

The Influence of Fuel Cetane Number on Catalyst Light-Off Operation in a Modern Diesel Engine

Eric Kurtz and Christopher J. Polonowski
Ford Motor Company

ABSTRACT

The design of modern diesel-powered vehicles involves optimization and balancing of trade-offs for fuel efficiency, emissions, and noise. To meet increasingly stringent emission regulations, diesel powertrains employ aftertreatment devices to control nitrogen oxides, hydrocarbons, carbon monoxide, and particulate matter emissions and use active exhaust warm-up strategies to ensure those devices are active as quickly as possible. A typical strategy for exhaust warm-up is to operate with retarded combustion phasing, limited by combustion stability and HC emissions. The amount of exhaust enthalpy available for catalyst light-off is limited by the extent to which combustion phasing can be retarded.

Diesel cetane number (CN), a measure of fuel ignition quality, has an influence on combustion stability at retarded combustion phasing. Diesel fuel in the United States tends to have a lower CN (both minimum required and average in market) than other countries. It is unclear from existing literature to what extent low CN influences the ability to retard combustion phasing while limiting engine-out hydrocarbon emissions during the catalyst light-off phase.

To begin to address this question, a single-cylinder engine study was conducted to compare the ability to generate exhaust temperature and enthalpy with low emissions with fuels of 46 and 53 CN. The fuels were found to produce comparable exhaust temperature, enthalpy and emissions when the engine was operated at the same calibration. However, when the calibrations were optimized separately for each fuel to maximize exhaust temperature and enthalpy while controlling emissions at or below a target level, the higher CN fuel tolerated significantly greater post injection retard within the hydrocarbon and particulate matter emissions constraints, thus enabling increased exhaust enthalpy and temperature.

This study suggests that while a change in market CN would have only a slight impact on catalyst light-off and tailpipe emissions in legacy vehicles, future vehicles may be limited by low cetane fuel in their ability to achieve ultra-low emissions such as those required for California LEV III and Federal Tier 3. The study also highlights the importance of the assessment methodology when making conclusions about the effect of fuels on legacy and future vehicles.

CITATION: Kurtz, E. and Polonowski, C., "The Influence of Fuel Cetane Number on Catalyst Light-Off Operation in a Modern Diesel Engine," *SAE Int. J. Fuels Lubr.* 10(3):2017, doi:10.4271/2017-01-9378.

INTRODUCTION

Increasingly stringent emission regulations for on-road diesel-powered vehicles have required the incorporation of sophisticated exhaust after-treatment systems in order to mitigate tail-pipe emissions, including nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM). Modern diesel after-treatment systems are typically comprised of three technologies: a Diesel Oxidation Catalyst (DOC) to mitigate HC and CO, a NO_x conversion catalyst such as Selective Catalytic Reduction (SCR) to mitigate NO and NO_2 emissions, and a Diesel Particulate Filter (DPF) to capture PM in the exhaust [1].

The DOC and SCR transition from a state in which they have no conversion efficiency at low temperature to high conversion efficiency at higher temperature. A DOC starts to achieve greater than 90% conversion efficiency of HC and CO at $\sim 220^\circ\text{C}$ [2]. Similarly, a urea-SCR catalyst will begin to achieve over 90% NO_x conversion efficiency at 200°C [3]. Typically, when the after-treatment temperature is below a threshold necessary to provide required function, the engine calibration is altered to quickly increase after-treatment temperature. In this mode, the engine is operated to increase exhaust temperature and enthalpy while limiting gaseous engine-out emissions, since these emissions are largely untreated and are ultimately emitted from the vehicle tailpipe. For emissions certification, this mode of operation can be necessary during the FTP city cycle both at the beginning of bag 1 (following a cold start) and

everything starts at ambient temperature) and the beginning of bag 3 (following a hot restart after the aftertreatment has cooled down during the 10 minute soak).

The most typical method for altering the calibration to generate exhaust temperature and enthalpy for catalyst light-off is to retard combustion phasing by employing post injections to retard the introduction of a portion of fuel to later in the expansion stroke. Although fuel injection strategies that employ post injection(s) can enable much higher exhaust temperature than simpler injection strategies, HC and CO emissions inevitably increase with retarded combustion phasing due to the combustion of fuel later in the expansion stroke when in-cylinder pressure and temperature are rapidly decreasing and slowing reaction rates, inhibiting the ignition and complete combustion of the post injection(s). As emissions standards become more stringent, it becomes increasingly challenging to both maintain in-cylinder emissions control prior to catalyst light-off and generate sufficient exhaust temperature and enthalpy to quickly achieve catalyst light-off. Thus, it is important to identify all possible avenues to ensure ignition and stable combustion of highly retarded post injection(s) needed for rapid catalyst light-off.

Cetane number (CN) is a measure of a fuel's ignition quality, with higher CN indicating auto ignition at a lower compression ratio (therefore at lower pressure and temperature) in a standard test engine [4]. Fuels with higher CN have shorter ignition delays, require shorter cranking times, and are able to start at colder ambient conditions than lower CN fuels [4, 5]. Higher CN fuels have also been shown to produce lower engine-out emissions. Many studies have shown that HC and CO emissions, which are a result of incomplete or unstable combustion, decrease as CN increases [5, 6, 7, 8, 9]. A number of studies have also shown that higher CN fuels tend to produce lower engine-out NO_x emissions [10, 11].

The ASTM specification for diesel fuel, D975-15a, specifies 40CN as a lower limit. This specification is referenced in diesel fuel quality regulations in the United States (US), Canada, and Mexico. US regulations (40 CFR §80.29) specify that fuel Cetane index (a surrogate for CN based on fuel properties and composition) should be greater than 40 or that aromatics should be less than 35% by volume [12]. As a result, the fuels in North America tend to have lower CN than fuels sold in other regions. Figure 1, which compares the CN of diesel fuels sold in other regions of the world, shows that both the minimum and average CN is lowest in the US (excluding Texas and California where higher CN is mandated), Canada and Mexico [13, 14]. While US fuels have a minimum and average CN of 40CN and 45CN, respectively, these values in Europe are 48CN and 54CN, respectively.

The goal of this study was to evaluate the influence of fuel CN on the ability to generate engine exhaust temperature and enthalpy while controlling engine-out NO_x, HC and CO emissions. Testing on a single cylinder diesel engine was conducted on an engine dynamometer running at various catalyst light-off relevant operating

conditions using both a US certification diesel with a CN of 46 and a low aromatic, an EU stage IV reference diesel fuel per CEC RF-06-03 with a CN of 53 to compare effects on emissions, noise, exhaust temperature and exhaust enthalpy.

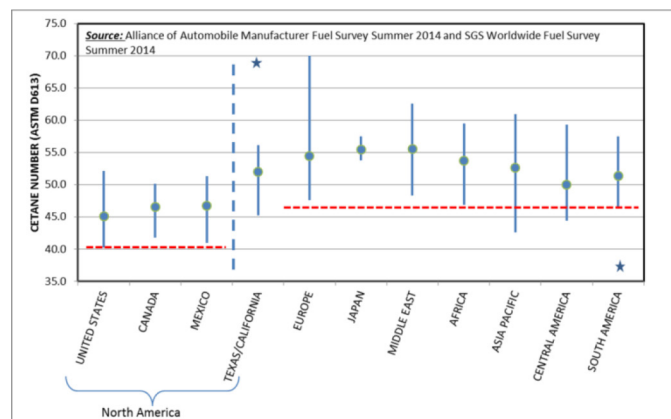


Figure 1. CN of diesel fuels sold in various regions of the world [15, 16].

EXPERIMENTAL SETUP

The engine used for this study was a 0.83L single cylinder diesel engine based on the 6.7L V8 PowerStroke® engine, which is designed to power full-size pickup trucks. Details of the engine geometry can be found in Table 1. The 6.7L V8 production engine includes inboard exhaust, 2000bar piezo common rail fuel injection, a variable geometry turbocharger, high-pressure EGR with low temperature cooling and water-to-air charge air cooling. Further detail about the production 6.7L V8 engine and its combustion system can be found in DeRadd et al. [17] and Styron et al. [18] respectively.

Table 1. Engine specifications.

Bore	99 mm
Stroke	108 mm
Connecting Rod Length	176 mm
Number of Valves	4
Compression ratio	16.2
Bowl design	Chamfered [18]

The engine dynamometer test cell setup, which is discussed in detail in Kurtz and Styron [19] and Kurtz et al. [20], provided externally conditioned coolant, oil, and air to the engine. Coolant and oil temperatures were controlled to either 20°C or 90°C in this study. The intake air system supplied air at the desired pressure and temperature for a given operating condition to mimic multi-cylinder boosted intake manifold conditions and the exhaust system pressure was controlled to simulate multi-cylinder engine exhaust manifold pressure. An EGR system that is controlled through the test cell was used to control the flow of exhaust gas from an exhaust surge tank to an intake surge tank, where it mixed with intake air prior to entering the intake runner.

Smoke was measured using an AVL 415S smoke meter located downstream of the exhaust pressure control valves. Exhaust NO_x , CO , HC , CO_2 and O_2 concentrations were measured with two emissions analyzers sampling from the exhaust surge tank and the exhaust line downstream of the exhaust pressure control valves. The exhaust surge tank measurement was used for analysis to minimize errors associated with water and hydrocarbon condensation, which could occur in the exhaust pipe. EGR was assessed using Equation 1, which combines intake and exhaust CO_2 wet mass concentrations ($\text{CO}_{2,\text{int}}$ and $\text{CO}_{2,\text{exh}}$, respectively) based on measurements in the intake and exhaust surge tanks and atmospheric CO_2 ($\text{CO}_{2,\text{bg}}$) mass concentration.

$$\text{EGR} = \frac{\text{CO}_{2,\text{int}} - \text{CO}_{2,\text{bg}}}{\text{CO}_{2,\text{exh}} - \text{CO}_{2,\text{bg}}} \cdot 100 \quad (1)$$

Air flow was measured both with a critical flow orifice and a Micromotion CMF050 flow meter. Fuel flow rate was measured using a Pierburg low flow fuel cart, but was also assessed using the critical flow orifice air flow measurement and the air fuel ratio determined by the emissions bench using the Spindt Method [21].

Sufficient exhaust gas enthalpy is crucial to minimizing the catalyst light-off time and managing the exhaust system thermal state to ensure sufficient catalyst conversion efficiencies. For this work, Equation 2, which is derived from the equation for the enthalpy of an ideal gas [22], is used to calculate the exhaust enthalpy. In Equation 2, $\dot{m}_{\text{Exh}}$ represents the exhaust mass flow through the after-treatment system, h_{Exh} is the specific exhaust enthalpy, which is a function of the exhaust gas temperature (T_{Exh}), the exhaust mass air to fuel ratio (A/F), and the fuels molar carbon to hydrogen ratio (C/H). This equation can be used for any diesel engine configuration as long as the measured inputs reflect the thermodynamic properties of the exhaust gases that are entering the after-treatment system. For diesel engines that employ high pressure EGR, exhaust enthalpy is also dependent on the EGR rate as it will affect the mass flow rate and composition of the exhaust going through the after-treatment components.

$$\dot{Q}_{\text{Exh}} = \dot{m}_{\text{Exh}} \cdot h_{\text{Exh}} \quad (2)$$

Cylinder pressure was measured and recorded at a 0.05 CAD resolution. Analysis of the measured cylinder pressure trace was used both for a first law analysis to determine the crank angle-resolved rate of heat release and for combustion noise analysis [23]. The cylinder pressure measurement was also used to control the load of the engine based on the net mean effective pressure (NMEP) assuming values for multi-cylinder friction (FMEP) as a function of the operating condition and a correlation developed from multi-cylinder engine data [19].

Fuels

Two fuels were tested in this study: a US certification diesel and an EU stage IV reference diesel fuel per CEC RF-06-03, which will be referred to in this paper as the high CN fuel. Key properties for these two fuels are presented in Table 2. The difference in CN between the

certification fuel and the high CN fuel is roughly equivalent to the difference in average CN in the United States and Europe as shown in Figure 1.

Table 2. Fuel specifications.

	US Certification Fuel	High CN Fuel
Cetane Number	46	53
LHV [MJ/kg]	42.9	42.9
Density [kg/m³]	842	837
H/C ratio	1.82	1.97
Aromatics [wt%]	29.2	8.2
Kin. Viscosity [cSt]	2.9	2.3
T10 [°C]	208	198
T50 [°C]	253	279
T90 [°C]	307	334

TEST CONDITIONS

The study was conducted at two operating conditions that are experienced over a significant amount of time during the first portion of bags 1 and 3 of the FTP-75 city cycle, before catalyst light-off has occurred. Both operating conditions were evaluated using 20°C and 90°C oil and coolant temperatures to simulate operation in both bag 1 (20°C) and bag 3 (90°C) of the FTP, making a total of four engine test condition. Each test condition has a unique set of boundary conditions and production calibration settings, which were based on production multi-cylinder engine test data.

For each operating condition, a 60-point space filling design of experiment (SFDOE) was run to map the effect of eight calibration parameters that were found to be critical for achieving higher exhaust temperature and enthalpy. Table 3 provides a list of all the relevant engine calibration parameters. Two of the parameters, designated by “baseline setting” on the right-hand side of the table, were held constant at the baseline value throughout the SFDOEs. Ranges in which each of the other parameters was varied relative to the baseline setting during the SFDOEs are provided on the right-hand side of Table 3. Main injection quantity was adjusted for each point to meet the target load. Since the main goal of this combustion mode was to increase exhaust temperature and enthalpy by retarding combustion phasing while controlling emissions, the calibrations employed a five-pulse injection strategy that included two pilot injections, a main injection and two burning post injections. This strategy, a typical strategy used for catalyst light-off operation [24], was the same as that used on the multi-cylinder production engine from which the baseline settings were established. Each 60-point SFDOE included a test point taken with the production calibration settings. While each parameter was varied as shown in Table 3, additional constraints were used to maintain the proper sequence of injections and to respect minimum separation between injections.