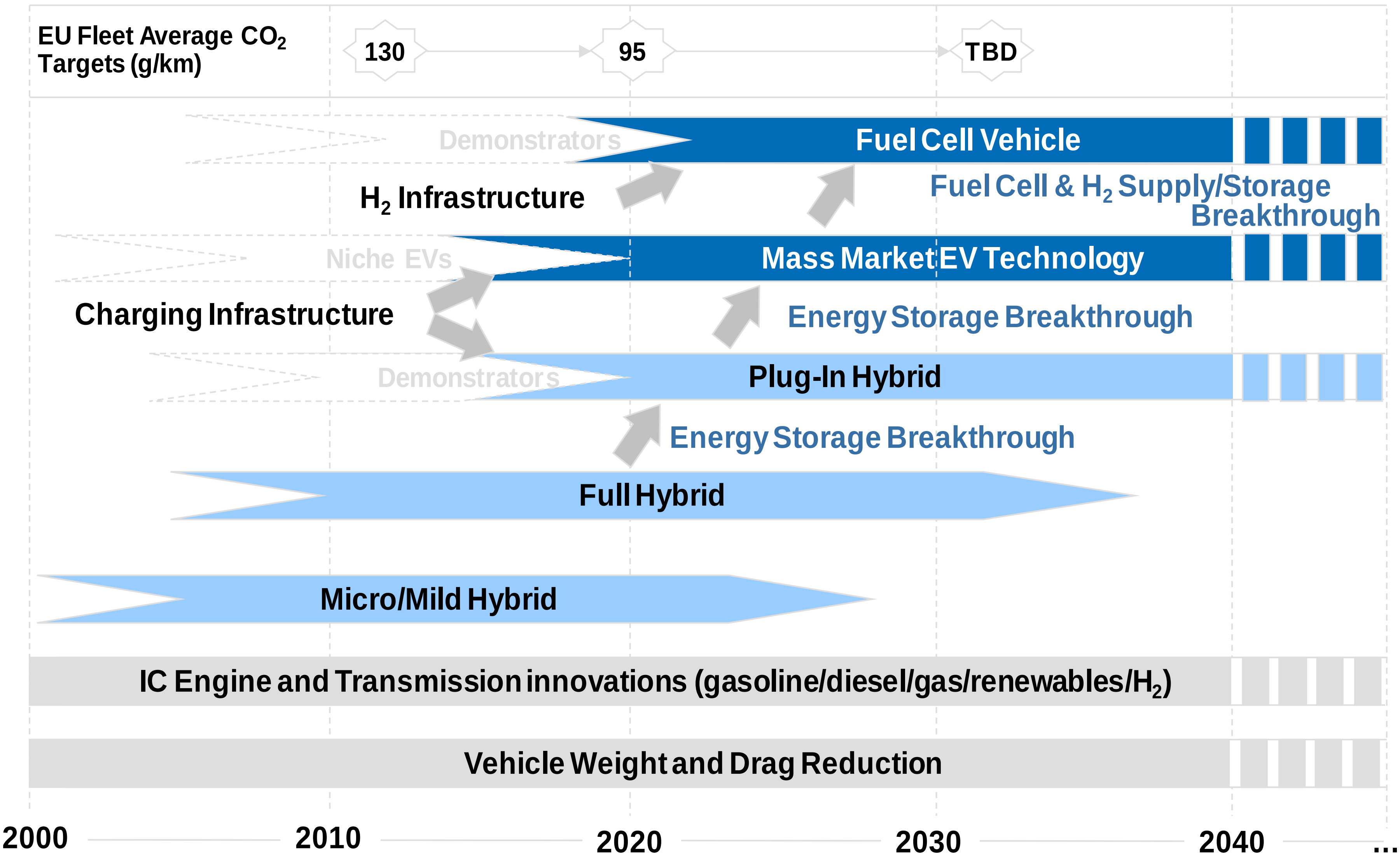
Hybridisation for Performance and Economy

Dave Greenwood
Head of Hybrid and Electric Systems
Ricardo UK Ltd.

Future Powertrain Conference

19 February 2014

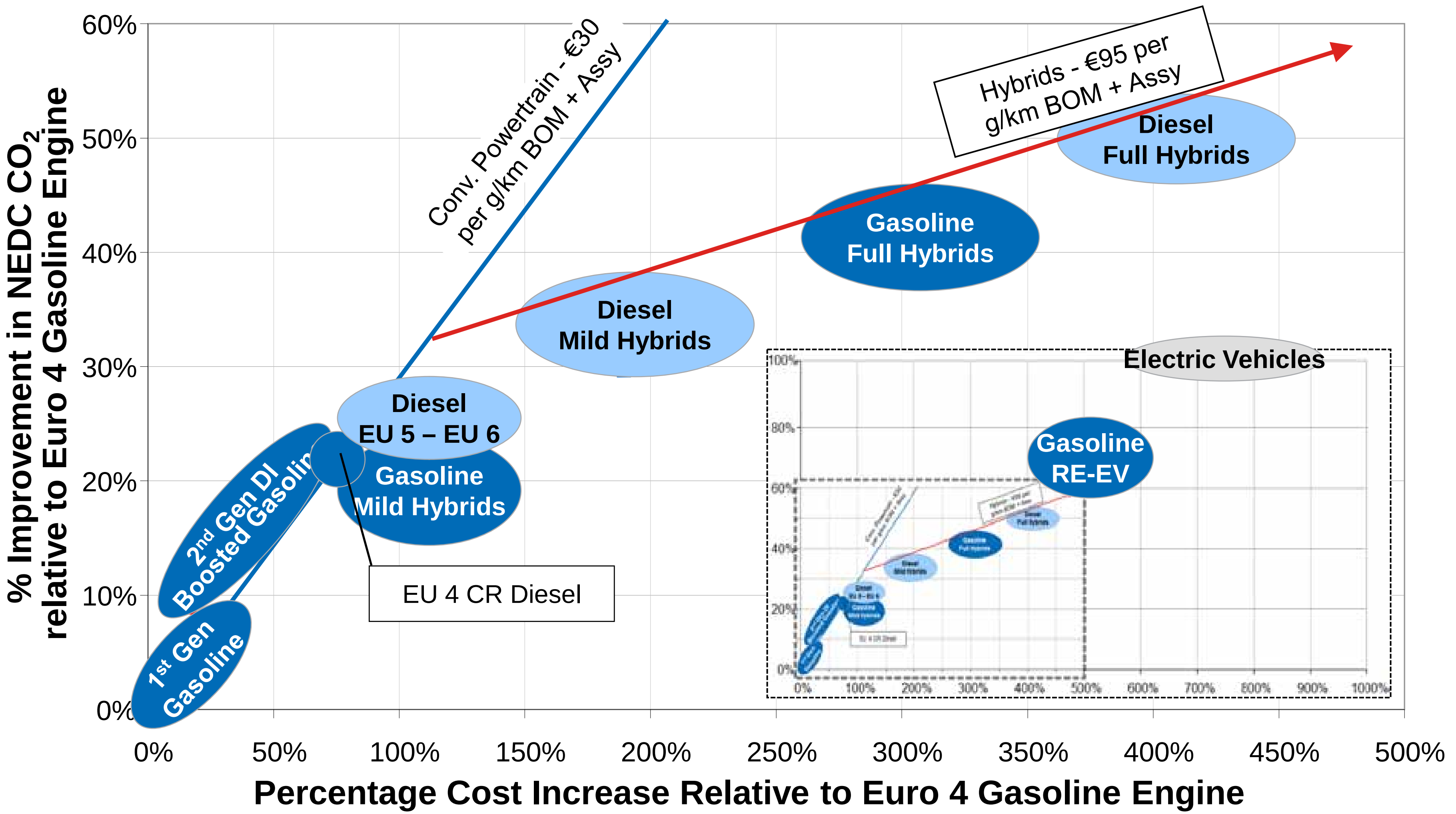
Driven by regulation and customer demand, the automotive industry continues to introduce CO2 reducing technologies



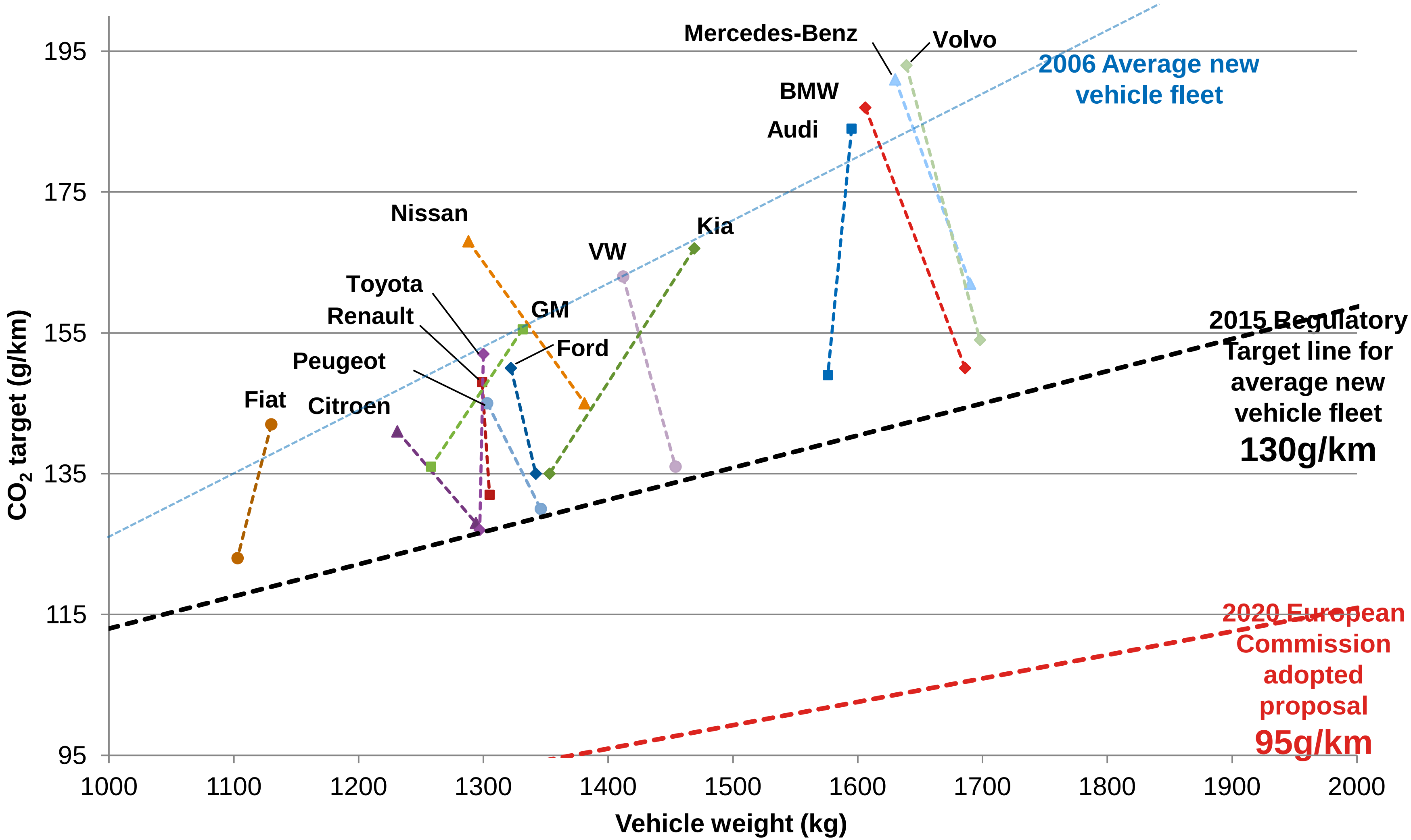
Source: An Independent Report on the Future of the Automotive Industry in the UK – New Automotive Innovation & Growth Team (NAIGT)

The most cost effective technologies are deployed first – across entire model ranges where possible

CO_2 cost/benefit for powertrain technologies – EU medium passenger car



As a result, fleet average CO2 emissions have reduced significantly since 2006.

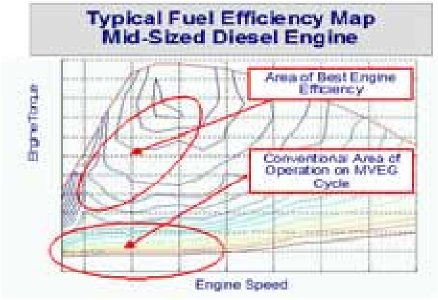


Source: ICCT; European Vehicle Market Statistics Pocketbook 2012

There are four key functions of a hybrid powertrain that can contribute to system efficiency improvements

1 Engine Downsizing and Load Management

- Electric machine provides torque assist to smaller engine
- Electricity generation used to increase load and store surplus energy for later use
- Engine stop at idle, coasting, and EV mode



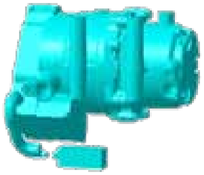
Regenerative Braking 2

- Uses e-machine as generator during braking events
- Converts vehicle kinetic energy to re-usable electricity instead of heat (to capacity of battery and e-machine)
- Energy used to power ancillaries and provide driving torque to vehicle

CO_2
Fuel economy
Driveability
Performance
Emissions
Noise

3 Reduced Ancillary Loads

- Electrification of ancillaries like pumps, fans, A/C compressors and PAS allows operation independent of engine speed
- High voltage systems are more efficient
- Ancillaries can be downsized and run at most efficient operating point


Electric A/C Compressor


Electric Vacuum Pump


12V DCDC converter

Zero Emissions Drive Mode 4

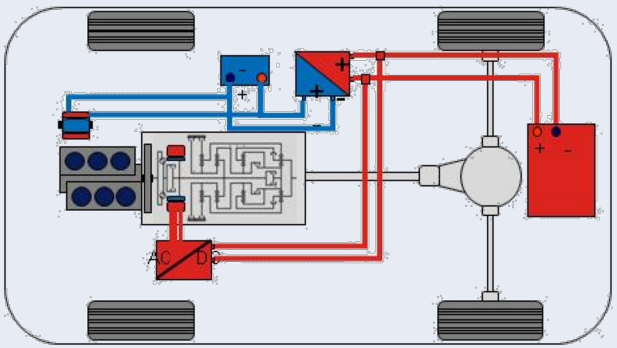
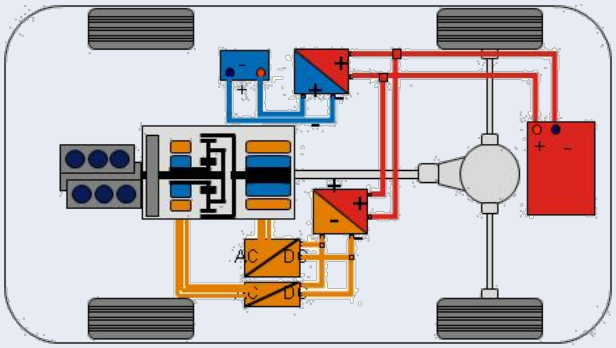
- Energy stored in battery can be used to drive vehicle
- This can be from fuel energy (charge sustaining hybrid) or charged from electricity network (Plug-In-Vehicle)
- Allows low noise, zero tailpipe emissions operation
- Provides useful outlet for electrical energy generated

HEVs already feature heavily in Premium sector product lines

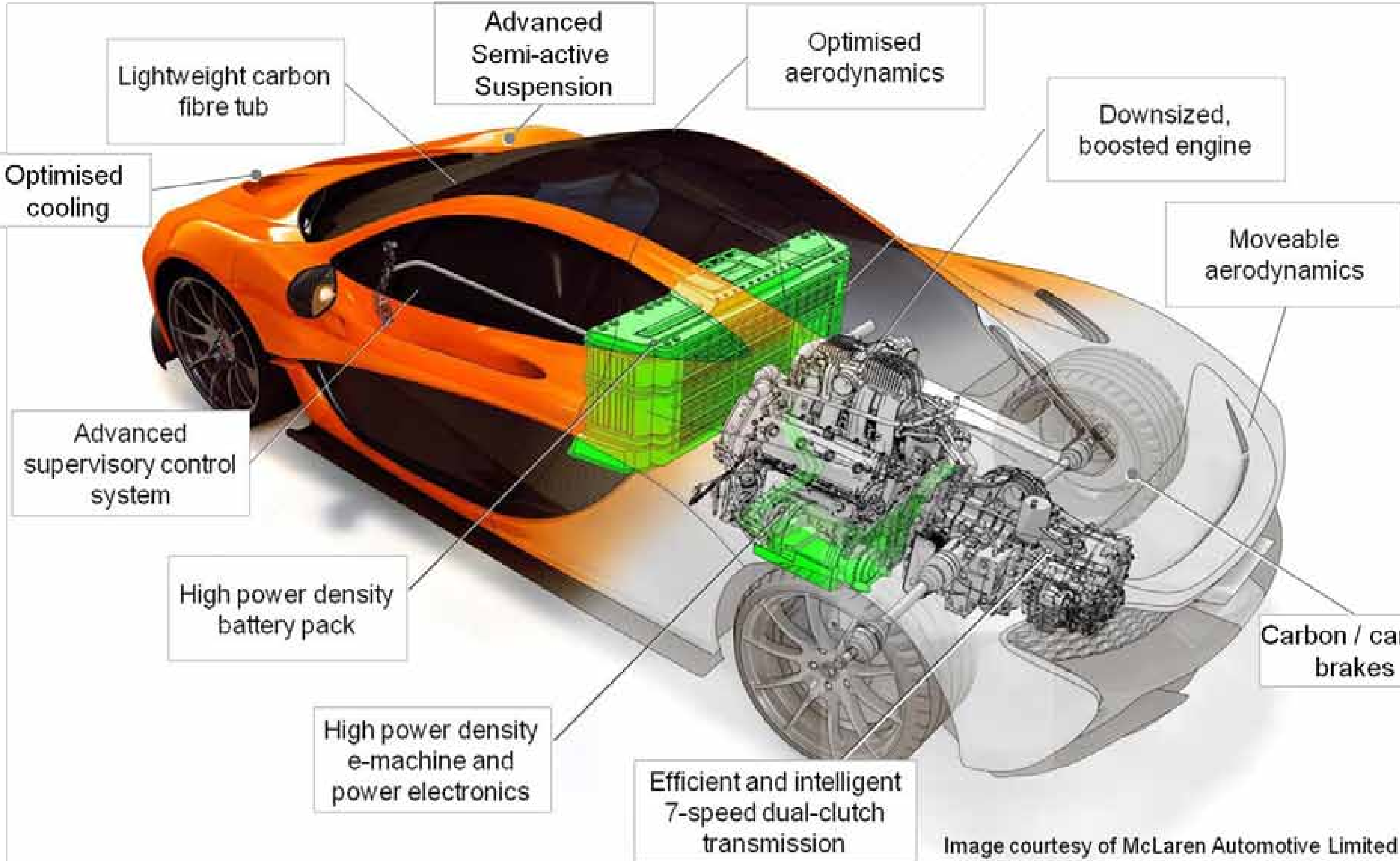
RICARDO

Manufacturer	Production HEV & EV Models	Strategy
BMW	ActiveHybrid 7 – 342kW V8 gasoline, 15kW P1 ActiveHybrid X6 – 300kW V8, 2-mode (cancelled) ActiveHybrid 5 – 225kW I-6 gasoline, 40kW P2 ActiveHybrid 3 – 225kW I-6 gasoline, 40kW P2 i3 EV / REEV – 125kW motor, 22kWh battery i8 PHEV – 170kW I-3, 10kW BSG, 96kW e-axle	Continue to pursue Efficient Dynamics Performance hybrids Investigating 48V system (2015 launch?) EV experiments with Mini EV, followed by major investment in "i" brand
Mercedes-Benz, smart	S400 Hybrid – 205kW V6 gasoline, 15kW P1 E300 BlueTEC Hybrid – 150kW I-4 diesel, 20kW P2 S500 Plug-in Hybrid – 240kW V6 gasoline, 80kW P2 Smart ED (2009) – 30kW motor, 13.2 kWh Li-ion Smart ED (2013) – 55kW motor, 17.6 kWh Li-Ion SLS Electric – 552 kW 4WD motors, 60 kWh Li-ion	Hybrids pitched for good fuel-economy First diesel-hybrid premium car (E300) First PHEV premium car (S500, 2014) Modular P2 hybrid architecture Small-volume EV experiments with Smart
Bentley, SEAT, Bugatti, Audi	VW e-Up – 60kW motor, 18.7kWh battery VW Jetta Hybrid – 110kW I-4 gasoline, 20kW P2 Audi A8 Hybrid – 152kW I-4 gasoline, 39kW P2 Audi Q5 Hybrid – 152kW I-4 gasoline, 39kW P2 Audi A3 e-tron – 110 kW I-4, 75kW P2, 8.8kWh Cayenne hybrid – 245kW V6 gasoline, 34kW P2 Panamera hybrid – 245kW V6 gasoline, 34kW P2 Panamera PHEV – 245kW V6, 69kW P2, 9.4kWh	RWD/AWD hybrids all use 2.0L I-4 (Audi) or 3.0L V6 (Porsche) + Automatic gearbox FWD hybrids all use 1.4L I-4 + DSG Multiple e-tron concepts (A1, A3, R8) with REEV, series-parallel , EV architectures, but production solutions more conservative
Jaguar, Land-Rover	Range Rover hybrid – 250kW V6 diesel, 35kW P2	SUV product hybridisation first Initially adopt transmission supplier tech (ZF)
Lexus, Toyota	Lexus CT200h – 73kW I-4, 60kW HSD Lexus IS300h – 130kW I-4, 105kW HSD Lexus GS450h – 215kW V6, 147kW HSD Lexus RX450h –183kW V6, 123kW HSD, 50kW ERAD Lexus LS600h – 290kW V8, 165kW HSD	Powersplit transmission, high motor power Unique engine derivatives (Atkinson) EV performance limited by current battery technology, but compatible with PHEV

The hybrid architectures in the premium sector are split into several different types, with P2 (European) and Powersplit (US/Japan) dominant

	P2	Powersplit
Manufacturers	BMW, Audi, JAGUAR, LAND ROVER	LEXUS, TOYOTA, Ford
Schematic		
Transmission	• Single electric motor ~ 40kW • Multi-speed Automatic (or DCT)	• 2 electric motors ~ 75+150kW • Powersplit (eCVT)
Power Electronics	• Single inverter ~ 40kW • One HV-LV DC-DC Converter	• 2 inverters ~ 75+150kW • One HV DC-DC converter ~ 40kW • One HV-LV DC-DC Converter
PHEV-ability	• Requires higher motor & inverter power	• No change to motor & inverters required
Why?	• Gasoline and diesel compatible • Maximise commonality to non-hybrid • Minimise motor + PE cost • Compatible with high GVW and GTW	• Stepless transmission with low complexity • Optimise engine & transmission together • Maximise powertrain electrification

And as hybrid system power densities improve, they are being used as much for performance as economy - the McLaren P1™ is an excellent example



But lower cost mild hybrid systems at 12 to 48V are becoming cost effective for wider deployment

RICARDO

Engine Stop / Start

- Eliminates idle fuel consumption and noise
- Requires fast, smooth restart for launch
- May require support for transmission, PAS etc during idle stop

3-4% CO_2

Basic micro-hybridisation (12-24V)

- 4-6 kW allows for more powerful ancillaries (PAS, fans)
- Allows for limited assist and some regeneration
- May allow use of GSI for NEDC certification

4-10% CO_2

48V micro/mild hybrid

- 6-12kW allows greater regeneration and assist
- Improved efficiency of electrical generation
- Better start extends DFCO and engine stop
- Some (limited) engine downsizing possible

10-15% CO_2

48V Ancillaries

- Larger energy store allows high current consumers (cooling fans, blowers, AC compressor, PTC heaters, coolant and oil pumps) lighter, more powerful and more efficient.

15-20% CO_2

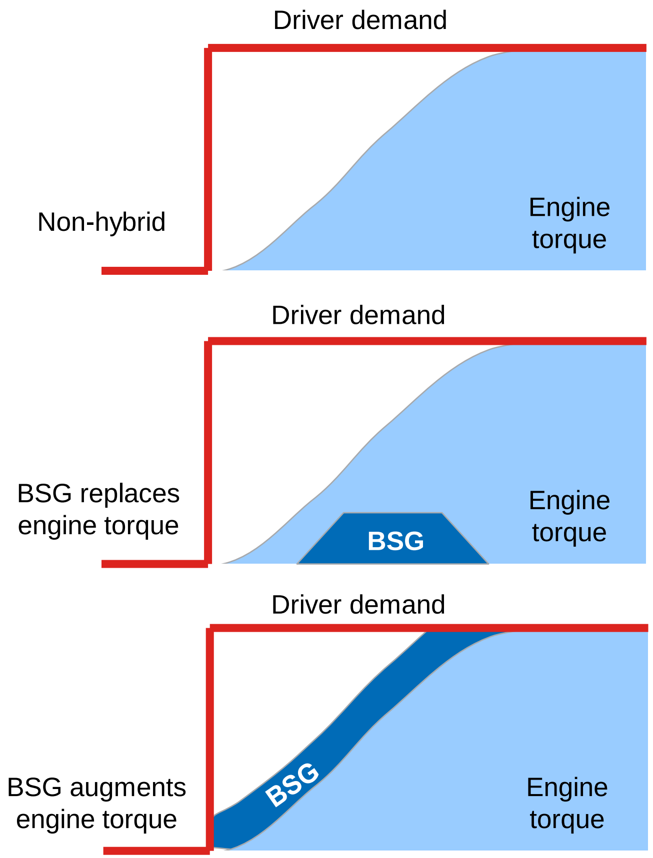
Energy Storage

- Lead Acid (AGM)
- Advanced Lead Acid (Bipolar, Spiral wound) or + Supercapacitor
- NiMH ?
- Li-Ion

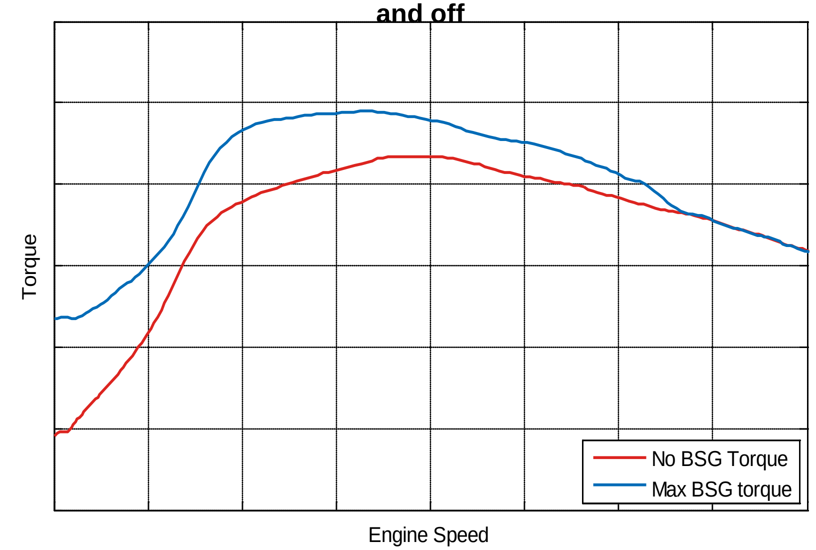
Source: Ricardo analysis

And with modest machine power and torque, the effect on low speed performance can allow engine downsizing

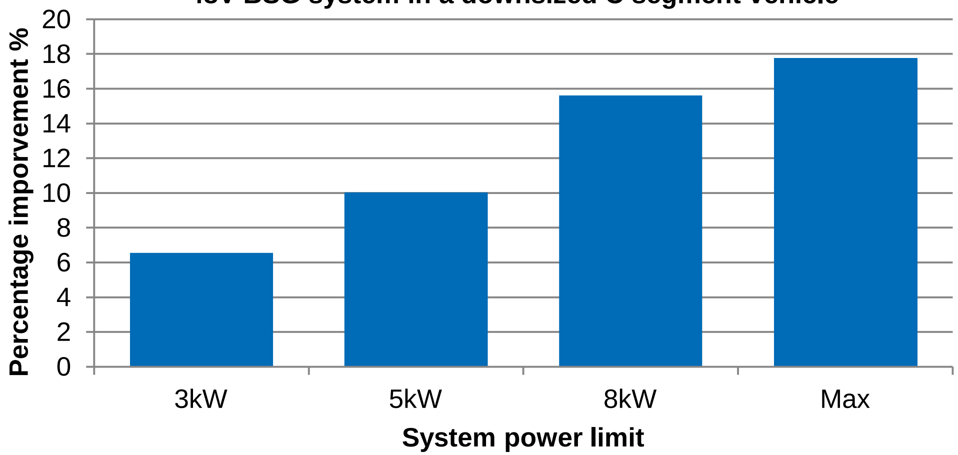
Torque augmentation enables downsizing and / or enhanced performance



Transient torque curves measured on chassis dynamometer during full-load in-gear acceleration with BSG boost torque on and off

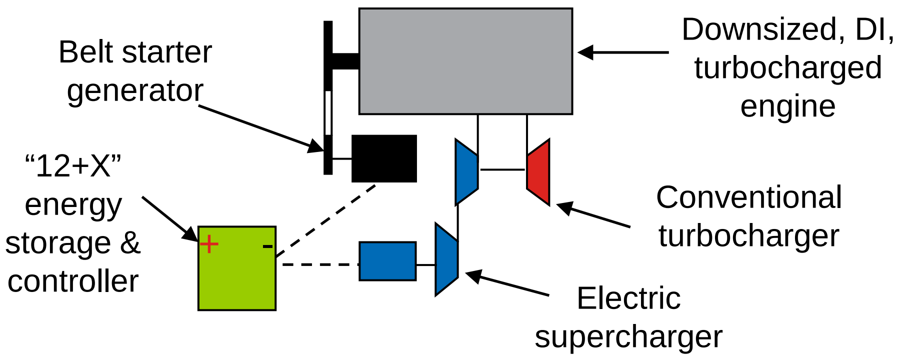


In gear 1000-2500rpm acceleration benefit for an 8kW nominal 48V BSG system in a downsized C segment vehicle



Source: Ricardo analysis

Ricardo Hyboost takes the concept further – using electric supercharging to allow up to 50% downsizing



Vehicle	*2009 Ford Focus 2.0L Duratec*	*2011 Ford Focus 1.6L EcoBoost*	*2011 Ford Focus 1.0L HyBoost P/T*	*2010 Toyota Prius*
Maximum power [PS(kW)]	145 (107) @ 6000 rpm	150 (110) @ 5700 rpm	**143 (105) @ 5500 rpm**	99 (73) @ 5200 rpm Hybrid system net power = 136 (100) @ 5200 rpm
Peak torque [Nm]	185 @ 4000 rpm	240 @ 1600 rpm (o/b)	**240 @ 3500 rpm**	142 Nm
0 – 62 mph*** [s]	9.2	8.6	**9.2**	10.4 sec
31 – 62 mph** [s]	11.9	8.6	**11.2**	TBC
Max. speed [mph]	128 mph	130 mph	**128 mph**	112 mph
Cycle CO_2 reduction	Baseline (0%)	18%	**41 – 47%**	47%

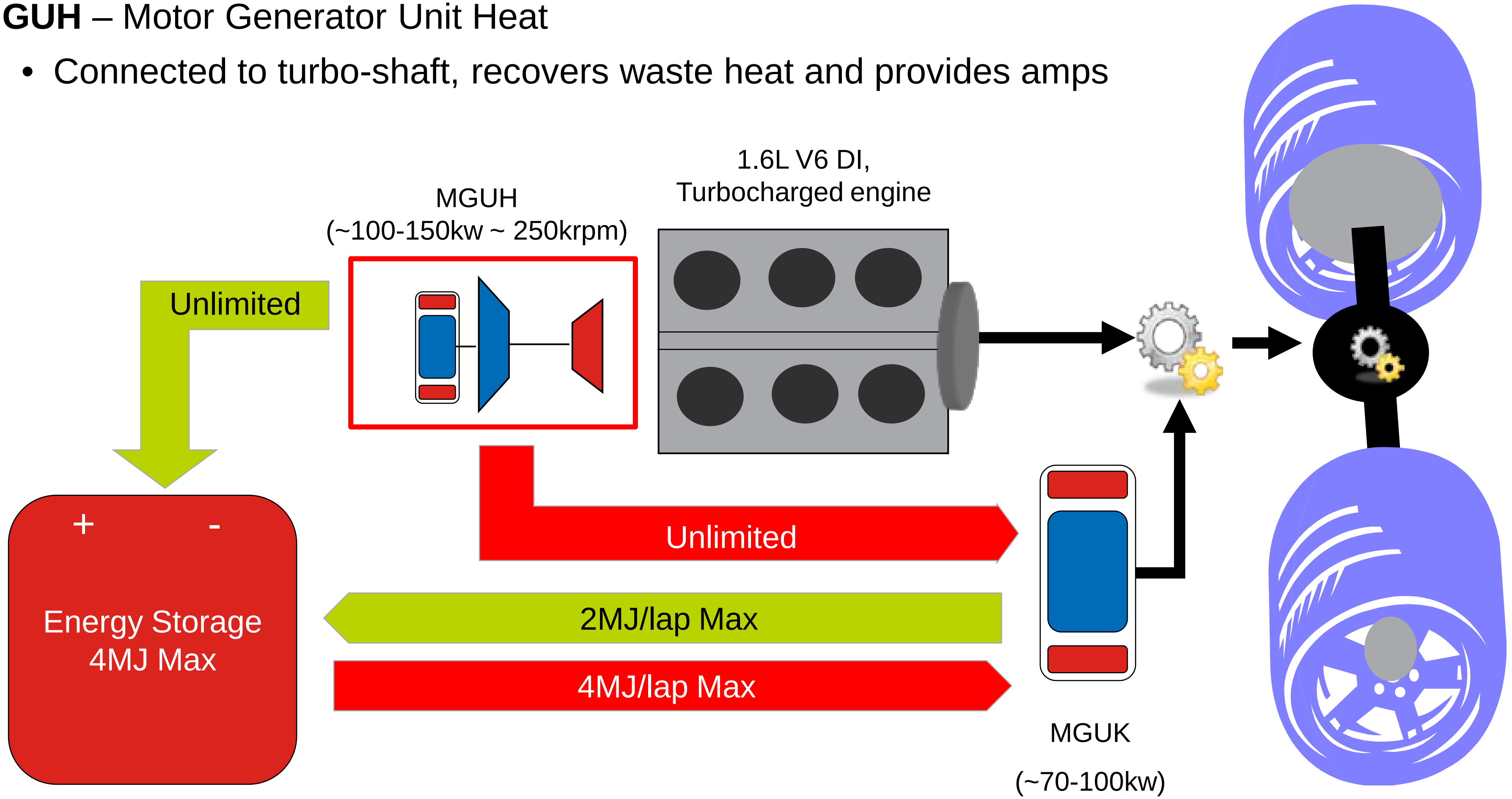
2014 Formula One extends this concept further and includes unlimited exhaust heat recovery

MGUK – Motor Generator Unit Kinetic

- Connected to wheels, recovers braking energy and provides torque

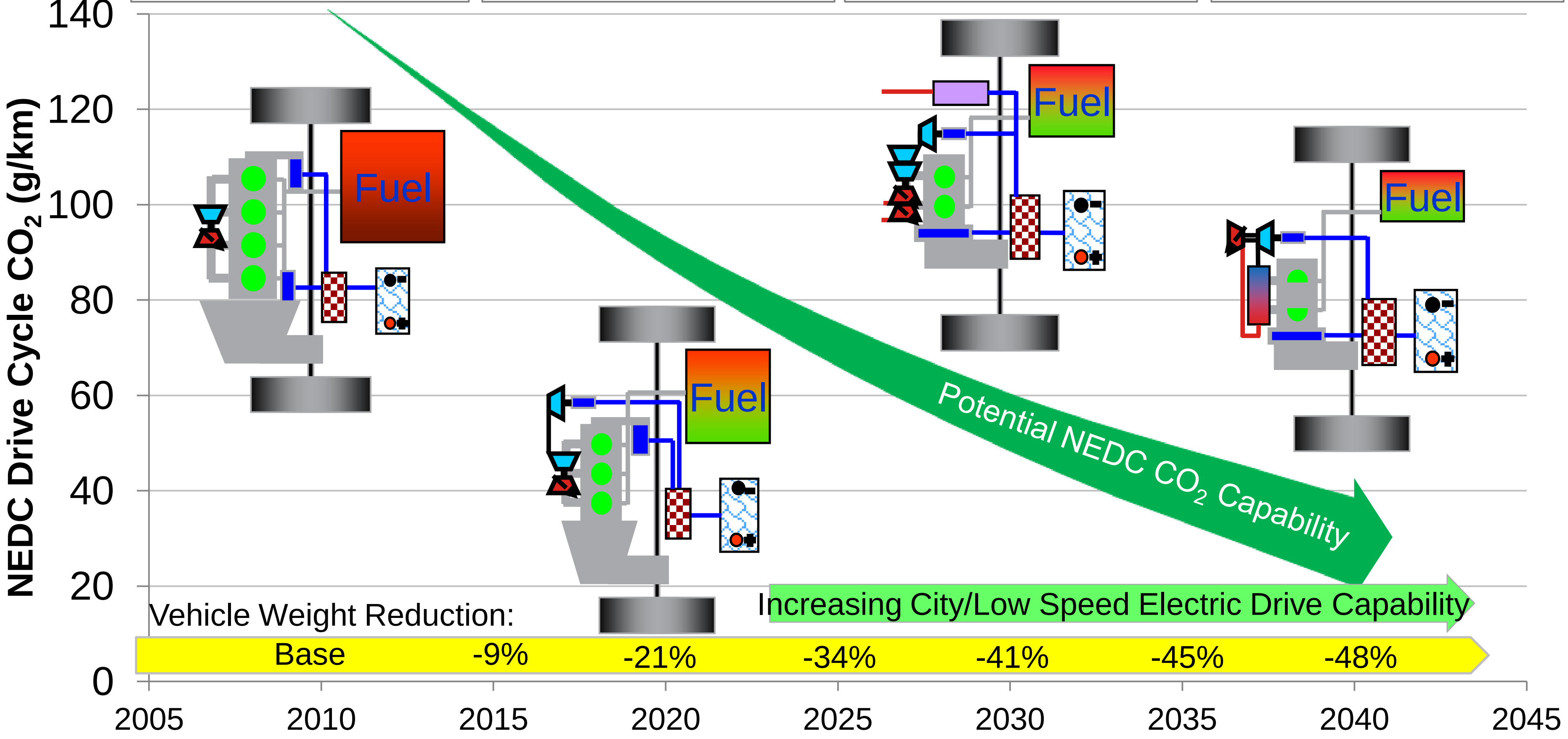
MGUH – Motor Generator Unit Heat

- Connected to turbo-shaft, recovers waste heat and provides amps



So what does the mainstream European passenger car powertrain of the future look like ?

Boosted Engine Variable Geometry Turbo 12 Volt Elec System Stop/Start 5% Bio fuel mix	Downsized 40% v Today Turbo/Supercharged 48 Volt Motor/Generator Low Cost Energy Store 10% biofuel mix	Downsized 70% v Today Dual Stage Boost Integrated Electric Machine Thermoelectric Generator 25% biofuel mix	Extreme Downsizing Advanced Cycle/Heat Rec. Integrated Systems Advanced Thermoelectrics Synthetic fuel mix



Source: Ricardo Analysis

Thank you for your attention

RESPECT · INTEGRITY · CREATIVITY & INNOVATION · PASSION