

Study of the Effect of the Engine Parameters Calibration to Optimize the Use of Bio-Ethanol/RME/Diesel Blend in a Euro5 Light Duty Diesel Engine

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ABSTRACT

In the global scenario of encouraging the use of renewable sources, the bioethanol as fuel supply in the automotive sector is receiving increasing interest. In the present paper the results of a research activity aimed to study the impact of a bioethanol/biodiesel/mineral diesel blend on performance and emissions of an automotive diesel engine are reassessed. An experimental campaign has been devoted to characterize the engine fuelled by the ethanol based blend highlighting the advantages and issues related to the bioethanol use. Moreover, the effects of the most important injection settings on the engine performance have been detailed, applying a Design of Experiment (DoE) method, to identify the potentiality offered by a proper engine calibration to optimize the ethanol blend use. The tests were performed on a 2.0 L Euro5 diesel engine, in steady-state at partial and full-load conditions, burning two fuel blends: the Rapeseed Methyl Ester (RME)/Diesel with 10% of biodiesel by volume, and the bioethanol/RME/Diesel with 20% of bioethanol and 10% of biodiesel by volume. The results showed a strong smoke emissions reduction for bioethanol blend in all tested conditions, together with a decrease of NO_x, confirming a well known trend. Nevertheless, an increment of CO and HC emissions for bioethanol blends were found, mainly at low load conditions. This issue has been investigated performing a specific test campaign inspired to the DoE method. Such activity identified in the calibration of the pilot injection quantity and rail pressure values the most influential factors in the gaseous unburned reduction.

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INTRODUCTION

In the effort to satisfy the goal of saving energy and protecting the environment, ethanol represents a valid alternative to fossil fuels in internal combustion engines. Even if its most common use is for gasoline engine applications, the interest in burning ethanol in diesel engine is increasing. The attention on ethanol is due to main reasons; first of all, it is a renewable fuel, which can be produced by alcoholic fermentation of sugar from different vegetable biomass (first generation bioethanol). Recently, the second generation bioethanol, which utilizes lignocellulosic biomass derived from forest residues, wood wastes, solid wastes, etc. has received much interest because the adopted feedstock is abundant, low-cost and above all does not compete with food crops [1].

From an environmental point of view, bioethanol is biodegradable and offers the benefit of reducing the net emissions of greenhouse gases. Furthermore it is a renewable fuel and can represent a different option to other alternative fuels, like methyl or ethyl ester derived from vegetable oil or animal fat (first generation biodiesels) or Fischer-Tropsch fuels (second generation biodiesels); these characteristics in the last years have been widely investigated, in the common aim to reduce the world's dependence on crude oil. Moreover, like other oxygenated biofuels, the ethanol can significantly contribute to particulate emissions reduction [2], thus appearing very interesting, in particular for diesel engines applications. Focusing on the use of ethanol in compression ignition engines, some critical aspects have to be taken into account. The physical and chemical characteristics of ethanol (high octane number, low lubricity, low cetane number as

example) do not make it suitable as pure fuel in diesel engines, unless both strong technical modifications and recourse to a powerful cetane improver and lubricant additives [3].

In the present activity, ethanol has been employed in the form of blends directly injected in the engine; this configuration, avoiding any engine modifications, represents the easiest method to use the alcohol fuel.

The scientific literature reports several studies of diesel/ethanol blends in compression ignition engines and the provided results are of course affected by different factors, as the typology of the adopted engine or the test procedure relative to the specific activity. However, as general overview, the use of diesel/ethanol blends in compression ignition engine certainly provides smoke emission reduction [4, 5]. On the other hand, the effects on carbon monoxide (CO) and nitrogen oxides (NOx) are less clear [6]; in fact while tailpipe HC emission increment are quite always detected [7, 8, 9], some authors refer that CO emissions increased at low load and decreased at high load [7, 10]. The results reported in literature reveals that the use of diesel/ethanol blends affects the NOx emissions, with zero or slightly reduction (4-5%), as reported by Hansen *et al.* [6], but many studies highlight even higher reduction [1, 11].

The present paper describes the experimental activity aimed to study the effect on engine performance and emissions of a bioethanol/biodiesel/mineral diesel blend tested in a direct injection automotive diesel engine. Biodiesel has been added for more reasons: it could act as a co-solvent to prevent ethanol separation, since it works as an amphiphile, a surface-active agent [12]; it has a high viscosity and cetane number that partly restore the cetane number of the blend and improve its lubrication [13]; it increases the percentage of renewable/oxygenated fuel in the blend, in view of future target on transportation fuels requested by European Union.

A first part of the activity has been dedicated to evaluate the performance offered by the bioethanol blend; while a second part has been designed to study the possibility to overcome the issue of high unburned emissions derived from the bioethanol blend use. To this aim, the effect of some engine parameters calibration to optimize the use of the alcohol blend has been evaluated.

The interest of the authors derives from a limited number studies published in the literature focused, in particular, on the adoption of this kind of blends to commercial light-duty diesel engines. The novelty of the present paper, in fact, lies in testing the alternative blend in a modern automotive diesel engine, Euro5 version, featuring the closed loop combustion control. This system represents a promising technology for the decisive development of the Flex-Fuel-Vehicle, as recent studies of the same authors highlight [14, 15, 16]. Another contribution of the paper is in the effort to offer a possible solution to the real applicability of the bioethanol blend in diesel engine, exploiting at the same time its potentiality on gas emissions reduction and environmental impact.

The experimental facilities, the adopted testing methodologies and the obtained results are illustrated in the following.

ENGINE AND FUELS

The experimental layout comprises a 4-cylinder in-line LD (Light Duty) diesel engine installed on a dyno test bench. The engine, whose main characteristics are reported in Table 1, is a Euro5 version and features the closed loop combustion control on the Indicated Mean Effective Pressure (IMEP) and the angular position relative to the fifty percent of Mass Burned Fraction (MBF50); details about CLCC working are reported in [15, 17]. Currently such a control is equipping the most advanced diesel engines for the premium cars and a wide spread to the other vehicle classes is expected.

Table 1. Main features of the multi-cylinder engine

Engine type	In-line 4 cylinders
Bore/ Stroke/ Compression Ratio	83.0 mm/ 90.4 mm/ 16.5
Injection system	CR/Bosch Solenoid CRI 2.16, 7 holes
Turbocharger	Single stage Variable Geometry Turbine (VGT)
After-treatment system	Close-coupled Catalyzed Diesel Particulate Filter (CC-CDPF)
Maximum Power	112 kW @ 4000 rpm

The engine was tested in steady state conditions for different engine speeds and loads. It was instrumented for temperatures and pressures monitoring in the intake and the exhaust lines. The engine was also instrumented for the indicated analysis (cylinder pressure, injection pressure, energizing injector's current): more in detail, the cylinder pressure signals were measured by the pressure sensor glow plugs in cylinder 2-3-4, while for the cylinder 1 a piezoelectric sensor (AVLGH13P) was used. The exhaust gaseous emissions (FID: Total unburned hydrocarbon; CLD: NOx; NDIR: CO and CO₂; PMD: O₂) were measured by means of a raw emission analysis test bench (AVL-CEB-2) in two sampling positions, upstream and downstream the aftertreatment device (Closecoupled Catalyzed Diesel Particulate Filter). For the HC measurement the FID technology represents the standard method for the automotive emissions regulation; anyway some recent studies on spark ignition engines have shown that this method has a low sensitivity to oxygenated compounds typically associated to the use of alcohol fuels [18]. However, such studies reveal that within moderate percentage of alcohol fraction (e.g. ≤20%), the reduction of the FID response factor is below of 5%. Therefore, even if in the present work (referred to a diesel engine) the HC values are slightly underestimated for the ethanol blend, the authors consider the comparative analysis reported in the following not compromised by the raw FID data. Anyway, for an accurate measurements of HC emissions burning oxy-fuels in diesel engines, future specific investigations will be need according to experiences carried out in [18]. Smoke was measured by high resolution (0.01

filter smoke number, FSN) smoke meter (AVL415S), at the engine out.

Table 2 reports, for the pure fuels and the blends, some of the most important parameters affecting the engine performance. More in detail, the adopted pure fuels were: a commercial diesel fuel compliant with EN590 European regulation; an EU-widely-available Rapeseed Methyl-Ester compliant with EN14112 European regulation and bioethanol (99,9% purity). The effect of bioethanol use was evaluated testing a blend, named E20B10, composed for 70% vol. of diesel, 20% vol. of ethanol and 10% vol. of RME. In order to decouple the effects of RME in the mixture and to focus only on the contribution of ethanol, the reference fuel was the B10 blend, composed for 90% vol. of diesel and 10% vol. of RME. Looking at Table 2, it is to put in evidence the high value of oxygen content in the ethanol-based blend, equal to 9.1%: a value to keep in mind for the interpretation of the results illustrated in the next. The bioethanol-biodiesel-diesel blend was prepared four months before starting the test campaign and no ethanol separation has been observed, also during the experimental activity and the next two months. These results suggest that the addition of biodiesel can increase the stability of the ethanol based blends however, further testing is needed to confirm.

Table 2. Main fuel characteristics

Feature	Method	Diesel	RME	Ethanol	B10	E20B10
Density @ 15°C [kg/m ³]	EN ISO 12185	833.1	883.1	792.8	838.0	829.8
Viscosity @ 40°C [mm ² /s]	EN ISO 3104	3.14	4.43	1.16	3.23	1.95
Cetane number	EN ISO 5165	51.8	52.6	5-8*	52.1	~40*
Low heating value [MJ/kg]	ASTM D 4868	42.96	37.57	26.87	42.50	39.15
Heat of vaporization [kJ/kg]		265	309	840	271	382
Distillation [°C]	EN ISO 3405					
	IBP	159	318	78	166	78
	10 [% vol.]	194	331	78	205	83
	50 [% vol.]	268	335	78	275	255
	90 [% vol.]	333	344	78	334	329
	95 [% vol.]	350	353	78	351	348
Fuel composition [% m/m]	FBP	361	355	78	360	359
	ASTM D 5291					
	Carbon	85.4	77.1	52.2	84.4	77.8
	Hydrogen	13.7	11.6	13.0	13.2	13.1
Stoichiometric air/fuel ratio	Oxygen	0.9	11.3	34.8	2.4	9.1
	From fuel composition	14.6	12.4	8.9	14.3	13.2

*estimated values

In Table 2 the values of the cetane number for pure Ethanol and for E20B10 blend have not been directly measured and have to be considered as approximate values. In particular the reported values have been estimated from various data found in technical literature relative to ethanol/diesel blends, see [1, 3, 7, 10].

TEST METHODOLOGY

The experimental campaign sought to test the engine in partial and full load conditions. The following seven partial load operative points, representative of the New European Driving Cycle (NEDC) procedure and an eighth point

indicative on an extra-urban condition have been selected: 1000 rpm at 0 bar of BMEP, 1500 rpm at 2 and 5 bar of BMEP, 2000 rpm at 2, 5, 10 bar of BMEP, 2500 rpm at 8 bar of BMEP, the extra-urban condition was at 2500 rpm and 16 bar of BMEP. In the next section the test points will be also called: 1000x0, 1500x2, 1500x5, 2000x2, 2000x5, 2000x10, 2500x8, 2500x16. Full load conditions have been investigated testing the engine at 2500 rpm at 100% of accelerator pedal position.

For each test point a Euro5 calibration was adopted as base calibration; the injection strategy was always composed of a pilot injection and a main injection. Moreover, as it will be discussed in the next, a proper injection setting calibration was detected and tested in the test point at low load conditions to optimize the use of the E20B10 blends.

The first part of the experimental activity was devoted to characterize the engine performance and emissions, in the described operative conditions, fueling the engine with B10 and E20B10 blends. The main scope was to determine the benefits and the issues linked to the use of an ethanol based blend as alternative fuel for automotive diesel engine. The second part of the engine test campaign was designed to analyze in detail the effect of E20B10 on engine behavior at low load conditions, changing the injection setting in order to overcome the issue of the high HC and CO emissions. For this goal, a test methodology and results analysis inspired to the Design of Experiment (DoE) method and Pareto-ANOVA analysis were adopted. The main objective of this investigation is focused on the analysis of the results obtained with the mentioned methods, rather than to show their potential. For this reason, in the present section such methodologies will be briefly described just to facilitate the results understanding. For details on these statistical analysis methods, please refer to [19, 20].

The analysis was performed at 1000x0, 1500x2 and 2000x2. As the main goal of investigation was to reduce the HC and CO emissions burning E20B10, preliminary four engine calibration parameters were detected as the main ones effecting the combustion efficiency at tested conditions. The chosen calibration sets are: pilot injection quantity (Q_{pilot}, also named parameter "A"), rail pressure (Prail, named "B"), fifty percent of Mass Burned Fraction (MBF50%, named "C") and dwell time between the main and pilot injections (DwellTime, named "D"). Even if influential, the EGR values have been kept unchanged (equal to Euro5 base calibration) in order to guarantee NO_x level inside the Euro5 limits.

For each parameter two levels have been defined: low and high level also indicated by signs "−" and "+" respectively; for the low level the reference engine calibration values have been assigned to the four parameters. For the high level some preliminary tests were carried out to detect different calibration values of the chosen parameters within reasonable limit. Then, according to the DoE method, a 2⁴ full factorial design was used to plan the 16 tests (four parameters, two levels) for each of the three engine operative conditions. In

Table 3, as example, the experimental plan at 1500x2 is reported.

Table 3. DoE 24 full factorial design and experimental conditions at 1500x2 (high level in green).

Case	A Qpilot (mm³/3/stroke)	B Prail (bar)	C MBF50% (c.a.° BTDC)	D DwellTime (µs)
1	-1	-1	-1	-1
2	-1	-1	-1	-1
3	-1	-1	-1	-1
4	-1	-1	-1	-1
5	-1	-1	-1	-1
6	-1	-1	-1	-1
7	-1	-1	-1	-1
8	-1	-1	-1	-1
9	-1	-1	-1	-1
10	-1	-1	-1	-1
11	-1	-1	-1	-1
12	-1	-1	-1	-1
13	-1	-1	-1	-1
14	-1	-1	-1	-1
15	-1	-1	-1	-1
16	-1	-1	-1	-1

The results of the DoE test campaign were analyzed according to Pareto-ANOVA method, focusing on the direct and combined effects of the injection calibration parameters on HC, CO and also on other important engine emissions and combustion behavior indicators, as it will be detailed in the results section.

Regarding the combined effects, only the second order effects (AB, AC, AD, BC, BD and CD) were studied, considering the higher order interaction among factors negligible. For all the effects, in the next section it will be analyzed the normalized contribution factors (CF) as a measure of the intensity of the effects of each parameter, or of the interaction between two parameters, on the response variables (the engine emissions or performances in this context). Please note that the contribution factors represent the relative intensity of each effect, expressed as percentage, but do not give information about the positive or negative effects they have on the response variables. For this reason, for the four direct effects (in the next also called “main effect” or “single effect”) the results of the parameters change on the response variables will be also reported.

Furthermore, the results of DoE test campaign were also used to elaborate a very simple predictive model of the engine response in terms of HC, CO, NOx, Smoke and combustion noise to the calibration settings variations. The analytical model adopted is based on the linear interpolation of the measured data. Despite the simplicity of this approach, starting from a relatively small set of experiments, it had been possible to process and investigate a great number of alternative injection parameter combinations. As it will be presented in the results section, the study led to an optimized calibration in the three test points burning the E20B10, with very positive effect on HC and CO reduction and without strong penalty in the overall engine performances.

RESULTS AND DISCUSSIONS

The present paragraph is divided in three parts. In the first, the engine performance and emissions with E20B10 are discussed, comparing the obtained results with the reference blend B10 ones. A second part regards the DoE method application with the discussion of the effect of some injection

parameters on engine performance and emissions and the identification of an optimized parameters calibration. In the third part a comparison analysis of the engine behavior with the adoption of the base and the optimized engine calibration is described.

Engine Performance and Emissions

In the present subsection the most significant results of the bioethanol blend effects on engine performance and emissions are reported; in all figures the alternative blend (E20B10) is compared to the reference one (B10) in all engine test points. The results are plotted in grams per kilowatt-hour so the values for 1000x0 are not displayed; anyway the trends are consistent with the low load conditions (1500 and 2000 at 2 bar of BMEP).

In Figure 1 the Brake Specific Fuel Consumption (BSFC) and the Fuel Conversion Efficiency (FCE) are reported, in the top and bottom row, respectively. In particular, FCE has been calculated with the following formula [21]:

$$FCE = \frac{1}{\frac{BSFC}{3.6} \cdot LHV} \quad (1)$$

The FCE represents the global efficiency of the engine.

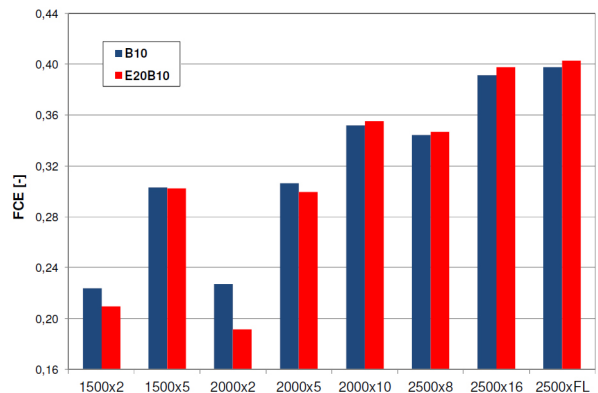


Figure 1. Brake Specific Fuel Consumption (above) and Fuel Conversion Efficiency (below), in all test points, for B10 and E20B10 blends.

A general increment of the fuel consumption can be observed burning E20B10, mainly linked to its low LHV value. The biggest differences between the two tested blends were found at low load conditions (especially at 1500 and 2000 rpm at 2 bar of BMEP). Looking at the bottom diagram of Figure 1, a strong reduction of the overall efficiency is observable at 1500x2 and 2000x2. This result is consistent with the high BSFC increment at low load condition and is related to the low cetane number of the alternative blend (see Table 2) which, as it will be clear from the next analysis of indicated curves, leads to a reduction of the efficiency of pilot injection combustion. It consequently effects on the all combustion process and thermodynamic efficiency. At higher