Analysis of engine control parameters effect to minimize GHG emissions in a dual fuel NG/Diesel light duty engine

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Abstract
In the present work, a 2.0L Euro 5 compliant diesel engine, equipped with an advanced electronic combustion control system, has been set up to operate in Dual Fuel (DF) Diesel- Natural Gas (NG) DF mode. An experimental campaign has been devoted to the engine optimization, in order to assess the achievable reduction of unburned hydrocarbon emissions, keeping the peculiar benefits of DF combustion.
A thorough analysis of the effects of many engine control parameters (e.g. NG substitution ratio, diesel pilot injection strategies, EGR, *etc.*) on DF engine performance was performed. Combustion timing and EGR- displayed a strong potential on Total Hydro-Carbon (THC) emissions control (represented for more than 90% by CH_4), exhibiting wider margins of engine recalibration, in comparison with the use of a standard Diesel calibration also in DF mode.

Introduction
The use of natural gas (NG) as fuel for internal combustion engines traces back to 30s [1] and the interest in its adoption is still increasing, due to well-known reasons, mainly linked to the environmental benefits in terms of particulate and carbon dioxide emissions reduction, to the availability of NG resources and in view of a desirable energy sources diversification [2]. In this respect, the Diesel-NG Dual Fuel (DF) concept can represent an opportunity to extend the NG use to Diesel architectures in the passenger cars' sector [3].
The DF combustion concept foresees the contemporary use of NG (or alternative high octane index fuels like biogas, ethanol, gasoline etc.) and Diesel fuel. The last one should be used to ignite NG, which would not burn spontaneously in absence of an ignition source. The most common solution consists in a port fuel injection (PFI) of NG, as easily adoptable for aftermarket Diesel engine modifications. In some cases, DF concept has proven to be not only viable, but also industrially appealing, as HD engines (e.g. trucks and buses) in DF version are effectively produced by manufacturers [2], applied to various engine classes, architectures and fuels combinations.
In this framework, a general agreement appears to be reached on the DF concept applicability to CI engines and the generic potential of this combustion mode for CO_2, NOx and soot reduction. On the other hand, the release of high amounts of

unburned methane, mainly at low engine loads, with correlated efficiency issues, is still widely recognized as an important limit for its practical application to light duty engines. Moreover, it turned out that, at low engine load, the extent of Diesel substitution is limited, due to unacceptably high methane emission levels [4].
Goal of the present paper was to assess the effect of critical engine parameters and evaluate the potentiality of a proper engine calibration in GHGs reduction, for a practical application of the DF concept to an existing Diesel architecture. In other words, the main scope of the parametric study was to minimize unburned gaseous, keeping the typical advantages of DF configuration in terms of CO_2, PM and NOx reduction.
A multi-cylinder automotive Diesel engine, Euro5 compliant, and equipped with an advanced electronic control system, named CLCC (Closed Loop Combustion Control), able to automatically adapt combustion phasing and engine torque to target values, was suitably modified to work in DF mode with NG PFI system. The considered architecture can be considered as representative of a significant share of the current EU fleet. The use of the CLCC system implies that the modification of a single parameter can determine the contemporary automatic adjustment of other parameters, to guarantee a prescribed target of engine torque and combustion phasing. This approach allows performing a consistent comparison among the various tested conditions, always keeping fixed the engine operating point. So, it is possible to evaluate the actual response of a real system to the parameterization, thus quantifying the attainable potentialities of a subsequent engine recalibration in terms of DF combustion optimization.

Methodology

The research activity started with a first engine characterization in transient operative condition, with a flat DF calibration map at constant energy substitution ratio (SRe) of 50% (except at idle), whose results have been published in [5]. This first calibration was chosen to carry out a “picture” of the engine behavior in DF mode during the NEDC homologation cycles. Then the experimental campaign addressed the analysis of the engine performance and emissions in steady-state conditions, varying the NG substitution ratio, trying to achieve the maximum gas substitution without the onset of critical functional conditions (mainly in terms of excessive THC emissions). In that paper, it was highlighted the potentialities and issues related to the DF application to a Euro 5 nominal diesel calibration, keeping the same values of all the engine control parameters apart from the gas substitution.
The present work describes the subsequent phase of the research, in which the engine response to crucial calibration parameters has been investigated, carrying out the identification and quantification of the potentialities of these parameters in the exploitation of DF benefits, in view of an optimized DF calibration.
The work was split in two phases. The first regarded the analysis of the SRe variation effects on engine performance and emissions, to obtain an optimal NG injection map. To this aim, the methodology, summarized in the next, was

followed.

An experimental campaign was designed to identify the emissions and engine performance trends, varying the SRe within a predefined domain.

A data fitting procedure allowed modeling every detected trend by means of 2nd order polynomials for each engine Operating Point (OP), thus obtaining the engine "surface response" to SRe variation.

A consolidated estimation procedure [6] was adopted to predict the engine behavior over the homologation driving cycle (NEDC), starting from emissions and performance values, for each OP, resulting from the implemented engine model.

Solving a multi-objective optimization problem, the optimal map of gas substitution ratio was identified, among various SRe combinations. The target was to minimize THC emissions, preserving the benefits of DF configuration in terms of CO_2, NOx, PM emissions, combustion efficiency and noise, at most matching the correspondent values of the conventional diesel mode.

In the second research phase, once fixed the optimized SRe values for each OP, the effects of other fundamental engine calibration parameters on DF combustion were analyzed. In the present study, the percentage of the premixed NG was quantified on an energy basis (SRe) according to the following formula:

$$SRe = \frac{m_{NG} \cdot LHV_{NG}}{m_{NG} \cdot LHV_{NG} + m_d \cdot LHV_d} \cdot 100\ [\%] \qquad (1)$$

Where m_{NG} and m_d are the mass flow rates of NG and diesel fuel, while LHV_{NG} and LHV_d represent the lower heating values of NG and diesel fuel, respectively.

Experimental Set Up

The engine employed in the experimental activity was a Euro 5 four-cylinder 2L diesel engine equipped with a close coupled DOC+DPF, whose characteristics are reported in [5]. The engine is equipped with pressure sensor glow plug from BERU. The engine Electronic Control Unit (ECU) is able to automatically adapt cylinder per cylinder and cycle per cycle the desired targets of 50% of the fuel mass burnt (MBF50%) and of the Indicated Mean Effective Pressure (IMEP), by the direct control of the Start Of main Injection (SOImain) and main injection Energizing Time (ETmain) [5].

The engine was coupled with a variable frequency fast response dynamometer and fully instrumented for emission analysis of the gaseous species (CO2, CO, THC, CH4, O_2 and NOx) and the particulate (mass of dry soot and mass of particulate) [5]. The engine was properly adapted in DF configuration, by means of an automotive NG Port Fuel Injection (PFI) retrofit system.

Results and discussion

Phase 1: Engine response vs SRe and SRe map optimization

In order to define a more suitable SRe map in the whole engine working area, the engine response to different SRe values was investigated. Six steady-state OP,

selected as the most representative of the engine behavior during the European homologation cycle (NEDC), were tested. The engine speed and load (rpm x bar BMEP) will be used in the text to schematically denote the tested engine points, as follow: 1500x2, 1500x5, 2000x2, 2000x5, 2000x10, 2500x8.
The choice of the SRe values domain was done on the basis of the previous results [5], which have clearly shown the upper limit of SRe in terms of engine emissions and performance. Then a proper SRe parametrization was performed in order to find the optimal value in each OP. At 1500x2 and 2000x2 test points, unacceptable CH_4 emissions were observed for SRe values higher than 40-45%, so no further SRe increment was possible. Then, the analysis of the engine behavior varying the SRe, will refer only to the four test points 1500x5, 2000x5, 2000x10, and 2500x8.
The best set of SRe values, for each OP, were obtained solving the multi-objective scalar problem, capable of providing the optimized combination, giving lowest THC and CO2 emissions levels, without penalties in NOx and PM emissions. In this way, the optimized SRe map for the whole engine working area was identified.
Table 1 reports the SRe optimal values selected for the six operative conditions. As expected, high SRe levels could be only achieved at high engine load, while at low and medium engine load it was not possible to exceed, within the prescribed constraints, values around 40% and 65% respectively.

Table 1. SRe optimized values at different operative points.

	1500	1500	2000	2000	2000	2500
SRe [%]	**39**	**66**	**40**	**63**	**82**	**68**

Phase 2: Engine response vs SRe and SRe map optimization
Once fixed the optimized SRe map, a pre-screening of the DF engine behavior varying some ECU Diesel parameters was performed, in order to identify the most effective ones in terms of DF configuration optimization. Their effect is discussed in the present section in the following order:

1. MBF50 - Engine combustion phasing, in terms of crank angle degree corresponding to the 50% of the fuel mass burned fraction;
2. Qpil - Diesel quantity of pilot injection, in a Pilot+Main pattern;
3. Prail - Diesel injection pressure;
4. DT - Dwell time between pilot and main Diesel injection event;
5. EGR - Exhaust gas recirculation rate.

The preliminary investigation highlighted that other controlling parameters (like air swirl ratio, air boost pressure, *etc*.) display a minor effect on the DF engine behavior, therefore, their effects are not reported here.
The optimization of DF configuration at high load appears less critical, due to the possibility to employ high SRe levels without excessive penalty in THC emissions. For this reason, the present analysis is focused on the OP namely 1500x2, 1500x5, 2000x2 and 2000x5.
A complete characterization has been carried out in terms of combustion analysis,

engine performance, fuel consumption and emissions. For sake of brevity, in the following sections the effects of MBF50 and EGR on THC emission are analyzed, resulted as the most meaningful parameters.

MBF50%

On the left plot of Figure 1, the engine out THC emissions over the MBF50 sweep. The higher slope of the curves clearly shows that the MBF50 has a higher influence on THC emissions at low loads. Conversely, at 1500x5 and 2000x5, the trends are less pronounced, so evidencing that MBF50 phasing is a less effective way to reduce THC. As visible in the plot on the right of Figure 5, reporting the measured pressure profiles (Pcyl) and the rate of the heat release (R.o.H.R.) at 1500x2 and 1500x5 over the MBF50% sweep, the combustion event occurs at higher pressure levels and high cylinder temperatures, enhancing the CH4 post-oxidation.

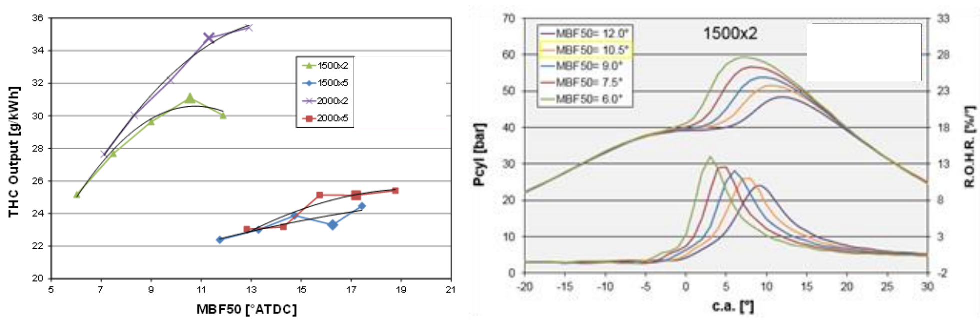

Figure 1. THC vs MBF50 at 1500x2, 1500x5, 2000x2 and 2000x5, on the left. Cylinder pressure and RoHR vs MBF50 at 1500x2.

EGR

Figure 2 reports THC versus EGR sweep for all OPs: as evident, a significant abatement of THC emissions occurred increasing EGR, in all Ops, more marked at low loads. Such result has to be partly ascribed to the lower exhaust flow rate corresponding to the increased EGR, an analogous trend was maintained in terms of raw ppm THC values too.

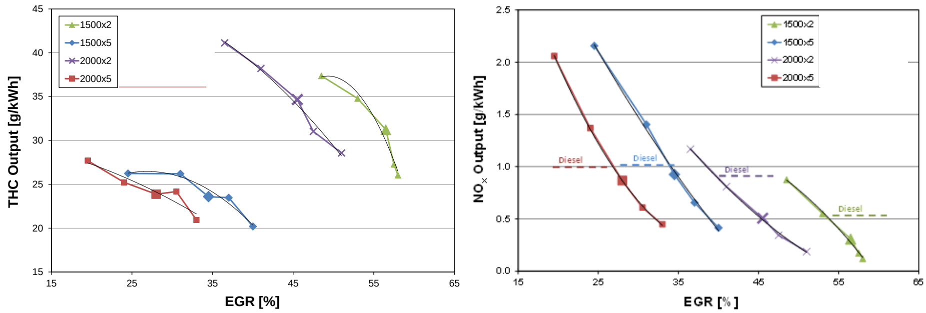

Figure 2. THC vs EGR at 1500x2, 1500x5, 2000x2 and 2000x5, on the left. NOx vs EGR at same OPs, on the right.

According to the CLCC strategy, keeping fixed the MBF50, the SOI_{main} and SOI_{pil} events were advanced as EGR was increased, determining a combustion process at higher cylinder thermodynamic temperatures and a longer premixing phase of diesel fuel in the methane-air charge. Such effects promote a better oxidation of the premixed air-CH4 charge. The expected benefits of EGR on NOx emissions can be observed in the right plot of Figure 2. At the highest EGR level, Euro 6 level were approached without the use of an after-treatment system, and also soot emission were well below the correspondent Diesel one.

Summary

The present study evidenced that the optimization of the DF engine calibration offers a wide margin for THC control. The benefits on THC emissions can be obtained without detrimental effects on the overall engine performance and the other regulated pollutant emissions. It is worth to highlight that, in view of a general GHGs emission reduction, the presented investigation showed how the mentioned advantages on exhaust methane can be reached keeping the typical DF benefits on CO_2. Among the investigated parameters, MBF50 and EGR displayed a very strong potential. The observed tendencies suggest the possibility to combine these parameters, to contemporarily mitigate THC and NOx emissions.

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