

Efficacy of EGR and Boost in Single-Injection Enabled Low Temperature Combustion

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ABSTRACT

Exhaust gas recirculation, fuel injection strategy and boost pressure are among the key enablers to attain low NO_x and soot emissions simultaneously on modern diesel engines. In this work, the individual influence of these parameters on the emissions are investigated independently for engine loads up to 8 bar IMEP. A single-shot fuel injection strategy has been deployed to push the diesel cycle into low temperature combustion with EGR. The results indicated that NO_x was a stronger respondent to injection pressure levels than to boost when the EGR ratio is relatively low. However, when the EGR level was sufficiently high, the NO_x was virtually grounded and the effect of boost or injection pressure becomes irrelevant. Further tests indicated that a higher injection pressure lowered soot emissions across the EGR sweeps while the effect of boost on the soot reduction appeared significant only at higher soot levels. Moreover, the peak soot values were observed to shift towards lower intake oxygen values. With high levels of EGR, the increased carbon monoxide emission largely followed the NO_x-Soot trade-off (reduced oxygen concentration, 11~14% of the working fluid), while the increased hydrocarbon emission was attributed to both the lowered flame temperature and the further reduced oxygen concentration (8~12%).

INTRODUCTION

Low temperature diesel combustion (LTC) systems result in ultra low emissions of in-cylinder NO_x and dry soot by limiting the combustion temperatures in conventional diesel engines. Such systems can be broadly divided into two categories [1,2]. The first 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 [3,4]. For a thoroughly mixed cylinder charge, the tendency for soot formation is low, largely regardless of the air-excess ratio.

The second category of 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 cooled EGR and/or retarded injection timing are commonly employed to prolong the ignition delay and to lower the flame temperature [5]. The work presented in this paper focuses on the second category of LTC with high levels of EGR and injection timing slightly earlier than TDC (up to 10°BTDC).

Previous research indicates that simultaneous low NO_x and low soot can be achieved by keeping the flame temperature below approximately 1650 K during combustion. Both the NO_x and soot formation zones are then avoided regardless of the air excess ratio [6,7]. Two

variations of this LTC mode have been reported. The first, called the MK combustion secured sufficient mixing time by prolonging the ignition delay with EGR and retarded injection timing (after TDC), and by dispersion of the injected fuel through increased turbulence (swirl ratio: 3 to 5) to achieve the premixed LTC [8–10]. Combustion photographs indicated the combustion flame with weak luminous intensity and this was thought to confirm an advanced state of mixture homogeneity before combustion [10]. The second, called the smokeless rich combustion employed large amounts of cooled EGR and near-stoichiometric operating conditions to achieve low NO_x and low soot. Based on CFD analysis, Akihama et al. attributed the low soot formation primarily to the temperature reduction achieved with EGR [7].

Based on the ϕ -T map [7], the soot formation can also be suppressed even at combustion temperatures around 2000 K if an over-rich mixture is avoided ($\phi < 2$) [11]. Therefore, smokeless and ultra-low NO_x combustion can be realized by improving the premixing while keeping the combustion temperature below 2000 K. To improve the air-fuel mixing, an extension of the ignition delay by advancing the injection timing, use of heavy EGR and elevating the fuel injection pressure may be effective. Advancing the injection timing is beneficial in terms of reducing the thermal efficiency penalty as well as preventing misfire [11].

A natural consequence of high EGR rates is a substantial increase in the ignition delay period as shown by the test results run at the authors' lab (Figure 1). An increase in the ignition delay above 50% of the baseline value (without EGR) (or > than 1.5ms) was repeatedly seen to push the combustion into the LTC regime, at different engine operating conditions [12–14]. The increased ignition delay allows more time for the fuel-air mixing and therefore improves the homogeneity of the cylinder charge. Other published results show the absence of a brilliant flame during the entire combustion period and that is taken as evidence of the low sooting tendency of the flame due to low temperature as well as the existence of an advanced state of premixing [10,15].

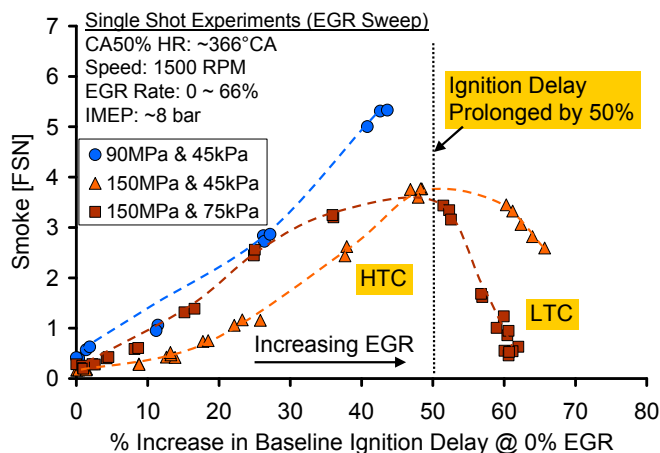


Figure 1: Ignition Delay for Enabling LTC

Additionally, 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 [2]. The CO and HC emissions can drain a substantial amount of fuel energy from the LTC cycles and presents 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 [16]. Nonetheless, these combustion modes offer the potential of simultaneous NO_x and soot reduction [17–25].

The load level of the LTC cycles is limited by the peak cylinder pressure, the maximum rate of pressure rise and the peak combustion temperature. The low combustion temperature and high homogeneity are more difficult to achieve as the engine load, and thus the fueling rate, increases. The excess oxygen depletes with higher fueling rates and the proportion of the premixed fuel reduces within the given ignition delay period. Without employing higher EGR rates to push the temperature down, any non-homogeneity may therefore increase the local flame temperature in regions close to the stoichiometric air/fuel ratio.

The implementation of the LTC cycles is commonly in low compression ratio (CR) engines such as 16:1, 14:1 or even lower. Engines with a CR of 17:1 or higher are generally considered not suitable or are commonly restricted to low load operation only while operating under LTC cycles. This is so because a higher compression ratio translates into a higher peak compression temperature (assuming EGR and other conditions to be the same). Therefore, the transition from the high temperature combustion to the LTC cycles requires higher EGR rates to lower the temperature which normally result in very high levels of soot during the transition phase (Figure 1).

It is noted that the improvements of fuel-air mixing can be significantly enhanced by higher fuel injection pressures, such as by raising the injection pressure to ~3000 bar levels [26]. However, this research reports the LTC enabling work based on injection pressures that can be conveniently achieved with a moderate conventional common-rail system, i.e. with an injection pressure up to 1600 bar for instance, typically suitable for light-duty applications.

In this work, a modern diesel engine with a CR of 18.2:1 has been used to investigate the attainment of simultaneous low NO_x and low soot with single-injection enabled LTC at 8 bar IMEP. Comparisons have been made between the individual effects of boost, EGR and moderate injection pressure on the engine-out emissions of NO_x, Soot, THC and CO, and the heat release rates.

EXPERIMENTAL SETUP

A modern 4-cylinder Ford common-rail diesel engine, running in single-cylinder mode was instrumented for the tests as shown in Figure 2. The 3 cylinders-to-1 cylinder configuration is a new exploration strategy that enables investigation of unstable combustion regimes with a non-motoring dynamometer. 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

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

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 (Table 2). 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. The control platform consists of a set of embedded real-time (RT) controllers, field programmable gate array (FPGA) devices, and synchronized high-speed signal conditioning, and recording units. 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.

Table 2: Intake & Exhaust Gas Sampling Analyzers

Analyzers	Species	Manufacturer & Model No.
Non-dispersive infrared (NDIR)	CO (ppm) CO ₂ (%)	CAI Model 300 CAI Model 200
Paramagnetic	O ₂ (%)	CAI Model 602P
Chemiluminescence (HCLD)	NO (ppm) NO ₂ (ppm)	CAI Model 600-HCLD
Flame ionization detector (HFID)	THC (ppm)	CAI Model 300M-HFID
Variable sampling smoke meter	Smoke (FSN) soot (mg/m ³)	AVL Model 415S

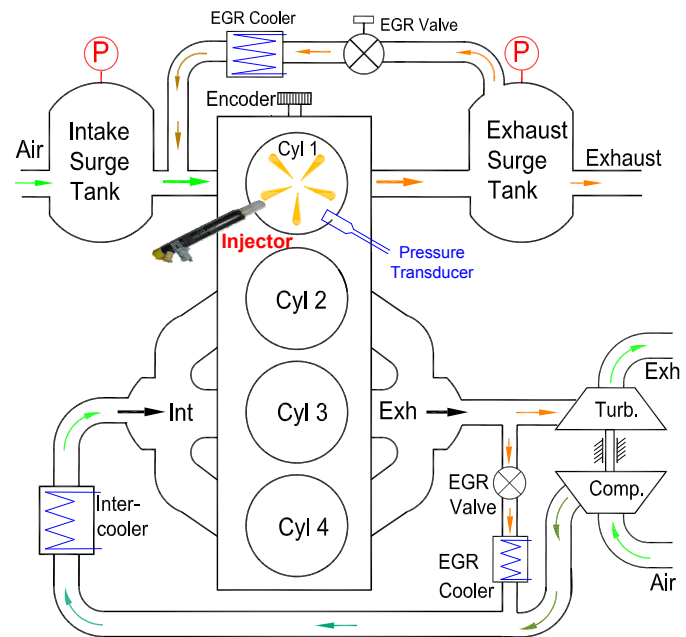


Figure 2: Schematic Representation of the Test Setup with independent control on intake boost and exhaust backpressure at University of Windsor.

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 phasing of the heat-release rates during the on-line monitoring of the combustion event.

To precisely regulate the amount of EGR, an exhaust backpressure valve was actuated by an in-house developed PC-control system, to control the pressure differential between the exhaust and the intake. The amount of EGR was then regulated with a combination of the EGR valve opening and the backpressure, independent of the engine operating conditions. The amount of EGR could be estimated from Equation (1), where $\dot{m}_{EGR}$ is the mass flow rate of the recycled gases, $\dot{m}_{air}$ is the mass flow rate of the fresh air and $\dot{m}_f$, the mass flow rate of the fuel.

$$\text{EGR Fraction} = \frac{\dot{m}_{EGR}}{\dot{m}_{air} + \dot{m}_f + \dot{m}_{EGR}} \quad (1)$$

Empirically, the amount of EGR could be evaluated with sufficient accuracy by measuring the carbon dioxide (CO₂) concentration in the intake and exhaust [4,27,28]. Alternatively, under steady operating conditions, the EGR rate could be evaluated from Equation (2) where $MAF_{current}$ and $MAF_{initial(w/o EGR)}$ are the fresh air mass flow rates with and without EGR application, respectively.

The MAF reading is taken upstream of the EGR line on the intake side.

$$\text{EGR Fraction} = 1 - \frac{\text{MAF}_{\text{current}}}{\text{MAF}_{\text{initial(w/o EGR)}}} \approx \frac{\text{Intake CO}_2}{\text{Exhaust CO}_2} \quad (2)$$

In this work, the EGR has been calculated based on the intake and exhaust CO₂ concentrations. The intake CO₂ is measured downstream of the EGR line on the intake side.

A 2007 certification ultra low sulphur diesel was used for the tests. The properties of the fuel are given in Table 3.

Table 3: Diesel Fuel Specifications

Fuel Parameter	Reported Value
Specific Gravity [-]	0.846
Sulphur [ppm]	14
LHV [MJ/kg]	43.1
Carbon [wt %]	86.4
Hydrogen [wt %]	13.6
Cetane Number	46.5

DEFINITIONS - The following terms have been used in the paper and are therefore defined here.

CA50 – is the crank angle at which the value of the normalized cumulative heat release curve is 0.5. This is taken as a measure of the combustion phasing.

Combustion Duration – is the duration from the crank angle at which the value of the normalized cumulative heat release curve is 0.05 to the crank angle at which the value of the normalized cumulative heat release curve becomes 1.

Slope 1– the segment of soot climbing but NO_x declining curve when EGR increases during HTC combustion. It represents the classical NO_x-Soot trade-off.

Slope 2 – the segment of simultaneous soot and NO_x declining curve when EGR increases (during LTC combustion). It represents the reduction in NO_x and soot enabled with a single injection using heavy EGR.

Heavy EGR – refers to large amounts of recycled exhaust gases that result in nearly halved oxygen and high carbon dioxide contents in the engine intake. This indicates EGR levels (typically 50~70%) beyond those commonly applied in production diesel engines.

LTC – refers to any combustion mode that results in ultra low emissions of in-cylinder NO_x and PM in conventional diesel engines.

RESULTS AND DISCUSSION

The aim of this work was to experimentally determine the influence of boost pressure, EGR and injection pressure (suitable for light-duty applications) on the combustion and emission performance of single-injection enabled LTC cycles. The mode of *EGR enabled LTC* employs a single injection of fuel, near or after the end of piston compression, i.e. the top dead centre (TDC) to which high levels of EGR are normally applied concurrently. The effect of temperature reduction by the piston expansion stroke provides a prolonged ignition delay period thereby facilitating more mixing, resulting in substantially enhanced premixed-burning in such a main combustion event [29]. Since the heat release phasing is fully controllable via injection timing, therefore, high energy efficiency is attainable by modulating the combustion phasing [7,30].

To investigate the effects of EGR, boost and injection pressure on the LTC cycles, a relatively high IMEP of 8 bar was chosen for this engine (CR: 18.2:1). This IMEP is considered high for this engine because previously published data for engines with similar CR (>17:1) is limited to 4-5 bar IMEP in LTC mode. A summary of this can be found in [1]. All the tests were performed at 1500 RPM. The fuelling was kept constant during the EGR sweep experiments. The EGR stream temperature was regulated to maintain the intake temperature within a narrow range of 28~32°C. Noted, this is lower than the normal engine operating temperature; however, the trends presented in this work have been empirically found to be consistent when using higher intake temperatures (40 to 80°C) by the authors [13,30,31]. Nonetheless, the low intake temperature during these tests was a physical limitation of the EGR loop (due to EGR loop being connected after the exhaust surge tank). To make a fair comparison between the results with variations in the boost pressure, all the test results have been plotted against the intake oxygen concentration in this work since one of the major effects of EGR is the cylinder charge dilution (reduction in the oxygen flow rate to the engine) as discussed in the next section [32,33].

EXHAUST GAS RECIRCULATION - The results for an EGR sweep from 10 to 64 % are shown in Figure 3. As EGR is applied, NO_x reduces significantly with minimal rise in soot. Further increases in EGR lead to additional NO_x reduction but cause a significant rise in soot (Slope 1). However, as heavier EGR is applied, the combustion process typically results in simultaneous reductions of NO_x and soot emissions as the combustion essentially enters the LTC regime (Slope 2). These results are consistent with previously published data [7].