

Steady-State and Transient Operations of a Euro VI 3.0L HD Diesel Engine with Innovative Model-Based and Pressure-Based Combustion Control Techniques

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ABSTRACT

In the present work, different combustion control strategies have been experimentally tested in a heavy-duty 3.0 L Euro VI diesel engine. In particular, closed-loop pressure-based and open-loop model-based techniques, able to perform a real-time control of the center of combustion (MFB50), have been compared with the standard map-based engine calibration in order to highlight their potentialities. In the pressure-based technique, the instantaneous measurement of in-cylinder pressure signal is performed by a pressure transducer, from which the MFB50 can be directly calculated and the start of the injection of the main pulse (SOI_{main}) is set in a closed-loop control to reach the MFB50 target, while the model-based approach exploits a heat release rate predictive model to estimate the MFB50 value and sets the corresponding SOI_{main} in an open-loop control.

The experimental campaign involved both steady-state and transient tests. The three control techniques were compared in steady-state tests under various conditions, featuring standard as well as PCCI combustion mode, different kinds of fuels, a disturbance added to the pressure signals from in-cylinder transducers (to simulate the effect of an aged or low-cost pressure transducer) and an injector with a reduced mass flow rate mounted on one cylinder. The behavior of the three controls was tested in transient conditions as well, analyzing in particular fast load and speed ramps.

The above mentioned testing conditions were performed to evaluate the robustness of the pressure-based and model-based techniques compared to standard calibration map-based control and their outcomes in terms of engine operation stability.

The proposed real-time combustion control techniques provided fuel consumption and emissions in line with the conventional map-based control. In addition, they lead to an improvement in combustion stability, which can be an important issue especially when transient operations are considered or when non-conventional combustion modes, such as PCCI, are implemented.

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INTRODUCTION

Meeting the increasing stringent pollutant emissions and energy saving limits fixed by legislative authorities are the main challenges for the development of innovative internal combustion engines. Many engine subsystems and control techniques have been studied in recent years to meet the requirements of these regulations. As far as diesel engines are concerned, real-time combustion control is one of the most widely researched application [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

This technology can highly improve diesel combustion, which is commonly affected by cycle-by-cycle and cylinder-by-cylinder variations both caused by internal and external factors (ambient

conditions, coolant temperature, exhaust gas recirculation (EGR) unbalance, engine component aging, etc.). Besides, these combustion control techniques are of interest as they can dramatically reduce the time-consuming calibration of today's engine control systems [3]. The conventional control architecture for modern electronic control unit (ECU) is map-based, requiring great experimental activity to be carried out in order to consider all possible engine operating conditions (e.g. taking into account transient corrections, multiple maps in function of the number of injections, etc.). With the adoption of innovative combustion control methods, exploiting the computational capabilities of modern ECUs, the main parameters related to engine performances could be determined in real time on the basis of inputs directly measured on the engine itself [2, 3, 4].

In this context, being combustion phasing recognized to be one of the most important features affecting diesel combustion, MFB50 (i.e. crank angle at which 50% of the fuel mass fraction has burned) [1,2] and start of combustion (SOC) [6,7] represent the most frequently used parameters for such types of real-time controls. In some applications, other quantities, such as indicated mean effective pressure (imep) and maximum of heat release rate (HRR) [1] are considered, possibly in addition to abovementioned quantities.

Two different ways of controlling the MFB50 and the SOC in real-time are possible: pressure-based and model-based approaches. The former [1,2,4,6] needs a pressure transducer for the instantaneous measurement of in-cylinder pressure, from which the corresponding mass fraction burned X_b and the actual value of MFB50 are calculated. The latter is generally based on semi-empirical modeling of in-cylinder phenomena: one possibility is proposed in [7] based on the identification of the SOC by modeling and estimating the ignition delay, i.e. the length of the time interval between the start of injection (SOI) and the SOC in premixed diesel combustion. Another possible methodology is based on an improved accumulated fuel mass (AFM) approach to estimate the heat release rate and the MFB50 by a low-throughput model which requires as inputs a set of engine quantities already measured or estimated by the standard ECU (such as engine speed, rail pressure, air mass, pressure and temperature in the intake manifold, fuel injected quantities and related injection timings) [8,9,11].

Another important benefit of combustion phasing control is related to the increased engine stability when new combustion concept such as Low Temperature Combustion (LTC) and Premixed Charge Compression Ignition (PCCI) are employed [2,5, 6, 7]. LTC, and in particular PCCI, has proven to be very effective in the simultaneous reduction of NO_x and soot exhaust emissions. For this purpose, heavy amount of EGR and advanced [14,15] or retarded [16] fuel injection timings are used with respect to conventional diesel combustion in order to obtain a premixed charge before the start of combustion [10,12,13]. In particular, as regards the “early injection” PCCI mode, the combined effect of shifting the injection pattern to earlier times (the fuel injection occurs well before the TDC, i.e. the top dead center, during the compression stroke, into initially cooler and less dense gases) and using heavy amount of EGR (which reduces the oxygen concentration of the intake charge adding inert chemical species, especially CO_2 and H_2O) leads to slower pre-ignition chemistry and higher ignition delay. Thus, better pre-combustion mixing than conventional diesel combustion is possible [10,12,13]. This avoids the formation of rich mixture pockets within the charge, which is the main cause of soot generation [17]. Moreover, using heavy EGR rates leads to lower flame combustion temperatures and thus to lower NO_x emissions [17,18].

Within these operating conditions, in-cylinder processes become significantly different with respect to conventional diesel combustion mode. In particular, in case of operation with an engine designed for standard combustion and where the injection system is not specifically designed for PCCI operation, it has been demonstrated that a huge variation may be obtained in terms of smoke and NO_x emissions thanks to the combustion temperature reduction. Although the mixture formation process is not significantly improved, the

presence of very high EGR rate lowers in-cylinder temperatures so that the whole combustion process would occur in an area in which both soot and NO_x formation rates are very low [13], referring to an equivalence ratio vs. temperature diagram such as the one proposed by Kamimoto and Bae [18]. In detail, soot particles would not be formed due to the fact that the combustion temperatures are not high enough to allow the evolution of polycyclic aromatic hydrocarbons to soot, while the presence of fuel rich pockets will produce a higher amount of unburned components which will result in higher presence of CO, HC (low boiling point fuel-derived particles) and the soluble organic fraction (SOF) which composes the particulate matter (PM) [13]. These additional amounts of CO, HC and SOF may be efficiently treated by standard oxidation catalyst, whose efficiency may also benefit from the higher exhaust temperature generated by a slower combustion.

Among the possible drawbacks for such a type of combustion mode, high combustion instability can occur (especially related to the very high EGR rate used and uneven distribution among cylinders), thus making almost mandatory the use of combustion control to implement PCCI concept in real vehicles [2,7]. As a matter of fact, in these conditions the combustion is highly sensitive to variations of the intake conditions [5,7] and this may easily cause instability, i.e. wide cylinder-by-cylinder variations in terms of imep and MFB50 up to the occurrence of misfiring events. For speed and load transient operations, the different delay of the airpath with respect to the fuelpath determines that actual intake conditions may substantially deviate from steady-state calibrated values. This becomes especially critical for PCCI/HCCI combustion bringing to high pressure and imep fluctuations. Due to the slow dynamic behavior of the airpath, closed-loop control on airpath controllers/actuators cannot provide fast enough adaptation to the transient conditions. Therefore, combustion control may be effectively provided only through an accurate control of injection parameters in order to cope with requirements in terms of combustion and torque distribution stability, acoustic comfort and pollutant emissions.

The potentialities of LTC/PCCI combustion mode applied to the low speed - low load region on a diesel engine designed for a standard combustion mode have been discussed in a previous work by means of an optimization on steady-state tests performed according to design of experiments [20]. The current version of the engine does not allow the operation in non-conventional combustion mode in a wide area of the map, while dedicated hardware modifications are going to be implemented in order to allow the calibration of PCCI combustion up to medium engine loads and on the whole engine speed range.

In this paper, the effects of both model-based and pressure-based combustion controls are analyzed under steady-state and transient operations and compared to the standard map-based control. As a preliminary assessment of the developed techniques, most of the tests here presented refers to the application of the abovementioned models to traditional diesel combustion, while a set of steady-state tests also involved PCCI combustion mode operations. The robustness of the controls has been assessed in order to evaluate the effectiveness in different working conditions, such as considering different EGR rates and SOI, varying the fuel composition and disturbing the in-cylinder pressure signal during steady-state tests.

PRESSURE-BASED AND MODEL-BASED TECHNIQUES FOR MFB50 CONTROL

The standard ECU calibration relies on a map-based approach, i.e. quantities are interpolated from look-up tables that mainly depend on the estimated fuel injected quantity (which is related to the engine load), the engine speed and other measured quantities, such as the intake air mass and the boost pressure. In particular, SOI maps depend on the total injected quantities and on the engine speed as well as on the number of pilot injections. When transient operations are considered, the ECU applies several corrections to take into account of the delays in terms of injection pressure, boost pressure, EGR, etc. Anyway, when SOI and ignition delay are no longer directly correlated, e.g. in PCCI combustion mode, a new calibration of SOI would be necessary in order to achieve a correct MFB50 for all conditions, and transient operation corrections would become less effective. The calibration task would be much more time consuming and less robust compared to approaches that are able to control directly the MFB50, such as pressure-based and model-based controls.

The pressure-based control for the MFB50 stems from the measurement of the time-history of the in-cylinder pressure in the combustion chamber. The actual MFB50 value is obtained from the net energy release Q_{net} , which in turn is evaluated from the measured instantaneous in-cylinder pressure p and chamber volume V , on the basis of a single-zone approach [20], as follows:

$$dQ_{net} = \frac{\gamma}{\gamma-1} p dV + \frac{1}{\gamma-1} V dp \quad (1)$$

where $\gamma = c_p/c_v = 1.37$. To have a short computational time a constant value of γ is chosen, even if, in a more refined calculation, γ would depend on the composition of the burned gas [8]. The integration of the dQ_{net} provides the net heat release profile Q_{net} , which is then normalized to its maximum value in order to get the mass fraction burned curve X_b and, in particular, to evaluate the MFB50, i.e. the crank angle at which the mass fraction burned is equal to 0.5. The evaluated cycle-by-cycle MFB50 is compared to the MFB50 target (i.e., $MFB50_{tgt}$) and the error between the target and the actual value is calculated. The SOI_{main} of the following cycle is then adjusted in order to minimize the MFB50 error, according to a closed-loop procedure described into details in a companion paper [22]. In order to avoid instability problems of the controller, the entity of the correction on SOI_{main} is generally lower than the MFB50 error. As all the cylinders are instrumented with piezoelectric transducers, the MFB50 error calculation and the SOI correction can be performed not only cycle-by-cycle but also cylinder-by-cylinder.

The model-based control implements a procedure that evaluates a low-throughput predictive heat release curve based on a refined version of the AFM approach [8]. As the MFB50 is not measured but estimated, the model is therefore of the open-loop type. The AFM approach considers, at any time instant, that the rate of chemical energy released by the fuel is proportional to the energy associated with the in-cylinder accumulated fuel mass, i.e. the difference between the chemical energy of the injected fuel mass and the fuel released chemical energy [8,9, 22]. The model was assessed on

steady-state tests evaluated on the considered engine (cf. the section *Engine and experimental setup*). In particular, a complete engine mapping (made up of 126 tests at different speeds and loads) and 12 EGR sweeps were considered. Therefore, the model is capable of predicting the effects of variations in engine speed, load and intake oxygen concentration on MFB50. The root mean square error between the predicted and the experimental MFB50 was around 0.8 °CA. The control is performed by means of the model inversion. The combustion predictive model is in fact able to simulate the heat release and the consequent MFB50 for a considered set of injection parameters and working conditions. The inverted model receives as an input the desired MFB50 target, and provides as output the corresponding SOI_{main} value that allows to obtain the desired target, adopting an iterative procedure with a fixed number of three iterations [22], capable of providing the desired SOI_{main} with an uncertainty lower than 0.2 °CA [9].

An overview of the three models is reported in Table 1.

Table 1. Overview of the features concerning the three considered control methods.

Control type	Features
Map-based	Standard ECU control based on SOI look-up tables.
Pressure-based	Closed-loop control on MFB50 evaluated cylinder-by-cylinder from the pressure signal.
Model-based	Open-loop control on MFB50 calculated from a predictive heat-release model.

ENGINE AND EXPERIMENTAL SETUP

The experimental activity has been performed on a four-cylinder, four-stroke, turbocharged 3.0L heavy-duty diesel engine by FPT Industrial (Fig. 1), whose main technical specifications are listed in Table 2.

The engine is endowed with a short-route cooled EGR system, with a cooled EGR valve placed on the hot side of the engine upstream of the cooler. The EGR flow is driven by the pressure difference between the exhaust and the intake manifolds, adjusted by the EGR valve and an exhaust flap located downstream of the turbine to increase the pressure in the exhaust manifold when the pressure drop across the EGR system is not sufficiently high. Moreover, the exhaust flap is used to effectively reduce the after-treatment system warm-up time by increasing the exhaust gas temperature during cold start.

Table 2. Main technical specifications of the engine.

Engine type	FPT F1C Euro VI diesel engine
Displacement	2998 cm ³
Bore / stroke	95.8 mm / 104 mm
Rod length	158 mm
Compression ratio	17.5
Valves per cylinder	4
Turbocharger	Single-stage variable geometry turbine type
Fuel injection system	1800 bar common rail system

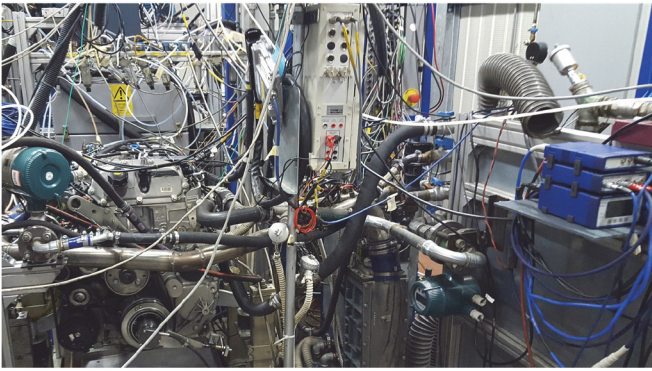


Figure 1. FPT F1C 3.0L Euro VI diesel engine installed on the dynamic test bench at the Politecnico di Torino. The rapid prototyping device can be seen on the right.

The test engine is fully instrumented with low-frequency piezo-resistive pressure transducers and thermocouples to measure, on a time basis, the pressure and temperature at different positions of the flow path (such as upstream and downstream the compressor, the turbine and intercooler, in the intake manifold and in the EGR circuit). Thermocouples are also installed to measure the temperatures in front of each cylinder in the intake and exhaust manifolds. Four Kistler 6058A high-frequency piezoelectric transducers are placed in glow-plug adapters to acquire for each cylinder, on a crank basis, the in-cylinder pressure time-histories, which are used as an input for the pressure-based MFB50 control. The in-cylinder pressure traces are pegged on the basis of the intake pressure that is measured by means of a high-frequency Kistler 4007C piezo-resistive transducer, located in front of cylinder #1. On the same cylinder, but on the exhaust side a high-frequency cooled Kistler 4049B piezo-resistive transducer is also installed.

The experimental tests were carried out at the dynamic test bench installed at the Politecnico di Torino ICEAL (Internal Combustion Engines Advanced Laboratory). The test bench is equipped with a cradle-mounted AC dynamometer and an 'AVL KMA 4000' fuel flowrate system, used to continuously measure the engine fuel consumption with an accuracy of 0.1%; the raw engine-out gaseous emissions are measured by means of an 'AVL AMAi60' endowed with two complete trains equipped with devices for the simultaneous measurement of gaseous concentrations of HC, CH₄, NO_x/NO, CO, CO₂ and O₂ both at the intake and exhaust manifolds. Finally, for the soot measurement an 'AVL 415S' smokemeter is used for steady-state tests whereas an 'AVL 439' opacimeter is adopted for transient tests.

All of the abovementioned measurement devices are controlled by a PUMA Open 1.3.2 and IndiCom automation system. The CAMEO software is used for automatic tests, related for instance to design of experiments analysis.

Rapid Prototyping Setup

The rapid prototyping (RP) setup is aimed at running new control strategies bypassing only the corresponding original ones present in the ECU, thus avoiding the need of completely reprogramming the

ECU. For this purpose, an ETAS ES910 RP device has been used to implement the MFB50 controls. The control algorithms were developed in Simulink and were deployed on the ETAS ES910 using the ETAS Intecrio software tool. In order to protect the engine, the functionalities of the new developed controls were initially tested in a Hardware-in-the-Loop configuration in which the RP device was connected to a real-time engine emulator running on a National Instruments PXIe-8135 device [22]. In a following step, the RP device was directly connected to the engine ECU (Fig. 1).

With reference to the setup for the pressure-based technique (Fig. 2a), a Kistler Kibox is used to calculate from the pressure signals acquired in all the cylinders the cycle-by-cycle real-time MFB50, using a single-zone model. The MFB50 values are sent in real-time to the RP device via CAN communication. The pressure-based control technique running on the RP device calculates the cycle-by-cycle SOI_{main} values needed to match the actual MFB50 for each cylinder to the target value. Then, it sends the updated SOI_{main} values to the engine ECU for each injector via ETK communication, thus bypassing the SOI_{main} values evaluated by the map-based control.

As far as the model-based technique setup (Fig. 2b) is concerned, the RP device receives the input signals needed for the low-throughput heat release model from the ECU via ETK. Then, the control algorithm calculates the SOI_{main} value, equal for all the cylinders, that allows the target MFB50 value to be reached, and sends this value to the ECU via ETK, thus bypassing the standard values derived from the ECU look-up tables.

RESULTS AND DISCUSSION

The experimental activity on the FPT F1C 3.0L Euro VI diesel engine was performed under steady-state and transient conditions with the map-based, the pressure-based and the model-based controls above described. The steady-state tests were relative to:

- Complete engine mapping with the three controls;
- SOI/MFB50 sweeps for three engine operating points with the map-based and the pressure-based controls;
- EGR sweep up to reach unstable conditions under PCCI combustion mode for the map-based and the pressure-based controls;
- Tests with different fuels, i.e. diesel, a 50%/50% blend diesel/JetA1 and a 100% JetA1 fuel;
- Tests with a disturbed pressure signal to simulate a degradation of the pressure signal or a pressure transducer of a lower quality;
- Tests with a reduced flow injector installed in one of the cylinders.

The transient tests were relative to fast load and speed ramps and to World Harmonized Transient Cycle (WHTC).