

Comparison of Fuel Consumption and Emissions of Automotive and Large-Bore Diesel Engines

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ABSTRACT

When comparing automotive and large-bore diesel engines, the latter usually show lower specific fuel consumption values, while automotive engines are subject to much stricter emission standards. Within an FVV (Research Association for Combustion Engines) project these differences were identified, quantified and assigned to individual design and operation parameters. The approach was split in three different phases:

1. Comparison of different-sized diesel engines
2. Correlation of differences in fuel consumption to design and operating parameters
3. Further investigations under automotive boundary conditions

The comparison in the first phase was made on the basis of operating data and energy balances as well as the separation of losses based on the thermodynamic analysis. To also determine the quantitative effects of each design and operating parameter, a 1D process calculation model of the passenger car engine was transformed gradually to a large-bore engine in the second phase. The advantage of the large-bore engines results basically from their higher combustion air ratio, shorter combustion duration, lower wall heat losses and high positive gas exchange work due to a high turbocharger efficiency.

Experimental tests showed that the benefits in fuel consumption of the large-bore engine can be transferred to an automotive engine by applying a scaled-down large-bore engine combustion process. The tests showed further that it is crucial to provide the high combustion air ratio of the large-bore engine with sufficiently high turbocharger efficiency and that the large-bore combustion system is much more sensitive to the air ratio concerning smoke emission.

CITATION: Wolf, R. and Eilts, P., "Comparison of Fuel Consumption and Emissions of Automotive and Large-Bore Diesel Engines," *SAE Int. J. Engines* 7(1):2014, doi:10.4271/2014-01-1100.

INTRODUCTION

The development of engines is nowadays more than ever dominated by the conflict between efficiency and the increasingly stringent exhaust emission limits. The introduction of taxation of CO₂ emissions is forcing engine manufacturers to always find new ways in developing their products in order to meet the conflicting goals in the future. The systems therefore become very complex. An example is hybridization. A view at the large bore engines shows that these in some cases have much lower fuel consumption compared to vehicle engines. Furthermore it is known that vehicle engines are subject to more stringent exhaust emission limits. In an FVV research project it was investigated wherein the differences are established and if it is possible to transfer the advantages of the one engine type to the other and vice versa. In this paper,

an overview of the work done in the project and selected results will be presented. The entire results can be found in the final report [1].

STATE OF THE ART

The theme of downsizing is also an issue with the diesel engine to reduce fuel consumption and affects practically all engine sizes. The relocation of the operating points to points of higher specific work promises higher efficiency. Diesel engines, especially against the background of downsizing, are no longer conceivable without turbocharging today. Here, a constant increase of the degree of supercharging is recognizable over the years and complex multi-stage systems have found their way into mass production. For compression ratio at passenger car engines (PCE) rather a trend towards lower values is observed, to improve NO_x-PM-trade-off [2]. However, a steady increase in peak pressure due to the downsizing can be

seen. At commercial vehicle (CVE) and large bore engines (LBE) the compression ratio rather increases to ease NO_x -BSFC-trade-off [3], [4].

General Approach

The project was split into three parts. In the first part different sized 4-stroke diesel engines were compared on the basis of operating values and energy balances as well as the separation of losses of the pressure curve analysis. From this section it was known which efficiency factor was responsible to which extent for the differences in fuel consumption. However, at this point in time, the quantitative impact of the individual design parameters on the partial efficiency factors was not yet known. About the cause of the differences in pollutant emissions there is information by trend.

The engines examined and a selection of their technical data are shown in Table 1.

Table 1. Selection of technical data of the engines examined.

Engine type	PCE	CVE	LBE		
Number of Cylinders [-]	4	6	7	18	9
Displacement [L / Cylinder]	0.5	2.0	32.2	32.2	88.6
Bore [mm]	81	135	320	320	430
Stroke [mm]	95.5	150	400	400	610
Stroke / Bore- Ratio [-]	1.18	1.11	1.25	1.25	1.42
Compression ratio [-]	16.5	16.8	14.5	14.5	15.5
Mean Piston Speed [m/s]	12.7	9.5	10.0	10.0	10.2
Rated Mean Effective Pressure [bar]	15.5	21.2	23.8	24.9	27.1
Injection System	Common-Rail	Pump-Line-Nozzle			

As the different-sized engines are used in totally different application areas, comparable operation points were defined. The typical operating lines of large bore diesel engines (propeller curve with $\text{MEP} \sim n^2$ and generator line with $n = \text{const.}$) were transferred to the maps of the vehicle engines at various speeds. Figure 1 illustrates the operating points compared in the example of the speed at minimum fuel consumption of the vehicle engines. Furthermore a mean piston speed of 10 m / s and the nominal speed were investigated. The operating points for the truck engine do not correspond to the propeller curve exactly because they were taken from an existing database and not measured for this project.

The second part of the project contained a transition from one engine to another. For this purpose, a simulation model of a vehicle engine was changed gradually to a model of a large bore engine, with the aim to determine the differences in fuel consumption quantitatively and to assign them to the individual design parameters. In order to verify the theoretical work, the studies were accompanied by experiments.

The aim of the third phase was a more fuel-efficient vehicle engine that, in compliance with the usual demands to a vehicle engine, benefits from the findings from the previous studies and thus benefiting from the advantages of large bore engine.

In this paper the results from the operating points on the generator line through the minimum fuel consumption and the associated propeller curve are discussed.

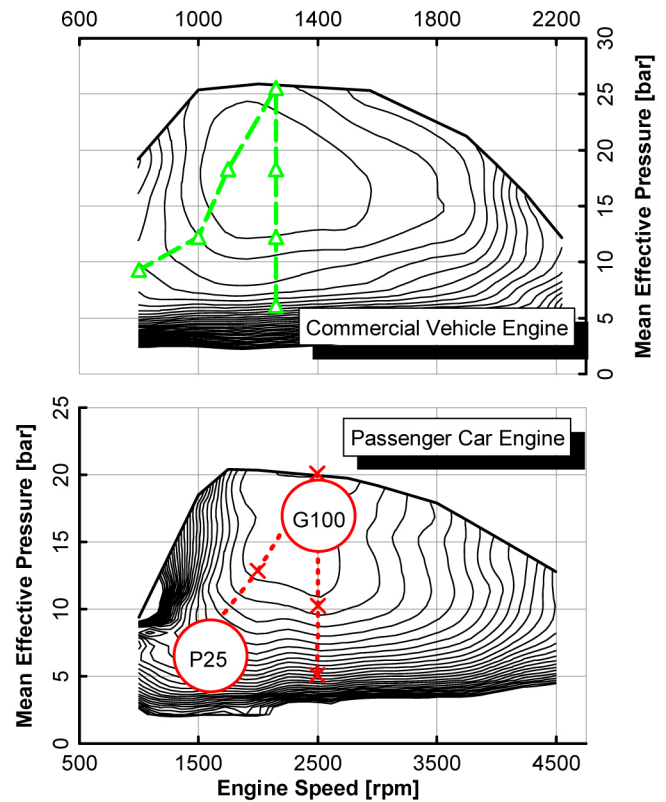


Figure 1. Operating lines investigated. Constant speed line through minimum BSFC of the vehicle engines and corresponding propeller curve.

ENGINE COMPARISON

Performance Data

When considering Figure 2 the first impression is a decreasing fuel consumption with increasing engine size.

The commercial vehicle engine makes an exception and shows similar low values as the largest large bore engine. At loads below a mean effective pressure of about 15 bar the commercial vehicle engine is even superior to all. The significant difference between the two large bore engines with 320 mm bore is due to a different layout. It will also be appreciated that the minimum fuel consumption of all engines is achieved both on the constant-speed line as well as with variable speed at about 2/3 to 3/4 of the maximum mean effective pressure.

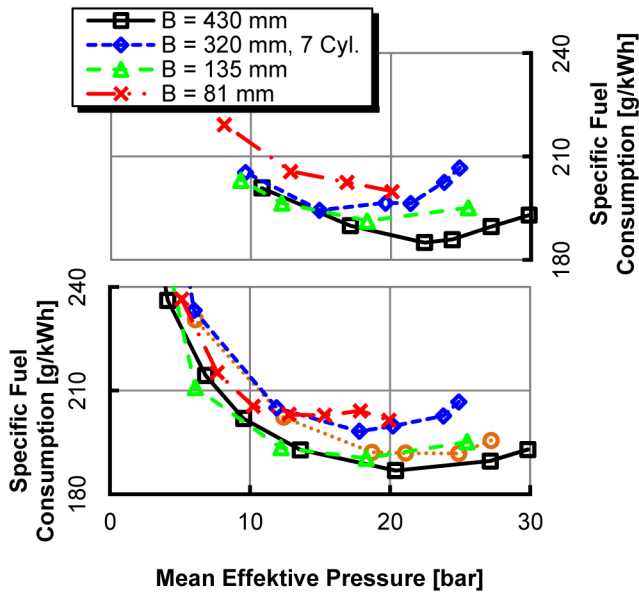


Figure 2. Brake specific fuel consumption as a function of mean effective pressure on constant speed line (below) through minimum BSFC and corresponding propeller curve (up).

The specific air flow (not shown) of the large bore engines is significantly greater than those of the vehicle engines. This is particularly due to the long valve overlap duration in combination with the high boost pressure and the large scavenging pressure difference (Figure 3) due to the high turbocharger efficiency (Figure 4) of the large bore engines.

The curve of air ratio (Figure 5) across the load is qualitatively similar to that of the air flow. The air ratio is the reciprocal of the equivalence ratio. For the large bore engines, an air excess clearly above 2 is aimed at over the entire load range. A comparison between combustion and total air ratio proves the major content of scavenging air in the exhaust of the large bore engines.

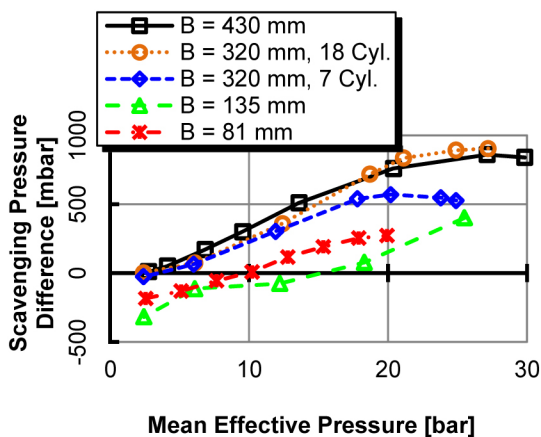


Figure 3. Scavenging pressure difference as a function of mean effective pressure on constant speed line through minimum BSFC.

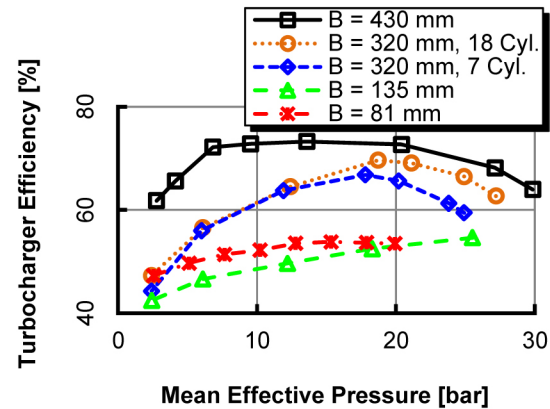


Figure 4. Turbocharger efficiency as a function of mean effective pressure on constant speed line through minimum BSFC.

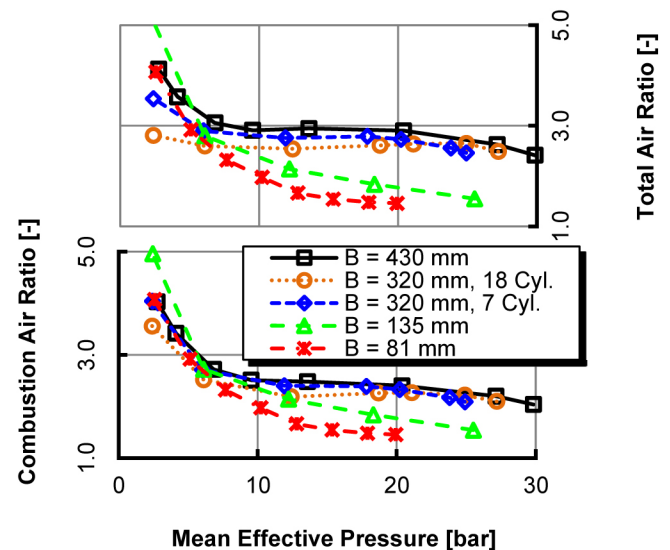


Figure 5. Combustion (below) and total (up) air ratio as a function of mean effective pressure on constant speed line through minimum.

The high air ratio in conjunction with the scavenging air ensures the lower exhaust temperatures (Figure 6) of the large bore engines. As a tribute to the heavy fuel oil operation an exhaust gas temperature of 500 deg C before turbine in new condition is typically sought for to prevent the formation of deposits on the turbine [5]. The step in the curve of the 7-cylinder large bore engine with 320 mm bore on the propeller curve is due to the use of a cylinder bypass at low loads to achieve a sufficient distance to the compressor surge limit.

Figure 7 shows that the peak firing pressures of the passenger car engine are highest up to about 15 bar mean effective pressure. Beyond the large bore engines show higher firing pressures, primarily due to their high boost pressure levels. The firing pressure of the commercial vehicle engine is lower than those of large engines.

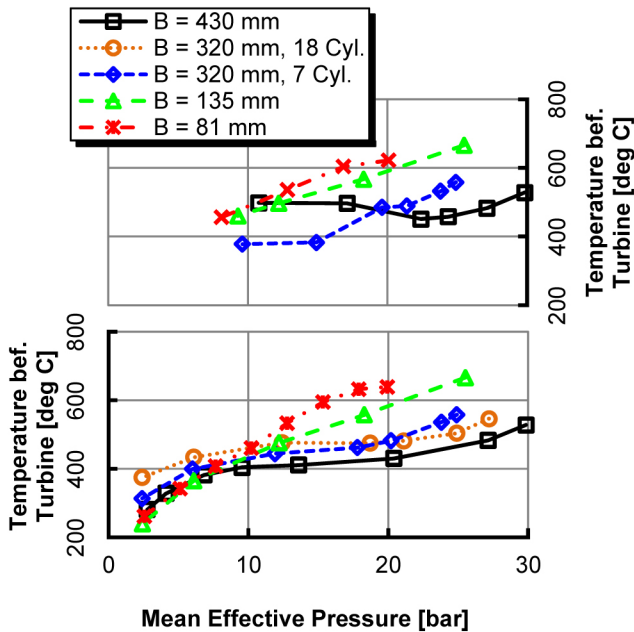


Figure 6. Exhaust gas temperature before Turbine as a function of mean effective pressure on constant speed line (below) through minimum BSFC and corresponding propeller curve (up).

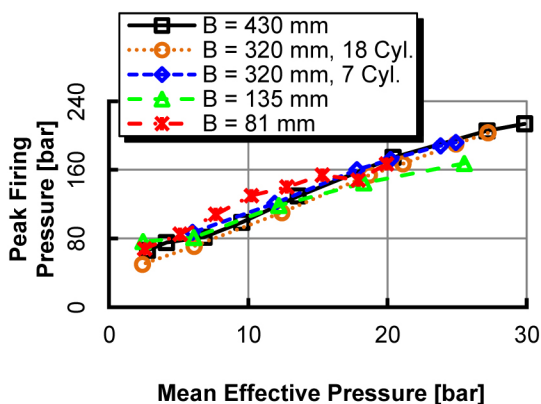


Figure 7. Peak firing pressure as a function of mean effective pressure on constant speed line through minimum BSFC.

Energy Balance

The heat balance gives quantitative information into which form of energy the engines convert the fuel energy. Figure 8 shows the principal scheme used here. On the one hand there is a small heat balance set up around the cylinder (Figure 8, system boundary 2) and on the other hand a large heat balance is set up including the turbocharger (Figure 8, system boundary 1).

From the small energy balance

- the effective power,
- the exhaust enthalpy before turbine - the charge air enthalpy after charge air cooler as well as
- the wall and friction heat are calculated.

From the large heat balance the effective power is also calculated. In contrast to the small energy balance here

- the exhaust enthalpy after turbine - the charge air enthalpy before charge air cooler
- the charge air cooling water heat and also
- the residual heat from wall, friction and radiation/convection are determined.

All the heats are shown relative to the fuel energy.

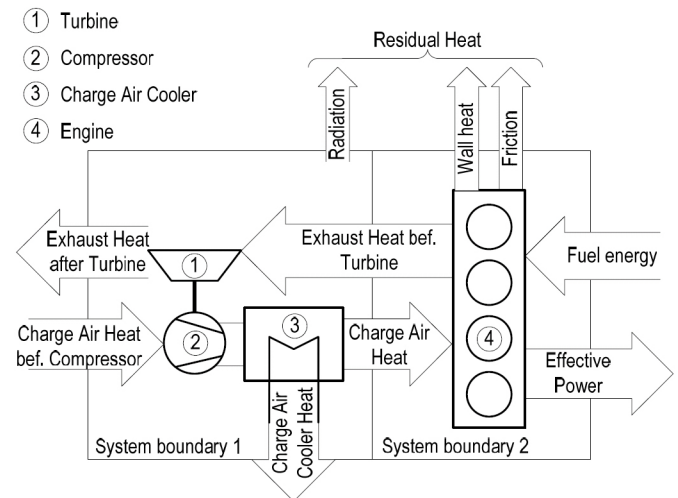


Figure 8. System boundary for energy balance.

The effective power relative to the fuel heat is equal to the effective efficiency, and thus inversely proportional to the specific fuel consumption, see Figure 2.

Figure 9 shows that the large bore engines have the largest amount of exhaust enthalpy before turbine. This tends to increase with load for all the engines both on the generator line and on the propeller curve. The vehicle engines make an exception in the lower load range on the generator line where the values initially show a slight decrease.

The amount of charge air cooler heat, not shown here, increases for all engines with the load. It is highest for the large bore engines because of their very high pressure ratio at an almost constant charge air temperature.

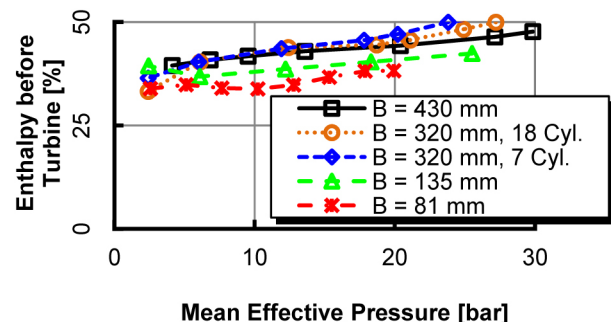


Figure 9. Exhaust gas enthalpy before turbine as a function of mean effective pressure on constant speed line through minimum BSFC.