

Alternative Diesel Fuels Effects on Combustion and Emissions of an Euro4 Automotive Diesel Engine

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ABSTRACT

The present paper describes the first results of a cooperative research project between GM Powertrain Europe and Istituto Motori of CNR aimed at studying the impact of Fatty-Acid Methyl Esters (FAME) and gas-to-liquid (GTL) fuel blends on the performance, emissions and fuel consumption of modern automotive diesel engines. The tests were performed on the architecture of GM 1.9L Euro4 diesel engine for passenger car application, both on optical single-cylinder and on production four-cylinder engines, sharing the same combustion system configuration.

Various blends of biodiesels as well as reference diesel fuel were tested. The experimental activity on the single-cylinder engine was devoted to an in-depth investigation of the combustion process and pollutant formation, by means of different optical diagnostics techniques, based on imaging multiwavelength spectroscopy. The tests on the multi-cylinder engine were done in a wide range of engine operation points for the complete characterization of the biodiesels performance in the new European driving cycle (NEDC).

The optical engine results have confirmed the good quality of spray formation of FAME fuels with engine and their capability to reduce soot formation, thanks to lack of precursors and oxygen in the fuel.

The four-cylinder engine results, besides validating single-cylinder outcomes, have also highlighted critical aspects on the interaction between the alternative fuel

characteristics and the engine-management strategies of electronically-controlled diesel engines.

INTRODUCTION

Even if the average CO₂ emissions of new passenger cars sold in EU were reduced by almost 16% between 1995 and 2008 to 157 gCO₂/km, further significant progress is needed in order to meet the EU mandatory target of 120 gCO₂/km by 2012. In particular, a bonus of 5 gCO₂/km is credited for cars able to run on biofuels blends of at least 7%_{VOL}. Such a bonus, in addition to specific policies at national level, is producing significant R&D efforts by manufacturers devoted to achieve compliancy and to investigate the benefits and challenges of higher biofuels blending rates.

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 1st 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 1st generation biofuels. On the contrary, 2nd 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 [1-3].

Within this framework, biofuel producers and OEMs are jointly devoting significant efforts in optimizing benefits from 1st generation biofuels while making 2nd 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. Moreover, as recently occurred for E-85 ethanol fuelling of SI engines, studies are ongoing in order to assess any potential advantages in diesel engine fuelling with high biodiesel blending.

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 thermo-chemical process involving methanol (transesterification) that features both high energy conversion efficiency and fuel yield from processed oil, and it is the main responsible for the overall GHG emissions benefit of biodiesel in WTW analyses [4].

More recently, starting from the well-known Fischer-Tropsch synthesis process, which is 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 fuel was developed. 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 important difference between 1st and 2nd generations of biodiesel lies in their chemical composition, the 1st generation being essentially a blend of methyl-esters and the 2nd of paraffin and olefin hydrocarbons.

Due to the production process, the methyl-ester speciation of 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 being 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. The European Union is currently the World's largest producer of biodiesel, even if in the Asia-Pacific region its market penetration is growing at the fastest pace thanks to specific national policies in India, China and Thailand. 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.

Given the above described framework, the research work described in the present paper is part of a wider study that involves both fuel injection and cold spray bomb investigations as well as single- and multi-cylinder assessment of the impact on engine behavior of three different types of alternative diesel fuels: two FAMES and one FT fuel. Being General Motors one of the largest producers of diesel engines for passenger cars and light-trucks application in EU, Asia-Pacific and US markets, it was considered of high importance within the present project the test of both the 1st generation biodiesels from different sources representative of those regions as well as the 2nd generation ones. Rapeseed- and palm-oil-based methyl-ester (RME) was selected from EU and Asia-Pacific regions, whereas soybean methyl-ester (SME) for North American market. Finally, 2nd 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 work has been carried out by Istituto Motori Napoli - CNR in cooperation with GM Powertrain with the following main goals:

- to decouple the biodiesel impact on the various thermodynamic processes over the engine cycle: injection, spray formation and fuel evaporation, fuel mixing with air/EGR (exhaust gas recirculation), ignition and combustion, pollutant formation;
- to identify the influences of biodiesel fuelling on control strategies and calibrations embedded in last-generation torque-controlled diesel engines;

In addition to the engine cold startability and oil dilution concerns, 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 last generation of electronically controlled diesel engines [5-9].

In a previous paper [10] the main results about injection and cold spray bomb studies were reported, and the effects of both the biodiesel density and viscosity on injection pattern and spray formation phenomena were analyzed. The outcomes clearly support the conclusion that the variations in performance and emissions, measured on the multi-cylinder engine with the same fuel

blends, 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.

The present paper, therefore, completes and integrates the studies in [10] with the results in firing conditions.

THE FUELS

Appendix 1 reports, for the specific fuels and their blends used in the present investigation, 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) and the selected blends were X10, X30, X50 and X100, where X denotes the specific source (GTL, RME and SME) and the number indicates the percentage of alternative fuel volume in the blend (100% meaning the pure biofuel).

In particular, it is evident that RME and SME have higher density and viscosity than the reference fuel, which, coupled with distillation curves stretched in the temperature intervals corresponding to the tail of conventional diesel (see Diagrams A, B, C 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 FAME fuelling, owing to increase 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 with blending, as RME and SME increasingly show their nature of essentially pure compounds (see their flat distillation curves). 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

MULTI-CYLINDER ENGINE

The production four-cylinder in-line engine employed in the project was the GM Powertrain Euro4 diesel engine whose main characteristics are reported in Table 1.

Engine type	4 cylinders in-line
Bore x Stroke [mm]	82.0 x 90.4
Displacement [cm ³]	1910
Compression Ratio	17.5
Valves per cylinder	4
Rated power and torque	110kW @ 4000rpm 320Nm @ 2000rpm
Injection system	Bosch Common Rail EDC16
Injector and nozzle	Solenoid CRI 2.2+, 7 holes, 440cc/30s @ 100bar
Turbocharger	Garrett single stage VGT
Swirl control	Rotary flap on secondary duct
Catalyst system	Closed-couple DOC

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

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 the diesel oxidation catalyst by means of a raw emission analysis test bench (AVL-CEB-2).

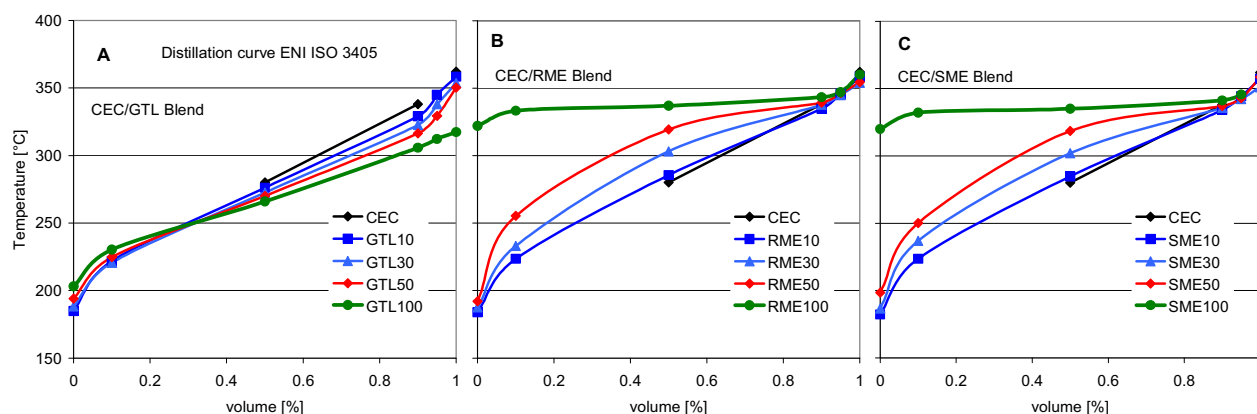


Figure 1: Distillation curves for CEC/GTL blends (A), CEC/RME blends (B), CEC/SME blends (C).

The fuel matrix was tested in the four-cylinder engine in eight steady-state operating 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 8th test point was devoted to the characterization of the performance behaviour. The selected test points are summarized in Figure 2, where the operating area of the engine running on NEDC is also displayed. The measurements in the seven test points enabled the NEDC engine performance estimation for all fuel blends using a well consolidated correlation procedure between the emission at steady state test engine with vehicle emissions on the chassis dynamometer.

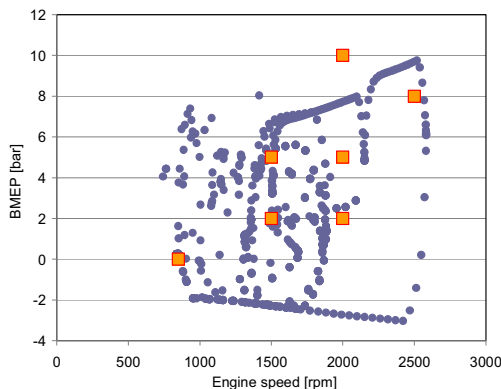


Figure 2: Test points together with the speed/load trace of the engine over NEDC for a D-class vehicle.

For each test point it was adopted a conventional Pilot + Main injection strategy. In order to have the same torque it was necessary to change the accelerator pedal position as the biofuel has a different LHV, then all control variable values (rail pressure, boost pressure, etc...) change. This effect is negligible at low speed and torque but become more and more relevant at increasing of injected fuel quantity, as it will be shown later.

OPTICAL SINGLE-CYLINDER ENGINE

The optical single-cylinder (SC) engine used for combustion diagnostics was equipped with same combustion system architecture and injection system of the four-cylinder production engine. The scheme of the engine and the experimental apparatus is shown in Figure 3.

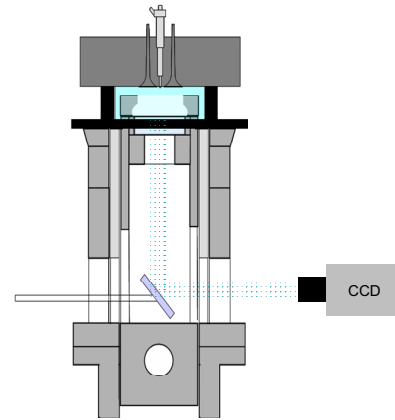


Figure 3: Optical SC engine experimental setup

Even its instrumentation is the same as the four-cylinder engine. The optical engine utilizes a conventionally extended piston with a piston crown window of 46 mm diameter which provides full view of the combustion bowl by locating an appropriate 45° UV-visible fixed mirror inside the extended piston. The window has been made of UV-grade fused silica. To compensate for the slightly lower compression ratio typical of the optical engines and to match the in-cylinder conditions of the multi-cylinder engine tests, an external air compressor has been used to supply pressurized intake air that was well filtered, dehumidified, and preheated. Moreover, a cooled EGR system has been used, and a pressure valve has been set in the exhaust pipe in order to ensure the correct operation of the burned gas recirculation system. Finally the optical SC engine ran in continuous mode. More details about the specifications of the engine are reported in [11].

Digital imaging analysis was performed by a CCD camera through the 45° mirror. The CCD camera with 640 x 480 pixels and a high sensitivity over a wide visible range was used in order to acquire the visible combustion. Through an appropriate filter selecting fixed wavelengths in the visible range, it was possible to determine the soot temperature and concentration by the two-color pyrometry technique [12]. Moreover, a gated intensified CCD (ICCD) camera having 512 x 512 pixels of 24x24 μm^2 area and high sensitivity in the UV-Visible range was used with "ad hoc" filter. The cameras were synchronized with the engine by means of a delay unit and the exposure time was set to 55 microseconds that corresponds to 0.5° crank angle at 1500rpm and at 0.67° crank angle at 2000rpm, respectively.

The OH spatial distribution and temporal evolution were investigated by means of the band pass filter at 310nm wavelength with a band width of +/- 5nm. This radical is characteristic of the autoignition and soot oxidation during the combustion process [11, 13]. Finally the knowledge of the pressure and temperature values at different crank angles allowed the calculation of the right values of OH concentration [14, 15].

RESULTS

FOUR-CYLINDER ENGINE TESTS AT FULL LOAD AND WITH EGR TRADE-OFF

Tests at full load

The evaluation of the alternative fuels impact on engine performance was carried out at 2500rpm, full load. This point was specifically chosen in order to decouple any effects due to the turbocharger, since the boost margin over nominal requirement peaks in this point. The diagrams A, B and C in Figure 4 report the comparison of the maximum torque attained by all fuel blends, the maximum torque versus the blend heat content and the fuel consumption (FC) versus the fuel blending ratio,

respectively. The variation is expressed as a percentage with respect to the CEC fuel assumed as 100%.

From the analysis of the figures 4A and 4B (max torque variation), the link between maximum attainable torque and the blend LHV is apparent. However, by looking at the curves of RME and SME, it emerges that for about the same LHV (the difference is only 0.3% for the pure fuel), SME gave a torque output of about 1% less than RME (diagram 4B). The result was confirmed also from the cylinder pressure measurement that showed a different value of indicative mean effective pressure (IMEP) between RME and SME, as reported in Figure 5.

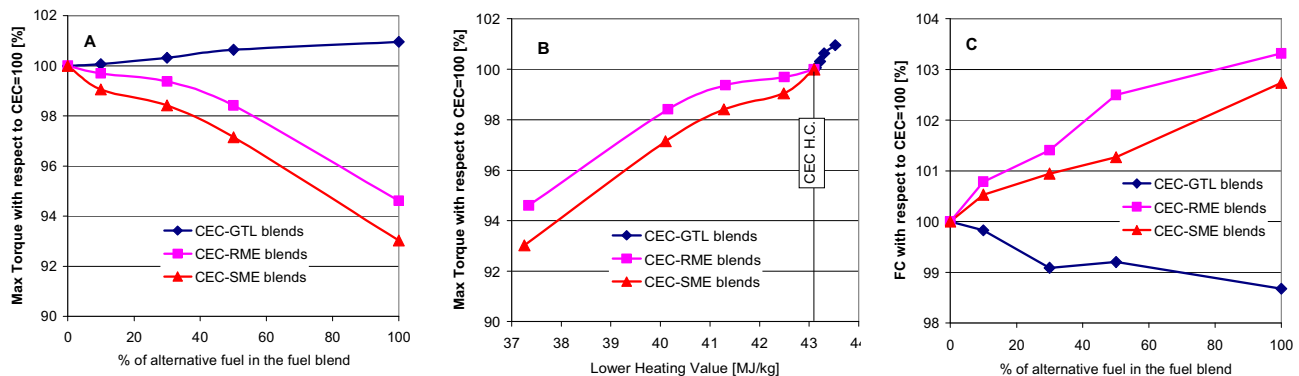


Figure 4: Maximum engine torque variation at 2500rpm [%] with respect to the CEC = 100% vs fuel blending ratio (A) and blend heat content (B); FC variation vs fuel blending ratio (C).

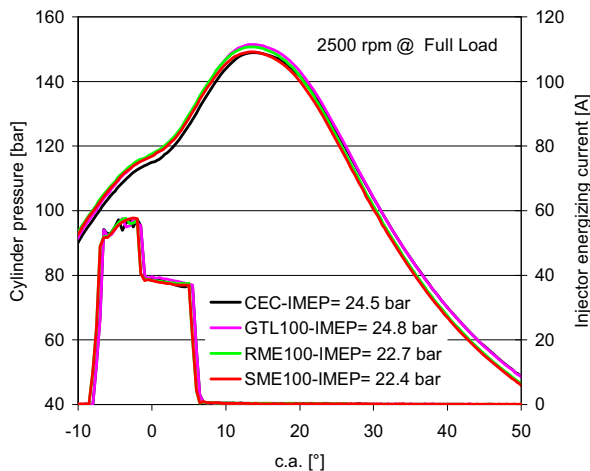


Figure 5: Cylinder pressure trace and injector energizing current for all pure fuels at 2500rpm and full load.

Figure 5 reports the measured cylinder pressure and injector energizing current traces only for the pure fuels (CEC, GTL, RME and SME). All injection parameters were equal for all fuels and also the injection volume

estimated by the PECU was constant for all tests. It is evident that the slight lower IMEP value of SME with respect to RME is linked with the lower pressure trace in the expansion stroke. On the contrary, GTL shows the highest pressure peak and trace in the expansion stroke, correspondent to the maximum IMEP value.

Full load results were also correlated with the injected fuel mass for each blend. The diagram 4C shows the obtained trends. Due to the lower density of the GTL, the injected mass slightly reduced as GTL fraction in the blend was increased, but thanks to its higher LHV and good combustion characteristics the net impact on the rated torque was positive. On the contrary, both RME and SME increased their fuelling with respect to CEC diesel, with RME consistently higher than SME. It is interesting to note that, while from the analysis of the fuel properties matrix in Appendix 1 it is possible to understand the increased fuelling with respect to CEC fuel, it is difficult to explain the difference between RME and SME, which show same viscosity and density at reference conditions. The authors argue that the observed results could stem from the actual fuel properties (e.g. viscosity or compressibility) that RME and SME have at full load engine working conditions with respect to the ones measured at more moderate

reference conditions. In the future, more specific investigations should be addressed to this.

Notwithstanding the detected torque penalty with FAME fuels, they tend to increase the fuel conversion efficiency (FCE), as demonstrated by the Figure 6. In the diagram also the GTL blends are reported showing better values than CEC but still lower than FAME. The highest FCE results for RME and SME at full load could be linked with the fuel oxygen content that at this engine condition promote the combustion efficiency. These results were in agreement with other results reported in the literature and performed on the EURO2 version of the 1.9L common rail diesel engine with 2-valves per cylinder and similar combustion architecture [18].

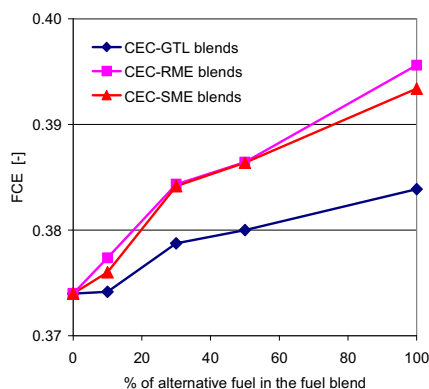


Figure 6: FCE at 2500rpm and full load vs the alternative fuel fraction in the blend.

Concerning GTL fuelling, its improved FCE with respect to CEC diesel could be linked to the more favourable 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, as detected in Figure 5

Trade-off versus λ at 1500rpm and 2bar BMEP

For the three most significant key-points of the overall set (i.e., 1500rpm x 2bar brake mean effective pressure - BMEP, 2000rpm x 5bar BMEP and 2500rpm x 8bar BMEP), pure alternative fuels were characterized by means of EGR sweeps. In particular, taking into consideration the pollutant species for emission target compliancy, the relevant trade-offs NOx-PM, or NOx-CO (this latter only at low speed/low load, where smoke emissions are negligible and sometimes almost insensitive to EGR rate variations) were analyzed. By performing EGR sweeps and comparing the resulting

trade-off curves, it is possible to reduce the effects of test-to-test variations in EGR rate as well as highlighting the PM/CO tendency versus λ of the fuels.

Figure 7 shows the trends of the engine efficiency parameters and the pollutant emissions of all pure fuels in the operating point 1500rpm and 2bar of BMEP.

As can be noted, the GTL fuel and the two FAME show opposite trends with respect to the reference fuel in the trade-off CO-NOx. At the same lambda values, RME and SME produce always higher CO emission than CEC, on the contrary GTL produces less CO. Looking at the initial point (at the right side) of the NOx-CO trade-off, corresponding to the condition without EGR, it is possible to note that GTL gives the highest NOx emissions, while both RME and SME produce lower NOx than CEC. For the present and followed showed trade-off plots the right start point is referred to the condition EGR=0. The showed trends can be understood referring to the combustion evolution plotted in Figure 8.

In particular, in Figure 8, the cylinder pressure traces, together with the corresponding rate of heat release (ROHR) curves, are reported for all pure fuels at 1500rpm and 2bar of BMEP and a λ value of 2.5. From the ROHR analysis, it emerges that GTL shows a pilot combustion closer to TDC because its higher CN, as a consequence at fixed lambda the NOx emission formation increase. Moreover, it is possible to observe that the two biodiesels show the lowest pilot combustion heat release.

These aspects influence the ignition delay time of the subsequent main injection and its combustion evolution and in turn, the unburned compound emissions.

Three main fuel properties can affect the spray formation and the fuel ignition behaviour characterizing Figure 8: the viscosity, the boiling curve and the cetane number (CN). Burning the pure GTL, characterized by a lower boiling curve and a lower viscosity, the pilot injection promotes mixing with air, on the other hand, the higher CN tends to reduce the overmixture of the injected fuel, the final result is a combustion efficiency higher than CEC as appear in the ROHR trace of pilot combustion, Figure 8. The ignition delay time of 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. Very similar results were found by Schaberg *et al.* in [19]. All these effects tend to reduce CO emissions.