

# Analysis of Performance and Emissions of an Automotive Euro 5 Diesel Engine Fuelled with B30 from RME and JME

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## ABSTRACT

The effects of using a B30 blend of ultra low sulphur diesel and two different Fatty Acid Methyl Esters (FAME) obtained from both Rapeseed Methyl Ester (RME) and Jatropha Methyl Ester (JME) in a Euro 5 small displacement passenger car diesel engine on both full load performance and part load emissions have been evaluated in this paper.

In particular the effects on engine torque were firstly analyzed, for both a standard ECU calibration (i.e. without any special tuning for the different fuel characteristics) and for a specifically adjusted ECU calibration obtained by properly increasing the injected fuel quantities to compensate for the lower LHV of the B30: with the latter, the same torque levels measured under diesel operation could be observed with the B30 blend too, with lower smoke levels, thus highlighting the potential for maintaining the same level of performance while achieving substantial emissions benefits.

Moreover, the effects of the two different 30% vol. blends on brake specific fuel consumption and on engine-out exhaust emissions (CO<sub>2</sub>, CO, HC, NO<sub>x</sub> and smoke) were also evaluated at 6 different part load operating conditions, representative of the New European Driving Cycle.

Both standard engine calibration (change of the accelerator pedal position) and specifically adjusted engine calibration (adjustment of the energizing time of main injection) were evaluated for part load operating conditions, highlighting a 4% average rise of fuel consumption, on a mass basis, at same fuel conversion efficiency and CO<sub>2</sub> emissions. A noticeable increase of CO and HC emissions at low load

could also be noticed, along with a significant NO<sub>x</sub> emissions decrease when using a specifically adjusted engine calibration, and a considerable smoke emission reduction.

## INTRODUCTION

In recent years biofuels have attracted considerable attention as renewable, biodegradable, and non-toxic fuels. In 2009 European directive 2009/28/EC introduced a new target for the European Union (EU) member states concerning the share of energy from renewable sources in all forms of transport; in particular a target of at least 10% of the final energy consumption in transport should be achieved by 2020. Today, biodiesel is the biofuel most commonly used in Europe, covering approximately 80% of the biofuel market. Moreover, Asian countries are nowadays exploring biodiesel sourced from non-edible seed oils like Jatropha Curcas, a wild plant which can grow in arid, semiarid and wasteland; therefore, JME represents a viable solution for biodiesel production, since allows green cover to wasteland [1].

Biodiesel fuels have different physical properties (i.e. cetane number, LHV, viscosity, density); these differences affect combustion and injection processes of biodiesel [2], with consequences on engine emissions; literature reports several studies concerning biodiesel effects on emissions, which generally indicate a substantial reduction of particulate matter (PM) [3], carbon monoxide (CO), and unburned hydrocarbons (HC) [4], while fuel consumption and nitrogen oxides (NO<sub>x</sub>) emissions usually increase [5, 6]. Fuel consumption increase is related to differences in fuel energy content of biodiesel, while studies suggest that the effect of biodiesel on NO<sub>x</sub> emissions is the result of a number of

competing mechanisms, that may prevail or cancel each another under different operating conditions [7].

Although several research programs have been carried out in the last decade on the performance and emissions of CI engines, fuelled with pure biodiesel and blends with diesel fuel, most scientific literature has dealt in the past with engines equipped with conventional injection systems [8, 9, 10, 11, 12, 13, 14, 15], and even if more recent works also examined engines with high pressure, electronically controlled injection systems [16, 17, 18, 19, 20], only few studies concerning last generation automotive engines are available. Moreover, experimental activities reported in literature are usually carried out running the engine with the original, diesel oriented, ECU calibration; a specifically adjusted ECU calibration optimized for biodiesel is rarely used [21] and the gap in engine torque output is usually recovered by increasing the torque demand through an increase of the accelerator pedal position, thus simulating a switch of the supplied fuel. An extension of the investigations to modern engines and after-treatment systems, which may include advanced combustion technologies [22] and closed loop combustion controls [23, 24] seems therefore to be necessary in order to fully understand the effects of biodiesel usage and to avoid jeopardizing its potential emission benefits.

Since the biodiesel usage appears to be particularly challenging in small displacement engines, due to the high risks of lube dilution caused by cylinder liner fuel jet impingement occurring during post-injections used for DPF regeneration and due to the increased risk of injector nozzle coking in small diameter nozzle holes, a wide research activity focused on the analysis of biodiesel usage effects on a Euro 5 automotive small displacement diesel engine is currently being carried out at Politecnico di Torino in the framework of the 2007 PRIN (Italian National Research Program): after a preliminary analysis concerning the effects of neat biodiesel usage [25, 26], the effects on engine performance and on engine out emissions of two biodiesel blends (30% by volume) sourced from rapeseed and Jatropha Curcas oils respectively are reported in this paper (the 30% by volume blending was chosen as being the upper limit that has been generally tested in captive fleets or in pilot programs [27, 28]). Further investigations, which are currently still in progress concerning the effects of biodiesel blends on aftertreatment system performance, will be discussed in a different paper [29].

## EXPERIMENTAL SETUP

Experiments were carried out at ICE Advanced Laboratory of Politecnico di Torino on a test rig (Fig. 1) equipped with an eddy current dynamometer connected to the engine under test, the main characteristics of which are listed in Table 1.

The engine is a modern automotive Euro 5 small displacement turbocharged Common Rail DI diesel engine, one of the smallest engines on the market if considering the unit displacement. Fuel consumption was measured by means of an AVL 733S gravimetric fuel meter, while engine-out emissions were evaluated by analyzing the exhaust gases (sampled between turbine outlet and DOC inlet) by means of a Fisher-Rosemount NGA-2000 gas analyzer (for gaseous emissions) and of an AVL 415S smoke-meter (for particulate emissions).

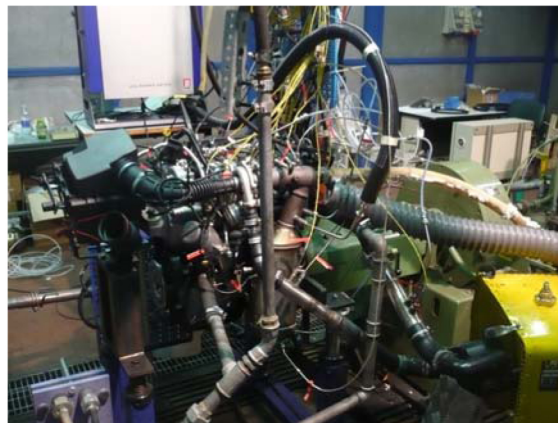


**Figure 1. Engine test rig.**

**Table 1. Main characteristics of the test engine.**

|                       |                         |
|-----------------------|-------------------------|
| Engine Type           | Diesel, 4 stroke        |
| Displacement          | 1248 [cm <sup>3</sup> ] |
| Cylinders arrangement | 4 in line               |
| Bore x Stroke         | 69.6 [mm] x 82 [mm]     |
| Compression ratio     | 16.8:1                  |
| Turbocharger          | Single-stage with WG    |
| Fuel injection system | Common Rail             |
| Max. Power            | 55 [kW] @ 4000 [rpm]    |

During the tests, all the engine control parameters were controlled by a PC that was directly connected to the engine ECU: the test engine was also equipped with a closed-loop combustion control capable of maintaining the angular position corresponding to the 50% of burned fuel mass, with respect to the TDC (MFB50) at its optimum position in order to achieve a certain BMEP target, under part load operating conditions [23, 24]. Moreover, the piezoresistive pressure transducers integrated in the glow plugs used for the closed loop combustion control, were also used for the measurement of the in-cylinder pressure. The output from these transducers were firstly filtered by a low-pass filter to reduce high frequency noise and to prevent aliasing errors and signal distortion and then finally sampled by means of a 12 bit high-speed multichannel data acquisition board (National Instruments DAQCard-AI-16E4), coupled to a high resolution (0.4°) crank-angle encoder to ensure proper timing

of the sampled data. At each operating condition 100 consecutive engine cycles were recorded to obtain a wide statistical sample.

Data acquisition and post-processing were performed by means of ICE Analyzer [30], a suitable developed program for internal combustion engine indicating analysis. Experimental tests were performed using the three following fuels:

- diesel: standard ultra low sulfur diesel fuel compliant with Directive 2003/17/EC (sulphur < 10 mg/kg);
- RME (B30): 30% vol. blend of Rapeseed Methyl Ester (RME) biodiesel with 70% diesel;
- JME (B30): 30% vol. blend of Jatropha Methyl Ester (JME) biodiesel with 70% diesel.

**Table 2. Properties of neat fuels.**

| Properties                                     | Diesel | RME   | JME   |
|------------------------------------------------|--------|-------|-------|
| Carbon content C [w%]                          | 86.5   | 79.6  | 79.7  |
| Hydrogen content H [w%]                        | 13.5   | 12.1  | 12.2  |
| Oxygen content O [w%]                          | -      | 8.3   | 8.1   |
| <b>Distillation Temperatures</b>               |        |       |       |
| Initial Boiling Point [°C]                     | 171.2  | 154.5 | 152.4 |
| 10% [°C]                                       | 204.0  | 346.7 | 343.0 |
| 50% [°C]                                       | 274.8  | 349.8 | 348.0 |
| 90% [°C]                                       | 342.3  | 354.6 | 352.9 |
| Final Boiling Point [°C]                       | 366.9  | 360.0 | 353.4 |
| Sulfur content S [ppm]                         | < 10   | < 10  | < 10  |
| Stoichiometric ratio (A/F) <sub>st</sub>       | 14.4   | 13.0  | 13.0  |
| Net heating value, LHV [kJ/kg] (ASTM D 240-00) | 42960  | 37365 | 37455 |
| Cetane Number (ISO 5165-98)                    | 51.8   | 51.5  | 56.6  |
| Density at 15 °C [kg/m <sup>3</sup> ]          | 840    | 883   | 880   |
| Viscosity at 20 °C [mm <sup>2</sup> /s]        | 3.14   | 7.09  | 7.00  |
| LHV/(A/F) <sub>st</sub> [MJ/kg]                | 2.99   | 2.88  | 2.88  |

**Table 3. Composition of neat fuels.**

| Fatty Acid        | Formula                                        | Cetane Number | RME [%] | JME [%] |
|-------------------|------------------------------------------------|---------------|---------|---------|
| Methyl Oleate     | C <sub>19</sub> H <sub>36</sub> O <sub>2</sub> | 54            | 56.4    | 41.2    |
| Methyl Linoleate  | C <sub>19</sub> H <sub>34</sub> O <sub>2</sub> | 43            | 23.5    | 33.7    |
| Methyl Palmitate  | C <sub>17</sub> H <sub>34</sub> O <sub>2</sub> | 74            | 9.0     | 15.6    |
| Methyl Linolenate | C <sub>19</sub> H <sub>32</sub> O <sub>2</sub> | 23            | 3.5     | n.d.    |
| Methyl Elaidate   | C <sub>19</sub> H <sub>36</sub> O <sub>2</sub> | -             | 2.9     | 1.3     |
| Methyl Stearate   | C <sub>19</sub> H <sub>38</sub> O <sub>2</sub> | 81            | 2.4     | 6.8     |
| Others            |                                                | -             | 2.3     | 1.4     |

The properties of pure diesel and biodiesel fuels used to obtain RME and JME B30 blends are listed in Table 2. The composition of neat biodiesel fuels, as well as the cetane numbers of each component (as reported in [31]), are listed in Table 3. It should be noticed that, as far as neat JME is concerned, the higher content of high cetane saturated fatty acids components, such as palmitic and stearic acids overcomes the effect of medium-low cetane unsaturated fatty acids compounds, such as oleic and linoleic acids, thus leading to a considerably higher cetane number for neat JME respect to neat RME.

Although not all fuel characteristics can be scaled on the basis of the blending percentage, the neat fuels analysis was preferred during this first part of the research project, in order to gather more accurate information concerning biofuel characteristics and to allow at least rough estimates also for different blending ratios that will be the object of further experimental investigation in future works. It should be noticed as, although the oxygen content of the biodiesel reduces both its stoichiometric ratio A/F<sub>st</sub> (13 instead of 14.5 of diesel, with a 11 % reduction) and its Lower Heating Value (37.4 MJ/kg instead of 43 MJ/kg of diesel, with a 13 % reduction), the LHV/A/F<sub>st</sub> ratio is more closely comparable for biodiesel and diesel (with differences lower than 4%), thus highlighting the potential for recovering engine performance at full load by means of a proper ECU recalibration, since the maximum BMEP which can be achieved at a given  $\lambda$  is proportional to the LHV/A/F<sub>st</sub> ratio.

## TEST PROCEDURE

Tests were initially carried out at full load without any modifications to the ECU injection strategy, in order to assess the impact of the fuel blends on engine performance (STD. CALIBRATION). Afterwards, further full load tests were performed adjusting the injected fuel quantities in order to achieve, for each revolution speed, the same relative air-fuel ratio  $\lambda$  measured under diesel operation, so to more

completely evaluate the performance potential of biodiesel blends (SPEC. CALIBRATION).

The effects of biodiesel blends on engine emissions and fuel consumption were then evaluated at 6 different part load operating points, listed in [Table 4](#), selected after a preliminary numerical simulation of different driving cycles as representative of the New European Driving Cycle.

**Table 4. Part load operating points.**

| Operating Point | SPEED<br>[rpm] | BMEP<br>[bar] |
|-----------------|----------------|---------------|
| 1               | 1500           | 2             |
| 2               | 1500           | 5             |
| 3               | 2000           | 2             |
| 4               | 2000           | 5             |
| 5               | 2500           | 5             |
| 6               | 2500           | 8             |

Since the change in fuel from diesel to RME and JME B30 blends leads to a reduction in the torque output due to the Lower Heating Value of the blend and, thus, in a change of the operating point on the ECU maps, two different strategies were adopted in order to achieve the same BMEP target:

- Change of the accelerator pedal position in order to obtain the same BMEP level as with diesel fuel; this strategy, that will be here on referred to as “STD. CALIBRATION” does not feature any change in the ECU calibration, but the operating point of the engine is simply shifted towards higher load values, since the lower heating value of the biodiesel has to be compensated with an increase of the pedal position. This strategy was chosen in order to simulate the effects of the switch to biodiesel blends by the end users, without any specific adjustment of the engine calibration parameters.
- Adjustment of the energizing time of the main injection in order to obtain the same BMEP level as with diesel fuel while keeping unchanged the pedal position, and thus the operating point position on the engine calibration map; this strategy, that will be here on referred to as “SPEC. CALIBRATION” was chosen in order to simulate the effects of the simplest recalibration of ECU parameters. However, it should be pointed out that in this way all the main engine control parameters (e.g. injection pressure and timing, EGR rate, etc.) are not changed from the standard calibration, while only the injected fuel quantity is adjusted.

Finally, further experimental activities were carried out to fully exploit the benefits that could be obtained for instance by adjusting the EGR rates in order to take into account the different biodiesel blends SOOT-BSNO<sub>x</sub> trade-off: the effects on the SOOT - BSNO<sub>x</sub> trade-off of the different blends were therefore evaluated at the three operating points listed in

[Table 5](#); for each operating point the engine was operated with the specific calibration and the EGR rate was varied from 0% to the maximum achievable value corresponding to the fully open EGR valve position.

**Table 5. Trade-off test operating points.**

| Operating Point | SPEED<br>[rpm] | BMEP<br>[bar] |
|-----------------|----------------|---------------|
| 1               | 1500           | 2             |
| 2               | 2000           | 5             |
| 3               | 2500           | 8             |

## TEST RESULTS

### FULL LOAD ENGINE PERFORMANCE

[Figure 2.a](#) shows the comparison of full load engine performance for the different fuel blends without any modification in ECU calibration; as expected, when fuelling the engine with RME and JME B30 blends a slight decrease ( $\sim 2\text{-}3\%$  on average) in the torque output can be observed over almost the entire speed range, due to the slightly lower LHV of the blends that cannot be compensated by the small increase in fuel density. From [Table 2](#) it can be noticed that neat RME and JME LHV are about 13% lower than diesel LHV, that means that with RME and JME B30 blends a 4% LHV loss should be expected. Moreover, because biofuel densities are 5% higher than diesel density and because neglecting the viscosity effects on the injection rate, the amount of fuel injected will scale as the square root of the pressure drop across the injector nozzle divided by the fuel density, the injected quantities with biofuel blends will be less than 1% higher than diesel, thus leading to an energy content introduced into the cylinder about 3% lower, which is in good agreement with the measured torque decrease, since the use of the biofuel blends does not change substantially the overall efficiency under full load operating conditions.

Finally, it should also be pointed out that smoke levels measured under both RME and JME B30 blends operations with standard calibration were significantly lower in comparison with diesel operation, showing average FSN reductions of about 0.4 with both blends.

[Figure 2.b](#) shows the results obtained with further full load tests, which were performed by increasing, at each revolution speed, the injected quantity up to reach the same torque or the same smoke level measured under diesel operation (whichever occurring first), so to more completely evaluate the performance potential of biodiesel blends. It should be noticed that the calibration adjustment allowed RME and JME B30 blends to fully recover the small performance gap previously highlighted, with even some performance benefit in the medium-low speed range. Moreover, it should also be

pointed out that, even after the calibration adjustment, smoke emissions were still appreciably lower in comparison with diesel values, with an average FSN difference of 0.25: further performance improvements could therefore be likely with biofuel blends, by modifying the engine calibration in order to obtain the same smoke levels measured under operation.

## PART LOAD ENGINE EMISSIONS

The experimental results obtained under part load operating conditions are shown in [Figures 3, 4, 5, 6](#) and [Figures 9, 10, 11](#), reporting respectively brake specific fuel consumption, engine fuel conversion efficiency, brake specific CO<sub>2</sub>, CO, HC and NO<sub>x</sub> emissions and smoke emissions. [Figures 7 and 8](#) depict the measured in-cylinder pressure and injector signal as well as the calculated heat release rate and the mass fraction burned during low load operation (2 [bar] BMEP) when the specifically adjusted ECU calibration was used. Brake specific fuel consumption shows a 4-5% average increase for both RME and JME B30 blends and for both the standard and specific ECU calibrations ([Figures 3.a and 3.b](#)), in good agreement with the 4% lower LHV of the fuel blends. Taking into account the slightly higher (+1.5%) density of the biodiesel blends, the volumetric fuel consumption increase with RME and JME B30 blends - which is the performance parameter perceived by the final user - would be reduced to a more acceptable value of 2.5-3.5%.

As expected from the previous BSFC analysis, fuel conversion efficiency ([Figures 4.a and 4.b](#)) does not show appreciable variations when switching from diesel fuel to RME and JME B30 blends for both the standard and specific ECU calibrations: in fact, under part load operating conditions, the closed-loop combustion control is capable of maintaining MFB50 at its optimum position, especially when the engine was operated in low load conditions, compensating for different fuel characteristics, such as for instance, the higher cetane number of JME B30 blend ([figures 7b and 8b](#)).

As far as CO<sub>2</sub> emissions are concerned, the lower carbon content of neat RME and JME allows to compensate for the higher fuel consumption measured under RME and JME B30 blends operation, thus significantly reducing the increase in CO<sub>2</sub> emissions levels that could be expected from BSFC data, as shown in [Figures 5.a and 5.b](#). As a result, from a pure Tank-To-Wheel approach, no substantial change in CO<sub>2</sub> emissions should be expected for RME and JME 30% vol. blends usage.

CO specific emissions ([Figure 6.a](#)) were comparable for both RME and JME B30 blends to diesel at medium-high loads, while an appreciable increase was measured at low loads (operating points at 2 [bar] BMEP), as already observed in previous works on neat biodiesel usage [[25, 26](#)]. Moreover,

no noticeable differences between standard and specific calibration can be noticed. The increase in CO emissions at low loads (which is accompanied by a corresponding increase in HC emissions as shown in [Figure 9](#)) could be attributed to a change in the combustion process, since the higher viscosity and the higher distillation temperatures of the biodiesel can lead to a substantial deterioration of the fuel atomization and vaporization [[2](#)], especially at low injection pressures and low in cylinder temperatures and pressures as for 2 [bar] BMEP operating points ([Figure 7a and 8a](#)). Moreover, the lower energy content of the biodiesel blends could also significantly affect the energy released by the pilot injection ([Figure 7b and 8b](#)), thus causing an increase of the premixed portion of the combustion, while at higher load this effect is usually not noticeable, as already observed in previous works on neat biodiesel usage [[25, 26](#)]. However, the analysis of the HRR profiles shown in [Figures 7a and 8a](#) does not show significant differences between different fuels, thus suggesting that the differences in the combustion process, although capable to produce appreciable changes in engine emissions, cannot be fully captured through the standard in-cylinder pressure analysis techniques.

As for CO emissions, an appreciable increase in HC specific emissions ([Figures 9.a and 9.b](#)) can be observed at low loads for both RME and JME B30 blends, while at medium-high loads HC emissions are comparable with diesel levels. Again, no noticeable differences between standard and specific calibration can be noticed.

NO<sub>x</sub> specific emissions measured under RME and JME B30 blends operation with standard calibration are reported in [Figure 10.a](#); at medium loads (5 [bar] BMEP) NO<sub>x</sub> emissions were comparable with diesel fuel, while a moderate increase can be observed at the highest load (8 [bar] BMEP), with a greater increase for JME B30 blend compared to RME 30% vol. blend. On the contrary, at low loads operating conditions (2 [bar] BMEP) NO<sub>x</sub> emissions were lower for RME and JME B30 blends respect to diesel fuel.

The moderate effect of fuel composition on NO<sub>x</sub> at medium loads could be expected since, if the pedal position change necessary to achieve the same BMEP target is small, and the EGR rate target is almost constant, the engine will be operated with closely comparable relative air/fuel ratios  $\lambda$  (and so with roughly the same oxygen availability and combustion temperatures). On the other hand, at higher loads, even a relatively small accelerator pedal position increase is likely to produce a reduction in the EGR rate target, thus leading to a noticeable NO<sub>x</sub> emissions increase with biofuels. Finally, at low loads the high EGR rate used is likely to