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Sensitivity of Combustion Noise and NO_x and Soot Emissions to Pilot Injection in PCCI Diesel Engines

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Abstract

Diesel engines are the most commonly used internal combustion engines nowadays, especially in European transportation. This preference is due to their low consumption and acceptable driveability and comfort. However, the main disadvantages of traditional direct injection Diesel engines are their high levels of noise, nitrogen oxides (NO_x) and soot emissions, and the usage of fossil fuels. In order to tackle the problem of high emission levels, new combustion concepts have been recently developed. A good example is the premixed charge compression ignition (PCCI) combustion, a strategy in which early injections are used, causing a burning process in which more fuel is burned in premixed conditions, which affects combustion noise. The use of a pilot injection has become an effective tool for reducing combustion noise. The main objective of this paper is to analyze experimentally the pollutant emissions, combustion noise, and performance of a Diesel engine operating under PCCI combustion with the use of a pilot injection. In addition, a novel methodology, based on the decomposition of the in-cylinder pressure signal, was used for combustion noise analysis. The results show that while the PCCI combustion has potential to reduce significantly the NO_x and soot emission levels, compared to conventional Diesel combustion strategy, combustion noise continues to be a critical issue for the implementation of this new combustion concept in passenger cars.

Keywords: PCCI combustion, Combustion noise, Pollutant emissions, Diesel engine, Pilot injection

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1. Introduction

Throughout recent years, direct injection (DI) Diesel engines have been the most often used propulsion system in automotive vehicles in Europe. In countries like Austria, Spain, France and Italy, the market share of Diesel cars has exceeded 50% [1]. Nevertheless, Diesel engines are not exempt from certain problems, including high nitrogen oxides (NO_x) and soot emissions, their dependence on oil-derived fuels, and the high levels of noise produced.

The noise produced by Diesel engines is currently receiving more and more attention, due to the discomfort that it causes on both passengers and pedestrians [2]. Combustion noise is noteworthy for being the main source of noise in vehicles equipped with Diesel engines. This noise is generated by the interaction of pressure and mechanicals forces. During the combustion process, a sudden pressure rise is produced which induces engine block vibration and the subsequent noise emission [3, 4]. Combustion noise mainly depends on the combustion chamber design, the fuel injection system, the in-cylinder temperatures, and the engine compression ratio [5]. This noise can be controlled by the application of both passive and active actions. A typical passive action is engine encapsulation, whereas engine hardware and engine operating conditions settings are among the active actions available for combustion optimization [6]. The geometry of the bowl plays an important role in engine noise control due to its influence on the development of resonant pressure fluctuations, which are induced by the ignition characteristics [7, 8]. Nevertheless, depending on the strategy employed the use of active controls can have a negative impact on engine performance, driveability and pollutant emissions.

To overcome the problems of Diesel engines regarding pollutant emissions, several advanced combustion concepts have been proposed. One of the most relevant combustion concepts is that of premixed charge compression ignition (PCCI) combustion. The PCCI combustion concept is well known for its ability to improve performance while reducing both NO_x and soot levels. Unlike the conventional diesel combustion, PCCI combustion uses early injections and relatively higher exhaust gas recirculation (EGR) rates for simultaneously reducing NO_x and soot emissions levels. However, many problems such as mixture preparation and control of the combustion phasing [9], together with knock, can damage the engine and generate annoying noise [10]. These characteristics complicate the application of this type of combustion. The use of a pilot injection has gained significant interest in recent years in conventional Diesel combustion as a means to reduce engine combustion noise [11]. Pilot injection reduces the ignition delay (ID) of the main injection and limits the amount of premixed combustion [12, 13].

The main objective of this paper is to analyze experimentally the pollutant emissions, combustion noise, and performance of a Diesel engine operating under PCCI combustion with the use of a pilot injection. For this purpose, a light-duty Diesel engine

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was adapted to operate under the PCCI combustion concept, taking into account the operating conditions in which this concept becomes more suitable for reducing NO_x and soot. A novel methodology based on the decomposition of the in-cylinder pressure signal was used to assess subjective and objective aspects of combustion noise [14, 15].

In the next section, the methodology used to perform the study is described. Then, the experimental set up and the diagnostic tools used are described in section 3. Results for combustion noise, pollutant emissions, and performance are presented and discussed in Section 4. Finally, the main conclusions of this investigation are summarized in Section 5.

2. Methodology

The present study is mainly based on the use of a multi-cylinder Diesel engine at low torque and medium speed (1500 rpm). The use of a pilot (or split) injection is one of the most promising solutions to reduce combustion noise and NO_x levels. It is for this reason that a fixed amount of 10 mg/stroke of fuel was injected in two injections for all the test cases. At the same time, and with the purpose of analyzing the effects of a pilot injection on PCCI combustion, different injection timings and quantities of injected fuel mass were selected.

Previously, an experimental study on PCCI combustion with a single injection was developed by the authors [16]. In that investigation, a methodology was devised that made it possible to identify the injection timing, intake oxygen concentration ($[O_2]_{IN}$), and injection pressure which would provide the best results for a given diesel engine in terms of emissions reduction and combustion noise while operating in PCCI combustion. In order to establish a PCCI combustion mode with similarly low emissions and noise, the operating conditions shown in Table 1 were selected.

An injection pressure of 800 bar was chosen, because higher injection pressures promote a better air-fuel mixing and thus a better combustion [1]. Relatively high EGR rates were used in order to reduce the $[O_2]_{IN}$ to 10% so that the start of combustion timing could be more easily controlled, combustion noise could be reduced, and lower in-cylinder combustion temperatures could be achieved (thus allowing for lower NO_x emissions) [17]. The range of start of energizing (SOE) explored for the pilot injection was from -38° to -26° after top dead center (aTDC), while that of the main injection was from -26° to -6° aTDC. These ranges were selected in order to achieve satisfactory results on pollutant emissions and performance, with an acceptable combustion noise level.

The effect of the pilot injection quantity was assessed by considering percentages between 20% and 60% of the total fuel mass. The maximum pilot quantity of 60% of the total fuel mass injected was set in order to minimize, if not to avoid completely, fuel spray wall impingement. The range of pilot injection quantities was chosen considering the parameters evaluated in previous experimental studies [18, 19, 20, 21]. In the end, 35 engine test conditions were considered to test the effects of pilot and main injection timings and quantities on the emissions and noise generated under PCCI combustion.

For the assessment of combustion noise, the engine noise at 1 m of the engine was measured in order to check that the overall noise (ON) value calculated using the procedure proposed by Torregrosa et al. [14] is also valid when the engine operates in PCCI combustion with a pilot injection.

3. Experimental configuration and diagnostic

3.1. Experimental setup

A 1.6 l light-duty four-cylinder Euro IV turbocharged DI diesel engine, equipped with a solenoid controlled and common rail injection system, was used. The main specifications of the engine and the injection system are given in Table 2. The engine was directly coupled to an asynchronous electric dynamometer, which allows control of the engine speed and load. The engine was installed in a fully equipped test cell, with all the auxiliary devices required for engine operation and control [22, 23]. The test bench was located inside an anechoic chamber with the purpose of recording engine noise in free field conditions, and subsequently to evaluate the suitability of the noise prediction tool for PCCI combustion with a pilot injection.

In order to achieve a controlled intake temperature of 45C, the EGR cooler used was approximately 40% larger than that used in the production version of the engine. Several K-type thermocouples were used to measure the temperature of all the fluids in the engine. NO_x emissions, oxygen concentration in the exhaust, equivalence ratio, and excess air ratio (λ) were measured with a Horiba MEXA-720 exhaust gas analyzer. Intake oxygen concentration was measured with a lambda sensor installed in the intake manifold. An AVL 451S filter-type smoke meter was used for measuring the filter smoke number (FSN) and the correlation proposed by Christian et al. [24] was used to transform it into soot concentration.

In-cylinder pressure was measured in all the cylinders by means of Kistler 6055Bsp glow-plug piezoelectric transducers. The pressure sensors were calibrated using the method described by Tich and Gautschi [25], based on a quasi-steady calibration by means of a deadweight tester with NPL and NIST traceability. In-cylinder pressure was recorded with a sampling frequency of 50 kHz, so that a bandwidth similar to the human domain of hearing (20 Hz - 20 kHz) was available. An open Engine Control Unit (ECU) was used in order to set the operation conditions established in the methodology.

Finally, in-cylinder pressure signals were filtered and averaged to obtain the heat release law by means of the combustion diagnosis code CALMEC [26]. This code is based on the resolution of the energy equation applied to the in-cylinder gases, under the assumption of uniform pressure and temperature across the whole combustion chamber volume. This single-zone model approach makes it possible to calculate the instantaneous mean temperature and heat release from the burned fuel.

3.2. Combustion noise characterization

Combustion noise was assessed through the approach proposed by Payri et al. [4]. In this novel methodology, in-cylinder pressure is decomposed into three sub-signals corresponding to

Table 1: Tests matrix considered in the study.

$[O_2]_{IN}$ (%)	Injection pressure (bar)	Pilot injection quantity (% of the total fuel)	Pilot timing (cad aTDC)	Main timing (cad aTDC)
10	800		-38	-6
		20	-34	-26
		30	-34	-18
		40	-34	-8
		50	-33	-10
		60	-30	-18
			-26	-18

the relevant physical phenomena taking place during the combustion process in DI Diesel engines: pseudo-motored operation (compression-expansion), combustion, and combustion chamber resonance. This decomposition of the pressure signal has been applied in subsequent investigations [14, 15] in order to find cause-effect relationships between the source signal (caused by combustion) and both the objective and subjective aspects of the resulting noise. The compression-expansion signal does not represent any fact related with combustion and it is therefore used in the methodology only as a reference signal. The combustion signal is influenced by the rate of heat release, which is governed by the injection strategy and engine operation conditions. Finally, the resonance signal is associated with the pressure wave oscillations of the burned gas inside the combustion chamber due to abrupt pressure rise rates [7, 8].

In this investigation, the procedures proposed by Torregrosa et al. [14] and Payri et al. [15] were used to predict the ON and sound quality of the combustion noise, respectively. In both investigations, indicators were highly correlated with the ON and sound quality. One operation indicator, I_n, is associated with the engine speed and is non-dimensionalized by the idle speed. Two combustion indicators were also derived: I_1 is related to the sudden in-cylinder pressure rise rate and I_2 considers the signal energy relative to the combustion chamber resonance [7, 8].

With these indicators, the ON and the sound quality of the combustion noise can be expressed as:

$$ON = C_0 + C_n I_n + C_1 I_1 + C_2 I_2 \tag{1}$$

$$\mathrm{MARK} = 10 - C_1 I_1 - C_2 I_2 \tag{2}$$

where C_i are coefficients dependent on the engine family and size.

The sound quality is qualified by a mark ranging from 0 to 10, which represents the satisfaction degree of an average customer. A mark of 7 was considered as an acceptable noise level for customers [15].

4. Results and discussion

In the following paragraphs, results of engine pollutant emissions, performance, and combustion noise from PCCI combustion are presented and analyzed. Comparison is shown between the NO_x, soot, and torque produced in PCCI conditions and those supplied by the engine operating in conventional Diesel combustion. Table 3 shows the relevant values for engine operation in conventional Diesel combustion.

Table 2: Engine and injector specifications.

Engine Type		DI Diesel engine
Cylinders		4 in line
Bore	(mm)	75
Stoke	(mm)	88.3
Compression ratio		18:1
Injector nozzle holes		6
Nozzle holes diameter	(mm)	0.124
Spray angle	(deg)	150

Table 3: Threshold values of engine operating with conventional Diesel combustion

	Threshold Values
NO_x [ppm]	80
Soot [mg/m^3]	20
Torque [Nm]	38
Mark	6

4.1. *Pollutant emissions and engine performance*

Bearing in mind that the goal of PCCI combustion is to reduce NO_x and soot emissions, the effects of variations in the pilot injection fuel mass on engine performance and pollutant emissions are analyzed in the following.

4.1.1. *Constant pilot injection timing*

With the purpose of analyzing the effects of the pilot injection fuel mass quantity and main injection timing, the SOE_{Pilot} was maintained constant at -34° aTDC while the SOE_{Main} was tested at -26°, -22° and -8° aTDC. The results related to the pollutant emissions and engine performance are shown in Fig. 1 where the ratio between the ID and the duration of injection (IT) of the main injection, NO_x and soot emissions, and torque are presented.

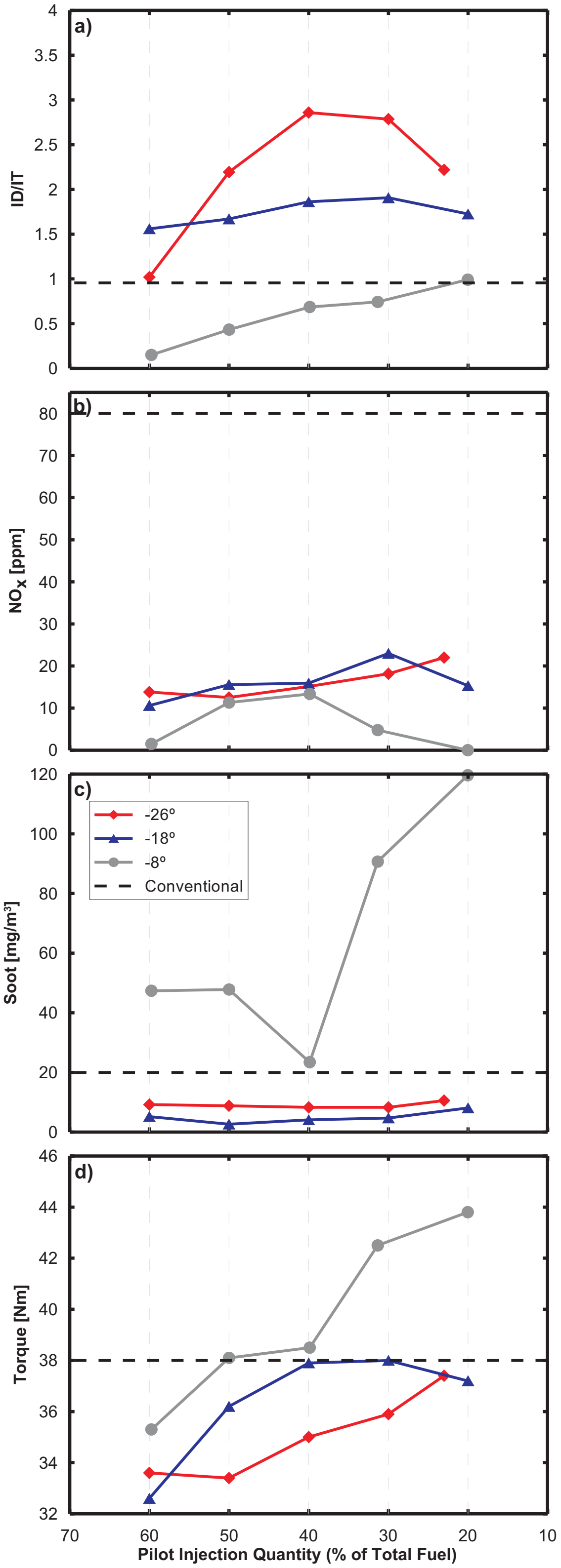

Figure 1: Effects of main injection SOE and pilot injection quantity on: ID/IT ratio (a), NO$_x$ emission (b), soot (c) and torque (d)

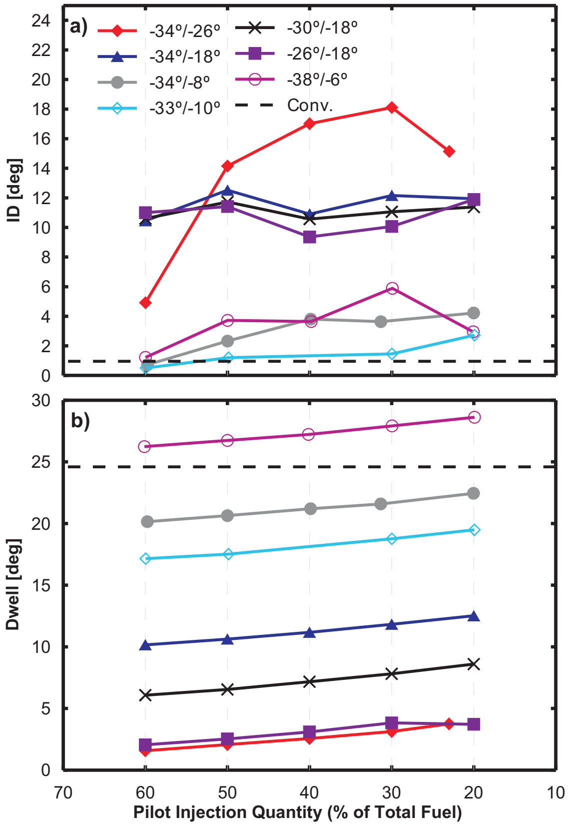

Figure 2: Ignition delay (a) and dwell between pilot and main injection (b) for all test conditions

The ID/IT ratio represents the degree of air and fuel premixing. This ratio increased above unity when there existed a positive delay between the end of injection and the start of the combustion process, showing that premixed combustion was attained. As shown in Fig. 1a, ID/IT decreased when more fuel mass was injected during the pilot injection due to the shorter injection duration of the main injection, resulting in more premixed combustion. Additionally, Fig. 2a shows that the ID of the main injection was longer for the PCCI combustion test conditions than for those of conventional Diesel combustion. It is largely accepted that longer ID of the main injection allows more time for the air and fuel to premix, thus producing a lower maximum local equivalence ratio in the bulk combustion chamber volume before SOC. This is helpful in reducing soot emissions [29, 30]. By comparing Fig. 2a and Fig. 2b, it is observed that selection of pilot and main injection timings with longer dwell time will generally cause decreased ID of the main injection.

It is observed in Fig. 1b that in all PCCI conditions tested NO$_x$ emissions levels were far below the threshold value of 80 ppm for conventional Diesel combustion. This significant NO$_x$ reduction is a consequence mainly of the high EGR rate used to reach an $[O_2]_{IN}$ of 10% in PCCI conditions. A high EGR rate reduces in-cylinder oxygen content and thus also the subsequent combustion temperatures, leading to lower NO$_x$ formation levels. At the same time, Fig. 1b illustrates that an increased mass of fuel in the pilot injection causes a slight decrease in NO_x emissions.

In Fig. 1c, it is seen that only in the case of the -8° aTDC (non-premixed conditions, as shown by an ID/IT lower than unity) did the increased pilot injection quantity cause a decrease of soot emissions. In the other cases tested, the main injection was far enough advanced (thus allowing premixed combustion conditions, as indicated by the ID/IT greater than unity) so that there was not any significant effect of the pilot injection quantity on the soot emissions.

Fig. 1d shows that increasing the pilot injection quantity caused a decrease in engine torque. This happens because when the quantity of injected fuel mass during pilot injection is greater, less quantity of fuel is injected by the main injection since the total mass is constant. It is for this reason that less fuel quantity is burned with a proper combustion phasing with the aim of providing power output. The established limit considering conventional combustion is exceeded by the strategies in which less fuel is delivered by pilot injection.

4.1.2. *Constant main injection timing*

In these operation conditions, the pilot injection timing varied from -34° to -26° aTDC and the main injection timing was kept constant at -18° aTDC. As shown in Fig. 3, soot and NO_x emissions remained significantly below the established conventional Diesel combustion threshold values. Soot emissions generally increase as the pilot injection timing was brought closer to TDC. These tendencies are attributable to an increase in percentage of the diffusion combustion in the main combustion because of an insufficient mixing of fuel and air [27, 28], as it is shown in Fig 3a with the ratio ID/IT. Concerning engine performance, the engine torque decreases when the pilot injection is advanced but, in spite of this reduction, many of the tested conditions produced engine torque values higher than the baseline conventional diesel threshold, especially when the pilot was closer to TDC and had less injection quantity.

Up to this point of the analysis, it is observed that the use of a pilot injection in PCCI combustion can be advantageous in reducing soot and NO_x emissions, and in increasing engine torque. The best test conditions for low emissions and increased engine torque were for a pilot injection quantity of 30-40% of the total fuel mass injected, a SOE_{Main} at -18° aTDC, and a SOE_{Pilot} between -26° and -30° aTDC.

4.2. *Combustion noise*

For the assessment of combustion noise produced from PCCI combustion with pilot and main injections, an analysis was performed by varying the pilot injection quantity and sweeping the pilot and main injection timings, as was done in the previous section.

4.2.1. *Effect of pilot injection mass variation*

Fig. 4 shows that ON and combustion noise quality are inversely proportional to each other. From a subjective point of view, Fig. 4b, a mark of 7 was exceeded in only a few of the tested conditions. In general, combustion noise quality

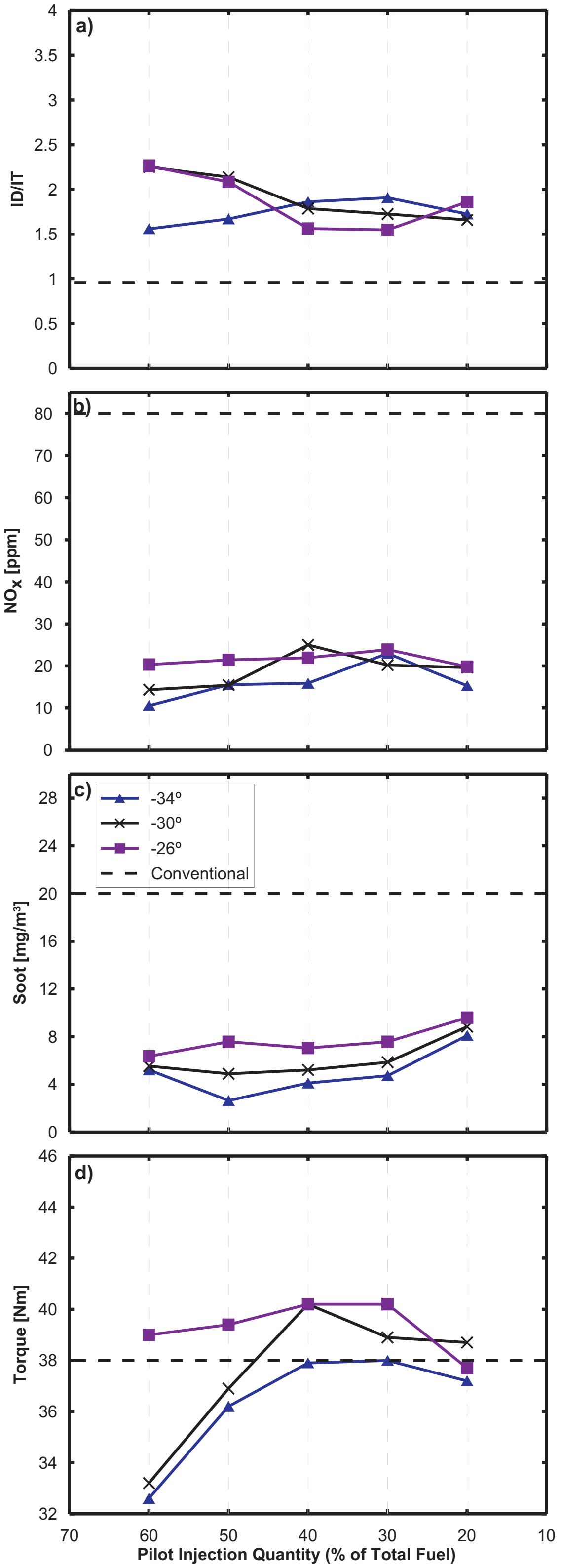

Figure 3: Effects of pilot SOE with a -18° aTDC main SOE on: ID/IT ratio (a), NO_x emission (b), soot (c) and torque (d)

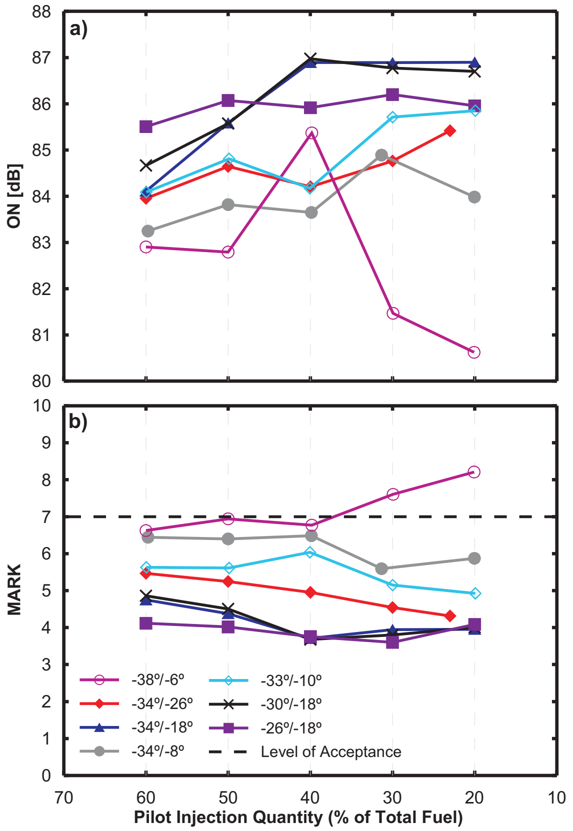

Figure 4: Combustion noise characterization at all tested conditions: overall noise (a) and sound quality (b)

increases slightly with an increase in the pilot injection quantity. Among the causes that contribute to the sound quality deterioration is the increased ID compared to conventional combustion, as shown in Fig 2a. By extending the ID, the fuel is burnt in more premixed conditions, typically causing a higher in-cylinder pressure rise rate, thus deteriorating the combustion noise quality. Nevertheless, it is worth noting that only one (SOE_{Pilot} at -38° aTDC and SEO_{Main} at -6° aTDC) of all the tested conditions showed an entirely different trend, which requires further discussion. Fig 5. shows an example of the sensitivity of the rate of fuel burning to the percentage of fuel mass injected during the pilot injection, with a SOE_{Pilot} at -34° and SEO_{Main} at -8°. This figure shows that the derivative of the combustion pressure decreases as the quantity of fuel injected during pilot injection is increased. However, these values are still higher than that of a conventional combustion signal.

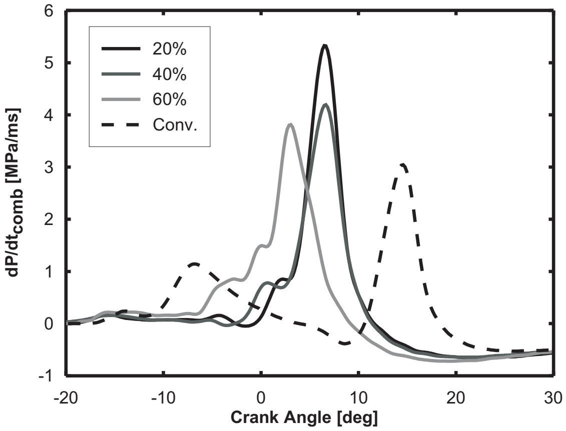

Figure 5: Effect of pilot injection mass variation on pressure derivative of the combustion signal for pilot injection timing at -34° aTDC and main injection timing at -8° aTDC

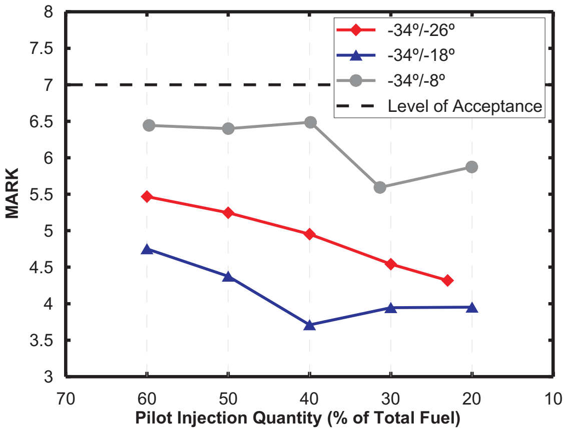

Figure 7: Sound quality characterization at constant pilot injection timing

The values of indicators I_1 and I_2 are illustrated in Fig. 6a and 6c. The results show that the indicator related to burning velocity (I_1) had the largest influence on decreased sound quality and increased noise levels. Fig 6a shows that in almost all PCCI operating conditions, indicator I_1 values were higher than that of a conventional Diesel combustion, which is represented by the dash dot lines. Meanwhile, all PCCI I_2 values were very similar to the reference value associated with conventional Diesel combustion. Fig 6b and 6d evidence that if one subtracts the contribution of both, the indicator I_1 and the indicator I_2 to calculate new noise marks, the most significant impact will be from the contribution of the indicator I_1. This means that the main source of the combustion noise was from the velocity at which the combustion developed (I_1) as opposed to the combustion chamber resonance indicator (I_2).

Constant pilot injection timing. In Fig. 7, the pilot injection was kept constant at -34° aTDC while sweeps were performed of the pilot injection quantity at selected main injection timings from -8° aTDC to -26° aTDC. From a subjective point of view, it was not possible for any of these PCCI test conditions to reach a rating better than conventional diesel combustion. In addition, it appears that the best results (in terms of minimizing combustion noise) would be when the dwell between injections is longer than 15 crank angle degrees (CAD).

A comparison of pressure derivate peaks during combustion for different main timing is given in Fig. 8. It is observed that the pressure rise rate was more abrupt when the main injection timing was more advanced. As reported by Okude et al. [19], in premixed combustion, when the injection timing is advanced

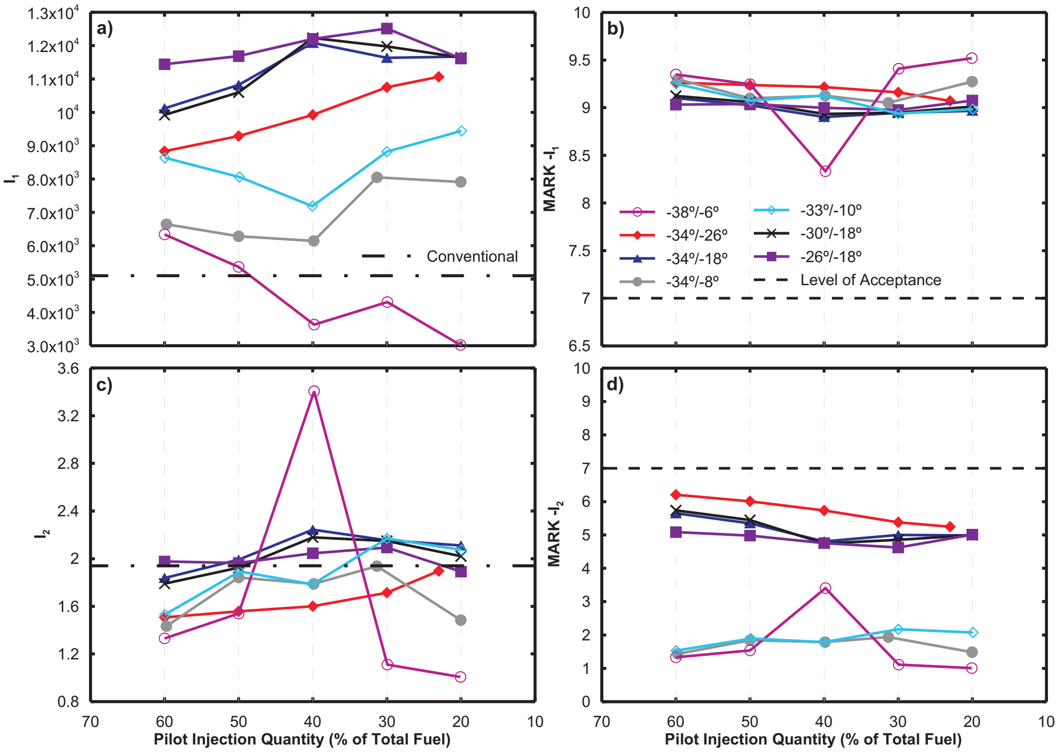

Figure 6: Combustion indicator variation: I_1 (a), combustion noise rating without the contribution of indicator I_1 (b), I_2 (c), and combustion noise rating without the contribution of indicator I_2 (d)

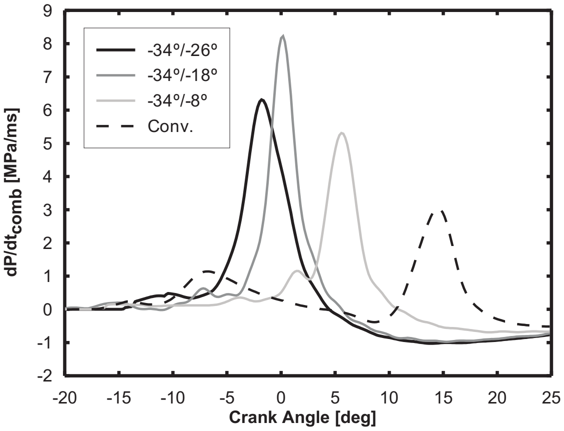

Figure 8: Effect of constant pilot injection timing on pressure derivative of the combustion signal

enough to suppress smoke emissions, this advance increases the pressure derivative of the combustion signal.

From these results, one may conclude that the ON and sound quality are influenced by the dwell. It may be said that the shorter this duration is, the worse is the effect on the mark and the ON.

Constant main injection timing. Similar trends to those observed when the main injection timing was changed are observed in the results shown in Fig. 9. These results coincide with an advanced pilot injection, maintaining a fixed position of -18° for the main injection timing.

Here, less significant variations were seen when the pilot injection timing wass changed, but a worse combustion noise quality was produced. In the case of partially premixed combustion, the rate of pressure rise is greatly affected by the early pilot injection [31]. Unlike in the previous results, Fig. 10 shows that the rate of pressure rise is scarcely sensitive to the advance of pilot injection. However, a significant increase can be appreciated, compared to conventional operation conditions, which are influenced by the ID extension.

Impact of oxygen concentration in the intake. In this subsection, the operation condition that did not follow the trend set by most of the other PCCI conditions (SOE_{Pilot} in -38° and SEO_{Main} in -6°) will be analyzed.

As it can be seen in Fig 4b, this was the only condition that exceeded the level of acceptance, especially when using low percentage of fuel mass in the pilot injection. In order to complement the analysis, different quantities of $[O_2]_{IN}$ were used to study its effect on combustion noise, pollutant emissions, and performance, as shown in Fig. 11.

An expected, NO_x levels and engine torque increase when $[O_2]_{IN}$ levels rise. Regarding soot, the existence of a trend relating this variable and $[O_2]_{IN}$ variations was not clear, and usually this effect is called the soot bump. Meanwhile, sound quality is affected with $[O_2]_{IN}$ increase. Bearing in mind previous results, a strategy that offers great benefits regarding pollutant emissions and sound quality employs a $[O_2]_{IN}$ of 10% and 25%

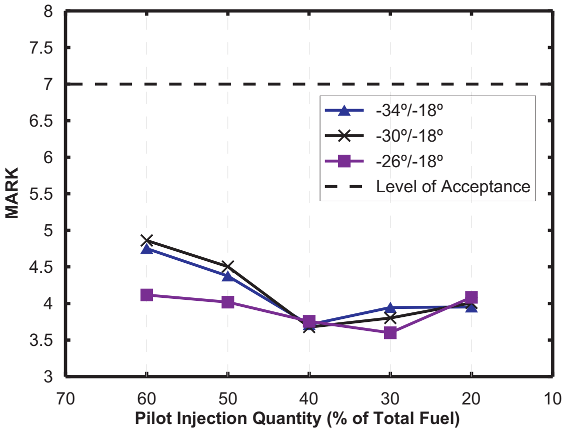

Figure 9: Sound quality characterization for three pilot injection timings at constant main injection timing.

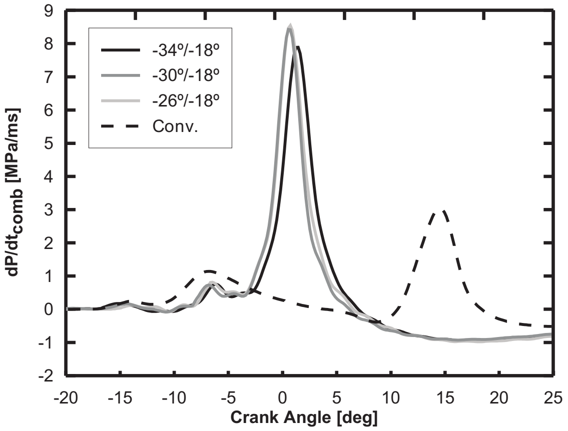

Figure 10: Effect of three pilot injection timings at constant main injection timing on pressure derivative of the combustion signal.

of pilot injection quantity. The only negatively affected parameter is engine torque, which decreases 8.6% in comparison with conventional Diesel operation.

5. Conclusions

Compared with conventional Diesel combustion, PCCI combustion with two injections (pilot and main) produced a significant reduction in emissions of NO_x (mostly due to the use of a high EGR rate) and soot (due to the increased levels of air and fuel premixing before SOC). Additionally, engine torque was influenced by the pilot injection quantity. For these engine operating conditions, torque decreased significantly as the pilot injection quantity increased above 40%.

From the acoustic point of view, sound quality deteriorated with almost all the injection strategies considered. The most influential factor in the deterioration of combustion noise was the huge increment of the indicator related to a sudden in-cylinder pressure rise, I_1. Consequently, a progressive decrease in combustion noise was observed by increasing fuel quantity of the pilot injection, but with the side-effect of decreasing engine torque.

The results described above confirm that the deterioration of combustion noise is one of the main problems of this type of combustion, a fact that might avoid its application in passenger cars and prevent a real appreciation of its important contribution to pollutant emission reduction.

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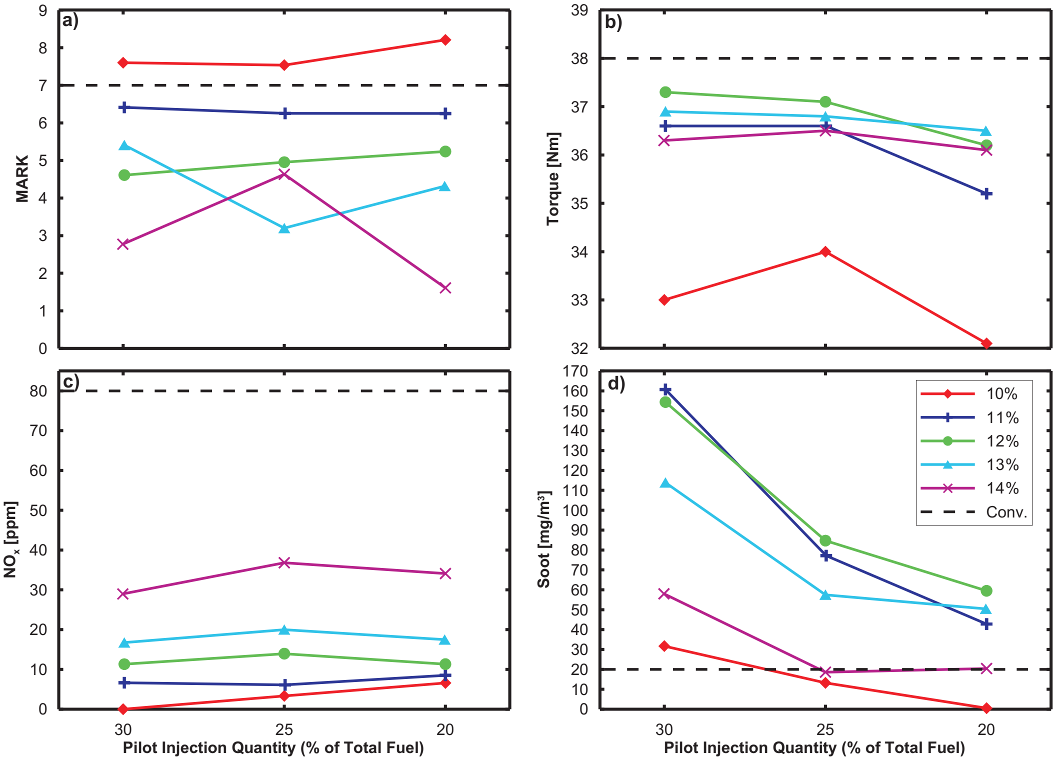

Figure 11: Effect of intake oxygen concentration on: Sound quality (a), Torque (b), NO_x (c) and soot (d).

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