

Mode Switching Control for Diesel Low Temperature Combustion with Fast Feedback Algorithms

Usman Asad, Prasad Divekar, Xiang Chen and Ming Zheng
Univ. of Windsor

Jimi Tjong
Ford Motor Company of Canada

ABSTRACT

Low temperature combustion (LTC) in diesel engines can be enabled using a multitude of fuel injection strategies, coupled with the elevated use of exhaust gas recirculation and intake boost. The common modes of LTC include the single-injection LTC with heavy EGR and the homogeneous charge compression ignition (HCCI), implemented with multiple early-injections during the compression stroke. Previous research indicates that the single-injection LTC is more suitable at low engine loads while the HCCI combustion can be targeted towards mid-load operation. To extend the load range of the LTC cycles, there is an urgent need to enable switching on-the-fly between the two combustion modes. The mode-switching is complicated by the fact that the challenges of enabling and ensuring stable engine operation under these two LTC modes are notably different. Moreover, the LTC cycles are inherently more sensitive to small changes in the operating variables such as the combustion phasing and the intake dilution, and therefore, the combustion control system must be able to adequately respond to such disturbances on a cycle-by-cycle basis.

In this work, cylinder pressure measurement-based computation of combustion phasing and indicated mean effective pressure (IMEP), demonstrated in the authors' previous work for single-injection diesel LTC, has been used to enable and stabilize the LTC modes by precise control of single/multi-injection events. The IMEP estimation technique has been extended to modulate multiple fuel-injection events for dynamic load and stability control of HCCI combustion. A mode-switching algorithm is then proposed and demonstrated with engine tests, for enabling seamless transition between the two modes of LTC, by executing a pre-defined sequence triggered by an IMEP threshold, while pressure feedback-based control over individual injection events ensures the stability of the combustion. Representative results with controller gain modification indicate the possibility of controller tuning for improving the mode-switching time and transient performance. Modifications in the proposed algorithm are suggested to optimize the performance and enhance the robustness of the mode-switching process.

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INTRODUCTION

Modern diesel combustion modes employing enhanced premixed lean charge offer the potential of simultaneous low NO_x and low soot emissions by limiting the combustion temperature below the generally accepted thermal NO_x threshold of 1800~2100 K while the high charge homogeneity ensures a near smokeless combustion [1,2,3,4,5]. The practical implementation of low temperature combustion (LTC) cycles is done either by scheduling a single fuel-injection close to the top dead centre (TDC) and using heavy exhaust gas recirculation (EGR) to delay the onset of combustion, thereby improving the homogeneity of

the cylinder charge or by preparing a near-homogeneous cylinder charge with multiple fuel-injections early during the compression stroke [3,6]. A comparison of two LTC combustion modes is shown in Figure 1.

The single-injection LTC mode, although being similar to the conventional injection in traditional diesel engines, differs in several important aspects. The ignition delay needs to be prolonged to enhance the homogeneity and to avoid conventional diffusion-controlled high-temperature combustion (HTC). The prolonged ignition delay is primarily achieved by the heavy use of EGR and the resulting highly-diluted, enhanced premixed combustion enables the

simultaneous reduction of NO_x and soot, albeit at the cost of elevated HC and CO emissions. A direct command over the combustion phasing is achieved by modifying the 'start of injection' (SOI) with respect to the TDC, but the combustion becomes highly sensitive to minor changes in the operating variables such as the combustion phasing and the intake dilution- the need of a closed loop control system is thus necessitated [7]. The implementation of this mode also requires a transition from the conventional NO_x-soot trade-off of the diesel HTC to simultaneous low NO_x, low soot LTC; the transition usually results in unacceptably high soot levels at higher engine loads. Therefore, this mode may be realized at low engine loads [3,4].

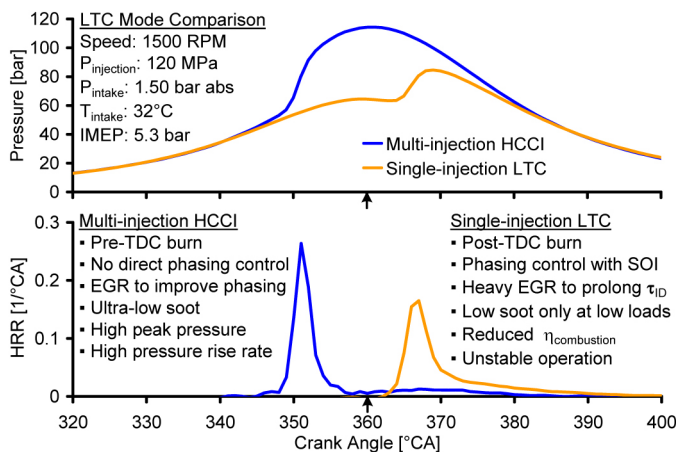


Figure 1. Characteristics of LTC Modes

For the multi-injection LTC, the fuel and air are premixed by scheduling the injection events early in the compression stroke and splitting the total amount of injected fuel into multiple injection events to prepare a cylinder charge with high homogeneity at the commencement of the combustion event. The implementation of such homogeneous charge compression ignition (HCCI) combustion results in the decoupling of the injection and ignition events, and therefore, typically suffers from a lowered energy efficiency due to the off-phasing of the heat release from the crank angle window for best efficiency, normally reported as 5~10°CA after top-dead centre [3,4,5,6,7,8,9,10,11]. To prevent early auto-ignition (premature burning early in the compression stroke) that usually results in high rates of pressure rise and even knocking combustion at high engine loads, EGR is usually applied to modulate the intake oxygen and to increase the heat capacity of the cylinder-charge that results in a delayed combustion phasing [3,12,13,14]. Additionally, as the fuelling rate increases, the propensity to auto-ignite improves along with the increased effectiveness (dilution effect) of EGR, thereby improving the stability of the combustion. Hence, this combustion mode is more suited under mid-load conditions.

Previous research including that done by the authors indicates that no single LTC mode is capable of operating over the entire engine operating regime because of the limited

applicability of each combustion mode in terms of the load range, exhaust emissions and robustness [3,6,12,13,14]. Moreover, the selection of an appropriate combustion mode depends on a number of factors including the targeted engine load, availability of boost and EGR, and the status of the aftertreatment systems. Therefore, a combustion management scheme needs to be devised if such clean combustion modes are to be implemented in a production engine system. The authors have previously proposed such a management scheme incorporating mode-switching among the different LTC modes based on the engine load level as shown in Figure 2 [4]. As the load requirements change, there is a need to switch between conventional diesel and one of the different LTC modes for maintaining emissions below the desired levels which can be implemented with different levels of EGR. At idle load, the emission targets can be achieved using high level of EGR with conventional diesel operation. Similarly, for high-to-full load operation, the combustion should be switched from LTC to conventional diesel operation with high amounts of EGR.

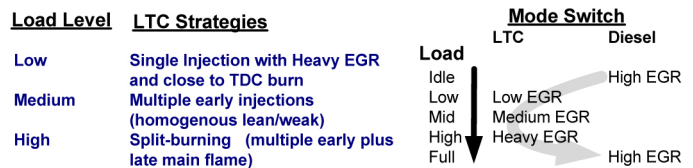


Figure 2. Combustion Management through Mode Switching Strategy

The multi-mode engine operation requires switching between the combustion modes at appropriate setpoints in the engine operating regime while fulfilling the load demand as requested by the driver, without departing from the low emission characteristics. The challenges of implementing the mode-switching are twofold. First, the stability and efficiency of each combustion mode must be guaranteed and second, the control system must be able to ensure seamless transition between the modes.

To overcome the first challenge, the authors have previously proposed and validated an 'overall control system' for stable, energy-efficient LTC that includes both the prompt (fuel-injection control) and systematic (boost and EGR) control elements [7,15]. The systematic control manages the EGR valve, exhaust backpressure (simulating the VGT position) and the intake boost (simulating the turbocharger), providing control over the density and dilution of the in-cylinder charge. The control action is slow, due to factors such as the physical gas-transport delays, sensor and actuator dynamics, and therefore cannot be directly used for cycle-by-cycle combustion control. Nevertheless, a coordinated control of EGR ratio (charge dilution) and boost (charge density) is necessary to achieve and stabilize the aforementioned combustion modes. A high sensitivity of the LTC stability to the characteristics of the trapped in-cylinder charge necessitates a precise control of these actuators. An EGR-

boost look-up-table (LUT), along with the intake dilution and air/fuel ratio feedback using a wide-band exhaust oxygen sensor has been demonstrated in the authors' previous work [7]. An exhaust NO_x sensor is also employed in the overall control system as a secondary feedback for EGR-boost control and to ensure conformity to emission requirements. The overall control system is not the focus of this paper and the reader is referred to [7,15] for further details.

The work reported in this paper addresses the challenges of enabling seamless transition from the single-injection LTC to the multi-injection HCCI with a mode-switching algorithm. These LTC modes have been achieved in a high compression ratio diesel engine by precise control over the fuel-injection events while precisely modulating the overall system variables including boost and EGR. Cylinder pressure measurement-based computation of combustion phasing and estimation of indicated mean effective pressure (IMEP), are employed for stabilizing the single-injection LTC. The IMEP estimation technique is extended to modulate multiple fuel injection events for dynamic load and stability control of the HCCI combustion. The proposed mode-switching algorithm, consisting of a pre-defined sequence triggered by an IMEP threshold value, is demonstrated with engine tests, while pressure feedback-based control over individual injection events ensures the stability of the combustion. Representative results with controller gain modification indicate the possibility of controller tuning for improving the mode-switching transient performance. Modifications in the proposed algorithm are suggested to improve the robustness of the mode-switching process. This research intends to demonstrate seamless switching between single-injection LTC and HCCI modes while maintaining the stability of the combustion process.

RESEARCH METHODOLOGY

The research methodology employs the 'prompt combustion control system' developed at the authors' laboratory that can be broadly divided into two categories: the 'fuel-injection control system' and the 'pressure feedback system'.

FUEL-INJECTION CONTROL SYSTEM

Modern diesel common-rail injection systems allow for precise modulation of the number of injection events per cycle and the location and duration of each injection event. The fuel-injection control system allows the crank angle-resolved control of the location of each injection, whereas the injection quantity can be controlled on a time-resolved basis by varying the pulse-width of each injection duration on a micro-second timescale. Although injector opening and closing delays exist in real injector functioning, the injector dynamics are neglected here.

Due to the inherent cyclic nature of internal combustion engines, the development of control structures in the discrete-event domain is simpler and robust. Hence, for a single-

cylinder engine platform, all the calculations are done in the crank angle domain and are updated every cycle. In subsequent discussions, the notation ' k ' will represent the current cycle and the corresponding calculations. Each injection pulse is represented as an independent control action and multi-injection strategies are used to achieve the HCCI mode of combustion. A maximum of 3 independent injections per cycle are used in this research; thus, for simplicity, injection events are represented as a set J , such that

$$J \subset \{1, 2, 3\}$$

For an injection event, $j \in J$, SOI_j and PWC_j represent the 'start of injection' and the 'pulse-width commanded' respectively. It may be noted that SOI_j is in the crank angle domain, synchronized with the piston position relative to the TDC and PWC_j in the time domain, corresponding to the amount of fuel injected. The total amount of fuel injected per cycle may then be represented as:

$$m_f(k) = \alpha \sum_{j \in J} PWC_j$$

where $m_f(k)$ is the total mass of fuel injected in the k^{th} cycle and α is a constant which depends on the fuel-injection pressure.

PRESSURE FEEDBACK SYSTEM

The fuel conversion efficiency and stability of LTC modes are highly sensitive to the EGR-boost interaction and the fuel injection variables (J , SOI_j , PWC_j). Stability concerns of LTC modes and the complex boundary conditions render open-loop or estimator-based control of the fuel-injection event a highly challenging task. Therefore, a closed loop control system using the in-cylinder pressure measurement has been proposed and investigated previously [16,17]. Fast-feedback combustion control has been demonstrated by the authors [7] which allows within-same-cycle or cycle-by-cycle analysis of the engine load using the IMEP estimation algorithm and cycle-by-cycle computation of the combustion phasing using the 'Pressure Departure Ratio' (PDR) algorithm.

The IMEP prediction uses an IMEP estimator that calculates the IMEP on either a cycle-by-cycle basis or within-same-cycle basis. For within-same-cycle estimation and control action, the IMEP calculation for the current cycle uses the history of pressure in the previous cycle to complete the current cycle. Thus, as the current cycle ' k ' progresses, the combustion event of the previous cycle ($k-1^{\text{th}}$ cycle) contributes in the estimation of the IMEP of the current cycle. The estimator can be written as,

$$\text{IMEP}(k) = \frac{\left[\sum_{i=\theta(k-1)}^{719} (0.5[p_i(k-1) + p_{i-1}(k-1)]dV) \right]_{w_1} + \left[\sum_{i=0}^{\theta(k)} (0.5[p_i(k) + p_{i-1}(k)]dV) \right]_{w_2}}{V_d}$$

Limiting factors w_1 and w_2 are applied to limit the contribution of the IMEP of the previous cycle in the estimation of the IMEP of the current cycle [7]. In this work, the IMEP estimator defaults to the cycle-by-cycle calculation with w_1 set to zero, $w_2 = 1$ and $\theta = 720$.

The *PDR* algorithm allows for fast and reliable feedback of the mass fraction burnt (*MFB*), which gives a satisfactory indication of the combustion phasing. It is based on the principle that the departure of cylinder pressure from the motoring pressure can give an adequate estimate of the location of the combustion event. The measured cylinder pressure is considered to be comprised of two components: the pressure rise due to the volume change and the pressure rise due to combustion. Hence, the *PDR* uses the fired pressure trace, p , and the motored pressure, p_{mot} , for estimation of the combustion, and consequently, the *MFB*. The *PDR* and *MFB* for the current cycle, k , at a crank angle, θ , can be expressed as,

$$PDR(\theta, k) = \frac{p(\theta, k) + FPC}{p_{mot}(\theta) + MPC} - 1 \quad MFB(\theta, k) = \frac{PDR(\theta, k)}{PDR_{max}}$$

where, *FPC* is the ‘fired pressure characterization’ coefficient and *MPC* is the ‘motored pressure characterization’ coefficient that can be determined by calibration and are constant for a particular engine [17].

FEEDBACK CONTROL SYSTEM-IMPLEMENTATION

The pressure-based feedback is then used to develop a closed-loop control structure of the form similar to that discussed in [18],

$$u(k+1) = u(k) + Ce(k)$$

where, u is the control input, C is the controller gain and e is the complex error function representing the deviation of the feedbacks, IMEP (k) and *MFB*(k) from the respective setpoints.

Using the control inputs of J , SCI_j and PWC_j , the different LTC modes can be achieved and controlled on a cycle-by-cycle basis. The closed loop control structure is linearized for different LTC modes for simplicity and ease of implementation. The implementation of the control system for the two LTC modes investigated is described hereon. As a part of the notation, an individual combustion mode, ‘ X ’ will be represented as m_x .

Single-Injection Combustion Mode Control

For consistency of the notation in subsequent sections of the paper, the single-injection LTC mode is represented by m_1 and is enabled using injection # 3 ($J=\{3\}$). The phasing and duration of the injection are controlled to maintain a combustion phasing set-point, MFB_{SP} , and a load set-point, $IMEP_{SP}$, respectively. This can be expressed in the previously defined feedback control structure as follows,

$$\left. \begin{aligned} J &= \{3\} \\ SOI_j(k+1) &= SOI_j(k) + C_1 (MFB(k) - MFB_{sp}) \\ PWC_j(k+1) &= PWC_j(k) + C_2 (IMEP(k) - IMEP_{sp}) \end{aligned} \right\} m_1 \quad (1)$$

MFB and IMEP computed during the current cycle, k , are used to control the timing and duration of the injection of the subsequent cycle, $k+1$, and constants C_1 and C_2 are the proportional gains.

Multiple-Injection Combustion Mode Control

In this mode, represented by m_2 , multiple injection events are used early in the compression stroke to prepare a premixed charge for auto-ignition. The location of the injection events has no direct correlation to combustion phasing as the combustion is governed by the chemical kinetics and the instantaneous conditions existing in the cylinder. Three injections are used for HCCI combustion in this work, although higher number of injections may be used and have been demonstrated in [19]. The injection timings (locations) are kept constant with a sufficient dwell between the injections, based on extensive mapping tests previously conducted by the authors.

$$\left. \begin{aligned} J &= \{1, 2, 3\} \\ SOI_1(k+1) &= C_a \\ SOI_2(k+1) &= C_b \\ SOI_3(k+1) &= C_c \\ PWC_j(k+1) &= PWC_j(k) + C_3 (IMEP(k) - IMEP_{sp}) \end{aligned} \right\} m_2 \quad (2)$$

Similar to the single-injection control strategy, the IMEP estimation of the current cycle, k , is used to control the duration of each injection of the subsequent cycle, $k+1$. Constant C_3 is the proportional gain and is chosen to be significantly lower than C_2 this control applies to all the 3 injections.

MODE-SWITCHING

The experimental investigation of a variety of LTC modes by different combinations of the control inputs can be found in [19,20]. Also, various researchers have demonstrated the use of multi-mode combustion strategies and the potential of switching between combustion modes to allow wide load

engine operation [21,22]. It has been experimentally demonstrated with the help of steady state testing, by the authors [19] that various LTC modes may be achieved at different loads by different combinations of multi-injection strategies. As a result, the combustion system can be represented as a switched, hybrid dynamical system described by [23] with multi-mode operation. The mode transitions may be represented by S_x^y for $m_x \rightarrow m_y$. Also, the mode transition is said to be complete when $S_x^y = m_y$. While a number of combustion modes can be implemented at different engine loads, including conventional diesel HTC modes, this work considers the two aforementioned LTC modes and investigates the mode-switching strategy from the single-injection LTC to the multi-injection HCCI for demonstration of the concept.

The cost function involved in the mode transition of any hybrid dynamical system has been elaborately discussed in the literature [23,24]. As a result, a systematic treatment of the mode transition sequence is required while minimizing the respective cost function. In combustion mode control, the cost functions have been identified as the departure from the optimal engine performance and noticeable disturbance in the driver's perception of the vehicle response. Heuristics-based, LUT-type, open-loop control architectures may be employed for such a control system by conducting extensive engine calibration testing. However, the narrow operating regions of each LTC mode may render impractical, this traditional method of engine ECU programming. Therefore, a mode-switching sequence based on the closed-loop control architecture described in equations 1 and 2, has been implemented in this work.

An IMEP threshold has been defined as a trigger for enabling the mode-switching sequence. The engine is operated in the single-injection LTC mode (m_1) at low loads and as the load increases, at a certain IMEP threshold, $IMEP_T$, the mode-switching is triggered and the injection control commands undergo a series of changes to allow transition into the multi-injection HCCI mode (m_2). A schematic of the mode-switching sequence for transition from m_1 to m_2 is shown in Figure 3. The condition required to initiate the mode transition sequence is indicated by $![\cdot]$.

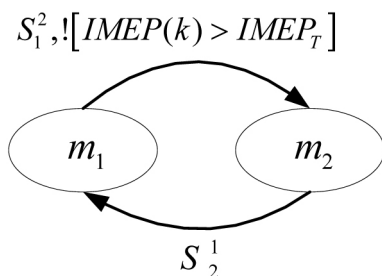


Figure 3. Mode Transition Sequence as Implemented in this Research

In the current work, the mode-switching sequence is executed in 6 steps and the cycle-to-cycle changes in the injection signals are kept to a minimum to ensure stability and to minimize departure from the demanded load. The injection control changes are pre-defined during each step of the sequence as detailed below. The input injection commands are described at each step of the sequence. It may be noted that the changes take effect during each cycle, ' k ' denotes the first cycle when the mode change S_1^2 is initiated while ' i ' is the current cycle within the respective step of the sequence. Also, the injection parameters that are not explicitly described in any step of the sequence remain the same as in the previous step.

$$J = \{3\}$$

Step 1 $SOI_3(i) = SOI_3(k)$

$$PWC_3(i) = PWC_3(k) + C_2 (IMEP(i) - IMEP_{sp})$$

$$J = \{1, 3\}$$

Step 2 $SOI_1(i) = C_a$

$$PWC_1(i) = 180\mu s$$

$$J = \{1, 2, 3\}$$

Step 3 $SOI_2(i) = C_b$

$$PWC_2(i) = 180\mu s$$

$$PWC_{1,2}(i) = PWC_{1,2}(i-1) + \delta PW_1$$

Step 4

$$\text{while } PWC_{1,2}(i) \leq C_4$$

Step 5 $SOI_3(i) = C_c \quad \wedge \quad \begin{matrix} PWC_{1,2}(i) = PWC_{1,2}(i-1) \pm \delta PW_2 \\ \text{while } PWC_{1,2}(i) \neq PWC_3(i) \end{matrix}$

Step 6 $PWC_j(i) = PWC_j(k) + C_3 (IMEP(i) - IMEP_{sp})$

The constants used in the mode switch sequence govern the total number of cycles required for the completion of the sequence; these are determined experimentally and the effect of varying them is discussed in the results section. It is noted that steps 1,2,3,6 require only one cycle each for execution while steps 4 and 5 continue until the stated conditions are satisfied, hence governing the speed of the mode switching.

EXPERIMENTAL SETUP

A modern 4-cylinder Ford common-rail diesel engine, running in a single-cylinder configuration was instrumented for the tests as shown in Figure 4. The 3 cylinders-to-1 cylinder configuration is a new exploration strategy that enables investigation of unstable combustion regimes with a non-motoring dynamometer [20]. The 3 cylinders are operated in the conventional HTC regime at low load for