

Impact of Fuel Properties on Diesel Low Temperature Combustion

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ABSTRACT

Extensive empirical work indicates that exhaust gas recirculation (EGR) is effective to lower the flame temperature and thus the oxides of nitrogen (NO_x) production in-cylinder in diesel engines. Soot emissions are reduced in-cylinder by improved fuel/air mixing. As engine load increases, higher levels of intake boost and fuel injection pressure are required to suppress soot production. The high EGR and improved fuel/air mixing is then critical to enable low temperature combustion (LTC) processes.

The paper explores the properties of the Fuels for Advanced Combustion Engines (FACE) Diesel, which are statistically designed to examine fuel effects, on a 0.75L single cylinder engine across the full range of load, spanning up to 15 bar IMEP.

The lower cetane number (CN) of the diesel fuel improved the mixing process by prolonging the ignition delay and the mixing duration leading to substantial reduction of soot at low to medium loads, improving the trade-off between NO_x and soot. Low load performance, such as cycle-to-cycle variability, was worsened by less effective post flames and the less reactive nature of the mixture.

The higher volatility of the lower T90 fuels promoted the evaporation of the injected fuel spray, thereby accelerating the fuel/air mixing process and improving the homogeneity of cylinder charge. The T90 effect on ignition delay is minor,

yet the improved vaporization and mixing translated in a noticeable soot reduction.

The higher aromatic contents in the diesel fuels prolonged the ignition delay. However, the soot emissions were not necessarily reduced according to the extended ignition delay. The soot trend competed with the aromatics, which are precursors of soot.

INTRODUCTION

Diesel LTC has been reported to produce ultra-low in-cylinder NO_x and soot emissions owing to its capability of restraining diesel combustion from entering into the stoichiometric premixed or diffusion controlled high combustion temperature regions of the conventional diesel cycle [1-2]. LTC can be implemented by a high level of EGR or by enabling a process of homogeneous charge compression ignition (HCCI) combustion [3].

In HCCI, the fuel is delivered very early in the compression stroke, and the air/fuel mixture is subjected to longer physical and chemical preparation than that in the conventional diesel cycle. Consequently, the combustion phasing largely depends on the kinetics of the chemical reactions of the cylinder charge rather than the fuel injection timing. The lack of precise control on combustion phasing is one of the major difficulties for HCCI [4].

The start of combustion (SOC) can be closely controlled through injection scheduling in EGR enabled LTC. In this mode of operation, the ignition delay between the fuel injection and the SOC is much shorter than that in HCCI. However, this ignition delay duration is substantially prolonged by EGR, compared with that in the conventional diesel. The fuel and air are sufficiently premixed prior to ignition. As the portion of the premixed combustion increases, soot emissions are reduced, as soot is generated mainly by diffusion burning. Enhanced mixing can be achieved through high injection pressures and high EGR levels [5]. The high injection pressure helps the mixing process, attributed to the longer spray penetration, better fuel atomization, and stronger air entrainment. EGR application increases the heat capacity of the cylinder charge, reduces the O₂ concentration, and prolongs the ignition delay that offers a longer duration to enhance the mixing process in producing lean combustible mixtures.

A modulated kinetics (MK) combustion mode reported by Nissan to successfully attain the premixed LTC, secures sufficient mixing time through a heavy use of EGR even with substantially retarded injection timing [6]. Investigation by the present authors proved that the duration of the ignition delay could be extended by 50% with EGR compared to that of zero EGR operation, and smoke emissions were reduced by the enhanced air fuel mixing during such prolonged ignition delay (Figure 1). The soot emissions also dropped with enhanced premixing effected by increased injection pressure and/or boost [7-8]. It is critical to generate the high-quality air/fuel mixture in order to simultaneously achieve ultra-low NO_x and soot emissions in diesel LTC.

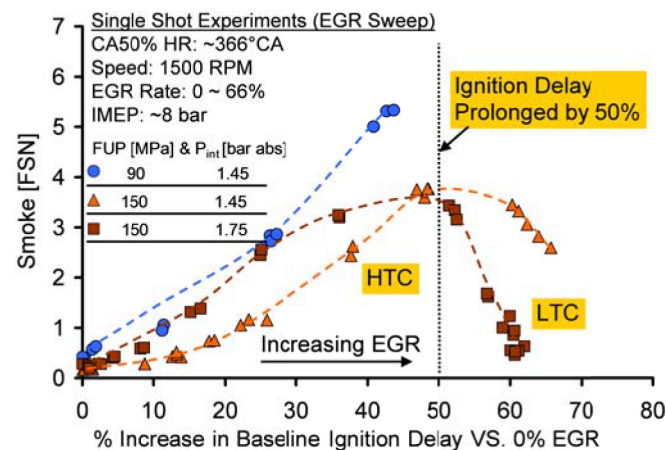


Figure 1. Prolonged Ignition Delay by EGR [7]

Apart from high injection pressure and EGR to prolong ignition delay, fuel properties can affect emissions significantly. Research experiments have shown that CN is an effective factor that influences the engine-out emissions, even on different DI engines and/or under various test conditions.

A small decrease of NO_x emission is usually observed with the increase of CN [9,10,11]. In a CN range of 40-65, less than 5% reduction of NO_x emission is reported for every increment of 10 CN [9]. However, a substantial reduction of the carbon monoxide (CO) and total hydrocarbon (THC) emissions has been found when the CN is increased by adding CN improvers [12]. On the other hand, the effect of CN on soot emissions is not consistent among researchers [13-14].

Some of the tests discussed in the last paragraph were performed in the 1980s and 1990s, when NO_x emission regulations were much less stringent than present standards. The reported NO_x emissions were at the levels of 4-7 g/bhp-hr or higher, indicative of conventional diesel high temperature combustion (HTC). In these diesel HTC cycles, particularly with the unavailability of high injection pressure technologies, locally lean, rich and stoichiometric regions were formed in the cylinder.

Modern diesel engines can operate with a lean (in contrast to stoichiometric) and near homogeneous cylinder charge via EGR and elevated injection pressure at NO_x levels ranging from 0.15 to 1.5g/bhp-hr. The burning of a lean and homogeneous mixture proceeds at a low temperature that limits NO_x formation with sufficient EGR, and the homogeneity of the cylinder charge suppresses soot emissions.

Recent studies on fuel properties, especially CN, indicate that the homogeneity of the cylinder charge is related to the CN of the diesel or diesel-like fuels [15]. The CN is a key measure of diesel fuel combustion quality, and it is inversely related to the ignition delay time. Low CN fuels that are slow to ignite create longer ignition delay durations, thereby resulting in extended mixing time for the fuel and air [16-17].

The strong resistance to auto-ignition of the low CN fuels may cause difficulties in certain combustion conditions, such as cold start. A further challenge may be in the application of a post injection, deployed to reduce soot emission [18-19]. The in-cylinder available oxygen (O₂) is partially depleted by the main (and pilot) injection events. The slow ignition of low CN fuels tends to further deteriorate the post combustion as the late injection competes with a low reactive fuel.

Table 1. Cetane Number Requirements [14]

	Cetane Number
PN-EN 590-1999	Min 49
EURO III-IV (2002-2005)	Min 51
Japan JISK 2204 (2003)	Min 50
US ASTM D 975 (2003)	Min 40
WFC Category 4	Min 55

Most emission regulation authorities require a minimum, sufficiently high, CN of diesel fuels for engine performance evaluation (Table 1). The oil industry is capable of producing fuels with wide ranges of different properties that could benefit the application of diesel LTC and research continues to identify the ideal properties.

In this paper, the authors explore CN, volatility and aromatic effects of the FACE matrix on engine emissions across a wide load range.

Table 2. Single Cylinder Test Engine Specifications

Engine Type	Single Cylinder, 4 Stroke
Displacement [cm ³]	0.744
Bore x Stroke [mm]	95 x 105
Compression Ratio	16.2:1
Combustion System	Direct Injection
Maximum Cylinder	~200 bar
Injection System	Common-rail (~ 180 MPa)
Injector Holes	6
Injection Cone Angle	156 deg

EXPERIMENT SETUP

A single cylinder test engine (SCTE) based on the Navistar MAXFORCE 6.0L engine is integrated to the dynamometer cell at University of Windsor (UW). The specifications of the engine are listed in Table 2.

A simplified schematic of the testing platform setup is shown in Figure 2. A DC dynamometer is coupled to the SCTE to measure the engine power/torque output. Dry and clean compressed air is introduced to simulate the intake boost. An air mass flow meter is installed upstream of the intake surge tank, and the cooled EGR flow is directed to the downstream

of the tank. A pressure transducer is flush-mounted in the combustion chamber to instantly acquire the cylinder pressure, and the sampled pressure signals are converted to voltage through a Kistler 5010B charge amplifier. The encoder with 0.1 degree crank angle (CA) resolution is utilized to accurately obtain the piston position and to provide the sampling clock for the pressure recording. The pressure of each data point is an average of 200 continuously recorded cycles, subsequently calculating the heat release rate (HRR), the crank angle of 50% of the total fuel burned (CA50), and the accumulated heat release[20].

In order to precisely regulate the EGR ratio, the differential pressure between the engine exhaust and the intake is controlled. The EGR ratio is evaluated by Equation (1),

$$EGR \text{ Ratio} = \frac{[CO_2]_{int}}{[CO_2]_{exh}} \quad (1)$$

Analyzers are equipped to sample the intake and exhaust emission compositions. The soot is measured by an AVL 415S smoke meter. The intake and exhaust gaseous emissions, including NO_x, THC, CO, CO₂, and O₂, are measured using a dual-bank analyzer system (Table 3). Additional analyzers for sampling hydrogen (H₂) and light HC species are instrumented as well.

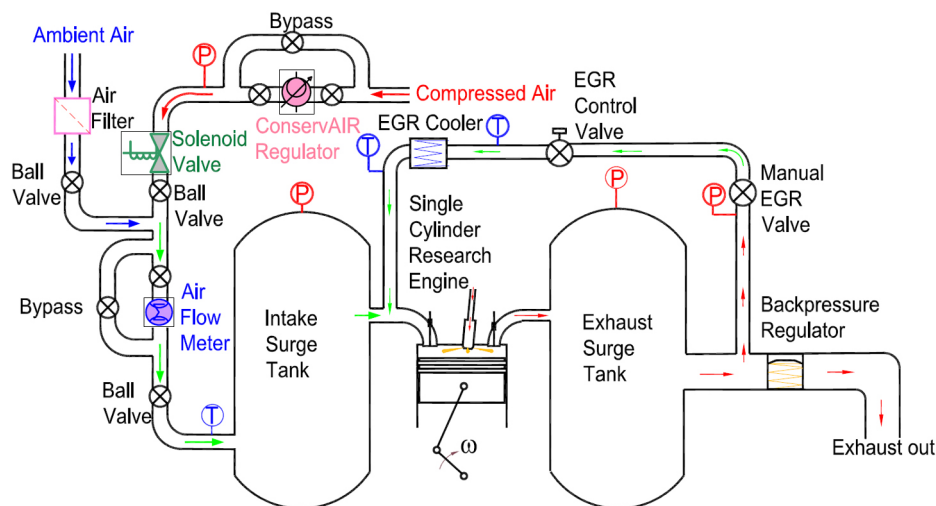


Figure 2. Schematic of Test Setup [20]

Table 3. Intake & Exhaust Emission Analyzers

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

FACE FUELS

FACE (Fuels for Advanced Combustion Engines) matrix resulted from the desire of a number of department of energy (DOE) project reviewers to have a consistent set of fuels that could be used in various advanced combustion (HCCI, PCCI, LTC, etc.) engines examining fuel effects. A consistent fuel set would allow comparison of the different engine and control scheme designs.

The FACE working group was set up at CRC (the Coordinating Research Council) with the support and participation of oil, auto, government and other interested participants to design a matrix of gasoline and a matrix of diesel fuels.

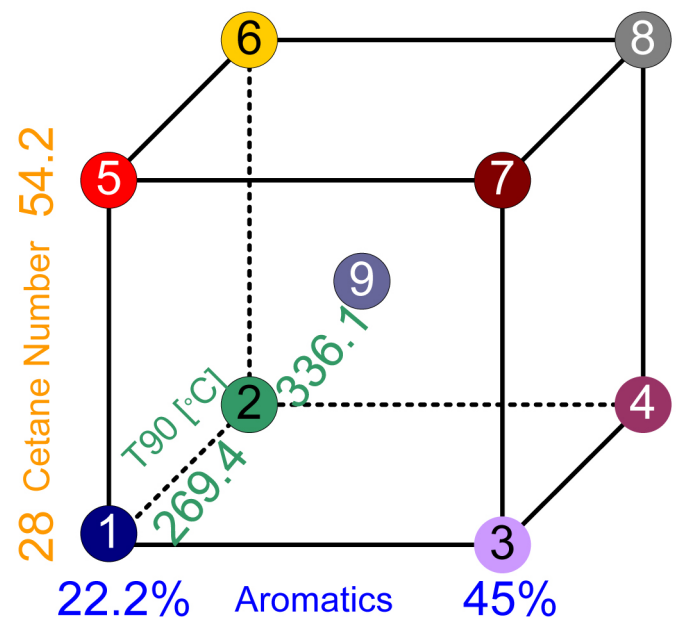
Of the many possible parameters, those chosen for the diesel design matrix were CN, aromatic content, and volatility as reflected by T90%, the temperature at which 90% of the fuel is recovered using the ASTM D86 standard test method for distillation of petroleum products at atmospheric pressure. These were thought to be possibly significant and a good starting point for investigation of fuel effects. It should be noted that CN and aromatic content are not completely independent of each other. Aromatic compounds are usually very low CN compounds, and high aromatic diesel fuels tend to be low CN.

A cubic design matrix was created by selecting a high and low value for each parameter, and a center point of the cube. The range for CN was selected to be 30 to 55 CN. The range for T90% was chosen as 270 and 340 °C. The range for aromatics was chosen to be 20 to 45% aromatics. These ranges stretch the typical ranges of US diesel fuel but

encompass fuels which could be used in advanced combustion strategies. The properties of the 9 matrix fuels are shown in [Table 4](#), and graphically presented in [Figure 3](#).

Table 4. Properties of Fuels in Research

Fuel #	Cetane Number	Distillation T90 [°C]	Aromatic Volume [%]
1	29.93	269.4	22.2
2	28	336.1	19.4
3	32.02	270.0	45
4	28.44	337.2	46.6
5	54.2	275.6	19.5
6	53.3	341.1	21.3
7	44.3	267.2	42.3
8	50	342.2	43.3
9	44.95	321.1	32.5

**Figure 3. Fuel Property Cube**

The fuels were blended by Chevron Phillips Chemical Company with close oversight by the FACE working group. The goal was to use refinery blend stocks to the extent possible. However to reach each corner of the cube some blend stocks were fractionated to a narrower cut and some single component fractions of diesel were used [21].

RESULTS AND DISCUSSION

Tests were performed with a single shot injection strategy, the timing of which was controlled to maintain a constant CA50 of 12.5° ATDC at all loads. Boost and injection pressures were adjusted as the load increased, to match the

production engine values [Table 5]. EGR was swept seeking to yield NOx levels from approximately 0.15 to 1g/kW-hr.

Table 5. Boost & Injection Pressure at Different Loads

IMEP [bar]	Boost [bar abs]	Injection Pressure [bar]	SOI [CA]
5.5	1.45	700	349.5~359.3
10.6	2.4	1300	355.4~359.5
14.6	2.8	1600	355.6~358.8

It should be noted that the study does not “optimize” the combustion system but is focused on studying the impact of fuel properties. For an efficiency evaluation of the multi-cylinder variant of the engine, the reader is referred to the work of de Ojeda et al [22].

FUEL PROPERTY EFFECT AT LOW LOAD

The EGR sweep is repeated for all 9 fuels at an engine load of 5.5 bar IMEP. The emissions are plotted versus intake O₂ concentration that represents the EGR dilution effect.

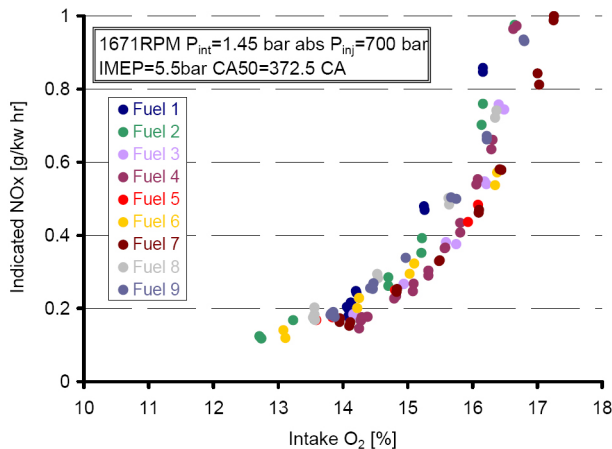


Figure 4. NOx Emissions of EGR Sweep at Low Load

The test results in Figure 4 show that NOx emissions are more dependent on the EGR ratio or the in-cylinder O₂ concentration rather than the fuel properties. The effect is more noticeable at higher levels of NOx emissions. As EGR is increased, the NOx emissions of all 9 fuels are reduced below 0.2g/kW-hr.

The soot emissions vary by several FSN points among the fuels, as shown in Figure 5. The soot trend correlates well with the CN. The highest soot emissions over the EGR sweep are observed for the high CN fuels, namely fuels 5, 6, and 8. On the other hand, the soot emissions of the low CN fuels are below 0.5 FSN.

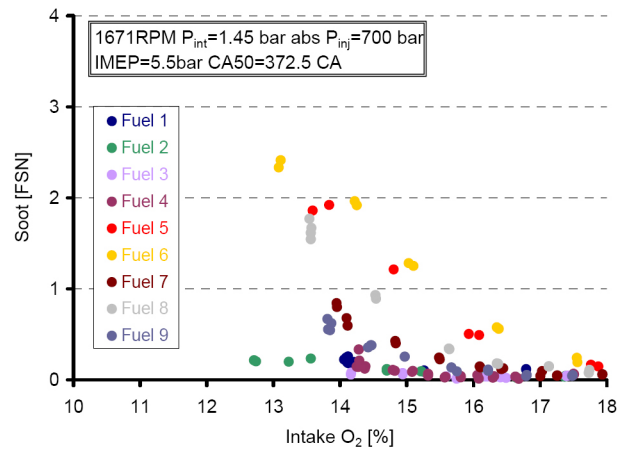


Figure 5. Soot Emissions of EGR Sweep at Low Load

Figure 6 illustrates a contour plot of the soot emissions versus CN and the intake O₂ concentration. Low CN offers better soot emissions in the tested conditions. The low CN prolongs the ignition delay, and during this ignition delay period, the fuel/air mixing is enhanced due to the longer mixing time. As a result, the rich regions where the soot is normally generated are reduced, and thus the soot emissions are lowered. Note that the curvature of the contour show that even at relatively low O₂ concentrations very low soot levels are achieved.

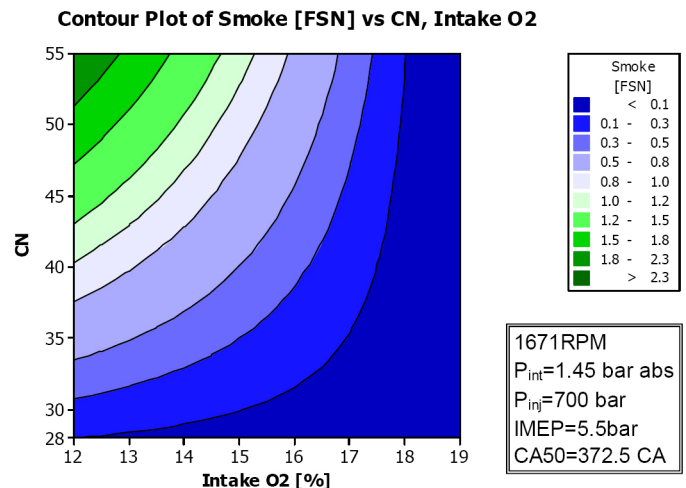


Figure 6. Soot Emissions vs. CN, Intake O₂ at Low Load

The soot & NOx trade-off is improved with the low CN fuels (fuel 1, 2, 3 and 4) as shown in Figure 7. This improvement of the low CN fuels is basically achieved by the reduced soot emissions at low O₂ levels because the CN has little direct impact on the NOx in the experiments (Figure 4).