Cold-start NOx emissions: diesel and waste lubricating oil as a fuel additive

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Abstract

NOx emissions from diesel engines are a concern from both environmental and health perspectives. Recently this attention has targeted cold-start emissions highlighting that emission after-treatment systems are not effective in this period. Using a 6-cylinder, turbocharged, common-rail diesel engine, the current research investigates NOx emissions during cold-start using different engine performance parameters. In addition, it studies the influence of waste lubricating oil on NOx emissions introducing it as a fuel additive (1 and 5% by volume). To interpret the NOx formation, this study evaluates different parameters: exhaust gas temperature, engine oil temperature, engine coolant temperature, start of injection/combustion, in-cylinder pressure, heat release rate, maximum in-cylinder pressure and maximum rate of pressure rise. This study clarified how cold-start NOx increases as the engine is warming up while in general cold-start NOx is higher than hot-start. Results showed that in comparison with warmed up condition, during cold-start NOx, maximum in-cylinder pressure and maximum rate of pressure rise were higher; while start of injection, start of combustion and ignition delay were lower. During cold-start increased engine temperature was associated with decreasing maximum rate of pressure rise and peak apparent heat release rate. During cold-start NOx increased with temperature and it dropped sharply due to the delayed start of injection. This study also showed that using waste lubricating oil decreased NOx and maximum rate of pressure rise; and increased maximum in-cylinder pressure. NOx had a direct correlation with the maximum rate of pressure rise; and an inverse correlation with the maximum in-cylinder pressure.

Keywords: Waste lubricating oil; cold-start; NOx emissions; diesel engine warm-up.

1. Introduction

Cold-start operation is a part of driving for majority of the vehicles [1]. In cities, many trips start and finish while the engine is still cold, such as driving from home to work in the morning and back to home in the afternoon [2]. A study on the driving patterns of 55 vehicles, including 1000 trips (71,000 km and 1260 hours of driving), reported that one third of the trips started and finished during cold-start [1]. A modelling study on cold-start excess emissions based on a survey of 39 European laboratories used the data from 35941 measurements from 1766 passenger cars and estimated that during cold-start the average distance in which NOx emissions were stabilised was 5.2 km [3].

The engine temperature during cold-start is not optimal due to the low temperature of the engine block and also sub-optimal temperatures of the engine coolant and lubricating oil. Engine operation when its temperature is sub-optimal impacts the exhaust emissions and engine performance parameters [4-6]. For example, higher emissions and fuel consumption were reported to be the result of low cylinder wall temperature [7]. Cao [8] reported that exhaust emissions were significantly influenced by incomplete combustion attributed to a cold engine block. Also, the low engine and fuel temperatures adversely influence the atomisation and evaporation of the injected fuel during combustion which consequently impact the engine emissions [9]. Exposure to the exhaust emissions adversely impacts people’s health [10-16].

Mendoz et al. [17] performed a real driving test on a Euro VI heavy-duty vehicle and reported that a large fraction (63.4%) of NOx emissions from whole trip—which was 154.8 km drive during 10712 s—was related to the cold-start section—which was less than 300 s—owing to the thermal efficiency of the engine and also low efficiency of catalytic converters. Roy et al. [18] used a diesel engine and studied NOx emissions and reported higher NOx in cold-start in comparison with hot-start. The average NOx reduction after cold-start was 48.9% at 800 rpm, 42.7% at 1000 rpm, and 36.3% at 1200 rpm. They reported that lean fuel mixture and higher fuel consumption during cold-start could be the reasons. Samhaber et al. [19] reported that the fuel consumption during cold-start was 13.5% higher than hot-start. Higher cold-start fuel consumption could be because of the higher friction cause by the increased viscosity of the lubricating oil due to its low temperature, therefore more fuel needs to be burned to compensate the brake power [7, 20]. Also, decreased in-cylinder temperature within cold-start would lead to less complete combustion and therefore influence the total fuel consumption and emissions.

Defined in the regulation—EU Directive 2012/46/EU—cold-start begins from the engine start for the first 5 minutes or until the coolant temperature gets to 70 degC, after a proper engine soak (12 hours engine-off or 6 hours with forced cooling). A previous study from our research group [21] has shown that even after the defined cold-start period in which the coolant temperature was above 70 degC, engine performance and emissions are influenced by sub-optimal temperatures. This is because of sub-optimal temperature of the engine oil.

This study proposes a way that different engine temperature conditions can be investigated. The duration of the designed test in this study is until the engine is fully warmed up and stabilised. Hence, there will be different conditions during the test. Aside from analysing and comparing the data during the cold-start period (defined in the regulation) and also during fully warmed-up/steady state condition, this study also evaluates emissions during the time in which the coolant temperature is above 70 degC (which cannot be not considered as cold-start period anymore) but it is also not optimal (which indicates that the engine is not stable). It also studies the emissions during the time where the coolant temperature was optimal but oil temperature was still increasing due to the time lag between their optimal points, as reported in the literature [21, 22].

At present, there is a need in the literature to show how and why NOx emissions in relation with other parameters change during engine warm-up under constant engine speed and load.

Most studies investigating cold-start in the literature used a driving cycle composed of varying speed and load. This limits the fundamental study on the engine temperature effects on NOx emissions as changing speed and load within the drive cycle adds more variables and influences the in-cylinder parameters, which consequently hide the effect of engine, coolant and oil temperatures on emissions. Potentially misleading results can occur with a transient only investigation owing to various parameters reinforcing/cancelling the influence of one another under various conditions and the impact of hysteresis.

In addition to the cold-start investigation, a further aim of this study is to investigate the effect of waste lubricating oil as a fuel additive on NOx emissions and related performance parameters, such as heat release rate, maximum in-cylinder pressure, and maximum rate of pressure rise. It is reported that during combustion, as well as the injected fuel, lubricating oil inside the cylinder can combust and consequently impact engine performance and exhaust emissions [23]. However, by artificially adding the lubricating oil to the combustion chamber via blending with diesel, the mechanisms can be different compared to when lubricating oil originates from the cylinder walls. Despite the potential for differences between directly introducing the lubricating oil with the fuel and that burned from the cylinder walls, this exasperated view of the impact of burning lubricating oil will improve our understanding of combustion when diesel is diluted with lubricating oil.

Utilising alternative fuels from waste materials to offset diesel usage [24-30] has been always of interest primarily owing to environmental issues, the price of fossil fuels and the depletion of fossil fuels [31, 32]. Residual oil waste products are in the order of 24 million tones/year worldwide and waste lubricating oil represent 60% of it [33]. However, the existence of waste lubricating oil in the combustion chamber has some disadvantages [34]. For example, a high fraction of particulate matter emissions (PM and PN) derived from heavy hydrocarbons and carbonaceous solids from the lubricating oil [34]. Also, the interference between the after-treatment systems and waste lubricating oil might lead to the premature failure of these systems [34, 35]. Hannu [34] studied the impact of lubricating oil on after-treatment systems and reported that ash accumulation in a diesel particulate filter (DPF) can increase exhaust backpressure therefore more maintenance will be required and fuel economy will be degraded. This study also reported that the sulfur, zinc, or phosphorus contents of lubricating oil can poison catalysts. Another issue is sulfate formation downstream of the oxidation catalysts [34] and the negative impact of lubricant sulfur and phosphorous on lean NOx trap (LNT) efficiency [35]. However, a reduction of sulfur, phosphorus and sulfated ash in the development of lubricating oil formulations can be used to mitigate the disadvantages of lubricating oil on after-treatment systems [34]. Also, there are some measures to overcome the mentioned disadvantages and convert the waste lubricating oil to a diesel like fuel, such as through a pyrolysis process, and thermal and catalytic treatment [36, 37].

Therefore, there is potential to use it as a fuel, however, using this alternative fuels should not compromise the engine emissions and performance. There are studies in the literature evaluating the use of lubricating oil as a fuel [23, 36-40]. However, in the literature, there is no such fundamental study which evaluates the influence of waste lubricating oil on NOx emissions under transient engine temperature during stages of cold-start, given that it is a significantly important period where after-treatment systems are not effective [7].

2. Methodology

2.1 Engine specifications and test set-up

In order to meet the requirements of emissions regulations, most new diesel vehicles (from Euro IV) are equipped with after-treatment systems such as exhaust gas recirculation (EGR), diesel oxidative catalyst (DOC), LNT, selective catalytic reduction (SCR) and/or DPF. For example, using EGR can significantly decrease NOx emissions [41]. Studying the impact of EGR on exhaust emissions of a direct injection diesel engine showed that by using a 30% EGR rate, NO emission decreased up to 64.78% (cold EGR) and 57.09% (hot EGR) [41]. The NO decrease with 10% EGR rate was 20.69% (Cold EGR) and 14.761% (Hot EGR). This study showed a negative linear correlation between EGR rate and NO emission.

Therefore, emissions from such engines depend on the type and performance of the emission-control devices [42, 43], which limits the fundamental study to investigate the pure influence of alternative fuels and cold-start operation which are the main focus of this research. In order to avoid such limitations, while gaining a better understanding of the actual engine-dependent NOx emissions, a Euro III engine (without any after-treatment system) was used in this study. Table 1 shows the specification of the engine, which was a common-rail Cummins diesel engine coupled to an electronically-controlled hydraulic dynamometer which can control the engine speed/load.

Table 1 Specifications of the tested engine

Model	Cummins ISBe220 31
Fuel injection	High pressure common rail
Aspiration	Turbocharged aftercooled
Emission standard	Euro III
Cylinders	6 in-line
Capacity (L)	5.9
Maximum torque (Nm @ rpm)	820 @ 1500
Maximum power (kW @ rpm)	162 @ 2500
Compression ratio	17.3:1
Bore × stroke (mm)	102 × 120
Dynamometer type	Electronically-controlled water brake dynamometer

Figure 1 shows a schematic diagram of the test setup. In this experiment, in-cylinder pressure data was collected with a Kistler 6053CC60 piezoelectric transducer with a manufactured stated sensitivity of ≈ -20 pC/bar. Crank angle data was collected with a Kistler type 2614 with the manufacture stated resolution of 0.5 crank angle degrees. Fuel injection timing was determining by recording the injector signal and applying an excitation offset [44]. The injector nozzle had 8 holes with a nozzle diameter of 4 mm. More specific information about the used facility can be found in Refs. [45, 46].

After the exhaust manifold, a fraction of the exhaust gas was directed to a CAI-600 NDIR CO_2 analyser (linearity > 0.5% of full scale and repeatability > 1% of full scale and) and a CAI-600 CLD NO/NOx analyser (linearity > 0.5% of full scale, repeatability > 0.5% of full scale, and convertor efficiency of 98%) [47].

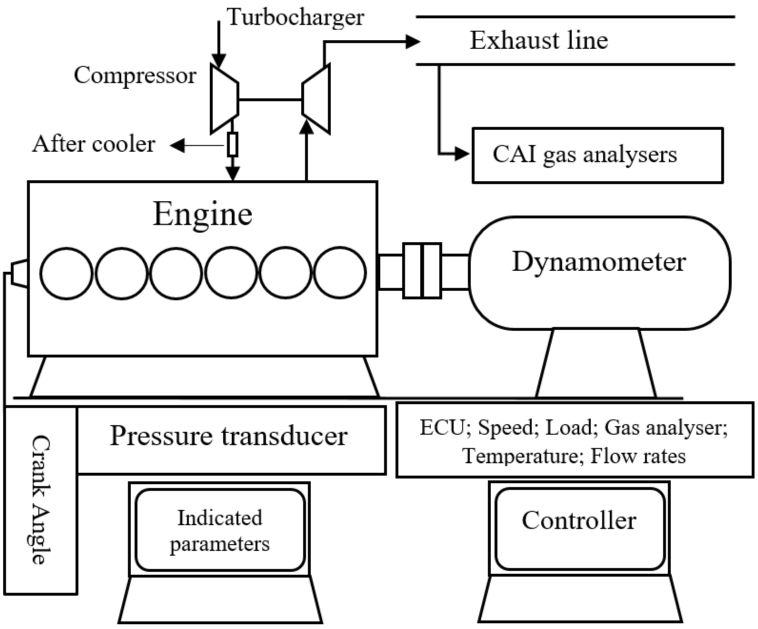


Figure 1 Schematic diagram of test set-up

2.2 Fuel selection

This study used D100 (100% diesel), D99W1 (1% waste lubricating oil added to diesel) and D95W5 (5% waste lubricating oil added to diesel). The blending ratio in the fuels is based on volume. Table 2 shows the fuel properties of waste lubricating oil and diesel. Fuel chemical composition was done with a GC/MS instrument (Trace 1310 Gas chromatograph, model ISQ, single quadrupole MS). D100 contains aromatic compounds (benzene and its derivates, xylene, mesitylene, phthalan, naphthalene) and aliphatic compounds (mainly alkanes with 7-13 carbons, low concentrations of limonene). D99W1 and D95W5 also contain cycloalkanes, mainly cyclohexane and cyclooctane. Aromatic content was higher in diesel than in the other two blends. Waste lubricating oil has a high calorific value (43.07 kJ/kg) which is similar to diesel, therefore blending waste lubricating oil with diesel does not change the heating value of the fuel significantly [37]. However, the higher viscosity of the lubricating oil will influence the fuel atomisation and also performance within cold-start period owing to the fact that viscosity increases at lower temperature. This will be discussed in detail in Result and discussion Section.

Table 2 Fuel properties [21, 37]

	Diesel	Waste lubricating oil
Lower heating value (MJ/kg)	41.77	43.07
Density (g/cc)	0.84	0.89
Viscosity (mm^2/s)	2.64	30.3
Sulfur (ppm)	5.9	7500
Ash (ppm)	1	7400
Flash point (degC)	71	98

2.3 Experimental design

There are various ways of conducting a cold-start experiments. Typically, in the literature, cold-start emissions are relevant to a part of a standard cycle such as NEDC (modal cycle) or WLTC (transient cycle). Given that the aim of this study is to look at the effect of engine temperature, cold-start and waste lubricating oil on NOx emissions, using driving cycle, which is mostly characterised by frequent speed/load change limits the fundamental study. The reason is that with a driving cycle, cold-start emissions will be influenced by various factors cancelling/reinforcing the influence of one another at different engine operation modes. Hence, the current study used a fixed engine load of 25% at the speed of 1500 rpm to run the cold-start test. This method decreases the number of variables leading to great understanding of the influence of engine temperature and also fuel properties on NOx emissions. At this engine load and speed, the injection pressure was 50 MPa, and the brake mean effective pressure (BMEP) with diesel was ~0.52 MPa.

The rationale for selecting a 25% engine load between the typical testing loads of 25, 50, 75 and 100%, was that during cold start engine load is usually lower than during fully warmed-up operation [48]. This can be seen in standard driving cycles as well. For example, in WLTC which is designed based on real driving data, within the first part of the cycle (called the low phase), which can be considered as cold start, the average vehicle speed is less than the other parts of the cycle [48]. The average speed within the four phases of the WLTP Class 3 cycle, in km/h, is 25.7 (low), 44.5 (medium), 60.8 (high) and 94 (extra High). Therefore, it was opted to use quarter load to have a reasonable replication of the real world, while keeping the experiment simple enough to study the fundamental influence of diesel engine warm-up.

2.4 Experimental procedure

Cold-start tests were run each day after more than 12 hours overnight engine soak at ambient temperature. At the beginning of each cold-start test, the oil and coolant temperatures of the engine were 23 ± 3 degC. Each test was conducted by running the engine at 1500 rpm under 25% engine load for at least 30 min within which the engine fully warmed up and stabilised. After each fuel change, the fuel lines were flushed cleaning the previous fuels. This was done by disconnecting the fuel tank to stop more entering and then running the engine at high load for at least 15 min to use the left over fuels from the fuel lines/pump. After that, a different fuel tank with the new fuel was connected and the engine ran for 30-60 min at high engine load to ensure that only the new fuel remained. The procedure was done prior to the overnight soak.

The repeatability tests were conducted two times with D100 and the statistical analysis for these tests was done using average, standard deviation (SD) and coefficient of variation (CV) for different parameters. Table 4 shows the engine speed, torque and CO_2 difference between the two repeats during cold-start and during fully warmed-up operation. As can be seen the difference between these parameters is very small which can indicate the repeatability of the test. For example, between the two repeats of cold-start the difference between engine speed, toque and CO_2 was less than 0.9%. Apart from the repeatability test, it should be mentioned that comparing the test results from D100 and D99W1, which are similar fuels, can also confirm the repeatability of the tests.

Table 4 Statistical analysis of the test repeatability

		Speed (rpm)			Torque (Nm)			CO_2 (%)		
		Average	σ	CV (%)	Average	σ	CV (%)	Average	σ	CV (%)
Cold-start	Test 1	1498.87	2.22	0.15	225.28	8.43	3.74	6.36	0.06	0.97
	Test 2	1499.19	1.95	0.13	227.20	12.32	5.42	6.51	0.15	2.27
	Difference	0.02%			0.82%			0.12%		
Fully warmed-up	Test 1	1498.94	2.20	0.15	238.28	3.2	1.34	6.47	0.03	0.51
	Test 2	1499.49	2.16	0.14	242.02	2.42	1.00	6.64	0.02	0.36
	Difference	0.04%			1.5%			0.17%		

3. Result and discussion

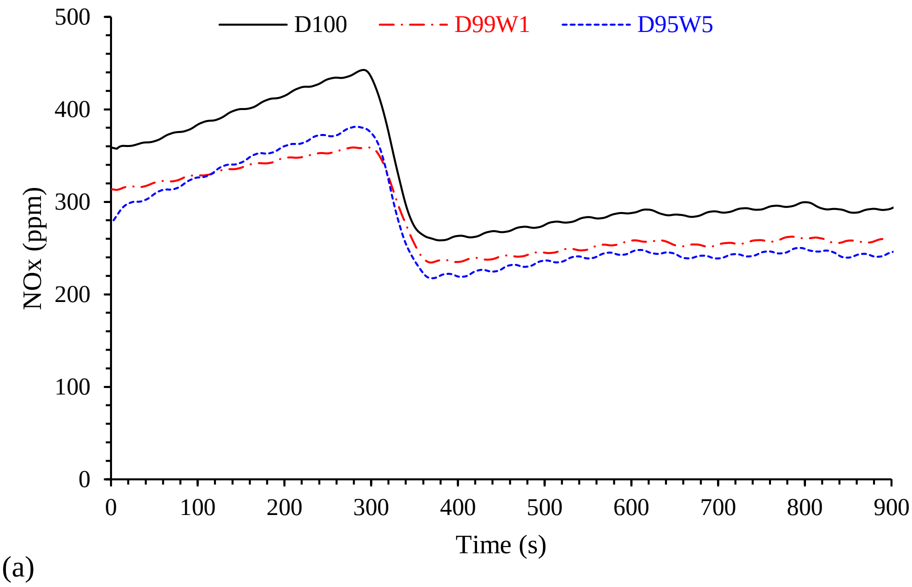
This section investigates NOx emissions with respect to engine performance parameters: engine oil temperature, engine coolant temperature, exhaust gas temperature, start of injection (SOI), start of combustion (SOC), heat release rate, maximum in-cylinder pressure and maximum rate of pressure rise. This section first studies the engine temperature and cold-start effects, then evaluates the influence of fuel properties.

3.1 Nitrogen oxides

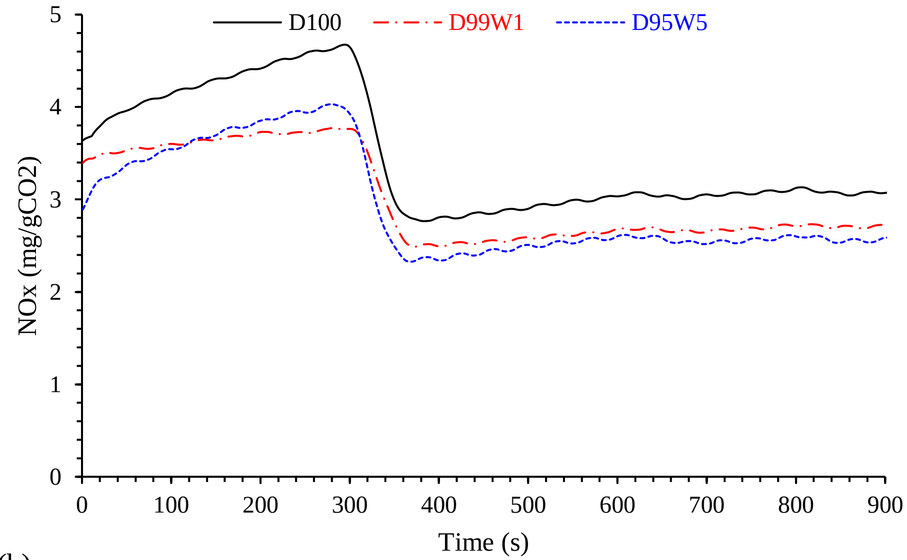
In diesel engines, NOx emissions are primarily formed through the oxidation of nitrogen at high-temperature during combustion. Exposure to these toxic emissions can lead to health issues. These emissions are also important from an environmental aspect as they are ozone precursors. NOx emissions are affected by various factors that can cancel/reinforce the effect of one another [49, 50].

3.1.1 Cold-start effect

Figure 2 illustrates NOx emissions during the test. As can be seen, for all the tested fuels, NOx increases gradually to its maximum value, drops sharply after that and start increasing moderately again until stabilising. For example, in Figure 2 (a), NOx for D100 was 358 ppm at the start of the test, gradually increased to its maximum value at 442 ppm, steeply dropped to 258 ppm, increased to 290 ppm and then stayed stable near 290 ppm afterward. A similar trend is seen in Figure 2 (b), which shows the normalised NOx emissions. For example, NOx emissions for D95W5 was 2.9 mg/gCO_2 (milligrams per grams of CO_2 which represents the amount of burned fuel) at the start of the test, gradually increased to its maximum point at 4 mg/gCO_2, steeply dropped to 2.3 mg/gCO_2, increased to 2.6 mg/gCO_2 and then stabilised near that value afterward.



(a)



(b)

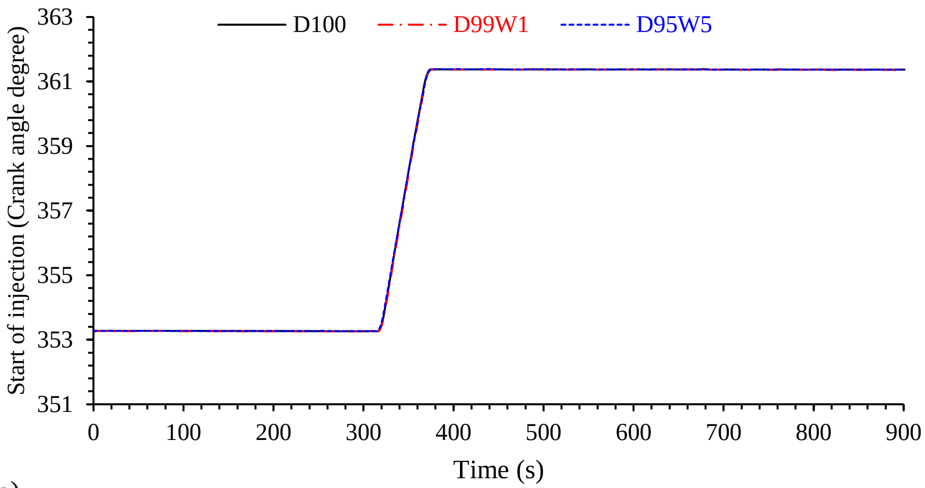
Figure 2 NOx (a) and normalised NOx (b) emissions during engine warm up

To analyse the observed trends in Figures 2 (a) and (b), the data will be split into four sections; from the start to the maximum value (~0-300 s), NOx drop (~300-370 s), the increment from minimum point to the steady-state value (370-630 s), and finally the stabilised points afterward.

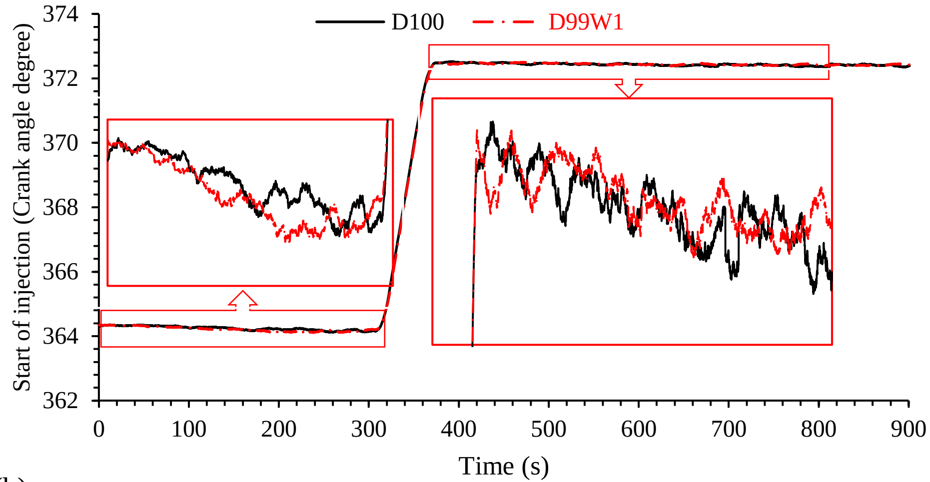
NOx increase in the first 300s: As shown in Figures 2, during the first ~300 seconds of cold-start test, NOx is increasing to its maximum value, which means as the engine is warming up, NOx emissions increases. These figures also show that NOx emissions during cold-start (the first ~300 s) is higher than hot-operation (after 630 s), which can give an impression that NOx emissions decreases as the engine warms up. However, this should be investigated in more detail. As mentioned before, NOx emissions are influenced by various parameters canceling/reinforcing the effect of one another. Injection parameters and engine operation conditions are one of these influential factors [4, 51, 52].

Fuel injection has a significant effect on NOx formation. In common-rail diesel engines, the fuel injection is time domain based; while, combustion occurs in the crank angle domain. Therefore, the engine speed/load is strongly influenced by injector design and tuning parameters such as injection timing [53, 54]. Start of injection (SOI), which is one of the injection timing parameters, is the point when the fuel pressure in the injection line reaches to the nozzle-opening-pressure of the injector. Figure 3 (a) shows the SOI for all the fuels during the custom test. As can be seen, SOI stays stable for ~4000 engine cycles, which corresponds to the first ~300 s, then it increases sharply (retarded injection) and stays constant after that. Therefore, SOI cannot be the reason for NOx increment during the first 300 s.

Given that the NOx formation is highly influenced by premixed phase and residence time under high temperature [9, 55], the start of combustion (SOC) parameter needs to be analysed to investigate the main influential factor for NOx increment. Figure 3 (b) illustrates the SOC during the custom test. As can be seen, SOC slightly advanced during the first ~4000 engine cycles, which corresponds to ~300 s. Given that during this period the SOI is constant, the reason for the observed slight decreasing trend of SOC is the increasing trend of the in-cylinder temperature, which could be the reason for the increasing trend of NOx formation during this period.



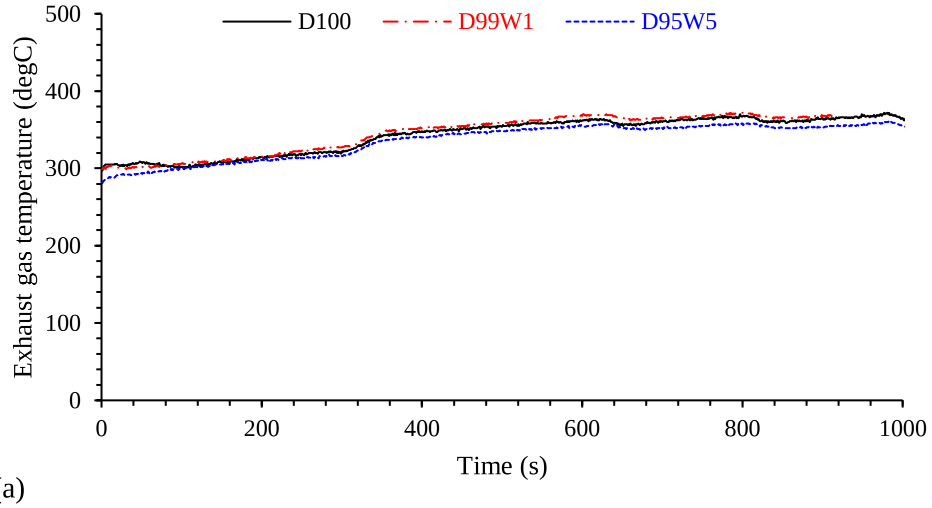
(a)



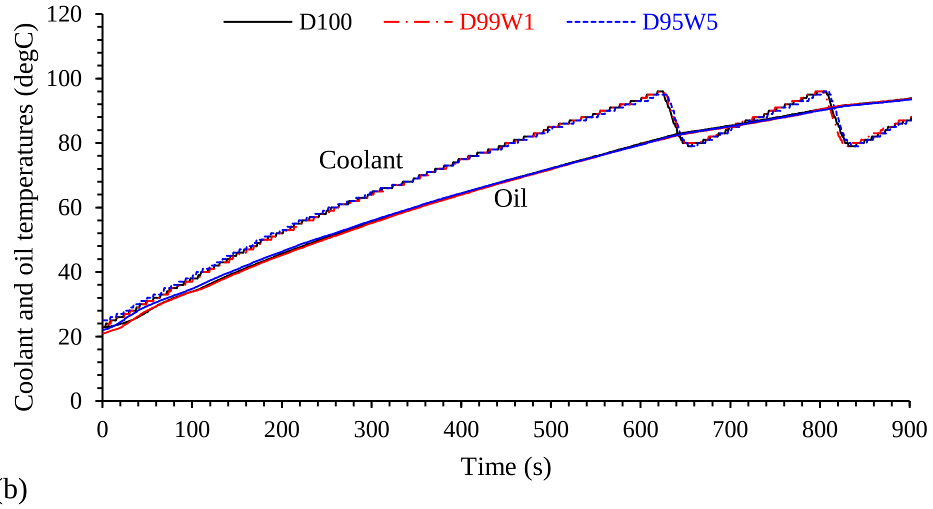
(b)

Figure 3 Start of injection (a) and start of combustion (b) during engine warm up

Temperature is a significantly influential factor in NOx formation [9]. The reason for the observed NOx increasing trend in this study is that during the first 300 s, combustion temperature is increasing which leads to higher NOx formation. The exhaust gas temperature could be taken as a proxy for the in-cylinder temperature during the combustion. Figure 4 (a) shows the exhaust gas temperature during the custom test. As can be seen, during the first ~300, which corresponds to the first section where NOx increased to its maximum value, the exhaust gas temperature increases gradually indicating that the in-cylinder temperature during combustion is increasing gradually. For example, with D95W5 during this period the exhaust gas temperature increased from 300 to 326 degC and NOx—shown in Figure 2 (b)—increased from 3.6 to 4.6 mg/gCO_2. Other representatives of the in-cylinder temperature are engine oil and coolant temperatures shown in Figure 4 (b). As can be seen, these temperatures increase gradually during the custom test.



(a)



(b)

Figure 4 Exhaust gas (a), engine coolant and oil (b) temperatures during engine warm up

NOx drop between 300 to 370 s: As seen in Figures 2, after the gradual increment at ~300s NOx drops from its maximum value to the minimum. The reason for this drop is due to injection parameters. It can be seen in Figure 3 that at ~300s both SOI and SOC increased (retarded), which means that the injection strategy commanded by the engine ECU changed at this point due to the engine calibration which defines the cold-start phase from the start to the point at which the coolant temperature reaches to ~65 degC. As can be seen, at 300 s, the engine coolant temperature reaches to 65 degC sending feedback to ECU consequently changing the SOI. Therefore, the delayed start of injection was the reason for the NOx drop.

NOx increment from minimum toward the stabilised points: As seen in Figures 2, after NOx drops to its minimum value at ~370 s, it increases moderately to its steady-state value (370-630 s). The steady value of NOx emissions after 630 s could be due to the constant SOI and less fluctuations in SOC (Figure 3), and optimal temperature of the engine (Figure 4). However, the NOx trend between 370-630 s is similar to the NOx increment during the first 300 s in which SOI is constant (Figure 3 (a)) and the driving force is the engine temperature represented by exhaust gas, engine oil and coolant temperatures owing to their increasing trend, shown in Figure 4. This can also be seen in Figure 3 where during this period the SOC has a decreasing trend (advanced combustion). In general, at a constant SOI, the NOx trend (Figures 2) within the custom test has an inverse correlation with the SOC trend, as one increases the other one decreases.

Using in-cylinder pressure and heat release data to study NOx emissions during cold-start:

NOx formation depends on in-cylinder parameters [9, 56]. Figure 5 shows the in-cylinder pressure diagram for D100 during the custom test at 7 consecutive phases from engine start, each corresponding to an average of 2 min. It can be seen that there are two peaks on the in-cylinder pressure diagram. The first one is a motored peak, occurring prior to combustion and the second peak is from the rise in pressure due to combustion. Figure 5 shows that from Phase #1 to 2, in which the SOI is constant (Figure 3), the first peak value on the diagram slightly increases as the engine warms. The increase in the motored peak indicates that the in-cylinder environment is becoming warmer as the engine temperature increases. This trend is associated with an increasing trend of NOx emissions, shown in Figure 2. Similar to Phase #1 to 2, comparing Phase #4 to 6, in which the SOI is also constant (Figure3), shows that as the engine warms up, the motored peak increases. This is also associated with a corresponding NOx increase.

This systematic increase in motored peak can be seen in Phase #3 as well; however, within this phase, the coolant temperature reached to 65 degC (Figure 4) and a subsequent injection strategy change caused the SOI and SOC to increase (Figure 3). Therefore, the similar trend might be due to the fact that this diagram is the average of two minutes. The shape of the diagram for Phases #4-7 is different to Phases #1 and 2. The reason for that is related to the retarded injection strategy leading combustion to occur significantly after TDC. As seen in Figure 2, the NOx emissions dropped significantly after this injection strategy change.

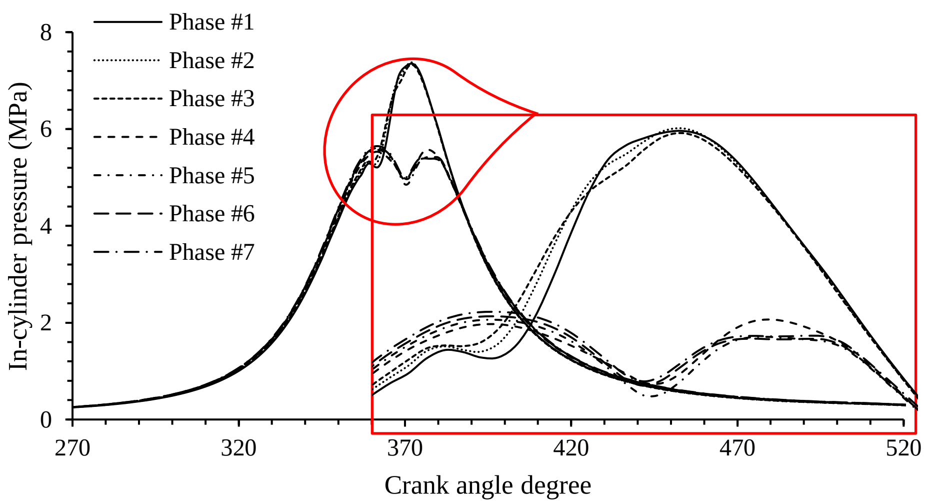


Figure 5 In-cylinder pressure during engine warm up with D100

Heat release rate diagram could be another indicator for NOx emissions. Figure 6 shows the apparent heat release rate (AHRR) for D100 during the custom test at 7 consecutive phases from the engine start each corresponding to the average of 2 min. In AHRR diagram, before the SOI, the rate of heat release is around zero as there is no fuel injection but only the air compression. After SOI, the rate of heat release has a negative value as the fuel is injected and heat is transferring from the hot air to evaporate the liquid fuel [57]. On AHRR diagram, the peak occurs within premixed combustion phase as a result of the rapid combustion of the premixed portion of the fuel. During ignition delay period, the injected fuel vaporizes and mixes with the air. And the main heat release driving force is the combustion of premixed air/fuel. Therefore, the longer mixing period can lead to a higher peak value on AHRR diagram. This can be seen by comparing Phase #1 to 3 in which the decreasing (advancing) trend of SOC at a constant SOI (Figure 3)—which leads to a decreasing trend of ignition delay and a shorter mixing period—is associated with the decreasing trend of the peak value on heat release rate diagram moving the occurrence of peak value toward lower crank angles (Figure 6), and with the increasing trend of NOx formation (Figure 2). For example, Phase #1 with the highest SOC (Figure 3) has the highest peak value of 110 (J/crank angle degree) on heat release diagram (Figure 6) and the lowest NOx (Figure 2) and Phase #3 with the lowest SOC has the lowest peak value of 76 (J/crank angle degree) and the highest NOx.

This is similar when comparing Phase #4 to 7. As can be seen, through these phases, the engine temperature increasing trend (Figure 4) is associated with the decreasing trend of SOC (therefore ignition delay) (Figure 3), decreasing trend of the peak value on AHRR diagram moving the occurrence of peak value toward lower crank angles (Figure 6), and increasing trend of NOx (Figure 2). As can be seen in Figure 6, the peak value is the highest within Phase #4 and it decreases through the rest of phases. However, Phase #5 and #6 have a similar peak value. These two phases are related to the steady state condition and have a very similar AHRR diagram and similar NOx emissions. Comparing these two phases with Phase #4 and 5 shows that as the engine temperature increases toward its optimum value, the peak value decreases and moves toward left (which can confirm the decreasing trend of SOC).

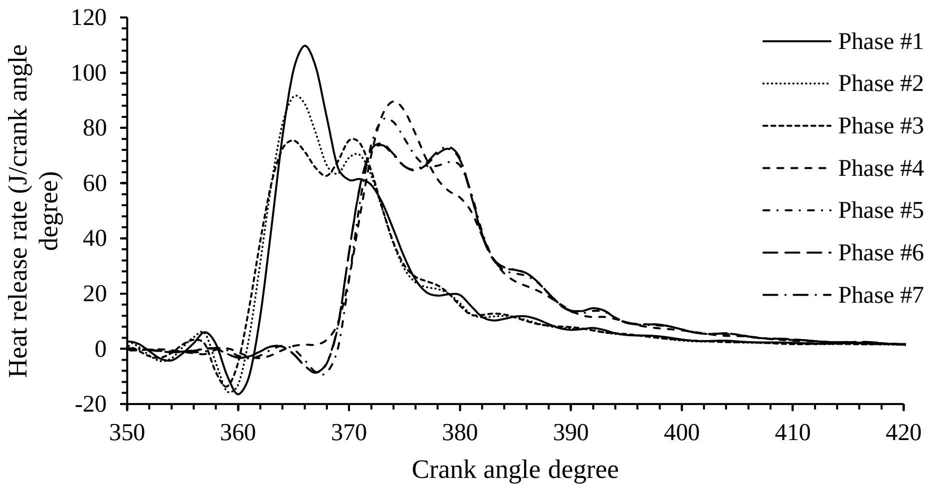
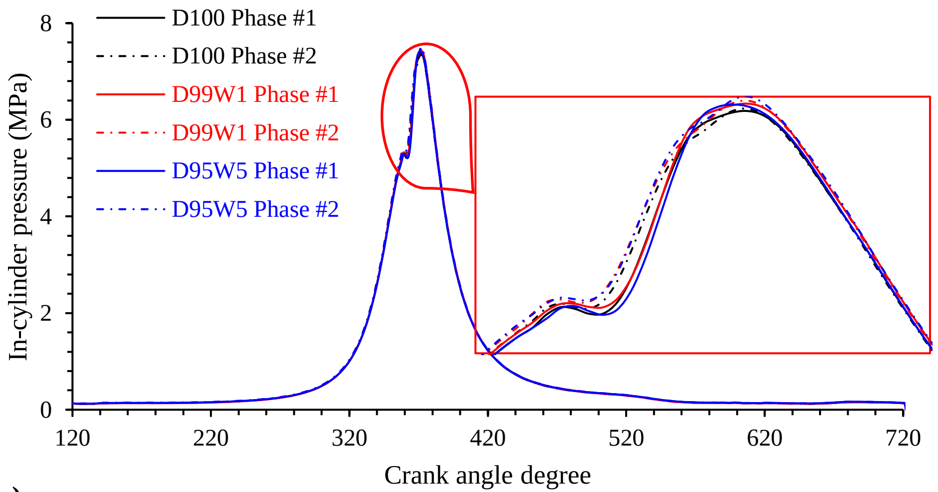


Figure 6 Heat release rate during engine warm up with D100

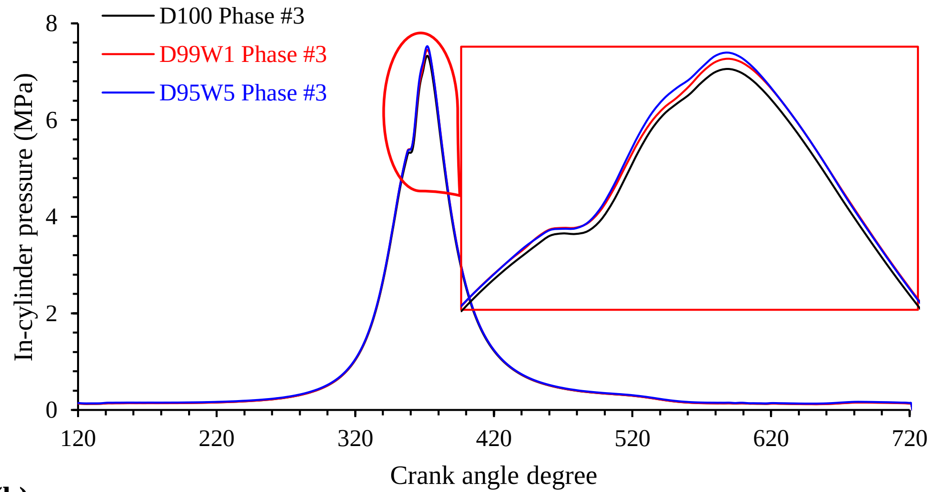
3.1.2 Fuel effect

As seen in Figure 2, D100 has the highest NOx throughout the test and using D99W1 and D95W5 decreases NOx emissions during both cold-start and hot-operation. For example, during cold-start using fuels with waste lubricating oil could decrease NOx by up to ~19% and during hot-operation the reduction was ~17%, as shown in Figure 2 (a). Similar trend can be seen in Figure 2 (b) which shows the normalised NOx emissions. The result from this study aligns with another study which used waste lubricating oil and NOx emissions decreased by 15% [38].

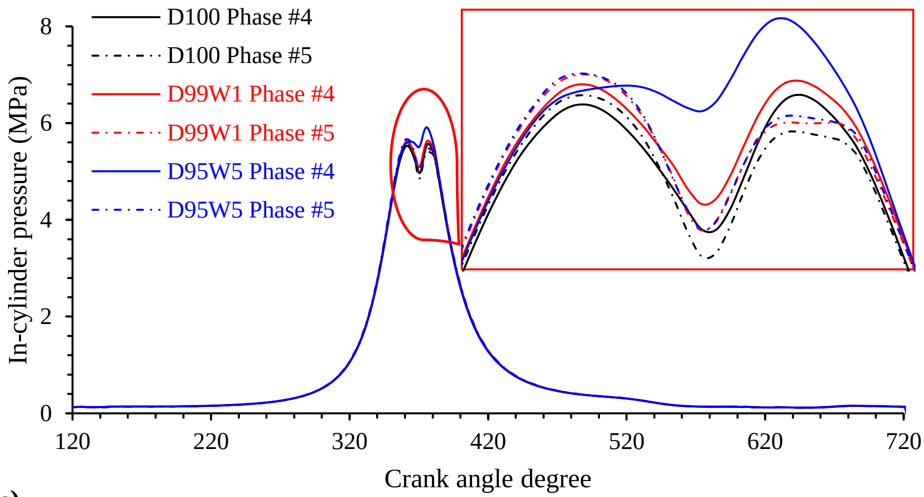
NOx formation highly depends on in-cylinder parameters [9, 56]. Figure 7 shows the in-cylinder pressure diagrams at different phases. Apart from Phase #1 and 2 in which the difference is not very clear and significant, it can be seen from the figure that for all the phases, adding waste lubricating oil to the blend increases the peak values on the diagram. This increase is associated with NOx decrease shown in Figure 2. This shows an inverse correlation between the peak value and NOx emissions. For example, during Phase #6 and 7, D100 with the lowest peak values on in-cylinder pressure diagram has the highest NOx emissions. This trend can be better observed by calculating the peak pressure in every cycle.



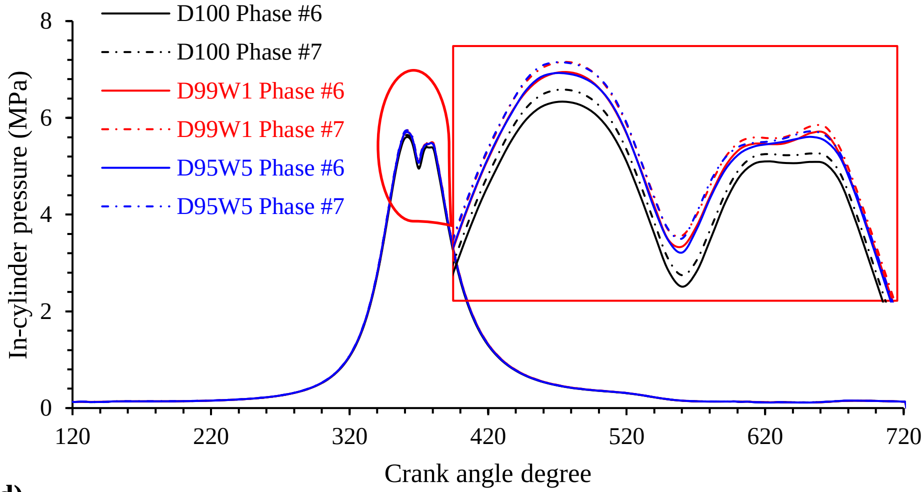
(a)



(b)



(c)



(d)

Figure 7 In-cylinder pressure vs. crank angle during engine warm up with all of the tested fuels

Figure 8 shows the maximum in-cylinder pressure within the test. As can be seen, D100 had the lowest value through the test which is contrary to the NOx with D100. From the effect on fuel point of view, the figure shows an inverse correlation with NOx; any fuel with highest value in Figure 8 has the lowest NOx in Figure 2. This inverse correlation has been reported by Jafari et al. [58] as well.

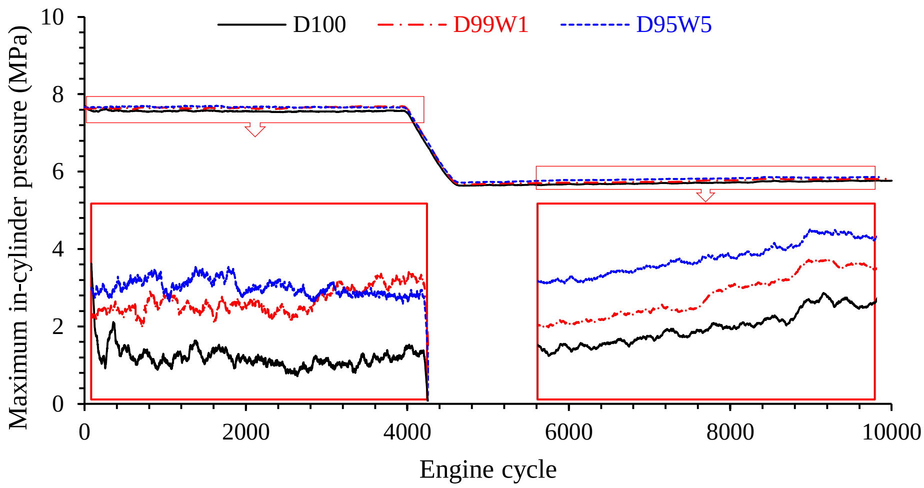


Figure 8 Maximum in-cylinder pressure during engine warm up with all of the tested fuels

There are different mechanisms for NOx formation during combustion such as thermal NOx, prompt NOx and fuel NOx [55]. Among these mechanisms, thermal NOx is dominant in diesel engine combustion and it highly depends on the in-cylinder temperature (including flame temperature) and the mixture's residence time under high temperature during combustion [9]. Horibe et al. [59] and Jafari et al. [58] studied the correlation between NOx and maximum in-cylinder pressure and maximum rate of pressure rise in a diesel engine and reported that these parameters correlated with NOx formation. This is owing to NOx formation being significantly influenced by combustion temperature and maximum in-cylinder temperature during combustion. The maximum in-cylinder pressure and maximum rate of pressure rise correlate to the temperature [58]. Therefore, this study uses these in-cylinder parameters to better explain the observed trend.

Figure 9 shows the maximum rate of pressure rise within the test. As can be seen, D100 has the highest value with a significant visible difference compared to D99W1 and D95W5 during both cold-start and hot-operation. This is similar to NOx with D100 which has a significant difference to other fuels. Similar to NOx, D99W1 and D95W5 values for maximum rate of pressure rise were close compared to D100.

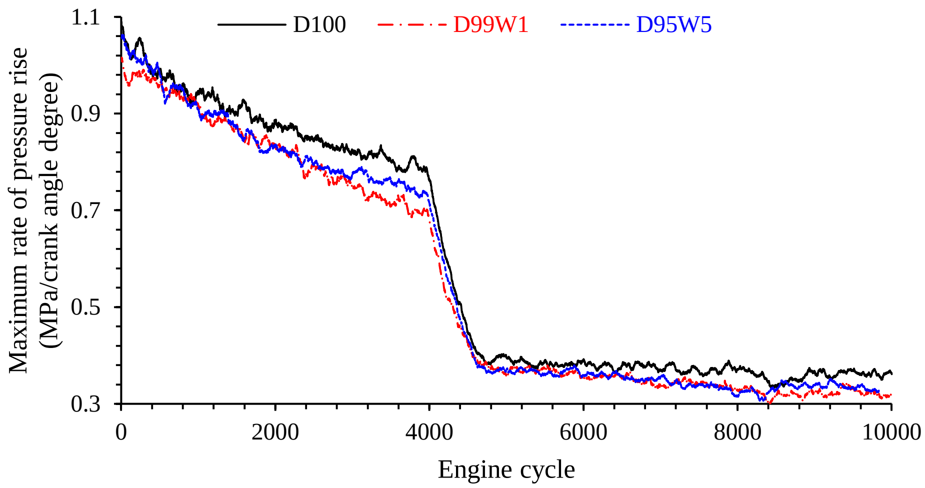
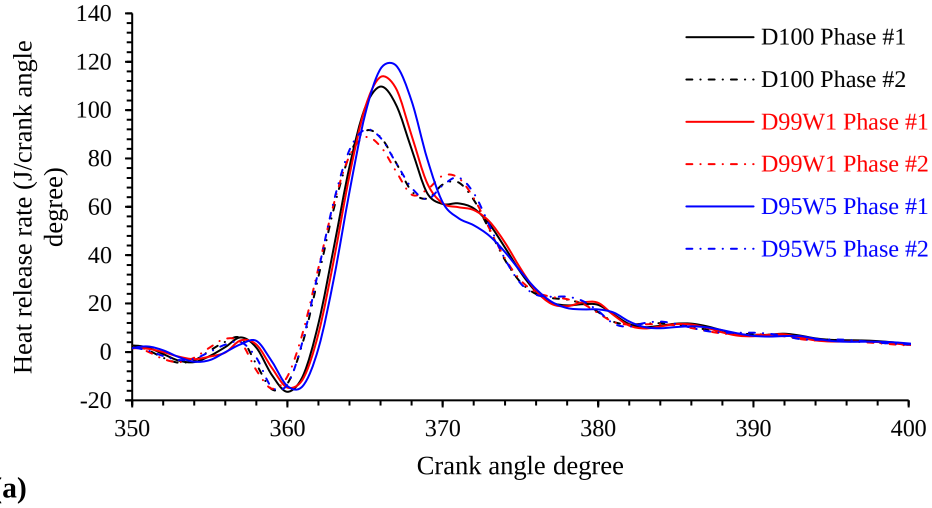
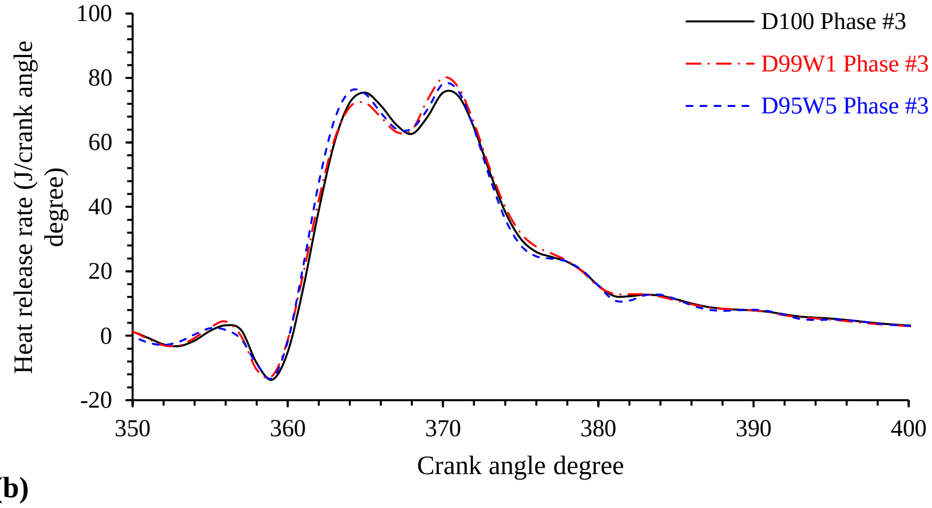


Figure 9 Maximum rate of pressure rise during engine warm up with all of the tested fuels

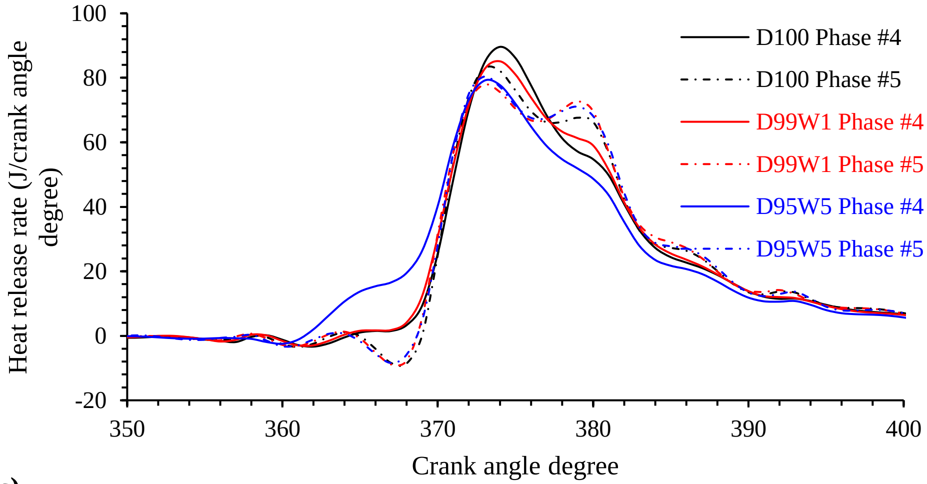
Figure 10 shows the heat release rate within the custom test for all the tested fuels. Figure shows that during Phase #1 using waste lubricating oil, which decreased NOx (Figure 2), increases the first peak value of the heat release rate moving it toward right, and decreases the second peak value moving it toward right. In Phase #2-7, by using waste lubricating oil in the blend, the first peak on the AHRR diagram decreases and the second peak value increases in most cases. For example, Phase #3 within which the injection strategy changed, shows that using waste lubricating oil increases the second peak value moving it toward left. In Phase #4 and #5, in which the injection strategy has already changed, using waste lubricating oil decreases the first peak value moves it toward left. Phase #6 and 7 show that by using waste lubricating oil in the bend, the first peak value on heat release rate graph decreases and moves toward left, however, the second peak increases and moves toward left.


Heat release rate (J/crank angle degree)
Crank angle degree
D100 Phase #1
D100 Phase #2
D99W1 Phase #1
D99W1 Phase #2
D95W5 Phase #1
D95W5 Phase #2

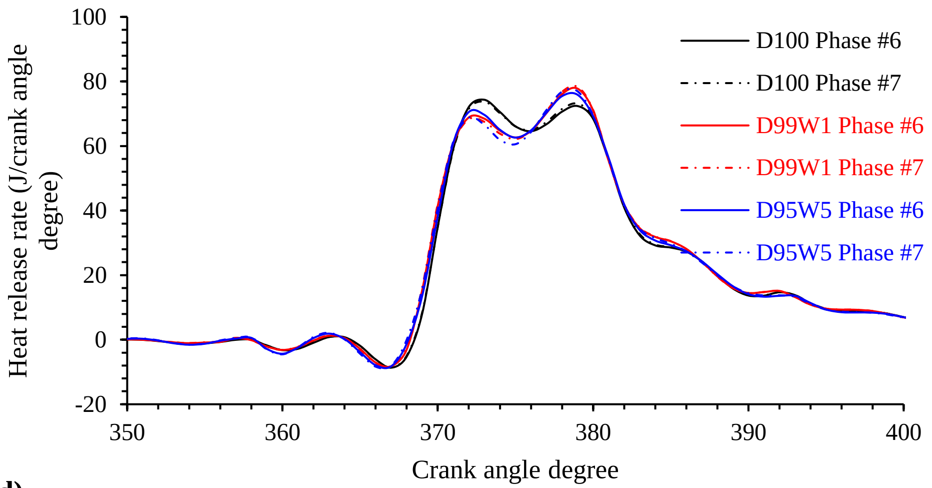
(a)


Heat release rate (J/crank angle degree)
Crank angle degree
D100 Phase #3
D99W1 Phase #3
D95W5 Phase #3

(b)


Heat release rate (J/crank angle degree)
Crank angle degree
D100 Phase #4
D100 Phase #5
D99W1 Phase #4
D99W1 Phase #5
D95W5 Phase #4
D95W5 Phase #5

(c)



(d)

Figure 10 Heat release rate vs. crank angle during engine warm up with all of the tested fuels

4. Conclusion

This research fundamentally studied NOx emissions at different stages of cold-start and engine warm up. This study also investigated the influence of waste lubricating oil on combustion and also introducing it as a fuel additive. A custom cold-start test was designed and run on a 6-cylinder, turbocharged common-rail diesel engine fueled with diesel and blends of waste lubricating oil with diesel (1 and 5%, by volume). To better explain the observed trend this study evaluated other parameters such as engine coolant temperature, engine oil temperature, exhaust gas temperature, SOI, SOC, in-cylinder pressure, heat release rate, maximum in-cylinder pressure and maximum rate of pressure rise. Following conclusions were drawn:

- During cold-start, NOx emissions were higher than hot-operation.
- During cold-start, NOx increased while the engine was warming up. The maximum value at cold-start with diesel and the blend with 5% waste lubricating oil were ~52 and 54% higher than steady state values.

- At the end of cold-start, NOx dropped steeply due to the injection strategy change. Injection parameters significantly influenced NOx emissions.
- Blending waste lubricating oil with diesel decreased NOx emissions during both cold-start and fully warmed-up operations.
- Compared to fully warmed-up period, during cold-start, SOI and SOC advanced and occurred at lower crank angles, and maximum in-cylinder pressure and maximum rate of pressure rise were higher.
- During cold-start, maximum rate of pressure rise decreased with increasing the engine temperature. Adding waste lubricating oil increased maximum in-cylinder pressure and decreased the maximum rate of pressure rise.
- With different fuels, NOx emissions had a direct correlation with maximum rate of pressure rise and an inverse correlation with maximum in-cylinder pressure.

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