

# Combustion Indexes for Innovative Combustion Control

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## ABSTRACT

The continuous development of modern Internal Combustion Engine (ICE) management systems is mainly aimed at combustion control improvement. Nowadays, performing an efficient combustion control is crucial for drivability improvement, efficiency increase and pollutant emissions reduction. These aspects are even more crucial when innovative combustions (such as LTC or RCCI) are performed, due to the high instability and the high sensitivity with respect to the injection parameters that are associated to this kind of combustion. Aging of all the components involved in the mixture preparation and combustion processes is another aspect particularly challenging, since not all the calibrations developed in the setup phase of a combustion control system may still be valid during engine life.

The most important quantities used for combustion control are engine load (Indicated Mean Effective Pressure or Torque delivered by the engine) and center of combustion (CA50), i.e. the angular position in which 50% of fuel burned within the engine cycle is reached. All these quantities can be directly evaluated starting from in-cylinder pressure measurement; however, the use of in-cylinder pressure sensors would significantly increase the cost of the whole engine management system. Due to these reasons, over the past years, many methodologies have been developed by the authors of this paper in order to evaluate combustion characteristics using low-cost sensors or sensors that are already present on-board. The approaches considered in this paper are based on engine speed fluctuations and engine block vibration. These measurements are performed through the magnetic pick-up facing the toothed wheel already present on-board and a low-cost accelerometer mounted on engine block. Each of these measurements allows estimating a combustion characteristic that can be used for combustion control, such as IMEP, pressure peak position, CA50. The paper presents how the combination of the information that can be extracted from the low or zero cost sensors employed enables the control of innovative combustions, as for example dual-fuel RCCI combustion.

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## INTRODUCTION

Modern compression ignited diesel engines can be considered the most efficient engine technology for commercial automotive applications. However, due to diesel direct injection, the air fuel mixture in the combustion chamber is heterogeneous in nature. Consequently, combustion produces both particulate matter (PM, in rich regions) and nitric oxides (NOx, in stoichiometric and lean regions), that have both a negative impact on health and environment.

Over the last years, increasingly stringent regulations on pollutant emissions requested, for diesel engines, a significant reduction in both NOx and PM. Such requests motivated a large amount of research in the field of innovative combustion methodologies. As a matter of fact, innovative low temperature combustions (LTC), such as reactivity controlled compression ignition (RCCI) [1] and partially

premixed combustion (PPC) [2], proved to be effective in the reduction of both PM and NOx. The thermal efficiency for LTC combustions is usually equal or higher than the efficiency of conventional diesel combustion (CDC) [3-4].

The main obstacle to the use of LTC strategies in large-scale applications is related to the fact that ignition and combustion event are driven by chemical kinetics. Consequently, combustion is very sensitive to cylinder thermal conditions and its control is very difficult over a wide range of operating conditions [4, 5, 6, 7]. The only way to keep LTC combustion stable over a wide operating range is to set up a closed-loop combustion control strategy.

This work proposes a closed-loop combustion control strategy that real-time varies the injection pattern in such a way to keep the center of combustion (CA50) at a proper target value. Center of combustion, i.e. the angular position in which 50% of the injected fuel amount is burned, can be directly calculated through a proper processing of in-cylinder pressure trace [5]. However, pressure sensors on-board installation is still uncommon, mainly due to problems related to sensors' reliability and cost. To overcome this problem, over the past years, several remote combustion sensing methodologies have been developed to extract information about combustion phasing within the engine cycle through the real-time processing of signals coming from low-cost sensors (such as speed sensors or accelerometers) mounted on the engine. This work presents a combustion control methodology based on the combination of information extracted by two low-cost sensors, i.e. the crankshaft speed sensor already present on-board and one accelerometer mounted on the engine block.

The aim of this work is the development of a strategy for the control of low temperature combustions. The strategy was developed and validated using a compression ignition engine run in RCCI mode. In such operating mode, low reactivity fuel (gasoline in the case under investigation) is premixed with the intake charge, while a high reactivity fuel (diesel) is directly injected in the combustion chamber using the standard Common-Rail system. As above mentioned, the way combustion takes place is strongly influenced by chemical kinetics, but RCCI mode has the additional benefit of being able to adjust diesel start of injection (SOI) and injected fraction (with respect to the amount of gasoline) to control combustion phasing and stability.

The engine used during the experimental activity is a 1.3L common rail diesel engine mounted in a test cell. To run the engine in RCCI mode, a specifically designed intake manifold with 4 gasoline PFI injectors (one per cylinder) was installed. The first part of the experimental activity consisted in the characterization of engine behavior when used in RCCI mode, the goal being to identify a nominal calibration of all the injection parameters. Then, the closed-loop strategy that controls the center of combustion was developed and validated using, as combustion feedbacks, both measured CA50 (from in-cylinder pressure measurement) and estimated CA50 (obtained through a proper processing of crankshaft speed and engine block vibration).

## EXPERIMENTAL SETUP

The analysis has been performed using a 1.3L Common-Rail Diesel engine mounted in a test cell. Table 1 summarizes the technical characteristics of the engine under investigation.

The engine under study is equipped with one piezoelectric pressure sensor (AVL GH14P) per cylinder. In-cylinder pressure signals are acquired and analyzed using an indicating system (OBI by Alma Automotive) that allows real-time calculation of indicated torque ( $T_{ind}$ ) and center of combustion (CA50). To measure engine block vibration, one accelerometer (PCB Piezotronic 352C33) was installed in the middle between cylinder 2 and 3. All the standard sensors, i.e. the ones already present on-board for other control purposes, are monitored and sampled using INCA software and ETAS hardware.

Table 1. Engine technical characteristics.

|                   |                        |
|-------------------|------------------------|
| Displaced volume  | 1248 cc                |
| Maximum Torque    | 200 Nm @ 1500 rpm      |
| Maximum Power     | 70 kW @ 3800 rpm       |
| Injection System  | Common Rail, Multi-Jet |
| Compression ratio | 16.8:1                 |
| Number of Valves  | 4 per cylinder         |
| Architecture      | I4                     |
| Firing Order      | 1-3-4-2                |

### Additional Injection System for Gasoline Injection

As discussed above, the aim of the activity is to set up an accurate and low cost methodology for LTC control. To develop and validate the methodology, RCCI combustion has been chosen. As a matter of fact, such combustion is significantly influenced by the amount of fuel and the start of the injection performed to introduce the high reactivity fuel (diesel in this case) in the combustion chamber [8, 9, 10]. Therefore, diesel start of injection can be real-time adjusted to keep CA50 constant, i.e. to keep RCCI combustion stable to a target value.

To test the potential of the proposed combustion control, air and fuel path of the Diesel engine were modified to be compatible with the RCCI operating mode. In this application, the selected low and high reactivity fuels are gasoline and diesel respectively. Gasoline is premixed with the intake charge, while diesel is directly injected in the combustion chamber using the standard Common-Rail system. According to Reitz [3,11], a new intake manifold with 4 gasoline PFI injectors (Magneti Marelli PFI injectors) installed was manufactured. The PFI injectors are connected to a rail filled with gasoline through a rotary fuel pump. During the tests, rail pressure has been kept constant at 5.5 bar using a pressure regulator. Figure 1 shows the intake manifold modified with the PFI gasoline injectors.

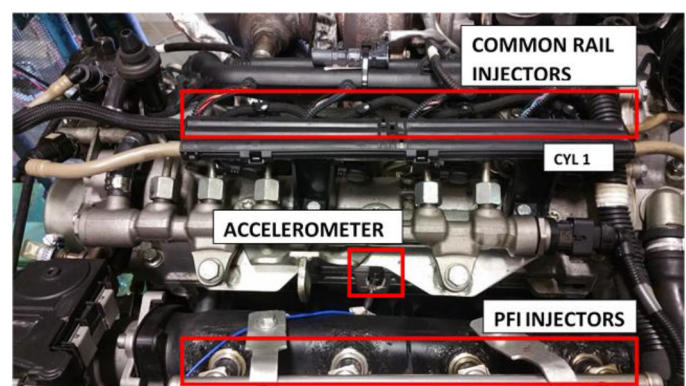


Figure 1. Modified intake manifold.

The additional gasoline system allows injecting gasoline in the intake manifold, creating a gasoline-air mixture that enters the combustion chamber when the intake valve opens. Then, combustion activation is obtained through Diesel direct injection, performed using commercially available Bosch common-Rail solenoid injectors (1600 bar system).

### RCP system for closed loop combustion control

Once the air path has been modified installing in the intake manifold one PFI injector per cylinder and connecting the injectors to a new gasoline fuel system, a Rapid Control Prototyping (RCP) system for closed-loop combustion control has been developed. Such system, based on a National Instruments cRio 9082, receives from OBI (indicating system) the calculated indicated quantities (torque and CA50) via CAN bus and acquires at high frequency both accelerometer signal (50 kHz) and the digital signal coming from the crankshaft speed sensor (20 MHz), used to determine the angular location of the block acceleration signal within the engine cycle. Finally, analog signals coming from standard sensors applied to the engine are all sampled at low frequency (100 Hz).

The RCP system is capable of communicating with the standard ECU via CAN bus to read or overwrite the values of the injection parameters of interest (Energizing Time and Start of Injection in this case). This functionality allows a real-time control of the amount of fuel (ET) and the angular location (SOI) of each diesel direct injection.

Also gasoline injection is managed by the RCP system, that outputs the logical injectors commands. Both Energizing Time ( $ET_{gas}$ , i.e. the amount of gasoline injected) and start of injection ( $SOI_{gas}$ , i.e. injection phasing) can be varied. The RCP system is connected to a dedicated ECU, that converts the logical commands and generates the corresponding electric commands for the PFI injectors. [Figure 2](#) reports a complete scheme of the developed experimental setup.

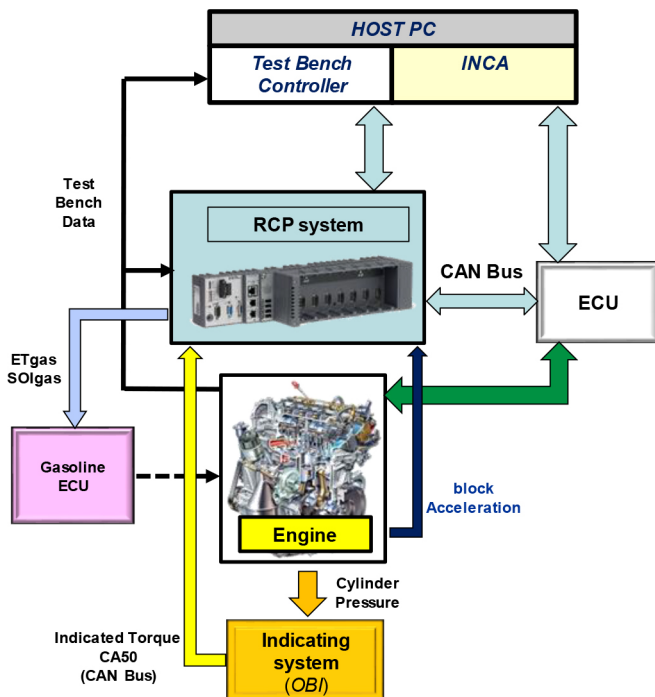


Figure 2. Scheme of the developed experimental setup.

The described RCP system has been used to implement a closed loop controller that manages gasoline injection and automatically varies the start of diesel injection to keep center of combustion equal to a target value.

### INVESTIGATION OF DUAL FUEL RCCI COMBUSTION

The first step of the activity consisted in the open loop characterization of dual fuel RCCI combustion in one operating condition of interest. For this study, the operating point at 2000 rpm and BMEP = 5 bar was chosen. This point provides information about engine performance in the NEDC driving cycle.

Since the engine under study is a standard Common Rail diesel engine, a brief characterization of combustion performance in the operating point of interest was necessary to identify a set of reasonable injection parameters for the dual fuel RCCI operating mode. To do so, engine was initially run at 2000 rpm and BMEP = 5 bar in CDC conditions, with multiple injections per cycle (3) performed at 760 bar of rail pressure and 10% EGR rate. Then, the amount of injected gasoline was gradually increased while reducing diesel ET to keep load constant. Several values of the gasoline/fuel target ratios were investigated. For each ratio, a complete diesel SOI sweep was performed, varying its value in the entire range of combustion stability. Both gasoline and diesel consumptions were measured using 2 AVL 733S fuel meters. Such measurements were necessary to calculate the overall brake specific fuel consumption (BSFC). During each test, engine out emissions were also measured, to identify the benefits related to the use of RCCI combustion with respect to CDC.

The experimental characterization led to the identification of the optimal operating point summarized in [Table 2](#). The selected injection pattern, characterized by a gasoline/diesel target ratio equal to 80/20, allows obtaining a significant pollutant emissions reduction (except for the HC increase, quite common in RCCI combustions) while keeping BSFC approximately equal to the CDC standard calibration. Finally, the peak pressure rise rate (PPRR) is equal to 4 bar/deg, that seems to be acceptable for engine reliability.

Table 2. Optimal set of injection parameters identified for the dual fuel RCCI operating mode at 2000 rpm and BMEP = 5 bar.

|                             |       |
|-----------------------------|-------|
| SOI [° BTDC]                | 55    |
| ET [μs]                     | 335   |
| SOI <sub>gas</sub> [° BTDC] | 380   |
| ET <sub>gas</sub> [μs]      | 2100  |
| EGR rate [%]                | 0     |
| Prail [bar]                 | 500   |
| Prail gas [bar]             | 5.5   |
| Gasoline/diesel ratio       | 80/20 |
| PPRR [bar/deg]              | 4     |
| CA50 [deg ATDC]             | 8     |

[Figure 3](#) reports a comparison between CDC and the optimal RCCI operating condition. Tests were run at constant speed (2000 rpm) and load (BMEP = 5 bar). this comparison provides information about the pollutant emissions reduction potential associated to the selected RCCI operating mode.

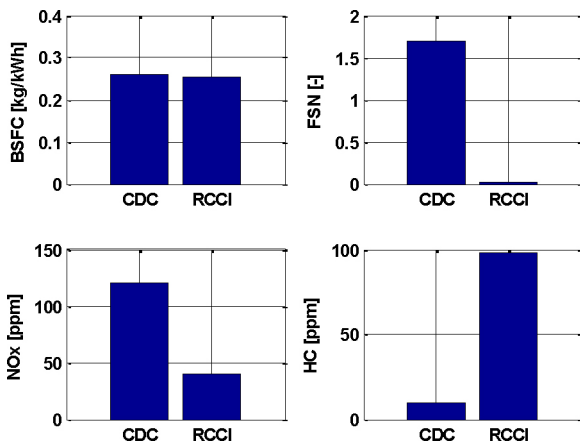


Figure 3. Comparison between CDC and dual fuel RCCI at 2000 rpm and BMEP = 5 bar, both in term of combustion performance and engine-out emissions.

Even if a detailed analysis and optimization of RCCI combustion is beyond the scope of this work, a brief characterization of combustion performance was necessary to identify an interesting operating point to be analyzed. Such optimal condition was used as a baseline for development and test of the closed loop control methodology.

## CLOSED LOOP CONTROL OF RCCI COMBUSTION

The proposed methodology for combustion control keeps constant the center of combustion of each cylinder. To do so, a proper closed loop controller was implemented in the RCP system. The controller is based on a PID that automatically corrects the start of diesel injection (SOI) based on the error between target and measured CA50. For each cylinder, measured CA50 is the average center of combustion measured over the last 20 combustions.

Due to the characteristics of RCCI combustion, it is also necessary to implement a methodology that validates the measured CA50 values to be used by the combustion controller. As a matter of fact, RCCI combustion is characterized by high cycle to cycle variability and low stability, mainly because of the very high sensitivity to cylinder thermal conditions. Such instability might lead to the occurrence of very poor combustions or misfires [12,13]. As it is well known, during these cycles measured CA50 might assume values not correlated with the behavior of the air/fuel mixture in the combustion chamber, mainly due to the very low signal to noise ratio in the calculation of cumulated heat release. For this reason, a strategy that automatically discards cycles with very poor combustions was implemented. The selection is performed based on the coherence between indicated torque delivered by each cylinder (measured) and expected indicated torque. As a matter of fact, torque can be predicted as a function of total amount of fuel injected (gasoline and diesel) and diesel SOI. Here, the effect of diesel SOI variation on torque delivery is similar to effect of spark advance variation in standard SI engines [14]. Eq. (1) defines a factor (named *TFactor*) that quantifies the deviations between measured and expected indicated torque.

$$TFactor = \frac{abs(T_{ind} - T_{indExp})}{T_{indExp}} \cdot 100 \quad (1)$$

When *TFactor* exceeds a calibrated threshold (approximately equal to 85%) the corresponding indicated quantities (Torque and CA50) are not taken into account in the closed-loop control. It is important to underline that the implemented CA50 plausibility check is only performed to avoid the use of combustion feedbacks (CA50) significantly affected by noise (very common in misfiring cycles) and not related to the real behavior of the air/charge mixture. Further work is currently being performed to develop and implement proper strategies to improve combustion stability in case the frequency of misfiring cycles exceeds a calibrated threshold.

Figure 4 reports a scheme of the RCCI combustion control methodology implemented in the RCP system. Here, the “Misfire detection” block implements the torque coherence check based on the value of the index *TFactor*, while the block “CA50 Buffer creation” calculates the average CA50 (*CA50avg*) over the last 20 valid combustions. Finally, the PID controller calculates the final start of diesel injection (SOI) based on the error between *CA50avg* and the target CA50 (*CA50target*).

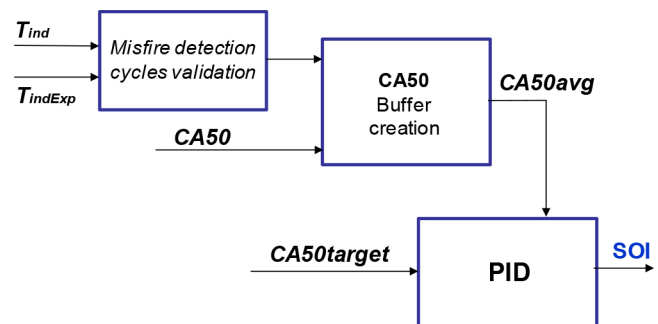


Figure 4. Scheme of the real-time injection controller implemented in the RCP system.

The first test was performed running the engine in steady state conditions at 2000 rpm and BMEP approximately equal to 5 bar. During the steady state tests, the total amount of injected fuel (gasoline+diesel) was kept constant and equal to the total amount of diesel injected to keep the standard diesel engine at 2000 rpm and BMEP = 5 bar (Multi-Jet base calibration).

The base calibrations for gasoline and diesel injections were set equal to the ones reported in Table 1, i.e. the optimal calibrations experimentally determined varying the injection parameters manually. Then, the closed loop controller was activated using as inputs the combustion indexes (indicated torque and CA50) calculated by the indicated system and sent to the RCP system via CAN bus. Figure 5 shows that the PID allows controlling the center of combustion while varying the target from 10 to 7 deg.