

The Impact of Biodiesel on Injection Timing and Pulsewidth in a Common-Rail Medium-Duty Diesel Engine

Joshua A. Bittle, Bryan M. Knight and Timothy J. Jacobs
Texas A&M University

Copyright © 2009 SAE International

ABSTRACT

Due to its ease of use in diesel engines, its presumably lower carbon footprint, and its potential as a renewable fuel, biodiesel has attracted considerable attention in technological development and research literature. Much literature is devoted to evaluating the injection and combustion characteristics of biodiesel fuel using unit injectors, where injection pressure and timing are regulated within the same unit. The use of common rail fuel systems, where fuel pressure is now equally governed to each injector (of a multi-cylinder engine), may change the conventionally accepted impact of biodiesel on injection and combustion characteristics. The objectives of this study are to characterize the responses of an electronically-controlled common-rail fuel injector (in terms of timing and duration) when delivering either 100% palm olein biodiesel or 100% petroleum diesel for a diesel engine, and correlate potential changes in injector characteristics to changes in combustion.

The experimental study relies on the analysis of injector command and needle lift measurements to identify major differences (or indifferences) of injection characteristics of biodiesel fuel (relative to petroleum diesel fuel). Further, in-cylinder pressure measurements provide the basis for apparent heat release rate analysis in identifying critical combustion characteristics (i.e., ignition delay and combustion duration). Differing from the typically-observed artificial advance in injection timing with biodiesel, this study finds that there are no observable differences in the injection timing or needle lift behavior with biodiesel (relative to petroleum diesel) in a common rail diesel engine.

INTRODUCTION

The use of biodiesel, as a fuel supplement in diesel engines, is likely to increase as greater concern and potential regulation of carbon emissions increase. Coupling biodiesel fuel with a diesel engine is reported to have substantial decreases in transportation-based net CO₂ emissions [1]. Further, the similarities in properties between biodiesel and petroleum diesel almost make biodiesel a transparent addition to the supply of petroleum diesel fuel.

Some properties, however, differ enough to create some challenges for using biodiesel in a diesel engine. As an example, the relatively lower heating value of biodiesel typically impacts the peak power, fuel consumption, and efficiency of the engine [2 - 11]. As another example, differences in certain fluid properties (e.g., bulk modulus) may affect the injection characteristics of biodiesel, which could manifest differences in performance, efficiency, and certain emissions such as oxides of nitrogen (NO_x) [12 - 16].

Related to the later example (i.e., fluid properties affecting injection characteristics), several literature cite the artificial advancement of injection timing as the cause of the often-observed increase in NO_x emissions. Specifically, Szybist, et al. [12] largely attributed a 6 – 9% increase in NO_x emissions to shifts in fuel injection timing manifested by bulk modulus differences between soy-based biodiesel and conventional diesel fuels. Shifts in the fuel start of injection and start of combustion can be substantial. For example, Canakci [14] reports about 2.2° advance in injection timing with 100% biodiesel

(B100), relative to petroleum diesel. When combined with its inherently shorter ignition delay, biodiesel is observed to have a 3° advance in start of combustion relative to petroleum diesel. It should be noted, however, that Cheng, et al. [13] further clarified the potential effect (or non-effect) of artificially advanced injection timing on observed increases in NO_x emissions. Their study tailored the experiments to match premixed-burn fractions between biodiesel and petroleum-based reference fuels. Their results reveal biodiesel NO_x increases (about 10%) in spite of matching premixed burned fractions. This suggests that additional factors other than start of combustion and premixed burn fraction affect the differences in NO_x emissions between the fuels.

Regardless of the potential impact of artificial advance of start of injection (or combustion) on NO_x emissions, another property plays a role to complicate the analysis. Specifically, the relatively lower heating value of biodiesel requires a longer injection pulsewidth (injection duration) to match brake torque produced with petroleum diesel. The lengthening pulsewidth, which corresponds to a higher perceived load (or torque), likely affects other control parameters [16]. For example, Tat, et al. [15] associated roughly half of the advanced start of injection with biodiesel (relative to petroleum diesel) to the controlled advance in injection timing with an increase in pulsewidth (load), and the other half to the artificial advance due to a higher bulk modulus of the fuel. These two injection timing effects combine to contribute to roughly half of the advanced start of the combustion; the other half is attributed to biodiesel's higher cetane number.

Tat, et al.'s [15] study, along with other cited studies [12 and 14], illustrate data from engines using mechanical unit injector pumps. The potential impact of biodiesel on injection characteristics, and thus combustion characteristics, could change substantially with the use of common rail fuel systems. For example, the effect of biodiesel's higher bulk modulus may impact injection timing to a lesser extent, since the common rail pump controls rail pressure for each individual injector (rather than unit injectors pressurizing the fuel).

Furthermore, the proliferating use of electronic controlled engines may impose differing injection timing trends with pulsewidth than those reported in literature. For example, Tat, et al.'s [15] study reveals an advancing injection timing with increasing pulsewidth (load); typically, for noise control, injection timing is retarded with increasing pulsewidth [17]. Electronic control of engine parameters creates additional flexibility, and complexity, in the trends of injection timing as speed, load, and other factors change.

The objectives of this study are to characterize the responses of an electronically-controlled common-rail fuel injector (in terms of timing and duration) when delivering either B100 or petroleum diesel for a diesel engine, and

correlate potential changes in injector characteristics to changes in combustion. This study is believed to be important since it may identify the influence of injection system responses on diesel combustion with the use of biodiesel. Following this introduction, the article describes the experimental methodology used in meeting the study's objectives. The results and discussion highlight crank-angle resolved injector command and needle lift signals, while heat release analysis provides details about in-cylinder combustion. The article finishes with summary and conclusions.

EXPERIMENTAL METHODOLOGY

TEST APPARATUS (ENGINE SYSTEM)

The study herein described analyzes data collected from a production four-cylinder medium-duty diesel engine. The relevant engine specifications are summarized in Table 1. Certain significant features of this engine include its use of a variable geometry turbocharger and exhaust gas recirculation (EGR) system. The test engine is coupled to a DC motoring dynamometer (dyno). The dyno loads the engine via adjustment of the field current until the desired engine torque is reached. The capabilities and repeatability of the engine test apparatus are summarized in [18]. Further, this same test apparatus is used in the studies described in [9, 11].

The test apparatus uses a fan-based cooling system, closely mimicking that which would appear in practical use. Thus, under normal operating conditions, the engine may operate at several different coolant temperatures. This clearly has important implications on several engine parameters, including combustion characteristics. Most notable for this study is the actuation of EGR. Less than 78°C coolant temperature, EGR remains nearly off so as to improve combustion and torque stability. The test points at which this occurs are described in the Test Methodology section.

Table 1: Specifications of medium-duty engine apparatus under investigation in this study.

Bore	106 mm
Stroke	127 mm
Displacement	4.5 L
Rated Power	115 kW at 2400 rev/min
Compression Ratio	16.57 ¹ (nominally 17:1)
Ignition	Compression
Fuel System	Electronic common rail, direct injection
Air System	Variable geometry turbocharger with EGR.

¹Measured by oil displacement.

FUEL PROPERTIES

This study focuses on the evaluation of a bio-based diesel fuel compared to a petroleum-based diesel fuel. The biodiesel used in this study is extracted from palm-olein and is furnished by Green Earth Fuels, LLC (Houston, Texas). The petroleum diesel used in this study is 2007 ultra-low sulfur (ULS) certification diesel fuel and is furnished by Chevron-Phillips Chemical Company (The Woodlands, Texas). These fuels are chosen to promote consistency among batches. Complete property data for both fuels are available. A summary of the properties of the two fuels is given in Table 2. All testing is performed with 100% concentrations of either fuel (i.e., no blending of fuels). Throughout the text, the petroleum-based certification fuel is referred to as "Reference" while the bio-diesel is referred to as "Biodiesel."

Table 2: Summary of the properties of the two fuels under investigation in this study.

Property [Standard]	ULS 2007 Certification Diesel ¹	Palm Olein Biodiesel ²
Density (kg/m ³) [ASTM D4052s]	845	875.7
Net heat val. (MJ/kg) [ASTM D240N]	42.89	37.137
Gross heat val. (MJ/kg) [ASTM D240N]	45.11	39.77
Sulfur (ppm) [ASTM D5453]	8.2	2.1
Viscosity (cSt) [ASTM D445 40C]	2.1	4.525
Cetane # [ASTM D613]	44	63.5
Hydrogen (%-m) [SAE J1819]	13.10	12.44
Carbon (%-m) [SAE J1819]	86.90	76.63
Oxygen (%-m) [SAE J1819]	0	10.93

¹Provided by Chevron-Phillips Chemical Company (The Woodlands, Texas)

²Measured or calculated by Southwest Research Institute (San Antonio, Texas).

TEST METHODOLOGY

Several engine speeds and loads are under investigation in this study. Three speeds (1400, 1900, and 2400 rev/min) and three loads (50, 150, and 300 ft-lbs, which are 67.8, 203.4, and 406.7 N-m, respectively) are combined to yield a total test matrix of nine operating conditions. Throughout this article, the 67.8, 203.4, and 406.7 N-m load conditions are referred to as low, mid, and high

load conditions, respectively. In the comparison between biodiesel and petroleum diesel fuels, the engine torques, as shown in Figure 1, are matched. Because of differences between the fuels' heating values and densities, the engine controller requires a longer injector pulsewidth with biodiesel to attain the same torque as petroleum diesel. Analysis of this effect, including its influences on injection and combustion characteristics, is part of the objectives for this study.

Within a sequence of tests, the engine was first brought to 1400 rev/min, 406.7 N-m torque after the initial warm up. A period of time was allowed to let the engine stabilize with respect to temperatures and operating control parameters. As discussed above, EGR is actuated when coolant temperature rises above 78°C; in particular, this occurs only for the high load conditions. Once the period of time elapsed such that the engine was stabilized, a time-based log of data was sampled. Each nine point test matrix is conducted twice for each fuel over separate days, with care taken to ensure the control parameters are the same between repeats. The data reported herein are the average values of the repeated samples taken over two days of testing for the two fuels.

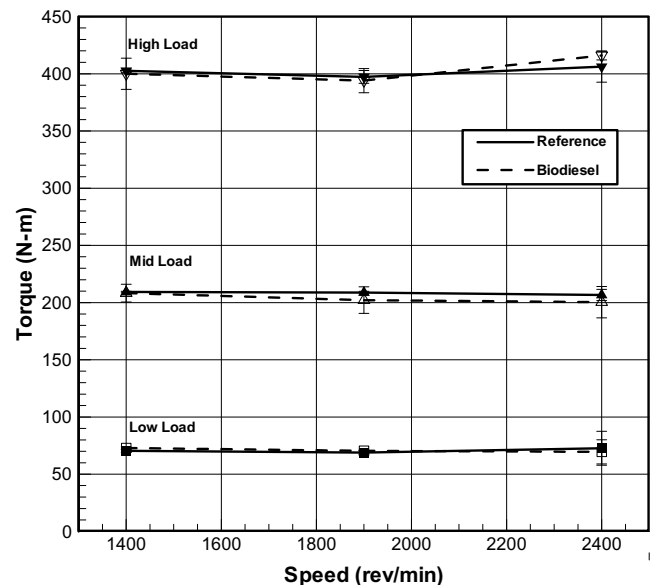


Figure 1: Torque as a function of engine speed illustrating the nine operating points under study.

MEASUREMENT TECHNIQUE

Measurements and calculations are used to generate the data that support the analysis of this study. The summary of the measured and calculated parameters is given in Table 3.

Table 3: Summary of parameters under analysis in this study.

Parameter	How Determined	Measurement
Injector Command Signal	Measured	Injector current (current probe)
Injector Needle Lift Signal	Measured	Needle motion (hall effect sensor)
Start of command	Calculated	Injector command signal
Start of injection	Calculated	Injector needle lift signal
Command pulsewidth	Calculated	Injector command signal
Injection pulsewidth	Calculated	Injector needle lift signal
Net rate of heat release	Calculated [19 - 22]	In-cylinder pressure and volume, F/A , $\dot{m}_f$, EGR level
Mass fraction burned	Calculated	Same as net rate of heat release
Engine ignition delay	Calculated	Injector needle lift signal and 10% burn location
Ignition delay	Calculated	Injector needle lift signal and minimum heat release location
Combustion duration	Calculated	10% and 90% burn locations

The injector command signal is measured using a current probe on the injector command wires to cylinder #1 injector. Injector #1 is used since it is also instrumented for needle lift, and cylinder pressure is measured in Cylinder #1. Injector needle lift signal is measured using a hall effect sensor, mounted within the body of Injector #1. Start of injector command, which is the crankangle location when the electronic control module energizes the injector, is determined from the injector command signal. It corresponds to the crankangle location of the rising edge of the injector current. Start of injection, which is the crankangle location when fuel injection is believed to occur, is determined from the injector needle lift signal. It corresponds to the crankangle location of the rising edge of the injector needle lift. Figure 2, which shows example traces of injector command and needle lift signals as functions of engine crankangle (in degrees after top dead center, or ATDC), summarizes this for both start of command and start of injection.

The command pulsewidth, which is the crankangle difference between end of command and start of command, is the crankangle rotation that the command signal is applied to the injector. Likewise, the injection pulsewidth, which is the crankangle difference between end of injection and start of injection, is the crankangle

rotation that the injector needle is unseated, and fuel is presumably being injected. End of command and end of injection are determined in a similar manner to how start of command and start of injection, respectively, are determined.

Combustion characteristics are determined from net rate of heat release, which is calculated using methods prescribed by [19 - 22]. Measured in-cylinder pressure, acquired with a 0.2° crankangle resolution, is used in the calculation of net heat release. As indicated above, pressure is measured in Cylinder #1. A standard piezoelectric transducer is used for pressure measurement, and its veracity has been determined for both motoring and firing conditions, as prescribed by [23]. Also used in net heat release calculation is the determination of mixture fuel-air ratio (to determine mass of air), mass of fuel, and EGR level (as a percentage of total mass). Fuel-air ratio (F/A) is calculated using measurements of exhaust concentrations of CO_2 , O_2 , and CO and the calculation presented by [24]. Equilibrium between CO , CO_2 , H_2O , and H_2 , and the equilibrium constant, are assumed in Heywood's [24] determination of equivalence ratio from exhaust species. This study uses an equilibrium constant (for the water-gas shift mechanism) of 3.8, as suggested by Stivender [25]. CO_2 , O_2 , and CO are measured with individual analyzers (non-dispersive infrared for CO_2 and CO and paramagnetic for O_2) in a full-scale raw engine exhaust emissions bench. Each analyzer is calibrated at the start of each test and checked routinely throughout the day's testing.

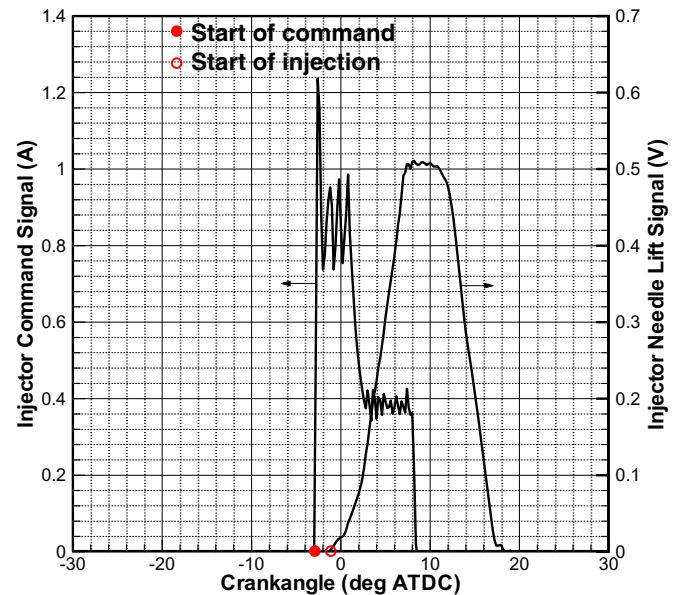


Figure 2: Injector command and needle lift signals as functions of engine crankangle at 1400 rev/min, high load condition using reference fuel. Also indicated are crankangle locations determined as start of command and start of injection.

Mass of fuel is calculated (using the appropriate fuel density) from the measured volumetric flow rate using a positive-displacement meter. Mass of air, thus, is calculated from the F/A calculation and the mass of fuel calculation. EGR level is calculated from the measurements of exhaust and intake CO₂ concentrations, and correlating to EGR mass.

Mass fraction burned is calculated from the integrated heat release (net heat release), the mass of fuel, and the fuel's heating value. Reported mass fraction burned is normalized to 100%, based on the maximum observed mass fraction burned, so that a systematic basis for end of combustion is introduced (i.e., 90% mass fraction burned is considered end of combustion). Actual maximum mass fraction burned values range from around 80% up to 92%, depending on the load condition (identifying deficiencies in heat transfer calculation and residual gas fraction determination). The engine ignition delay, calculated as the crankangle difference between 10% burn location and start of injection, is determined from both the needle lift sensor (for start of injection) and the normalized mass fraction burned (for 10% burn location). An additional way to interpret ignition delay is also presented in this article. Referred to as ignition delay, this parameter is calculated as the crankangle difference between minimum heat release (after injection) and start of injection. Combustion duration, calculated as the crankangle difference between 90% burn location and 10% burn location, is determined from normalized mass fraction burned.

DETERMINATION OF UNCERTAINTY

Uncertainties in measurements are determined by considering the precision and accuracy of each respective instrument, as well as the repeatability of the engine test sequence. Each test sequence is repeated several times over several days to capture an understanding of random uncertainty (i.e., fluctuations in daily ambient conditions and the capability to repeat the same engine operating condition). Using methods prescribed by [26], reported uncertainty combines the instrument's precision and accuracy with the test data's standard deviation. Two standard deviations are used to give roughly 95% confidence in the reported range.

A limitation of the reported indicated parameters (i.e., injection characteristics and combustion characteristics) is their respective measurements from one cylinder. Although injection characteristics and combustion characteristics could potentially vary from cylinder to cylinder, it is assumed for the purposes of this study that the measured cylinder is representative of the whole engine.

The data values in the figures showing the nine operating conditions are connected with series lines, to provide ease in distinguishing data series between the fuels. The

lines connecting data points in these figures are not meant to represent potential values or trends between data points.

RESULTS AND DISCUSSION

The following section provides the results and corresponding discussion in analyzing the stated objectives of the study. The discussion is divided into two major components: injection characteristics and combustion characteristics.

INJECTION CHARACTERISTICS

The use of an alternative fuel, such as biodiesel, in place of petroleum diesel in a diesel engine could affect injection characteristics in several ways. As described earlier, two commonly observed alterations to injection include a change to the commanded timing of injection and a change to the actual timing of injection (the latter alteration being irrespective of a potential change to the command timing). The injector command signals for the 1400 rev / min speed conditions under study in this investigation are shown in Figure 3. The injector command signal identifies the energizing current delivered by the electronic control module to the fuel injector. Three load conditions are shown at 1400 rev / min: low load, mid load, and high load in Figure 3 (a), (b), and (c), respectively. The other engine speeds (i.e., 1900 rev / min and 2400 rev / min) are not shown for clarity. Notice from Figure 3 (a) that the low load condition utilizes multiple injections (i.e., a pilot and a main injection).

There are two important differences to identify between biodiesel and petroleum diesel. First, the command pulsewidths for biodiesel are longer than those for petroleum diesel. This lengthening command results from the constant torque constraint applied during the test sequence; biodiesel has a lower heating value, thus requiring more fuel delivery for the same torque as petroleum diesel. Second, the timings of the command signals remain essentially unchanged; this observation will be further discussed with Figure 5.

In addition to potential changes in the commanded injection timings, the use of biodiesel may also affect the actual injection timings. In other words, even if commanded start of injections were aligned between fuels, certain fuel fluid properties may manifest changes to the injector needle response, causing differences in actual start of injection. Figure 4 illustrates the actual injector needle motion following the command signal from the engine's electronic control module. The same conditions shown in Figure 3 are shown in Figure 4.