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# Performance Assessment of Gasoline PPC in a Light-Duty CI Engine

Vittorio Ravaglioli, Fabrizio Ponti, Giacomo Silvagni, and Davide Moro  
University of Bologna

Federico Stola and Matteo De Cesare  
Marelli Europe SpA

## Abstract

In the past years, stringent emission regulations for Internal Combustion (IC) engines produced a large amount of research aimed at the development of innovative combustion methodologies suitable to simultaneously reduce fuel consumption and engine-out emissions. Previous research demonstrates that the goal can be obtained through the so-called Low Temperature Combustions (LTC), which combine the benefits of compression-ignited engines, such as high compression ratio and unthrottled lean operation, with a properly premixed air-fuel mixture, usually obtained injecting gasoline-like fuels with high volatility and longer ignition delay.

Gasoline Partially Premixed Combustion (PPC) is a promising LTC technique, mainly characterized by the high-pressure direct-injection of gasoline and the spontaneous ignition of the premixed air-fuel mixture through compression, which showed a good potential for the simultaneous reduction of fuel consumption and emissions in CI engines. Despite its potential, gasoline PPC might suffer from low combustion controllability and stability, because gasoline spontaneous ignition is significantly affected by slight variation of the local in-cylinder thermal conditions.

This paper summarizes the work carried out to optimize gasoline PPC in a light-duty CI engine, operated in a test cell. The investigated system has been slightly modified to guarantee a stable operation, using gasoline instead of diesel, over a wide load range. The first part of the analysis has been focused on the study of gasoline auto-ignition, the goal being to define an injection strategy suitable to guarantee combustion stability. Then, further activity has been focused on performance investigation through a properly defined span of the main control parameters of interest, such as injection pressure and exhaust gas recirculation.

## Introduction

Road transportation is still mainly based on the use of IC engines, therefore the improvement of its efficiency is of utmost importance to reduce the production of greenhouse gases and pollutant emissions. High efficiencies can be achieved using compression-ignited (CI) engines, currently the most efficient and reliable engine technology used in automotive applications. However, CI engines are usually powered by the high-pressure direct injection of Diesel, which leads to a combustion process that is heterogeneous by nature.

Despite the well-known benefits of diesel combustion, the more and more stringent emissions regulations, especially for nitrogen oxides (NO<sub>x</sub>) and carbon dioxide (CO<sub>2</sub>) production, have led a great amount

of research in the field of innovative combustion approaches. Such solutions, called Low Temperature Combustions (LTC), have shown a good potential to replace conventional combustions mainly because of their high efficiency and low emissions [1,2].

Over the past years, these combustion methodologies, characterized by the lean combustion of a mixture of air and gasoline-like fuels, have been studied to explore their potential in the field of developing cleaner and more efficient IC engines for transports [2]. Since LTC proved to be an effective solution to limit emission and pollutants in IC engines, the main challenge which limited their diffusion is the controllability of the combustion process [3,4].

Homogeneous Charge Compression Ignition (HCCI), characterized by the auto-ignition of a fully premixed homogeneous air-fuel mixture, was the most studied LTC combustion. Since HCCI is a chemical driven process, slight variations of the in-cylinder thermal condition might compromise combustion stability [4]. Many studies conducted on HCCI showed that the most critical aspect to control is the start of combustion (SOC) position, demonstrating that a wrong SOC positioning (defined by the chemical properties of the mixture) could lead to misfire [4] or knocking [5,6]. Several solutions have been proposed to predict the ignition delay in HCCI combustion [7,8]. However, the presented models are usually not accurate enough, mainly due to HCCI strong dependency on charge and engine thermal conditions [9]. As a result, the very small HCCI working range (compatible with engine reliability limits and avoiding misfire) has hindered the diffusion of this combustion process in standard applications [5].

To overcome HCCI limitations, several approaches have been explored. Reactivity Controlled Compression Ignition (RCCI) tackles the problem of combustion controllability combining 2 fuels with different reactivity. The low-reactivity fuel is usually premixed with the intake charge, while the high-reactivity fuel is directly injected in the combustion chamber (to start the combustion process) [10]. Mazda has presented the Spark Controlled Compression Ignition (SPCCI), that triggers the combustion of the premixed air-fuel mixture by using the energy coming from a spark plug. Thanks to injection pressure up to 700 bar and in-cylinder pressure sensors, Mazda has demonstrated the applicability of the SPCCI to industrial applications [11]. Moreover, among other researchers, Delphi-Aramco widely studied gasoline Partially Premixed Combustion (PPC) [12,13]. Performing a properly calibrated sequence of high-pressure fuel jets (from 400 to 1000 bar) per cycle, they proved the stability of the combustion of a compression ignited lean mixture with benefits both in terms of pollutants [14] and efficiency [15] (with respect to diesel combustion). With gasoline PPC, only the first injection burns as an HCCI combustion, while the following fuel jets occur in stratified conditions

(stratification gradient depends mainly on fuel pressure and thermodynamic condition of the combustion chamber [16]). Despite the negative effects of the stratification on pollutants (NO<sub>x</sub> increases), the controllability (with respect to HCCI operation) of the combustion process has been significantly improved by using high-pressure multiple injections [13,17,18].

As reported in literature, despite the improvement in PPC controllability with multiple injections, a detailed knowledge of gasoline auto-ignition mechanisms still plays a crucial role [19,20]. Since the combustion of the first injection can be considered chemically driven, an accurate knowledge of the SOC is necessary to stabilize the combustion of the following fuel jets [21,22,23]. As a result, injections optimization (rail pressure, number and positioning of injections) might be considered the key point to guarantee a reliable and efficient combustion process, and therefore the need of a high-performance injection system becomes crucial working with PPC [24,25,26]. For this reason, Marelli developed an injection system able to overcome the limitations of standard gasoline high-pressure systems (especially maximum fuel pressure) [27].

This work summarizes the activities carried out to convert a light-duty 1.3L turbocharged standard diesel engine to a gasoline PPC engine. Starting from the experimental investigation of gasoline spontaneous ignition in a compression ignited engine, a wide activity has been performed to evaluate how injection pattern design, injection pressure variation and intake conditions (air temperature and boost pressure) affect combustion efficiency, stability, and impulsiveness. By using a “single-cylinder” approach, different engine speeds and loads have been tested, the goal being to identify a reliable reference injection management suitable to operate gasoline PPC over the whole engine operating range. Once the base injection pattern has been defined, always bearing in mind the reliability limits of the engine (Peak Pressure Rise Rate equal to 10 bar/deg in this work), the full conversion of the engine has been performed. Additional components, such as volumetric compressor, custom ECU and intake air thermoregulation unit have been mounted and managed to guarantee gasoline PPC stability in all the critical conditions that would compromise gasoline ignitability (low boost pressure and intake temperature) with the standard engine layout (especially cranking, idle and low loads). Once the engine has been fully converted, an experimental activity has been carried out, aimed at quantifying the pollutants reduction potential of gasoline PPC (especially soot). However, according to the literature [11,12,13], the obtained results confirm the need to use the Exhaust Gases Recirculation (EGR) system to also limit NO<sub>x</sub> production. As a result, the last step of the experimental activity has been focused on testing gasoline PPC with external EGR, the goal being to evaluate the effects on pollutants production and efficiency of this solution. The comparison between efficiency and pollutants obtained with conventional diesel combustion (CDC) and gasoline PPC demonstrated that this LTC can be considered an effective solution moving toward cleaner and more efficient IC engines.

## Experimental setup

The activity presented in this study is based on a wide set of experimental tests carried out using a light-duty 1.3L turbocharged compression-ignited engine installed in a test cell. The main technical characteristics of the reference engine are summarized in Table 1.

Displaced volume	1248 cc
Maximum Torque	200 Nm @ 1500 rpm

Maximum Power	70 kW @ 3800 rpm
Injection System	Common Rail, Multi-Jet
Bore	69.6 mm
Stroke	82 mm
Compression ratio	16.8:1
Number of Valves	4 per cylinder
Architecture	L4
Firing Order	1-3-4-2

**Table 1. Engine technical characteristics.**

During the first part of the work, a preliminary investigation of gasoline PPC was conducted developing the “single cylinder” configuration: one cylinder (fueled with gasoline) tested the LTC while the 3 cylinders fueled with diesel provided the load needed to keep the engine in stable conditions (mainly rpm and boost pressure). An additional common-rail fuel system (high pressure pump, rail, and ducts) was added fueling one of the 4 solenoid injectors with commercial 95 RON gasoline, while the others were kept in a standard configuration (diesel-fueled). To control the additional fuel system, a specifically designed control strategy was implemented in a Rapid Control Prototyping (RCP) system based on a National Instrument hardware (cRio 9082). Gasoline pressure management was simply performed changing the duty cycle of the flow control solenoid valve, which manages gasoline flow upstream the high-pressure pump. Through a PID controller, the RCP system acquired the gasoline pressure signal (coming from the rail-mounted pressure sensor) and changed the PWM command according to the difference between target and feedback gasoline pressure. Furthermore, the RCP system also managed the gasoline injector both in terms of number of injection pulses per cycle, injection location and duration (injected mass during each injection). To do so, the RCP system acquired the signal coming from the encoder installed in the flywheel and calculated in real-time the angular position of the crankshaft. Once the injection strategy was chosen (for each injection: Start of Injection angle, SOI, Energizing Time, ET) the RCP communicated with the standard ECU via CAN bus the calculated values overwriting the default ones (thus, the electrical command for the gasoline injector was generated by the ECU).

In the “single cylinder” layout, no intake/exhaust systems modifications were made. Therefore, the management of the intake conditions (boost pressure and temperature) was obtained using the standard engine-mounted devices (air cooler and turbocharger with VGT actuator). To analyze the combustion process, the engine was equipped with 4 piezoelectric in-cylinder pressure sensors (AVL GH14P) acquired at high frequency (200 kHz) and real-time processed by the indicating system (OBI). The combustion indexes [28], such as center of combustion (CA<sub>50</sub>), indicated mean effective pressure (IMEP) and peak pressure rise rate (PPRR) calculated with the OBI system were sent to the RCP via CAN bus and used as inputs for the closed-loop combustion controllers (load and center of combustion), usually necessary to guarantee the stability of LTCs. During the experimental tests, both standard and additional sensors were acquired and used as inputs/feedbacks for the control algorithms. The standard sensors were monitored and logged using INCA software and ETAS hardware (ES591.1, connected to the standard ECU). With regard to the thermal efficiency calculation, an ultrasonic fuel flow meter (FlowSonic FFM LF DP-010-02) was installed in the low-pressure fuel line monitoring the instantaneous fuel consumption. A complete scheme of the discussed experimental setup is reported in Figure 1.

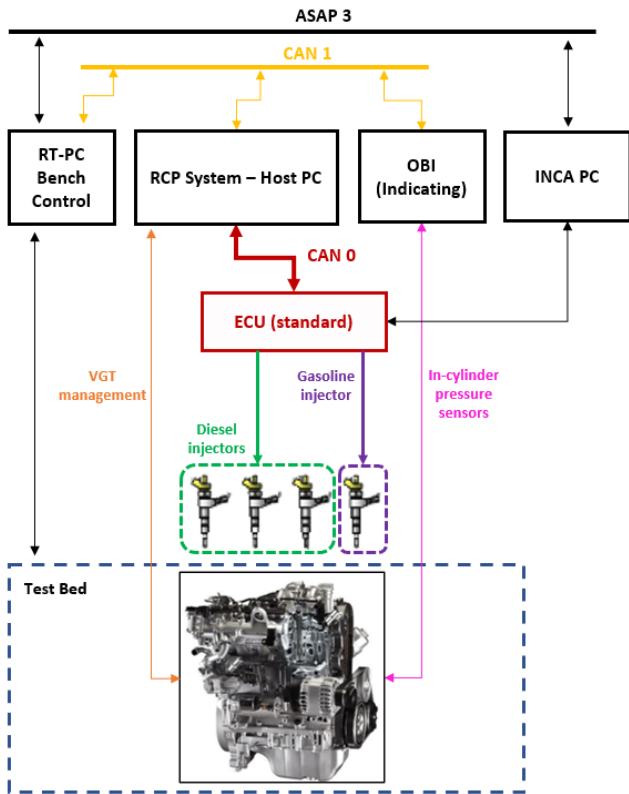


Figure 1. Scheme of the experimental layout developed to investigate gasoline PPC combustion in “single cylinder” mode.

Despite the “single cylinder” layout proved to be effective investigating gasoline PPC sensitivity to some crucial control parameters, such as rail pressure, injection phasing and intake conditions, it was not possible to obtain information about engine-out emissions, mainly because the location of the pollutants measurement systems did not allow distinguishing between the cylinder fueled with gasoline and the others fueled with diesel.

To further explore the LTC under study, during the second part of the experimental activity the engine was fully converted to gasoline PPC, running all the 4 cylinders with gasoline PPC. After removing the additional injection system (gasoline will simply replace diesel in the standard injection system), the air path of the engine was modified adding a volumetric supercharger (Eaton Compressor M24, driven by an electric motor) upstream the dynamic compressor and a diathermic oil thermoregulation unit (TEMPCO T-REG HCE 609/15-O). These two systems allowed to guarantee gasoline ignitability even during cranking, idle and low load conditions i.e., when the low energy content of the exhaust gases is not enough to drive the turbine. Once the engine overcomes these critical conditions and the turbocharger has enough energy to reach the speed required to control the boost pressure directly with the VGT, the external compressor is switched off and by-passed. Therefore, no negative energy contribution spent on the volumetric compressor needs to be considered in the evaluation of combustion efficiency.

To maximize the flexibility in the management of both engine and actuators and to overcome limitations of the production ECU (when is used in unconventional testing conditions), all the control strategies for the engine and external devices management have been implemented in a custom ECU (SPARK by Alma Automotive) based on National Instruments hardware and fully programmable via LabView software.

The integration of this new component in the test bench network allowed simplifying the control layout (the RCP controls only the diathermic heater) and improving testing operations. Figure 2 shows the control systems and the engine layout developed to manage the fully converted gasoline PPC engine.

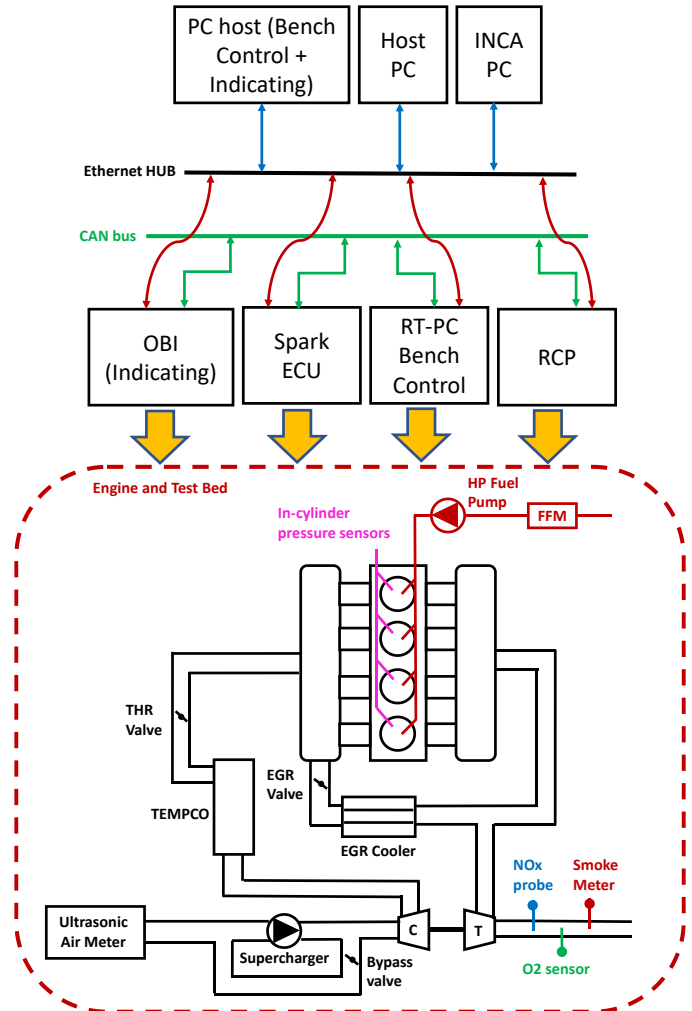


Figure 2. Scheme of the fully converted gasoline PPC engine and control system layout.

As mentioned before, the full engine conversion allowed the measurement of gasoline PPC engine-out emissions. To do so, a Continental (SNS14) NO<sub>x</sub> sensor and an AVL Smoke Meter (415S) were installed in the exhaust line. Finally, the last part of the activity was focused on testing the impact of the EGR (the system is already present in the production engine configuration) on efficiency and pollutants while running the engine in gasoline PPC mode at different speeds and loads.

## Results and Discussions

### Analysis of the Ignition Mechanisms for Pilot Injection Calibration

The spontaneous ignition of multiple consecutive gasoline injections is strongly influenced by the thermal condition experienced by the fuel after its injection. In particular, the first fuel jet of the pattern behaves

as an HCCI combustion, with high ignition delay and, consequently, difficult controllability of its combustion phasing. Then, after the combustion of the first fuel jet, in-cylinder pressure and temperature rise, reducing the ignition delay of the following fuel jets and improving the controllability. Due to the crucial role played, in the design of the combustion process, by the combustion of the first fuel jet, the first part of the activity has been focused on the study of its ignition mechanisms [16,19, 24, 25]. In particular, the impact of intake conditions (temperature and pressure) and injection pressure on the ignition delay has been investigated, for a given mass of injected fuel, through properly designed SOI sweeps, operated in one cylinder of interest with the “single-cylinder layout” (the other cylinders have been simply run at a load high enough to achieve the target boost pressure). To clarify this consideration, Figure 3 reports the comparison between three SOI sweeps (with SOI ranging from 10 to 50 deg BTDC) performed injecting 4 mg/stroke of gasoline (amount of fuel compatible with a Pilot injection) at 300 bar and changing the intake conditions (intake pressure and temperature). Here, the ignition delay has been calculated as the time interval between SOI and start of combustion, defined as the angular position in which the measured apparent heat release (calculated from the cylinder pressure trace [28]) overcomes a fixed threshold (2 J/deg in this case).

efficiency that can be achieved, because it varies the amount of fuel that burns in a pre-mixed or in a diffusive way [20, 23, 24].

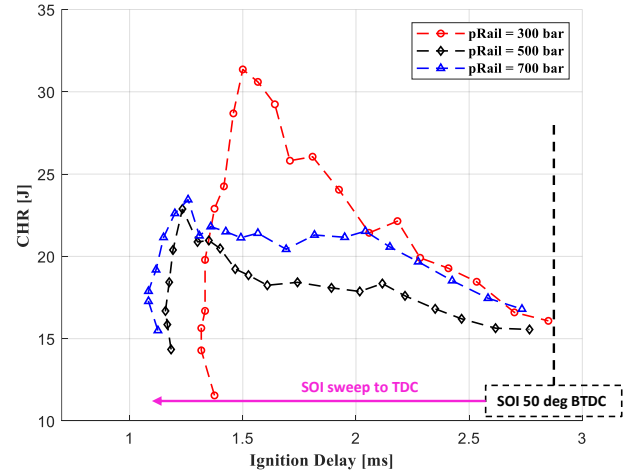


Figure 4. SOI Sweeps run at 2000 rpm, injecting 4 mg/stroke with different rail pressure at boost pressure 1500 mbar and intake temperature 75 °C.

The detailed investigation of gasoline auto-ignition led to the definition of an optimal injection strategy for Pilot injections, i.e., a strategy that automatically corrects the SOI to guarantee high combustion efficiency and stability of the Pilot injections.

### Analysis of Multi-Jet Injection Patterns operated with gasoline PPC

Once the stability of the ignition process has been guaranteed, the second step of the activity has been mainly focused on the definition of a stable multi-jet pattern (within the cycle) for gasoline PPC. As it is well known, the injection pattern can be designed using many degrees of freedom (such as number, duration and start of each injection). To limit the total number of degrees of freedom, the maximum number of injections used to design the PPC injection pattern was set to three (Pilot, Pre, Main) and the fuel mass injected in Pilot and Pre was set to 1 mg/stroke (suggested by literature review and previous experience on the engine under study). The Dwell Time (DT) between the pre-injections was kept nearly equal to the one used in the standard diesel calibration (compatible with the dynamic of the injector’s needle and pressure waves in the fuel system).

Combustion investigation was initially performed using the single-cylinder layout. Several CA50 sweeps were performed to quantify ISFC and PPRR in the cylinder operated with gasoline PPC. During each test, the center of combustions was varied changing the start of the Main injection, while the amount of fuel introduced was adjusted (simultaneously) to keep the IMEP of the cylinder at a proper target value (the pre-injections were not varied and kept at their optimal SOI, values determined with the experimental activity discussed in the previous section depending on pRail and intake conditions). During the CA50 sweep, the variation of the fuel quantity of the Main injection is obviously necessary to compensate the variation of the torque, which is maximum in correspondence of an optimal CA50 value. To accurately determine the ISFC of the single cylinder operated with gasoline PPC, the previously mentioned high accuracy ultrasonic fuel flow meter (Flowsonic LF) was used.

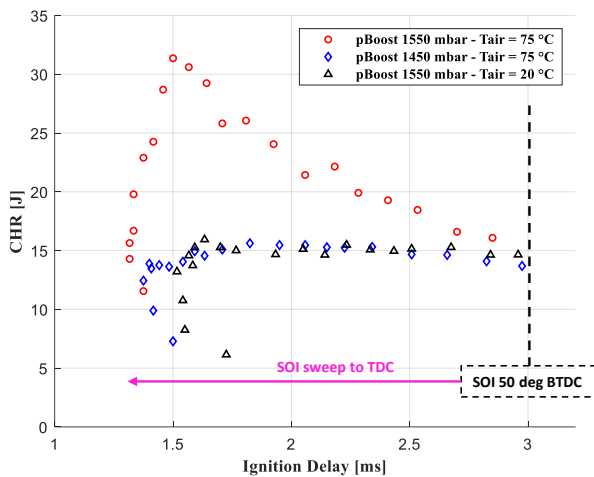


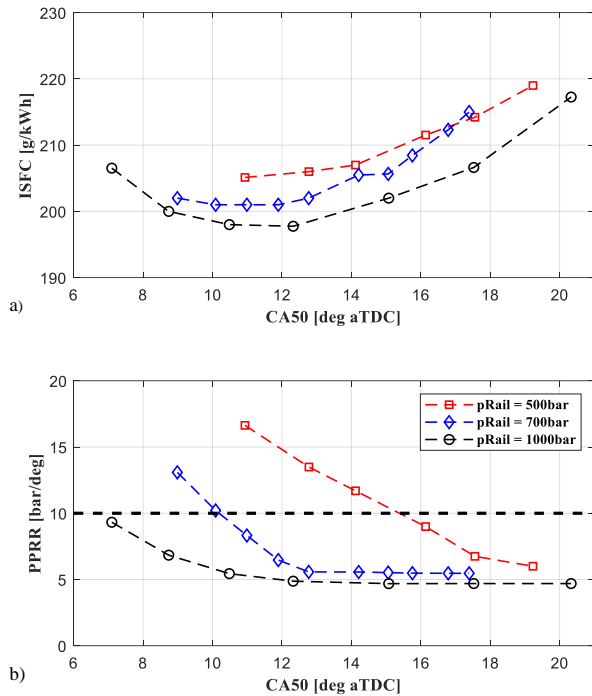
Figure 3. SOI Sweeps run at 2000 rpm, injecting 4 mg/stroke with different intake conditions (pressure and temperature) at pRail 500 bar.

As it can be observed, even though the injected mass is the same, the combustion efficiency obtained during the sweep performed with intake pressure approximately equal to 1550 mbar and intake temperature 75°C is significantly higher, while, in the same SOI range, the maximum Cumulate Heat Release (CHR) [28] of the other sweeps is nearly constant and stands around 15 J. This result highlights the sensitivity of the combustion of a small amount of gasoline (directly injected in a compression ignited engine) to variations of SOI and intake conditions.

The discussed analysis has been also extended to different injection pressures. Comparing similar tests run at different injection pressures highlights that also the variation of this parameter has a strong impact on combustion efficiency and ignition delay. As an example, Figure 4 shows that, for constant intake conditions, the increase of the rail pressure fastens the ignition process (same SOI), therefore reducing the ignition delay of the mixture. In addition, Figure 4 demonstrates that also the selected rail pressure varies the maximum combustion

The variation of the center of combustion also results in a variation of the combustion impulsiveness, which might lead to reliability issues and engine failure. To quantify such impulsiveness, during the tested CA50 sweeps the PPRR was measured and compared with the maximum acceptable PPRR for the tested engine (10 bar/deg) [19,20].

The CA50 sweeps were carried out at different rail pressures. As a matter of fact, previous works [20,22] highlight the effect of rail pressure on gasoline spontaneous ignition, especially that higher pressures significantly increase jet penetration and reduce the size of the injected fuel drops, consequently improving fuel vaporization and charge homogeneity. Figure 5 reports a comparison between 3 CA50 sweeps performed at 2000 rpm, IMEP = 14 bar and setting the rail pressure equal to 500, 700 and 1000 bar.



**Figure 5. a) ISFC and b) PPRR measured during the CA50 sweeps run at 2000 rpm, IMEP=14 bar, PRail equal to 500, 700 and 1000 bar. Different CA50 ranges available at each rail pressure level.**

As it can be observed, increasing the rail pressure has a beneficial impact on the ISFC, which shows its minimum with pRail = 1000 bar and CA50 approximately equal to 11 deg. It is also interesting to notice that, while anticipating the combustion process, the measured PPRR tends to increase at all the investigated rail pressures. However, higher rail pressures show a remarkable PPRR reduction potential. The PPRR measured during the sweep carried out at 500 bar exceeds the maximum acceptable PPRR (10 bar/deg) when the CA50 is approximately 15 deg aTDC, while the sweeps run at 700 and 1000 bar become progressively less critical in terms of PPRR. Both at 700 and 1000 bar it is possible to operate the engine at optimal CA50 and keep the maximum measured PPRR always below the established reliability limit.

The first stage of the combustion investigation activity, performed running CA50 sweeps at different loads and speed in the single cylinder operated with gasoline PPC, allowed determining a baseline

calibration (injection pattern and air system) suitable to achieve combustion stability over the whole engine load range. Then, hardware and software were improved to obtain a 4-cylinder compression-ignited engine fully operated with gasoline PPC. As already discussed, the main hardware improvements necessary to run the 4-cylinder gasoline CI engine was the addition of a volumetric compressor.

The discussed testing layout, specifically developed to run the CI engine with gasoline, was finally used to quantify the potential of gasoline PPC both in terms of performance and engine-out emissions reduction.

### Optimization of High-Pressure EGR

Based on the previously described fully converted engine layout, a wide experimental activity has been carried out to investigate the performance of gasoline PPC in terms of pollutants and efficiency. Starting from the baseline calibration obtained during the “single cylinder” activity, several engine operating points, which represent the typical gasoline PPC operating range, were tested. Despite clear improvements in fuel consumption and Filter Smoke Number (FSN), previous works demonstrated that gasoline PPC operated without EGR always produces higher NOx with respect to the reference CDC [11,12,13].

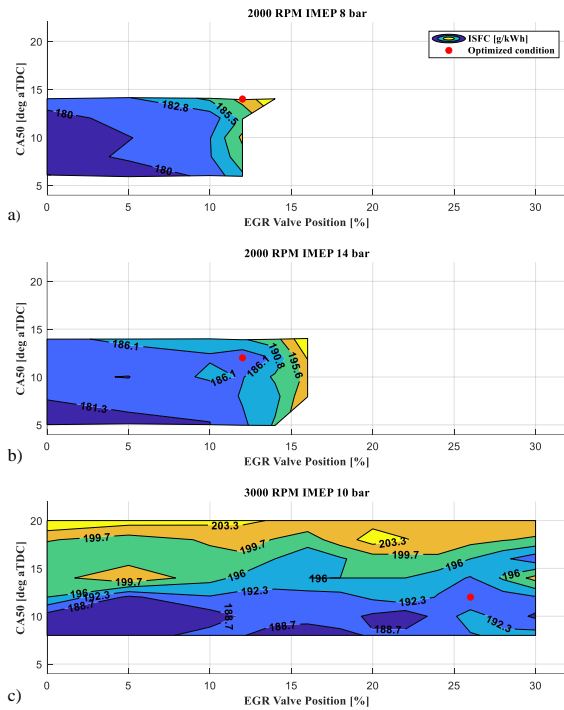
As widely reported in literature [29,30,32], since the EGR increases charge dilution (the amount of oxygen available for fuel oxidation decreases), the peak combustion temperature decreases and, consequently, the quantity of NOx produced decreases. As a result, EGR is needed to improve engine-out emissions of gasoline PPC.

Previous works [30,31] demonstrated that the presence of EGR strongly affects the combustion of Pilot injections (chemically driven) in compression ignited engines. Although hotter gases (with respect to intake temperature) are recirculated, the chemical inertia given by the exhaust gases modifies the charge composition increasing the ignition delay of the pre-injections. As a result, retarding the ignition, combustion becomes more impulsive and unstable (with very high EGR rates). Therefore, to guarantee combustion stability, further pilot injections position optimizations are needed using high EGR rates [33, 34]. Since the presence of the exhaust gases decreases the total amount of oxygen available for fuel oxidation, also the combustion of the main injection is affected, mainly because the mixing process between air and fuel becomes slower and combustion becomes longer and less efficient.

To verify the impact of EGR on NOx and efficiency, the experimental activity has been focused on testing different EGR valve positions while performing CA50 sweeps (without compromising combustion stability). Three different operating points were tested, which cover a significant portion of the gasoline PPC operating range, the goal being to obtain a reference gasoline PPC engine calibration respecting the manufacturer targets in terms of pollutants and efficiency.

Figure 6 shows the effect of EGR on ISFC in the tested engine operating points. As expected, increasing the CA50 at constant EGR valve position, the IFSC will rise (lower thermal efficiency). As explained before, since the EGR makes the combustion process slower, increasing the EGR valve position at a constant CA50 (keeping constant the intake/exhaust pressures) the combustion process will be characterized by higher fuel consumption. The operating conditions run at low (2000 rpm / IMEP 8 bar) and high (2000 rpm / IMEP 14 bar) load, reported in Figure 6 a) and b) respectively, clearly highlight the impact of the EGR and CA50 on ISFC. Furthermore, since higher

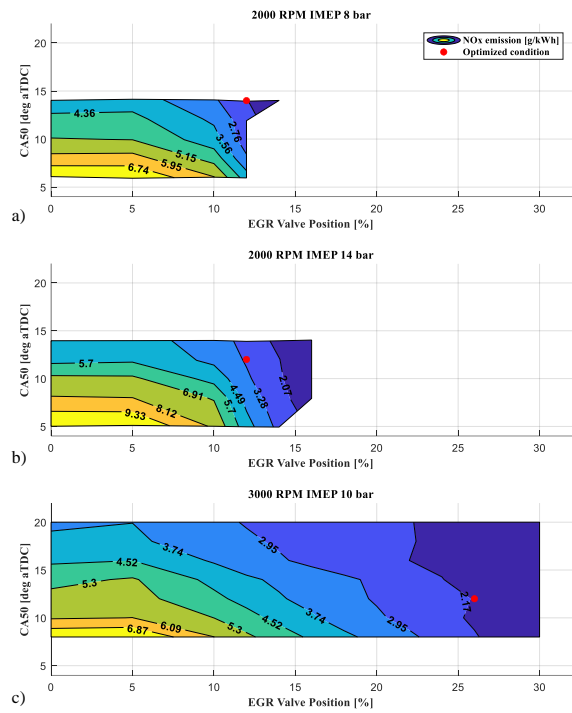
engine speeds promote charge mixing, the operating condition reported in Figure 6 c) (3000 rpm / IMEP 10 bar) shows less pronounced dependency on the EGR because better air-fuel mixing is always achieved.



**Figure 6. Impact of EGR on ISFC performing a CA50 sweep in different engine operating points: a) 2000 rpm – IMEP 8 bar, b) 2000 rpm – IMEP 14 bar and c) 3000 rpm – IMEP 10 bar.**

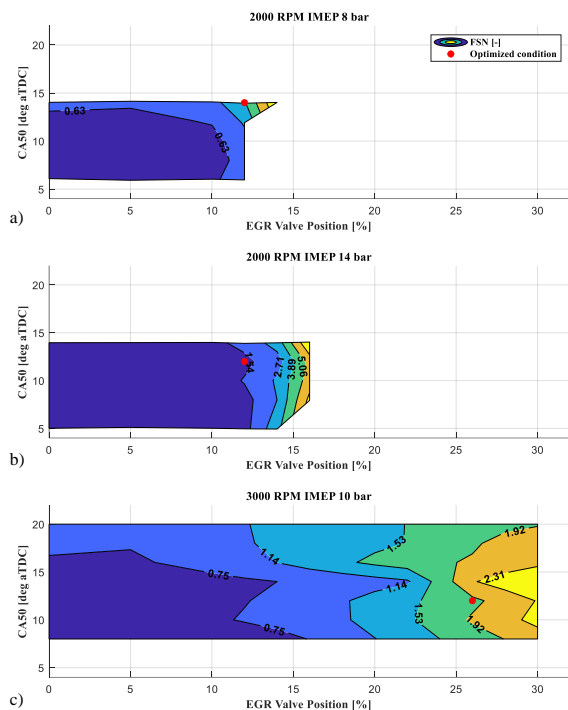
Figure 7 and Figure 8 show the pollutants (NOx and FSN) measured during the experimental activity. As for the standard CI combustion process, NOx concentration decreases while increasing the EGR rate, mainly because of the lower oxygen content of the mixture, slowing down the combustion process. The main drawback using EGR is the FSN increment. As a matter of fact, due to lower oxygen concentration and poor air-fuel mixing (not enough to fully oxidize the injected fuel until the end of combustion), particulate matter will rise. Those trends can be observed both at high and low load and for different engine speeds. It is important to underline that combustion instability limits the gasoline PPC operating range (especially at low load) and therefore reduces the applicability of this combustion approach.

Since the aim of the activity is to identify a reference gasoline PPC calibration respecting the targets of the manufacturer both in terms of efficiency and pollutants, the optimized condition has been identified (and reported in the related maps) as best trade-off between pollutants and efficiency for each tested operating point. The optimized conditions identified through this experimental activity confirm that, to limit NOx production, gasoline PPC needs high values of EGR.



**Figure 7. Impact of EGR on NOx production performing a CA50 sweep in different engine operating points: a) 2000 rpm – IMEP 8 bar, b) 2000 rpm – IMEP 14 bar and c) 3000 rpm – IMEP 10 bar.**

Once the optimized conditions have been defined, a comparison between efficiency and engine-out emissions produced with gasoline PPC and CDC in the same engine (and test bench) has been performed. Table 2 summarizes the performance assessment for the optimized tested conditions (these results are the difference between CDC and GCI, therefore positive values quantify the benefit obtained with gasoline PPC with respect to standard CDC).



**Figure 8. Impact of EGR on FSN production performing a CA50 sweep in different engine operating points: a) 2000 rpm – IMEP 8 bar, b) 2000 rpm – IMEP 14 bar and c) 3000 rpm – IMEP 10 bar.**

By looking at the reported results, benefits in efficiency (up to 3.7% ISFC reduction), NOx (up to 21% reduction) and FSN (up to 22% reduction) can be clearly found at high loads and engine speeds. However, at 2000 rpm - 8 IMEP improvements in fuel consumption and engine-out emission are not as visible as at higher load (especially for NOx production the use of EGR demonstrated to be ineffective). Since the use of EGR changes the ignition delay of the pre-injections, a further optimization of pre-injection position is needed to increase the benefits of this LTC concept even at lower loads (in which this combustion process did not show clear advantages with respect to CDC).

Engine Operating Point	$\Delta$ ISFC [%]	$\Delta$ NOx [%]	$\Delta$ FSN [%]
2000 rpm – IMEP 8 bar	0.5	-41	7
2000 rpm – IMEP 14 bar	3.7	21	21
3000 rpm – IMEP 10 bar	3.1	9	22

**Table 2. Performance assessment (ISFC, NOx and FSN) between standard Diesel combustion with manufacturer calibration and gasoline PPC performed in the same engine and test bench.**

## Summary/Conclusions

This work summarizes the activity carried out to convert a standard light-duty CI engine (originally operated with diesel) to gasoline PPC combustion. To guarantee a stable operation in all the load and speed range of the engine under study, the engine was modified adding a

volumetric compressor, suitable to provide the minimum level of boost pressure necessary to auto-ignite the air-gasoline mixture.

The first part of the study, performed on a single cylinder operated with gasoline PPC, was mainly aimed at the investigation of gasoline auto-ignition mechanisms. Such activity led to the identification of an injection strategy which guarantees a robust and efficient combustion of the Pilot injections (which behave as HCCI combustions).

Then, gasoline PPC was tested using a 3-injection pattern, analyzing the impact of several injection parameters (especially rail pressure) on combustion efficiency and impulsiveness. This stage of the study was started on the single-cylinder layout and then applied to the whole engine operated with gasoline PPC. This activity was finally extended to operating conditions with exhaust gas recirculation (high-pressure). To assess gasoline PPC performance on the engine under investigation, several scans were run, varying the rate of recirculated EGR, while keeping constant the center of combustion. During these scans, ISFC, NOx and soot were measured. EGR proved to be useful to mitigate gasoline PPC NOx emissions, but the use of high EGR rates might have a negative impact on efficiency and PM emissions. However, the obtained experimental results demonstrated the potential associated to gasoline PPC, which, for loads higher than IMEP 9 bar, improved both engine efficiency and emissions with respect to the optimal values obtained with standard CDC operation. It is important to notice that, in the presented study, the engine hardware was kept nearly identical to the one used its standard CDC configuration (only the volumetric compressor was added). As a result, the obtained results demonstrate that a significant benefit, both in terms of emissions and fuel consumption, can be obtained through a proper optimization of the management system, with no major hardware cost.

Further activity is currently being performed to collect more data and set-up a control-oriented model of the ignition delay (with and w/o EGR), the goal being to operate the engine with gasoline PPC over its whole operating range, always achieving the best compromise between emissions and fuel consumption.

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## Definitions/Abbreviations

aTDC

After Top Dead Center angle

bTDC	Before Top Dead Center angle	PWM	Pulse Width Modulation
CA50	Center of combustion	RCP	Rapid Control Prototyping
CAN	Controller area network	RON	Research Octane Number
CDC	Conventional diesel combustion	SOC	Start of Combustion angle
CHR	Cumulate Heat Release	SOI	Start of Injection angle
CI	Compression Ignited	SPCCI	Spark Controlled Compression Ignition
CO2	Carbon Dioxide	TDC	Top Dead Center angle
DT	Dwell Time	V <sub>BDC</sub>	Volume at Bottom Dead Center angle
EGR	Exhaust Gas Recirculation	VGT	Variable geometry turbine
ET	Energizing Time		
FSN	Filter Smoke Number		
HCCI	Homogeneous charge compression ignition		
IC	Internal Combustion		
ID	Ignition Delay		
IMEP	Indicated mean effective pressure		
ISFC	Indicated specific fuel consumption		
LTC	Low Temperature Combustion		
NO <sub>x</sub>	Nitrogen Oxides		
PPC	Partially premixed combustion		
PPRR	Peak pressure rise rate		
pRail	Gasoline injection pressure		