

Development and Assessment of Pressure-Based and Model-Based Techniques for the MFB50 Control of a Euro VI 3.0L Diesel Engine

Roberto Finesso, Omar Mareello, Daniela Misul, Ezio Spessa, Massimo Violante, and Yixin Yang
 Politecnico di Torino

Gilles Hardy and Christian Maier
 FPT Motorenforschung AG

ABSTRACT

Pressure-based and model-based techniques for the control of MFB50 (crank angle at which 50% of the fuel mass fraction has burned) have been developed, assessed and tested by means of rapid prototyping (RP) on a FPT F1C 3.0L Euro VI diesel engine.

The pressure-based technique requires the utilization of a pressure transducer for each cylinder. The transducers are used to perform the instantaneous measurement of the in-cylinder pressure, in order to derive its corresponding burned mass fraction and the actual value of MFB50. It essentially consists of a closed-loop approach, which is based on a cycle-by-cycle and cylinder-to-cylinder correction of the start of injection of the main pulse (SOI_{main}), in order to achieve the desired target of MFB50 for each cylinder.

The model-based technique, instead, requires the adoption of a heat release predictive model to simulate MFB50; this model is based on an improved version of the accumulated fuel mass approach, which requires the injection rate as input. This control technique is essentially based on the inversion of the heat release model, in order to identify the optimal value of SOI_{main} that allows the desired MFB50 target to be achieved cycle-by-cycle. The approach is therefore of the open-loop type.

Both control techniques were developed and assessed by means of Model-in-the-Loop (MiL) and Hardware-in-the-Loop (HiL) techniques, and then tested on the engine using a rapid prototyping device. The experimental tests were performed on a highly dynamic test bench at the Politecnico di Torino.

These techniques have shown a good potential for MFB50 control, compared to the standard methodology implemented in the Engine Control Unit (ECU).

CITATION: Finesso, R., Mareello, O., Misul, D., Spessa, E. et al., "Development and Assessment of Pressure-Based and Model-Based Techniques for the MFB50 Control of a Euro VI 3.0L Diesel Engine," *SAE Int. J. Engines* 10(4):2017, doi:10.4271/2017-01-0794.

INTRODUCTION

The increasing computational performance of modern engine control units (ECUs) is offering the opportunity to develop and implement more and more complex techniques for combustion control in diesel engines. These techniques can lead to a significant contribution in order to reduce fuel consumption, combustion noise and engine-out emissions in real time. In this context, the control of combustion phasing can play a significant role. One of the most frequently used combustion metrics for such types of controls is represented by MFB50, i.e., the crank angle at which 50% of the fuel mass fraction has burned. The control techniques for MFB50 control can roughly be divided into two types: closed-loop and feed-forward (or model-based) categories.

In closed-loop methods, MFB50 is diagnosed by the ECU in real-time, and is compared with a target value, which is appropriately identified in order to minimize engine-out emissions, combustion noise and fuel consumption. The injection parameters (typically, the start of injection of the main pulse) are adjusted in real-time, cycle-by-cycle, in order to achieve the desired MFB50 target [1].

In these kinds of methodologies, the MFB50 estimation is usually performed on the basis of the heat release rate that is derived from the measured in-cylinder pressure [1, 2, 3, 4]. If each cylinder is instrumented, a cylinder-to-cylinder correction of MFB50 can also be achieved. This approach can be effective in reducing the cyclic and cylinder dispersion of MFB50, especially for highly premixed combustion modes in which high EGR levels are adopted [5], with a consequent deterioration in the combustion quality.

An alternative approach to diagnose MFB50, on the basis of the engine speed measurement, has been presented in [6, 7, 8]. This method has the advantage of not requiring any additional cost, because it is based on the instantaneous engine speed measurement that is already performed in modern engine control systems [8].

A model-based (also termed as “feed-forward”) approach, instead, is a methodology that allows MFB50 to be predicted in advance by means of a model, and which can therefore be used to adapt the main engine parameters in real-time in order to achieve the required MFB50 target. The predictive estimation of MFB50 is generally obtained by using semi-empirical methods [9] or predictive heat release rate (HRR) models [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27]. Several approaches have been presented in the literature to simulate HRR in diesel engines.

The most detailed approach to predict the in-cylinder combustion process is represented by 3D-CFD models [10, 11]. These models have the potential of reproducing the physical and chemical processes that take place in the chamber during the injection-combustion process, but they require a considerable computational time and suffer from the drawback of still being conditioned by a lack of precise knowledge on the physics of some processes.

Quasi-D and multizone modeling approaches [12, 13, 14] generally include a fuel spray model that is coupled with a thermodynamic combustion model. The latter is generally based on the discretization of the in-cylinder content into several homogeneous zones, to which the energy and mass conservation equations are applied. These models are capable of estimating the in-cylinder gradients of temperature and chemical composition, therefore they are suitable to be coupled with pollutant formation submodels (NO_x, soot). However, they require a computational time that is not compatible with real-time combustion control applications, at least considering the computational performance of modern ECUs.

Wiebe functions [15, 16] are adopted extensively to reproduce the heat release shape, and require very little computational effort. However, the Wiebe function approach is a pure mathematical method, lacking physical consistency, because it does not link the injection rate directly to the heat release process.

Models based on the apparent combustion time have been proposed in [17, 18]. These models take into account the effects of in-cylinder air density, oxygen concentration, nozzle diameter and injection rate on the heat release rate, but do not link the injection rate with the heat release trend directly.

Models based on the accumulated fuel mass approach assume that the rate of released chemical energy is proportional to the energy associated with the fuel quantity made available for combustion at the considered moment [19, 20, 21, 22, 23, 24, 25, 26, 27]. This energy can be computed as the difference between the chemical energy associated with the injected fuel quantity and the cumulative heat release. This approach has the great advantage of being able to correlate the injection rate directly to the combustion process, and is therefore physically consistent. Moreover, it does not require a high calibration effort, and is therefore suitable for control-oriented applications.

Finally, the last category of models, which is often used in the field of engine design and control, includes artificial intelligence systems such as support vector machines (SVM), genetic algorithms (GA) and artificial neural networks (ANNs). These methods have been used extensively in the automotive field [28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38]. In general, they can also be referred to as “black box” or “gray box” approaches, as they do not require any detailed physical knowledge of the investigated process and are able to capture complex nonlinear system behavior by means of relatively simple mathematical operations. Moreover, they are characterized by a limited computational time, and as a result they are the best candidates for implementation in ECUs for control-oriented tasks. However, in order to be trained, they usually require a high number of experimental tests, and they are not reliable outside the pre-fixed calibration range.

Contribution of the Present Study

Considering the previous background, the present study has been devoted to the development of closed-loop and model-based open-loop techniques for the control of MFB50, and to their testing on a FPT F1C 3.0L Euro VI diesel engine. The closed-loop technique is based on the measurement of the in-cylinder pressure in each cylinder, and it has therefore been referred to as “pressure-based” throughout the paper.

Both control techniques were developed and assessed by means of Model-in-the-Loop (MiL) and Hardware-in-the-Loop (HiL) methods, and then tested on the engine using a rapid prototyping (RP) device. The experimental tests were performed on a highly dynamic test bench at the Politecnico di Torino.

The activity was carried out in the frame of a research project in collaboration with CNH/FPT Industrial, which is currently ongoing and which is focused on the investigation of the potential of the PCCI (Premixed Combustion Compression Ignition) combustion mode for a 3.0L diesel engine for light-duty applications. This combustion mode is in fact characterized by the use of high EGR rates in conjunction with early injection, which could lead to a significant deterioration in combustion quality, especially in transient conditions. Therefore, the implementation of a combustion control algorithms is highly recommended to guarantee stable engine operations.

However, the results reported in the present study mainly refer to the development and preliminary testing of the controls on the engine in conventional combustion mode, while the results obtained in PCCI combustion mode will be presented in the near future.

In general, the developed pressure-based technique is capable of achieving a cycle-by-cycle and cylinder-to-cylinder MFB50 control, by modulating the start of injection of the main pulse (SOI_{main}).

The model-based technique, instead, exploits a low-throughput heat release predictive model that had previously been developed by the authors in [25] and refined in [26], which is based on an improved version of the accumulated fuel mass approach. The latter approach was selected because it has the great advantage of being able to correlate the injection rate directly to the heat release process, and is

therefore physically consistent. Moreover, it is also characterized by a very fast computational time [26], which makes it possible to implement it on a rapid prototyping device for real-time cycle-by-cycle MFB50 prediction and control.

ENGINE AND EXPERIMENTAL SETUP

The experimental calibration and validation tests of the developed methods were conducted on a 3.0L Euro VI diesel engine. The main technical specifications of the engine are reported in [Table 1](#).

Table 1. Main technical specifications of the engine.

Engine type	FPT F1C Euro VI diesel engine
Displacement	2998 cm ³
Bore x stroke	95.8 mm x 104 mm
Rod length	160 mm
Compression ratio	17.5
Valves per cylinder	4
Turbocharger	VGT type
Fuel injection system	High pressure Common Rail

The engine ([Fig. 1](#)) is equipped with a short-route cooled EGR system, in which the EGR valve is located upstream from the cooler. A flap is installed in the exhaust pipe downstream the turbine, to control the temperature of the exhaust gas flowing to the aftertreatment system and to allow high EGR rates to be obtained when the pressure drop between the exhaust and intake manifolds is not sufficiently high.

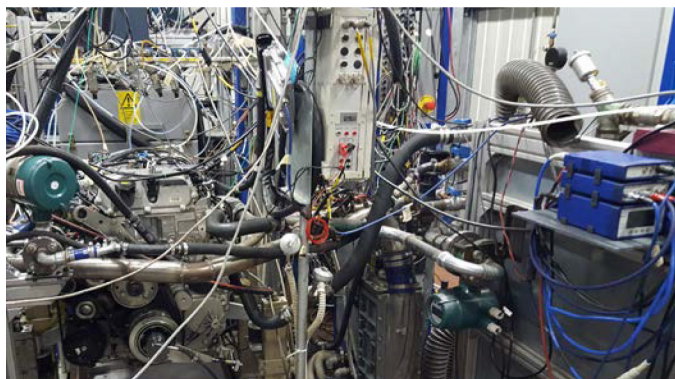


Figure 1. FPT F1C 3.0L Euro VI diesel engine installed on the highly dynamic test bench at the Politecnico di Torino. The rapid prototyping device can be observed on the right.

The test engine was instrumented with piezoresistive pressure transducers and thermocouples to measure the pressure and temperature at different locations, such as upstream and downstream from the compressor, from the turbine and intercooler, in the intake manifold and in the EGR circuit. Thermocouples were also used to measure the temperatures in each intake and exhaust runners. KISTLER 6058A high-frequency piezoelectric transducers were fitted to the glow-plug seat to measure the in-cylinder pressure time-histories, which were used for the pressure-based MFB50 control. The in-cylinder pressure traces were corrected on the basis of

the intake pressure that was measured by means of high-frequency KISTLER 4007C piezoresistive transducers, which were located at the inlet runners of the cylinders.

All the experimental tests were carried out on the highly dynamic test bed at ICEAL at the Politecnico di Torino. The test rig is equipped with an 'ELIN AVL APA 100' cradle mounted AC dynamometer and an 'AVL KMA 4000', with a reading accuracy of 0.1% over a 0.28-110 kg/h range, to continuously measure the fuel consumption. An 'AVL AMAi60' system, consisting of three analyzer trains, was used to measure the engine-out gaseous raw emissions. Two analyzer trains were equipped with complete devices for the analysis of THC, CH₄, NO_x, and low as well as high CO, CO₂ and O₂, and were used to measure the intake and exhaust gas composition. All of the abovementioned measurement devices were controlled by a PUMA OPEN 1.3.2 automation system. In order to minimize the testing effort, the test bed environment was interfaced with AVL CAMEO software to run intelligent engine calibration procedures on the basis of the DoE (Design of Experiment) approach.

Rapid Prototyping Device and Real-Time Engine Emulator

An ETAS ES910 rapid prototyping device was used to test the developed controls on the engine. This device is in fact capable of by-passing the standard functionalities of the ECU. For this purpose, the novel control algorithm was modeled using Simulink and deployed on the ETAS ES910 hardware using ETAS Intecrio software tool.

The main specifications of the ETAS ES910 device are reported in [Tab. 2](#).

Table 2. Main specifications of the ETAS ES910 rapid prototyping device.

Main processor	Freescale PowerQUICC™ III MPC8548 with 800 MHz clock Double precision floating point unit
Memory	512 MByte DDR2-RAM (400 MHz clock) 64 MByte Flash 128 kByte NVRAM
ECU and bus interfaces	ETK 1 Channel, ETK Mode: Basic, Compatibility, Advanced ETK bypass method: hook based or service based (Service Based Bypass (SBB V2) and SBB V3) XETK / iLinkRT™ 1 channel, bypass in parallel to measurement and calibration possible iLinkRT™ connection to test bench for INCA-MCE CAN 2 Channels, High Speed (up to 1 MBaud) or Low Speed LIN 2 Channels, LIN V2.0 Extension modules ES920.1 FlexRay Module (1 Node) or ES921.1 CAN Module (2 Channels) EtherCAT connection to test bench for INCA-MCE

For safety reasons, the functionalities of the developed controls were preliminary tested with Hardware-in-the-Loop (HiL) testing by coupling the ETAS RP device to a real-time engine emulator. The engine emulator was realized by means of an NI PXIe-8135 device, equipped with a 2-port CAN Interface for communication with the

ETAS RP device. A real-time mean-value GT-power engine model was used to simulate engine performance with the PXI. The main specifications of the PXI device are reported in Tab. 3.

Table 3. Main specifications of the PXI device used for HiL testing.

PXI type	NI PXIe-8135
Controller	Core i7-3610QE 2.3 GHz Controller, Win 7 (64-bit)
I/O interfaces	2-port CAN Interface, High-Speed/FD
Real-time operating system	Pharlap OS
Execution mechanism	Veristand Engine
Engine model	Real-time mean-value GT-power model

Experimental Activity

The experimental tests that have been considered in the present paper include steady-state tests and transient tests, which were carried out in conventional combustion mode. The steady-state tests were mainly used to calibrate the low-throughput heat release model that was used in the model-based MFB50 control technique. To this aim, the following tests were considered (Fig. 2):

- A full engine map with baseline operating parameters.
- EGR-sweep tests at fixed key-points.

The developed control techniques were tested on the engine over different load/speed ramps and over a WHTC interval. Details on these tests are reported in the “Results and discussion” section.

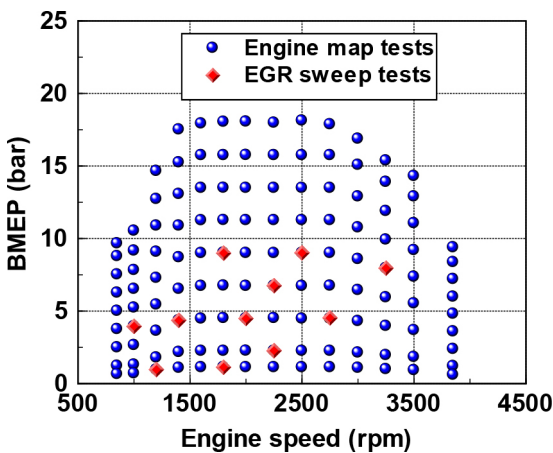


Figure 2. Experimental tests used for the calibration of the low-throughput heat release model.

MFB50 CONTROL

Pressure-Based Technique

The pressure-based technique for the control of MFB50 exploits the measurement of the in-cylinder pressure in the combustion chamber of each cylinder. In short, an MFB50 target (i.e., $MFB50_{tgt}$) is identified at a given time instant. The actual MFB50 value is extracted from the measured in-cylinder pressure of each cylinder at

each cycle, and the start of injection of the main pulse (i.e., SOI_{main}) is then adjusted in the subsequent cycle in order to achieve the MFB50 target, according to a closed-loop approach.

In other words, the actual MFB50 value is derived from the net energy release Q_{net} , which in turn is estimated from the measured in-cylinder pressure on the basis of a single-zone approach [39], as follows:

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

where, $\gamma = \frac{c_p}{c_v} = 1.37$, p is the measured in-cylinder pressure and V is the in-cylinder volume. It should be noted that, in general, γ depends on the composition of the burned gas (see [25]) and has a significant impact on the heat release shape obtained from a single-zone heat release approach. However, it was decided to use a constant value of γ in order to reduce the computational time. A value of 1.37 has been set in order to be coherent with the outcomes of the acquisition software installed at the test bench, which implements the abovementioned value of γ .

The net energy release curve is then normalized to its maximum value in order to estimate the burned mass fraction curve, and MFB50 is obtained as the crank angle at which the normalized heat release curve is equal to 0.5. The MFB50 correction algorithm is described hereafter.

The actual MFB50 value for the generic cylinder ‘j’ and cycle ‘i’, i.e., $MFB50_i^j$, is compared with the target value, i.e., $MFB50_{tgt,i}^j$. The error between the target and the actual values of MFB50 is then estimated as follows:

$$Err_i^j = MFB50_{tgt,i}^j - MFB50_i^j \quad (2)$$

The start of injection of the main pulse in the subsequent cycle, ‘i+1’, is corrected according to the following equation:

$$SOI_{main,i+1}^j = SOI_{main,i}^j + K_{m,i}^j \cdot Err_i^j \quad (3)$$

where $K_{m,i}^j$ is a modulation factor that was introduced in order to optimize the response of the controller and to guarantee stable operations.

It was in fact verified that the behavior of the control can be unstable if the value of $K_{m,i}^j$ is set constant and equal to 1 (see the “Results and discussion” section), and it is therefore necessary to adjust its value cycle-by-cycle.

An optimal strategy for the definition of the $K_{m,i}^j$ parameter was identified during the Model-in-the-Loop (MiL) phase, in order to guarantee a fast response of the controller and to avoid the occurrence of instability. In particular, the value of $K_{m,i}^j$ was limited to the [0, 1-1]

range, and was varied, cycle-by-cycle, as a function of the sign of the error between two consecutive cycles, according to the following method:

$$\begin{aligned}
 &K_{m,i}^j \in [0.1, 1] \\
 &\text{if } \text{sign}(Err_i^j) = \text{sign}(Err_{i-1}^j): K_{m,i}^j = K_{m,i-1}^j \cdot 2 \\
 &\text{if } \text{sign}(Err_i^j) \neq \text{sign}(Err_{i-1}^j): K_{m,i}^j = \frac{K_{m,i-1}^j}{2} \\
 &\text{if } Err_i^j \geq 3: K_{m,i}^j = 1
 \end{aligned} \quad (4)$$

The boundary values of $K_{m,i}^j$ were identified on the basis of simulations carried out in the MiL phase. In particular, this range has been found to provide a good response time of the control without any instability issue. The initial value has been set at 0.5.

Model-Based Technique

The model-based technique implements a predictive heat release model that is based on an improved version of the accumulated fuel mass approach [26], and is therefore of the open-loop type. The control has been realized by means of a model inversion. The combustion model is in fact able to simulate the heat release and MFB50 for a given set of injection parameters. The inverted model receives the MFB50 target as input, and identifies the SOI_{main} value that allows the desired target to be achieved by means of an iterative procedure.

The energy release was simulated by adopting an enhanced version [26] of the baseline model presented by the authors in [25], which is based on the accumulated fuel mass approach.

The accumulated fuel mass approach assumes that the rate of chemical energy released by the fuel, at any time instant t , is proportional to the energy associated with the in-cylinder accumulated fuel mass. This energy, at time instant t , is the difference between the chemical energy of the injected fuel mass and the released chemical energy.

It was verified in [26] that this approach leads to accurate results for pilot injections. For this reason, the chemical energy release rate was evaluated as follows:

$$\frac{dQ_{ch,pil,j}}{dt}(t) = K_{pil,j} [Q_{fuel,pil,j}(t - \tau_{pil,j}) - Q_{ch,pil,j}(t)] \quad (5)$$

where $K_{pil,j}$ and $\tau_{pil,j}$ are model calibration quantities related to the combustion rate and to the ignition delay, respectively, and $Q_{fuel,pil,j}$ is the chemical energy associated with the injected fuel mass. It should be noted that the fuel evaporation process is not modeled by the accumulated fuel mass approach, therefore, the Q_{fuel} term refers to the energy associated with the globally injected fuel mass, independently on its actual phase.

The chemical energy release of the main pulse was instead simulated by means of a modified formulation that had been proposed in [26]:

$$\begin{aligned}
 \frac{dQ_{ch,main}}{dt}(t) = &K_{1,main} [Q_{fuel,main}(t - \tau_{main}) - Q_{ch,main}(t)] \\
 &+ K_{2,main} \frac{dQ_{fuel,main}(t - \tau_{main})}{dt}
 \end{aligned} \quad (6)$$

The formulation proposed in Eq. (6) needs an additional calibration parameter to the Eq. (5) baseline approach (i.e., $K_{2,main}$).

From a physical point of view, the term that is proportional to the injection rate takes into account the effect of the turbulence induced by the fuel injection on the heat release, which is not negligible in diesel sprays.

The chemical energy Q_{fuel} associated to the injected fuel quantity is defined for each injection pulse j as follows:

$$Q_{fuel,j}(t) = \int_{t_{SOI,j}}^t \dot{m}_{f,inj}(t) H_L dt \quad t \leq t_{EOI,j} \quad (7)$$

$$Q_{fuel,j}(t) = \int_{t_{SOI,j}}^{t_{EOI,j}} \dot{m}_{f,inj}(t) H_L dt \quad t > t_{EOI,j} \quad (8)$$

where t_{SOI} is the start of the injection time, t_{EOI} is the end of the injection time, H_L is the lower heating value of the fuel and $\dot{m}_{f,inj}$ is the fuel mass injection rate. The approach therefore requires the injection rate as input. A triangular injection rate, which is calculated on the basis of the injection parameters (injection timings/quantities and injection pressure), has been used, taking into account the nozzle opening delay (NOD) and nozzle closure delays (NCD) of the injector, which are obtained from look-up tables as a function of the energizing time and injection pressure.

The total chemical energy release is given by the sum of the contributions of all the injection pulses:

$$Q_{ch} = \sum_{j=1}^n Q_{ch,j} \quad (9)$$

It can be noted, from Eqs. (1-2), that the baseline approach described in [25] was used for the pilot shots, as it had already been verified that it provides satisfactory results [26].

Instead, an enhanced formulation, which includes an additional term proportional to the injection rate, was developed for the main pulse. It had been verified in [26] that the addition of this term leads to an increase in the accuracy of the predicted heat release trend and of MFB50, especially for high-load operating conditions, where the combustion of the main pulse is of the premixed/mixing-controlled type.

In general, it can be noted that the model takes into account the effects of variations in the injection rate or duration on the heat release rate curve and therefore on MFB50, because the injection profile is a direct input to the model (see Eqs. (5, 6, 7, 8)). This approach is therefore physically consistent.

The model was assessed considering the steady-state conditions reported in Fig. 2. In particular, the optimal τ and K parameters were identified by comparing the predicted and experimentally-derived heat release profiles, and minimizing the sum of errors and the MFB50 prediction error by means of a genetic algorithm (see [26]). The adopted correlation variables for ignition delay were chosen in accordance with the study proposed in [40]. In particular, at the beginning, all the engine variables were included in the correlations, and a sensitivity analysis was carried out in order to exclude the least influential ones, thus a stepwise regression was adopted. This approach was also adopted to identify the engine variables that had to be included in all the correlations reported hereafter.

The following correlations were identified as functions of the in-chamber thermodynamic quantities at SOI/SOC (start of injection/start of combustion) and of other engine variables:

$$K_{pil} \left[\frac{1}{\text{deg}} \right] = 2.49e-05 p_f^{-0.4449} O_2^{1.38} n^{1.065} q_{pil,tot}^{-0.293} \quad (10)$$

$$K_{1,main} \left[\frac{1}{\text{deg}} \right] = 0.0059 \rho_{SOC,main}^{0.608} O_2^{0.761} n^{-0.159} q_{main}^{-0.243} \quad (11)$$

$$K_{2,main} [-] = 2.34 p_f^{0.369} \rho_{SOC,main}^{-0.847} O_2^{-0.016} n^{-0.404} q_{main}^{0.299} \quad (12)$$

$$\tau_{pil} [\text{deg}] = 15.61 p_f^{0.659} \rho_{SOIP}^{-1.97} \quad (13)$$

$$\tau_{main} [\text{deg}] = 24.57 p_f^{-1.43} \rho_{SOI,main}^{-2.59} n^{1.73} q_{f,inj}^{0.625} \quad (14)$$

ρ_{SOI} , T_{SOI} , ρ_{SOC} and T_{SOC} in equations (10, 11, 12, 13, 14) indicate the in-chamber densities and temperatures evaluated at the start of injection or combustion, respectively, and were expressed in kg/m³ and K. They can be estimated in real-time on the basis of the intake manifold pressure and temperature [25], which are known quantities of the ECU. The injection pressure p_f is expressed in bars, the engine speed n in rpm, the total injected fuel quantity $q_{f,inj}$ (used as a load parameter) in mm³/cyc/cyl, the total injected fuel quantity of the pilot shots $q_{pil,tot}$ in mm³/cyc/cyl and the intake oxygen concentration O_2 in %. The in-chamber thermodynamic conditions evaluated at SOC were selected for the combustion rate parameters, as they were considered more representative than those evaluated at SOI.

Differently from the study reported in [40], the effect of the intake O_2 concentration has not been found to be significant for the prediction

of the ignition delay of the main pulse. This is mainly due to the fact that the experimental tests considered in the present study were characterized by a more limited variation range of intake O_2 concentration.

All the input model parameters were derived in real-time from the ECU variables, except for the O_2 intake concentration. The latter quantity was estimated by means of a sub-model, which is summarized hereafter.

First, the total inducted mass m_{ind} , which is the sum of the trapped air and EGR mass, was estimated using a feed-forward neural network, which was trained on the basis of the experimental tests shown in Fig. 2:

$$m_{ind} = \text{NeurNet}(N, p_{int}, T_{int}) \quad (15)$$

The trapped EGR mass was then estimated by subtracting the measured trapped air mass $m_{air,meas}$ (which is derived from the engine MAF flow sensor) from the total inducted mass:

$$m_{EGR} = m_{ind} - m_{air,meas} \quad (16)$$

Finally, the O_2 intake concentration was estimated as a function of the X_r/λ parameter (see [41]), where X_r is the EGR rate and λ is the relative air-to-fuel ratio:

$$O_2 = -20.35 \frac{X_r}{\lambda} + 20.79, \quad X_r = \frac{m_{EGR}}{m_{ind}} \quad (17)$$

Model Inversion

The physical model was inverted in order to predict the SOI_{main} value which that allows the desired MFB50 target to be reached. Model inversion is in fact mandatory if the model is to be used in a combustion control algorithm in which MFB50 is set as a target.

The model was inverted by adopting an iterative procedure, in which the first run was based on the initial assumption of the SOI_{main} control variable and a cycle-based integral control was applied to adjust the control variable value in order to attain convergence of the target variables (i.e., MFB50_{tgt}). The iterative procedure stops when the difference between the predicted value and required value of the target variable falls below the predefined threshold. In general, it was shown in [26] that convergence can be achieved after two or three iterations, when a reasonable threshold level is set (e.g., 0.2 degree for MFB50). The controller is able to increase or decrease its own integral gain according to the instantaneous error in order to accelerate convergence.

Figure 3 shows the model inversion scheme.