

Alternative Diesel Fuels Effects on Combustion and Emissions of an Euro5 Automotive Diesel Engine

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ABSTRACT

The present paper describes some results of a cooperative research project between GM Powertrain Europe and Istituto Motori of CNR aimed at studying the impact of FAME and GTL fuel blends on the performance, emissions and fuel consumption of the latest-generation automotive diesel engines. The investigation was carried out on the newly released GM 2.0L 4-cylinder “torque-controlled” Euro 5 diesel engine for PC application and followed previous tests on its Euro 4 version, in order to track the interaction between the alternative fuels and the diesel engine, as the technology evolves.

Various blends of first generation biodiesels (RME, SME) and GTL with a reference diesel fuel were tested, notably B20, B50 and B100. The tests were done in a wide range of engine operation points for the complete characterization of the biodiesels performance in the NEDC cycle, as well as in full load conditions. For a good readability of the paper, only the results regarding the pure fuels (B100) are discussed here. The results have confirmed the good capability of FAME fuels to reduce soot formation thanks to the lack of precursors and the presence of the oxygen in the fuel. At the same time, thanks to its high “combustion efficiency” GTL offers a simultaneous reduction of both fuel consumption and pollutant emissions.

The investigations put in evidence that the impact of the alternative fuels on the modern diesel engines remains significant, through the interaction between the alternative fuel characteristics and the engine-management strategies. Nevertheless, such interaction can be strongly reduced through the adoption of the torque-controlled engine

management, enabled by the use of commercial instrumented pressure transducer glow-plug.

INTRODUCTION

It is well known that from an environmental point of view, 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 it a significant advantage on the other first generation biofuels. However, because of growing concerns about energy crops impact on environment and on food prices, an increasing number of countries and stakeholders have recently challenged first generation biofuels. On the contrary, second generation biofuels, 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 [1,2,3].

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.

First generation biodiesel designates a wide range of methyl-esters blends (generally indicated with the acronym FAME, Fatty-Acid Methyl Esters) produced from vegetable oils and animal fats through a trans-esterification 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 [4].

More recently, a second generation of alternative diesel fuel was developed starting from the well-known Fischer-Tropsch synthesis process. It is usually indicated with XTL, where X denotes the specific source feedstock and TL (to Liquid) highlights the final liquid state of the fuel. The input feedstock can be either renewable Biomass (hence BTL) or fossil fuels, as natural Gas (GTL) or Coal (CTL). Looking at the renewable BTL production, it has minor interferences with the human food chain, since non-edible biomasses can be employed or, in case of animal-edible biomasses, the whole plant can be processed, as for the cellulosic ethanol production.

From the diesel engine fuelling point of view, a significant difference between first and second generations of biodiesel lies in their chemical composition, the first generation being essentially a blend of methyl-esters and the second of paraffin and olefin hydrocarbons.

FAME retains trace of original feedstock used for oil production, which has different implications in terms of chemical and physical properties of the biodiesel itself, such as oxidative stability (primarily), lower heating value (LHV), stoichiometric air-to-fuel ratio, viscosity, evaporation curve, etc. In particular, 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. The XTL shows, instead much better stability in the chemical composition, which is essentially driven by the synthesis process itself and not by the baseline feedstock, and can therefore be managed in a more consistent way.

Because of the different production areas of FAME, a large basis of feedstocks are employed, and this has undoubtedly drawbacks in terms of the composition stability. For different reasons, the biodiesel production is mainly concentrated in three areas: European Union, Asia-Pacific region and USA and the major feedstocks for biodiesel production are rapeseed, sunflower, imported palm oil and soybean in Europe, palm oil and jatropha in the Asia-Pacific region, soybean in US.

General Motors is one of the largest producers of diesel engines for passenger cars and light-trucks application in EU, Asia-Pacific and US markets. Therefore, it was considered of high importance the test of the first generation biodiesels from different sources representative of those regions as well as the second generation ones in the last generation GM LD diesel engine.

In addition, there is evidence in the literature that biodiesel fuelling can have a remarkable impact on engine performance, such as Fuel Consumption (FC) and full torque/

power performance, and even more significant on pollutant emissions, in particular for the modern electronically controlled diesel engines [5,6,7,8,9].

To this aim a cooperative project between GM Europe and Istituto Motori of CNR was established.

In this paper part of the results obtained from the experimental activity is presented. In particular, the impact of three different types of alternative diesel fuels, two FAMEs and one FT fuel, on the behavior of the last generation LD diesel engine is discussed. Rapeseed and palm-oil-based methyl-ester (RME) were selected from EU and Asia-Pacific regions, whereas soybean methyl-ester (SME) for the North American market was investigated. Finally, a second generation alternative diesel fuel from natural gas (GTL) from a leader European oil company has been considered as representative of this latter category according to the aim of the present paper.

The experiments have been carried out in Istituto Motori of CNR with the following main goals:

- to decouple the biodiesel impact on the thermodynamic processes of the engine cycle and on the pollutant emission;
- to identify the influences of biodiesel fuelling on control strategies and calibrations embedded in last-generation torque-controlled diesel engines;

An experimental test plan of the selected biofuels on a GM 1.9L Euro 4 diesel engine of similar architecture was already carried out previously within the same research project. The related results are reported in [10]. The outcomes clearly support the conclusion that the variations in performance and emissions measured on the multi-cylinder engine using the same biodiesel blends of the present investigation, can be primarily traced back to the chemical composition of the fuel itself and to the drift in engine working point more than to variations in injection and spray formation.

Therefore, the present paper completes and integrates the studies performed in [10] on a diesel engine of latest-generation technology, focusing the study on the ability of the modern programmable engine electronic control unit (PECU) in the adaptation of the combustion management to the fuel quality variation.

The experimental work comprised the analysis of various blends of the selected biofuels with the reference fossil diesel fuel, notably B20, B50 and B100. However, in order to keep the paper length in a reasonable limit and with a good readability, only the most significant results related to the pure fuels are discussed in the following.

THE FUELS

Table 1 reports, for all pure fuels considered in the present paper, some of the most important parameters affecting the fuel injection, spray pattern and air/fuel mixture formation, notably fuel density, viscosity and distillation curve. The reference diesel fuel was an EU certification diesel fuel (CEC, RF-03-A-84).

Table 1. Main fuel parameters

Analyzed Fuels					
Feature	Method	CEC	GTL100	RME100	SME100
Density @ 15 °C [kg/m ³]	EN ISO 12185	840.1	777.5	883	884.4
Viscosity a 40 °C [mm ² /s]	EN ISO 3104	3.141	2.547	4.254	3.958
Oxydation Thermal Stability at 110°C h	EN 14112	-	-	8.6	7.9
Cetane Number	EN ISO 5165	51.8	73.9	52.3	48
Low Heating Value [MJ/kg]	ASTM D3338	43.1	43.53	37.35	37.25
Distillation [°C]	IBP	184.8	203.1	322	320
	°C 10% vol.	221.9	230.3	333.2	332.1
	°C 50% vol.	276.1	265.9	337	335
	°C 90% vol.	329.1	305.8	343.3	341.2
	°C 95% vol.	344.9	312.2	347	345.6
	°C FBP	358.3	317.3	360	362
Carbon [% , m/m]	5991	86.5	84.3	78.5	78.4
Hydrogen [% , m/m]	5991	13.5	14.4	10.8	11.0
Nitrogen [% , m/m]	5991	-	1.3	0.2	0.2
Oxygen [% , m/m]	5991	-	0.0	10.5	10.4

In particular, RME and SME have higher density and viscosity than the reference fuel, that, coupled with distillation curves stretched in the temperature intervals corresponding to the tail of conventional diesel (see diagrams in Figure 1), increases the penetration of their spray with respect to conventional diesel, especially in cold conditions. Spray over-penetration is actually one of the most important concerns of diesel-FAME blend fuelling, owing to increased oil dilution and time residence in oil. These drawbacks could be worsened by specific injection strategies characterized by late injections, as for example the DPF/DeNOx regeneration.

The above described behaviors become more severe using pure RME and SME. GTL, on the contrary, keeps a wide distillation temperature window as the reference diesel fuel (so improving engine cranking at low ambient temperatures as well as limiting oil dilution), whereas its density decreases due to the higher H/C ratio.

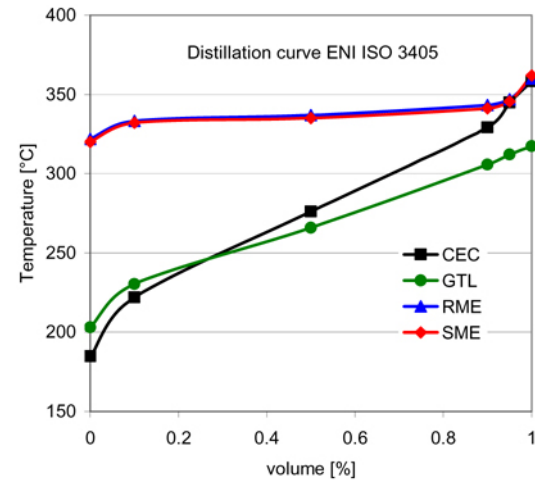


Figure 1. Distillation curves for CEC, GTL, RME and SME.

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. For convenience, they are compared with the features of the Euro 4 version previously investigated and whose results are reported in [10].

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

	EURO 4	EURO 5
Engine type	4 cylinders in-line	4 cylinders in-line
Bore x Stroke [mm]	82.0 x 90.4	83.0 x 90.4
Displacement [cm ³]	1910	1956
Compression Ratio	17.5	16.5
Valves per cylinder	4	4
Rated power and torque	110kW @ 4000rpm 320Nm @ 2000rpm	118kW @ 4000rpm 380Nm @ 2000rpm
Injection system	Bosch Common Rail EDC16	Bosch Common Rail EDC17
Injector and nozzle	Solenoid CRI 2.2+, 7 holes, 440cc/30s	Solenoid CRI 2.2+, 7 holes, 480cc/30s
Turbocharger	Garrett single stage VGT GTB1749MV	Garrett single stage VGT GTB1549MV
Swirl control	Rotary flap on secondary duct	Rotary flap on secondary duct
Catalyst system	Closed-coupled DOC & Under-floor DPF	Integrated closed-coupled DOC & DPF

In particular, the Euro 5 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 [11]. It is therefore of high interest within the present project to analyze the capability of these specific functionalities to compensate the variations induced in combustion by alternative fuel properties as Cetane Number (CN) and LHV.

The engine was installed on a dyno test bench fully instrumented for indicated signal measurements (cylinder pressure, injection pressure, energizing injector current). 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 eight 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), while the eighth test point (rated torque) was devoted to the characterization of the performance behaviour. The selected k-points are summarized in Figure 2, where the operating area of the engine running on NEDC is also displayed. The measurements in the seven part-load test points enabled the NEDC-cycle vehicle performance estimation for all fuel blends using 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.

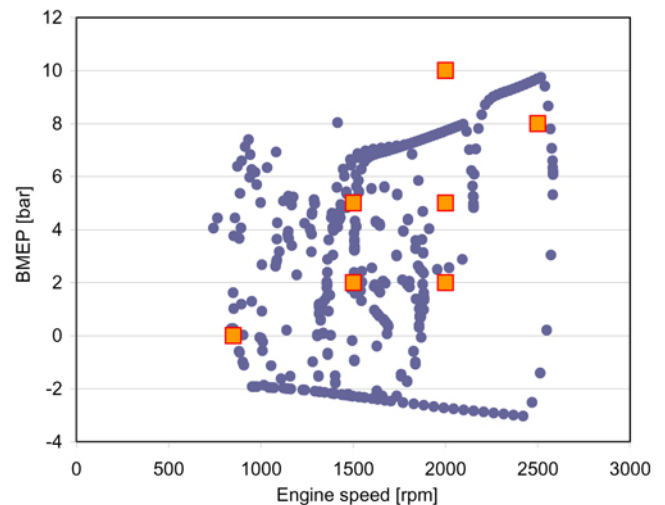


Figure 2. Test points together with the speed/load trace of the engine over NEDC for a D-class vehicle.

RESULTS

The analysis on the Euro 5 engine of the relationships between the combustion behaviour and the alternative fuel properties has been focused on part load behaviour, where the interactions with engine control unit operating strategies are more complex. In fact, concerning full load assessment, the results are in full agreement with the ones previously published in [10] on the Euro 4 engine, and highlight a performance loss at rated torque of up to 7% for pure FAME. For lower FAME blending ratios, performance loss shows a good linearity with the blending level itself. GTL, on the other hand, is almost transparent from performance point of view, in line with Euro 4 engine findings.

The analysis of the partial load investigations reported in [10] highlighted that the fuel properties, in particular LHV, influence the ECU operation mode. In the case of biofuels with low LHV it was necessary to increase the accelerator pedal signal (APS) in order to keep constant the torque. This variation was “interpreted”, from the programmable electronic control unit (PECU) point of view, as a change in the required torque and so in the engine operating point. Therefore the PECU updated the control variable values (rail pressure, boost pressure, EGR rate, etc.) to the mapped values of the new virtual operating point. In general, an APS increment triggers higher trapped air mass (lower EGR rates), boost, rail pressures etc., influencing the emissions.

In order to assess the potential outcomes of closed-loop combustion control (featured only by the Euro 5 engine) in mitigating the emission drift already highlighted in [10] for the Euro 4 engine configuration, specific tests were performed, comparing all the fuels in all the k-points in the following operating control modes:

- Open loop control mode;

- Closed-loop control on MFB50 only;
- Closed-loop control on both MFB50 and IMEP.

At each control mode corresponds a different procedure to match the BMEP setpoint for low LHV fuels. In particular:

- In the case of open-loop control mode, it was necessary to increase the APS above repeatability level; such variation triggers, as above-mentioned, increases of the boost pressure, injection pressure and air mass setpoint, according to the calibration maps.
- In MBF50 closed-loop control mode, the APS was increased to keep constant the BMEP, and the start of the main injection (SOImain) was automatically adapted by PECU to match the calibrated MBF50 setpoint related to the actual APS value.
- In the case of MFB50 and IMEP closed-loop control mode, the lower LHV of the alternative fuel was compensated by PECU by adjusting the main injection quantity at reference APS value, keeping the same set of operating conditions as the CEC fuel. In particular, the PECU control acts on both SOImain and energizing time (ET), modifying them in order to match BMEP and MBF50 targets.

As claimed in the previous paragraph, for each fuel, the engine was tested in seven NEDC test points in all operating control modes. As the experimental campaign and the related results were very extensive, for the sake of readability, the authors dedicated a detailed analysis of the results obtained in only three test points:

- 1500rpm @ 2bar BMEP (indicated briefly as 1500×2);
- 2000rpm @ 5bar BMEP (indicated briefly as 2000×5);
- 2500rpm @ 8bar BMEP (indicated briefly as 2500×8);

This selection stems from the consideration that they have the heaviest weight in the NEDC cycle and are representative of different engine running conditions in the NEDC area. These results will be illustrated in the next two sections, first in terms of engine operating data and cylinder-pressure-based combustion evolution, and later in terms of pollutant emissions, FCE and BSFC. The estimated engine performance with all fuels and for all operative control mode in the NEDC procedure will be shown in a third section at the end of this paragraph, so taking into account also the results of the other k-points not described in detail.

ENGINE PARAMETERS AND COMBUSTION ANALYSIS FOR THE SELECTED K-POINTS

Diagrams in [Appendix 1](#) report the main engine working parameters for all fuels at the k-point 1500×2. Left column refers to open-loop mode, center column to MFB50 closed-

loop mode, while right column to MFB50 and IMEP closed-loop mode. The diagrams in the right column represent the RME and SME data with striped bars to put into evidence the effect of imep control on biofuels, as it will be explained in the next. From the top to the bottom, the reported quantities on the different rows are: APS, IMEP, MFB50, SOImain and ET, rail pressure (Prail), trapped air mass (Mair) and boost pressure (Pboost). In all the diagrams are also displayed the “engine” standard deviation (STD) bars measured on three repetition tests with CEC fuel, in order to decouple the engine repeatability from the net fuel effects.

[Appendix 2](#) reports, for the same operating condition and the same fuels, the related indicating data, i.e. the cylinder pressure (Pcyl), energizing current to the injector (EC), heat-release rate (ROHR) and cumulative mass fraction burned (HR) measured for cylinder 1 and 2.

As a matter of fact, a laboratory reference AVL pressure transducer (GH13P) was installed in the cylinder 1 and the signal was fed to the signal recording system (AVL Indicom), whereas the cylinders 2, 3 and 4 are fitted with the engine pressure transducers by Beru, whose signals are routed to both PECU and AVL Indicom. Therefore, PECU control for cylinder 1 works on the basis of average corrections calculated for cylinder 2, 3 and 4. In the analysis of MBF50 and IMEP data for cylinder 1 the value acquired by AVL Indicom is considered, while for the other cylinders the PECU data. For this reason, it has to be underlined that the shift of MBF50 value between cylinder 1 and the other cylinders 2,3 and 4 (approximately 1.5 crank angle degrees) for the reference fuel (CEC) is due to a combination of a small difference in the TDC referencing between AVL Indicom and PECU, as well as to the different algorithms they employ for HR evaluation.

Finally, the reported data of ET and SOImain are the average values of the cylinder 1, 2, 3 and 4 both in open-loop mode and in closed-loop mode.

Looking at the diagrams reported in [Appendix 1](#) it is possible to observe that, for GTL fuelling, in each engine control mode the calibration parameters were not changed with respect to the CEC ones. This outcome was expected considering the past results on Euro 4 engine [10] and the similarity between CEC and GTL energy properties.

In open-loop mode, for FAME fuelling, it was necessary to increase the APS signal to obtain the same torque of the correspondent test with CEC, as already described. The shift of the APS was “interpreted”, from PECU point of view, as a change of engine operating point. This, in turn, caused a variation of engine control input parameters as it is possible to see in [Appendix 1](#), left column. In particular, the small increment of Pboost was due to the poor turbocharger boosting capability typical of low speed/low load operating

points. In fact, in the operating region around 1500×2 , the Pboost keeps just above the atmospheric pressure, therefore for little variations of APS no significant increment of pressure was recorded. Generally, at low rpm and load the effect of the APS variation is not relevant in terms of change of operating input parameters, but it becomes stronger and stronger as engine speed and load increase, as it will be shown next.

Looking at the results obtained with MFB50 closed-loop mode in [Appendix 1](#), for FAME fuelling, approximately the same engine parameter variations of the open-loop mode were observed, except for MBF50. For this latter, the SOImain was adapted to match the MBF50% setpoint. As it will be seen later, this control, even if it leads to the same MBF50% of the CEC, doesn't assure the same ROHR shape. It has to be specified that, by changing the control mode from open-loop to closed-loop, the resulting MBF50 values show generally a difference. It was due to a difference between the two engine calibrations, the first one SOImain based and the second one MBF50 based. This explains the differences that can be noted in the SOImain and MBF50 diagrams plotted in the [Appendix 1](#).

In the case of MFB50 and IMEP closed-loop mode, instead, a variation of engine operating input parameters is observed only in terms of SOI and ET, modified to match the desired BMEP and MBF50%. It is important to underline again that the control of MBF50% and IMEP on cylinder 1 is not performed by means of the direct measurement of cylinder pressure but is the average of the corrections of cylinders 2, 3 and 4. For this reason the adaptation on cylinder 1 is slightly worse with respect to the other cylinders, as it is possible to observe in the diagrams reported in center and right columns.

In [Appendix 2](#), the indicating diagrams highlight primarily the beneficial effect of closed-loop modes in re-centering the pressure cycles for FAME fuelling. Data obtained for cylinder 1 and cylinder 2 are reported, acquired by the laboratory pressure transducer and the production pressure transducers, respectively. The first transducer offers a high quality signal allowing a more accurate analysis of the ROHR, while, the glow plug transducer enables the study of the production PECU control.

Considering the data obtained for GTL, it is possible to observe a stronger peak of pilot ROHR with respect to the CEC fuel. On the other hand, the main combustion is less retarded and presents a lower ROHR peak. As already pointed out in the previous work [10], this is consistent with GTL fuelling properties (lower boiling curve and lower viscosity than CEC), which enhance the pilot injection mixing with air and ignition. On the other hand, the higher CN tends to reduce the overmixture of the injected fuel and the final result is a more efficient pilot combustion than CEC one, as appears in the ROHR trace. The ignition delay time of

the subsequent main injection is reduced, the air-fuel mixing is enhanced, the combustion timing tends toward the TDC and the correspondent fuel conversion efficiency is higher than CEC one. These results can be ascribed only to the fuel, as calibration parameters of GTL and CEC are the same.

RME and SME show about the same trends in terms of combustion history, that is influenced both by the change of the engine calibration parameters with respect to CEC fuel and by their physical - chemical properties. In open-loop mode, both RME and SME show a delayed combustion timing with respect to the CEC. Taking into account the shift of engine parameters plotted in [Appendix 1](#), the higher Prail and Mair favor a faster combustion. In addition, for RME and SME, there is a strong fuel properties influence on the pilot combustion that in turns emphasizes the fuel effects on main combustion. In fact, the higher viscosity and final boiling temperatures worsen the spray formation, reducing the pilot combustion efficiency, while the low LHV reduces the heat released by the combustion of the pilot injection (which is controlled in volume and is equal for all fuels). These effects on pilot combustion behavior contribute, together with the fuel parameters, to the increase of the ignition delay time and to move the combustion timing of main injection in the expansion stroke. This result is particularly evident for SME, which is characterized by a combination of lowest LHV and smaller CN than CEC. Thus, the fuel injected during the main injection for RME and SME burns with longer delay and the correspondent combustion phasing (MBF50 values) are reduced (see MBF50 diagrams in [Appendix 1](#)). These results are similar to those observed with the Euro 4 engine [10].

In MBF50 closed-loop mode the so far observed shift of MBF50 is entirely compensated by PECU control. This effect is less evident in cylinder 1 because the correction of SOI is obtained as the average of the other cylinder correction values. As shown in the diagrams reported in the center column of [Appendix 2](#), even if the combustion phasing is centered with respect to the CEC fuel, the behavior of the ROHR curves is different. This can still be ascribed to the influence of fuel properties. In particular, as in the open-loop mode, a lower peak of pilot ROHR of both RME and SME is observable. In fact, as reported above, the pilot quantity is not adjusted versus fuel quality, so energy produced during pilot combustion is lower. The main combustion is more premixed mainly because of the higher Prail and Mair due to the shift of APS.

Finally, in MBF50 and IMEP closed-loop mode all the parameters of the FAME are the same of CEC, with the exception of the SOImain and ET, and the difference on IMEP values among all fuels are fully compensated (see IMEP graphs in the third column of [Appendix 1](#)). However, it is interesting to note that still some differences remain among the fuels in terms of combustion history. These differences are only due to fuel properties and are related to the variation

of the pilot combustion for GTL, RME and SME as described before.

Another interesting effect relates to the difference in the SOI_{main} adjustment between the MBF50 closed-loop mode and the MBF50 plus IMEP closed-loop mode. In the first case, due to the Mair and Prail increment, the SOI adjustment requires significant variation of SOI_{main} only for SME (with the lowest CN), while in the second case, the same values of Mair and Prail lead to early SOI_{main} values for both RME and SME in order to keep constant the MBF50 value. This behavior of the PECU operating mode, that has negligible effects on emissions in the present test point, becomes more important at 2000×5 test point as will be showed for the next test point analysis.

Appendix 3 and 4 show the same quantities of Appendix 1 and 2, respectively, for the 2000×5 operating point. While most of the comments noted during the analysis of the 1500×2 test point are still valid, the tests performed in the current operating point highlighted an interesting effect of the MFB50 closed-loop mode. In particular, when only MFB50 control is active, for both RME and SME the related APS drift (see APS graphs in Appendix 3) causes the PECU to target a different MFB50 setpoint with respect to CEC fuel. The energizing current traces in Appendix 4 confirm this conclusion, showing a significant shift in injector energizing current traces for the two FAME with respect to CEC.

This effect was not significant at 1500×2, as it is possible to see looking again the previous relative diagrams in Appendix 2. In that case, the little change in APS variation does not cause great differences in terms of MBF50 target value. On the contrary, as the engine operative area relative to the present test point is particularly critical in terms of combustion noise control, the correspondent SOI_{main} values are targeted to have a delayed combustion timing, as observable from the high MBF50 values reported in Appendix 3. As a consequence, any rise in APS value to the PECU triggers a delayed MFB50 setpoint with respect to CEC fuel, thus reducing the engine thermodynamic efficiency, which in turn requires a further increment in APS to keep constant the engine torque. Therefore, such a sequence of actions and PECU reactions leads to reach a final steady-state point with the highest APS drift for the FAME with respect to the CEC fuel for all tested k-points. To confirm this results, the Figure 3 reported below shows the percentage variation of the APS signal for RME with respect to CEC for the seven selected k-points.

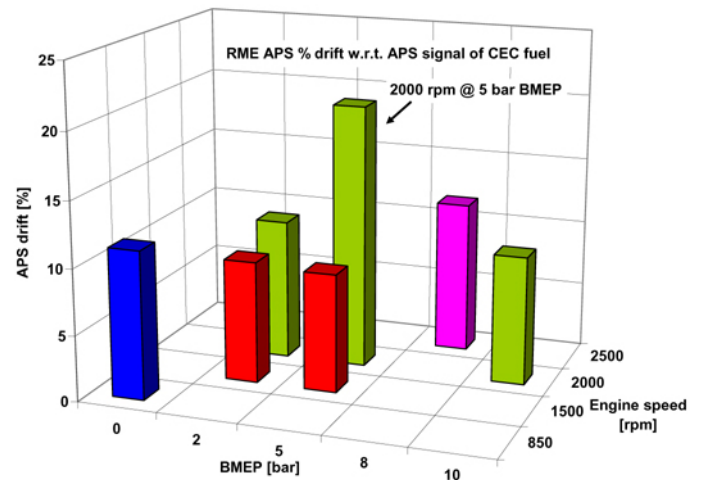


Figure 3. APS percentage increment for pure RME with respect to CEC for the seven selected k-points.

Therefore, it appears important to underline that the shift in APS signal is not simply proportional to the LHV variation of the fuel in the whole engine operative area, but the specific engine calibration itself can have a significant non-linear influence the APS drift. Moreover, also the low pilot combustion efficiency, as observable in the ROHR traces reported in Appendix 4, does not help to mitigate such a combustion timing delay in the present operating conditions.

In comparison to the two FAME fuels, the GTL doesn't show any significant variation of the engine parameters with respect to the CEC fuel. Only for the ROHR traces reported in Appendix 4, a higher pilot combustion peak and a lower premixed combustion peak of the main combustion in all engine control modes is observable. Even if the differences appear very small, they have a great impact on smoke emission as shown in the following sections.

As expected, the above-described engine behaviour found with open-loop FAME fuelling, changes employing the MBF50 and IMEP closed-loop mode. In this last case even if the effects linked with the APS drift were annulled and only the ET and the SOI_{main} were adjusted to match both the IMEP and the MBF50 values, a different ROHR shape (more premixed with more combustion noise) was observed for the two FAMES with respect to the CEC fuel. This result is more visible in the ROHR of cylinder 2 (see Appendix 4, right column, fourth rows) than of cylinder 1, where the average correction of the other cylinders doesn't match very well the MBF50 target. The FAMES influence on ROHR shape is due to the different air/fuel mixing level linked with the fuel properties and to the low pilot combustion efficiency, as just described for the previous k-point.

It is important to highlight for the present test k-point, that the employment of the MBF50 and IMEP closed-loop mode is not sufficient to compensate the influence of the fuel

properties on the combustion evolution. A better results in the compensation of the ROHR shape variation could be obtained through a further control on the pilot injection quantity versus fuel quality.

At 2500×8 the same results carried out at 1500×2 were obtained, as can be seen in [Appendix 5](#) and [6](#). Also in this case GTL doesn't show any variation with respect to the CEC fuel, both in terms of engine parameters and combustion evolution pattern.

The APS drift in the case of FAMES fuelling causes a larger variation in the engine parameters as can be observed in the [Appendix 5](#). This is of particular importance for the correspondent varied values of Prail, Mair and Pboost and their effects on NOx and PM emissions, as it will be observed later. The high Prail, Mair and Pboost also have effect on cylinder pressure traces in both open-loop mode and MBF50 closed-loop mode, as observable in [Appendix 6](#), while the MBF50 and IMEP closed-loop mode permits a good compensation of both cylinder pressure and ROHR traces among all fuels.

It is also interesting to compare the PECU response for the same APS drift, fuelling the FAMES, in terms of SOImain and MBF50 for the first two control modes: open-loop and MBF50 closed-loop. Even if the SOImain reference value for the two control modes is little bit different, due to a different MBF50 calibration, in the open-loop mode the APS drift causes an early injection timing, while with the MBF50 closed-loop mode, to match the CEC MBF50 target value, the SOImain is delayed. The behavior observed in the last case depends on the higher Mair and Prail reached fuelling the FAME, that increase the combustion speed (as highlighted in the following ROHR analysis, see [Appendix 6](#)). Being this point particularly critical in terms of NOx emissions, the different PECU response give different results as it will be possible to observe later.

At high engine speed and load, the diffusive combustion phase is dominant and mitigates the effect of fuel properties. Then the critical effects of the FAME on ROHR pattern linked with the low pilot combustion efficiency and a different air/fuel mixing are reduced thanks to the high cylinder temperature reached at the TDC. As a consequence, with the exception of the open-loop and MBF50 closed-loop modes where the higher Mair and Prail values rise the ROHR peak, at same calibration input parameters typical of MBF50 and IMEP closed-loop mode, the ROHR shapes for all fuels almost completely overlap (see ROHR diagram in the fourth row, right column of [Appendix 6](#)).

FCE, BSFC AND POLLUTANT EMISSION ANALYSIS FOR THE SELECTED K-POINTS

In the [Appendix 7](#) the result data for the three most heavy k-points (1500×2, 2000×5 and 2500×8) are compared among all fuels for all the control modes and in terms of FCE, BSFC, NOx, PM, while [Appendix 8](#) reports the correspondent CO₂, HC and CO emissions. In all the diagrams the standard deviation (STD) bars measured on three repetition tests with CEC fuel are also displayed.

The general trends for all data relative to the open loop control mode confirm the results outlined on the Euro 4 engine and reported in [\[10\]](#).

FCE values of GTL, displayed together with other fuels in the first row of [Appendix 7](#), are higher than the values relative to the reference fuel, in all the reported k-points and for all the engine control modes. FAME offers a different behavior according whether to the engine operation point or to the control mode. In particular, in open loop control mode and MFB50 closed-loop control mode at 1500×2 and 2000×5, FCE values are inside the STD; whereas, at 2500×8 the FCE values increase over the STD. In MFB50 and IMEP closed-loop control mode for all the test engine points the FCE values of the FAMES remain inside the test to test variation.

Concerning GTL fuelling, its improved FCE with respect to CEC diesel could be linked to the more favorable evaporation curve and viscosity, which both may enhance the fuel spray evaporation and mixing with air, thus promoting a significantly quicker and more complete combustion.

The highest FAME FCE at 2500×8 in open-loop control mode and MFB50 closed-loop control mode is clearly linked with the increase of the Pboost, Mair and Prail coming out from the APS drift (see [Appendix 5](#)) that in turn increases the combustion efficiency. An additional effect could be linked with the oxygen fuel content that promotes the combustion efficiency, as already analyzed on an EURO 2 1.9L CR diesel engine and reported in literature [\[12\]](#). However it is not possible to separate the contribution of the two described effects in this result analysis. The increment of FCE due to the APS drift is not present at 1500×2 and 2000×5. In the first one the increment of the calibration engine parameters (Prail, Pboost and Mair) is too little to affect significantly the FCE of the FAMES, in the second case the reduced thermodynamic efficiency due to a delayed combustion balances the effect of the APS increment.

When MBF50 and IMEP closed-loop control is activated, the APS drift effects are eliminated. In this case, for all analyzed k-points both RME and SME show FCE values inside the STD bar. It is thinkable that the possible benefit of the