The Tailored Engine & Powertrain for 48V

Comprehensive Solutions for Optimum Efficiency and Cost

Dr. Helfried Sorger
Future Powertrain Conference
Birmingham, 28.02.2018
SOME HEADLINES

**Automotive News Europe**

German push to ban combustion-engine cars by 2030 wins support

**Transport & Environment**

The beginning of the end for the infernal combustion engine

By Greg Archer, clean vehicles director

**The Guardian**

Oslo temporarily bans diesel cars to combat pollution

**AVL**

Germany Asks EU To Think About Banning Internal Combustion Engines

STUTTGART TO BAN DIESELS AS LONDON LAUNCHES ‘TOXICITY CHARGE’

February 23, 2017
Technologies until 2025

**Conventional ICE:**
- Significantly higher effort for emission compliance (RDE, China6, SULEV xx, ...),
- “Zero Impact Emission Concepts”

**Mild Hybrid:**
- 48 V in various configurations P0 – P4
- Power Increase 15 $\rightarrow$ 20 $\rightarrow$ 30 kW
- ICE utilizes synergies

**Full Hybrid:**
- Primarily with Japanese OEM’s

**Plug In Hybrid:**
- CAFE and city access as driver

**BEV:**
- Dependent on infrastructure, incentives and access restr.

**Fuel Cell:**
- Limited to specific markets?

2025 $\rightarrow$ 50% electrified - still 100 mio ICE´s - but high scatter of predictions
Refined combustion

- Improved knock: \(\rightarrow\) higher CR, \(\rightarrow\) accept GPF gen2 (higher backpressure)
- Refined charge motion \(\rightarrow\) extended Miller / Atkinson, increased EGR tolerance
- Advanced charging \(\rightarrow\) extended efficiency / spec. performance trade off
- Reduced emission & PN especially with cold drive-off (RDE 2)
- Full stoichiometric operation

Min. BSFC in map [g/kWh]

- TGDI standard (wastegate TC) \(T_3 \leq 950^\circ\)
- TGDI IEM \(T_3 \leq 980^\circ\)
- TGDI MILLER IEM \(T_3 \leq 980^\circ\)
- TGDI MILLER IEM \(T_3 \leq 980^\circ\)
- TGDI MILLER IEM \(T_3 \leq 980^\circ\)
- TGDI VCR \(T_3 \leq 1000^\circ\)
- TGDI VCR (var. MILLER) IEM \(T_3 \leq 980^\circ\)
- TGDI VCR (var. MILLER) IEM SC
- TGDI VCR (var. MILLER) IEM SC - VGT

\(\lambda \leq 1 / \text{actual}\)

RON95, typical PC engines from measurements

Specific \(\lambda=1\) Power ICE [kW/l]
Fuel efficient Gasoline Solutions for Lambda=1 at full load

IEM: (c-head) Integrated Exhaust Manifold
VCR: Variable Compression Ratio
VVL: Variable Valve Lifts
VGT: Variable Geometry Turbine
WI: Water Injection
SC: Series Compressor (intercooled)

Min. BSFC in map [g/kWh]

TGDI standard (wastegate TC) $T_3 \leq 950^\circ$

Specific $\lambda=1$ Power ICE [kW/l]

RON95, typical PC engines from measurements

By projective 1D-engine simulations

Series Compressor

Honeywell

Currently up to 170 kW/l

Dr. Helfried Sorger | PTE - D2 | 26 Februar 2018 | 5
Low Emission Diesel Extended RDE emission compliance

Example: PC 2.0L Diesel, HP EGR, LNT + SDPF, CW 1700kg

**Compliance Factor (CF)**
- CF 2017: 2.1
- CF 2020: 1.5

**Fuel Consumption [%]**

**DIESEL – Walk towards CF<<1**
- HP-EGR
- HP-/EGR
- HP-/LP /-EGR
- 48V with 4kW Ecot
- 48V with 4kW Ecot and 10 kW P0 e-Motor Boost / Recuperation

**Reduction of Fuel Consumption & Emissions.**

**Electrificationm to support Emission stability & CO₂**
Technology Trends Combustion Engine

**Gasoline (SI)**
- **today**
  - Miller, Atkinson

**Diesel (CI)**
- **today**
  - Lean NOx Trap + SCR

**tomorrow**
- Extended Miller, advanced boosting
- Refined emission
- VCR, HCCI, ....

**48V**
- Extended 48V systems (15→20→>30 kW) as enabler for low emission & CO2
- Advanced EAS & Temperature Management, adapted operating strategy

**Electrification as enabler for next refinement level of ICE**

EAS ... Exhaust gas Aftertreatment System
HCCI .... Homogeneous Charge Compression Ignition
VCR ... Variable Compression Ratio

Public
48V Powertrain architectures
## Features and functions vs. architectures

<table>
<thead>
<tr>
<th>Function</th>
<th>P0</th>
<th>P1</th>
<th>P2</th>
<th>P3/+P0</th>
<th>P4/+P0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced stop start</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charging at standstill</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charging at driving</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recuperation</td>
<td></td>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Boost</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sailing</td>
<td>○</td>
<td></td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coasting</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>eCreep</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric drive</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine shutdown assist</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine stall protection</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
<tr>
<td>eAWD</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) MT with eClutch  
2) P2 with SSM
### Vehicle attributes vs. architectures

<table>
<thead>
<tr>
<th>Attribute</th>
<th>P0</th>
<th>P1</th>
<th>P2</th>
<th>P3/+P0</th>
<th>P4/+P0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumption</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Performance</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+/0</td>
</tr>
<tr>
<td>Emissions - Gasoline</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Emissions - Diesel</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>NVH</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Drivability</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Ride Comfort</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Handling</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+/-</td>
</tr>
</tbody>
</table>

**Rating:**
- 0 ... similar to baseline vehicle
- + ... better than baseline vehicle
- - ... worse than baseline vehicle

1) Baseline vehicle with mechanical AWD

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**P2 configuration combines best attributes with lowest complexity**
Recuperation Energy vs. Architectures NEDC, WLTC, Highway

Significantly increased importance of electrification by the higher dynamics of the cycle
Recuperation Energy vs. Architectures
WLTC - 48V up to 20 kW

20kW is sufficient with the exception of the heavy vehicles
Recuperation Energy vs. Architectures
WLTC - 48V up to 30kW

25 - 30kW is useful for
• Heavy vehicles
• Extended electric driving
Architecture comparison

P0 as basic electrification
Especially for smaller, cost sensitive segments

2025 and beyond not sufficient to meet severe CO2 legislation with significant mild hybrid market share

P2 is appropriate before 2020
depending on individual fleet demand

2025 and beyond mandatory to meet severe CO2 legislation with significant mild hybrid market share

How to realize a P2 architecture?
Gasoline & Diesel Base engine Variants
Integration in C-Segment Vehicle

In line 4 Cyl TGDI Base engine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement [l]</td>
<td>1.6</td>
</tr>
<tr>
<td>Rated speed [min-1]</td>
<td>4850</td>
</tr>
<tr>
<td>Rated Power [kW]</td>
<td>120</td>
</tr>
<tr>
<td>Max Torque [Nm]</td>
<td>251</td>
</tr>
<tr>
<td>Start / Stop</td>
<td>Yes</td>
</tr>
<tr>
<td>Intake system</td>
<td>CAC</td>
</tr>
<tr>
<td>Water pump</td>
<td>Fixed ratio</td>
</tr>
<tr>
<td>Oil pump</td>
<td>Fixed sump pump</td>
</tr>
<tr>
<td>FEAD</td>
<td>A/C, tensioner, idler, W/P, alternator, PS pump</td>
</tr>
<tr>
<td>Piston cooling</td>
<td>Pressure regulated</td>
</tr>
</tbody>
</table>

In line 4 Cyl Diesel Base engine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement [l]</td>
<td>1.5</td>
</tr>
<tr>
<td>Rated speed [min-1]</td>
<td>4000</td>
</tr>
<tr>
<td>Rated Power [kW]</td>
<td>80</td>
</tr>
<tr>
<td>Max Torque [Nm]</td>
<td>250</td>
</tr>
<tr>
<td>Start / Stop</td>
<td>Yes</td>
</tr>
<tr>
<td>Intake system</td>
<td>CAC</td>
</tr>
<tr>
<td>Water pump</td>
<td>Fixed ratio</td>
</tr>
<tr>
<td>Oil pump</td>
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<tr>
<td>FEAD</td>
<td>A/C, tensioner, idler, W/P, alternator, PS pump</td>
</tr>
<tr>
<td>Piston cooling</td>
<td>Pressure regulated</td>
</tr>
</tbody>
</table>

Both with 12V e-SC + Long Final Gear Ratio

Base engines - state of the art
Electrified Gasoline & Diesel engine Integration in C-Segment Vehicle

<table>
<thead>
<tr>
<th>C-SEGMENT BASE VEHICLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Tank Volume</td>
</tr>
<tr>
<td>Total Length</td>
</tr>
<tr>
<td>Total Width</td>
</tr>
<tr>
<td>Total Height</td>
</tr>
<tr>
<td>Wheelbase</td>
</tr>
<tr>
<td>Curb Weight (=dry weight)</td>
</tr>
<tr>
<td>Gross Weight</td>
</tr>
</tbody>
</table>
What can be electrified to simplify the base engine?

<table>
<thead>
<tr>
<th>Function</th>
<th>Effect on performance</th>
<th>Effect on FC &amp; efficiency</th>
<th>Package</th>
<th>Customer value</th>
<th>Functional risk</th>
<th>Complexity reduction</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator/E-machine</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>P2 architecture</td>
</tr>
<tr>
<td>E-Water pump</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>Mechanical and e-driven</td>
</tr>
<tr>
<td>E-Oil pump</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>Needed for pure e-drive</td>
</tr>
<tr>
<td>AC compressor</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>PS pump</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>Needed for pure e-drive</td>
</tr>
<tr>
<td>Vacuum pump</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>E-cam phaser</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Needed for pure e-drive</td>
</tr>
<tr>
<td>E-Charger</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>Highest potential in FC</td>
</tr>
<tr>
<td>E-catalyst</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Heating strategy</td>
</tr>
</tbody>
</table>

Supporting measures

<table>
<thead>
<tr>
<th>Supporting measures</th>
<th>Effect on performance</th>
<th>Effect on FC &amp; efficiency</th>
<th>Package</th>
<th>Customer value</th>
<th>Functional risk</th>
<th>Complexity reduction</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grill Shutter</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Reduction Air-Drag</td>
</tr>
<tr>
<td>Thermal encapsulation</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>Faster Warm Up and Restart</td>
</tr>
</tbody>
</table>

0 → Basis 12V w BSG+SS
The ideal base engine for 48 Volts

Features

Removal of 12V starter motor
The ideal base engine for 48 Volts

Features

- 48V 20kW E-machine
- Gear drive 1:3
- Separation clutch C0
The ideal base engine for 48 Volts Features

Elimination of FEAD
The ideal base engine for 48 Volts

Features

Repositioning of AC compressor at transmission side
Electrification of A/C compressor
Electrification of A/C compressor
Electrification of A/C compressor
The ideal base engine for 48 Volts

Features

- Repositioning of oil cooler and filter
- Elimination of chain driven oil pump
The ideal base engine for 48 Volts

Features

- Elimination of conventional coolant pump
- Combined oil cooler/filter module with e-pump
The ideal base engine for 48 Volts

Features

Introduction of electrical coolant pump
The ideal base engine for 48 Volts

Features

Electrification of vacuum pump
The ideal base engine for 48 Volts

Features

- No front cover needed
- Damping element instead of TVD
- No front sealing required
The ideal base engine for 48 Volts

Features

Electrical cam phasers
The ideal base engine for 48 Volts

Features

Electrification of vacuum pump
The ideal base engine for 48 Volts

Features

Implementation of turbo charger with recuperation potential
The ideal base engine for 48 Volts

Features

Electrical Waste Gate actuation
The ideal base engine for 48 Volts

Features

Catalyst heating element
The ideal base engine for 48 Volts

Features – Diesel engine

- Catalyst heating element
- Electrical coolant pump
- Oil cooler/filter module with e-pump
- Electric Supercharger
- Electric Cam-phaser
- 48V 20kW e-Motor

Features – Diesel engine

- Diesel engine

Public
The ideal base engine for 48 Volts Integration

DCT 7 speed transmission
The ideal base engine for 48 Volts Integration
The ideal base engine for 48 Volts Integration

Electric brake booster
Active grill shutters
The ideal base engine for 48 Volts
Integration

48V battery
48 Volts battery

- Design to ensure cold cranking under extreme conditions
- 550Wh usable energy
- LN7 size with increased height
- Air or water cooled depending on the requirements
- 9kg
The ideal base engine for 48 Volts Integration

DC / DC converter
The ideal base engine for 48 Volts Integration

Power electronics
The ideal base engine for 48 Volts
Package Envelope almost neutral

Additional e-motor drive assembly

Removal of FEAD and oil pump drive
Ideal base engine for 48v
Minimised overall weight increase

Production engine & 48V electrification

Electrified base engine & 48V electrification
Architecture optimization by means of global vehicle simulation

Change of operating point in 3 dimensions:
BMEP, engine speed and temperature

Real-life Cycles on the Road

Outcome

Fuel consumption

f(BMEP, speed, T)

Contribution of each sub-system to the operating conditions

Coolant Circuit
Oil Circuit
Battery and Electrical Sys.
Control Strategy
Vehicle + Driver
Drive train and Gearbox
Impact of electrified auxiliaries
Coolant pump in WLTC

Fuel consumption reduction potential for the coolant pump ~0.4%

Energy Requirement reduced by 50% with switchable coolant pump → main benefit enhanced warm-up (not considered here!)

Energy requirement of electrical driven pump - coolant flow controlled on demand
Impact of electrified auxiliaries
Up to 4% CO$_2$ reduction in WLTC

Cumulated mechanical power of auxiliaries
during WLTC

- HT Coolant Pump
- Oil pump
- Vacuum pump
- Idlers
- Steering pump
- Auxiliaries (sum of)
- Auxiliaries (sum of) relative to engine [%]
Impact of 48V hybridization on gasoline
Up to 13% CO₂ reduction in WLTC

Significant e-Drive capability and energy recuperation in WLTC

Base engine thermal encapsulation not included
Not active vehicle grill shutters
CO₂ optimization potential comparison of 48V Diesel and Gasoline in WLTC

![Graph showing CO₂ emissions comparison between 48V Diesel and Gasoline engines with various optimisation techniques.](image)

- Optimised Baseline
- 48V Hybrid
- FEAD
- Additional
- VTMS

Δ = 17.5g CO₂

-20.50% 

-21.70%
Cost to benefit vs. architectures

Assumptions:
>500,000 units p.a.
Established supplier base for 48V Base engine modifications considered

---

**Cost / CO2 Range**

| <= 80 €/(gCO₂/km) |
| <= 60 €/(gCO₂/km) |
| <= 40 €/(gCO₂/km) |
| <= 20 €/(gCO₂/km) |

**Attractive cost to benefit ratio for P2**
Cost to benefit vs. features

Summary of all features
35€/g CO2 km

Assumptions:
>500,000 units p.a.
Established supplier base for 48V
Base engine modifications considered
Benefit from AVL’s system approach

- 48V Mild Hybrids will achieve significant market share
- Overall CO₂ Reduction from 20.5 up to 21.7% in WLTC
- Dedicated 48V Base Engine
- Powertrain Vehicle integration
- Energy Management
- Thermal Management
- Product Cost Improvement
Dedicated beltless engines for 48V introduced in 2017

M 256 – the new Mercedes-Benz high-performance six-cylinder in-line gasoline engine with intelligent 48V electrification

M 264 – Der neue Mercedes-Benz 4-Zylinder Toptype-Ottomotor mit 48V-Elektrifizierung

(Source: Daimler AG, 38th Vienna Engine Symposium 2017)
48V – AVL is ready

2015


2016

- Engine Technology International – The optimized engine concept for 48 Volt (ETI 09/2016)
- Der Einfluss von 48 V auf Grundmotorreibungs- und Effizienzoptimierung – Ansatz zur Quantifizierung in zukünftigen Fahrzyklen (ATZ - Lecture 11/2016)
- Vehicle Integration of a new engine concept for 48 Volts – Opportunities for Efficiency improvement and optimization of the overall system complexity (Motorenkongress Baden-Baden - Lecture 02/2016)

2017

- The ideal Powertrain for 48V – Comprehensive Solutions to Efficiency and Cost Optimization (MTZ 05/2017)
- The tailored powertrain for 48V – Options for the Gasoline Engine – Chance for future Diesel Engines (HDT München - Lecture 04/2017)
- The tailored powertrain for 48V – Options for the Gasoline Engine – Chance for future Diesel Engines (Motorenkongress Baden-Baden - Lecture 02/2017)
- Elektrifizierung des Fahrzeugantriebs mit 48V Architektur (Essay SHW Geschäftsbericht 02/2017)
AVL - Rightsizing the electrification