Light-Duty Diesel Engine - Impact of Fuel Properties on Emissions and Performance

ABSTRACT

The increased demands placed on the powertrain community to develop propulsion systems with high fuel efficiency has led to advanced technologies for improving the engine's overall thermal efficiency, while maintaining low emission levels. Additionally, developing fuels that provide improved combustion and reduce the emission footprint have gained importance as well.

This study outlines the impacts of five different fuel types, which have significantly different fuel properties, on a state-of-the-art light-duty HSDI diesel engine. The cetane number for these fuels ranges from 26 to 76. The boiling characteristics and the heating values for these fuels are vastly different. Included in the fuel selection is one pure biodiesel fuel (SME – Soy Methyl Ester). This study utilized a state-of-the-art HSDI diesel engine with tests conducted under part load and full load operating points. The part load operating points used combustion parameter sweeps to broaden the understanding of the combustion dynamics associated with the variety of fuel properties, regarding performance and emissions. However, under full load the impact of constant volume fuel injection over performance and emissions became the focus, without conducting parameter sweeps.

This study's primary purpose is to provide the fuel and engine development community with greater insight into the impact fuel type has on engine out emissions and performance.

INTRODUCTION

The combination of worldwide demand for petroleum-based transportation fuels and environmental concerns are driving manufacturers and lawmakers towards efficient alternative fuels and technology. Lawmakers around the world are continuously tightening the existing strict emissions limits, due to concerns over global warming caused by greenhouse gas emissions and hazardous health impacts from a variety of emissions from internal combustion engines. Current concerns over global warming and the dependency on crude oil have the lawmakers around the world establishing strict fuel economy requirements, along with imposing more strict emissions limits. Those limitations pose an enormous challenge for most engine and vehicle manufacturers.

Manufacturers are required to establish new strategies to meet the unique challenges presented by the latest fuel economy standards and emission regulations. The end result is a new strategy for internal combustion engine technologies that increase efficiency, while reducing emissions. A correlation on fuels and combustion control parameters is preferred, to assist these strategies. The primary purpose of this study is to address the impacts of fuel and combustion control parameters.

This project highlights the study of four different petroleum-based diesel fuels that have a variety of cetane and boiling characteristics, representing both conventional certification types and non-regulatory fuels. A fifth fuel was included in this study, which was a 100% pure biodiesel fuel. It was added due to rising concerns over global warming and interest from the transportation industry over renewable fuels such as biodiesel.

The study's test results describe the impacts different fuels have on performance and emissions during the following combustion-related parameters:

- Start of injection
- Pilot injection timing and quantity
- Rail pressure
- EGR level
- Boost pressure level

Variations in these parameters will be shown at two part load points (2000 rpm at 2 and 6 bar BMEP). Data on full load is also provided under constant parameter settings, which provide a detailed analysis of the various fuels on performance.

The impacts of fuel type were measured on all gaseous emissions (NOx, HC, CO), Smoke and BSFC. Testing was conducted using a light-duty HSDI diesel engine, equipped with a state-of-the-art fuel injection system, VGT turbocharger, and a high-pressure cooled EGR system.

TEST HARDWARE AND FUEL SPECIFICATIONS

For the purpose of understanding the effects of diesel fuel properties on engine performance and emissions, a HSDI light-duty diesel engine was used in the test cell environment. In the following sections a detailed description of the test hardware, test boundary conditions and specifications of the fuel used are provided.

ENGINE SPECIFICATIONS AND TEST CONDITIONS

A Euro 4 equivalent light-duty HSDI diesel engine was used in the test cell environment to conduct the fuels study. Table 1 outlines the engine hardware specifications.

Table 1: Test Engine Specifications

Engine power	100 kW @ 3500 rpm
Peak torque	300 Nm @ 2000 rpm
Max engine speed	4500 rpm
Number & arrangement of cylinders	4 cylinder inline
Firing order	1 - 3 - 4 - 2
Valve train	4 Valve DOHC
Displacement	2.5 L
Compression ratio	18
Fuel injection system	Common rail

The engine was instrumented to measure and record thermodynamic data from the intake and exhaust systems, which includes temperature, pressure, humidity and mass flow. The engine was equipped with a high efficiency EGR cooler and a water cooled intercooler with close loop control. Additionally, an air-conditioner was used to control the inlet air temperature, pressure and humidity during testing; also a vehicle exhaust system with back pressure control was installed to achieve the testing consistency.

The test cell setup for the engine is shown in Figure 1.

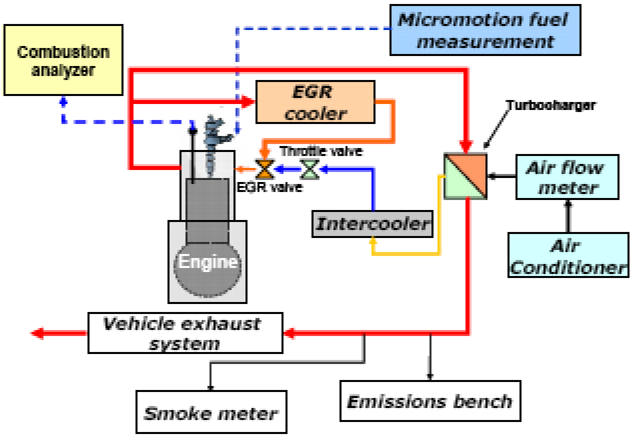


Figure 1: Test Cell Engine Setup

The testing environment utilized a proprietary test cell control system for data acquisition, engine speed and load control. A Kistler 6055B pressure transducer with an A&D combustion analyzer was incorporated for combustion data acquisition and analysis. A HORIBA 7000 series MEXA emissions bench was used for gaseous emissions measurement as well as

Lambda and an AVL 415S for smoke measurement. The fuel and air measurement used a Micromotion meter (coriolis type) and HFM [Heated Film Mass air flow sensor] sensor calibrated for high accuracy in the testing range.

Figure 2 represents the engine out specific NOx map with an embedded European drive cycle scatter for the test engine.

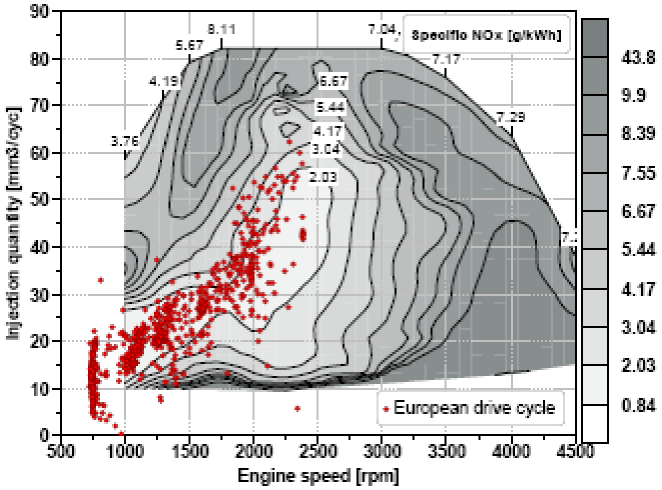


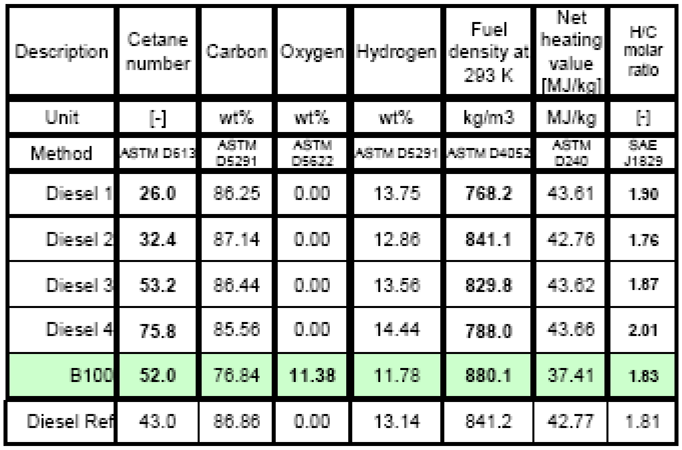
Figure 2: Engine out Specific NOx with European Drive Cycle Scatter

The engine was calibrated for low NOx and with a conventional combustion system configuration for the European driving cycle. Although the engine was equipped with highly efficient emissions control hardware, the influence of environmental parameters and additional corrections to the combustion and air management control parameters were deactivated for stable and repeatable operation. For each and every fuel change, the fuel supply system was completely purged to avoid fuel mixing. Following the fuel system purge, the engine was operated at high load for 2 hours to ensure that the complete system was conditioned using the current fuel. Throughout the test, reference point checks were made based on the type of fuel used to observe any drift in system operational integrity.

FUEL SPECIFICATIONS

In this study, five different fuels were used. Four of the fuels were petroleum based and have a cetane number ranging from 26 to 76. The fifth fuel is a 52 cetane number 100% biodiesel, derived from soybean feedstock (SME – Soy Methyl Ester) commonly available in the USA. Diesel Ref [Reference], a 2007 US certification diesel fuel, was not part of the emissions and performance analysis, but was used in the beginning for combustion analysis based on the cetane comparison. Table 2 describes the fuel specifications that were derived using ASTM standards. Figure 3 outlines the boiling curve characteristics that were derived using ASTM D86 method.

Table 2: Fuel Specifications



Description	Cetane number	Carbon	Oxygen	Hydrogen	Fuel density at 293 K	Net heating value [MJ/kg]	H/C molar ratio
Unit	[-]	wt%	wt%	wt%	kg/m3	MJ/kg	[-]
Method	ASTM D613	ASTM D5291	ASTM D5622	ASTM D5291	ASTM D4052	ASTM D240	SAE J1829
Diesel 1	**26.0**	86.25	0.00	13.75	**768.2**	43.61	**1.90**
Diesel 2	**32.4**	87.14	0.00	12.86	**841.1**	42.76	**1.76**
Diesel 3	**53.2**	86.44	0.00	13.56	**829.8**	43.62	**1.87**
Diesel 4	**75.8**	85.56	0.00	14.44	**788.0**	43.66	**2.01**
B100	**52.0**	76.84	**11.38**	11.78	**880.1**	37.41	**1.83**
Diesel Ref	43.0	86.86	0.00	13.14	841.2	42.77	1.81

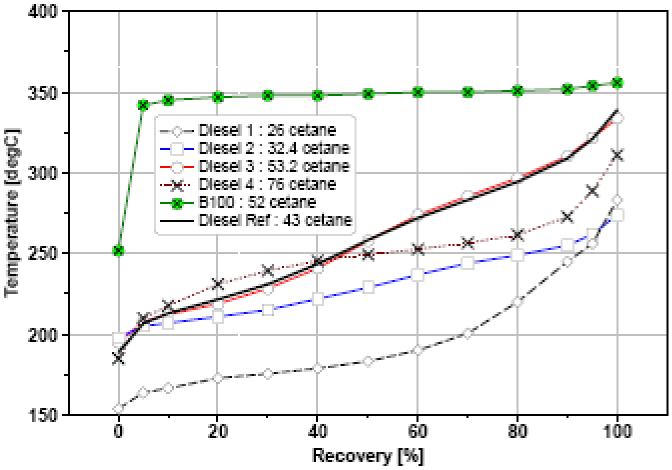


Figure 3: Boiling Curve Characteristics of the Various Test Fuels

It is important to understand the fuel properties, such as density, energy content, cetane number and H/C molar ratio and their correlation based on boiling curve to understand their emissions and performance behavior. The boiling curve for any hydrocarbon fuel provides the relationship of the carbon number versus concentration. However, it does not explain whether or not the given carbon number is at a saturated or unsaturated level. Typically, diesel fuel is made of a combination of Paraffins (C_nH_{2n+2}), Naphthenes (C_nH_{2n}), Olefins (C_nH_{2n}), and Aromatics (C_nH_{2n-6}), and their isomers. Paraffins and Naphthenes are classified as saturated hydrocarbons, whereas Olefins and Aromatics are classified as unsaturated hydrocarbons. The cetane number is representative of the ease of combustion; therefore, the higher the cetane number the lower the auto-ignition temperature. The fuel with the highest cetane number will be a more saturated hydrocarbon. The cetane number increases with an increased degree of saturation. Also, for a given class of hydrocarbon cetane, the number increases with increasing molecular weight. The fuel density increases with an increased carbon number and is thus proportional to molecular weight. However, for a given carbon number, aromatics have the highest density and paraffins have the lowest density.

Diesel 2 and Diesel 4 fuels have a boiling curve recovery in the range of 200 to 300°C, but have significant differences in cetane and H/C molar ratio. The boiling curve shows the carbon number dependent distribution of hydrocarbons, which are similar in both these fuels, but Diesel 4 fuel has a higher H/C ratio. This is representative of more saturated hydrocarbons, which have a higher cetane number. The low fuel density could also be due to more straight chain saturated hydrocarbons and less aromatics. On the other hand, Diesel 2 fuel has a low cetane, low H/C molar ratio and high fuel density; although it has a boiling curve characteristic very similar to Diesel 4. This is representative of more unsaturated hydrocarbons and increased density due to more aromatics.

Diesel 1 has the lowest cetane number and fuel density, but has a very similar H/C molar ratio as Diesel 4 fuel. Since the boiling curve for this fuel is the lowest, with recovery ranging between 150 – 300°C, most of the hydrocarbons are in the carbon number range of C12 or lower. The low molecular weight of Diesel 1 results from a makeup of mostly short straight chain hydrocarbons, which leads to low density, low cetane number and high H/C ratio.

Diesel 3 has its recovery ranging between 200 to 350°C, which is higher than Diesel 2 and 4. Diesel 3 also has a higher cetane number than Diesel 2, but lower than Diesel 4. The Diesel 3 fuel, with 60% or more recovery above 250°C, shows more concentration of higher molecular weight hydrocarbons than Diesel 2 and 4, which promote a higher cetane number. Diesel 3 has a lower H/C ratio than Diesel 4, but higher than Diesel 2, resulting from a moderate concentration of unsaturated hydrocarbons.

B100 is the pure 100% biodiesel derived from soybean feedstock (SME – Soy Methyl Ester). The boiling curve characteristic is distinctly different for this fuel with more than 90% of the recovery at 350°C and above. This indicates that the fuel contains the highest carbon number hydrocarbons consisting of long chain high molecular weight. Due to the high molecular weight and number of saturated long straight chain hydrocarbons, it has a high cetane number and high density. However, B100 has a low heating value and low H/C ratio due to the presence of oxygen.

TEST PLAN

The engine operating points selected for this fuels study are identified in Figure 3. Two part load operating points at 2000 rpm, with 2 bar and 6 bar BMEP, were selected to study the effect of parameter sweeps at constant load conditions. These operating points proved to provide stable operating conditions in the test cell environment. The operating point at

2000 rpm 2 bar BMEP was a light load operating point outside the European drive cycle; whereas, the 2000 rpm 6 bar BMEP operating point happen to be inside the low NOx area calibrated for the European drive cycle.

To characterize the performance and efficiency of the different fuels, the engine was tested for its full load capability at engine speeds from 1000 rpm to 4500 rpm in incremental steps. Full load was provided by the fixed volume of injection representative at the 100% accelerator pedal position. No parameter sweeps were conducted during full load testing.

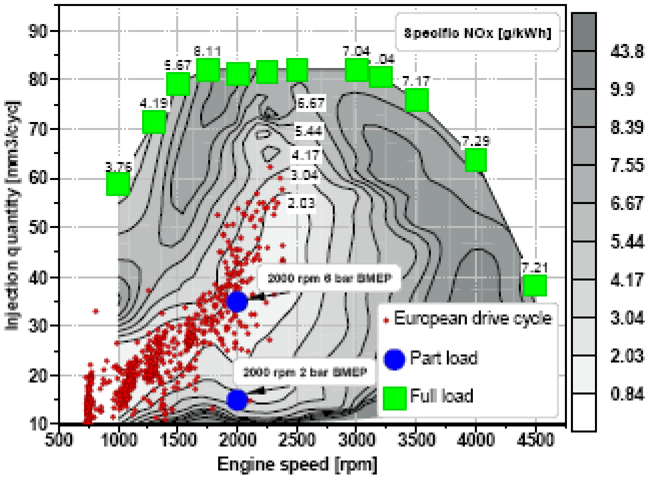


Figure 3: Operating Modes Selected for Fuel Study

As mentioned above, only at part load operating points were the combustion influencing control parameters, such as Start of Injection, Rail pressure, Pilot injection timing as well as quantity, EGR and Boost were varied in specific order for all test fuels. While studying the influence of one parameter, others were kept constant at fixed positions to minimize or decouple the interaction among control parameters. This allowed the observation of the effect on emissions and performance as a result of the interaction between fuel property and combustion control parameters alone. Table 3 shows the typical matrix of testing conducted for each of the five test fuels that were selected.

Table 3: Control Parameter Sweeps

		Rail pressure	Start of main Injection	Pilot timing	Pilot quantity	EGR	Boost
		[bar]	[degCA]	[degCA]	[mg/cyc]	[mg/cyc]	[hpa]
Rail pressure	[bar]	x	_	_	_	_	_
Start of main Injection	[degCA]	_	x	_	_	_	_
Pilot timing	[degCA]	_	_	x	_	_	_
Pilot quantity	[mg/cyc]	_	_	_	x	_	_
EGR	[mg/cyc]	_	_	_	_	x	_
Boost	[hpa]	_	_	_	_	_	x

As shown above, x is an active parameter of variation, while _ represents a parameter that is held constant. During the parameter sweeps, each parameter was varied for 5 to 7 steps within the minimum and maximum thresholds that were chosen, based on the operable conditions in order to understand their influence across a broader spectrum. Between fuels, the parameters steps and levels were held constant for later comparison.

TEST RESULTS AND ANALYSIS

In this section the data analysis is subdivided into the following three segments: COMBUSTION ANALYSIS, PART LOAD WITH PARAMETER SWEEPS and FULL LOAD OPERATION. Although six different parameter effects were studied on 5 different fuels, this section emphasizes the effect of start of injection, rail-pressure and EGR. Also, a brief discussion on boost, pilot timing and pilot quantity is provided. The characterization of fuel behavior with respect to emissions and performance is carried out using NOx, HC, CO, Smoke and BSFC. Lambda, as a function of engine out gaseous emissions and Efficiency as a percent ratio of brake power to total fuel energy supplied, are also used to further support the discussion. Particulate Matter [PM] was not part of the characterization; instead, smoke was used to determine the equivalent soot emissions.

COMBUSTION ANALYSIS

In this section a brief description on the effect of the cetane number on the combustion behavior of a fuel was studied to establish a clear platform of explanation that could support some of the observations made during the Part load and Full load operation. Note that the positive crank angle degrees represent fuel injection before TDC, which is a convention that is used throughout this document.

To establish a better understanding of the combustion behavior, only three fuels were selected, based upon cetane number, for the combustion analysis. Diesel 1 at 26 cetane and Diesel 4 at 75.8 cetane were selected out of the fuel study lot. Diesel Ref with 43 cetane was selected to replace Diesel 2 at 32.4 cetane and Diesel 3 at 53.2 cetane such that the three selected fuels represent the low, middle and high cetane range. Subsequent engine testing of the three selected fuels provided the data shown in Figure 4. Figure 4 shows the combustion pressure, heat release rate, pressure rise rate, and mass burn fraction.

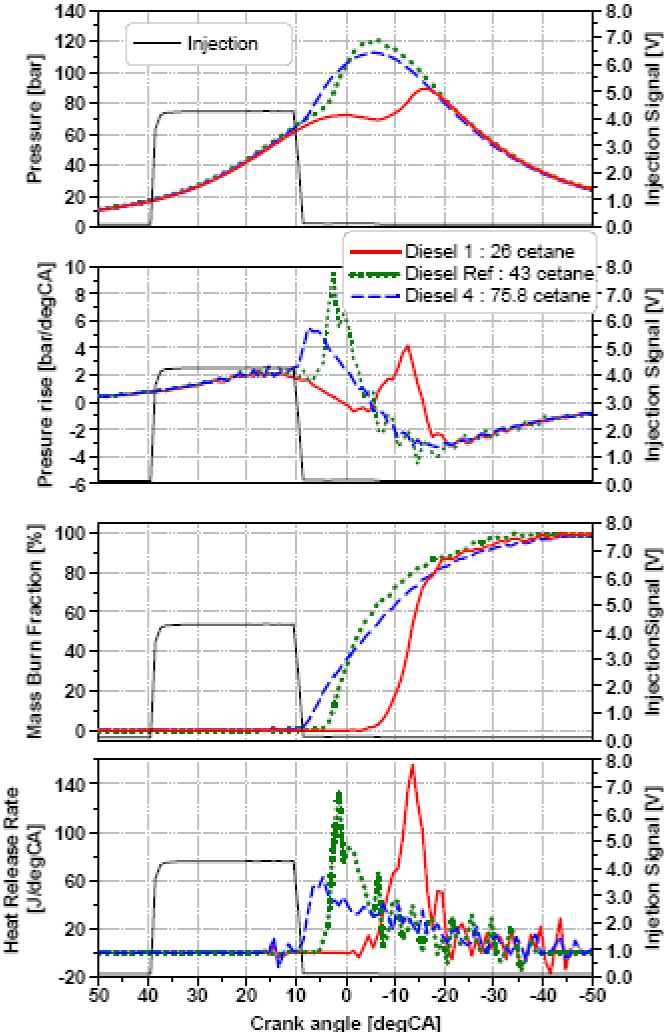


Figure 4: Combustion Analysis

Diesel Ref, having a cetane number of 43, shows an average combustion rate with a combination of premixed and rate limited combustion phases that make up a complete combustion event. The moderate cetane number yielded an ignition delay of 30 [degCA] and the peak heat release rate of 130 J/degCA. This indicates a rapid heat release rate where 60% of mass was burned in 9 [degCA], which is characteristic of premixed combustion. The remaining 40% of mass burned over 43 [degCA] highlighted the existence of a rate limited combustion phase. This fuel showed the highest peak pressure of ~ 125 bar and highest rate of pressure rise of 10 bar/degCA. This can be attributed to the point of injection and cetane number.

In summary, lower cetane fuels exhibit higher ignition delay and stronger premixed combustion. Lower cetane fuels have a short duration of rate limited combustion phase. As the cetane number increases the ignition delay is reduced along with the duration of the premixed combustion phase thus increasing the duration of the rate limited combustion phase.

PART LOAD WITH PARAMETER SWEEPS

2000 rpm 2 bar BMEP

Start of injection sweep:

The effects of start of injection on NOx, Smoke, HC and BSFC were also included in the study. The convention used for the start of injection is positive crank angle degrees, representing fuel injection before TDC. The parameters that were held constant during the start of injection sweep were also included as a part of the study.

As the start of injection is retarded, a drop in NOx emission was observed in association with an increased in HC and BSFC. The combustion phasing is moved more towards the expansion stroke, which limits the time available for combustion resulting from the increasing volume of the combustion chamber. This increased volume reduces pressure and temperature, which minimizes NOx formation and increases the chances of combustion quenching that result in higher HC emissions and BSFC, while maintaining same load. The difference in NOx, HC and BSFC among fuels becomes more significant as the start of injection is retarded. At any given start of injection, NOx emissions and smoke increases with increasing cetane, while HC emissions drop. Low cetane fuels, such as Diesel 1 and Diesel 2 that are characterized by longer ignition delays, stronger premixed combustion and a poor rate limited combustion event show low NOx emissions. The premixed charge always has air and fuel in stoichiometric condition, but under excess lean conditions, such where the lambda is in the range of 2.8 to 3.6. The excess air in that case acts as heat sink. When a premixed charge is ignited, it exhibits a shorter combustion event characterized by a localized higher heat release rate and high temperature, but the presence of excess air acts as a heat sink and reduces overall combustion temperature. This further affects the continuation of the mixing controlled combustion phase, reduced overall combustion temperature and also minimizes the oxygen utilization during combustion that mitigates the overall NOx production. Thus, both Diesel 1 and 2 fuels are characterized with reduced NOx and increasing HC emissions with a retardation of the start of injection.

Since smoke emissions are greatly affected by rate limited or mixing controlled combustion duration and aromatic content, Diesel 1 fuel, with its dominant premixed portion, has the lowest smoke emission. The smoke emissions were not affected by the retarding of start of injection as mixing controlled combustion duration becomes even shorter. The BSFC changed significantly with the retardation of the start of injection, since the low cetane fuel is very sensitive to the time available for combustion. The advanced injection provides more time to cover longer ignition delay, such that much of the injected fuel is burnt in the premixed portion. Thus, the low cetane fuel has the lowest BSFC at 8 [degCA]. The BSFC increases when the start of injection is retarded, which is the result of more fuel required to maintain the same load due to low combustion efficiency. The low cetane fuel Diesel 1 had the highest BSFC of all the diesel fuels [1-4] tested at – 6 [degCA].

Diesel 2 fuel, although it has lower cetane number than Diesel 3 and 4, does not show a BSFC improvement at advanced injection timing as Diesel 1. The BSFC for Diesel 2 remained high over Diesel 3 for most of the start of injection sweep, unlike Diesel 1, as a result of low combustion efficiency that is due to a high concentration of aromatic hydrocarbon, which is also evident from its high smoke emissions. For any given fuel, the lowest BSFC is associated with the highest NOx point. The low BSFC is associated with advanced injection timing, which results in more time available for combustion and thus increases the portion of fuel burned. This increased time increases the combustion temperature and air utilization. As the start of injection is retarded, the time available for fuel to burn is reduced. Thus, more fuel is necessary to maintain the same load which increased the BSFC, reduced lambda and reduced NOx, due to low combustion temperature.

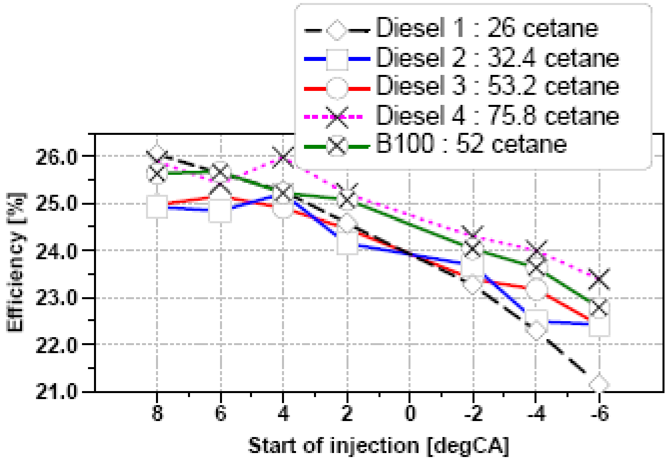


Figure 5: Efficiency versus Start of Injection at 2000 rpm 2 bar BMEP

Diesel 3 fuel with the higher cetane number has a shorter ignition delay and longer rate limited combustion phase, thus increasing the heterogeneous combustion portion which increases the smoke emissions. The higher NOx emissions are due to the longer overall combustion event, which maintained sufficient temperature for NOx formation under lean burn conditions. As shown in Figure 5, Diesel 3 has a low efficiency of energy utilization. Thus more fuel is required to maintain the load, which results in increased combustion temperature that supports higher NOx. As the start of injection is retarded from 8 [degCA], the smoke emissions increased and peaked at 2 [degCA], which is the combustion phasing that is optimum for higher peak cylinder pressures, short ignition delay and longer rate limited combustion. The shorter time for fuel-air mixing increases the rich combustion, resulting in more smoke emissions.

The Diesel 4 fuel has a higher cetane number than Diesel 3, but it produced lower NOx than the Diesel 3 fuel. This is due to the fact that higher cetane shortened the ignition delay significantly and it is characterized with highest efficiency. This reduced the amount of fuel required to maintain the load, which is supported by lowest BSFC and highest lambda. So the total mass of NOx released using the Diesel 4 fuel is lower compared to the Diesel 3 fuel. However, Diesel 4 produced the highest smoke due to its longer heterogeneous rate limited combustion duration.

B100 biodiesel shows a mixed range of emissions and BSFC compared to other fuels. Although B100 has a cetane number of 52, which is the same as Diesel 3 fuel, it does not behave the same. B100 has the lowest heating value and requires a higher amount of fuel to maintain the same load which is why it has the highest BSFC. Since it is carrying oxygen it has the highest lambda of all fuels. This increases the oxygen availability for combustion and since higher cetane is mostly associated with rate limited / mixing controlled combustion better oxygen availability improves combustion efficiency. Thus B100 is characterized with efficiency similar to Diesel 4 as shown in Figure 5. The B100 has a higher efficiency than Diesel 3 fuel, resulting from the improved mixing phase. The combustion efficiency improvement reduces heterogeneity through fuel-based oxygen produced low smoke, which can also be attributed to no aromatics in the fuel as seen from its boiling curve characteristic. The NOx emissions with B100 are in the same range as Diesel 4 at some portions of combustion and mostly lower than Diesel 3 at all times. Due to the oxygen availability in the fuel, the energy utilization is better with biodiesel compared to Diesel 3 as seen in Figure 5. The oxygen in the fuel results in less hydrocarbon portion of fuel burned for the same load. This reduces the temperature of combustion and lowers NOx compared to Diesel 3, even though both B100 and Diesel 3 fuels have the same cetane number.

Rail pressure sweep:

Figures 6, 7 and 8 outline the Emissions, BSFC, Lambda and efficiency respectively. Figure 6 shows that a reduction in rail pressure reduces NOx emissions for most of the fuels. A reduction in rail pressure reduces the rate of fuel injection, which increases the duration of injection for a desired volume of fuel. This reduces the fuel amount burned per [degCA], thus reducing combustion temperature and leading to a reduction in NOx emissions. As the rail pressure is reduced, the duration of injection increases. This results in more fuel injection into the burning charge of fuel and air increasing rich zones of combustion, thus producing higher smoke emissions. The effect of rail pressure on BSFC is not significant. The effect of rail pressure on HC emissions is only observed with Diesel 1 of 26 cetane fuel, but not with any other fuel.

The high cetane Diesel 3 and Diesel 4 fuels show more enhanced sensitivity to reduced rail pressure over smoke emissions compared to low cetane and B100 fuels. Higher cetane as it is always characterized with longer rate limited combustion, increased duration of injection, due to low rail pressure increases the amount of fuel injection collision with burning charge that increases the rich combustion regimes causing high soot emissions. Diesel 4 fuel showed lower BSFC with higher rail pressure, which improves the fuel atomization and air-fuel mixing. The B100 fuel with cetane similar to Diesel 3 showed less sensitivity to an increased duration of injection, due to the fuel carrying oxygen. The oxygen in the B100 fuel helps reduce heterogeneity and increases localized lambda making it less sensitive to soot emission also higher in efficiency, as shown in Figures 6 and 8.

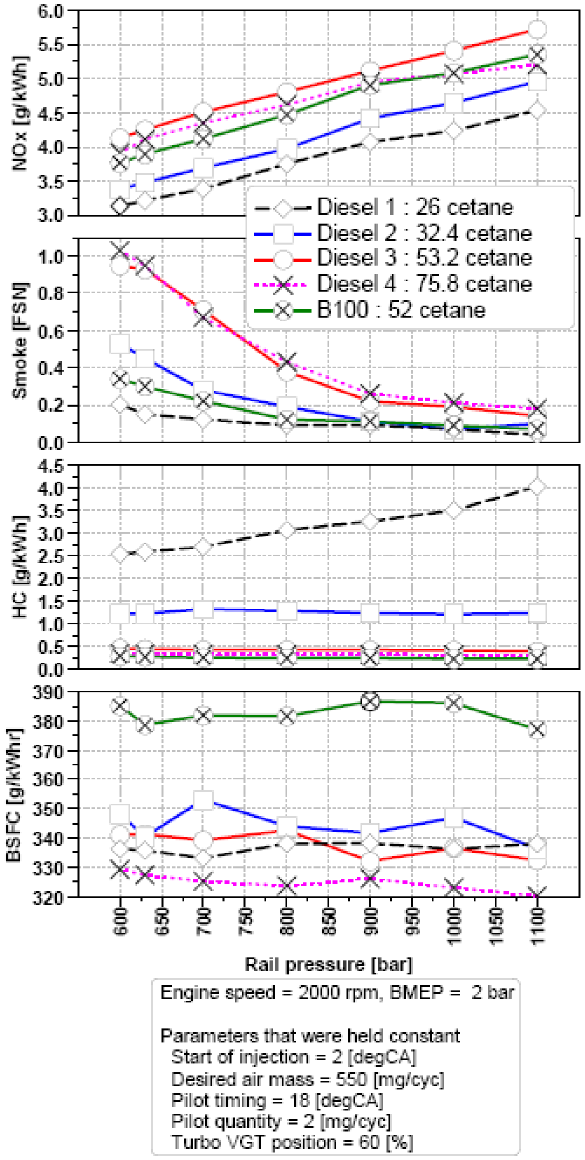


Figure 6: Rail Pressure Effect at 2000 rpm 2 bar BMEP

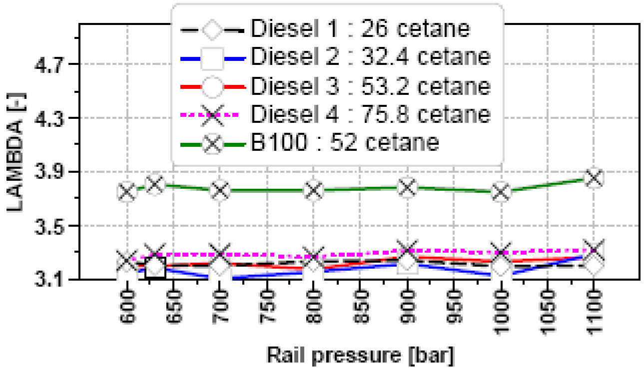


Figure 7: Lambda versus Rail Pressure at 2000 rpm 2 bar BMEP

Diesel 4, with highest cetane, shows the highest efficiency due to a shorter ignition delay (Figure 8).

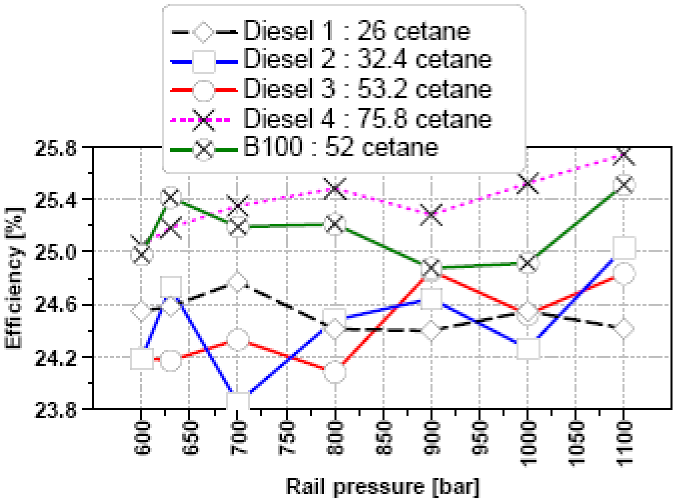


Figure 8: Efficiency versus Rail Pressure at 2000 rpm 2 bar BMEP

As shown in Figure 8, the efficiency difference among fuels is mainly driven by start of injection, which held constant at 2 [degCA], whereas the effect of rail pressure was minimal.

Exhaust Gas Recirculation [EGR] sweep:

The study also included the effect EGR has on emissions. The results of the study show that as the air mass flow decreases the EGR % increases. The increased EGR rate reduces the fresh air, which reduces oxygen availability for combustion. This reduces the combustion efficiency and peak temperature, which leads to lower NOx emissions. The effect of EGR on different cetane fuels is marginal, but all fuels show a trend of reduced NOx with higher EGR rates.

The EGR effect on smoke is similar to the rail pressure effect but more significant with high cetane fuels, such as Diesel 3 and Diesel 4, compared to low cetane fuels, such as Diesel 1 and 2. This is due to the longer burn period where higher EGR rates create more rich combustion regimes, thus increasing smoke emissions.

Increased EGR rates show higher HC emissions with Diesel 1 as a result of poor rate limited combustion. The higher EGR rate decreases the combustion efficiency greatly with these low cetane fuels.

Boost pressure effect:

The study also illustrated that higher boost pressure reduces NOx emissions. The NOx reduction with higher boost is a result of increased EGR rate required to maintain the same air mass during testing.

Diesel 1 NOx and HC emissions decrease with higher boost. The higher boost is causing a higher EGR rate, which lowers NOx emissions. The reduction in HC emissions results from the ignition delay reduction for Diesel 1 fuel, due to increased intake manifold temperatures.

The higher boost yields higher BSFC, which is a result of higher pumping losses and in turn demands more fuel to maintain the same load. Diesel 4 fuel shows better BSFC than the other fuels, due to the high cetane number and better combustion efficiency. The lambda was reduced, primarily because of the increased EGR rate, but also from higher fueling rates required to maintain the load.

Pilot timing effect:

The pilot timing is expressed in degree crank angles [degCA] and is the duration that elapsed between start of pilot injection and main injection. Figure 9 shows the effect of pilot timing on emissions. During this pilot timing sweep the pilot quantity was kept constant at 2 mg/cyc. Increasing the pilot timing from 14 to 30 [degCA] reduces NOx emissions. Further increase in pilot timing beyond 30 [degCA] does not show any significant effect on NOx emissions. The use of pilot injection reduces combustion noise through reducing the rate of heat release. The position and quantity of the pilot injection plays a significant role on heat release. A pilot injection that is close to the main injection will cause the burning pilot fuel quantity to overlap with the main injection event. This leads to rich zones of combustion that result in the high smoke conditions shown in Figure 9. This close pilot timing also leads to higher temperatures and high NOx emissions. As pilot injection timing separation is increased the pilot quantity burning zone overlap with the main injection event is reduced, which also reduces the smoke emissions. The heat released by the pilot quantity helps reduce the ignition delay of main injection, thereby increasing the mixing controlled combustion period and minimizing the combustion temperature and NOx emissions. Increasing the pilot separation further away from the main injection event may quench the pilot quantity ignition. As a result, Diesel 1 and 2 have low cetane numbers, show poor combustion initiation and have significantly higher HC emissions.

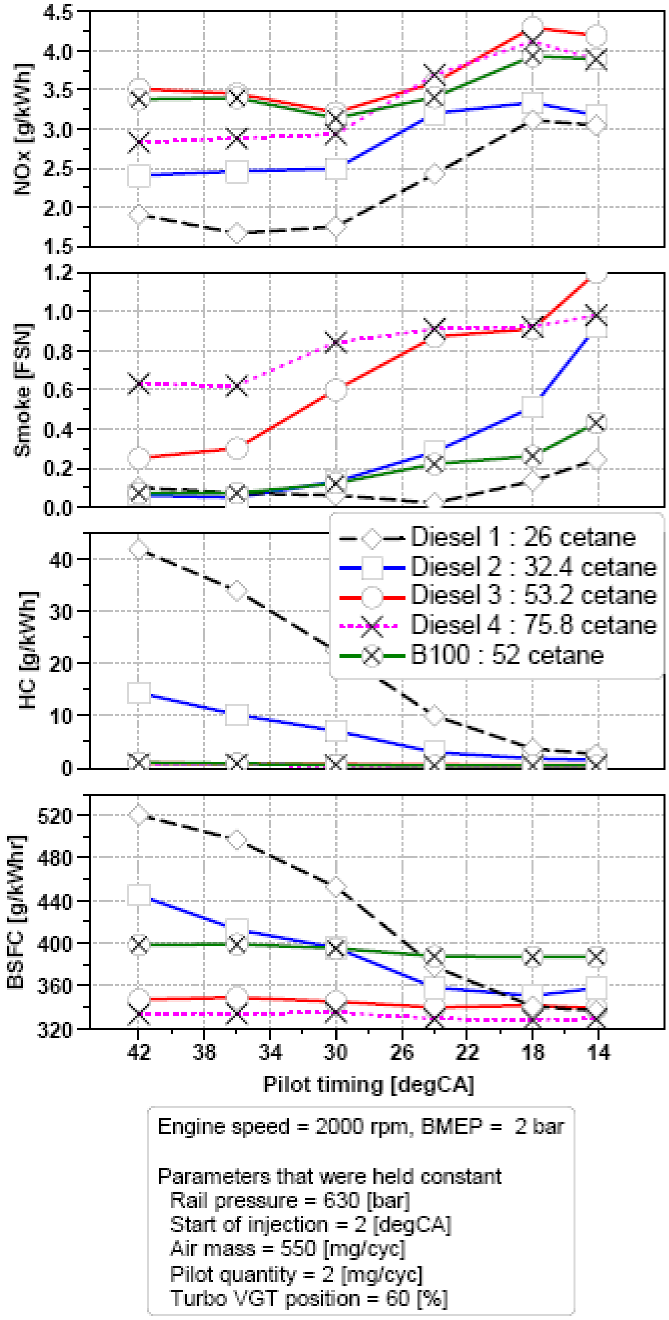


Figure 9: Pilot Timing Effect at 2000 rpm 2 bar BMEP

When the pilot quantity does not get ignited during the increased pilot timing separation, the latent heat of evaporation of fuel derived from compressed air in the chamber is not replaced by pilot quantity combustion. This reduces the overall heat available, which further increases the ignition delay for the main injection. This requires an increased fuel quantity to maintain the same load, which increases the BSFC. Diesel 1 and 2 fuels exhibit this trend. The delay in ignition initiation of main injection shifts the combustion more into the expansion stroke. The increasing volume of chamber causes the rate limited combustion to quench early, increasing HC emissions. Figure 10 shows both Diesel 1 and 2 having a significant decrease in lambda and efficiency. This is an indication of poor combustion and increased fuel injection quantity. The effect is more prominent with low cetane fuel, due to their poor combustion initiation.

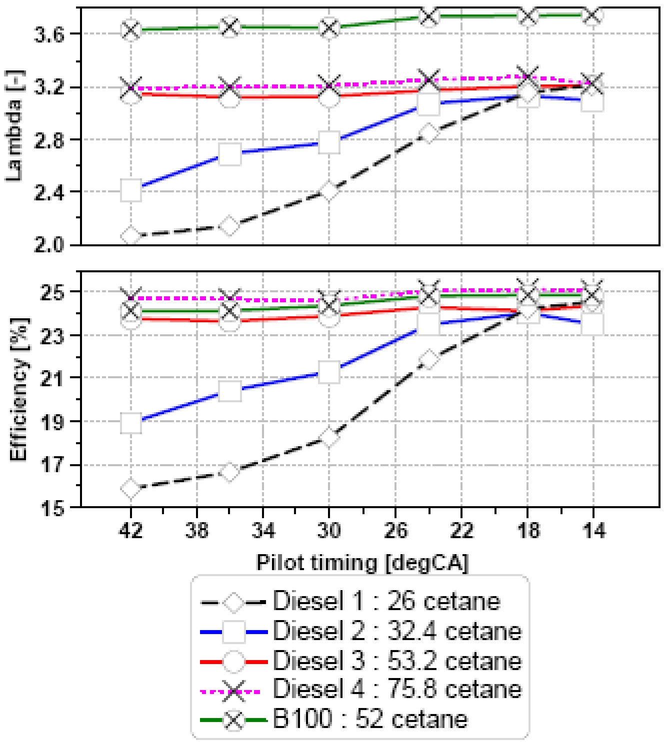


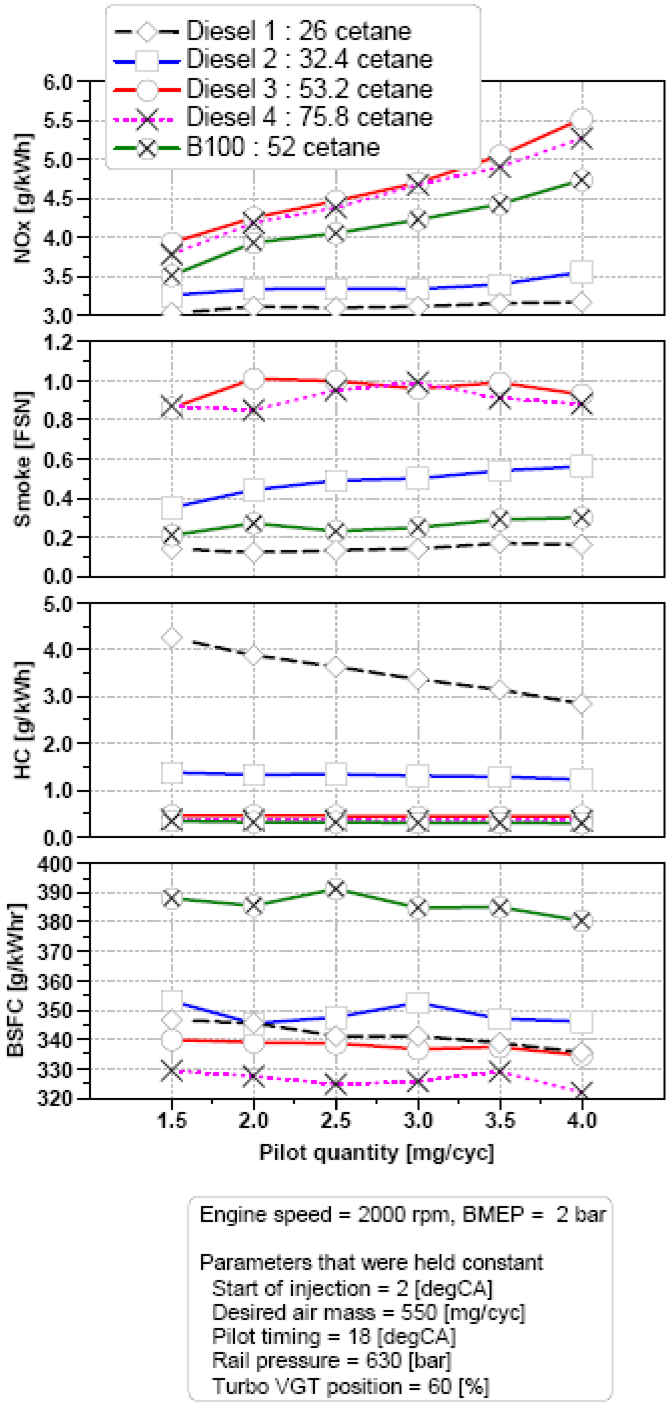
Figure 10: Lambda and Efficiency versus Pilot Timing at 2000 rpm 2 bar BMEP

Pilot quality effect:

Figure 11 shows the effects of pilot quality on emissions for the various fuels tested.

As shown in Figure 11, higher pilot qualities increase NOx emissions and slightly reduce the BSFC for most of the fuels tested. As the pilot quantity increased, more heat generated by the pilot quantity significantly minimized the ignition delay for the main injection. In a common rail system both the pilot and main quantities are considered as torque forming units with higher pilot quantities reducing main injection quantity, while maintaining balance on total fuel injected for torque formation. With higher heat released due to pilot fuel combustion, the ignition delay for main quantity is reduced significantly resulting in longer and improved rate limited combustion. Improved air utilization associated with longer combustion event increases NOx emission and decreases BSFC. This effect is more prominent with high cetane fuels, such as Diesel 3, 4 and B100, which are inherently characterized by longer rate limited combustion.

Diesel 1 fuel shows a drop in HC emission with higher pilot quantities. The higher pilot quantity results in higher combustion heat that reduces the ignition delay for main injection. This coupled with lower main quantity reduces the fuel burnt in the late rate-limited combustion event. This effect of increasing pilot quantity is very similar to effects of advancing the start of main injection.



Engine speed = 2000 rpm, BMEP = 2 bar

Parameters that were held constant
Start of injection = 2 [degCA]
Desired air mass = 550 [mg/cyc]
Pilot timing = 18 [degCA]
Rail pressure = 630 [bar]
Turbo VGT position = 60 [%]

Figure 11: Pilot Quantity Effect at 2000 rpm 2 bar BMEP

2000 rpm 6 bar BMEP

This chapter outlines discussion on how emissions and performance vary with each fuel at higher loads. Critical parameter sweeps, such as start of injection and rail pressure, were selected for such a discussion.

Start of injection sweep:

As previously discussed under the 2000 rpm 2 bar BMEP portion of the study, retarding the start of injection reduces NOx emissions. For low cetane fuels such as Diesel 1 and 2, retarding the start of injection increases HC emissions due to incomplete combustion. These low cetane fuels exhibit a high magnitude of BSFC change with retarding the start of injection as a result of the increased fuel required to maintain the load under low efficiency conditions. Diesel 1 fuel shows a sudden increase in combustion efficiency and an increase in lambda when the start of injection is advanced beyond 4 [degCA]. This is the balance effect on ignition delay and premixed combustion portion and its position with respect to TDC.

High cetane fuels such as Diesel 3 and 4 behave similar to low load operation. The resulting higher smoke is due to a longer burn duration and the low BSFC is due to short ignition delay and better efficiency. Diesel 3, 4 and B100 fuels do not exhibit the same sensitivity as Diesel 1 and 2 for the start of injection, due to improved combustion initiation with reduced ignition delay.

One of the significant differences in this high load operation was found in the reversal of NOx emissions compared to light load operation with respect to fuels. The low cetane Diesel 1 fuel, which had lowest specific NOx at 2000 rpm 2 bar BMEP, had higher specific NOx than the high cetane fuel Diesel 4. For this discussion only Diesel 1 and 4 were selected, Figure 12 and 13 show the comparison of emissions and performance of these fuels at 2000 rpm 6 bar and 2 bar BMEP.

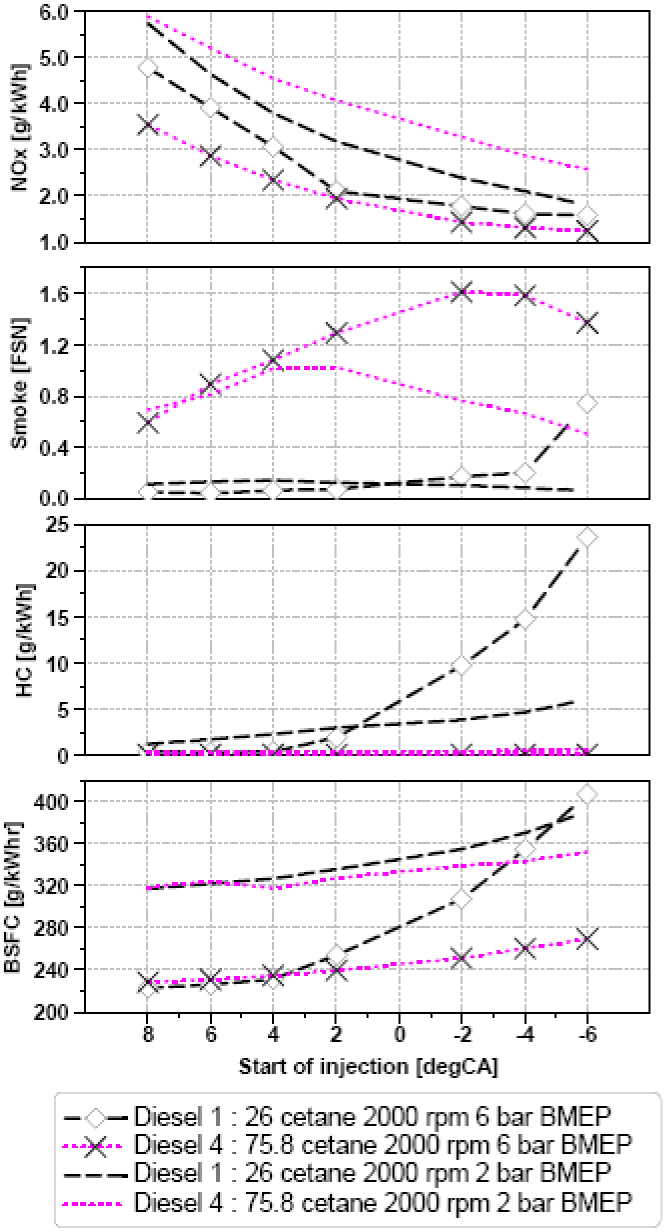


Figure 12: Start of Injection Effect on Emission and Performance Comparison for Diesel 1 and 4 Fuels at 2000 rpm 6 bar and 2 bar.

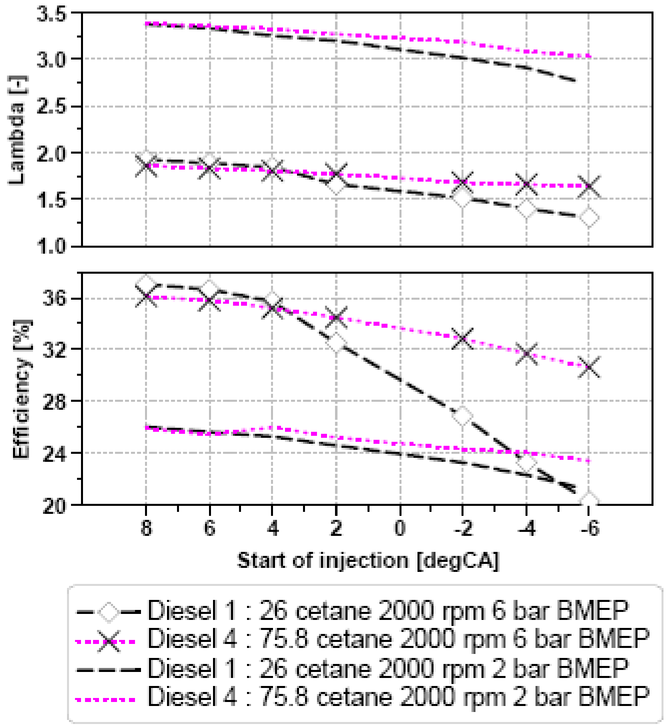


Figure 13: Start of Injection Effect on Lambda and Efficiency Comparison for Diesel 1 and 4 Fuels at 2000 rpm 6 bar and 2 bar.

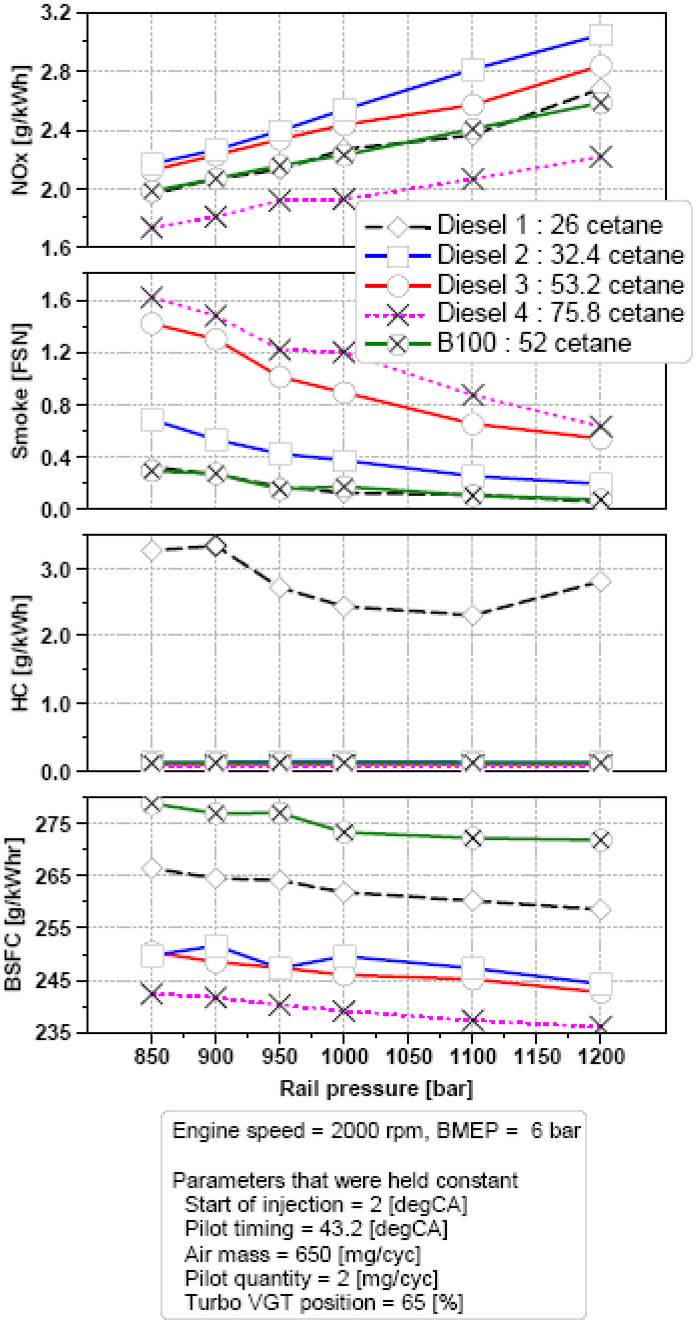
Diesel 4 the high cetane fuel characterized by a dominant rate limited combustion event shows a higher magnitude of drop in specific NOx with increasing the load. As the load increases, the lambda drops and efficiency increases (Figures 12 and 13). Reduction in lambda indicates less excess air in the combustion chamber, which minimizes the heat sink effect and results in increased overall combustion temperature. Higher combustion temperature improves the combustion efficiency. However, with improved efficiency the specific NOx emissions drop. As seen from Figure 12 with higher loads, the BSFC also drops indicating high efficiency and less fuelling requirement per unit of work done. This reduction in specific fuelling results in less specific NOx emissions by increasing the load.

Diesel 1 low cetane fuel characterized by dominant premixed combustion shows a lower magnitude of drop in specific NOx emissions with an increase in load compared to high cetane fuel, such as Diesel 4 (Figure 12). With low cetane fuel such as Diesel 1, as the load increases the ignition delay increases. This is evident from the higher HC emissions and BSFC with retarding the start of injection. Once the combustion is initiated; the premixed combustion duration remains almost the same irrespective of load and barely affected the NOx generation. At higher loads with reduced lambda and higher combustion temperatures, the low cetane fuels exhibits improved and longer rate limited combustion events, resulting in higher overall efficiency (Figure 13). The combination of these resulted in a marginal difference in specific NOx emissions with respect to load.

Diesel 2, 3 and B100 showed very similar NOx emissions. Although B100 had a higher lambda, the NOx emissions were the same due to the average efficiency leading to moderate combustion temperatures. The low heating value of B100 lead to the highest BSFC of all of the fuels tested. However, B100 fuel showed less smoke emissions as a result of enhanced oxygen availability. Diesel 1 shows a lean burn operation at the advanced start of injection, since the fuel required to maintain the load was reduced. Although Diesel 2 has a lower cetane than Diesel 3 and 4, it does not show improved efficiency and BSFC at advanced start of injection. It does produce higher smoke, unlike Diesel 1; this can be attributed to high aromatic content in the fuel resulting in poor energy utilization.

Rail pressure sweep:

Figures 14 and 15 show the emissions, lambda and efficiency recorded with different fuels during the rail pressure sweep. Similar to previous discussions and observations made under low load 2000 rpm at 2 bar BMEP operation, the effect rail pressure had on emissions were the same even under high loads. A reduction in rail pressure increased injection duration, which reduced NOx and increased smoke emissions. Significant differences were found with the high cetane Diesel 4 fuel, which showed the lowest NOx, lowest BSFC and highest efficiency due to the causes discussed earlier under the start of injection sweep. The effect of rail pressure showed no crossover effects on emissions trends especially with low cetane fuels. Diesel 2 fuel showed the highest NOx and was more affected by the start of injection being held at 2 [degCA] than any rail pressure effect.



Engine speed = 2000 rpm, BMEP = 6 bar

Parameters that were held constant
Start of injection = 2 [degCA]
Pilot timing = 43.2 [degCA]
Air mass = 650 [mg/cyc]
Pilot quantity = 2 [mg/cyc]
Turbo VGT position = 65 [%]

Figure 14: Rail Pressure Sweep at 2000 rpm 6 bar BMEP

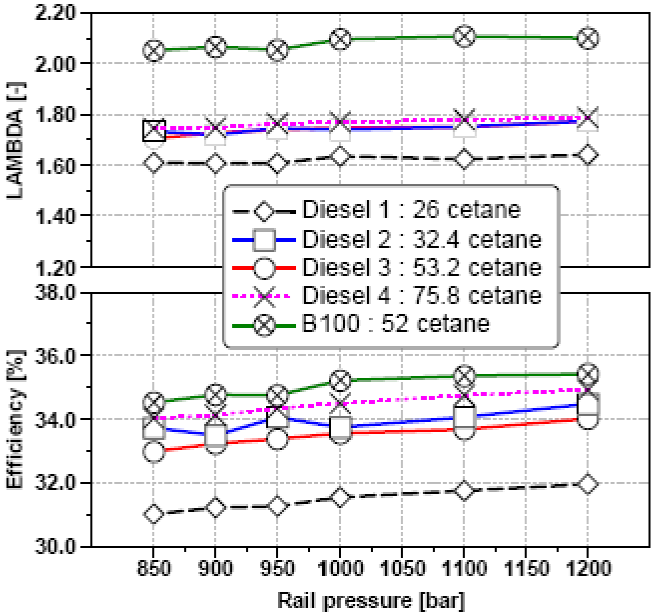


Figure 15: Efficiency and Lambda versus Rail Pressure at 2000 rpm 6 bar BMEP

As shown in Figure 15, efficiency drops with the reduction of rail pressure, as the injection duration increases so is the portions of rich combustion zones which leads to poor air utilization and high smoke seen in Figure 14. The reduced efficiency is also supported by the increased BSFC, indicating more fuel is required to maintain the same load, due to poor combustion.

The effect of EGR, boost, pilot quantity and pilot timing are very similar to the observations made under 2000 rpm at 2 bar BMEP operation.

FULL LOAD OPERATION

In order to observe the effect of constant volume injection on emissions and performance, full load tests were conducted for all fuels. Figures 16, 17 and 18 show the important emissions and performance parameters for this discussion.

B100 fuel showed highest NOx emissions throughout full load operation. Biodiesel has the highest density of all the fuels tests, which means for a constant volume of injection, as shown in Figure 17, a larger mass of fuel was injected into the combustion chamber and more fuel was burnt. Due to the high efficiency of burning B100 fuel and since it carries oxygen, which is evident from higher lambda, it produced more NOx emissions. But biodiesel showed the highest BSFC, due to the lowest heating value per unit mass of fuel. Although B100 fuel showed better efficiency, the high density and lower heating value offsets the efficiency gain leading to highest BSFC.

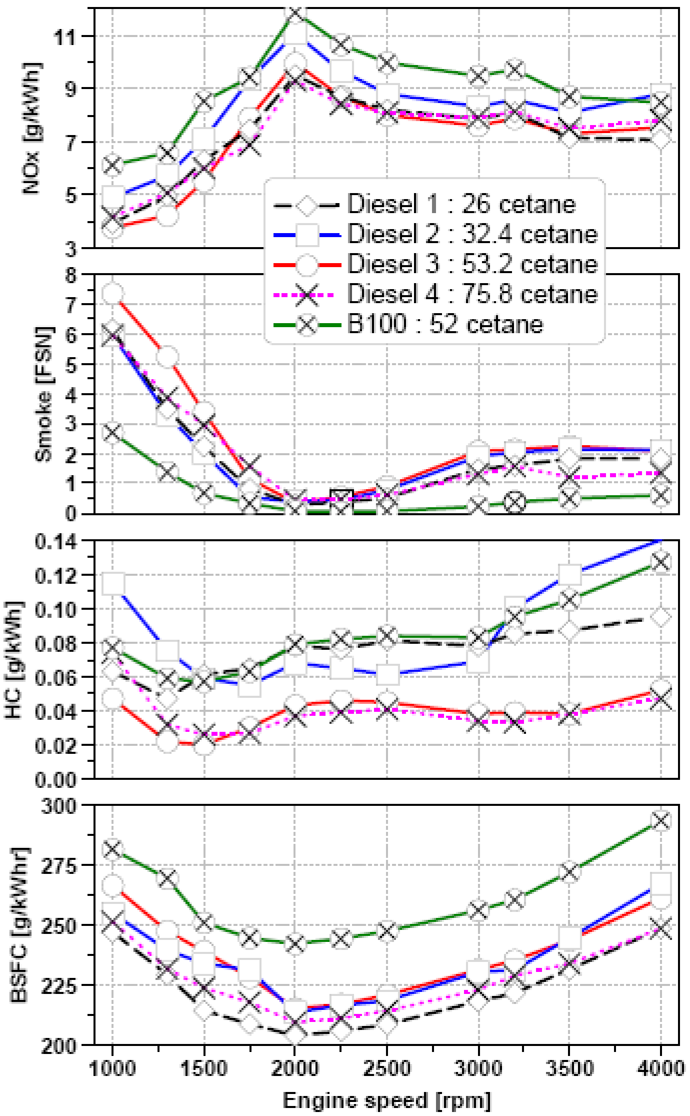


Figure 16: Emissions at Full Load

Diesel 1 fuel showed the lowest BSFC and highest lambda operation among petroleum diesels. Diesel 1 has lowest density and mass of fuel that was injected for the constant volume of injection. During the full load operation the start of injection ranged between 2 [degCA] to 18 [degCA] from an engine speed of 1000 rpm to 4000 rpm (Figure 18). The time available for combustion was sufficient to help the ignition delay for this low cetane fuel. Diesel 1 fuel has increased volatility, as indicated by its boiling curve characteristics that contribute to the high premixed and short rate limited combustion portion. The result is high efficiency and the lowest BSFC as shown in Figure 16 and 17.

As the cetane increases for the Diesel 2 and 3 fuels, the NOx emissions decrease and the BSFC increases with a reduction in overall efficiency and lambda. Since the air mass flow remained constant as shown in Figure 18, for all fuels the drop in lambda is due to a variation in fuel mass. Diesel 2 fuel has the highest density among petroleum diesel fuels and thus more injected fuel mass. However, the low cetane and advanced timing improved the fuel's efficiency and produced high NOx emission, but more HC emissions at some points and higher BSFC than Diesel 1 as a result of high aromatic content. Diesel 3 has the second highest density, resulting in low lambda since it also has high stoichiometric AFR. The relatively high cetane number resulted in longer duration of combustion and low efficiency, which is evident from higher exhaust temperatures (Figure 18).

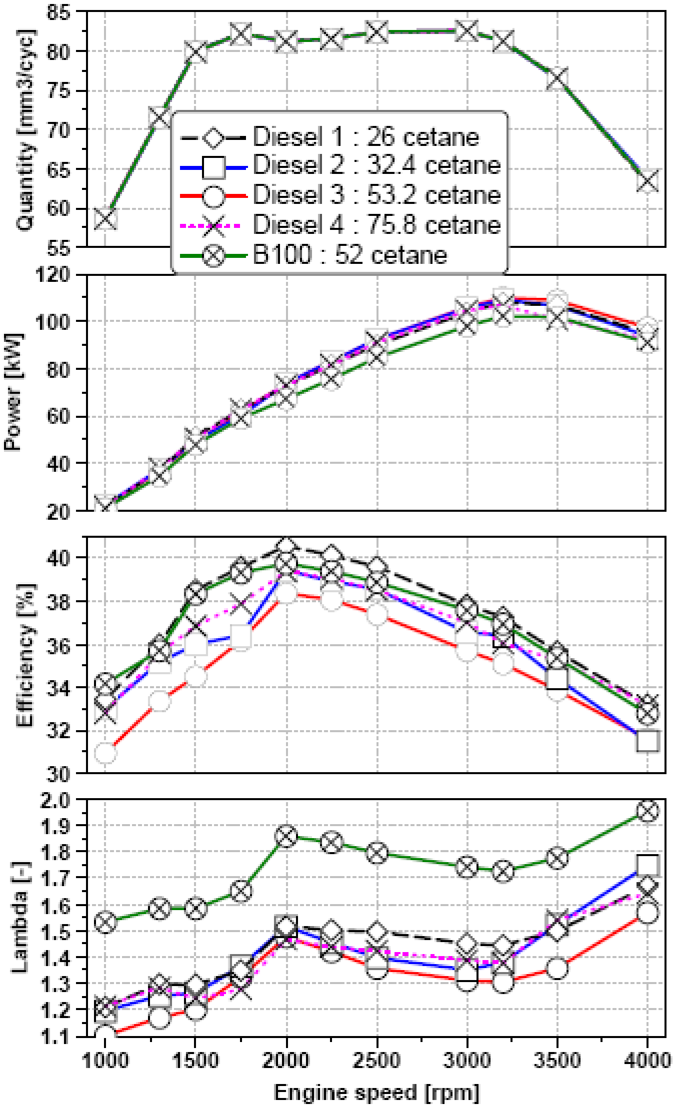


Figure 17: Performance at Full Load

Although Diesel 4 has the highest cetane, it has the lowest density that lowers the fuel mass injected. The reduced injected fuel mass resulted in higher lambda and lower NOx. The Diesel 4 fuel had better efficiency than Diesel 2, but Diesel 4 has very low aromatics in comparison to Diesel 2. Although the fuels have very close boiling curve characteristics, Diesel 4 has better combustion efficiency than Diesel 2. In addition, the BSFC of Diesel 4 is lower as a result of the low fuel mass and high efficiency, which also produced low specific NOx emissions.

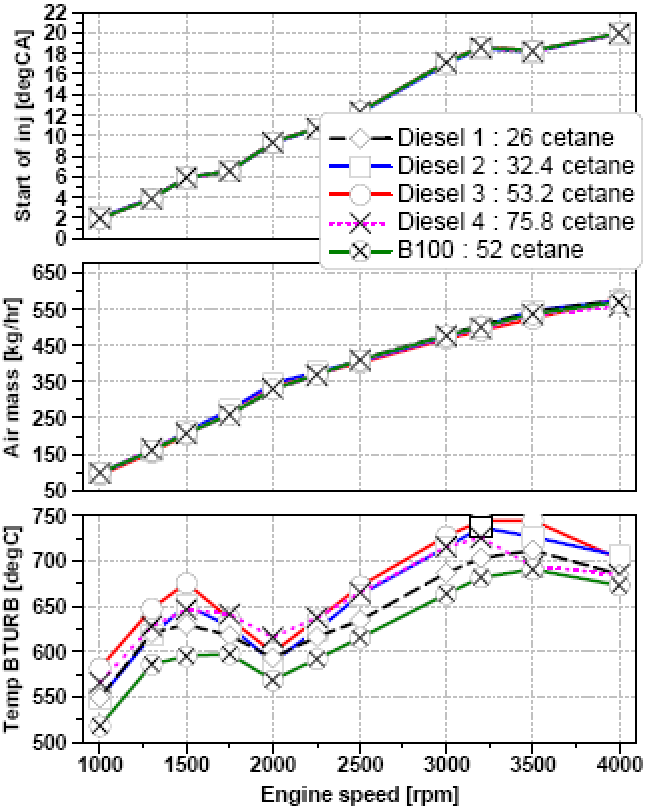


Figure 18: Full Load Influencing Parameters

CONCLUSION

This study centered on the impacts of fuel properties on emissions. A variety of combustion parameters provided the interaction required to impact emissions and performance. The full load portion of the study focused particularly on fuel properties, such as density and the heating value impacts on the performance parameters of combustion efficiency, BSFC, power and efficiency. The following conclusions were made regarding the impacts of fuel properties on emissions and performance, based on this study:

- High cetane fuels achieve higher efficiency under most conditions, because of their inherent low ignition delay. Under high load conditions, Diesel 4 fuel demonstrated the best BSFC and low NOx at higher loads.
- Under low loads, raising the fuel cetane increases NOx, because of the increased combustion duration and oxygen utilization.
- Low cetane fuels show greater efficiencies under advanced injection timing, because of premixed combustion dominating rate limited combustion.
- Fuel containing a higher aromatic content lowers its overall efficiency and increases smoke.
- The fuel's efficiency factor is influenced by density, cetane and heating value, which determines the fuel utilization to produce load.
- Biodiesel fuel exhibits greater efficiency, because of fuel carrying oxygen aiding combustion. However, Biodiesel generates more NOx and increased BSFC, due to the oxygen level in the fuel and its lower heating value.
- Less smoke is produced by Biodiesel fuel, because of its low rich combustion zones / heterogeneity during combustion as it carries oxygen.
- A significant impact on emissions and efficiency is made by pilot timing, particularly when using low cetane fuels.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFR: Air Fuel Ratio

bar: Unit of pressure

BSFC: Brake Specific Fuel Consumption

BMEP: Brake Mean Effective Pressure

Boost: Intake manifold pressure

BTURB: Before turbine

CO: Carbon monoxide

cetane: Cetane Number

cyc: Combustion cycle

DOHC: Double Over Head Camshaft

DI: Direct Injection

degCA: Degree Crank Angle

degC: Degree centigrade

EGR: Exhaust Gas Recirculation

g: Gram

HSDI: High Speed Direct Injection

HC: Hydrocarbon

H/C: Hydrogen to Carbon molar ratio

hr or h: Hour

hpa: Hexa Pascal

inj: Injection

kg: Kilogram

kW: Kilo Watt

L: Liter

MEXA: Motor Exhaust emissions Analyzer

MJ: Mega Joule

m3: Cubic meter

mm3: Cubic millimeter

mg: Milligram

Nm: Newton Meter

NOx: Nitrogen Oxides

PM: Particulate Matter

rpm: Revolutions Per Minute

SOI: Start Of Injection

SME: Soy Methyl Ester

TDC: Top Dead Center

Temp: Temperature

µs: Micro second

V: Volt

wt%: Weight percent

W: Watt

%: Percent

- : No units