Near Term Spark Ignition Engine Technologies for Improved Fuel Economy

Hugh Blaxill
ERC 2011 Symposium
‘Future Engines and their Fuels’
Near Term Spark Ignition Engine Technologies

Contents

- Market Drivers
- Near Term Market Trends
- Downsizing
- Range Extending
- Ultra Lean Combustion
Fuel Economy a Multi Faceted Issue

- Increasing oil demand from developing nations
- Increasing oil prices
- Security of supply

Source: OPEC World Oil Outlook 2010

Source: Mineralöwirtschaftsverband e.V.

Source: BP Statistical Review of World Energy, June 2010
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Market Drivers:
Regional Fuel Economy Status & Legislation

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Market Drivers: Drive Cycle Effect

Toyota Prius Fuel Consumption By Drive Cycle

- Japan 10-15
- EU NEDC
- US FTP75

Fuel Consumption, mpg

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Market Drivers: NOx & HC Emissions

<table>
<thead>
<tr>
<th></th>
<th>US Tier I</th>
<th>Japan '00</th>
<th>Japan '05&amp;'09</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx (g/km)</td>
<td>0.20</td>
<td>0.25</td>
<td>0.30</td>
</tr>
<tr>
<td>HC (g/km)</td>
<td></td>
<td></td>
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</tbody>
</table>

Euro                    US                 Japan

Tier II Bin 4

Tier II Bin 5

Euro III

Euro IV

Euro V, VI

Tier II Bin 5

Japan '05&'09

Japan '00

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Market Drivers: Particulate Emissions
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Increasing volumes of 4 cylinder engines forecast

Data taken from CSM WW Database Q1 2010
Rapid ramp in direct injection and variable valvetrain technologies across all manufacturers

Notable increase in boosted or downsized application and hybrid powertrains
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Benchmark – Ford 2.0 Ecoboost

4-cylinder 4v DOHC
1999cc (87.5mm x 83.1mm)
33% downsized

- Power: 176kW at 6000rpm
- Torque: 340Nm from 1900 to 3500rpm
- Cr: 10:1

Single BW K03 turbocharger
Central direction injection
Twin cam phasers
Thin skin exhaust manifold

Comparable performance to 3.0l V6
Due for Explorer, Focus, Mondeo, S-Max, Taurus, etc.
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Benchmark – Daimler 3.5l V6 BlueEFFICIENCY

- 6 cylinder 4v DOHC
- 3500cc Naturally aspirated

- Power 225kW at 6000rpm
- Torque 370Nm from 3500 to 5250rpm

- Central piezo direct injection with multi spark
- Stratified lean operation
- Twin cam phasers
- Variable length intake manifold
- Stop start

- Released in the S350 in the EU
- 24% improvement in economy from previous engine
Extreme Engine Downsizing with a Single Turbocharger

MAHLE Powertrain

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Gasoline Engine Downsizing
How low can you go?

![Graph showing specific power output vs. peak BMEP for various engines, including MAHLE Downsize 2-Stage Turbo and Single Turbo, and other models like VW 1.4l SC/TC, Fiat 1.8 TGDI, Audi 1.8 TFSI, Audi 2l TFSI AVS, Audi 2l TFSI, Ford 2.0l EcoBoost, and others.](image)
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Next Generation MAHLE Downsizing Engine

- State-of-the-art clean-sheet design for 50% downsized concept DI-3 1.2 L
  - 30 bar BMEP +
  - 100 kW/L Single Stage Turbo
  - 120kW/l Twin Turbo

Up to 30% fuel economy improvement possible with similar performance levels

Excellent low speed torque and transient response with twin turbo configuration

Vehicle and engine demonstrators available
Developed with MAHLE & Bosch advanced components
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Downsizing: Unstable Combustion Issues

- Combustion phasing can be retarded due to detonation, which leads to high exhaust valve opening pressures
- Advancing combustion phasing allows higher boost and torque levels to be achieved

To achieve this:

- Turbocharger selection has a strong influence
- Reduced duration exhaust cam has a positive effect
- Optimised exhaust manifold design reduces trapped residuals
- Combustion chamber is shape-optimised
- Oil consumption is minimized
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Downsizing: Boosting Systems

A) Single Turbocharger

B) 2-Stage Turbocharger

C) Supercharger & Turbocharger

D) Electric Supercharger & Turbocharger
Challenges for Increased Efficiency Through Gasoline Engine Downsizing

Downsizing: Boosting Systems

Steady State

Engine Speed [rpm]

Time [s]

Average IMEP [bar]

BMEP [bar]

Target Curve
2-Stage Turbocharger
LP Turbo Only
VTES & LP Turbo

LP Turbo Only
2-Stage Turbocharging
VTES + LP Turbo
SC / TC

2009-01-1053
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Vehicle Installation & Results

- **Demonstrator Vehicle:**
  - 1600 kg, ‘D’-class
  - 6 – speed manual transmission

**Vehicle targets and results**

<table>
<thead>
<tr>
<th>Targets</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption FTP75:</td>
<td>30mgUSg</td>
</tr>
<tr>
<td>CO2 output NEDC:</td>
<td>135 g/km</td>
</tr>
<tr>
<td>Emissions target:</td>
<td>Euro 5</td>
</tr>
<tr>
<td>Acceleration 80-120 km/h</td>
<td>10.0 sec</td>
</tr>
<tr>
<td>(5th gear):</td>
<td></td>
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</tbody>
</table>

* VW Passat 2.0TFSi EPA data 27.1mpUSg

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MAHLE Powertrain LLC, MPT LLC, Hugh Blaxill, 23-May-2011

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Downsizing CO₂ Reduction

- 2.4 L NA
- 2.0 L Turbo GDI
- MAHLE 1.2 L Turbo GDI
- MAHLE 1.2 L Turbo GDI + Idle-stop
- MAHLE 1.2 L Turbo GDI + Mild-hybrid
- Concept 0.8 L Turbo GDI + Mild-hybrid

NEDC CO₂ [Percentage compared to 2.4 L NA]
Extreme Engine Downsizing with a Single Turbocharger

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**Extended-Range Electric Vehicle (E-REV)**

- Vehicle propelled purely by electric motors with small battery pack (c.f. EV)
  - Typical range of 20 to 100 km using only battery power
  - Battery pack can be charged from residential electrical outlet
- On-board electrical generator (IC Engine or Fuel Cell) can also be used to re-charge battery on the move
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Range Extender - Conflicting Targets - Range / Cost / Weight

- **Baseline – Short Range Electric Vehicle (EV)**
  - Compact Class
  - Range: 80 km
  - Battery Capacity: 15 kWh

Baseline EV

- Battery cost: 500 EUR/kWh
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Range Extender - Conflicting Targets - Range / Cost / Weight

- **Baseline – Short Range Electric Vehicle (EV)**
  - Compact Class
  - Range: 80 km
  - Battery Capacity: 15 kWh

- **Range Extender (RE)**
  - (inc. Generator, 40 l Tank, Controller, …)
  - Weight: +130 kg
  - Cost: +3000 EUR
  - Range: +550 km

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*Battery cost: 500 EUR/kWh*
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- **Electric Vehicle #1 (identical additional cost)**
  - Weight: +75 kg
  - Range: +30 km

**Baseline EV**

- RE: +3000 EUR, +130 kg, +550 km
- EV #1: +3000 EUR, +75 kg, +30 km

*Battery cost: 500 EUR/kWh*
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Range Extender - Conflicting Targets - Range / Cost / Weight

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- **Electric Vehicle #1 (identical additional cost)**
  - Weight: +75 kg
  - Range: +30 km

- **Electric Vehicle #2 (identical range)**
  - Weight: +1375 kg
  - Cost: +52000 EUR

* Battery cost: 500 EUR/kWh
MAHLE Range Extender

- Two-cylinder Inline, 4-Stroke Gasoline
- 900 cm³ Swept Volume
- 30 kW Peak Power at 4000rpm
- Port-fuel Injection ($\lambda = 1$)
- 180°/540° Firing Order
- Flexible Installation

Specific Power

- Power 30 kW
- Weight (incl. Generator) 70 kg
- Power to Weight Ratio 2.3 kg/kW
  *(Competitors: 2.75 to 4.3 kg/kW)*
Extreme Engine Downsizing with a Single Turbocharger

Ultra Lean Combustion System

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MAHLE Ultra Lean Combustion

- **Ultra Lean Combustion System, \( \lambda \geq 2 \)**
  - Net Indicated thermal efficiencies in excess of 42%
  - NA Fuel economy improvement of 14%
  - TC Fuel economy potential significantly higher

- **No expensive NOx reduction catalyst needed**
- **99% NOx reduction**
- **Low HC emissions**

- **Enabled by a patented high energy jet ignition system**
- **Combustion is partial HCCI**

- **Easily integrated into existing engine technology**
- **Highly synergistic with boosting & hybridisation**

- **Research engine currently running on test bed**
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Ultra Lean Combustion

- Demonstrated significant FE improvements over modern production baseline SI ($\lambda = 1$)
  - 10 – 20 % FE improvement measured
  - 18 % improvement at the world wide mapping point (1500, 3.3 bar IMEPn)
  - 14 % drive cycle (NEDC, FTP) FE improvement in PFI GM vehicle utilizing same base engine

- Improved Burn rate & distributed ignition
  - $\lambda > 2$ achievable at part load
  - Knock limit extension which allows for increased compression ratio

- Significant emission improvements
  - Single digit (near zero) engine out NOx
  - Controllable HC and CO emissions
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Ultra Lean Combustion

- With base engine hardware update (DI, compression ratio increase, optimized turbulence),
  - Currently achieving 42% Net Indicated TE
  - ~ 45% peak thermal efficiency predicted
    - 19% improvement over SI stoichiometric
  - ~ 25% drive cycle FE improvement predicted over baseline

- Synergies with other FE approaches
  - Synergies with hybrid / range extender
  - Synergies with downsizing
  - Synergies with high EGR concepts
Thank you for your attention