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# Suitability analysis of advanced diesel combustion concepts for emissions and noise control

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## ABSTRACT

During the last years, the preservation of the atmospheric environment has played an increasingly important role in society. The Diesel engine can be considered an environmentally friendly engine because of its low consumption and the subsequent carbon dioxide ($CO_2$) emissions reduction. However, in the near future it will face strong restrictive emission standards, which demand that the current nitrogen oxides ($NO_x$) and soot emissions are halved. To comply with these restrictions new combustion concepts are emerging, such as PCCI (premixed charge compression ignition), in which the fuel burns in premixed conditions. Combustion noise is thus deteriorated and consequently end-users could be reluctant to drive vehicles powered with Diesel engines and their potential for environment preservation could be missed. In this paper, Diesel combustion is addressed through the analysis of performance, emissions and combustion noise in order to evaluate the suitability of PCCI engines for automotive applications. The results show that PCCI combustion offers great possibilities to fulfill future emission restrictions, but the engine noise is strongly deteriorated. The great sensitivity of users to this factor requires vehicle manufacturers to focus their efforts on the optimization of passive solutions for implementing the PCCI concept in passenger car and light-duty engines, even with the subsequent increase in the cost of vehicle. This aspect is less restrictive in heavy-duty engines, since the great benefits in emissions reduction compensate the deterioration of engine noise.

## 1. Introduction

In the last years, Diesel engines have increased their share in the European passenger car market in detriment of spark ignition engines. Diesel engines are being preferred mainly due to their low specific fuel consumption, which results in a decrease of $CO_2$ (carbon dioxide) emission levels. According to the European Automobile Manufacturers Association [1] Diesel engines burn 30% less fuel and emit 25% less $CO_2$ on average than petrol engines. Unfortunately, particulate matter (PM) and nitrogen oxides ($NO_x$) emissions from Diesel engines are high. Usually, attempts at the reduction of one of these pollutant emissions lead to an increase in the other; this is usually referred to as the "Diesel dilemma" or as the soot/$NO_x$ trade-off [2,3]. For this reason, new Diesel combustion concepts are emerging, which are characterized by the reduction of combustion temperature by using premixed combustion and large quantities of exhaust gas recirculation (EGR), leading respectively to the reduction of soot levels and $NO_x$ [4–7]. As reported by Shi et al. [8], increasing the EGR rate can also decrease the speed of the combustion reaction and thus knock is avoided. The change from a heterogeneous to a homogeneous Diesel combustion process is considered one possibility to avoid costly and voluminous exhaust gas after-treatment systems [9]. As reported by Payri et al. [10], the emissions are strongly dependent on the operating settings of the fuel injection system (injection pressure, start of the injection and injection pattern).

Two solutions for developing these new Diesel combustion concepts have been proposed. In the first one, the injection event is delayed toward the expansion stroke, so that very low $NO_x$ and soot emission levels are achieved, as well as low combustion noise levels. However, engine thermal performance decreases, which makes its application difficult in production engines [11]. In the second solution, the injection event is advanced toward the compression stroke. This modification produces $NO_x$ and soot levels similar to those observed retarding the injection event, but without

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*Abbreviations:* aTDC, after top dead center; Cad, crank angle degree; $CO_2$, carbon dioxide; DI, direct injection; ECU, engine control unit; EGR, exhaust gas recirculation; FSN, filter smoke number; ID, ignition delay; IT, injection time; $NO_x$, nitrogen oxides; ON, overall noise; $[O_2]_{IN}$, oxygen concentration of the intake air; PCCI, premixed charge compression ignition; PM, particulate matter; SOE, start of energizing; TDC, top dead center.

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**Nomenclature**

*Latin*

| | |
|---|---|
| $C_i$ | coefficients of the combustion noise assessment equation (−) |
| $I_1$, $I_2$ | combustion indicators (−) |
| $I_n$ | operation indicator (−) |

*Greek symbols*

| | |
|---|---|
| $\lambda$ | excess of air (−) |
| $\xi$ | mark ratio obtained with different injection pressures (−) |

noticeable effects on fuel consumption and $CO_2$ emission levels [12]. However, with early injections the combustion starts near the TDC (top dead center) and most of the fuel burns in premixed conditions [13], which results in an extremely fast heat release leading to high pressure time-derivatives and thus to noisy engine operation, as in the premixed charge compression ignition (PCCI) combustion [14–16]. A good comparison of these two solutions is given by Sayin and Canakci [17]. If injection starts earlier, the initial air temperature and pressure are lower so that the ignition delay (ID) increases, thus providing time to allow for the formation of more premixed fuel [18].

This work is focused on the second solution, the PCCI combustion concept, which may provide significant reductions of $NO_x$ and soot emissions [19,20]. Furthermore, in this concept the mixture formation process, and hence the rate of heat release, can be controlled by the injection settings [21]. Proper control of the combustion process increases the torque range of application of the PCCI concept and also the overall engine efficiency obtained, whereas pollution emissions and noise levels are both reduced. Despite the undeniable benefits of the PCCI concept, some challenges must still be faced before its massive implementation in production engines is possible, most notably the control of the noise produced by the fast and uncontrolled combustion, which may even limit in some instances the implementation of injection strategies potentially feasible for reducing $NO_x$ and soot emissions.

Noise is a significant issue in passenger cars, and the engine is the main noise source in Diesel-powered vehicles. Consequently, car manufacturers have devoted significant efforts to mitigate engine noise in order to comply with regulations and satisfy customer demands [22,23]. The noise emitted by the engine consists of both combustion and mechanical noise, which in certain conditions are coupled [24]. When combustion takes place, a sudden pressure rise is produced causing the vibration of the engine block, which in turn radiates air-borne noise. The block vibration is caused by the pressure forces exerted directly by the gas and the mechanical forces associated with piston slap, bearing clearances and friction. Pressure forces strongly depend on the combustion process, which is mainly dominated by the fuel-burning velocity. In addition, this velocity is controlled by the injection rate. The excitation source (pressure and mechanical forces) of combustion noise is characterized by in-cylinder pressure, the system response is associated with the vibration of the block wall and the radiated noise is the final effect of such a vibration [25,26].

Combustion noise may be reduced with either active – actuating on the source – or passive – packaging the engine – actions. Active actions may involve both hardware and settings optimization to control combustion characteristics. Split injection is one of the most effective strategies for the reduction of the rate of change of in-cylinder pressure and thus for the control combustion noise in automotive DI (direct-injection) Diesel engines [27,28]. Together with the injector layout, other parameters are significant to combustion noise, such as injection timing and pressure, which affect also the fuel burning velocity [29]. The bowl geometry also plays an important role in engine noise control, since it has an important influence on the development of resonant pressure fluctuations, which are induced by the ignition characteristics [30,31]. Usually, the use of active actions to control combustion noise has a negative impact on engine performance, driveability and pollutant emissions. Thus, combustion noise should be considered together with these design factors from the earliest stages of engine development.

In this paper, a methodology to address Diesel combustion through the combined analysis of performance, emissions and combustion noise is proposed in order to evaluate the suitability of PCCI engines for automotive applications. With this purpose, the PCCI combustion concept was implemented in a light-duty DI Diesel engine operating at conditions for which such concept is most suitable regarding $NO_x$ and soot emissions reduction. A procedure based on the decomposition of the in-cylinder pressure signal was used to evaluate both objective and subjective aspects of combustion noise [23,29].

The methodology used in this study is presented in Section 2, where the importance of each of the parameters chosen for testing is justified. In Section 3, the experimental configuration is described, with special focus on PCCI combustion requirements and the diagnostic technique used to analyze combustion noise. The results obtained are discussed in Section 4 in two separate subsections, focused respectively on pollutant emissions and combustion noise. Additionally, in Section 5, the trade-off among the combustion noise, pollutant emissions and torque is examined. Finally, Section 6 summarizes the most relevant conclusions extracted from this investigation.

## 2. Methodology

A multi-cylinder Diesel engine operating at low torque and medium speed (1500 rpm) was used for the experiments, because at such condition PCCI combustion offers its major potential and acceptable noise emission is produced with conventional Diesel combustion. As usual in PCCI strategies, the intake temperature was set to 45 °C in order to increase the delay time, thus allowing for a partially premixed combustion. The temperatures of the rest of the engine fluids (fuel, oil, coolant) were kept constant at the nominal values reached with conventional combustion. In all the tests, 10 mg/stroke of fuel were injected in a single injection.

The data base for the evaluation of the suitability of PCCI combustion for emissions reduction and noise control was obtained from engine tests in which the most relevant combustion parameters (injection timing, injection pressure and oxygen concentration of the charge) were varied according to the following lines:

- The injection timing was modified by actuating on the Start of Energizing (SOE) signal. 17 levels of SOE variation were considered in the experimental matrix. The variation range was chosen considering the values often used in PCCI [27,32] and the maximum possible advance avoiding excessive wall impingement. For the spray angle and the bowl size used this limit was established in −60 cad aTDC (after top dead center).
- The effect of the injection pressure was assessed by considering two levels of variation, 800 and 600 bar, which were chosen in order to avoid the wall impingement of fuel when the engine operates with the maximum advance.
- The oxygen concentration of the charge was controlled through the oxygen concentration of the intake air ($[O_2]_{IN}$). In this study,