

The Effects of Neat Biodiesel Usage on Performance and Exhaust Emissions from a Small Displacement Passenger Car Diesel Engine

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ABSTRACT

The effects of using neat FAME (Fatty Acid Methyl Ester) in a modern small displacement passenger car diesel engine have been evaluated in this paper.

In particular the effects on engine performance at full load with standard (i.e. without any special tuning) ECU calibration were analyzed, highlighting some issues in the low end torque due to the lower exhaust gas temperatures at the turbine inlet, which caused a remarkable decrease of the available boost, with a substantial decrease of the engine torque output, far beyond the expected engine derating due to the lower LHV of the fuel. However, further tests carried out after ECU recalibration, showed that the same torque levels measured under Diesel operation can be obtained with neat biodiesel too, thus highlighting the potential for maintaining the same level of performance.

Moreover, the effects of FAME on brake specific fuel consumption and on engine out exhaust emissions (CO_2 , CO, HC, NO_x and PM) were also evaluated at 7 different part load operating conditions, representative of the New European Driving Cycle.

Both standard and specifically adjusted engine calibrations were evaluated for part load operating conditions, highlighting a 13% average rise of fuel consumption, on a mass basis, at same fuel conversion efficiency and CO₂ emissions. A remarkable increase of CO and HC emissions at low load could be noticed, along with an almost negligible increase in NO_x emissions when using a specifically adjusted

engine calibration, and a considerable smoke emission reduction.

INTRODUCTION

The usage of bio-derived fuels as an alternative to fossil fuels for diesel engines has been widely investigated in recent years, since it can provide interesting opportunities in terms of reductions of greenhouse gases emissions and of particulate matter (PM) emissions, as well as in terms of energy sources diversification [1,2,3].

In particular, in the transportation sector the usage of transesterified vegetable oils (often referred to as biodiesel, or FAME, Fatty Acid Methyl Ester), pure or in blend with fossil fuels, has been spreading, thanks to the similarity between its chemical and physical properties with those of fossil diesel fuel.

However, although several research programs have been carried out on the performance and emissions of compression ignition engines, fuelled with pure biodiesel and blends with diesel fuel, most scientific literature has dealt in the past with engines equipped with conventional injection systems [4,5,6,7,8,9,10,11], and even if more recent works also examined engines with high pressure, electronically controlled injection systems [12,13,14,15,16], only few studies concerning last generation automotive engines are available.

The research activity presented in this paper is therefore focused on the analysis of the effects of neat biodiesel usage

on performance and exhaust emissions from small displacement (1.3 liter) Euro 5 passenger car diesel engine.

EXPERIMENTAL SET-UP

The engine used for the research activity is a modern automotive Euro 5 small displacement (1.3 liter) common rail turbocharged diesel engine, the main characteristics of which are listed in [Table 1](#).

Table 1. Main characteristics of the test engine

Engine Type	Diesel 4 stroke
Displacement	1248 cm ³
Cylinders arrangement	4 in line
Max Power	55 kW @ 4000 rpm
Bore x Stroke	69.6 mm x 82 mm
Compression Ratio	16,8 : 1
Turbocharger	Single-stage with WG
Fuel injection system	Common Rail

The experimental tests were carried out at ICE Advanced Laboratory of Politecnico di Torino on an engine test bench equipped with an eddy current dynamometer. Fuel consumption was measured by means of an AVL 733S gravimetric fuel meter. Although the engine is equipped with a close coupled aftertreatment system, featuring a DOC and a catalyzed DPF integrated in a single canning, since the research activity was focused on engine-out emissions, exhaust gases were sampled only between the turbine outlet and the catalytic converter inlet: in particular, a Fisher-Rosemount NGA-2000 gas analyzer was employed for the measurement of the gaseous emissions and an AVL 415S smoke meter was used for the measurement of the particulate emissions.

During the tests, all the engine control parameters were controlled by a PC that was directly connected to the engine ECU: the test engine was also equipped with a closed-loop combustion control capable of maintaining the center of weight of the combustion process at its optimal position. Moreover, the piezoresistive pressure transducers integrated in the glow plugs used for the closed loop combustion control, were also used for the measurement of the in-cylinder pressure. The output from these transducers were firstly filtered by a low-pass filter to reduce high frequency noise and to prevent aliasing errors and signal distortion and then finally sampled by means of a 12 bit high-speed multichannel data acquisition board (National Instruments DAQCard-AI-16E4), coupled to a high resolution (0.4°) crank-angle encoder to ensure proper timing of the sampled data. At each operating condition 100 consecutive engine cycles were recorded to obtain a wide statistical sample.

Data acquisition and post-processing were performed by means of ICE Analyzer [17], a suitable developed program for internal combustion engine indicating analysis, while the combustion noise was computed on the basis of the methodology proposed in references [18,19,20].

Experimental tests were performed using the following fuels:

- B100: pure FAME, complying with EN 14214
- B0: pure typical European ultra low sulfur diesel fuel compliant with Directive 2003/17/EC (S content < 10 mg/kg).

The main properties of the tested fuels are listed in [Table 2](#). It should be noticed as, although the oxygen content of the biodiesel reduces both its stoichiometric ratio A/F_{st} (12.3 instead of 14.5 of diesel, with a 15 % reduction) and its Lower Heating Value (37.35 MJ/kg instead of 43.1 of diesel, with a 13 % reduction), the LHV/ A/F_{st} ratio is slightly higher for biodiesel, thus highlighting the potential for a better engine performance at full load, since the maximum bmep which can be achieved at a given λ is proportional to the LHV/ A/F_{st} ratio.

Table 2. Compositions and Properties of Tested Fuel

Properties	B0	B100
Carbon content C [w%]	86.5	78.5
Hydrogen content H [w%]	13.5	10.8
Oxygen content O [w%]	-	10.5
Sulfur content S [ppm] (EN ISO 14596-98)	< 10	< 10
Stoichiometric ratio (A/F) _{st}	14.5	12.3
Net heating value, LHV [kJ/kg] (ASTM D 240-00)	43100	37350
Cetane Number (ISO 5165-98)	51.8	52.3
Density at 15 °C, [kg/m ³]	840.1	883
Viscosity at 40 °C, [mm ² /s]	3.141	4.254
LHV/(A/F) _{st} [MJ/kg]	2.972	3.037

TEST PROCEDURE

Tests were initially carried out at full load without any modifications to the ECU injection strategy, in order to assess the impact of the neat biodiesel usage on engine performance. Afterwards, further full load tests were performed, by adjusting the engine calibration parameters in order to achieve, for each revolution speed, the same relative air-fuel

ratio λ measured under Diesel operation, so to more completely evaluate the performance potential of neat biodiesel.

Finally, part load tests were carried out in order to evaluate the effects of biodiesel usage on fuel consumption and pollutant emissions at 7 different operating points, which are listed in [Table 3](#) and were selected after a preliminary numerical simulation of different driving cycles as representative of the New European Driving Cycle.

Table 3. Part load operating conditions

Point	Speed [rpm]	Bmep [bar]
1	1500	2
2	1500	5
3	2000	2
4	2000	5
5	2500	5
6	2500	8
7	2750	12

At part load conditions two different strategies were used in order to achieve the bmep target values with biodiesel, compensating for the Lower Heating Value of the fuel:

- Change of the accelerator pedal position in order to obtain the same BMEP level as with diesel fuel; this strategy, that will be here on referred to as “FAME std. calibration” does not feature any change in the ECU calibration, but the operating point of the engine is simply shifted towards higher load values, since the lower heating value of the biodiesel has to be compensated with an increase of the pedal position. This strategy was chosen in order to simulate the effects of the switch to neat biodiesel by the end users, without any specific adjustment of the engine calibration parameters.
- Adjustment of the energizing time of the main injection in order to obtain the same BMEP level as with diesel fuel while keeping unchanged the pedal position, and thus the operating point position on the engine calibration map; this strategy, that will be here on referred to as “specifically adjusted FAME calibration” was chosen in order to simulate the effects of the simplest recalibration of ECU parameters. However, it should be pointed out that in this way all the main engine control parameters (e.g. injection pressure and timing, EGR rate, etc.) are not changed from the standard calibration, while only the injected fuel quantity is adjusted. Further experimental activities will be carried out to fully exploit the benefits that could be obtained for instance by

adjusting the EGR rates in order to take into account the different biodiesel NO_x-soot trade-off.

TEST RESULTS

FULL LOAD ENGINE PERFORMANCE

The full load engine performance with diesel fuel and with neat biodiesel are compared in [Figure 1](#) (labelled as “Diesel” and “FAME” respectively): as expected, without any modifications in the ECU injection strategy, the B100 causes a decrease of about 11% on average in engine power, because of the slightly higher biodiesel density cannot compensate its lower LHV. From [Table 2](#) it can be noticed that biodiesel LHV is 13% lower than diesel LHV, while biodiesel density is 5% higher than diesel density; since, neglecting the viscosity effects on the injection rate, the amount of fuel injected will scale with fuel density root squared, the biodiesel injected quantities will be roughly 2,5% higher than diesel, thus leading to an energy content introduced into the cylinder about 11% lower, which is in good agreement with the measured torque decrease, since the use of biodiesel does not change substantially the overall efficiency under full load operating conditions.

Moreover, some issues in the low end torque are quite evident, in particular at 1250 rpm, with a considerable decrease (38 %) of the engine torque output, far beyond the expected engine derating due to the lower energy content of the injected biofuel: the root cause of the poor low end torque performance can be ascribed to the lower exhaust gas temperatures at the turbine inlet (see [Figure 2](#)), which causes a remarkable decrease of the available boost pressure (see [Figure 3](#)), thus producing a substantial decrease of the engine torque output, since according to the “standard” ECU calibration the maximum injected quantity at full load is limited on the basis of the air mass flow in order to control smoke emissions.

Further full load tests were then performed, by adjusting the engine calibration parameters in order to achieve, for each revolution speed, the same relative air-fuel ratio λ measured under Diesel operation, so to more completely evaluate the performance potential of neat biodiesel (the results of these further tests have been labeled as “FAME Recal.” in [Figures 1, 2 and 3](#)). From [Figure 1](#) it can be clearly noticed that, in the high speed range (above 2500 rpm), the same torque levels measured under Diesel operation can be obtained with neat biodiesel after the recalibration, while some increases in the torque output are evident in the intermediate speed range (from 1500 to 2500 rpm); finally, also the huge torque gap at 1250 rpm is remarkably reduced, thanks to the reduction in the turbine inlet temperature gap, that allows to re-establish the target boost level, as shown in [Figures 2 and 3](#). Finally, it should be pointed out that further torque output improvements could be achieved by modifying the engine calibration in order to obtain the same smoke levels measured