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Preliminary optimization of the PCCI combustion mode in a diesel engine through a design of experiments

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Abstract

A premixed-charged compression ignition (PCCI) combustion mode has been applied to a Euro VI heavy-duty production engine to simultaneously diminish particulate matter and nitrogen oxide exhaust emissions. The considered methodology exploits statistical techniques to efficiently plan tests, analyze acquired data and provide cause-and-effect relationships about the observed phenomena. Regression models were designed to predict the desired outputs as functions of selected inputs. The model-based optimal calibration of the PCCI combustion led to a reduction of up to 90% in NO_x and 99% in soot emissions, along with a fuel penalty of 9-13%, and an excessive increase in HC and CO.

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Keywords: premixed-charged compression ignition (PCCI) ; diesel advanced combustion; design of experiments; model-based optimization.

1. Introduction

Increasingly stringent regulations concerning pollutant emissions and fuel consumption have stimulated the exploration of new internal combustion engine development strategies in recent years. In particular, as far as diesel engines are concerned, lowering particulate matter (PM) and nitrogen oxide (NO_x) exhaust emissions has long been a challenge, and still remains a major issue [1]. After-treatment technologies, such as selective catalytic reduction devices, lean NO_x traps and diesel particulate filters, have proven to be effective for the abatement of NO_x and soot emissions, but durability issues, high economic costs and fuel consumption penalties still represent serious

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drawbacks. Therefore, in-cylinder advanced combustion strategies have been widely investigated, with the aim of simultaneously reducing engine-out NO_x and soot emissions, thus minimizing, or even avoiding, the need for the employment of the above mentioned after-treatment technologies [2].

Premixed charge compression ignition (PCCI), which can be achieved by using large amounts of exhaust gas recirculation (EGR), and advanced or retarded fuel injection timing [2-8], can be considered a promising alternative combustion strategy. Under these working conditions, the combustion process and the mechanism of pollutant formation differ significantly from those of conventional diesel combustion. The combined effect of advancing or retarding fuel injections and using high EGR rates (which reduce the oxygen concentration of the intake charge) leads to a slower pre-ignition chemistry, and to a higher ignition delay. This in turn allows a better pre-combustion mixing than conventional diesel combustion [3], hence the formation of rich mixture pockets within the cylinder is avoided, which is the main cause of soot generation [9]. Moreover, high EGR rates diminish flame combustion temperatures, and thus lower NO_x emissions [2, 9]. On the other hand, due to heavily reduced oxygen content, low combustion temperatures and early injections, the formation of incomplete combustion products, such as carbon monoxide (CO) and unburned hydrocarbons (HC), can be significant, and can require a higher conversion efficiency of the diesel oxidation catalyst [10]. Penalties in fuel consumption have also been observed [9]. In addition, due to sharp rises in the in-cylinder pressure, high noise levels are generally related to PCCI combustion [11].

In this work, a PCCI combustion mode, featuring a single "early injection" strategy, has been applied to a four-cylinder, four-stroke 3.0-liter Euro VI heavy-duty production engine, made by FPT Industrial. Statistical design of experiments (DoE) techniques have been used to find the optimal calibrations. For the sake of conciseness, only the results relative to one engine working point, namely the one at engine speed n = 1800 rpm and brake mean effective pressure bmep = 1 bar, will be presented.

2. Experimental Setup

The experimental activity has been performed at the highly-dynamic test bed installed at the Politecnico di Torino Internal Combustion Engines Advanced Laboratory, equipped with an 'AVL APA 100' AC dynamometer, an 'AVL KMA 4000' system, to measure the fuel consumption, and an 'AVL AMAi60', which simultaneously measures THC/CH_4, NO_x/NO, CO/CO_2 and O_2 concentrations in the intake and exhaust manifolds. An 'AVL 415S' smokemeter is used to measure the soot.

The test engine (ref. Table 1), equipped with a single-stage variable geometry turbocharger, a high-pressure common-rail injection system and a short-route cooled EGR system, has been designed to run under conventional diesel combustion mode. As a consequence, the desired PCCI combustion mode can only be implemented for quite low loads, and for low to medium rotational speeds. The engine is fully instrumented with low-frequency piezoresistive pressure transducers and thermocouples, as well as four high-frequency in-cylinder piezoelectric transducers. All of the measurement devices are controlled by Puma Open software and Indicom automation systems.

3. Model-based calibration methodology

The increasing complexity of the phenomena involved in engine technology makes the task of optimal calibration complex and challenging. As a result, there is growing interest in model-based approaches, in which design of experiments, statistical modeling and optimization techniques are employed, as these can simplify and efficiently produce high quality engine calibrations [12].

Nomenclature

aTDC	after top dead centre	DoE	design of experiment
bmep	brake mean effective pressure	EGR	exhaust gas recirculation
bsfc	brake specific fuel consumption	MFB50	50% of mass fraction burned
bTDC	before top dead centre	n	engine speed
°CA	crank angle degree	PCCI	premixed charge compression ignition
CN	combustion noise	SOI	start of injection

Table 1. Main specifications of the test engine.

Engine type	3.0L Euro VI 16V
Displacement	2998 cm^3
Bore / stroke	95.8 mm / 104 mm
Connecting rod	158 mm
Compression ratio	17.5
Valves per cylinder	4
Turbocharger	Single-stage variable geometry turbocharger
Fuel injection system	Common Rail, solenoid injectors

Experiments can be expensive and time consuming, and DoE has been found to be an efficient technique that can significantly reduce the necessary quantity of empirical data collected at the test bench. In this technique, experiments are expressed in terms of 'factors', which are the independent input variables that are varied at each test point in order to understand the effect on the dependent parameters, which are referred to as 'responses' [13]. After the selection of the factors of greatest influence based on the physical knowledge of the system under investigation, specific values, or 'levels', have to be determined, in order to specify a 'level-combination' for each test [14]. Different kinds of designs can be applied when DoE is adopted: classical (including full factorial, central composite designs, etc.), space-filling, and computer-generated optimal designs [14]. The tests obtained with DoE can be analyzed and can provide accurate data to create the statistical models that relate the experimental input factors to the measured response outcomes [15]. One of the most adopted fitting methods is the Response Surface Methodology, which generally uses second-order polynomial equations as response surface approximating functions, and least squares regression analysis as a fitting method [13].

If the resulting regression models show a good fit (a correlation coefficient close to one), they can be used to generate an optimal calibration. Optimization techniques can then be applied to establish how to set input values in order to obtain the desired outputs within a feasible range which satisfy the optimality criteria [9, 10].

4. Preliminary experimental analysis on PCCI combustion

A preliminary test activity has been performed in order to identify the main engine control variables that can be managed in order to obtain a PCCI combustion strategy.

In conventional diesel combustion, the mixture ignites in the region where the local equivalent ratio is between 2 and 4 [16], i.e. in fuel-rich conditions. The targets of PCCI combustion strategies are, first, to ignite the charge at much lower local equivalent ratios in order to reduce the formation of soot, and, secondly, to slowdown the combustion development to lower peak temperatures, and consequently decrease the formation of NO_x [17]. The attainment of PCCI combustion conditions basically means increasing the ignition delay [3, 18, 19]. During this time interval, the injected fuel atomizes, vaporizes and mixes with air before reaching auto-ignition conditions. The duration of the ignition delay depends on the charge density, fuel and oxygen concentrations and in-cylinder temperature [20]. The oxygen concentration and in-cylinder temperature for a certain engine working point are affected to a great extent by the EGR rate. This clearly points out that EGR is the most important engine working parameter for the realization of PCCI combustion.

SOI timing also plays an important role when direct injection engines are considered. PCCI combustion strategies usually involve a very early [4-7] or late [8] injection event. In the former case, the in-cylinder charge density and temperature at SOI are relatively low, with a consequent prolongation of the time available for the charge to mix, together with an increase in wall impingement phenomena. In the latter case (late injection), the fuel is injected just after TDC, when the high density of the charge requires additional EGR to increase the ignition delay. The potentialities of these two strategies, with respect to the reduction in the local equivalence ratio and in the combustion temperatures, have been clearly shown in [21]. The fuel injection pressure may also play a relevant role as it affects the fuel atomization process as well as the liquid penetration length, which is the cause of wall impingement phenomena, especially when very early injection strategies are employed.

Moreover, a reduction in the intake air temperature and an increase in the intake pressure would be beneficial to increase the ignition delay, while reducing wall impingement [22]. Further improvements may be obtained by increasing the mixing rate through a design which would enhance the swirl motion, and by designing the combustion chamber geometry and the injectors in an appropriate way [7].

An early injection strategy, with a single injection event, has been chosen as the starting activity. Preliminary tests were executed on the reference engine working points by gradually changing the relevant variables (i.e. EGR rate, SOI and rail pressure) with a "one-factor-at-a-time" approach [14]. The limit values of the variables that allow the realization of a PCCI-like combustion event were then identified as a preliminary step for the DoE activity. Limits on the lower values of SOI and EGR were set, taking into account the trends in the engine-out concentrations of NO_x and soot: these two pollutants generally have opposite trends in conventional combustion, while a simultaneous reduction in both pollutants is obtained in PCCI combustion. Maximum values for SOI advance were dictated by the increase in HC and CO emissions above acceptable levels. Limits on the highest EGR rate value are imposed by two phenomena: first, an increase in the EGR rate above a certain value generates high combustion instability and high cylinder-to-cylinder variations (due to the increase in the EGR unbalance); second, because large amounts of EGR are obtained by opening the EGR valve wide and, at the same time, increasing the engine backpressure by means of a dedicated flap valve. The increase in backpressure degrades fuel consumption and, after certain levels, increases combustion instability and the occurrence of misfiring, due to the difficulties involved in managing the inlet and outlet flows from the cylinders.

The results of the preliminary tests are shown in Figs. 1-3. All the data refer to a single engine working point, namely 1800 x 1 (engine speed in rpm x bmep in bar). The engine-out pollutants are considered in terms of brake specific emissions, evaluated as the ratio between the pollutant flow rate and the engine brake power. For confidentiality reasons, the figures have been normalized with respect to a reference condition, i.e. according to the standard engine map, featuring a conventional diesel combustion. Soot emissions have been evaluated, starting from the measurement of the filter smoke number (FSN), according to [23].

Fig. 1a shows the soot vs. NO_x emissions and EGR rate for various values of SOI, where the SOI is expressed in terms of crank angle degrees before TDC (°CA bTDC). Soot is reduced, for constant NO_x emissions, by advancing the injection event due to the longer mixing time. Soot increases, for a certain SOI value, for decreasing NO_x, to a certain point where the soot starts to decrease simultaneously with NO_x. This is obtained high EGR rates, and the specific EGR value at which the standard trend is inverted depends on the SOI. This inversion does not occur if the start of injection is set to 16 °CA bTDC, even at the maximum possible EGR rate, and this condition cannot therefore be considered suitable for PCCI combustion. For earlier injection events, e.g. when SOI occurs at 20 or 24 °CA bTDC, the simultaneous decrease of the two pollutants is obtained for higher EGR rates than 66%. If SOI is advanced further, e.g. to 28 or 30 °CA bTDC, the soot emissions are almost null, and the corresponding variations are therefore not significant. On the other hand, Fig. 2a shows an increase in the brake specific fuel consumption with SOI, due to an advance in the barycenter of combustion, while the increase in the EGR rate does not significantly affects bsfc for the tested conditions. Moreover, advanced injection in a low density and low temperature environment leads to possible wall impingement and lean-charge pockets, which determine an increase in CO (Fig 1b) and HC emissions, which partially contributes to a deterioration in combustion efficiency. The HC emissions have not been reported since they show a similar trend to that of CO, that is, HC is roughly one fourth of CO: the increase in unburned hydrocarbons that can be observed as the SOI is advanced may also be due to the increase in the oil dilution phenomena, and to a general deterioration of the fuel atomization process, due to a lower in-chamber density when the fuel is injected. Furthermore, the dilution effect of EGR contributes to the increase in HC and CO emissions. In these conditions, as the HC and CO emissions are extremely high, the CO_2 emissions (Fig. 1c) are not directly proportional to bsfc, and tend to decrease slightly as the EGR rate for a given SOI value increases, although increasing the EGR rate also produces an increase in the amount of CO_2 in the intake gases. Fig. 2-3 show the effect of EGR and SOI on the development of the combustion event, in terms of the barycenter of the mass fraction burned (MFB50, Fig. 2c), peak firing pressure (PFP, Fig. 2b) and combustion noise (CN, Fig. 3a). Advancing the injection event in fact causes an increase in the PFP, while an increase in EGR slows the development of combustion, and reduces the corresponding PFP and the pressure rate, which in turn affects the combustion noise to a great extent; reduced variations are obtained for high values of EGR and high values of SOI. Furthermore, an earlier SOI causes a shift in combustion to lower crank angle values (as MFB50 tends to be advanced), while an increase in the EGR rate tends to retard/delay the combustion event; the variations that are obtained when SOI is changed for very early combustion events (e.g. curves related to SOI at 24, 28 and 30 degCA bTDC) are almost negligible. Therefore, an appropriate combination of the two control parameters can provide acceptable values of MFB50.

As far as the density of the intake charge is concerned, it is worth pointing out that the favorable reduction in the intake temperature (Fig. 3b) and the increase in the boost pressure (Fig. 3c) in real working conditions compete with the increase in the EGR rate. In fact, the higher the amount of exhaust gas recirculated in the intake manifold, the higher the temperature of the air-EGR mixture. Moreover, since the engine is equipped with a short-route EGR system, the higher the EGR rate, the lower the flow rate through the turbine blades and – as a consequence – the lower the work available to compress the fresh air, and therefore the lower the boost pressure.

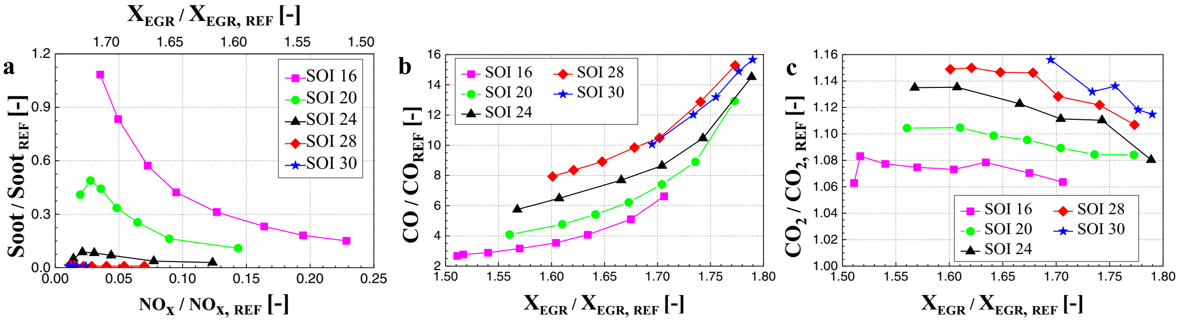

Fig. 1. Brake specific soot (a) as a function of brake specific NO_x emissions and EGR rate, CO (b) and CO_2 brake specific emissions (c) as a function of the EGR rate

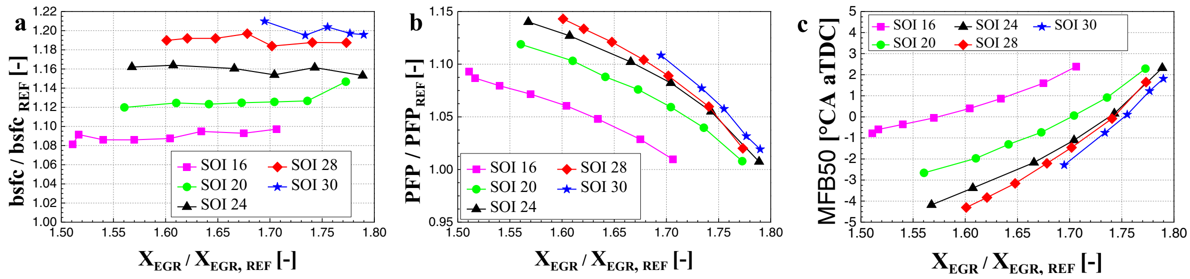

Fig. 2. bsfc (a), peak firing pressure (b) and MFB50 (c) vs EGR rate at/for different SOI

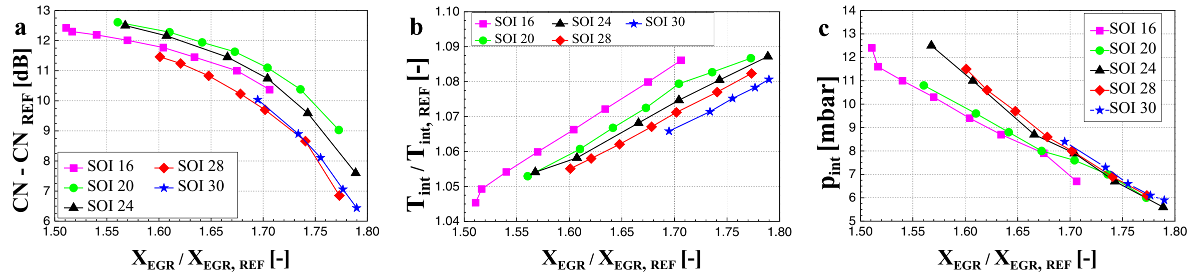

Fig. 3. Combustion noise (a), intake manifold temperature (b) and intake manifold temperature (c) vs EGR rate at/for different SOI.

5. Design of experiments and Model-based optimization of PCCI combustion

The limit values of the input parameters for the execution of a DoE have been set according to the above presented preliminary analysis, and are reported in Table 2. The following input parameters have been identified as the ones that mainly affect PCCI combustion: the rail pressure, the start of injection and the position of the backpressure flap valve used to regulate the EGR rate, since the EGR poppet valve was fully open in all the PCCI working conditions. Considering the limit values for each of these variables, and provided there is an appropriate number of levels, a "V-optimal" design, which minimizes the values of the predicted error variance in the test plan, has been implemented by means of the 'MBC model' Matlab software tool. The following variables were set as outputs of the linear coefficient models, which were built by fitting the experimental values as second order polynomial functions of the input control variables (rail pressure, SOI, EGR flap position): bsfc, brake specific emissions (NO_x, Soot, HC and CO), CN and MFB50. The Box-Cox transformation [24] was applied, where necessary, in order to normalize the distribution of the residuals. Moreover, the "stepwise regression" method [14] was used to eliminate any regressors that showed a negligible effect on the outputs. The models show a good correlation with the experimental data for the analyzed statistical indices. As an example of the results obtained with the modeling, Fig. 4 depicts the predicted bsfc versus the experimental one. The validation root mean square error (RMSE), obtained by comparing the validation tests with the model outcomes, was generally very similar to the model RMSE.

Once the response models had been validated, a model-based optimization of the PCCI combustion in the considered engine working point was set up. Different optimization strategies were tested and the results were compared. In particular, the focus was on the minimization of the NO_x emissions or of the bsfc, and some upper boundaries were sometimes set on other output parameters. A 'conjugated gradient optimization' method was adopted for single-objective optimizations, while multi-objective optimizations were computed employing a Normal Boundaries Intersection (NBI) algorithm. Details on the optimizations are reported in Table 3.

Figs. 5-7 show a comparison of the experimental results pertaining to the optimized PCCI combustion modes and the standard engine calibration conducted in conventional diesel combustion mode. The first and second optimizations (Opt 1 and Opt 2) were obtained by minimizing the NO_x emissions, which resulted in a reduction in the NO_x brake specific emissions of more than 90%, and smokeless combustion, thanks to an increase in the EGR rate to more than 60%. On the other hand, the CO and HC emissions increased by more than 2-fold and 8-fold , respectively, while the bsfc increased by 13%, due to an advance of the barycenter of the combustion of more than 11 °CA. The third optimization (Opt.3) was computed minimizing the brake specific fuel consumption, and it resulted to be the best trade-off for the tested conditions: in this case, it was possible to reduce the NO_x emissions by 60% and the soot by more than 80%, while the bsfc penalty was slightly lower than 10%, the increase in CO was contained to less than 3-fold and the HC emissions were almost the same as the reference condition. As far as the model-based optimization results are concerned, the fourth optimization point (Opt 4) should minimize NO_x emissions and bsfc at the same time, while limiting HC and soot emissions to constrained levels. Experimental tests performed with the Opt. 4 calibration provided even lower NO_x levels than Opt 1 and Opt 2 (due to the model and experimental uncertainty for such low values), while bsfc was slightly higher than in Opt 3, and HC and CO were considerably lower with respect to Opt 1 and Opt 2, but much higher than Opt 3. Soot emissions were reduced by 46%, but were still far from the target of a PCCI-like combustion. In all the tested conditions, the combustion noise was considerably higher than in the reference condition, with an increase from 11.7 to 13.1 dB, which was in part due to the fact that the PCCI tests were performed with a single injection strategy, while the Euro VI calibration used a triple injection strategy for the considered engine point. Moreover, the advance in the combustion event and the longer ignition delay had to be accounted for as additional causes of the increase in combustion noise.

Table 2. DoE input boundary values

Input	Lower Limit	Upper Limit
EGR flap position	85	95
SOI (°CA bTDC)	18	30
Rail pressure (bar)	500	700

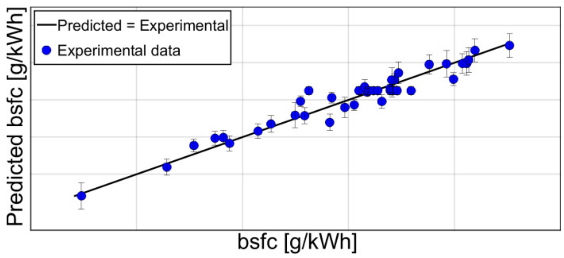

Fig. 4. bsfc: predicted vs. experimental values

Table 3. Euro VI point and optimization point parameters

Point	EGR valve (%)	EGR flap (%)	SOI (°CA bTDC)	Rail pressure (bar)	Minimization	Constraints (-)
Euro VI	100	71.4	6.9	583		
Opt 1	100	95.0	30	700	NO_x	
Opt 2	100	95.0	30	500	NO_x	$CO/CO_{REF} < 8.5$
Opt 3	100	91.5	18	500	bsfc	$NO_x/NO_{X,REF} < 0.5$ $Soot/Soot_{REF} < 0.4$
Opt 4	10095	95.0	21	500	NO_x bsfc	$HC/HC_{REF} < 2$ $Soot/Soot_{REF} < 0.2$

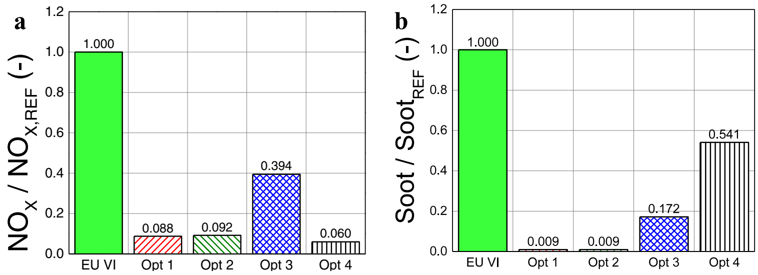

Fig. 5. NO_x (a) and soot brake specific emissions (b): comparison between/of the base EU VI calibration and the optimized PCCI points.

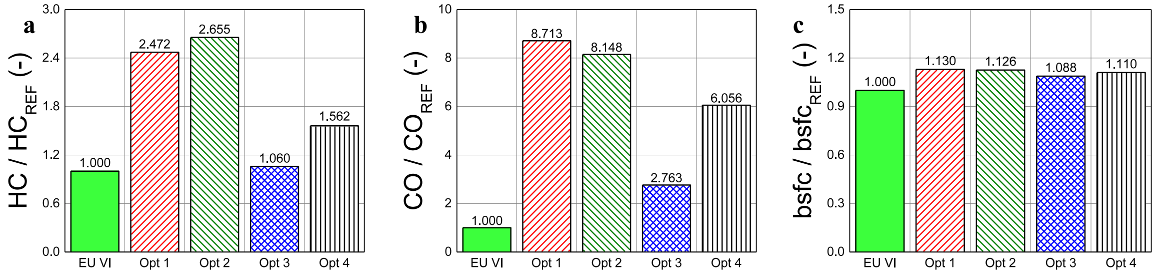

Fig. 6. HC (a) and CO (b) specific emissions and bsfc (c): comparison between/of the base EU VI calibration and the optimized PCCI points.

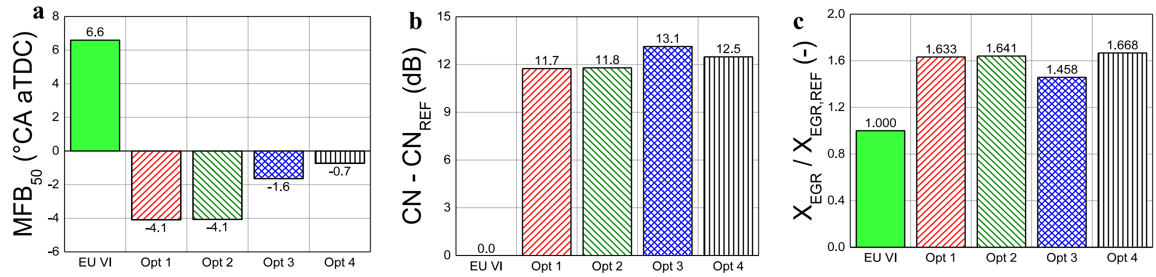

Fig. 7. MFB50 (a), combustion noise (b) and EGR rate (c): comparison between/of the base EU VI calibration and the optimized PCCI points.

6. Conclusions

In the present activity, the possibility of simultaneously reducing Soot and NO_x emissions in diesel engines with a PCCI combustion mode has been examined for a low load working point. The main outcomes for the considered working point, but which could be extended to other low load points, are summarized as follows:

- PCCI combustion is obtained with a proper combination of high EGR levels and advanced combustion. A lower SOI than 16 °CA bTDC is not able to allow the engine to enter the PCCI combustion mode, regardless of the EGR level;
- It has been possible to simultaneously reduce engine out NO_x and soot by 90% and 99% of the base point values, respectively.
- The reductions in NO_x and Soot are always related to important increases in HC and CO, due to advanced injection taking place in a colder and low density environment. Moreover, bsfc and CN have also shown an undesirable increase.
- A proper calibration can be obtained through DoE to find the best trade-off among all the considered output values.

In addition, DoE has been shown to be able to effectively support the effort of the experimenter in optimizing the engine calibration.

A further improvement of the obtained results and a simultaneous minimization of the corresponding drawbacks could be obtained by considering a proper design and the replacement of the standard conventional hardware with other hardware dedicated to PCCI combustion.

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