

Efficiency & Stability Improvements of Diesel Low Temperature Combustion through Tightened Intake Oxygen Control

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ABSTRACT

Diesel engines operating in the low-temperature combustion (LTC) mode generally tend to produce very low levels of NO_x and soot. However, the implementation of LTC is challenged by the higher cycle-to-cycle variation with heavy EGR operation and the narrower operating corridors. Small variations in the intake charge dilution can significantly increase the unburnt hydrocarbon and carbon monoxide emissions as well as escalate the consecutive cyclic fluctuations of the cylinder charge. This in turn adversely affects the robustness and efficiency of the LTC operation. However, Improvements in the promptness and accuracy of combustion control as well as tightened control on the intake oxygen concentration can enhance the robustness and efficiency of the LTC operation in diesel engines. In this work, a set of field programmable gate array (FPGA) modules were coded and interlaced to suffice on-the-fly combustion event modulations on a cycle-by-cycle basis. The cylinder pressure traces were analyzed to provide the necessary feedback for the combustion control algorithms. The combustion phasing was estimated using a computationally-efficient *Pressure Departure Ratio Algorithm* that helped to anchor the combustion within a narrow crank angle window for the best efficiency. The load variations were minimized by regulating the indicated mean effective pressure that helped to stabilize the LTC cycles. Engine dynamometer tests demonstrated that such *systematic* and *prompt* control algorithms were effective to optimize the LTC cycles for better fuel efficiency and exhaust emissions. The reported techniques were in part to establish a model based control strategy for robust diesel LTC operations.

INTRODUCTION

The low temperature combustion in diesel engines is capable of reducing oxides of nitrogen (NO_x) and soot simultaneously, which can be implemented by the heavy use of exhaust gas recirculation (EGR), or the homogeneous charge compression ignition (HCCI) type of combustion [1,2,3]. Unlike conventional diesel cycles where the phasing of combustion is tightly controllable via fuel injection timing modulation [4,5], the scheduling of fuel delivery in LTC cycles especially in HCCI cycles may have lesser leverage on the exact timing of auto-ignition that may even occur *before top dead center* (BTDC). The decoupling tendency between the timings of fuel injection and ignition accrues with an earlier or fuller homogeneous charge [6,7,8,9,10]. Moreover, EGR-induced cyclic variations are largely associated with the prolonged ignition delay caused by increased carbon dioxide and decreased oxygen concentrations in the intake. An increased ignition delay deteriorates combustion efficiency that, in turn, causes fluctuations in the combustion products. These variations escalate the consecutive cyclic variations of the cylinder charge in terms of temperature, pressure and composition. Thus the characterization (or even quantification) of the combustion events on-the-fly and a tightened control on the intake oxygen concentration (or intake charge dilution) are of paramount importance for realizing improvements in the combustion process.

Low temperature diesel combustion (LTC) systems can be broadly divided into two categories [6,7]. In one category, the LTC is enabled with EGR using a single-shot injection strategy in which the combustion phasing is closely coupled to the scheduling of the fuel injection event, thereby providing a method for controlling the engine performance. Since a relatively short ignition delay normally precludes thorough pre-mixing of the fuel-air mixture, high levels of



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cooled EGR and/or retarded injection timing are commonly employed to prolong the ignition delay and to lower the flame temperature [11].

A natural consequence of the high EGR levels is the increased sensitivity of the LTC operation to small changes in the EGR as shown by the test results run at the authors' lab (Figure 1). These tests were run by manually adjusting the start-of-injection crank angle (SOI) to maintain the crank angle of 50% heat released (CA50) at 366°CA. However, the reduced combustion temperature and the high dilution rate result in incomplete combustion as the available oxygen is depleted during the combustion event even with high homogeneity [7]. The CO and HC emissions can drain a substantial amount of fuel energy from the LTC cycles indicated by a drop of 0.6 bar in the indicated mean effective pressure (IMEP) and present a major challenge for LTC implementation. A higher intake pressure is generally beneficial to reduce the incomplete combustion in addition to lowering the equivalence ratio of the cylinder charge [3]. Nonetheless, these combustion modes offer the potential of simultaneous NOx and soot reduction [12,13,14,15,16,17,18].

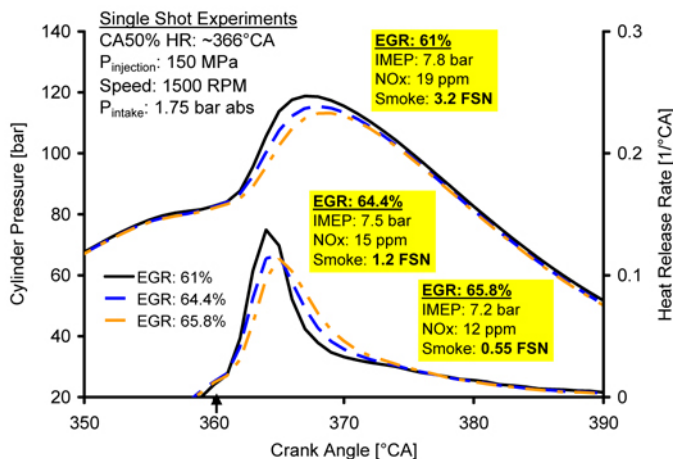


Figure 1. Sensitivity of LTC Cycles to EGR

The second category is usually referred to as the homogeneous charge compression ignition (HCCI) system in which the combustion phasing and the injection timing are highly decoupled from each other and the combustion phasing is largely controlled by the kinetics of the chemical reactions. In HCCI type of combustion system, the fuel and air are premixed, via early fuel injections during the compression stroke so that a near homogeneous mixture is available at the start of combustion and is characterized by an air-excess ratio, λ that is everywhere greater than the stoichiometric value. Low combustion temperatures are achieved by either pre-mixing to very lean air-excess ratios ($\lambda \geq 2$) or by employing exhaust gas recirculation (EGR) to reduce the combustion temperature of mixtures with lower (richer) air-excess ratios and to control the combustion

phasing [19,20], a representative test result of which is shown in Figure 2. In this mode of combustion, a tight control on the intake charge dilution is also essential to optimize the trade-off between the combustion off-phasing (from the best efficiency crank-angle window of 5~10°CA ATDC) and the exhaust combustibles, so that the fuel efficiency penalty can be minimized [21].

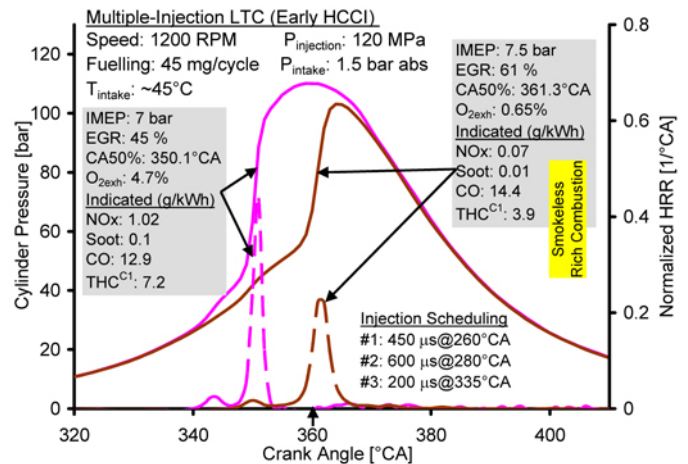


Figure 2. Smokeless Rich Combustion with Multiple-Injection LTC [22]

The work presented in this paper focuses on the first category of LTC with high levels of EGR and a single fuel-injection with injection timing slightly earlier than TDC (up to 10°BTDC). A modern diesel engine with a CR of 18.2:1 has been used to investigate the efficiency & stability improvements of diesel LTC through tightened intake oxygen control. A set of FPGA modules were coded and interlaced to suffice on-the-fly combustion event modulations on a cycle-by-cycle basis. To provide feedback on the EGR levels and to ensure emission conformance, a wide lambda sensor and a smart NOx sensor were installed in the exhaust system. The combustion phasing was estimated using a computationally-efficient *Pressure Departure Ratio Algorithm* that helped to anchor the combustion within a narrow crank angle window for the best efficiency. The load variations were minimized by regulating the indicated mean effective pressure for the *current* engine cycle that helped to stabilize the LTC cycles. Engine dynamometer tests demonstrated that the management of the intake charge dilution, integrated with the combustion control algorithms was effective to optimize the LTC cycles for better fuel efficiency and exhaust emissions.

EMPIRICAL APPROACHES AND RESEARCH METHODOLOGY

A modern 4-cylinder Ford common-rail diesel engine, running in single-cylinder mode was instrumented for the tests as shown in Figure 3. The 3 cylinders-to-1 cylinder configuration is a new exploration strategy that enables

investigation of unstable combustion regimes with a non-motoring dynamometer [18]. The 3 cylinders are operated in the conventional high temperature combustion (HTC) mode at low load for stable engine operation. The combustion in Cylinder 1 is then pushed into the LTC cycles by independently controlling the EGR, boost, exhaust backpressure and fuel scheduling. The geometric specifications of the test engine are given in [Table 1](#).

Table 1. Test Engine Specifications

Model	4 Cylinder, DI Ford DuraTorq "Puma"
Displacement	1998 cm ³
Bore x Stroke	86 mm x 86 mm
Compression Ratio	18.2:1
Maximum Cylinder Pressure	~18 MPa (180 bar)
Injection System	Common-rail (up to $P_{\text{Rail}} \sim 160 \text{ MPa}$)
Swirl Ratio	1.7

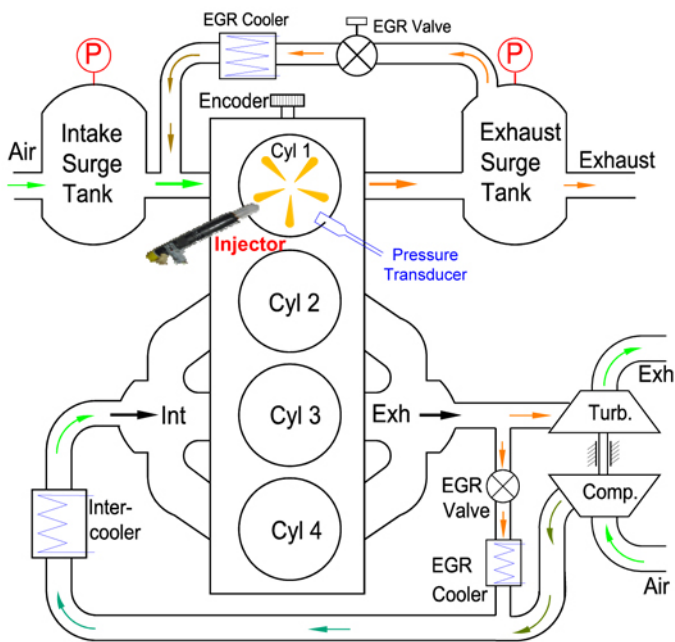


Figure 3. Schematic Representation of the Test Setup with independent control on intake boost and exhaust backpressure at University of Windsor

A dual-bank exhaust analyzer system (NO_x, THC, CO, CO₂, O₂, and soot) has been instrumented for the tests; one for the exhaust emissions and the other for the intake gas concentrations. The engine boost, exhaust backpressure, and EGR valve opening are precisely controlled with a set-of PC-

based systems. The engine coolant and lubricant oil conditions are monitored and controlled closely with external conditioning systems to minimize the discrepancies of the testing results.

In-cylinder pressures were acquired using a flush-mounted AVL GU13P pressure transducer in Cylinder 1 connected through a Kistler 5010B charge amplifier. The pressures were recorded for 200 cycles at 0.1°CA (degree crank angle) resolution and averaged to calculate the indicated mean effective pressure (IMEP), net heat-release rate and the cumulative heat-released. The 0.1°CA resolution was used to provide accurate ignition delay periods and thus, the phasing of the heat-release rates during the on-line monitoring of the combustion event.

COMBUSTION CONTROL PLATFORM

The control platform consists of embedded real-time (RT) controllers, field programmable gate array (FPGA) devices, and synchronized high-speed signal conditioning, and recording units. Three sets of real-time controllers embedded with FPGA devices have been programmed to analyze the cylinder pressure data and to generate the necessary control signals for dynamically and precisely commanding the fuel injection strategies as shown in [Figure 4](#) [21,23]. The system allows the injection scheduling to be commanded on a crank angle-resolved basis and the injection quantity to be controlled on a time-resolved basis. The functioning of each of the FPGA/RT system is as follows:

The Fuel Injection controller can configure up to 12 independent injections/cycle (injection timing, pulse width) and generates a TTL pulse train that serves as the input for the injector power drives. The controller can perform prompt combustion pattern recognition using the maximum cylinder pressure p_{max} or the maximum rate of pressure rise, $(dp/d\theta)_{\text{max}}$ as the feedback parameters.

The Combustion Characterization controller is programmed to provide an estimate of the IMEP for within same-cycle or on a cycle-by-cycle bases control. The details of the algorithm have been published previously [21,23]. The controller also calculates the combustion phasing represented by the CA50 either by using the apparent heat release analysis or the 'Pressure Departure Ratio (PDR)' algorithm developed by the authors for cycle-by-cycle combustion control. The detailed analysis and performance comparison of the PDR algorithm has been published by the authors [24].

The System Pre-control maintains the rail pressure using a PID controller for the pressure control valve (PCV) and the volume control valve (VCV) of the fuel injection pump. The data transfer between the FPGA devices is done using the high speed digital/analog channels. The FPGA devices are based on the Virtex-II FPGAs (28,672 LUTs per device) with

each slice containing two 4-input LUTs, two flip-flops, wide-function multiplexers, and carry logic. The injector power drives enable the injector opening/ closing voltages to be adjusted between ± 200 V and the current between ± 20 A. An RS-485 link is used to program the power drives.

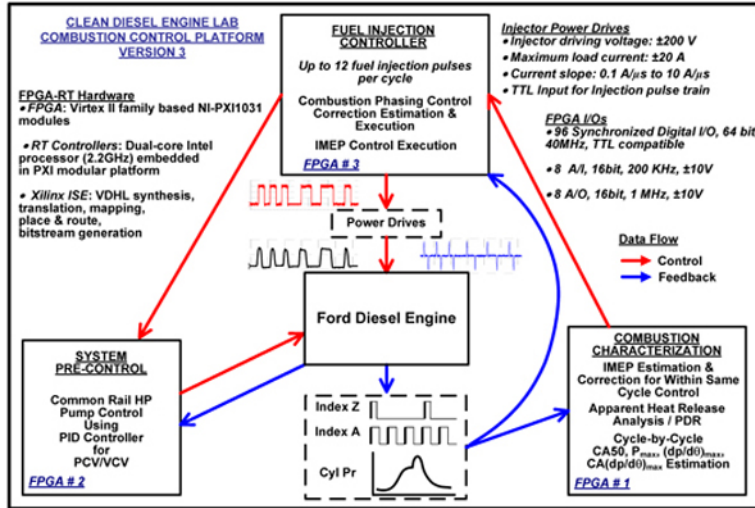


Figure 4. CDEL Combustion Control Platform [23]

DIESEL PRESSURE DEPARTURE RATIO ALGORITHM

The Diesel Pressure Departure Ratio algorithm (referred to as PDR algorithm hereafter) was proposed by the authors for fast and reliable estimation of the mass fraction burnt (MFB) for diesel combustion [24]. The algorithm was validated with engine tests over a wide range of boost, EGR, compression ratios and combustion modes as shown in Figure 5 [24]. It is based on the principle that the fractional pressure rise due to combustion can provide an estimate of the MFB. The PDR algorithm utilizes the fired and the motoring traces for cycle-by-cycle estimation of the CA_{50} and the MFB closely matches the normalized cumulative heat release trace. The PDR is mathematically expressed at any crank angle, θ as:

$$PDR(\theta) = \frac{p(\theta) + FPC}{p_{mot}(\theta) + MPC} - 1 \quad (1)$$

where $p(\theta)$ is the fired cylinder pressure data, $p_{mot}(\theta)$ is the motored cylinder pressure, FPC is the 'fired pressure characterization' coefficient, and MPC is the 'motored pressure characterization' coefficient. The calibrated values of MPC and FPC were 4.8 and 4.0 respectively for the Ford engine used in the experimental investigation.

An estimate of the mass fraction burnt is then obtained by normalizing the PDR from equation (1) with its maximum value PDR_{max} as follows:

$$MFB_{PDR}(\theta) = \frac{PDR(\theta)}{PDR_{max}} \quad (2)$$

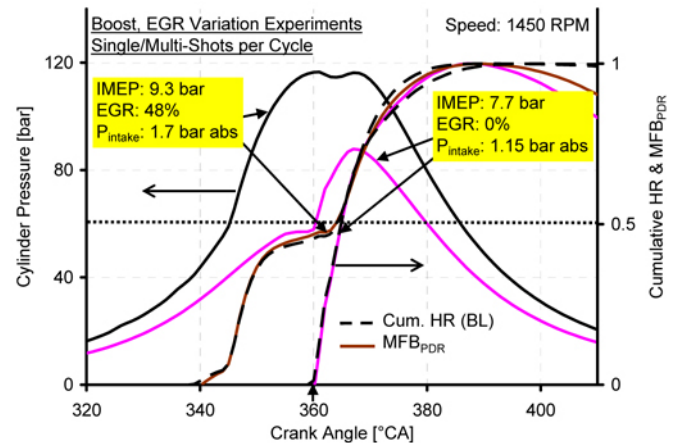


Figure 5. Validation of PDR for EGR, Boost & Fuel Injection Strategy Variations [24]

BOOST AND EXHAUST BACK-PRESSURE CONTROL

An automatic closed-loop feedback control system was used to actively control the intake boost and exhaust back-pressure. The exhaust back-pressure is primarily affected by the engine speed, engine load and the EGR valve opening while the intake pressure varies with the engine speed and the exhaust back-pressure. The closed-loop control system maintains the intake pressure and the exhaust back-pressure within prescribed limits around the desired setpoints. To precisely regulate the amount of EGR, the amount of EGR was regulated with a combination of the EGR valve opening and the exhaust backpressure, independent of the engine operating conditions. The control of the EGR valve was programmed using National Instruments' Controller Area Network (CAN) hardware and LabVIEW programming interface.

The amount of EGR was evaluated with sufficient accuracy by measuring the carbon dioxide (CO_2) concentration in the intake and exhaust [4,21,25]. Alternatively, under steady operating conditions, the EGR rate could be evaluated from Equation (3) where $MAF_{current}$ and $MAF_{initial}$ (w/o EGR) are the intake mass air flow rates with and without EGR application, respectively: