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IMPLEMENTATION OF A NEW AUTOMATIC BLENDING DETECTION PROCEDURE IN MODERN DIESEL ENGINES BY MEANS OF DIRECT MEASUREMENT OF THE INDICATED MEAN EFFECTIVE PRESSURE

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Abstract

Within the cooperative research project DAX605 between GM Powertrain Europe and Istituto Motori - CNR, the capability to develop a method (economic and simple) for on-board biodiesel blending detection was studied. The method is based on the direct measurement of the Indicated Mean Effective Pressure (IMEP). The present research report summarizes the main results of this activity.

The study was carried out on a 2.0L 4-cylinder “torque-controlled” Euro 5 diesel engine for passenger car (PC) application. This engine, equipped with instrumented glow plug for combustion closed loop control, represents the state of the art of the diesel engine control technology.

Two biodiesels were chosen for the experiments: a Rapeseed-Methyl-Ester (RME) and an aged RME, while the conventional diesel fuel was an European (EU) certification diesel fuel.

Results indicate generally a good response in blending detection of the method. However, in order to attain an acceptable accuracy, a pre-calibration appears necessary.

Keywords: Fuel blending detection, Diesel engines, biodiesels, engine electronic control, combustion pressure sensors.

Abbreviations

- *BD: Fuel blending detection*
- *BR: Fuel blending ratio [%]*
- *BMEP: Brake Mean Effective Pressure*
- *BSFC: Brake Specific Fuel Consumption*
- *ECU: Electronic Control Unit*
- *FAME: Fatty-Acid-Methyl-Esters*
- *FCE: Fuel Conversion Efficiency, FCE= 1/(BSFC * Net Heat Value)*
- *GHG: GreenHouse Gases*
- *IMEP: Indicated Mean Effective Pressure*
- *LHV: Lower Heating Value of fuel*

MBF50: Angular position corresponding to the 50% of Burned Fuel Mass, with respect to the piston top dead center [engine crank angle]

- *NEDC: New European Driving Cycle*
- *PC: Passenger Car*
- *Qfuel: Injected fuel volume per engine cycle*
- *RME: Rapeseed Methyl-Ester*
- *SME: Soybean Methyl-Ester*

Introduction

It is accepted that from an environmental point of view, the use of bio-derivable fuels can contribute to a significant well-to-wheel (WTW) reduction of greenhouse gas (GHG) emissions. Thanks to an efficient and well consolidated process, the Fatty-Acid Methyl Esters (FAME) biodiesel is the most worldwide diffuse biofuel for the diesel engine.

Taking into account the interest about the use of biodiesel due to its advantages in terms of emission reduction [1, 2, 3] and at the same time such use being partly bound by future European legislation

[4], 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 [5, 6]. Similarly, it was established that an efficient use of these kind of fuel, allowing them to fully exploit all potentials, can only be achieved through an “ad hoc” calibration of engine parameters and their control strategy (injection set and EGR rate on all) [6].

Based on the above, to create a flexible engine that can work efficiently (and smartly) either with conventional diesel than with biodiesel, it appears extremely important to develop a system, integrated with the ECU, able to detect a biodiesel supply and moreover to estimate the percentage of biodiesel blended with conventional diesel (possible definition of BD). To this aim, a dedicated research activity has been carried out, focusing on those methods that may have a concrete application from the viewpoint of economic sustainability, easy integration in engines already under development and rapid adjustment procedure. The method presented in this article was checked for blending detection capability and is based on the evaluation of "the effects" that involve the biodiesel fueling, which result from physical and chemical properties of biodiesel. First of all, the oxygen content of the FAME is significant, exceeding 10% of the total mass, and is responsible of the fuel LHV reduction of the same magnitude, among conventional diesel fuels and the correspondent decrement in engine power and torque performances. Therefore, an innovative method based on real-time imep calculation is presented; it uses the lower LHV of FAME and the increment of the injector fuelling with respect to the conventional fossil diesel fuel.

The experiments have been carried out with the following main goals:

- the precise definition of the calculation procedure for BD (ECU and engine variables involved);
- the execution of validation tests with the two RMEs (test plan with B0 B20 B50, B100 and B100A fuels);
- the preliminary evaluation of the accuracy of the methods and its potential.

Following these activities, the verification of functionality of the entire detection/correction strategy was performed, at steady-state, in order to evaluate the overall improvement in the engine operation.

Experimental apparatus, fuels and test plan.

The engine employed in the project is a GM Powertrain Euro 5 four-cylinder in-line engine, whose main characteristics are reported in Table 1.

Engine type	4 cylinders in line
Certification	Euro5
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	118 kW @ 4000 rpm; 380 Nm @ 2000 rpm
Injection system and nozzle	BOSCH solenoid CRI 2.2+; 7 holes, 480cc/30s
Turbocharger	Garrett single stage VGT GTB1549MV
Swirl control	Rotary flap on 2nd duct
After-treatment emission system	Integrated closed-coupled DOC&DPF

Table 1. Main features of the GM multi-cylinder engine.

The engine features the CleanTech closed-loop combustion control, 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 are continuously resettled by adjusting the main injection timing and quantity for the following combustion cycle [7]. As biodiesels, two RME fuels were chosen. The first one was a fresh RME sold on the European market, while the second one was an aged RME, in order to check the BD capability of the method, taking into account the possible aging process of the FAME. The reference diesel fuel was an EU certification diesel fuel (CEC, RF-03-A-84). Table 2 reports, for all fuels, some of the most important parameters affecting the engine-fuel interaction, notably: LHV, A/Fst, chemical composition and density, plus the induction period value that characterizes the aging factor of the aged RME (RME$_{aged}$).

Feature	Method	RF	RME	RME$_{aged}$
Stoichometric A/F		14.54	12.44	12.31
Low Heating Value [MJ/kg]	ASTM D4868	42.965	37.57	37.43
Carbon [%, m/m]	ASTM D 5991	85.22	77.1	76.94
Hydrogen [%, m/m]	ASTM D 5991	13.03	11.6	11.53
Nitrogen [%, m/m]	ASTM D 5991	0.04	0.03	0.04
Oxygen [%, m/m]	ASTM D 5991	1.45	11.25	11.49
Density @ 15°C [Kg/m^3]	EN ISO 12185	833.1	883.1	884.2
Viscosity @ 40°C [mm^2/s]	EN ISO 3104	3.141	4.431	4.539
Oxydation Thermal Stability @ 110°C h	EN14112	-	6.5	2.4
Oxydation Stability [mg/100ml]	EN ISO 12225	-	0.6	1.2
Cetane Number	EN ISO 5165	51.8	52.6	57
C.F.P.P. [°C]	EN 116	-	-14	-14
Lubricity @ 60°C [μm]	EN ISO 12156-01	-	179	195
POV [meg O$_2$/Kg]	NGD Fa 4	-	16.6	68.6
TAN [mg KOH/g]	UNI EN 14104	-	0.13	0.19

Table 2. Main parameters of tested fuels.

As reported in the introduction, together with the pure fuels, identified as B0 (pure diesel) and B100 (pure RME) other two blends were considered to test the BD method: B20 and B50, that means 20% vol. and 50% vol. of RME in diesel respectively. 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 behaviour on new European driving cycle (NEDC) when installed on a D-class vehicle (1590kg IW). The eighth and ninth test points were devoted to the characterization of the performance behaviour in an extra urban point (2500 rpm at 16 bar of BMEP) and at rated torque at 2500 rpm. The Pilot + Main injection calibration was always employed.

Blending detection procedure

The BD procedure tested in the present project has been derived from a patent by GM Powertrain [8], developed within a co-operative research project between Istituto Motori and GM Powertrain. In order to be applicable on a large-scale, such a blending detection strategy needs to be reliable, sufficiently accurate, robust towards biodiesel types and aging, as well as cost-effective. This was the aim of the present study, taking into account that all employed sensors are already installed on the engine, whose reliability is proven. So, combining their information with the diesel/biodiesel mixture properties, quantitative informations on blending rate were carried out.

Because of the IMEP is closed-loop controlled by CleanTech system, the injection quantity variation (burning a diesel/FAME blend) could be directly linked to biodiesel LHV and BR; so in this case the BR calculation formula is:

$$BR = 100 \cdot \frac{\left(Qfuel_{FAME} \big/ Qfuel_{diesel} \right) - 1}{\left(LHV_{diesel} \big/ LHV_{FAME} \right) - 1} \qquad (1)$$

and the BR is linked to the increase of fuel consumption (Qfuel) when a biodiesel is burned. In closed loop operation mode, the variation in Qfuel is only dependent on the variation of LHV of the using fuel. Since the variation in FCE between diesel and diesel/FAME blend was estimated less then 2%, it is negligible and not affecting the accuracy of the method.

For completeness' sake, Table 3 reports the value of LHV for the fresh rapeseed (RME), and a soybean (SME) methyl esters tested in previous experiments [3].

	LHV		Δ IMEP w.r.t. B0 [%]	
Blend	RME	SME	RME	SME
B0	43.1	43.1	0	0
B20	41.95	41.93	-2.7	-2.7
B40	40.8	40.76	-5.3	-5.4
B50	40.23	40.18	-6.7	-6.8
B60	39.65	39.59	-8	-8.1
B80	38.5	38.42	-10.7	-10.9
B100	37.35	37.25	-13.3	-13.6

Table 3. Typical LHV values for pure biodiesels and blends.

Previous table highlights that the LHV variation from B0 to B100 is about 13.5%, with a small difference among biodiesel feedstock (≈ 2‰ of the B100 value). On the other hand, this variability is confirmed also by some literature data, as reported by Rakopoulos *et al*. [9], were a variation of 3.5‰ was detected on a large number of methyl-esters from different feedstocks.

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

Discussion of results

In the following, the capability of the IMEP method in BD is illustrated by means of all nine operative tested points. 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 1 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 plus the pure aged RME. For mineral diesel, the standard deviation bars have been also reported (in orange), in order to characterize the specific variability of each engine operative point.

In Figure 1, the blending detection was calculated (in accordance to 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.

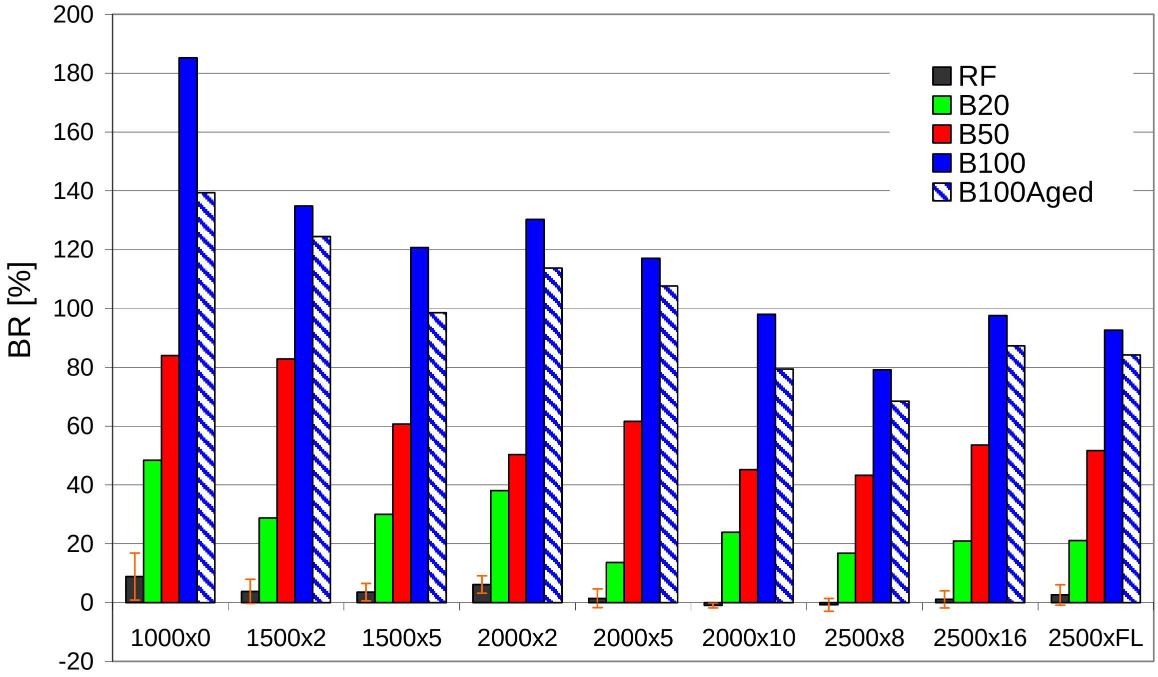

Figure 1. Blending detection for fresh and aged RME by means of IMEP method. ECU input data. Individual test points results.

The not zero value of BR burning pure diesel fuel derives from the drift between the estimated $Qfuel_{nominal}$ in the operating point (mapped in the calibration as function of engine speed and accelerator pedal position) and the corrected Qfuel ($Qfuel_{actual}$) actuated by ECU on the base of the measured IMEP value. As it can be seen, the drift is variable point to point and depends on 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.) with respect to the reference configuration released from manufacturer.

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, both for fresh and aged RME. 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 (1000x0). Of course, in this point, the very low fuelling condition, that gives very small variation in ET between RF and RME, does not exhibit acceptable results. However, without any corrective/refining remedy on the $Qfuel_{nominal}$ with respect to the actual injection quantity, and except the minimum point, the potential of the method is evident also looking at the BR values of the first row of Table 4, where the BR average values over the all tested points (except 1000x0) are reported. If a learning procedure for $Qfuel_{nominal}$ correction is implemented in the ECU, so the difference between $Qfuel_{actual}$ and $Qfuel_{nominal}$ is resettled, the method shows better average results as reported in the second row of Table 4.

Blend	B0	B20	B50	B100	$B100_{aged}$
Result mean value w/o injector drift correction [%]	2.1	24.2	56.2	108.8	95.5
Result mean value with injector drift correction [%]	0	22.1	54.1	106.7	93.4

Table 4. Mean values results of blending detection for fresh and aged RME with IMEP method and ECU input data.

The averaged results show a quite good physical correspondence, so the method is certainly sensible to the different blending levels. The tests with RME_{aged} show always estimated BR values below the fresh RME ones. Considering that no repetition tests were performed with the RME_{aged}, it is not possible to discriminate if the results depend on a systematic difference or fall within the test to tests variation of the engine conditions. Also for the RME_{aged} the average results appear in a quite good correspondence.

To evaluate the accuracy of the ECU for the fuel consumption estimation, in each tested engine point, $QFuel_{actual}$ by ECU has been compared with the value of consumption measured by the fuel flow meter. This last has been assumed as the "real" value of the fuel consumption, taking into account that the precision of the flow meter instrument has been previously checked. The comparison results are shown in Figure 2, relatively to reference fuel test cases. In particular, on the left side the $Qfuel_{actual}$ values supplied by the two systems are plotted, while on the right side the following $Qfuel_{drift}$ percentage values are plotted:

$$Qfuel_{drift} = \frac{(Qfuel_{actual} - FuelflowmeterQfuel)}{FuelflowmeterQfuel} \cdot 100 \qquad (2)$$

It's evident the presence of a little difference between the QFuel values derived from the two systems and in particular at 1500x2, 2000x2, 2000x5, 2500x8 such deviations appear more significant, but always inside the maximum error of 3%. In general it could be observed a random patter at low and medium engine speeds and loads, while an overall ECU overestimation of fuel consumption at high speed and loads. However, the average error in all the nine test points (sum of the individual error) is an overestimation of ECU of +0.4 %.

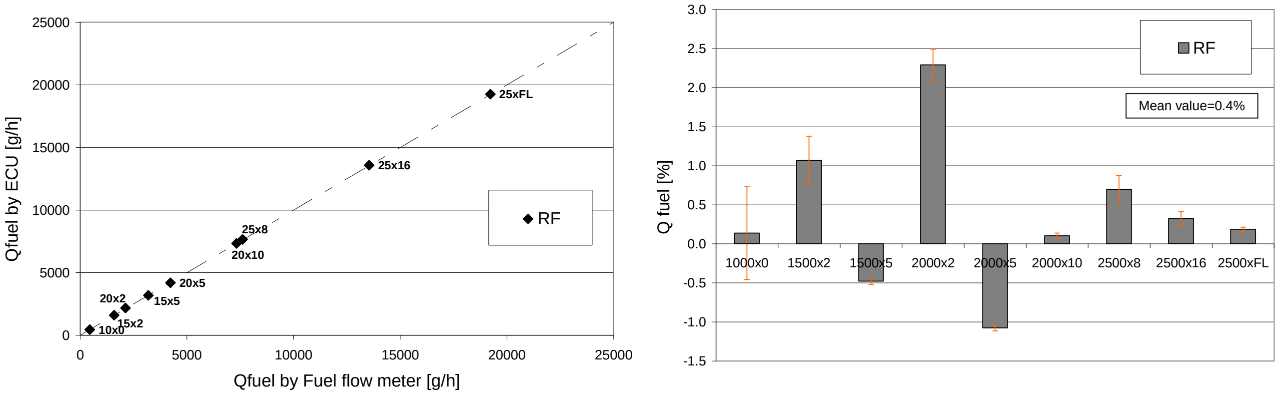

Figure 2. Comparison between the fuel consumption values supplied by ECU and fuel flow meter.

A further evidence of the sensibility and accuracy of the IMEP method, is well illustrated in Figure 3 and Table 5, where the results of blending detection for all the individual points and the BR mean values, refer to the IMEP algorithm calculated by using the fuel flow meter measurements. The orange bars in Figure 3 represent, for each engine operating point, the uncertainty in the blending detection procedure stemming from the statistical error propagation in the calculation chain.

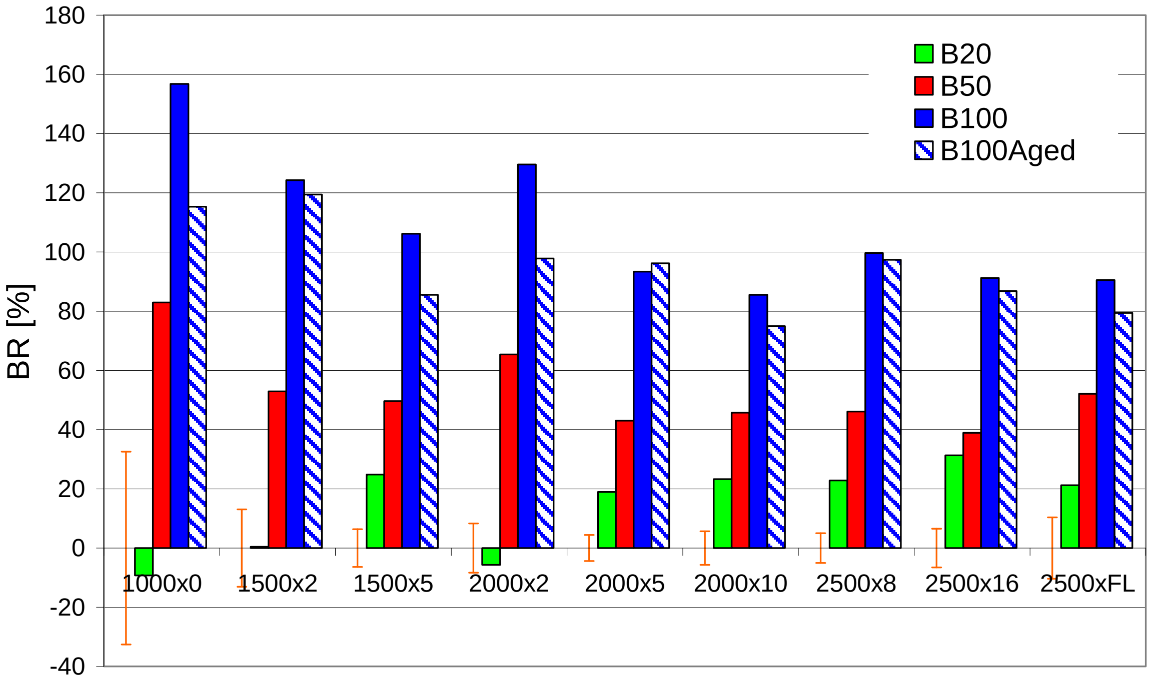

Figure 3. Blending detection for fresh and aged RME by means of IMEP method. Fuel flow meter input data. Individual test points results.

The adoption of the assumed "real" QFuel values allows to an evident improvement of the results; the percentages in Table 5 clearly show as the blending ratio mean values are very close to the effective level of biodiesel in the tested blends. The maximum drift between real and estimated blend was for B20 and equal to about 3%, corresponding to a measurement error of 10.5%.

Blend	B0	B20	B50	B100	$B100_{aged}$
Result mean value [%]	0	17.2	49.2	102.5	92.2

Table 5. Mean values results of blending detection for fresh and aged RME with IMEP method and fuel flow meter data.

As for the results of Figure 1, also using injected fuel mass from the fuel flow meter (Figure 3 and Table 5), the BR values of RMEaged remain lower that the fresh one. Also if the correspondence between real blend and method output remains good, further specific tests will be necessary in order to check the influence of the changing parameters with aging biodiesel process (like cetane number as example) on the imep BD method results.

In order to obtain a statistical value of the precision of the fuel consumption provided by ECU, the ECU Qfuel estimation has to be checked in a wide number of engine types. Moreover to evaluate the global robustness of the IMEP BD method, the accuracy of all components of the measurement chain has to be evaluated in a statistical way. This aspect is out on the aim of the activity done, that was more addressed to a first screening of the quality of the imep BD method, and it will be subject of future work. On the basis of the presented results and taking into account the engine repeatability reported in Figure 3, the accuracy of the method can be reasonably and preliminarly estimated as ±25%. Such value has to be considered as the minimum diesel/FAME blend detectable by the method. However, BR variation within the accuracy of method gives negligible effects on engine performance and emission, as already proved by past experiences of the authors [3].

The only limit of the IMEP method lies, of course, in its applicability to only engine equipped with closed loop torque control. This comment can only increase the interest in the implementation of the closed loop control, as its potentiality in terms of biodiesel combustion impact mitigation.

One more comment is that for the implementation of the blending detection procedure, in order to calculate the correct BR value, the ECU-based strategy needs to take into account the density variation of the blend when biodiesel is added to the diesel. This can be easily implemented via an iterative process that, starting from a tentative BR calculation with B0 density, updates the density on the basis of the actual BR, quickly reaching convergence due to the relatively small density variation from B0 to B100.

5. Conclusions

This report describes the results of a research activity aimed at studying the capability of the Closed-Loop Combustion Control system to detect the level of biodiesel blending.

The potentiality offered by the production pressure sensors employed in closed loop combustion control to detect the blending level of biodiesels, whether fresh or aged, has been described. The blending detection IMEP method is certainly sensible to the different blending levels showing a good physical correspondence.

The main cause of the small inaccuracy of the IMEP method lies in the ECU calculation of the fuel consumption. The results highlight that the fuel consumption has been overestimated by ECU, but the blending ratio mean values are very close to the effective level of biodiesel in the tested blends. Moreover, BR variation within the accuracy of method gives negligible effects on engine performance and emission as already proved by past experiences of the authors. Employing corrective remedy or learning procedure for fuel flow estimation, the accuracy of the method can be further improved.

The authors think that a prerequisite to exploit in the best way the benefits offered by the use of alternative bio-fuels like biodiesel and the closed loop combustion control is the employment of a blending detection system.

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References

[1] M. Lapuerta, O. Armas, J. Rodríguez-Fernández, Effect of biodiesel fuels on diesel engine emissions. Prog Energy Combust Sci 2008;34:198–223.

[2] D. Kawano, I. Hajime, G. Yuichi, N. Akira, A. Yuzo. Application of Biodiesel Fuel to Modern Diesel Engine, SAE Tech. paper 2006, 2006-01-0233.

[3] C. Beatrice, S. Di Iorio, C. Guido, E. Mancaruso, B. M. Vaglieco, A. Vassallo. Alternative Diesel Fuels Effects on Combustion and Emissions of an Euro4 Automotive Diesel Engine. 2009, SAE Tech. paper 2009-24-0088.

[4] DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, 23 April 2009, web reference: www.energy.eu/directives/pro-re.pdf.

[5] Soltic P., D. Edenhauser, T. Thurnheer, D. Schreiber, A. Sankowski, Experimental investigation of mineral diesel fuel, GTL fuel, RME and neat soybean and rapeseed oil combustion in a heavy duty on-road engine with exhaust gas aftertreatment, 2009, Fuel 88 (2009) 1–8.

[6] C. Beatrice, C. Guido, S. Di Iorio. Experimental analysis of alternative fuel impact on a new ‘‘torque-controlled” light-duty diesel engine for passenger cars. Fuel 89 (2010) 3278–3286.

[7] C. Mueller, B. Ras Robotti, M. Wesslau, H. Drangel, U. Agricola, A. Catanese, E. Manta, Opel´s new 2.0L BiTurbo Diesel engine with highly innovative CleanTech combustion concept, 2009, MTZ Worldwide, 12/2009.

[8] C. Ciaravino, F. Guglielmone, A. Vassallo. Method for Biodiesel Blending Detection Based on Internal Mean Effective Pressure Evaluation. European Patent EP 0918272.6, 2009.

[9] C. D. Rakopoulos, K.A. Antonopoulos, D.C. Rakopoulos, D.T. Hountalas, E.G. Giakoumis. Comparative performance and emissions study of a direct injection Diesel engine using blends of Diesel fuel with vegetable oils or bio-diesels of various origins. 2006. Energy Conversion and Management 47 (2006) 3272–3287.