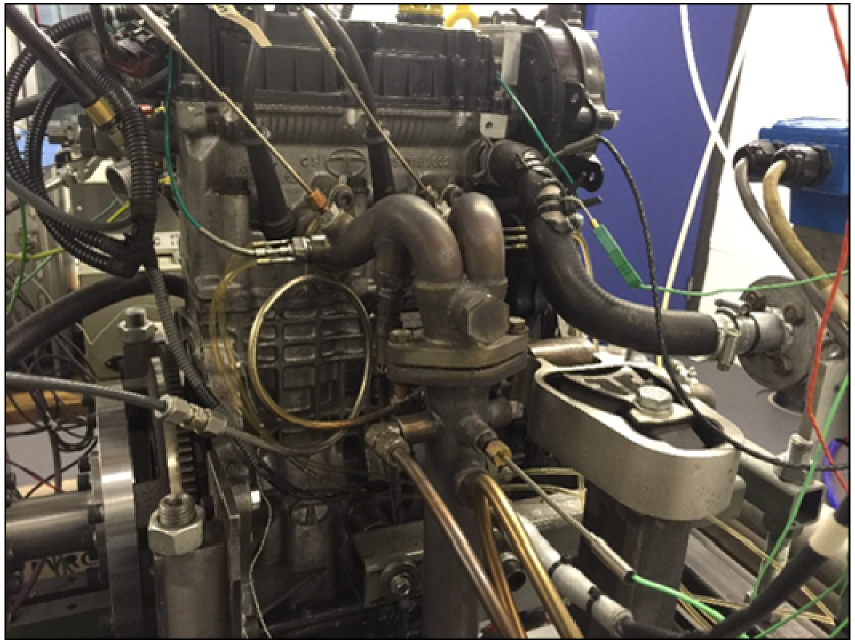




Optimised Intake and Exhaust Manifolds

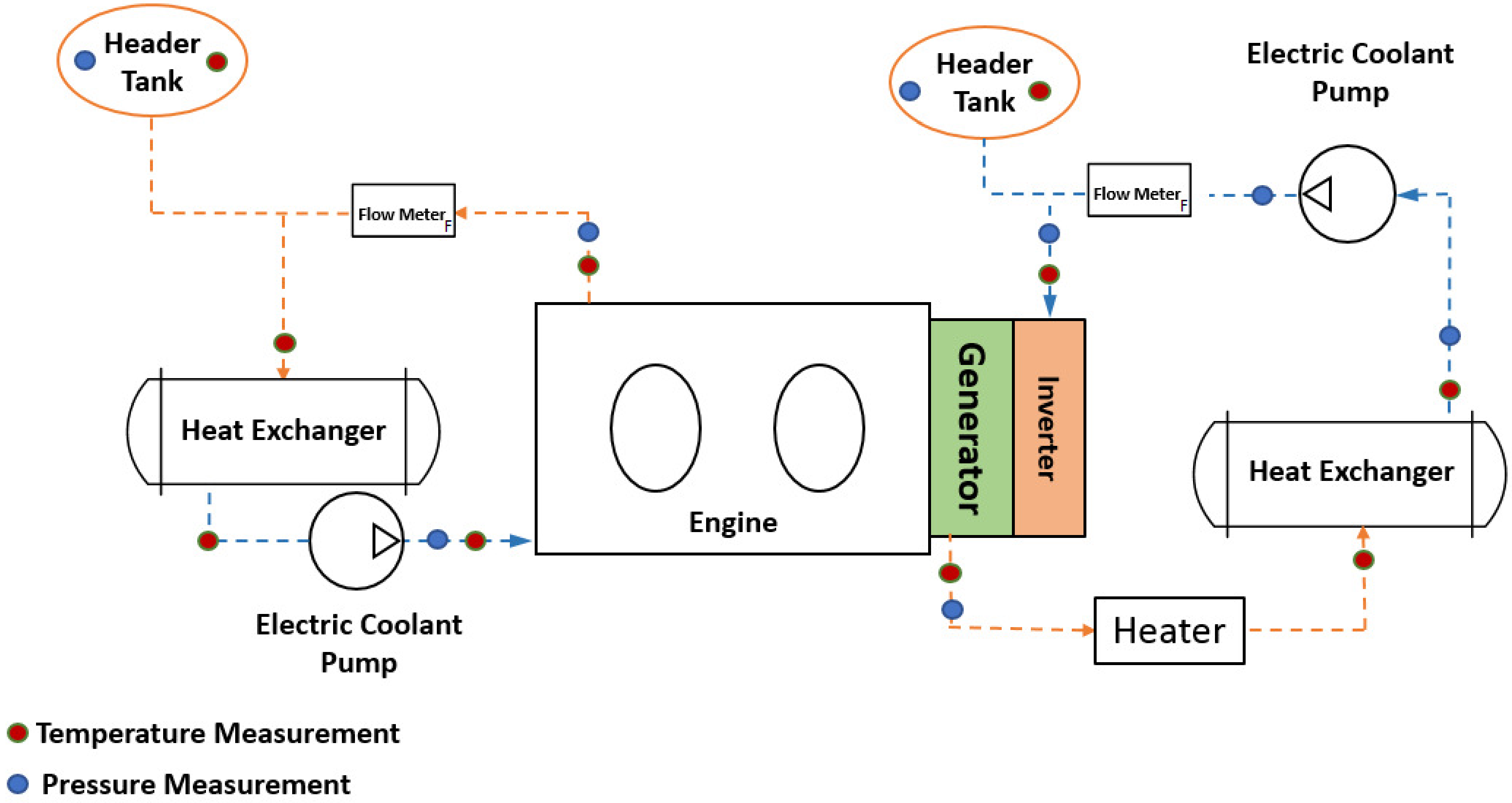
- Minimise package volume
- Improved VolEff between 2000 – 4500 rpm
- GT-power 1D Simulation by TMETC
- Optimized runner length considered too long from packaging perspective
- Resonator system selected for its compact size with only a small reduction in volumetric efficiency





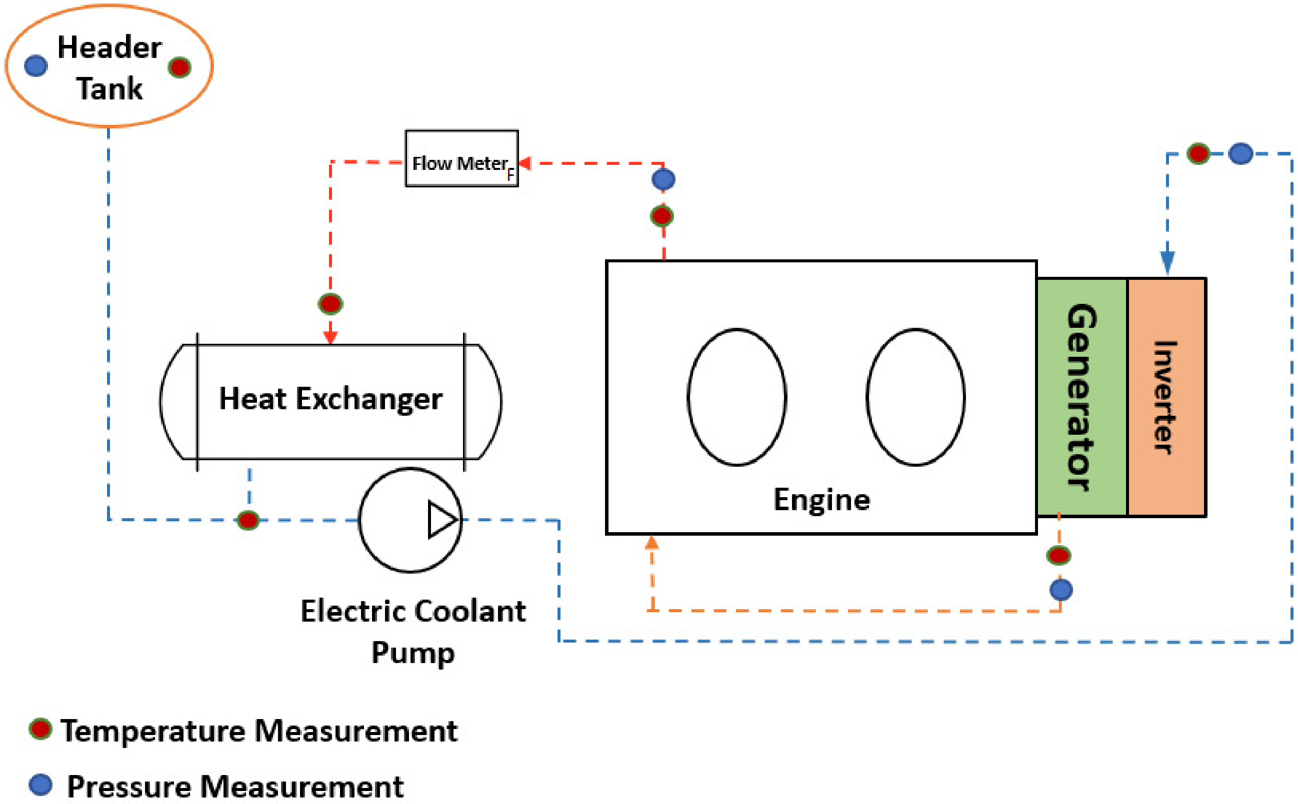
APU cooling topologies (1)

- Separate coolant loops for engine and generator
- Duplication of pumps and heat exchangers.
- Permits optimum control of engine and generator coolant temperatures for maximum efficiency



APU cooling topologies (2)

- Combined coolant loop for engine and generator
- Simplified overall package
- Reduction in component cost/mass
- Compromise in engine and generator coolant temperature to achieve satisfactory performance

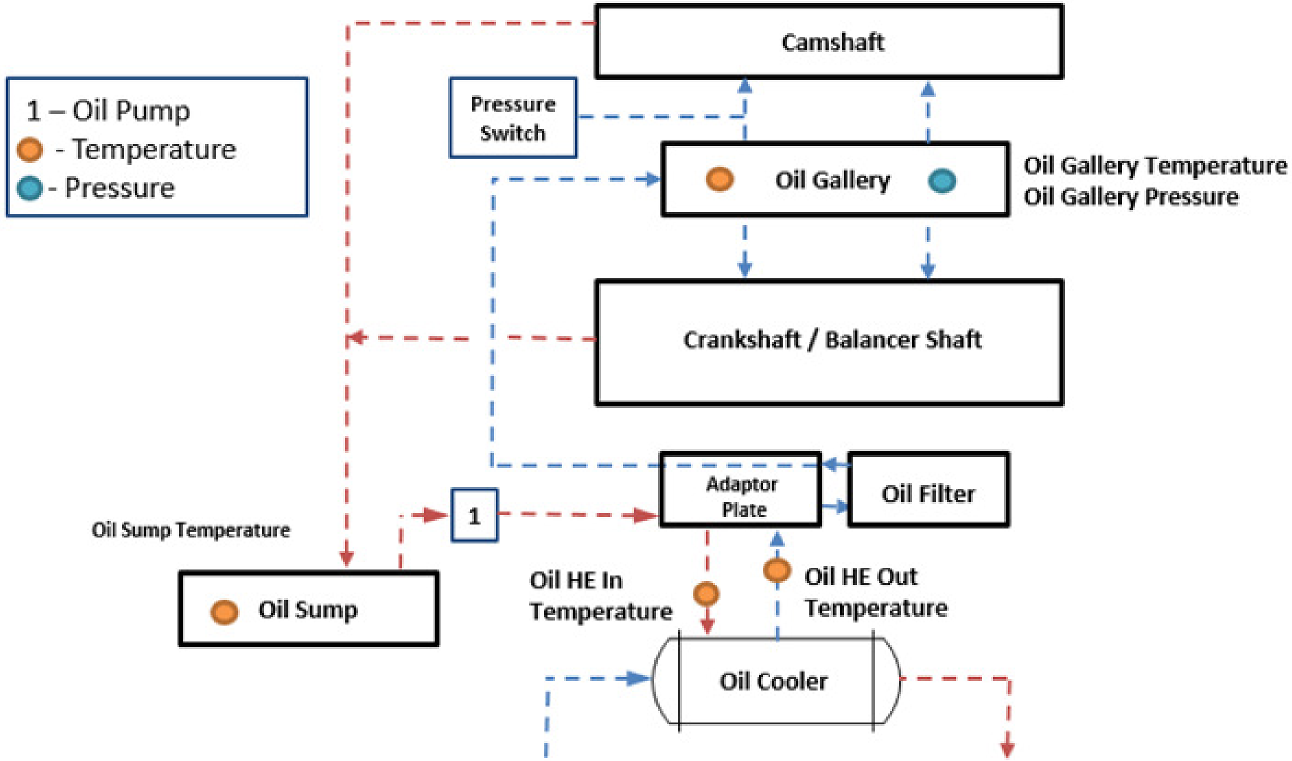


Installation of Electric Water Pump (EWP)

- Disadvantages of Mechanical Pump
  - Inevitably oversized for normal operation
  - Production engine – mechanical gear driven coolant pump
  - Continuous parasitic loss
- Advantages of an EWP
  - Improvement in fuel economy
    - Demand driven cooling independent of engine speed
    - Reduces impeller energy consumption
  - Flexibility in component packaging
  - Facilitates implementation of common coolant loop for engine and liquid cooled generator and inverter

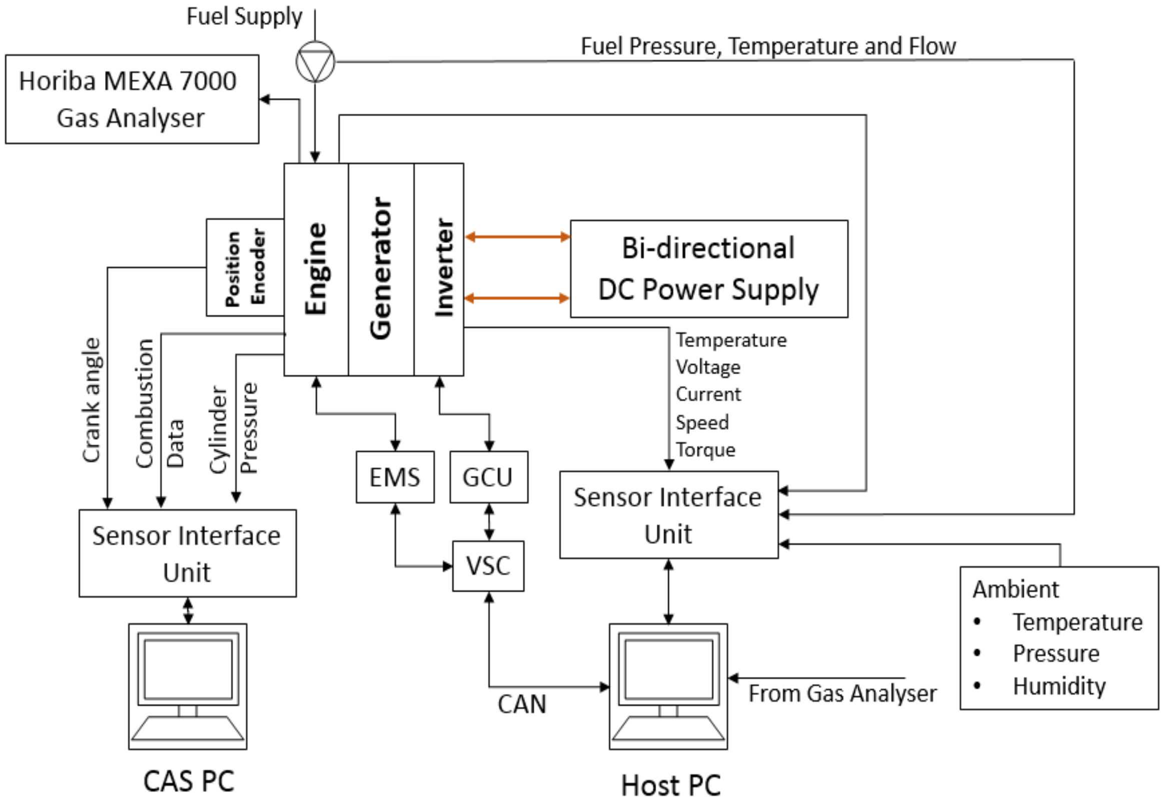
Oil circuit

- Engine oil gallery temperature controlled independently of coolant temperature*
- Provided greater degree of flexibility for optimisation study



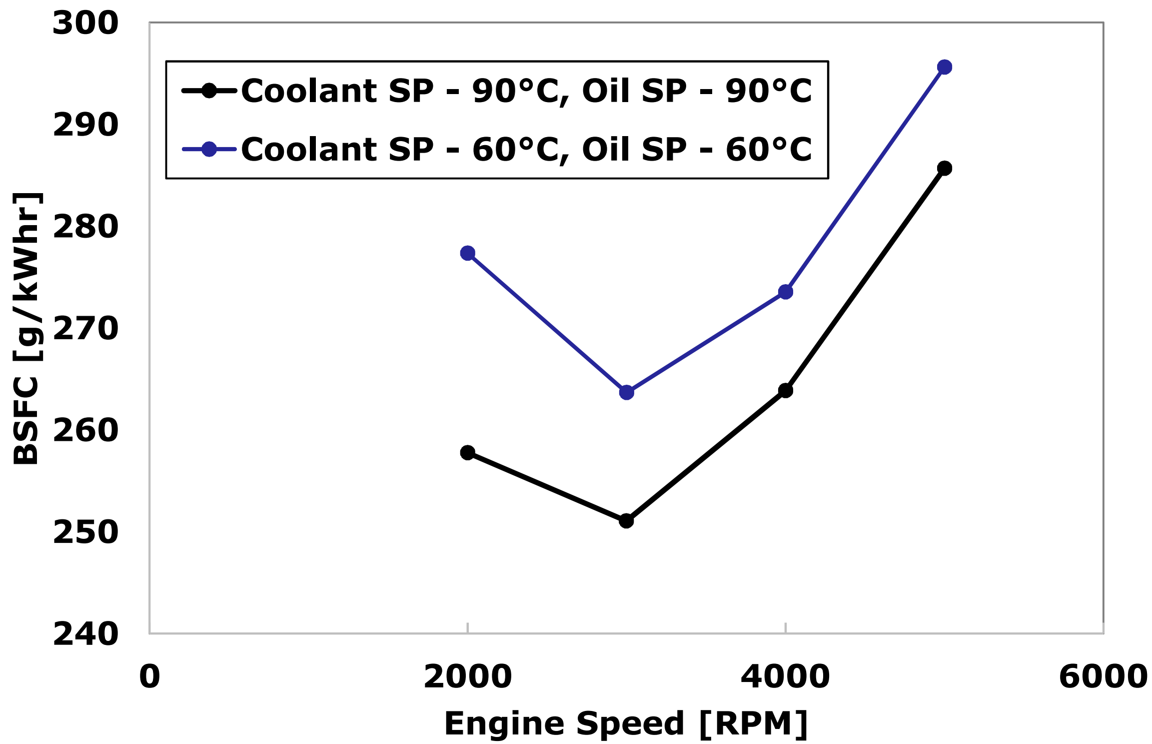
APU test-bench facility

- APU test facility at University of Bath
- Dyno 1 for engine-only experiments
- Dyno 2 for motor-only experiments
- APU power output connected to a bi-directional DC power supply for battery emulation



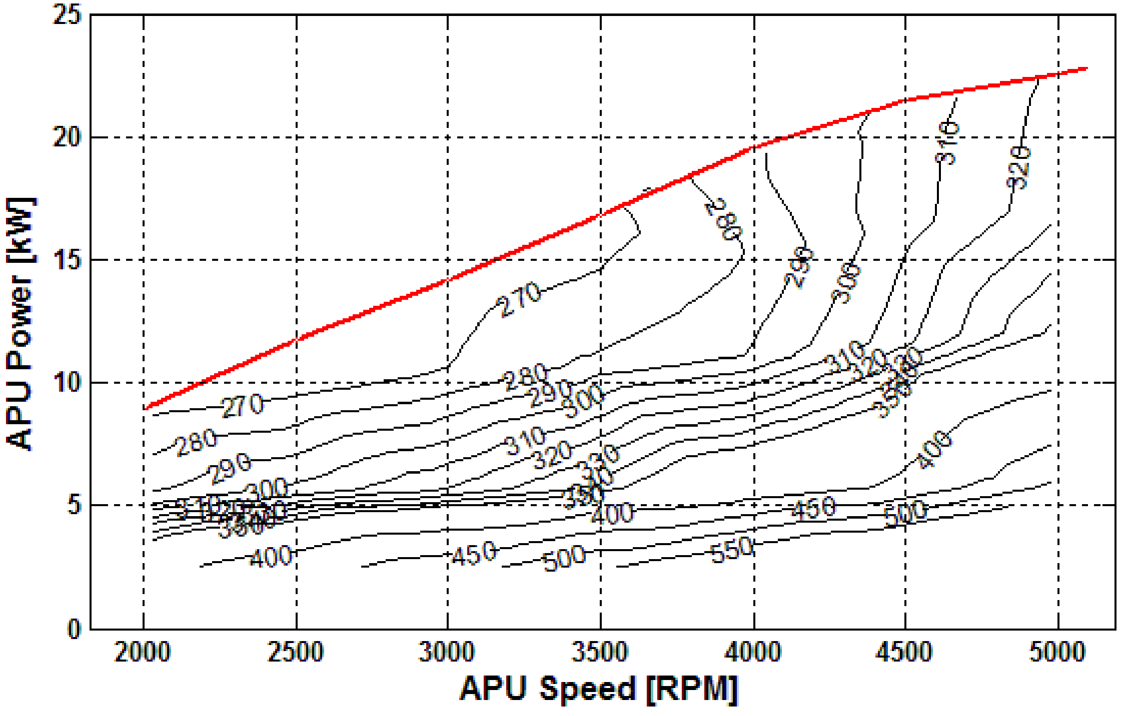
Thermal survey of engine

- Engine BSFC increased by c. 5% under wide open throttle conditions when oil and coolant temperatures lowered from 90°C to 60°C



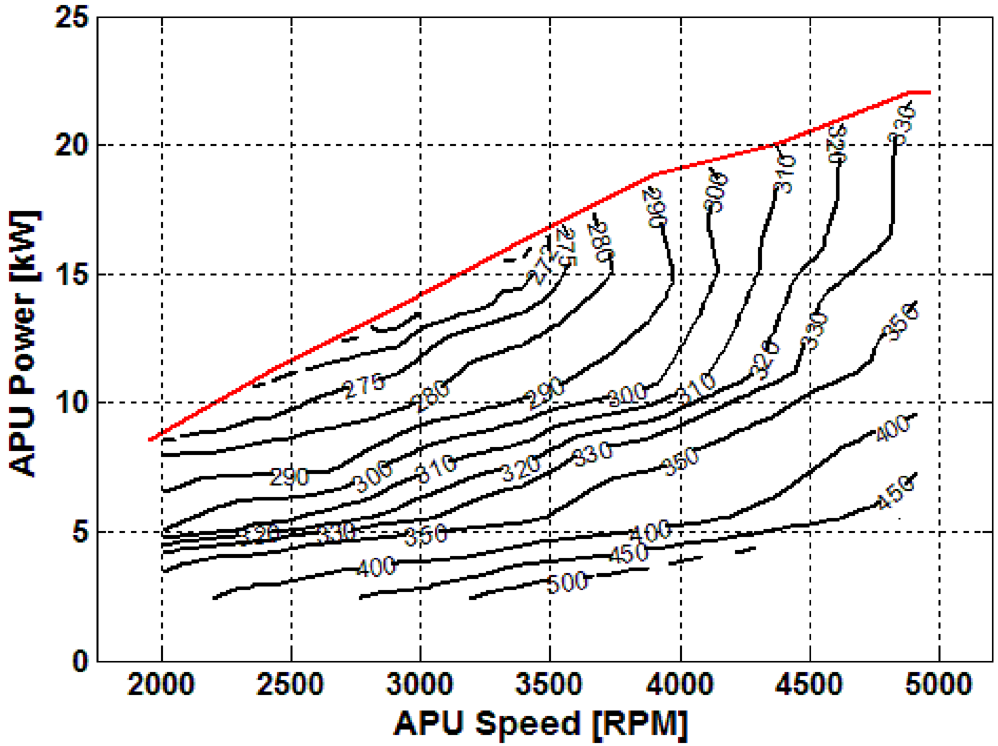
Target setting for APU performance

- Independent coolant loops
- Generator coolant inlet set point 35°C
- Engine coolant outlet set point 90°C
- Engine oil gallery set point 90°C
- Best ESFC of **260** g/kWh at 2500rpm



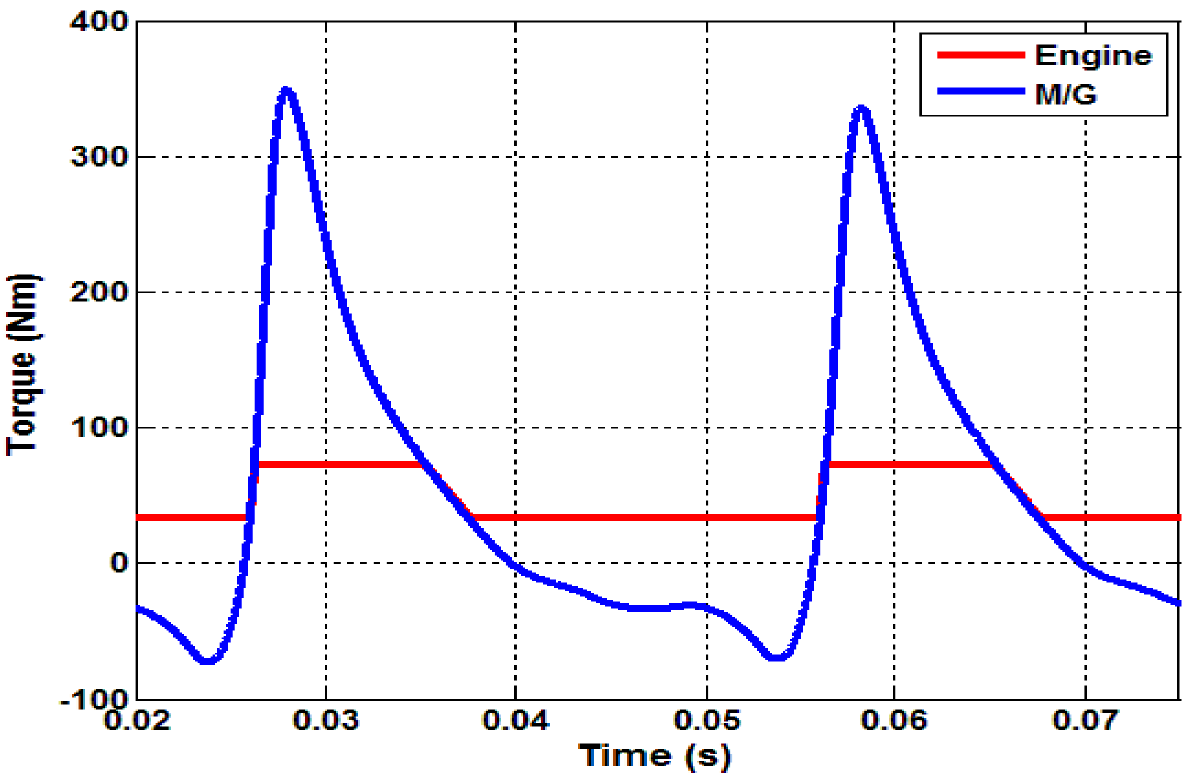
System optimisation considering inverter thermal state

- Oil and coolant set points 80°C
- Small increase in ESFC observed
- Best ESFC of 271 g/kWh at 2500 and 3000 rpm



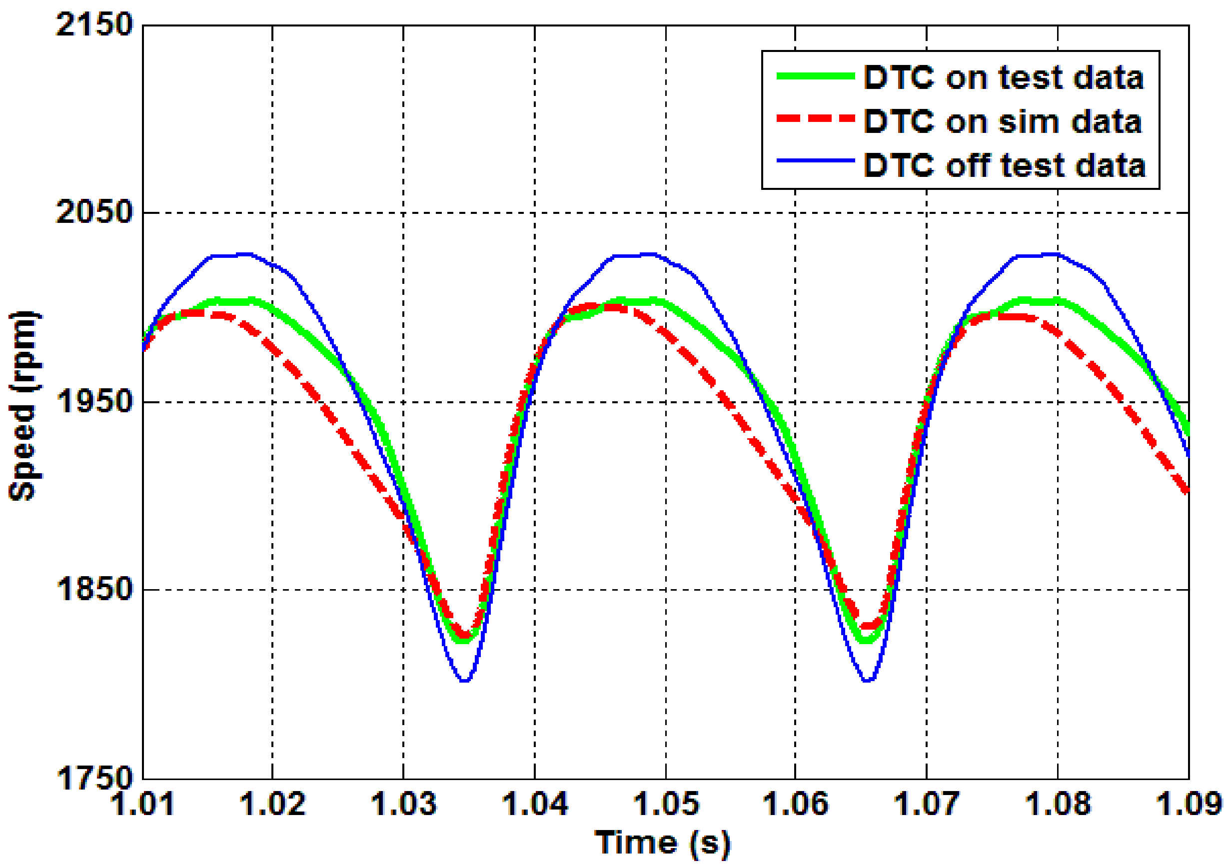
In cycle speed control

- Use the generator as an actuator to counteract IC engine torque pulsations
- Limited authority due to practical constraints on generator sizing



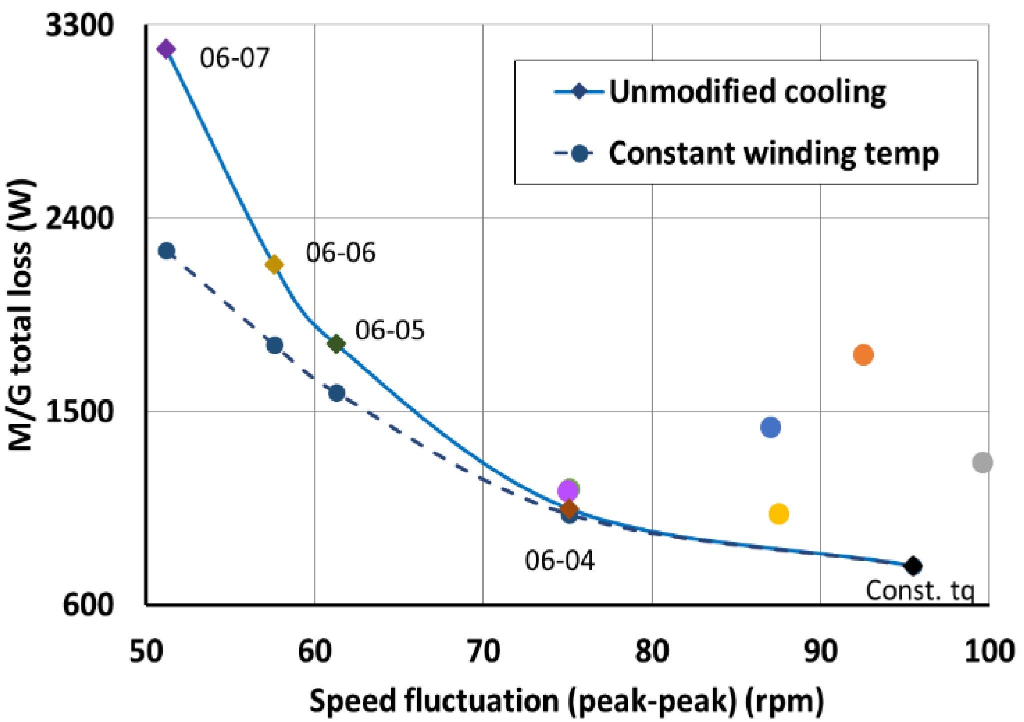
Speed ripple improvements

- Comparison of measured and speed ripple with and without dynamic torque control
- Simulated ripple also shown



Speed control v motor losses

- Pareto front of losses against in cycle speed fluctuations
- Non linear copper losses cause elevated losses as greater variation in torque selected, even with unchanged mean power
- Improved cooling can help



Conclusions

- Most powertrains are likely to be hybridised by 2025?
- IC Engine has a changing role
  - Air quality a key driver
  - System level optimisation is essential (even more so than previously!)
  - Efficiency / cost trade off redefined

Two characteristic branches

- Increased complexity
  - Downsized
  - Fast air path
  - Flexible
  - Core mild hybrid prime mover
- Simple and efficient
  - High thermal efficiency
  - Limited dynamics
  - REEV or full hybrid

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