

## Optimization of a Euro 5 Vehicle Powered by an Ethanol Based Diesel Fuel

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### ABSTRACT

Diversifying energy resources and reducing greenhouse gas emissions are key priorities in the forthcoming years for the automotive industry. Currently, among the different solutions, sustainable biofuels are considered as one of the most attractive answer to these issues.

This paper deals with the vehicle application of an innovative Diesel fuel formulation using Ethanol to tackle these future challenges. The main goal is to better understand the impact of using biofuel blends on engine behavior, reliability and pollutants emissions. This alternative oxygenated fuel reduces dramatically particulate matter (PM) emissions; this paves the way to improve the NO<sub>x</sub>/PM/CO<sub>2</sub> trade-off. Another major interest is to avoid adding a particulate filter in the exhaust line and to avoid modifying powertrain and vehicle hardware and therefore to minimize the overall cost to fulfill upcoming emission regulations.

After a first part devoted to a description of the fuel properties, the paper focuses on some combustion analysis pointing out the effects of the new formulation. Then the fuel/engine compatibility and its optimization on a production turbocharged Diesel multi-cylinder engine with high pressure exhaust gas recirculation are investigated. Owing to advanced calibration methods such as design of experiments, new maps are provided to fully take advantage of the ethanol/diesel blend properties and to enhance the engine behavior. It leads to a simultaneous decrease of nitrogen oxides and particulate matter emissions with a potential CO<sub>2</sub> emissions reduction and combustion noise decrease. The main drawbacks could be an increase of unburned hydrocarbons and carbon monoxide emissions.

Furthermore, after having successfully validated the new settings on the test bench, some vehicle results on a chassis

dynamometer are presented on the New European Driving Cycle (NEDC) to illustrate the effectiveness of this innovative fuel formulation and the calibration adaptation. Finally the recalibrated vehicle, integrating only Euro 4-compliant technologies (not equipped with a Diesel particulate filter device), with this new fuel satisfies potentially Euro 5 emissions standards without sacrificing drivability and service life.

### INTRODUCTION

Increasing energy consumption and petroleum requirements for transportation and moving towards CO<sub>2</sub> emissions minimization opened up new research fields in alternative resources during the past years. Blends incorporating ethanol in Diesel fuel have been extensively presented to achieve sustainable mobility [1,2,3,4,5,6].

These environmentally friendly fuels allow a significant global greenhouse gas emissions reduction owing to the CO<sub>2</sub> absorption during the vegetable growth in the overall life cycle assessment of the vehicle. Another main benefit of oxygenated fuel is the large decrease of soot emissions [1,2,3,4,5,6,7,8,9] within the scope of more and more stringent emission regulations, especially for Diesel engine powered vehicles. Hence, due to an update of the engine calibration, it enables to enhance the NO<sub>x</sub> / Particulate Matter (PM) / CO<sub>2</sub> trade-off relationship, and to meet future standards such as Euro 5. This could be potentially performed without powertrain hardware modification of a Euro 4-compliant vehicle and without being equipped with a Diesel particulate filter. This recalibration of an existing vehicle using an innovative biofuel formulation is proposed as a solution to the compromise between cost and environmental issues in the forthcoming years. Therefore this paper deals with the fuel properties, its effects on the combustion in a Diesel engine and the update of the engine control settings on

the test bed and then validated on the New European Driving Cycle (NEDC) on a vehicle.

## BLEND PROPERTIES

Since the blend properties as well as the main issues have been extensively described in a previous paper [10] this point will be shortly introduced in this paragraph before presenting the adopted solution that have been tested.

When blending ethanol with Diesel fuel, the final fuel characteristics are drastically modified and have to be corrected. This is the case with the autoignition properties (Cetane Number), the lubricity (HFRR) and the flash point. Nevertheless prior to these main modifications, one major issue have to be addressed; it concerns the blend miscibility. It was decided to use Biodiesel, in this case vegetable oil methyl ester (VOME), as co-solvent. The final blend never shows any phase separation during months of testing.

Therefore, by introducing ethanol the cetane number drops significantly. The cetane number is then corrected by the use of synthetic fuel (synfuel) having very good autoignition properties. The synfuel can be replaced by a standard Diesel fuel. In this case the use of cetane improver is necessary. These two compounds are well known for their poor lubricity performance. The VOME, notwithstanding the fact that it prevents phase separation, brings positive lubricity performance without requiring additional lubricity improver. Thus these three compounds entering the final fuel formulation show very good synergy, allowing incorporating 20 up to 30 % of ethanol into the blend.

Regarding the flash point issue, which drops around 13°C as soon as ethanol is incorporated to Diesel fuel (Figure 1), it was chosen to challenge this issue by modifying the formulation. Usually this drawback is treated via hardware solution (dry-lock tank, etc.). The principle is to add a volatile hydrocarbon to the fuel blend, in order to produce an over-rich fuel/air mixture in the empty space that will not be ignitable when exposed to a potential ignition source.

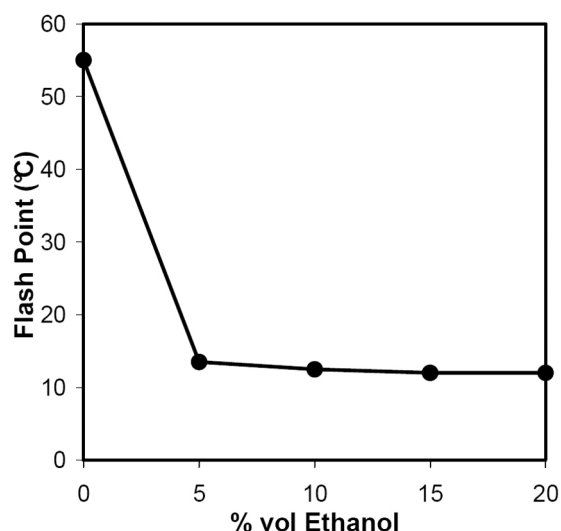


*Figure 1. Influence of ethanol ratio on the flash point for Ethanol-Diesel blends.*

Following is the [Table 1](#) presenting the main characteristics of the tested fuel and its main compounds.

(See [Table 1](#) after last section of paper.)

## EXPERIMENTAL APPARATUS

The experimental facilities used during this project are a dynamic test bed to perform steady-state tests as well as transient operations and a chassis dynamometer.

The engine test bed configuration is as close as possible to the vehicle one in order to be representative of the vehicle. The good representation of the reference vehicle speed tracking (operated by the driver during dynamometer testing) is one of the issues of reliable reproduction of vehicle behavior. Thus the simulation takes into account driver behavior, the road profile and the vehicle parameters. The integration of real time simulation in the test bed is then considered as a test platform “Hardware-in-the-Loop”, where a complex system of real and virtual components interact in real time. In this case the only hardware elements are the engine and its engine control unit. Hence the testing environment can be described as a “Engine-in-the-Loop”. The driver (simulated) manages the engine operation (real), via the accelerator pedal provided by the engine control (real). It supervises also the vehicle (simulated), via the clutch pedal, the brake and the gear box position. The vehicle model, based on the actions of the driver, is able to calculate the engine speed setpoint which permits to define the dynamometer machine load setpoint. Finally, the vehicle speed information allows the driver to adjust the engine load to follow a predefined road profile. [Figure 2](#) illustrates the dynamic test bed architecture.

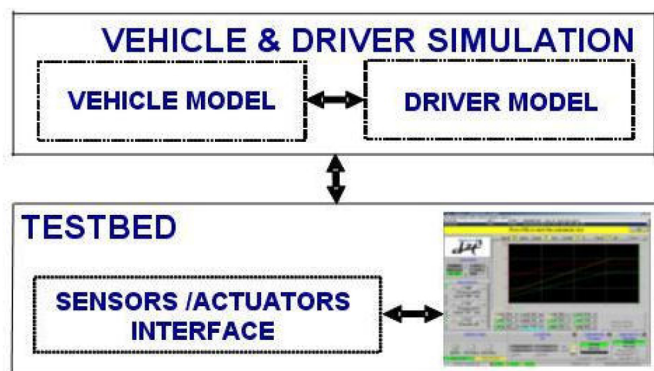


Figure 2. Dynamic test bed layout.

The fluid circuits definitions are key issues to ensure a good vehicle reproduction. Therefore an optimization of the coolant circuit for example has been carried out in order to achieve a similar behavior as shown in Fig. 3<sup>4</sup>. High test bed cooling possibilities (with added pumps and exchangers) allow completing fast cooling and soak and thus to perform higher numbers of cold cycles. Therefore, some hot and cold start NEDC cycles can be realized at the test bed to check performance of a new set of control parameters for example before implementing it on vehicle for validation.

Pollutants emissions are also representative of the vehicle as shown for CO<sub>2</sub> emissions in Figure 4. Main differences are due to the driver demand variations and exhaust gas analyzer dynamics difference between the two facilities.

(See Figure 3 after last section of paper.)

(See Figure 4 after last section of paper.)

The engine for both testing facilities is a turbocharged Diesel 1.6L 4-cylinder engine (DV6 from PSA Peugeot-Citroën). It is equipped with a second-generation common rail injection system. It has a high pressure cooled exhaust gas recycling circuit. The exhaust line has only a Diesel oxidation catalyst and it is not equipped with a Diesel particulate filter. The original vehicle meets Euro 4 regulation. The main specifications of the engine are given in Table 2.

The vehicle is a Citroën C4 vehicle without any hardware modification. Its inertia class for chassis dynamometer testing is set to 1360 kg.

Table 2. Specifications of the multi-cylinder Diesel engine.

|                        |                                                       |
|------------------------|-------------------------------------------------------|
| Type                   | PSA DV6 ATED4 – 4 cylinders<br>– 66kW – 90hp – Euro 4 |
| Bore                   | 75 mm                                                 |
| Stroke                 | 88.3 mm                                               |
| Compression ratio      | 18:1                                                  |
| Injection system       | Common rail Bosch                                     |
| After-treatment system | Oxidation catalyst                                    |

## FUEL FORMULATION EFFECTS ON COMBUSTION

The effects of such blends on the engine behavior have been deeply investigated and detailed in previous publication [11]. The main impacts on combustion to take into consideration are summarized hereafter.

First the autoignition properties are modified. Even with a global cetane number of the blend shifted up owing to the use of synfuel base, the low boiling point of the ethanol associated to its low cetane value and its strong latent heat of vaporization induces a longer autoignition delay by cooling down the medium in which the blend is injected. The consequences will be antagonist depending on the load of the operating point. These blend properties will also affect the HC emissions due to longer time let to the mixing process to occur.

Second, the high oxygen content of the blend improves the combustion speed during rich or over-rich combustion, but can also lead to an over-lean mixture at low load when global equivalence ratio is already low. In this case the strong latent heat of vaporization can be an added negative point leading to incomplete combustion, thus increasing HC and CO emissions.

Third, as expected, the high oxygen content allows decreasing soot emission. These emissions are also reduced due to less soot precursors (aromatics, naphthenes...) content and the more homogeneous combustion achieved.

All these impacts on combustion allow optimizing the engine settings to better phase the combustion. Increasing the start of injection lead to an increase in noise level. To manage this issue, the decrease of the injection pressure is necessary as well as the increase of the EGR rate. This allows improving the combustion efficiency as well as decreasing the NOx emissions. The HC and CO still remains an issue and should be manage by changing the injection scheme, number and

<sup>4</sup>The vertical red line in Figures 3, 4, 7 and 8 is a cursor indicating the value of the parameter which is plotted in the graph and this value is given in the text at the bottom.

characteristics (quantity and timing) of the injection [11]. It is noteworthy that each pollutant is very sensitive to engine parameter modification, and there are many interactions between parameters. Furthermore, behavior can be different depending on the operating points. It is then useful to optimize engine control maps with advanced calibration methods, as described in next section.

The effects of this alternative fuel on combustion are further analyzed at 2000 rpm and 4 bar of BMEP. [Figure 5](#) shows the results obtained without modifying the engine control parameters. The new blend increases the auto ignition delay. The ethanol based Diesel blend weakens the pilot combustion and therefore the pilot injection burns in the same time of the main injection. The increase of the auto ignition delay also promotes the premixed combustion. The combustion duration is also shortened. These results are also confirmed by previous references [9,12,13,14,15]. Consequently the maximum rate of heat release goes up and occurs later. Therefore there is a dramatic increase of the pressure gradient and higher combustion noise levels. It can be noticed that higher maximum combustion temperatures are also obtained. The higher latent heat of the alternative fuel leads to a slow vaporization and air/fuel mixing, and thus higher HC and CO emissions. The brake specific fuel consumption is also increased due to the lower density and lower calorific value of the biofuel. These fuel properties changes lead to an injection quantity variation required by the engine control, and then to an air mass flow setpoint variation (maps depend on injected quantity). The EGR rate drops off about 4 % and consequently NOx emissions increase. The oxygen content of the fuel enables near zero PM emissions.

Main results on this operating point are summarized in [Table 3](#).

(See [Figure 5](#) after last section of paper.)

Further analyses were performed to better understand combustion behavior with the new fuel, and find some guidelines to control parameter changes in order to optimize raw emissions, combustion noise level and fuel consumption. First an update of the fuel density in the engine control software is performed to counteract the fuel density and energy content impact on the injected quantity. Second some single parametric variations of rail pressure, injection timing, air mass flow, etc. were performed to assess the combustion behavior with the new fuel. It was decided to focus on the pilot combustion by varying the dwell time between the pilot and the main injections since the combustion seems very sensitive to this parameter with this kind of fuel as described in previous references [12, 14]. [Figure 6](#) and [Table 3](#) illustrate these tests at 2000 rpm and 4 bar of BMEP. Several dwell times are tested (with a reduction of 750  $\mu$ s until an increase of 500  $\mu$ s of this time). A case without pilot injection is also presented and compared to the original calibration strategy.

The pilot combustion occurs when it gets closer to the main injection due to better thermodynamic conditions to burn. Hence the maximum heat release rate drops, which leads to a decrease of the combustion noise of 5 dB. It is also noticed that HC and CO emissions also drop off more than 20 %. NOx and PM emissions are hardly affected. Similar results could be observed with a variation of the pilot quantity (from 0.8 mg/strk until 1.2 mg/strk); under a threshold (higher than with standard Diesel) the pilot combustion does not start burning before main injection.

(See [Figure 6](#) after last section of paper.)

(See [Table 3](#) after last section of paper.)

Several injection schemes are also studied to optimize the combustion process with this alternative blend : main injection alone, one pilot and main injections, two pilot and a main injections. At low loads and low engine speeds, multi-injection strategies enable to manage the combustion behavior more efficiently and to control the heat release rate in order to limit noise peaks and pollutants emissions, especially HC and CO. [Table 4](#) illustrates this statement at 1500 rpm, BMEP 3 bar since the two pilots and main injections scheme is interesting to drop the HC and CO emissions with a compromise with NOx emissions. PM emissions on this operating point are very low and soot emissions measurements are barely reliable in this area. At higher loads the benefits of several injections is less obvious and main injection strategy could be also used as shown in [Table 5](#) at 2750 rpm and BMEP 8 bar.

(See [Table 4](#) after last section of paper.)

(See [Table 5](#) after last section of paper.)

Beyond the PM emissions reduction due to the oxygenated content of this new fuel, these analyses lay down guidelines for recalibration and prove the potential benefits of updating the engine settings to improve the engine/fuel matching.

## ENHANCEMENT OF ENGINE/FUEL MATCHING

The effects of this innovative fuel formulation on the combustion are significant as explained previously and require a new calibration to fully take advantage of this blend on the NEDC.

The fuel change without any engine parameter modification on a transient test and even in steady-state conditions shows that for a similar driver demand (accelerator pedal demand), the required injected quantity is higher with the alternative fuel than with the standard Diesel fuel ([Fig. 7](#)), owing to the fuel energy content change. It leads to an increase of NOx emissions ([Table 6](#)) on the NEDC cycle due to the change of