

Impact of RME and GTL Fuel on Combustion and Emissions of a “Torque-Controlled” Diesel Automotive Engines

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ABSTRACT

The present paper describes some results of a research project aimed at studying the impact of alternative fuels blends on the emissions and fuel consumption of an Euro 5 automotive diesel engine.

Two alternative fuels were chosen for the experiments: RME and GTL. The tests were done in the three most important operating conditions for the engine emission calibration.

Moreover, the NO_x-PM trade-off by means of EGR sweep was performed in the same operating conditions, in order to evaluate the engine EGR tolerability when burning low sooting fuels as the RME.

The investigations put in evidence that the impact of the alternative fuels on modern diesel engines remains significant. This also depends on the interaction between the alternative fuel characteristics and the engine-management strategies, as described in detail in the paper.

INTRODUCTION

Great concerns are growing up on environmental impact of fossil fuel and poor air quality in urban areas due to traffic-related air pollution. In the last years special attention was paid mainly to the toxic emissions (HC, CO, PM and NO_x) of diesel engines for their adverse health effects and photochemical smog. Nowadays, the overall concern about the global warming determines an increased interest also for CO₂ emissions, one of the major greenhouse gas (GHG). In this respect, a significant improvement can be reached with the increased use of “clean” and renewable fuels. Some of them may offer the possibility to overcome the emission regulations without significant changes to engine layout and

fuel economy. As known, great attention is paid to the 1st generation of biodiesel, named as FAME (acronym of Fatty-Acid Methyl Esters) or more generally as “biodiesel”, for the following reasons:

- it is technically competitive with the conventional diesel fuel and virtually no changes are required in the fuel distribution infrastructure [1];
- it can be blended with commercial diesel fuel within limited percentages without any engine modification [2,3];
- it has a high potential to lower CO₂ emissions thanks to a reduced well-to-wheel (WTW) factor of GHG [4].

More recently, starting from the well-known Fischer-Tropsch synthesis process, able to produce liquid fuels from the so-called syngas (a mixture of H₂, CO, CO₂, H₂O as well as other compounds), a 2nd generation of alternative diesel fuels was developed. It is usually indicated as 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, thereby making its use very attractive. Furthermore, the XTL fuels exhibit a much better stability in the chemical composition than FAME, which is essentially driven by the synthesis process itself and not by the baseline feedstock [5].

Within this framework, biofuel producers and automotive OEMs are jointly devoting significant efforts in optimizing the benefits from the 1st generation biofuels, while making

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the 2nd generation technologies economically viable as soon as possible.

Many papers available in literature refer on the effects of the 1st and the 2nd generation biodiesels on engine performance and emissions. A recent review of the effects of the FAME use in diesel engines was presented by Lapuerta *et al.* [1], while some examples of the FT fuel influence on engine behaviour can be found in [5]. As also pointed out in [1], it is of great importance to evaluate the impact of the engine alternative fuelling on emissions as the engine technology evolves. This aspect is important in order to exploit at the best the synergies between the engine technology and the alternative fuel technology. A discussion on these possibilities can be found in [6].

To this aim, an experimental activity was planned in Istituto Motori fuelling a light duty diesel engine at the EURO 5 state of the art of engine technology with RME and GTL. The definition of the engine at the latest-generation technology was based on its advanced torque-control system, as explained in the following.

The experimental tests plan was accurately designed in order to obtain the following information:

- the effects of the 1st and 2nd generation biodiesels on the latest-generation diesel engine performance;
- the influence of the different control methodologies offered by the most advanced engine control systems.

A similar test methodology for a heavy duty engine can be found in the experimental work performed by Soltic *et al.* [7].

The following results have indicated a great potential of the new engine control systems to limit the engine behavior drift caused by fuels of different quality, confirming some previous results obtained by the authors on an Euro 4 engine technology [8].

THE FUELS

Table 1 reports, for all pure fuels considered in the present paper, some of the most important parameters affecting fuel injection, spray pattern and air/fuel mixture formation, notably fuel density, viscosity and distillation curve.

(See Table 1 after last section of paper)

The reference diesel fuel was an EU certification diesel fuel (CEC, RF-03-A-84).

As known, RME has density and viscosity values higher than the reference fuel and shows distillation curves with a temperature intervals corresponding to the tail of conventional diesel. These characteristics, could generally

increase the spray penetration with respect to the conventional diesel, especially in cold conditions. Nowadays, spray over-penetration is one of the most important concerns of diesel-FAME blend fuelling, owing to the increased oil dilution and residence time in oil [9, 10]. These drawbacks could be worsened by specific injection strategies characterized by late injections, as for example the DPF/DeNOx regeneration.

The above described disadvantages become more severe using pure or high RME blending. 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.

EXPERIMENTAL APPARATUS AND TEST PLAN

The four-cylinder in-line engine employed in the project was supplied by GM Powertrain. The main engine characteristics are reported in Table 1, while Figure 1 shows a scheme of the engine intake and exhaust layout. As noticeable in Figure 1, the EGR system is a conventional high pressure system with high efficiency cooler and the intake flow system includes a water cooling intercooler.

(See Figure 1 after last section of paper)

The employed 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 the in-cylinder pressure traces, heat release rate analysis is performed by ECU EDC17 using proprietary algorithms, and the actual values of MFB50 and IMEP are then compared to the target ones. As a consequence, deviations are continuously resettled by adjusting the main injection timing and quantity for the subsequent 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 such 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).

The fuels were tested in the three following steady-state operating points of the emission engine calibration procedure in the new European driving cycle (NEDC) when installed on a D-class vehicle (1590kg IW):

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

The selected points, that cover low/medium/high speed and load conditions, were chosen because of their high weights in the NEDC emission estimation.

In the same test points, the fuel influence was characterized also in terms of NO_x-PM trade off versus EGR sweep in order to evaluate the EGR tolerability of the engine for the different fuels. Moreover, a fourth test point was devoted to the engine characterization at the rated torque at 2500 rpm.

For each test point the injection strategy was composed by Pilot + Main events.

As already described in a previous paper [8], in electronic controlled CR engines, the fuel properties, in particular LHV, influence the ECU operation mode. In fact, in the case of biofuels with low LHV it was necessary to increase the accelerator pedal signal (APS) in order to keep the torque constant. 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 [8] for the Euro 4 engine configuration, specific tests were performed, comparing all the fuels in the three selected test points in the following operating control modes:

- Open loop control mode (indicated as OLC);
- Closed-loop control on both MFB50 and IMEP (indicated as CLC).

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

- In the case of CLC mode, it was necessary to increase the APS above repeatability level; such variation triggered, as above-mentioned, increments in the boost pressure, injection pressure and air mass setpoint, according to the calibration maps.

- In the case of CLC 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 acted on both SOI_{main} and energizing time (ET), modifying them in order to match BMEP and MBF50 targets.

The injection strategy was Pilot+Main in OLC and CLC; in particular the setting of the Pilot injection was the same changing the control mode (about 1 mm³/cycle in all the tested point).

The results will be illustrated in the next two sections, first in terms of engine performance (indicated signals, BSFC, emissions etc.) versus combustion control mode, then in terms of NO_x-PM trade-off versus EGR sweep. Finally the full load performance at 2500 rpm will be analyzed.

RESULTS

FUEL EFFECTS AT PART LOAD ON ENGINE OPERATING PARAMETERS AND COMBUSTION PATTERN

Diagrams of [Figure A1](#) in [Appendix A](#) report the main engine working parameters for all fuels at the three selected test points and for both engine control modes. From the top to the bottom, the reported quantities, indicated on the y axis of the diagram are: APS, rail pressure (Prail), trapped air mass (Mair), boost pressure (Pboost), SOI_{main}, ET of main injection (both as average values of all cylinders) and MFB50. In all the diagrams the “engine” standard deviation (STD) bars measured on three repetition tests with CEC fuel are also displayed, in order to decouple the engine repeatability from the net fuel effects.

[Appendix B](#) reports, for the same operating conditions and the same fuels, the related indicating data, i.e. cylinder pressure (referred as P_{cyl}) and heat-release rate (ROHR) measured for cylinder 1. [Appendix C](#) shows the parameters characterizing the engine performance such as: NO_x, PM, HC, CO Fuel Conversion Efficiency (FCE) and Brake Specific Fuel Consumption (BSFC).

Looking first at the diagrams of the test case 1500×2 reported in [Appendix A](#), 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 rather expectable considering the past results on Euro 4 engine [8] and the similarity between CEC and GTL energy properties.

In OLC mode, for RME fuelling, it was necessary to increase the APS signal to obtain the same torque of the correspondent

test with CEC, as already described. The corresponding variation of engine control input parameters is displayed in [Figure A1](#), first row left column. Actually, due to a marginal variation in APS at low speed and low loads, its effect on engine control parameters is less relevant (see for example the Pboost variation at 1500×2), but it becomes stronger and stronger as engine speed and load increase, as shown in the next.

In the case of CLC mode, instead, a variation of engine operating input parameters is observed only in terms of ET and SOI_{main}, modified to match the desired BMEP and MBF50 respectively.

For the same operating point (1500×2), the diagrams of the first row in [Figure B1](#) ([Appendix B](#)) show the relative indicating curves for both engine control modes.

As regards GTL, it shows 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 [8], this is consistent with GTL properties (lower boiling curve and lower viscosity than CEC), which enhance the pilot injection mixing with air and ignition. The higher efficiency of the pilot combustion is linked with the high CN of GTL, as evidenced also in other past papers [12, 13]. As a consequence, the MBF50 of main combustion moves toward the TDC and the correspondent fuel conversion efficiency is higher than CEC one. These results can be only ascribed to the fuel, as calibration parameters of GTL and CEC are identical.

RME is influenced both by fuel characteristics and the change of the engine calibration parameters. In OLC, it shows a delayed combustion timing with respect to the CEC. This result depends mainly on the drift of the SOI_{main} target (see [figure A1](#)) that is shifted in the expansion stroke by the APS drift, but also by the reduced effect of pilot combustion. In fact, at constant injected volume of pilot, it produces less effect on ignition delay time reduction on main injection for low LHV fuels. In addition, the higher viscosity and final boiling temperatures worsen the spray formation, reducing the pilot combustion efficiency.

In CLC mode all the parameters of the RME are the same of CEC, with the exception of the SOI_{main} and ET. However, it is interesting to note that some differences still 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 and RME, as described before.

[Appendix A](#) and [B](#) also show the results for the test point 2000×5 . The comments relative to the analysis at 1500×2 are mostly still valid for the present test case.

GTL shows an influence only on cylinder pressure and ROHR traces. Higher pilot combustion peak and lower premixed combustion peak of the main combustion are observable. Even if the differences appear very small, they have a great impact on smoke emission, as shown in the following.

As expected, the previously described engine behaviour with RME fuelling changes employing the CLC mode. In this case, even though the effects linked with the APS drift were annulled, a RME influence on ROHR shape (more premixed with more combustion noise) was observed. This 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 test point.

It is important to highlight that the employment of the CLC mode is not sufficient to totally compensate the influence of the fuel properties on the combustion evolution. 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.

The results on PECU parameters and indicated signals at 2500×8 , also reported in [Appendix A](#) and [B](#), essentially showed the same trends of the two previous test points. The engine remains almost insensitive fuelling GTL in both engine control modes and both in terms of engine parameters and combustion evolution pattern.

The APS drift in the case of RME fuelling under OLC mode causes a larger variation in the engine parameters, as can be observed in the [Appendix A](#). This is of particular importance for the correspondent different values of SOI_{main}, Prail, Mair and Pboost and their effects on NO_x and PM emissions, as will be later observed. The high Prail, Mair and Pboost also have an effect on cylinder pressure traces, while the CLC mode permits a good compensation of both cylinder pressure and ROHR traces.

As regards the fuel influence on combustion history, at high engine speed and load, the diffusive combustion phase is dominant and mitigates the effect of the fuel properties. Then the critical effects of the RME on 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, only with the OLC mode with the higher Mair and Prail values a rise of the ROHR peak was detected. In CLC mode, the ROHR shapes were almost completely overlapped for all fuels (see right diagram in the third row of [Figure B1](#)).

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

In the [Appendix C](#), the results for all test points and engine control mode are plotted in terms of HC, CO, NO_x, PM, FCE and BSFC, respectively. The pollutant emissions values are relative to engine out measurements. In all the diagrams the standard deviation (STD) bars measured on three repetition tests with CEC fuel are also displayed.

FCE values of GTL are higher than the values relative to the reference fuel for all test points and both engine control modes. The improved FCE with respect to CEC diesel could be linked to the more favorable evaporation curve and viscosity, which may both enhance the fuel spray evaporation and mixing with air, thus promoting a significantly quicker and more complete combustion.

RME offers a different behavior according either to the engine operation point or to the control mode. In particular, in OLC mode at 1500×2 and 2000×5, FCE values are inside the STD; whereas, at 2500×8 the FCE values increase over the STD. This is clearly linked with the increase of the Pboost, Mair and Prail coming out from the APS drift that in turn increases the combustion efficiency. An additional effect could be linked to the oxygen fuel content that tends to promote combustion efficiency, as already reported in literature [14, 15]. However it is not possible to separate the contribution of the two described effects in this analysis. The increase of FCE for RME is not present at 1500×2 and 2000×5. At 1500×2, in fact, the increment of the calibration engine parameters like Mair etc. is weak; at 2000×5 the reduced thermodynamic efficiency due to a delayed combustion balances the effect of the APS increment. In CLC mode for all the test points the FCE values of the RME remain inside the test to test variation. In CLC mode, the APS drift effects are eliminated and RME shows FCE values inside the STD bar.

BSFC is generally affected by FCE, fuel density and LHV values. The BSFC results are reported in the last diagram of [Figure C1 \(Appendix 3\)](#). For GTL, the BSFC is slightly lower than the STD bar of the reference fuel, in agreement with FCE results. For this latter, the influence of both the FCE and the LHV increase (see [Table 1](#)) exceeds the fuel density reduction.

The high BSFC values for RME in all test points are in-line with the reduced LHV value and with the trend of FCE, and so its increment becomes only LHV dependent.

Looking at the NO_x, PM, HC and CO emission diagrams in the [Appendix C](#), the trends of emissions versus fuel quality

carried out from the present engine confirm the results generally reported in the literature [1, 8].

The GTL benefits in terms of PM are mainly linked to the lack of poly-aromatic content. Only at 2000×5 smoke emissions remain in CEC STD bar, while decrease in the other two test points. It is possible that, being 2000×5 the most critical test point from the PM emission point of view, the higher pilot combustion efficiency of the GTL promotes the diffusive combustion phase annulling the benefits of the poly-aromatic-free characteristic with respect to the reference fuel.

On the contrary, no significant NO_x reduction was detected for GTL with respect to the CEC, in both control modes. This result differs from the trend observed in other papers [5, 8, 12, 13] on engines of past technology (Euro 4 and older), where a decrease of NO_x burning GTL was detected and ascribed to its lower adiabatic flame temperature (due to its higher H/C ratio). The present results are explainable with the overall increment of the EGR level (the main driver in NO_x reduction) with the Euro 5 engine calibration to match the NO_x emission target. In fact, the average percent increment of the EGR rate from Euro 4 to Euro 5 calibration was about 15% and so it is reasonable to expect a reduction in the influence of the fuel quality on NO_x emission when high EGR and low NO_x exhaust level are reached. To confirm this, a general trend of specific NO_x emission reduction versus EGR rate measured for different engines and operating conditions carried out from FIAT Powertrain experiences [16] is plotted in [Figure 2](#).

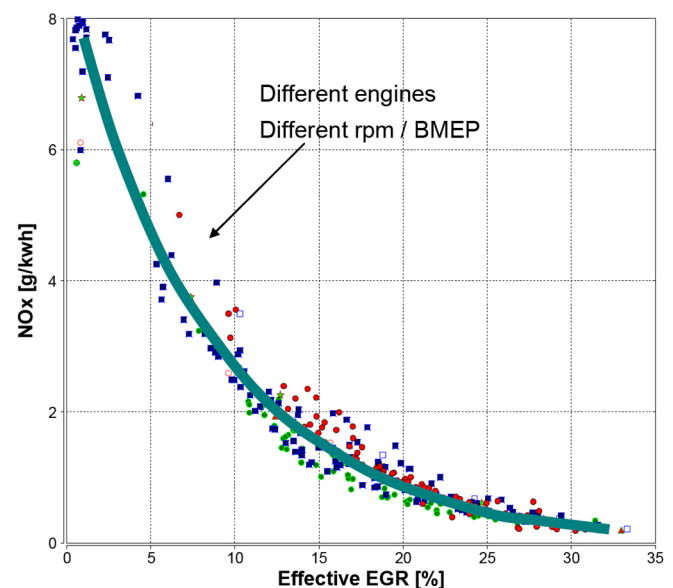


Figure 2. Relationship between Specific NO_x and EGR, including different operating points and different engines [16].

The lack of poly-aromatic content of GTL and its good pilot combustion efficiency that promotes a reduction of the overmixture zones, are the main reasons for its good performance in terms of HC emissions. The GTL CO emission levels are generally inside the CEC STD bars except for 1500×2 case. In this test point, as observable from the ROHR traces, the high CN of the GTL tends to reduce the ignition delay time and the peak of premixed combustion fraction partially responsible of the unburned CO emissions. These results are valid for both the engine control modes.

As expected from the analysis on engine control parameters and indicated signals, RME's emissions depend on both the engine operating point and the engine control mode.

At 1500×2, for the two engine control modes, a weak but not negligible reduction of NOx for RME is evident. In the case of OLC mode this tendency is in contrast with the reduction of EGR rate due to the APS increment; however the APS drift is small and so the EGR variation is less than 2% with respect to a total value of about 60%. So the weak NOx reduction for RME is imputable to the delayed combustion timing and also to a leaner air/fuel charge that reduces the combustion temperature. This leaner air/fuel charge is linked to the increased Prail (see [Appendix A](#)) and the longer ignition delay time derived from the low pilot combustion efficiency. This consideration is also supported by the NOx trend of RME for the CLC mode where it appears that, at same EGR rate, the NOx reduction is more pronounced than the one measured in OLC mode.

The RME influence on NOx increases when rising speed and load and changing the engine control mode. At 2000×5 and 2500×8, in OLC mode, the APS drift causes a significant increase in NOx emissions, with respect to the CEC, of 50% and 40%, respectively. Of course, these results are affected by a concomitance of effects due to the variation of different parameters (primarily Mair, then Prail, Pboost, early MBF50 at 2500 rpm, etc.).

The RME's NOx emissions for CLC mode highlight the most interesting results in terms of electronic control engine and fuel quality interaction. It clearly appears that, when the low LHV is compensated with an increase of ET without any change of the other engine parameters, NOx emissions of RME fall down within the STD bar of the CEC. In the recent literature it was generally observed an increase of NOx emissions at medium and high load engine using oxygenated fuels, mainly due to a variation of engine parameters [1].

The results carried out in the present work evidence that for the latest generation “torque-controlled” engines, the influence of fuel quality on engine parameters is nearly annulled. Moreover, the chemical effect linked with the fuel oxygen content is vanished, thanks to the possibility to work with new engines running at medium/high load with massive

EGR rate without excessive smoking levels, as reported in the PM diagrams of [Appendix B](#). Therefore, it has to be remarked that for the new generation engines the primary driver in the control of NOx emission level is only the EGR rate.

PM emissions for RME show an impressive reduction with respect to CEC, in agreement with general literature results [1, 8, 15]. In OLC mode the drastic reduction (up to 90%) is due to the concomitant effects of the fuel oxygen content and the engine calibration shift. In CLC mode a PM reduction higher than 70% was measured at the same NOx level of the reference fuel. This last result, obviously, only depends on the RME oxygen content.

Looking at the unburned compounds (HC and CO) in the [Appendix C](#), it appears that they are not affected by engine control mode. The lower HC emissions of RME with respect to the CEC are imputable to the low polyaromatic content of the biodiesel. CO emissions are influenced by the combustion timing and combustion duration. To this reason they are slightly higher for RME with respect to the CEC at 1500×2 where the combustion is a little bit shifted toward the expansion stroke. At 2000×5 and 2500×8, CO emissions are very low and within the STD interval.

The above described analysis can be considered as representative of what occurs in the low, medium and high speed/load operating area of current technology engines burning fuels of different quality.

In the following section all the fuels will be compared in terms of NOx -PM trade-off versus EGR sweep, highlighting the benefits on NOx emission reduction burning oxygenated fuels in the engine of current technology.

NOX-PM EMISSION TRADE-OFF BY EGR SWEEP

As often happens with the oxy-fuel's studies in diesel engines, the low PM emissions offered by the RME can be seen as an higher EGR tolerability of the fuel. So, it could be exploited increasing the EGR calibration at same exhaust PM loading and reducing further the NOx emissions.

To this aim NOx-PM trade-off by EGR sweep in CLC mode were carried out only for CEC and RME. The diagrams in [Figures 3, 4 and 5](#) show the NOx-PM trade-off versus EGR sweep in the three test points: 1500×2, 2000×5 and 2500×8 respectively. In the first diagram (1500×2) also the CO trade-off is reported, as at low speed low load operating points its emission level becomes critical for the emission targets.