

The Key Role of the Closed-loop Combustion Control for Exploiting the Potential of Biodiesel in a Modern Diesel Engine for Passenger Car Applications

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ABSTRACT

The present paper describes the results of a cooperative research project between GM Powertrain Europe and Istituto Motori - CNR aimed at studying the capability of GM Combustion Closed-Loop Control (CLCC) in enabling seamless operation with high biodiesel blending levels in a modern diesel engine for passenger car applications. As a matter of fact, fuelling modern electronically-controlled diesel engines with high blends of biodiesel leads to a performance reduction of about 12-15% at rated power and up to 30% in the low-end torque, while increasing significantly the engine-out NO_x emissions. These effects are both due to the interaction of the biodiesel properties with the control logic of the electronic control unit, which is calibrated for diesel operation. However, as the authors previously demonstrated, if engine calibration is re-tuned for biodiesel fuelling, the above mentioned drawbacks can be compensated and the biodiesel environmental inner qualities can be fully deployed.

In order to enable such calibration re-tuning, it is fundamental to achieve a reliable biodiesel blending detection, and to use

it for real-time combustion optimization, chiefly by optimizing the injection train. Therefore, the authors investigated the capability of CLCC to detect biodiesel blending ratio on the recently released 2.0L Euro5 GM diesel engine equipped with embedded pressure sensors in the glow plugs.

Various blends of biodiesel were tested, notably 20% by volume (B20), 50% (B50) and pure biodiesel (B100). Tests on the multi-cylinder engine were carried out in a wide range of engine operating points for the complete characterization of the biodiesel performance in the NEDC cycle.

The results demonstrated the successful capability of the CLCC control to detect biodiesel blending with reasonable accuracy and to implement the corrective actions to avoid emission drift and performance losses.

INTRODUCTION

It is well known that the use of biofuels can contribute to a significant well-to-wheel (WTW) reduction of greenhouse gas (GHG) emissions. In particular, Fatty-Acid Methyl Esters (FAME) biodiesel is produced through an energy efficient

process that gives a significant advantage in terms of CO₂ emission with respect to first generation biofuels. FAME designates a wide range of methylesters blends produced from vegetable oils and animal fats through a transesterification process that features both high energy conversion efficiency and fuel yield from processed oil: these two characteristics are the main responsible for the overall GHG emissions benefit of biodiesel in WTW analyses [1].

However, because of growing concerns about energy crops impact on environment and food price, an increasing number of countries and stakeholders have recently challenged first generation biofuels. On the contrary, the second generation biofuels (Biomass-To-Liquid Fischer-Tropsch fuels), which show high energy yield in the production process as well as the capability to extend input feedstock to cellulosic biomasses, are considered very attractive [2].

Within this framework, biofuel producers and OEMs are jointly devoting significant efforts in optimizing benefits from first generation biofuels while making second generation technologies economically viable soon. In particular, in order to enlarge biofuel market penetration, common fuel standards need to be defined and the compatibility of the engines with biofuels improved.

One of the main differences of FAME with respect to petro-based diesel fuel is its oxygen content, exceeding 10% of the total mass, which is directly responsible of the LHV reduction of the same magnitude and eventually of the engine performance loss of about 12-15% at rated power and up to 30% in the low end torque.

Taking into account the interest about the usage of biodiesel due to its advantages in terms of emission reduction [3, 4, 5] and, at the same time being partly bound by future European legislation [6], it should be stressed that several studies have shown that the impact of biodiesel on the modern diesel engines is significant, through the interaction between the biodiesel characteristics and the engine-management strategies [7, 8]. Similarly it was established that an efficient use of alternative diesel fuels, allowing to fully exploit all the potentials, can only be achieved through an “ad hoc” calibration of engine parameters and its control strategy (injection set and EGR rate on all) [8].

Based on the above, to create a flexible engine that can work efficiently either with conventional diesel than with biodiesel, it appears extremely important to develop a system able to detect the diesel biodiesel blending ratio present in the fuel tank and, automatically, to adapt engine calibration in order to fully exploit the fuel properties. In this respect, the adoption in the modern engines of the last recent combustion control methodology, named “Closed Loop Combustion Control” - CLCC, and based on the engine torque control by means of the instantaneous cylinder pressure measurement of

the ECU [8], has opened new scenarios for the development of the actual flex-fuel diesel engines.

Since year 2007, within this frame, GM Powertrain Europe and Istituto Motori - CNR have started a cooperation aimed to investigate the interaction between the modern engine technology and alternative fuels. On the basis of the previous experiences [5, 8], specific research activities were addressed to exploit and assess the capabilities offered by the CLCC technology in the development of the flex-fuel diesel engine. In order to get those targets, the investigation was focused on three main aspects:

- Development of a biodiesel-diesel blending detection (BD) methodology;
- Mitigation of the impact of alternative fuels on emissions;
- Exploitation of the alternative fuel quality for engine performance improvement.

In the present paper, some of the main experimental results coming out from research activities are reported and commented.

THE FUELS

Table 1 reports, for the pure fuels considered in the present paper, some of the most important parameters affecting the combustion, the exhaust gas properties and the mechanical work generation, notably: LHV, A/F_{st}, chemical composition and density. The reference diesel fuel (RF) was an EU certification diesel fuel (CEC, RF-03-A-84) compliant with EN590, while the tested biodiesel was a EU-widely-available RME compliant with EN14112.

As it is well known from the literature, the most important differences between conventional diesel and FAME (RME in the specific case) involve an appreciable reduction of LHV and A/F_{st}, both due to the oxygen content of biodiesel (about 11% by mass). In addition to the effects on combustion that these properties induce, RME's higher density and viscosity, coupled with its distillation curve stretched in the temperature interval corresponding to the high-temperature boiling fractions of conventional diesel, increase significantly the penetration of its sprays with respect to reference diesel, especially in cold conditions. Spray over-penetration is actually one of the most important concerns of diesel-FAME blends because it leads to increased oil dilution, as well as risks of piston and liner scuffing. Furthermore, higher boiling curve of biodiesel leads to higher resident time of fuel in the oil. Such drawback could be even more critical in case of specific injection strategies involving late injections in the exhaust stroke, as for example the DPF/DeNO_x regeneration. In such cases, fuel injection occurs in low-density charge and is targeted well above the bowl edge: experimental verifications performed by the authors using pure biodiesel have assessed an oil dilution rate up to three times the

Table 1. Main fuel parameters

Feature	Method		RF	RME100
A/Fst			14.54	12.44
Low Heating Value [MJ/kg]	ASTM D 4868		42.965	37.570
Carbon [%, m/m]	ASTM D 5291		85.220	77.110
Hydrogen [%, m/m]	ASTM D 5291		13.030	11.600
Nitrogen [%, m/m]	ASTM D 5291		0.040	0.030
Oxygen [%, m/m]	ASTM D 5291		1.450	11.250
Cetane Number	EN ISO 5165		51.8	52.6
Density @ 15 °C [kg/m ³]	EN ISO 12185		833.1	883.1
Viscosity @ 40 °C [mm ² /s]	EN ISO 3104		3.141	4.431

Feature	Method		RF	RME100
Distillation [°C]	EN ISO 3405	IBP	158.9	318.0
		10% vol.	194.3	331.0
		50% vol.	267.6	335.0
		90% vol.	333.4	344.0
		95% vol.	350.0	353.0
		FBP	360.9	355.0
Oxydation stability [mg/100ml]	EN ISO 12205		-	0.6
Oxydation Thermal Stability @ 110°C [h]	EN 14112		-	6.5
C.F.P.P. [°C]	EN 116		-	-14
Lubricity @ 60°C [µm]	EN ISO 12156-01		-	179
POV [meq O ₂ /Kg]	NGD Fa 4			16.60
TAN [mg KOH/g]	UNI EN 14104			0.13

Table 2. Main features of the GM multi-cylinder engine

Engine type	4 cylinders in-line
Certification	EURO 5
Bore x Stroke [mm]	83.0 x 90.4
Displacement [cm ³]	1956
Compression Ratio	16.5
Valves per cylinder	4
Rated power and torque	118kW @ 4000rpm 380Nm @ 2000rpm

Injection system	Bosch Common Rail EDC17
Injector and nozzle	Solenoid CRI 2.2+, 7 holes, 480cc/30s
Turbocharger	Garrett single stage VGT GTB1549MV
Swirl control	Rotary flap on secondary duct
Catalyst system	Integrated closed-coupled DOC & DPF

baseline, depending on engine type, operating conditions and injection strategy [9].

EXPERIMENTAL APPARATUS AND TEST PLAN

The four-cylinder in-line engine employed in the project was the recently released GM Powertrain Euro 5 diesel engine whose main characteristics are reported in [Table 2](#).

The Euro 5 engine features the CleanTech closed-loop combustion control (CLCC), which enables individual and real-time control of MFB50 and IMEP (see acronyms list for explanation), cycle-by-cycle and cylinder-by-cylinder. In particular, based on in-cylinder pressure traces, heat release rate analysis is performed by ECU EDC17 using proprietary algorithms, and the actual values for MFB50 and IMEP are then compared to the target ones. As a consequence, the deviations of these two parameters are continuously resettled by adjusting the main injection timing and quantity for the following combustion cycle [10]. Based on these operating characteristics, the CLCC technology has been employed in order to develop a new diesel-biodiesel BD methodology, to

mitigate or improve the engine emissions and increase the full load engine performance.

The engine was installed on a dyno test bench fully instrumented for indicated signal measurements (cylinder pressure, injection pressure, energizing injector current). Such measurements were carried-out by means of an AVL-based indicating acquisition system with an high-accuracy pressure sensor fitted on first cylinder, that was used as reference for validating the accuracy of the ECU-based CLCC (of course, for the evaluation of blending detection capability of the “IMEP method”, only the ECU quantities were considered). At the engine exhaust, smoke was measured by a high-resolution (0.01 filter smoke number, FSN) smoke meter (AVL415S), while gaseous emissions were measured upstream and downstream of the diesel aftertreatment device by means of a raw emission analysis test bench (AVL-CEB-2).

For all fuel blends, the engine was tested in nine steady-state operating points (k-points). The first seven test points were selected as the most representative ones of the engine operation on New European Driving Cycle (NEDC) when

matched to a D-class vehicle (1590kg IW). The eighth (2500 rpm at 16 bar of BMEP) and ninth (2500 rpm full load) test points were devoted to the characterization of the engine performance in real life aggressive driving.

The selected NEDC k-points are summarized in Figure 1, where the operating area of the engine running over NEDC is also displayed. The measurements in the seven part-load test points enabled the NEDC-cycle vehicle performance estimation for all fuel blends by means of a well consolidated correlation procedure between the specific emission at steady-state dyno engine testing with vehicle emissions on the chassis dynamometer. For each test point the injection strategy was composed by Pilot + Main events.

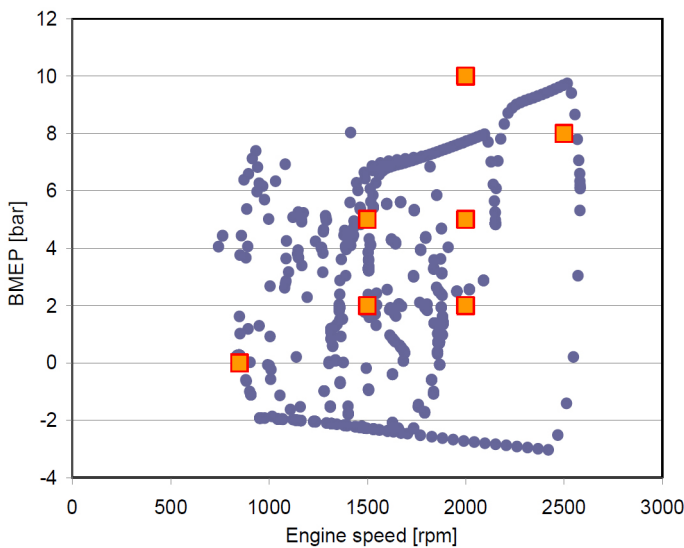


Figure 1. Test points (k-points) together with the entire speed/load trace of the engine over NEDC for a D-class vehicle.

The following sections will be focused on the description of the BD methods and on the analysis of the capability of the experimental system to detect the level of biodiesel blending through the use of specific detection algorithms.

RESULTS

DESCRIPTION OF BLENDING DETECTION PROCEDURES

The BD procedure tested in the present project has been derived from a patent application of GM [11], developed within a cooperative research project between Istituto Motori and GM Powertrain. In order to be widely implemented, such a blending detection strategy needs to be reliable, sufficiently accurate, robust towards biodiesel types and aging, as well as cost-effective. Taking in consideration all those key factors, the research activity was focused towards a BD strategy that employs sensors already installed on the engine, whose

reliability is proven. Therefore, the strategy combines the information given by sensors with the diesel/biodiesel mixture properties quantitative information to estimate the blending rate.

In particular, the methodology described by Ciaravino et al. [11], leverages the information carried by in-cylinder pressure transducers about the actual cycle-averaged IMEP, denoted as IMEP1, which is obtained by integration of the high-frequency pressure signal, measured by the instrumented glow plugs of each cylinder:

$$IMEP_i = \frac{\oint p_i dV}{V} \quad \text{being } i \text{ the } i\text{-th cylinder} \quad (1)$$

and by its following averaging:

$$IMEP1 = \frac{\sum_i IMEP_i}{i} \quad (2)$$

This latter can be compared, over each engine cycle, with the estimated IMEP produced on the basis of the IMEP mapping performed with pure diesel fuel, as a function of engine speed and accelerator pedal position. Since the actual IMEP mapped for pure diesel fuel depends, for a certain engine speed and accelerator pedal position, on fuel conversion efficiency FCE, fuel injected quantity Q_{fuel} (mass per cycle), lower heating value LHV and friction losses FMEP, its variation when the engine is fueled with some rate of biodiesel is due only to a lower LHV. In fact, in previous investigations, the authors verified that biodiesel does not significantly affect the engine FCE when the engine runs at the same operating point [5, 8], while FMEP, mapped as a function of the operating point and coolant temperature, is characteristic of the whole engine system architecture. Thus, the estimated IMEP from the engine mapping can be defined as IMEP2:

$$IMEP2 = BMEP + FMEP = \frac{FCE \cdot Q_{fuel} \cdot LHV}{Engine \text{ Displacement}} + FMEP \quad (3)$$

Hence, two formulations can be leveraged for Blending Detection (BD), depending on the diesel engine operation mode, with either open-loop or closed-loop IMEP control [11]. In particular, if the engine is in IMEP open-loop control, the Blending Ratio BR is:

$$BR = 100 \cdot \frac{\left(\frac{IMEP2}{IMEP1}\right) - 1}{\left(\frac{LHV_{diesel}}{LHV_{FAME}}\right) - 1} \quad (4)$$

and the BR is linked to the reduction of IMEP when a biodiesel is burned. Actually, the BR calculation in open loop mode is affected by inaccuracy, due to the drift in engine operating point (i.e. different lambda, heat losses, etc), which impacts the FCE to an extent that does not allow to consider it constant in the working point with IMEP1 (using the diesel/FAME blend) and the estimated working point from engine speed and accelerator pedal position. However, as shown by the authors in two previous papers [5, 8], in open loop control mode, the differences in FCE between diesel and FAME become significant only for the medium load range (e.g. 2500 rpm and 8 bar of BMEP). Therefore, notwithstanding its inaccuracy, this method is suitable for a first rough estimation of the BR of the burned fuel.

The case with the engine closed-loop IMEP control is different. In this case the BR calculation formula becomes:

$$BR = 100 \cdot \frac{\left(\frac{Q_{fuel_{FAME}}}{Q_{fuel_{diesel}}}\right) - 1}{\left(\frac{LHV_{diesel}}{LHV_{FAME}}\right) - 1} \quad (5)$$

and it is linked to the increase of fuel consumption (Qfuel) when a biodiesel is used.

In closed loop operation mode, the variation in Qfuel is only dependent on the variation of LHV of the used fuel. Since the variation in FCE between diesel and diesel/FAME blend was estimated less than 2%, it is negligible and not affecting the accuracy of the method.

For completeness' sake, as reported in other papers [5, 12], the LHV variation from BO to B100 is about 13÷14%, with a small difference among biodiesel feedstock ($\approx 22\%$ of the B100 value).

The experimental validation of the procedure by means of specific tests is described in the following section.

IMEP BD METHOD RESULTS

In the following, the capability of the IMEP BD method is shown by means of nine engine operating points. As claimed above, also with a reduced accuracy, the BD method is suitable for application when the engine runs in open-loop combustion control, but it is evident that its potential lies on the use of the closed-loop control. So, both to simplify the

results analysis and highlight the potentiality of the closed-loop control in BD method, only the results relative to this last control mode will be shown and discussed in this section.

Before starting the tests campaign, a check of the engine hardware equipments has been done; in particular the ECU injection maps have been checked with a reference fuel flow mass meter (AVL Fuel Balance 731). The check indicated a deviation between ECU fuel flow estimation and fuel balance measurement within the 3%, in line with the normal engine to engine variation from production line.

Figure 2 reports the results of the IMEP method in the nine test points for the detection of 0% (reference diesel fuel), 20%, 50% and 100% of RME blending level. For mineral diesel, the standard deviation bars have been also reported (in orange), in order to characterize the specific variability of each engine operative points. In Figure 2, the blending detection was calculated (in accordance of the above described algorithm), adopting as input variables the fuel consumption (Qfuel), calculated by ECU; so these first results represent the current capability for the tested hardware.

The not zero value of BR burning pure diesel fuel derives from the drift between the estimated $Q_{fuel_{nominal}}$ in the operating point (as mapped in the calibration as function of engine speed and accelerator pedal position and corrected for coolant temperature) and the corrected Qfuel ($Q_{fuel_{actual}}$) actuated by ECU by means of measured IMEP value. As it can be seen, the drift is variable point to point and depends on the differences between the laboratory engine configuration in the test cell (as air path layout, auxiliary components, deviation of injector flow characteristics with respect to the nominal values, etc.) and the reference engine configuration as installed on the vehicle.

An overall analysis of the results highlights that the method is able to detect the blending trend, showing an increase of the estimated blends with the blending level. As expected, the method is more and more precise as the fuelling is increased when high speed/load conditions are approached. The highest error was detected at minimum operating point 1000 rpm and zero load, for brevity indicated in the following as 1000×0. The reason why the highest BR error occurs at 1000×0 is the very little injected quantity in that operating condition which, in turn, leads to:

- an higher injected quantity estimation error because the accuracy and the repeatability of the injection system decreases in case of small injected quantities;
- an higher IMEP estimation error because of relatively small in-cylinder pressure variations which are more sensitive to sensor noise and accuracy.