

The Effect of Cycle-to-Cycle Variations on the NO_x-SFC Tradeoff in Diesel Engines under Long Ignition Delay Conditions

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ABSTRACT

Cycle-to-cycle variations in internal combustion engines are known to lead to limitations in engine load and efficiency, as well as increases in emissions. Recent research has led to the identification of the source of cyclic variations of pressure, soot and NO emissions in direct injection common rail diesel engines, when employing a single block injection and operating under long ignition delay conditions. The variations in peak pressure arise from changes in the diffusion combustion rate, caused by randomly occurring in-cylinder pressure fluctuations. These fluctuations result from the excitation of the first radial mode of vibration of the cylinder gases which arises from the rapid premixed combustion after the long ignition delay period. Cycles with high-intensity fluctuations present faster diffusion combustion, resulting in higher cycle peak pressure, as well as higher measured exhaust NO concentrations. In this study the effects of pressure fluctuations on the NO_x-specific fuel consumption (SFC) tradeoff are determined. The investigation is performed on a single-cylinder heavy-duty diesel engine, and focuses on the variation of injection parameters (injection timing and pressure) under constant, long ignition delay conditions. Single-cycle NO concentrations are measured using a fast-NO analyzer placed near the exhaust valve, whereas the indicated SFC is determined from the measured cylinder pressure. The results show that the presence of pressure fluctuations is not beneficial for the NO_x-SFC tradeoff, with the cycles showing higher fluctuation intensities leading to higher emission levels for constant indicated SFC.

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INTRODUCTION

Cycle-to-cycle variations in reciprocating internal combustion engines, where the in-cylinder pressure varies significantly on a cyclic basis, have been a subject of increased interest in the past decades. Cyclic variations are generally undesirable since they are understood to lead to lower efficiency and higher emissions, as well as power output (drivability) problems [1, 2]. Cycle-to-cycle variations are most commonly observed in Spark Ignition (SI) engines, where they are caused by changes in the burn rate for each successive cycle. This variation can have numerous root causes; cyclic variation in the cylinder gas motion, cyclic variation in the amount of fuel, air and exhaust gases present in the cylinder, cyclic variation of the mixture composition near the spark plug, or changes in the spark discharge characteristics, leading to differences in combustion speed or local end-gas autoignition [3, 4, 5]. These effects have been studied extensively in the past through experimental investigations [6, 7, 8] and using numerical tools [4, 9, 10, 11].

Significant cycle-to-cycle variations are less common in conventional Compression Ignition (CI) diesel engines. This is due to the nature of dominantly non-premixed CI combustion, where fuel injection primarily governs air-fuel mixing and thus combustion. Any cyclic

variation in background turbulence (swirl, etc.) will not affect the combustion rate significantly during the injection, since its intensity is multiple times lower than the injection-sourced turbulence. Nevertheless, there exist cases where CI combustion also exhibits cyclic variability; in Rakopoulos et al. [12], studies of cold start in CI engines showed that colder in-cylinder conditions led to increased Ignition Delay (ID), which resulted in heavy cycle-to-cycle variations of in-cylinder pressure. Furthermore, in several investigations [1, 2, 13, 14, 15, 16] increased cycle-to-cycle variations were observed in direct injection (DI) diesel engines when changing the intake temperature, intake pressure (load) and injection timing parameters in order to create conditions of prolonged ID. Studies concerning the variation of in-cylinder pressure using various fuels or fuel blends have shown a dependency of cyclic variation on the ignition characteristics of the fuels tested, with fuels with lower cetane number (CN) exhibiting larger cycle-to-cycle variation [1, 2, 15, 16, 17, 18, 19].

The observed cyclic variations in pressure have also been connected to variations in emissions. In Hagen et al. [20], fast NO measurements in a heavy duty diesel engine showed variation in the NO concentration in the exhaust at constant operating conditions.

Similarly, ultra-fast crank angle-resolved NO measurements in the exhaust stream of a marine two-stroke and a marine four-stroke engine showed variations of 20-25% and 15-20% respectively from cycle-to-cycle, at constant operating conditions [21, 22, 23]. Significant cyclic variations in NO production rate which were not coupled to changes in heat release rate (HRR) were also observed in complete cylinder dumping experiments during combustion in a DI diesel engine in Donahue et al. [24]. Wagner [25] revealed that under conventional diesel combustion conditions with constant, stable injection, NO concentrations measured through sampling of the exhaust gases showed cyclic variations of the order of 10%, while in-cylinder pressure, ID and HRR exhibited only very slight cyclic variation. Nevertheless, there was no clear correlation between variations in HRR and NO observed in this study, leading to the conclusion that variations in NO emissions were caused by random effects, possibly not coupled to the HRR. More recently, in measurements of in-cylinder NO concentrations in an optical engine using NO PLIF (Planar Laser-Induced Fluorescence), Verbeizen et al. [26, 27] observed significant cyclic variations, attributed to local NO concentration and temperature variations, as well as variations in signal attenuation.

Recent research from current authors has shown that cyclic variability in the cylinder pressure and emissions can be observed under long ignition delay conditions [28, 29, 30, 31, 32]. In Kyrtatos et al. [29], measurements under low end-of-compression temperature conditions and variable charge O_2 concentration showed that in-cylinder pressure fluctuations - i.e. excitation of the first radial mode of vibration of the cylinder gases (for the calculation of the mode of vibration see Vressner et al. [33]), caused in single cycles by the rapid premixed combustion under long ignition delay conditions - resulted in increases in diffusion HRR. The average intensity of the pressure fluctuations was shown to increase with increasing amount and reactivity of the premixed combustion. This resulted in higher cycle-to-cycle variations under these conditions, revealed by higher cyclic deviations of maximum pressure. A study of the single-cycle intensity of pressure fluctuations under long ID conditions revealed that although the average intensity of fluctuations increases with increasing premixed reactivity, even with high premixed amounts, some cycles exhibited no pressure fluctuations. This indicates that the high premixed combustion rate is not in itself a sole prerequisite for the onset of the resonance of cylinder gases, with other, seemingly "random" effects also required to induce the pressure oscillations.

The above results indicate an increased apparent fuel-air mixing caused by the pressure oscillations within the combustion chamber, which leads to increased heat release and soot oxidation rates during the mixing-controlled diffusion combustion phase. Thus, there is clear evidence that the intermittent presence and intensity of pressure oscillations is the main cause for the observed cyclic variation in combustion rate and thus in-cylinder pressure. These findings are in line with observations arising from mixing and combustion experiments of single droplets and sprays under conditions having pressure oscillations. Błaszczyk [34] showed that high frequency (200Hz-5kHz), high energy pressure oscillations consistently increased the combustion rate of single diesel fuel droplets by 2-10%, when compared to non-oscillating cases. This increase was attributed to increased air-fuel mixing due to the relative movement of gas

molecules caused by the vibrating air field. Similar results have also been shown in single droplet experiments by Saito et al. [35, 36] and Kumagai and Isoda [37], with the latter arguing that these effects should also apply to spray combustion. More recent numerical investigations have shown that various distinct mechanisms are involved in the increase of burning rate of single droplets under pressure oscillations, with heat transfer from the flame to the droplet due to the intermittent changes in flow velocity being the most significant [38]. In experiments studying spray combustion, similar effects have been observed. Yoshida et al. [39] showed that turbulence in turbulent jet diffusion flames is increased when they are externally subjected to acoustic excitation, significantly enhancing combustion rate, while shortening and broadening the flame. The same effects were also observed under oscillating conditions in Rocha et al. [40], where diffusion flames were externally excited using a loudspeaker. These experiments showed that the individual droplet lifetime was significantly reduced when oscillations were present, and created flames which had premixed flame characteristics.

The current study is based on the findings presented in Kyrtatos et al. [28], where single-cycle NO emissions, measured using a Fast-NO analyzer placed in the exhaust manifold of a heavy-duty single-cylinder research engine, showed increased cyclic variations under prolonged ID conditions. This study showed that pressure fluctuations arising from the fast premixed combustion resulted in faster diffusion combustion rate and ultimately in increased NO emissions. Overall, the high NO emissions from single cycles under long ID conditions (ID=1.27ms) were determined contribute to an increase of up to 10% to the average NO concentration, compared to the same operating point without taking into account the extreme cycles. This presents a significant increase of NO emissions, the source of which would remain unidentified without the single-cycle NO measurements.

The aim of the present investigation is to extend the abovementioned findings and evaluate the effect of pressure fluctuations on the NO_x-Specific Fuel Consumption (SFC) tradeoff. For this purpose the measurements presented in Kyrtatos et al. [28] are extended to include variations in Start of Injection (SOI) and injection pressure (P_{rail}). These variations are used in the present investigation to study the effect of single-cycle increase of efficiency and NO emissions caused by pressure fluctuations, and to compare these increases to the similar increases due to combustion phasing caused by changes in SOI and P_{rail} . This article starts with a description of the experimental setup, a presentation of the measurement points used and a description of the measurement post-processing methodology. These are followed by a presentation of the results which also includes a discussion of the findings, and finally the conclusions are presented.

EXPERIMENTAL PROCEDURE

The experiments presented in this work were conducted on a heavy-duty single-cylinder research engine, which provides the possibility of independent variation of intake and exhaust thermodynamic (temperature, pressure) and chemical conditions (intake O_2 , CO_2 concentration), as well as injection parameters. The following sections describe the experimental setup, the measurement conditions used in the study as well as the methodology for determining the single-cycle NO concentration and indicated SFC (ISFC). Document Sharing Hub

The Single Cylinder Engine

The single-cylinder engine, located in ETH Zurich, is based on a MTU 396 series engine and is retrofitted with a Ganser-CRS Common Rail injection system. The engine is supplied with pressurized (up to 5bar) and cooled/heated ($T_{in}=20$ to 100°C) air, while an external cooled Exhaust Gas Recirculation (EGR) system using an electrically-driven compressor allows the variation of intake $[\text{O}_2]$ concentration independently from the intake and exhaust pressure setting. [Table 1](#) below contains all relevant engine data.

Table 1. Test engine specifications

	Units	MTU 396 1-cyl
Displacement	l	3.96
Bore	mm	165
Stroke	mm	185
No. of Cylinders		1
Valves/Cylinder		4 (3)
Compression Ratio		13.7
Effective Compr. Ratio		11.65
Engine Speed Range	rpm	800-2100
Max. Injection Pressure	bar	1600

For the current investigations a constant, early Miller valve timing (Inlet Valve Closure (IVC) is before Bottom Dead Centre - BDC) was employed, which results in an effective compression ratio of 11.65. Additional information concerning the test rig can be found in [28, 29, 41, 42].

Measurement Conditions

The measurement conditions for this investigation were chosen in order to capture the NO_x-SFC tradeoff and compare this to the single-cycle measurements, while keeping the charge temperature at Top Dead Centre (T_{TDC}) low in order to prolong the ID. To accomplish this, the engine was run at a constant speed (1050 rpm), with a constant intake temperature ($T_{in}=20^{\circ}\text{C}$) and pressure ($P_{in}=2.9\text{bar}$), which results in a temperature at TDC of $T_{TDC}=780\text{K}$. In order to study the NO_x-SFC tradeoff, variations in SOI and P_{rail} were conducted, while in the latter case the injection duration (DOI) was adapted in order to keep the injected mass constant. [Table 2](#) and [Table 3](#) show the operating conditions for the SOI and P_{rail} variations respectively. For each point all the engine settings were kept constant for >5 minutes until all engine parameters were stabilized, before the measurement of the relevant quantities was initiated.

Table 2. Start of Injection variation operating conditions

T_{in}	P_{in}	T_{TDC}	Intake $[\text{O}_2]$	Hydraulic SOI	P_{rail}	DOI	Injection Quantity	Engine Speed
C	bar	K	%vol	deg bTDC	bar	ms	mg/cycle	rpm
20	2.9	780	20.95	2.4	1000	2.30	285	1050
				4.4				
				6.4				
				8.4				
				10.4				

Table 3. Injection Pressure variation operating conditions

T_{in}	P_{in}	T_{TDC}	Intake $[\text{O}_2]$	Hydraulic SOI	P_{rail}	DOI	Injection Quantity	Engine Speed
C	bar	K	%vol	deg bTDC	bar	ms	mg/cycle	rpm
20	2.9	780	20.95	4.4	1100	2.12	285	1050
					1200	1.99		
					1300	1.84		
					1400	1.67		
					1500	1.45		

Single-Cycle NO Concentration Measurement

For the measurement of the single-cycle NO concentration a Cambustion CLD500 FastNO NO_x analyzer was used. In the device the NO concentration is determined within the device sampling head, allowing a time response as low as $t_{10-90\%} = 2$ ms, well shorter than the required response time for cyclic variations in a medium speed engine (cycle time ~ 60 ms). The device has been used in the past for fast and/or cycle-resolved NO measurements in spark ignited [43] and diesel engines [28, 44, 45]. In the current investigation the sampling probe was placed just above the exhaust valve in order to ensure the minimum possible response time for the sampling and avoid mixing of consecutive cycles. The probe placement can be seen in [Figure 1](#).

[Figure 2](#) shows the FastNO output versus time, in relation to the measured in-cylinder pressure for 10 consecutive cycles. The figure shows the variation of the NO concentration for each cycle, with clear differentiation between consecutive cycles. The determination of a representative NO concentration for each cycle was achieved by cycle-individual averaging of the NO signal. To avoid discrepancies in the measurement due to mixing of exhaust gases from consecutive cycles, the NO signal was averaged over a period of 50ms, starting at 60ms after the exhaust valve opening (EVO). The determination of the average NO concentration for a cycle is shown graphically in [Figure 3](#). More information about the measurement process and the expected limitations can be found in [28].

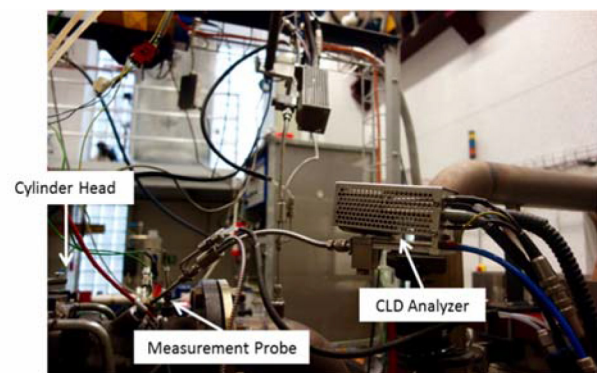


Figure 1. FastNO probe placement in the exhaust of the 1-cylinder engine