Hybridisation for Performance and Economy

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Future Powertrain Conference
19 February 2014
Driven by regulation and customer demand, the automotive industry continues to introduce CO2 reducing technologies.

<table>
<thead>
<tr>
<th>EU Fleet Average CO₂ Targets (g/km)</th>
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</thead>
<tbody>
<tr>
<td>130</td>
</tr>
<tr>
<td>95</td>
</tr>
<tr>
<td>TBD</td>
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### EU Fleet Average CO₂ Targets

- **2000**: 130 g/km
- **2010**: 95 g/km
- **2020**: TBD

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**Charging Infrastructure**

- **Full Hybrid**
  - Demonstrators
- **Plug-In Hybrid**
  - Energy Storage Breakthrough
- **Mass Market EV Technology**
  - Fuel Cell Vehicle
  - Fuel Cell & H₂ Supply/Storage Breakthrough
- **Niche EVs**
  - Demonstrators
- **H₂ Infrastructure**
  - Fuel Cell & H₂ Supply/Storage Breakthrough

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**IC Engine and Transmission innovations (gasoline/diesel/gas/renewables/H₂)**

**Vehicle Weight and Drag Reduction**

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**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

CO₂ cost/benefit for powertrain technologies – EU medium passenger car

- Gasoline
- Diesel
- Mild Hybrids
- Full Hybrids
- Electric Vehicles

% Improvement in NEDC CO₂ relative to Euro 4 Gasoline Engine

Percentage Cost Increase Relative to Euro 4 Gasoline Engine
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

2. **Regenerative Braking**
   - 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

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

4. **Zero Emissions Drive Mode**
   - 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

**Source:** 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

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HEVs already feature heavily in Premium sector product lines

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Production HEV &amp; EV Models</th>
<th>Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW</td>
<td>ActiveHybrid 7 – 342kW V8 gasoline, 15kW P1</td>
<td>Continue to pursue Efficient Dynamics</td>
</tr>
<tr>
<td></td>
<td>ActiveHybrid X6 – 300kW V8, 2-mode (cancelled)</td>
<td>Performance hybrids</td>
</tr>
<tr>
<td></td>
<td>ActiveHybrid 5 – 225kW I-6 gasoline, 40kW P2</td>
<td>Investigating 48V system (2015 launch?)</td>
</tr>
<tr>
<td></td>
<td>ActiveHybrid 3 – 225kW I-6 gasoline, 40kW P2</td>
<td>EV experiments with Mini EV, followed by major investment in “i” brand</td>
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<td></td>
<td>i3 EV / REEV – 125kW motor, 22kWh battery</td>
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<tr>
<td></td>
<td>i8 PHEV – 170kW I-3, 10kW BSG, 96kW e-axle</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Continue to pursue Efficient Dynamics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Performance hybrids</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Investigating 48V system (2015 launch?)</td>
<td></td>
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<tr>
<td>Mercedes-Benz</td>
<td>S400 Hybrid – 205kW V6 gasoline, 15kW P1</td>
<td>Hybrids pitched for good fuel-economy</td>
</tr>
<tr>
<td></td>
<td>E300 BlueTEC Hybrid – 150kW I-4 diesel, 20kW P2</td>
<td>First diesel-hybrid premium car (E300)</td>
</tr>
<tr>
<td></td>
<td>SS00 Plug-in Hybrid – 240kW V6 gasoline, 80kW P2</td>
<td>First PHEV premium car (SS00, 2014)</td>
</tr>
<tr>
<td></td>
<td>Smart ED (2009) – 30kW motor, 13.2 kWh Li-ion</td>
<td>Modular P2 hybrid architecture</td>
</tr>
<tr>
<td></td>
<td>Smart ED (2013) – 55kW motor, 17.6 kWh Li-Ion</td>
<td>Small-volume EV experiments with Smart</td>
</tr>
<tr>
<td></td>
<td>SLS Electric – 552 kW 4WD motors, 60 kWh Li-ion</td>
<td></td>
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<tr>
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<td>RWD/AWD hybrids all use 2.0L I-4 (Audi) or 3.0L V6 (Porsche) + Automatic gearbox</td>
<td></td>
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<tr>
<td></td>
<td>FWD hybrids all use 1.4L I-4 + DSG</td>
<td></td>
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<td>Multiple e-tron concepts (A1, A3, R8) with REEV, series-parallel, EV architectures, but production solutions more conservative</td>
<td></td>
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<tr>
<td></td>
<td>Range Rover hybrid – 250kW V6 diesel, 35kW P2</td>
<td>SUV product hybridisation first</td>
</tr>
<tr>
<td></td>
<td>Initially adopt transmission supplier tech (ZF)</td>
<td></td>
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<tr>
<td></td>
<td>Lexus CT200h – 73kW I-4, 60kW HSD</td>
<td>Powersplit transmission, high motor power</td>
</tr>
<tr>
<td></td>
<td>Lexus IS300h – 130kW I-4, 105kW HSD</td>
<td>Unique engine derivatives (Atkinson)</td>
</tr>
<tr>
<td></td>
<td>Lexus GS450h – 215kW V6, 147kW HSD</td>
<td>EV performance limited by current battery technology, but compatible with PHEV</td>
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<td></td>
<td>Lexus RX450h – 183kW V6, 123kW HSD, 50kW ERAD</td>
<td></td>
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<tr>
<td></td>
<td>Lexus LS600h – 290kW V8, 165kW HSD</td>
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</tbody>
</table>
The hybrid architectures in the premium sector are split into several different types, with P2 (European) and Powersplit (US/Japan) dominant.

<table>
<thead>
<tr>
<th>Manufacturers</th>
<th>BMW</th>
<th>Mercedes</th>
<th>Audi</th>
<th>Volkswagen</th>
<th>Land Rover</th>
<th>Lexus</th>
<th>Toyota</th>
<th>Ford</th>
</tr>
</thead>
</table>

### Schematic

#### Transmission
- **P2**
  - Single electric motor ~ 40kW
  - Multi-speed Automatic (or DCT)
- **Powersplit**
  - 2 electric motors ~ 75+150kW
  - Powersplit (eCVT)

#### Power Electronics
- **P2**
  - Single inverter ~ 40kW
  - One HV-LV DC-DC Converter
- **Powersplit**
  - 2 inverters ~ 75+150kW
  - One HV DC-DC converter ~ 40kW
  - One HV-LV DC-DC Converter

#### PHEV-ability
- **P2**
  - Requires higher motor & inverter power
- **Powersplit**
  - No change to motor & inverters required

#### Why?
- **P2**
  - Gasoline and diesel compatible
  - Maximise commonality to non-hybrid
  - Minimise motor + PE cost
  - Compatible with high GVW and GTW
- **Powersplit**
  - 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

<table>
<thead>
<tr>
<th>Engine Stop / Start</th>
<th>3-4% CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic micro-hybridisation (12-24V)</td>
<td>4-10% CO₂</td>
</tr>
<tr>
<td>48V micro/mild hybrid</td>
<td>10-15% CO₂</td>
</tr>
<tr>
<td>48V Ancillaries</td>
<td>15-20% CO₂</td>
</tr>
</tbody>
</table>

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

- 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

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

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

Source: Ricardo analysis

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**Energy Storage**

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

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>2009 Ford Focus 2.0L Duratec</th>
<th>2011 Ford Focus 1.6L EcoBoost</th>
<th>2011 Ford Focus 1.0L HyBoost P/T</th>
<th>2010 Toyota Prius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power [PS(kW)]</td>
<td>145 (107) @ 6000 rpm</td>
<td>150 (110) @ 5700 rpm</td>
<td>143 (105) @ 5500 rpm</td>
<td>99 (73) @ 5200 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hybrid system net power = 136 (100) @ 5200 rpm</td>
<td></td>
</tr>
<tr>
<td>Peak torque [Nm]</td>
<td>185 @ 4000 rpm</td>
<td>240 @ 1600 rpm (o/b)</td>
<td>240 @ 3500 rpm</td>
<td>142 Nm</td>
</tr>
<tr>
<td>0 – 62 mph*** [s]</td>
<td>9.2</td>
<td>8.6</td>
<td>9.2</td>
<td>10.4 sec</td>
</tr>
<tr>
<td>31 – 62 mph** [s]</td>
<td>11.9</td>
<td>8.6</td>
<td>11.2</td>
<td>TBC</td>
</tr>
<tr>
<td>Max. speed [mph]</td>
<td>128 mph</td>
<td>130 mph</td>
<td>128 mph</td>
<td>112 mph</td>
</tr>
<tr>
<td>Cycle CO₂ reduction</td>
<td>Baseline (0%)</td>
<td>18%</td>
<td>41 – 47%</td>
<td>47%</td>
</tr>
</tbody>
</table>
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

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**1.6L V6 DI, Turbocharged engine**

**MGUH**

- (~100-150kw ~ 250krpm)

**Energy Storage**

- 4MJ Max

**MGUK**

- (~70-100kw)

- Motor Generator Unit Kinetic
- Connected to wheels, recovers braking energy and provides torque

- Motor Generator Unit Heat
- Connected to turbo-shaft, recovers waste heat and provides amps

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**Unlimited**

- 4MJ/lap Max

- 2MJ/lap Max

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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
  - Thermolectric Generator
  - 25% biofuel mix

- **Extreme Downsizing**
  - Advanced Cycle/Heat Rec.
  - Integrated Systems
  - Advanced Thermoelectrics
  - Synthetic fuel mix

**Vehicle Weight Reduction:**
- **Base**
- **-9%**
- **-21%**
- **-34%**
- **-41%**
- **-45%**
- **-48%**

**Potential NEDC CO₂ Capability**

**Source:** Ricardo Analysis
Thank you for your attention

Respect · Integrity · Creativity & Innovation · Passion