Heavy-Duty (HD) Diesel Engines Roadmap

SAE-NA 2015

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Arbon, Switzerland
16 September 2015
1. FPT Industrial
2. Last decade HD development: ATS
3. Thermal Efficiency Improvement
4. 3D CFD Combustion Analysis
5. Conclusions
FPT Industrial

CNH Industrial: Group Structure

Agricultural Equipment

Construction Equipment

Commercial Vehicles

Powertrain

Financial Services
FPT Industrial

Location

FPT Motorenforschung AG
Schlossgasse 2
CH-9320 Arbon

FPT Industrial
Via Puglia 15
IT-10156 Turin
FPT Industrial
CNH Industrial: Product Portfolio
FPT Industrial
Brands and timeline

1929 > 1975: “Fiat Veicoli Industriali”, later incorporated into the newly-born **Iveco**

2004: creation of **Iveco Motors** dedicated to industrial (both on and off highway), marine and power generation applications

2005: creation of FPT, Fiat Powertrain Technologies, unified all of the powertrain activities within the Fiat Group

2010: Fiat demerged its agricultural and construction equipment business (CNH), trucks and commercial vehicles business (Iveco) and the related powertrain activities (FPT Industrial) to a newly established company, **Fiat Industrial S.p.A**

2013: CNH Global N.V. and **Fiat Industrial S.p.A.** were merged into **CNH Industrial N.V.**
FPT Industrial
Innovation in industrial engines

1980 - First turbocharged Heavy Duty engine
1985 - First Direct Injection engine on LCVs
1989 - First engine with Electronic Diesel Control
1992 - First Common Rail engine on LCVs
1999 - Introduction of SCR technology for Euro IV - V
2002 - HI-eSCR on IVECO Euro VI heavy range
2005 - First EGR on Diesel engines for LCVs
2009 - First CNG engine on LCVs
2012 - Launch of MultiJet technology
2012 - Launch of MultiAir Technology
FPT Industrial
Example H-D Truck mission

Cruise 100 kW
FPT Industrial
Example Farm Tractor mission

Engine Load [%]

Engine RPM [1/min]

% Lastkollektiv

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FPT Industrial
Example Combine Harvester mission
FPT Industrial
Example Excavator mission
FPT Industrial
Example Marine Speed Yacht mission

![Graph showing engine load percentage vs. engine RPM](image)
Outline

1. FPT Industrial
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Emission Regulation in Europe

Timeline

Not only stricter limits but more demanding test procedures (dynamic) and in particular ISC-PEMS (real time driving) has driven the development and technology selection.

EU3:
NOx = 5.0 g/kWh
PM = 0.1 g/kWh

EU6:
NOx = 0.4 g/kWh
PM = 0.01 g/kWh
# Technologies Development

## Technologies vs regulation

| Year | Naturally aspirated | Turbo | Turbo + IC | VTG, WG, IC, 2-stage TC | FIE: Distributor, in-line pump | UI | Common Rail | Mechanical control | EDC, map-based | model-based | Non-EGR | EGR | No ATS | Oxicat / DPF | SCR / DPF | IDI on small high speed diesel | DI on small high speed diesel |
|------|---------------------|-------|------------|--------------------------|-------------------------------|----|-------------|-------------------|----------------|--------------|---------|------|------|-------------|-------------|-------------|--------------------------|--------------------------|
| 1970 |                     |       |            |                          |                               |    |             |                   |                |              |         |      |     |             |             |             |                          |                          |
| 1980 |                     |       |            |                          |                               |    |             |                   |                |              |         |      |     |             |             |             |                          |                          |
| 1990 |                     |       |            |                          |                               |    |             |                   |                |              |         |      |     |             |             |             |                          |                          |
| 2000 |                     |       |            |                          |                               |    |             |                   |                |              |         |      |     |             |             |             |                          |                          |
| 2010 |                     |       |            |                          |                               |    |             |                   |                |              |         |      |     |             |             |             |                          |                          |
| 2020 |                     |       |            |                          |                               |    |             |                   |                |              |         |      |     |             |             |             |                          |                          |

<table>
<thead>
<tr>
<th>Year</th>
<th>Power density hp/liter</th>
<th>Oil drain interval km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>20</td>
<td>3'000</td>
</tr>
<tr>
<td>1980</td>
<td>26</td>
<td>20'000</td>
</tr>
<tr>
<td>1990</td>
<td>37</td>
<td>50'000</td>
</tr>
<tr>
<td>2000</td>
<td>43</td>
<td>150'000</td>
</tr>
<tr>
<td>2010</td>
<td>45-50</td>
<td>150'000</td>
</tr>
<tr>
<td>2020</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

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Euro VI Technology

Moderate EGR approach
Euro VI Technology
HI-eSCR approach
Euro VI Technology
HI-eSCR approach for On-Road Euro VI

2NO₂ + 4NH₃ + O₂ → 3N₂ + 6H₂O
Euro VI Technology
HI-eSCR approach (no PDF) for Off-Road Tier 4b

Hydrolysis Catalyst

\[
\text{CO(NH}_2\text{)}_2 + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2
\]

Exhaust gases

SCR Catalyst

\[
8\text{NH}_3 + 6\text{NO}_2 \rightarrow 7\text{N}_2 + 12\text{H}_2\text{O}
\]

\[
4\text{NH}_3 + 4\text{NO} + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}
\]

\[
2\text{NH}_3 + \text{NO} + \text{NO}_2 \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O}
\]

Oxidation Catalyst

2NO + O\text{2} \rightarrow 2NO\text{2}

2CO + O\text{2} \rightarrow 2CO\text{2}

4HC + 5O\text{2} \rightarrow 4CO\text{2} + 2H\text{2}O

4NH\text{2} + 3O\text{2} \rightarrow 2N\text{2} + 6H\text{2}O
Euro VI Technology
In use emissions summary

- On-road emissions of Euro VI heavy duty trucks (fully loaded) are about four times lower than a single passenger car in g/(kmT).

<table>
<thead>
<tr>
<th>EU6</th>
<th>NOx g/kWh</th>
<th>Speed km/h</th>
<th>Power kW</th>
<th>NOx g/km</th>
<th>NOx g/km.T</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD Truck 40T</td>
<td>0.4</td>
<td>80</td>
<td>100</td>
<td>0.5</td>
<td>0.0125</td>
</tr>
<tr>
<td>Passenger Car 1.6T</td>
<td></td>
<td></td>
<td></td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>Ratio</td>
<td></td>
<td></td>
<td></td>
<td>6.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

- Criteria Pollutants in the exhaust are within max workplace concentration limits (ppm).
- The PEMS requirements will guarantee that emissions remain within the limits over the useful life of the vehicle.

Euro VI = near zero emission truck
Euro VI Technology
Fuel Consumption Development

AVERAGE FUEL CONSUMPTION (GROSS VEHICLE WEIGHT 38/40 T)

Source: lastauto omnibus 4/2014

Original test track
Slightly Modified test track
New test track

Euro 6
Outline

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**Technology Drivers**

Paradigm change

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**IN RECENT YEARS**

- Innovation driven by emissions legislation NO\textsubscript{x} / PM
- Maintaining or improving fuel consumption / CO\textsubscript{2} and operating cost
- Improving cost, reliability and weight

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**PARADIGM CHANGE**

- Innovation driven by fuel consumption / CO\textsubscript{2} and operating cost
- Maintaining low NO\textsubscript{x} / PM emission level
- Improving total cost of ownership, reliability and weight
**Thermal Efficiency (best point)**

**Timeline**

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>1893</td>
<td>FIRST DIESEL ENGINE</td>
</tr>
<tr>
<td>1980</td>
<td>FIRST TURBOCHARGED HEAVY DUTY ENGINE</td>
</tr>
<tr>
<td>1999</td>
<td>ADVANCED AIR-HANDLING SYSTEMS</td>
</tr>
<tr>
<td>2013</td>
<td>FPT INDUSTRIAL HI-eSCR ENGINES</td>
</tr>
<tr>
<td>2020</td>
<td>INTEGRATED ENERGY MANAGEMENT</td>
</tr>
</tbody>
</table>

### bsfc

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1893</td>
<td>26%</td>
</tr>
<tr>
<td>1980</td>
<td>39%</td>
</tr>
<tr>
<td>1999</td>
<td>42%</td>
</tr>
<tr>
<td>2013</td>
<td>44%</td>
</tr>
<tr>
<td>2020</td>
<td>&gt;50% (?)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>bsfc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1893</td>
<td>320 g/kWh</td>
</tr>
<tr>
<td>1980</td>
<td>215 g/kWh</td>
</tr>
<tr>
<td>1999</td>
<td>200 g/kWh</td>
</tr>
<tr>
<td>2013</td>
<td>189 g/kWh</td>
</tr>
<tr>
<td>2020</td>
<td>168 g/kWh</td>
</tr>
</tbody>
</table>

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Efficiency Segregation

Definition

\[
\eta_{Eng} = \frac{P_e}{Q_{fuel}} = \frac{P_e}{P_i} \cdot \left(1 + \frac{P_{iLP}}{P_{iHP}}\right) \cdot \frac{P_{iHP}}{\dot{Q}_{fuel} - \dot{Q}_{wall}} \cdot \frac{\dot{Q}_{fuel}}{\eta_{Comb}} - \frac{\dot{Q}_{wall}}{\eta_{Wall}}
\]

\(\eta_{Mech}\) ... Mechanical Efficiency  
\(\eta_{Comb}\) ... Combustion Efficiency  
\(\eta_{Wall}\) ... Wall Heat Loss Efficiency  
\(\eta_{GasEx}\) ... Gas-Exchange Work Efficiency

\(P_e\) ........ Brake Power (at flywheel)  
\(P_i\) ........ Indicated Power (at pistons)  
\(Q_{Fuel}\) ....... Fuel Energy  
\(Q_{Wall}\) ....... Total Wall Heat Flux  
\(P_{iHP}\) ...... Ind.Power during high pr. Cycle  
\(P_{iLP}\) ...... Ind.Power during low pr. cycle

Fuel Consumption for 100 % Efficiency (Hu = 42.8 MJ/kg): \(\eta(100\%) \approx 84.1\text{ g/kWh}\)
Brake Thermal Efficiency
What are the Limitations?

<table>
<thead>
<tr>
<th>Approach</th>
<th>Combustion Efficiency [%]</th>
<th>Mechanical Efficiency [%]</th>
<th>Wall Heat Loss Efficiency [%]</th>
<th>Gas Exchange Efficiency [%]</th>
<th>Brake Thermal Efficiency [%]</th>
<th>BSFC [g/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EURO VI (best BSFC)</td>
<td>55.7 %</td>
<td>93.5 %</td>
<td>85.5 %</td>
<td>99.3 %</td>
<td>44.2 %</td>
<td>190.2</td>
</tr>
<tr>
<td>Vision 2020</td>
<td>60.0 %</td>
<td>95.0 %</td>
<td>87.0 %</td>
<td>101.0 %</td>
<td>50.0 %</td>
<td>167.9</td>
</tr>
<tr>
<td><strong>Delta</strong> (EU VI – Vision 2020)</td>
<td><strong>4.3 %</strong></td>
<td><strong>1.5 %</strong></td>
<td><strong>1.5 %</strong></td>
<td><strong>1.7 %</strong></td>
<td><strong>5.8 %</strong></td>
<td><strong>22.3</strong></td>
</tr>
</tbody>
</table>

**Limitations**

- Achievable with shorter combustion duration
- Seems max. achievable, little effect of further improvements
- No feasible solution yet, further effort required. Any improvement on combustion worsens Wall HT
- Small further improvement (intake ports), more map optimisation

**Highest potential for further thermal efficiency improvement:**
Reach higher combustion and wall heat losses efficiencies simultaneously
Brake Thermal Efficiency
How to improve it?

➢ Compression Ratio
➢ Combustion Duration
➢ EGR – AdBlue
➢ Two-Stage T/C
Compression Ratio
Mixed / Sabathé / Seilinger Cycle

\[ \eta_{\text{Seiliger}} = 1 - \frac{1}{\varepsilon^{\kappa-1}} \cdot \frac{\psi^\kappa \xi - 1}{\xi - 1 + \kappa \xi (\psi - 1)} \]

\[ \xi = \frac{p_3}{p_2} = \frac{T_3}{T_2}; \quad \psi = \frac{V_4}{V_3} = \frac{T_4}{T_3} \]

Friction loss \( \propto \) PCP
(Peak Cylinder Pressure)
Compression Ratio

Peak Cylinder Pressure

Cylinder Pressure Trend FPT HD - On Road Engine

- Euro V
- Euro VI
- Euro III
- Injection retarded!!

PCP [bar]


100 120 140 160 180 200 220 240 260
Brake Thermal Efficiency

How to improve it?

- Compression Ratio
- **Combustion Duration**
- EGR – AdBlue
- Two-Stage T/C
Combustion duration
CR and Combustion duration effect on BSFC

 Turbo Charger: Virtual (1-Stage)
 Compressor Efficiency: 74%
 Turbine Efficiency: 70%

 B.S.F.C. [g/kWh]

 Speed: 1'200 rpm
 Load: 100 kW
 Air excess ratio: 2.20
 Optimised Injection Timing

 Compression Ratio [\textstyle \frac{1}{C}]

 Combustion Duration [%] (100% about EURO V)

 -2 g/kWh
 -3 g/kWh
Combustion duration
Injector Nozzle Permeability

Cruise Load

<table>
<thead>
<tr>
<th>Combustion Duration [°CA]</th>
<th>Std Holes</th>
<th>Large Holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q10% [-2.7° aTDC]</td>
<td>-2.7</td>
<td>-2.7</td>
</tr>
<tr>
<td>Q 10%-90% [33.4° aTDC]</td>
<td>33.4</td>
<td>36.6</td>
</tr>
<tr>
<td>Q50% [4.3° aTDC]</td>
<td>4.3</td>
<td>3.9</td>
</tr>
</tbody>
</table>

>> BSFC improvement 0.2% !!! (negligible)

Combustion duration can be misleading !!
Combustion duration
Injector Nozzle Permeability

Potential gain to run with larger holes but at the expense of Soot!!

FIE future development: Variable Nozzle Permeability
Brake Thermal Efficiency
How to improve it?

- Compression Ratio
- Combustion Duration
- EGR – AdBlue
- Two-Stage T/C
EGR Strategy
Total Fuel + Adblue Cost

BSNOx as Function of EGR Rate and Air Excess Ratio

- Lambda:=1.2
- Lambda:=1.4
- Lambda:=1.6
- Lambda:=1.8
- Lambda:=2
- Lambda:=2.5

Relative BSNOx [%]

EGR Rate [%]

0% 5% 10% 15% 20% 25% 30% 35% 40% 45% 50%
EGR Strategy
Total Fuel + Adblue Cost

A75 Load

Increased Heat Rejection (leading to aerodynamic loss)

EGR rate [%]

+25%
Brake Thermal Efficiency
How to improve it?

- Compression Ratio
- Combustion Duration
- EGR – AdBlue
- **Two-Stage T/C**
Two-Stage T/C

Layout

- Improved BSFC by downsizing: about 2-3 %
- High Power density
- Requires higher PCP (Friction increase)
- Higher Cost

**C13 VTG compared to C10 2-stage (2 x FTG)**

![Diagram showing C13 VTG compared to C10 2-stage (2 x FTG)](image)

<table>
<thead>
<tr>
<th>B.S.F.C. [g/kWh]</th>
<th>Relative BMEP [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>80</td>
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<td>60</td>
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<tr>
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</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

CURSOR - 2-stage Turbo Charging (1'400 rpm)
Two-Stage T/C Efficiency

Comparison 1- & 2-stage Turbo Charging

Compressor Efficiency = 72%
Turbine Efficiency = 72%
HP & LP CAC Efficiency 90%
Exhaust gas temp. = 650°C
Typical pr. losses at 1200rpm

Current HD On-road

Downsizing
Application of Technologies
FPT Heavy-Duty FEP demonstrator

- Higher Compression Ratio
- Optimised Bowl Shape & Swirl
- L-EGR
- Thermal Management
- Low Friction Bearings
- Turbo Charger upgrade
Combustion

FPT Heavy-Duty

\[ \eta_{\text{Comb}} = \frac{P_e}{\dot{Q}_{\text{fuel}}} = \frac{P_e}{P_i} \left( 1 + \frac{P_{\text{ILP}}}{P_{\text{IHP}}} \right) \frac{P_{\text{IHP}}}{\eta_{\text{GasEx}}} \frac{\dot{Q}_{\text{fuel}} - \dot{Q}_{\text{wall}}}{\dot{Q}_{\text{fuel}}} \frac{\dot{Q}_{\text{fuel}} - \dot{Q}_{\text{wall}}}{\eta_{\text{Combustion}}} \frac{\dot{Q}_{\text{fuel}}}{\eta_{\text{Wall}}} \]

\begin{align*}
\text{bsfc } \eta \text{ Comb} & : 55.7\% \\
\text{Map Area } > \eta 57\%: 60\% \\
\text{bsfc } \eta \text{ Comb} & : 58.7\% \\
\text{Map Area } > \eta 57\%: 90\%
\end{align*}

+3.0% abs. \( \eta \) Combustion
Wall Heat Loss

\[ \eta_{\text{Eng}} = \frac{P_e}{\dot{Q}_{\text{fuel}}} = \frac{P_e}{P_i} \left( 1 + \frac{P_{\text{ILP}}}{P_{i\text{HP}}} \right) \cdot \frac{\dot{Q}_{\text{fuel}}}{\epsilon_{\text{GasEx}}} \cdot \frac{P_{i\text{HP}}}{\epsilon_{\text{Combustion}}} \cdot \frac{\dot{Q}_{\text{fuel}} - \dot{Q}_{\text{wall}}}{\epsilon_{\text{Wall}}} \]

C11 EU6

bsfc \( \eta \) Wall HT : 85.5%
Map Area > \( \eta \) 84%: 45%

C11 FEP

bsfc \( \eta \) Wall HT : 84.4%
Map Area > \( \eta \) 84%: 30%

-1.1% abs. \( \eta \) Wall Heat Loss
Burnt Duration: Q 90%-10% [°CA]
FPT Heavy-Duty

C11 EU6

bsfc Q 90%-10% : 33.4°
pRail: 900 bar
EGR: 0%

C11 FEP

bsfc Q 90%-10% : 25.8°
pRail: 1300 bar
EGR: 4%

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Combustion Efficiency

What's next?

**Turbo Compound**
+1% at Full Load

**WHR: Rankine Cycle**
+2-3% at Part Load

**Mission Optimisation**
+1% in Mission Load

**Hybridisation**
+?% depends on power and battery capacity
1. FPT Industrial
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3D CFD Combustion Analysis
Tools to optimise Combustion efficiency

- 3D CFD Combustion to analyse and improve $\eta$ Combustion
- Sector calculation from IVC $>$ EVO as cost effective
- Current Combustion model (like ECFM) and Heat Transfer models not very predictive for High Load HD Diesel
- Started in-house project to develop a combustion model being validated with HD-like condition flame structure and Engine High Load conditions
CFD Combustion Analysis

NexGenComb

 Constant Volume Bomb Experiments at TU/e (EHPC)
- Flame Structure (OH, CH2O, CO)
- Flame wall interaction with Heat Flux measurements
- Ambient Density, Nozzle orifice similar to HD Diesel engine at SOI

Engine Experiments
Heat Release and Pollutants
- HD Cursor11 EU6 and High PCP
- LD F1C EU6
- LD F1C PCCI

Validation of flame structure and wall heat flux for HD diesel conditions

Next Generation Combustion Model into OpenFoam
1) Model based on pre-tabulated complex chemistry: TABKIN
2) HRR, NOx and CO: trends and absolute values (no or very limited tuning)
3) Multi-fuel capabilities (Dual Fuel Diesel-Gas engine)

Refs:
Thiesel 2014
SAE 2015-01-0375

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CFD Validation of Flame Structure (Spray A)
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Figure 1: Comparison of flame structures at 0.6, 0.7, 0.8 ms after start of injection.
CFD Validation of CR sweep for Cruise load point

FPT Heavy-Duty

CR16.50 (Low swirl)

CR25.50 (Low swirl)
Outline

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Conclusions
FPT Heavy-Duty

✓ 50% brake thermal efficiency is probably achievable without add ons but wall heat loss reduction is a big challenge.
✓ Add on such as WHR, Turbo Compound, Electrification could bring thermal efficiency up to 52-53% but cost and maintenance is an issue.
Acknowledgments

- Politecnico di Milano, prof. A. Onorati and his group
- TU Eindhoven, prof. B. Somers and his group
- FPT Motorenforschung, dr. H. Fessler & Colleagues
… any questions?

Thank you very much for your attention!

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