

Functional Requirements to Exceed the 100 kW/l Milestone for High Power Density Automotive Diesel Engines

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ABSTRACT

The paper describes the challenges and results achieved in developing a new high-speed Diesel combustion system capable of exceeding the imaginative threshold of 100 kW/l. High-performance, state-of-art prototype components from automotive diesel technology were provided in order to set-up a single-cylinder research engine demonstrator.

Key design parameters were identified in terms boost, engine speed, fuel injection pressure and injector nozzle flow rates. In this regard, an advanced piezo injection system capable of 3000 bar of maximum injection pressure was selected, coupled to a robust base engine featuring ω -shaped combustion bowl and low swirl intake ports.

The matching among the above-described elements has been thoroughly examined and experimentally parameterized. The tests confirmed the benefits of the employment of very high fuel injection pressures as a way to decouple the trade-off between an excellent power rating and emissions / NVH / CO₂ at part load, whose combination truly defines the leading edge of modern diesel engines for automotive application.

The paper also discusses the system sensitivity to the boundary conditions, of the charging and exhaust systems, and develops a balanced set of targets for the entire system based on thermo-structural, fluid-dynamics and efficiency considerations. This would represent, in the authors' view, the 'recipe' for the next generation of premium diesel engines for automotive application.

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INTRODUCTION

While the history of Diesel engines for passenger car application dates back to 1930s, it was not until 1970s that their market share reached a significant level, following the oil shocks. At that time, indirect-injection Diesel cars started to be the natural option for consumers looking primarily to ownership cost.

The power density of those engines was quite low for the present standard, in the range 20-30 kW/l, with the highest values reached by first turbocharged engines then appearing on the market. The situation improved gradually in the mid-1980s, with electronically-controlled diesel hitting the market, and progress continued during the 1990s thanks to the introduction of fuel direct-injection for passenger cars.

Specific power exceeded for the first time 40 kW/l in 1997 with the introduction, now in the history books, of Common Rail technology. Since then, the pace of performance increase has even accelerated, as can be seen in detail [Figure 1](#). The recent years, in which Diesel have exceeded 50% market share in Europe (with up to 70% in the

premium and CUV/SUV segments), have recorded an easing of specific power for the core market FGT and VGT applications, in the fork between 55-60 kW/l [1]. The premium VGT market still shows modest gains, with best-in-class applications approaching 75 kW/l (which means a notable ~ 100 hp/l). On the other hand, the high-end market is still showing a race towards higher power densities, driven by sophisticated charging architectures based on Bi-, Tri-, and Quadri-Turbo as well as combinations of turbine-driven and electrically-driven compressors [2].

The engineering community has been wondering if and where a practical limit for a power density of mass-produced diesel engine does exist. Although some preliminary indication of such a limit for very high power density were provided in 2009 and 2010 by the experiences of Thirouard *et al.* and Lamping *et al.*, the recent achievement of ~ 100 kW/l by BMW in a commercial engine brings that question back again [2, 3, 4]. Starting from the experiences carried out by Thirouard and Pacaud [5], the present paper analyzes the limiting factors to diesel power density and the innovations now

available which may overcome them at the light of the increased emissions and efficiency requirements. In fact, just achieving a very high power rating would not be a particular engineering challenge per-se, but combining it with RDE emissions, premium NVH and low CO₂ at part load, truly defines the leading edge of modern diesel engines for automotive application. The trade-off between rated performance and emissions / NVH / CO₂ at part load was more or less always present during the evolution of diesel engine pictured in Figure 1, but the level of legislative requirements and customers' expectations in the present time is unprecedented. To make a few examples of what such an approach requires, the authors employed a 'constrained optimisation' to the hardware set-up, using the highest available fuel pressure and low flow number nozzle injection systems that can provide both short injection duration at rated and good fuel atomization and mixture formation at part load. On the same page, boost level at rated was limited to consider the low-end torque and part load requirements that stem from balanced charging architectures. Eventually, even the peak firing pressure (pfp) was constrained to a relatively 'common' value of 200bar on recent engines, in order to avoid compromising too much the engine design for keeping the mechanical efficiency at part load on a high level [6].

Among such advances, and based on previous experiences, boost levels of 4 barA (absolute pressure), refinement to combustion system design and 3000 bar of fuel injection pressure appear as the main thermodynamics enablers.

In order to carry out an experimental analysis on the capability to exceed a power density of 100 kW/l for the combustion systems architecture under development, an experimental single-cylinder

research engine (SCE) has been designed and setup, integrating several advanced and prototype technologies considered as an enabler for the project target. The authors eventually combine them in a balanced way (considering also the emissions and fuel economy fulfilling future legislation limits), in what they view as a 'recipe' for the next generation of high-performance diesel engines for passenger cars application.

The data carried out and described in the present paper provide the guidelines for the development of new high-power diesel engines. The present work complements and extends previous author's experiences [7]. In particular, new information about power sensitivity to the nozzle specification, thermodynamic boundary conditions and engine speed are provided in the following.

EXPERIMENTAL SETUP

The development targets for the whole project include 'exceeding' 100 kW/l power density, in compliance with the new WLTP and RDE emission homologation cycles, premium NVH levels and brake specific fuel consumption (bsfc) goal at part load.

Such combination of conflicting targets is the challenge the authors face with and which requires a careful technologies integration defining the combustion system (cylinder head, piston), the fuel injection system (FIS), etc. The work is done integrating and assembling several components, representing the state of the art of the automotive diesel engines and FIS technologies under development.

Diesel Engine Performance Trend

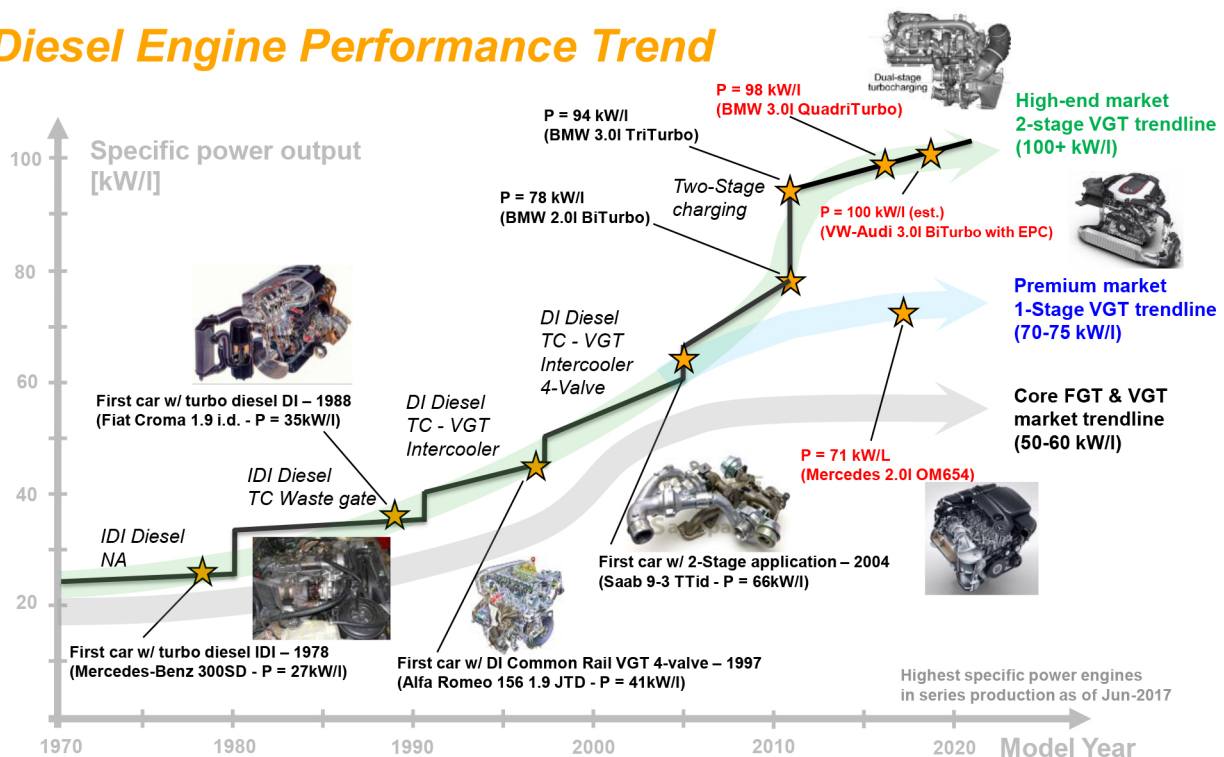


Figure 1. Diesel engine specific power evolution.

Figure 2 shows the provided technologies and a picture of the final assembled prototype SCE. The engine manufacturer provided the cylinder head, piston and conrod, while the prototype FIS system featured an advanced piezo driven injector capable of very high injection pressures. The main engine components (head, piston, conrod, etc.) were derived from a two-stage turbo multi-cylinder engine (MCE) specifically developed for a high-performance production series. The research group affiliated with the authors provided the design and manufacturing of the special components, like crankcase, crankshaft and cylinder liner, and the final integration and setup of the SCE demonstrator.

The employed injector, provided with three properly designed nozzles, is a prototype and robust concept capable of 3000 bar. A special focus was given to the main nozzle and hole design parameter to improve the nozzle permeability allowing to reduce the hole diameter at a constant hydraulic flow rate. In the present work, three nozzles with different hydraulic flows (HF) have been employed. The HF selection is based on the fuel delivery rate requirements at full load conditions. However, since higher atomization requirements would be needed at lower load conditions, the authors are also investigating the HFs impact on efficiency and emissions at lower loads.

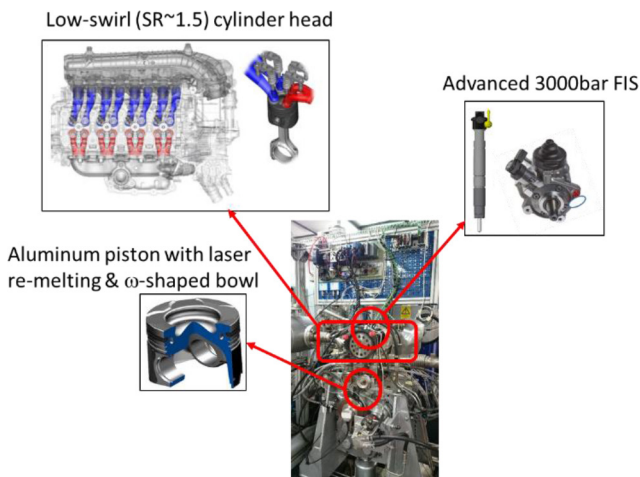


Figure 2. Integration of the technologies provided for the setup of the SCE.

Table 1 reports the main characteristics of the SCE and FIS. The main SCE features are representatives of typical values of diesel automotive engine for passenger car application. Figure 3 shows a scheme of the test cell demonstrator layout.

Table 1. Main technical data of SCE and FIS.

Displaced volume [l]	0.489
Bore x Stroke [mm x mm]	83 x 90.4
Bore pitch [mm]	90
Compression ratio [-]	16.0
Piston	Aluminium - ω shaped bowl
Injector hydraulic flow [cm ³ /min @100 bar Δ p]	880-960-1040
Number of holes	7
Maximum injection pressure [bar]	3000

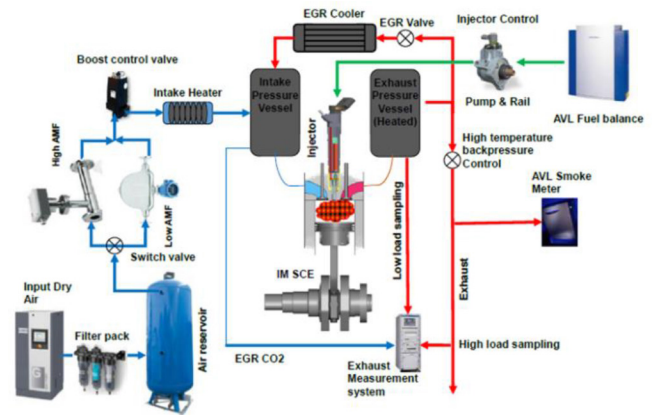


Figure 3. The test cell layout.

The demonstrator consists of a “modular” research SCE. The term “modular” refers to the combustion system components that can be re-designed and re-arranged without substantial crankcase architecture modifications. The crankshaft and cylinder liner for the SCE were designed and realised to comply with the high thermo-mechanical stress at rated power. Similarly, each component of the auxiliary systems (like intake air compressor, coolers, pumps, controllers, etc.) were selected to fit the requested engine boundary conditions for the 100 kW/l target. The air and exhaust systems have been designed to satisfy the working conditions reported in Table 2.

Table 2. Operating specifications for intake and exhaust systems.

Feature	Value
Max air flow [kg/h]	350
Max temp. at the intake valve [°C]	90
Max boost pressure at the max air flow rate [barA]	10
Max temp. in the exhaust pipe [°C]	920
Max temp. @ max exhaust pressure [°C @ barG]	700 @ 6.5
Max temp. for backpressure valve [°C]	650

The main devices and sensors employed for the engine thermodynamic analysis are listed in Table 3. An integrated emission test bench, composed by Emerson, ABB, and Ecophysics devices for the regulated emissions measurement has been adopted. The AVL 415S smoke meter has been used for the smoke and then specific PM measurement. NOx and lambda sensors have been installed in the exhaust line.

Table 3. Main sensors employed for the engine performance measurement.

Feature	Value
Monitoring/Acquisition	AVL Indimicro & Indicom
Cylinder pressure	Kistler 6125C
Rail pressure	Kistler 4067C3000S
Intake pressure	Kistler 4045A5V200S
Fuel flow rate	AVL 733 fuel gravimetric balance
Torque	HBM T10 high precision torque meter
Encoder	AVL 3650

TEST METHODOLOGY

Definition of the Boundary Conditions for 100 kW/l

The assessment of the combustion system architecture potential in terms of the power density target (100kW/l) has required the definition of the boundary intake and exhaust operative limits. The assumed mechanical limits, cooling and lubrication conditions were those of the reference four-cylinder engine.

The definition of the starting boundary conditions was carried out by means of an intensive simulation activity using a one-dimensional GT-Power model [8] calibrated on the reference prototype MCE [9] from which the SCE architecture derives. Figure 4 shows the architecture of the two-stage turbo MCE model capable of attaining very high boost pressure levels.

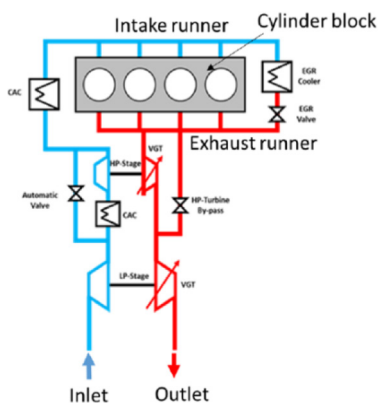


Figure 4. Scheme of the GT-Power model of the four-cylinder MCE engine.

The 1D model has been used to perform the estimation in terms of:

- Air flow requirements;
- Injected fuel estimation;
- Intake - Exhaust boundary conditions (p, T, etc.).

The simulation results have provided the operation range of the intake and exhaust conditions for which the power density target should be attained.

Figure 5 displays the simulated results in terms of brake mean effective pressure (bmep), indicated mean effective pressure (imep) and the sum of the friction mean effective pressure (fmep) and pumping mean effective pressure (pmep) versus the engine speed, required for the 100kW/l target.

It can be observed that, in the typical maximum speed range of automotive diesel engines, imep values in the range of 32-37 bar, depending on the regime, have to be reached to attain the power target.

The graphical trends in terms of p_{boost} , p_{back} , exhaust temperature, etc. versus engine speed are here omitted for brevity. However, the assessed boundary conditions values for enabling the specific power target or the imep values of Figure 5 (e.g. ≥ 35 bar at 4000 rpm) are listed in Table 4 [7].

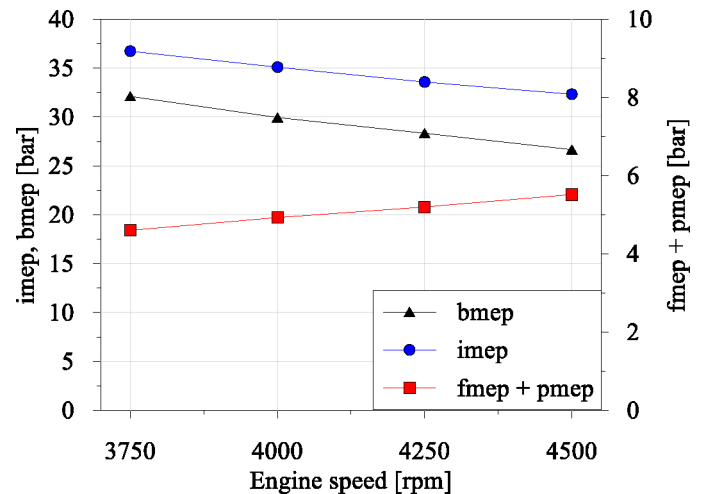


Figure 5. Simulated imep, bmep and fmep + pmep of the reference MCE for enabling the 100kW/l target.

Table 4. Boundary conditions for enabling 100 kW/l target.

Feature	Value
Absolute intake pressure [barA]	4
Temperature at the exhaust valve outlet [°C]	900
Peak firing pressure [bar]	200
Minimum fuel injection pressure [bar]	2700

The same boundary conditions have been employed for the speed and nozzle HF assessment. Actually, the engine components can operate with peak firing pressure (pfp) values higher than 200 bar. Anyway, in order to carry out reliable and transferable data for robust multi-cylinder applications, in this test campaign, it was preferred to keep the pfp limit as in Table 4.

Based upon the simulation results described in the previous section, a parameterization on the maximum reachable load was carried out varying the engine operating factor on different levels as reported in Table 5.

Table 5. Engine parameter set values for maximum load parameterization

Parameter	Set value in test matrix
Engine speed [rpm]	3750/4000/4500
p_{boost} [barA]	3.0/3.5/4.0
p_{rail} [bar]	2500/2750/3000
T_{exh} (SCE) [°C]	770/800/830
pfp [bar]	180/200
Smoke emission limit [FSN]	2.5

A maximum limit of 2.5 FSN on the exhaust smoke was imposed in order to reproduce test conditions compatible with the Diesel Particulate Filter (DPF) functionality. The temperature at the exhaust valve outlet (T_{exh}) values refers to the SCE actual operation. They were chosen assuming the following relationship for the full load conditions in the range 3750 - 4500 rpm:

$$T_{\text{exh}} (\text{SCE}) = T_{\text{exh}} (\text{MCE}) - 70^\circ \text{C}$$