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Study of combustion performance of biodiesel for potential application in motorsport

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ABSTRACT

The variability in viscosity and combustion quality has been identified from the literature as a barrier to the use of biodiesel fuels in motorsport. These parameters can affect performance, emissions and fuel consumption. Diesel engines have had recent success in endurance and touring car racing; biodiesel is an opportunity to increase the sustainability of this emerging area of motorsport.

Methyl esters from rapeseed, soybean and sunflower oils were tested alongside EN 590 diesel fuel. Variations in fuel consumption, output torque and power were observed between the fuels. Further tests were carried out on an automotive diesel engine to evaluate the in–cylinder pressures for soybean B100, beef tallow B50 and EN 590 to gain understanding of the reasons behind the performance differences noted in the initial tests.

Retarding the start of injection for B50 and B100 biodiesel improved the peak torque by up to 5% enabling the production of equal torque at the same engine speed when compared to EN 590 but with lower peak in–cylinder pressure and a shorter ignition delay. The application of this to motorsport is the potential to achieve higher peak power outputs; the shorter ignition delay and more rapid combustion has the potential to be used to raise the maximum engine speed and therefore the peak power output of diesel engines for motorsport.

1. Introduction

Sales of diesel cars have increased year on year since 2000, and as of 2012 had a majority market share of 50.6% in the UK (SMMT, 2012). This move away from gasoline power which had traditionally been more popular for passenger vehicles in the UK, is an indicator that environmental concerns, whether they are voluntary or enforced by government, are having an effect on the motor industry. Government taxation of cars which emit high levels of CO_2 and the rising price of fuel are examples of the economic factors which have driven this change in buyer behaviour. For example, the level of Vehicle Excise Duty in the UK is determined by the emissions of the vehicle; the higher the emissions, the higher the duty.

The push for sustainability has resulted in several alternatives to petrochemical fuels being suggested to provide the motive power for road vehicles (Dovì et al., 2009). Hybrid and fully electric powertrains, hydrogen fuel cells and naturally derived alternatives to gasoline and diesel (known collectively as biofuels) have all been demonstrated in passenger vehicles (Zapata and Nieuwenhuis, 2010). Of these alternatives, biodiesel was identified as having the greatest potential as a sustainable fuel for motorsport (Zapata and Nieuwenhuis, 2010).

Biodiesel is usually manufactured by base-catalysed transesterification involving the catalytic reaction of triglycerides with alcohol, although many alternative methodologies have also been published (Basha et al., 2009). Base-catalysed transesterifications are widely used for making biodiesel from a variety of crops as it utilises low cost starting materials, low energy input and usually in excess of 90% yield. The catalyst is usually a base metal; most commonly used is NaOH (Knothe et al., 2005) but other methods have been studied within the literature (Hayyan et al., 2014; Leung et al., 2010; Singh and Patel, 2014) but due to their complexity and cost the simple and low-cost base hydroxide route is the preferred option. Methanol is the most commonly used alcohol due to its low cost and widespread availability, which results in fatty acid methyl esters (FAME) being produced, but transesterification with other

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alcohols such as propanol, butan-1-ol and ethanol has been studied.(Hussan et al., 2013; Knothe, 2005).

The motorsport industry had been less open to adoption of these alternative fuels and powertrains, instead developing the internal combustion engines which have been used for more than a century to unprecedented levels of efficiency, which in the motorsport environment is translated into greater power output. However, the use of compression ignition engines powered by diesel fuel for competitive motorsport has become a familiar concept since 2006 when Audi announced it would enter the *24 Heures Du Mans* endurance race with a diesel car. The Audi R10s were powered by V12 turbodiesel engines and finished one of the world's most famous motor races in 1st and 3rd place. Diesel-powered cars have won the race every year since 2006 with diesel-electric hybrids being the most recent winners in 2012 and 2013. Such is the success of the diesel powered cars at Le Mans that it has been suggested that the regulations are biased in their favour (Bamsey, 2008). This is due to the power and fuel efficiency advantage that they are able to achieve, allowing faster lap times but also fewer pit stops. For endurance racing, this combination is difficult to beat with a gasoline-fuelled car.

In terms of fuels for diesel engines, there are a number of factors which affect suitability. Of critical importance is the cetane number (CN) which is used as a measure of combustion quality. The higher the cetane number the faster a fuel vaporizes and induces an increase in pressure inside the cylinder; this faster transition from liquid to gas can result in increased power output by allowing higher engine speeds. In the context of motorsport and therefore this paper, improved performance is defined as improved torque and power output.

Natural variation in plants, oils etc. presents an opportunity to tune fuels to optimize the output and performance. For example, saturation and chain length of the alkyl esters of vegetable oils and fats have been shown to greatly affect the physical properties of biodiesel (Knothe, 2005; Pereira et al., 2012) as well as polymers designed for industrial uses (Coles et al., 2008).

Fuels manufactured from the useful part of a plant such as the seed, oil, or fruit are known as first generation biodiesel. A perceived problem with the use of these crops for biodiesel production is that the agricultural land that they grow on and the crops themselves could be used to produce food. There have been criticisms of the use of potential food crops and agricultural land for the manufacture of automotive biofuels (Brown, 2006; Pimentel et al., 1988; Runge and Sennauer, 2007) particularly in relation to the increase in demand and therefore potentially the price of crops such as corn (Stein, 2007). These claims have been refuted by the World Bank who have shown that there is no evidence to support commodity price rises as a result of biofuel production (Baffes and Haniotis, 2010).

In order for this to occur, there are several problems with prolonged and widespread use of biodiesel from waste sources as a fuel that need to be addressed (Farooq et al., 2013). The main points can be summarised as viscosity, combustion quality and variability. In order to focus on the improvements required for high performance diesel engines, this paper focuses on the issues surrounding combustion, which encompass variability to a lesser extent.

The period during which fuel has been injected into the cylinder and started to mix with the compressed air but has not yet ignited is known as the ignition delay. Isolated areas of mixture start to autoignite before the whole air-fuel charge has mixed effectively. This premixed combustion causes a sharp increase in the in–cylinder pressure (and therefore temperature). Finally, the controlled combustion phase begins when the continual flow of fuel from the injector mixes with the hot air in the combustion chamber.

As engine speed increases the time available for complete combustion to occur decreases. If combustion is still taking place as the piston travels beyond bottom dead centre (BDC) and begins to compress the gases within the cylinder, the expanding combustion gases will resist the upward movement of the piston increasing stress on internal components and reducing efficiency. In order to operate at higher engine speeds, diesel engines require fuel which combusts rapidly, and has a short ignition delay. If the ignition delay of a fuel is different to that for which the engine was designed, the fuel will be injected either too early or too late, resulting in inefficiency, loss of power and potential engine damage.

The ignition delay of a fuel is partly due to its combustion quality, indicated by its CN. Higher cetane numbers indicate reduced ignition delay times and therefore limit the formation of NO_x by preventing nitrogen reacting fully before combustion ends. The CN of biodiesels increases with chain length and saturation (Knothe et al., 2003) making these properties of esters an important consideration when selecting feedstocks for fuel use. It has also been shown that the level of unsaturation of biodiesel hydrocarbons affects the formation of NO_x (Ban-Weiss et al., 2007). Unsaturated molecules have higher flame temperatures, thus they increase the formation of NO_x during combustion.

Biodiesel is a complex of compounds, the exact properties of which are dependent on a number of factors but particularly on the type of feedstock used to manufacture the biodiesel. It has been shown that the properties of biodiesel show direct correlation with the fatty acid composition of the feedstock oil (Knothe, 2005).

The higher cetane number of the biodiesel should allow for improved combustion and performance much closer to that of diesel, but this would require adjustment of the injection timing. Until the necessary adjustments can be quantified experimentally the performance of biodiesel will be inferior. The lower calorific value of biodiesel may also require adjustment to the amount of fuel injected to compensate for the increased volume of fuel required to achieve similar power outputs to diesel.

Variation in power, torque and fuel consumption are commonplace when using biodiesel as a fuel (Alptekin and Canakci, 2008; Rakopoulos et al., 2006). Researchers have also attempted to explain this variation by examining the chemical composition and properties of the individual fatty acid components of the fuel (Knothe, 2005). It is therefore the purpose of this paper to be able to identify the extent to which the above variables impact on the power and torque output of the engine, and to demonstrate methods by which any performance deficiencies can be counteracted and show that a diesel engine running on biodiesel could replace a gasoline engine running on fossil fuel for competitive motorsport.

2. Material and methods

Methyl esters of soybean oil, sunflower oil, rapeseed oil and beef tallow oil were prepared using literature methods (Ahn et al., 1995). The composition was measured using GC–MS following a standard

Table 1
Composition of oils (in % w/w) used in biodiesel production.

Fatty acid	Beef tallow	Soybean	Rapeseed oil
Palmitic (C16:0)	28.1 ± 1.4	7.2 ± 0.4	–
Stearic (C18:0)	16.7 ± 0.8	2.6 ± 0.2	7.7 ± 1.4
Oleic (C18:1)	43.4 ± 2.2	27.8 ± 1.4	56.1 ± 2.8
Linoleic (C18:2)	–	51.3 ± 2.6	22.0 ± 1.1
Linolenic	–	7.6 ± 0.4	11.2 ± 0.6
Others	11.8 ± 1.2	3.5 ± 0.2	3.0 ± 0.2

procedure (Barker et al., 2007) and is reported in Table 1 with an error of ±0.5%. Diesel fuel was sourced from a local fuel station and was therefore to EN 590 standard. The biodiesel was used for testing within 48 h of manufacture to avoid any loss of oxidative stability or increase in water content caused by long-term storage.

2.1. Characterisation

Densities were determined by measuring the mass of a known volume of each fuel using a four point balance. Cetane numbers and kinematic viscosities were tested experimentally using the EN ISO 5165 and EN ISO 3104 standards respectively by Intertek Laboratories in Middlesborough, UK.

2.2. Power & torque testing procedure

The test rig consisted of a English Electric Company powered dynamometer rated to 200 bhp and with a maximum operating speed of 8250 rpm diesel engine connected to a water-brake dynamometer and remotely operated from an adjacent control room. Fresh air was supplied to the engine by means of an electric fan. Exhaust gases were removed to the atmosphere by means of an extraction fan connected to a catalyst and particulate filter. Cooling for the engine was provided by a 500 W electric fan and cowling which provides air flow over the engine and dynamometer components to compensate for the reduction in air flow compared to normal operating conditions.

2.3. Dynamometer testing

The test rig consisted of a Yanmar L100V engine connected to a dynamometer and remotely operated from an adjacent control room. The engine had a rated speed of 3600 rpm and output of 9.1 horsepower. A custom engine mounting frame and propshaft adaptor were designed and manufactured. Fresh air was supplied to the engine by means of a 150 mm diameter flexible intake hose and in-line electric fan. Exhaust gases were removed to the atmosphere by means of a similar hose connected to a catalyst and particulate filter. Cooling for the engine was provided by a 500 W electric fan and cowling which provides air flow over the engine and dynamometer components. The speed governor on the engine was controlled via a push–pull cable from the control room. The engine had a built-in fuel tank which was equipped with a millilitre scale and transparent level tube allowing fuel consumption measurements to be taken over time at a given load and engine speed.

The dynamometer cell used was at Scott Racing Ltd in Durham, UK, and is built around SuperFlow Corporation's SF901 engine stand with an SF-833 water brake absorber. This can withstand torque up to 1350 Nm and operate up to a speed of 10,000 rpm (continuous) or 12,000 rpm (intermittent). The control and data-logging software used was SuperFlow's WinDyn. The dynamometer was attached to a load cell which measures the torque applied by the engine at different speeds and loads. This was displayed in the control room adjacent to the test cell and recorded either manually or using a data logger.

A Fisher Scientific weather station was used to measure the ambient temperature and atmospheric pressure in the dynamometer room at the time of testing to allow correction factors to be applied. Before blending, the mass of a fixed volume (100 mL) of each fuel was measured using a four point balance, and these values were used to calculate the density of each fuel at room temperature (23 °C).

2.4. Power and torque curves

One litre of each fuel was used for test runs, with an extra litre of diesel fuel being run through the engine first to bring it up to operating temperature. Due to the high viscosity of biodiesel blends, one litre of diesel was run through the engine between tests to ensure no deposits or biodiesel fuel remained in the engine or fuel tank. Readings of torque output [Nm] were recorded manually at increments of 100 rpm from 1500 rpm to 2800 rpm for each fuel. The engine speed was controlled by adjusting the speed governor which changes the amount of fuel being delivered to the engine. A correction factor was applied to these results to account for changes in ambient temperature and atmospheric pressure according to BS ISO 2534:1998 (BSI, 1998).

2.5. Fuel consumption

In order to measure fuel consumption the time taken for the engine to consume 100 mL of fuel at two engine speeds; 2000 rpm and 2800 rpm, were recorded. The torque output and fuel level were recorded when the engine had reached operating temperature, and the engine was run at this speed and load until 100 mL of fuel had been consumed. The time taken to consume this amount of fuel was recorded and used along with the measured density of the fuel to calculate the specific fuel consumption.

The in–cylinder pressure measurements were taken using a Kistler 6056A pressure sensor, housed in a glowplug adapter. The signal from this has to be sent to a charge amplifier to convert it to a ±10 V signal. A USB Instruments ds1m12 USB scope was then used to capture the output from the charge amp and the crank sensor to allow association between the in–cylinder pressure measurements and the rotational position of the crankshaft.

2.6. SOI testing

The start of injection (SOI) point was varied for the biodiesel fuels and the variation of in–cylinder pressure recorded. Tests were carried out at 2000 rpm and with the accelerator depressed by 63%. 2000 rpm was chosen as it was above idle speed but allowed accurate measurements to be taken; faster engine speeds did not facilitate the capturing of the relevant data. Baseline pressure measurements using only the starter motor and no fuel injected were taken to establish the in–cylinder pressures achieved without combustion. These measurements are shown as "motored" in the figures. The start of combustion is indicated by a sharp increase in pressure compared to the motored values. By comparing this to the SOI, it is possible to calculate the ignition delay.

In these experiments SOI is indicated by a number of degrees before top dead centre; a higher number indicates an earlier (advanced) start of injection, with a lower number indicating a later (retarded) start of injection. The output torque of the engine was measured and recorded for each SOI point to give an indication of the relationship between in–cylinder pressure and torque for the different fuels.

3. Calculations

Engine power is equal to the torque of the engine multiplied by the engine speed. Engine power was calculated for each torque output using the equation below.

$$P = \tau \cdot \frac{2\pi \cdot N}{60}$$

where:

- P = Power [W]
- τ = Torque [Nm]
- N = Engine Speed [rpm]

The uncertainties in the measurements taken in the paper are listed below based on the manufacturer's guidelines for the equipment used.

- Torque – ±0.2%
- Engine Speed - ±0.5%
- Calorific value - ±1.5%
- Mass - ±1 g; this equates to ±1.1% when measuring the mass of 100 mL of fuel

These errors have been used in calculating the error in power and fuel consumption stated within the paper. Uncertainties on the measurements for gross calorific value, cetane number and kinematic viscosity have been obtained directly from Intertek and the ISO standards used in each test as stated.

4. Results and discussion

A range of biodiesels synthesized from plant oils were selected for an initial comparison against conventional EN 590 diesel. The physical properties were characterized and can be seen in Table 2. The EN 590 standard column indicates the current regulatory standards for commercially-sold diesel in the UK as per EU directive 2009/30/EC.

All of the synthesized biodiesel meet the current specification for cetane number; in fact they surpass the level of conventional diesel indicating that they combust more quickly. This is agreement with previous publications that propose that decomposition mechanisms are based on breaking α- or β-positions from the ester group with lower bond dissociation energies when compared with aromatic C=C bonds; often prevalent in standard EN 590 mixtures (El-Nahas et al., 2007; Glaude et al., 2010; Saggese et al., 2013). Whilst biodiesels vaporize faster, modeling has shown that the likely decomposition pathways to small molecules such as acetylene and cyclopentadiene are more readily available in aromatics, thus meaning that aromatic-based diesel fuels are likely to achieve (near to) complete combustion sooner than biodiesels, hence their current high levels of power and torque output (Saggese et al., 2013). It would therefore follow that by advancing the SOI point for biodiesel fuels near-complete combustion should be achieved.

4.1. Power and torque curves

The power and torque of the fuels was assessed using a dynamometer. Soybean B80 biodiesel achieved peak torque of 26.4 Nm between 2390 rpm–2510 rpm and peak power of 7.5 kW at 2800 rpm. The drop in torque is again observed, but between 1940 rpm and 2320 rpm. Rapeseed B80 produced peak torque at lower speed than the other fuels; 25.3 Nm at 1860 rpm. Peak power was 6.8 kW at 2810 rpm. Sunflower B80 produced peak torque of 25.8 Nm at 1870 rpm, and peak power of 7.1 kW at 2850 rpm. The torque and power peaks for each fuel are summarised in Table 3.

Table 3
Peak torque and power of diesel fuels.

Fuel	Peak torque [Nm @ rpm]	Peak power [kW @ rpm]
EN 590 Diesel	24.5 ± 0.1 @ 2490	6.9 ± 0.1 @ 2800
Soybean B80	26.4 ± 0.1 @ 2390	7.5 ± 0.1 @ 2800
Rapeseed B80	25.3 ± 0.1 @ 1860	6.8 ± 0.1 @ 2810
Sunflower B80	25.8 ± 0.1 @ 1870	7.1 ± 0.1 @ 2850

Fig. 1 shows a comparison of the fuel consumption of each fuel at 2000 and 2800 rpm. The gross calorific values of each fuel are also shown on the graph. At 2000 rpm Sunflower B80 had the lowest fuel consumption and Rapeseed B80 consumed the most fuel per kilowatt hour. At high engine speeds, the faster combustion of biodiesel due to increased cetane number means you can put more fuel into the cylinder without generating 'diesel knock', therefore generating higher torque/power. The higher the engine speed, the greater the advantage of reduced combustion time can be exploited and therefore the more fuel you use.

This initial testing has confirmed that variation in the properties of biodiesel result in performance differences both between biodiesels and compared to EN 590 diesel fuel. Biodiesel fuels produced greater torque and power (with the exception of Rapeseed B80) than diesel fuel, but with a corresponding increase in fuel consumption. This can be attributed to the higher cetane number of biodiesel fuels increasing the speed and quality of combustion, and therefore increasing performance. The differences between the highest and lowest peak power (10.30%) and peak torque (7.76%) are significant and therefore have clear implications for the performance use of biodiesel fuels. The feedstock used for production must be carefully selected if no modifications to the engine are intended.

A second, more advanced engine with electronic control was used for further testing This not only allowed more accurate control of the testing, but was also more relevant to a competition engine and therefore of interest to the motorsport industry. An increase in CN results in less ignition delay and efficient combustion of the fuel/air mixture and hence a shift in the time at which peak in–cylinder pressure occurs. Providing this is achieved at the appropriate crankshaft rotation, a corresponding increase in power is possible by allowing the engine to operate at higher speed. This improvement in combustion quality compared to diesel could be used to offset the lower calorific value and therefore efficiency of biodiesel fuels, as well as improving their performance.

A B100 soybean biodiesel was tested as it appeared to be the most promising (consistently higher power & torque) from the initial tests, alongside conventional EN 590 diesel as well as a B50 beef tallow biodiesel. The choice of beef tallow was intended to allow evaluation of non-food feedstocks as high-performance fuels. The high viscosity of this fat (solid at room temperature) makes transesterification and subsequent blending with diesel a necessity to reduce the viscosity of the finished fuel. A B50 blend was therefore selected. These fuels were again characterised to give their physical properties (Table 4). This time, both of the alternative biofuels meet the specification for kinematic viscosity and cetane number, as well as having comparable results in terms of gross calorific value.

Table 2
Fuel properties (Rakopoulos et al., 2006).

Fuel	EN 590 standard	Diesel	Soybean ME	Rapeseed ME	Sunflower ME
Density [g cm^{-3}] @ 23 °C	0.820–0.845 (@15 °C)	0.845 ± 0.01	0.901 ± 0.01	0.902 ± 0.01	0.882 ± 0.01
Gross Calorific Value [MJ kg^{-1}]*	–	42.70 ± 0.01	38.38 ± 0.01	38.38 ± 0.01	38.54 ± 0.01
Kinematic Viscosity [mm^2 s^{-1}]	2.0–4.5	2.80 ± 0.01	4.86 ± 0.01	4.53 ± 0.01	4.75 ± 0.01
Cetane Number	>51	52.0 ± 0.9	59.8 ± 1.0	54.1 ± 0.9	57.4 ± 1.0

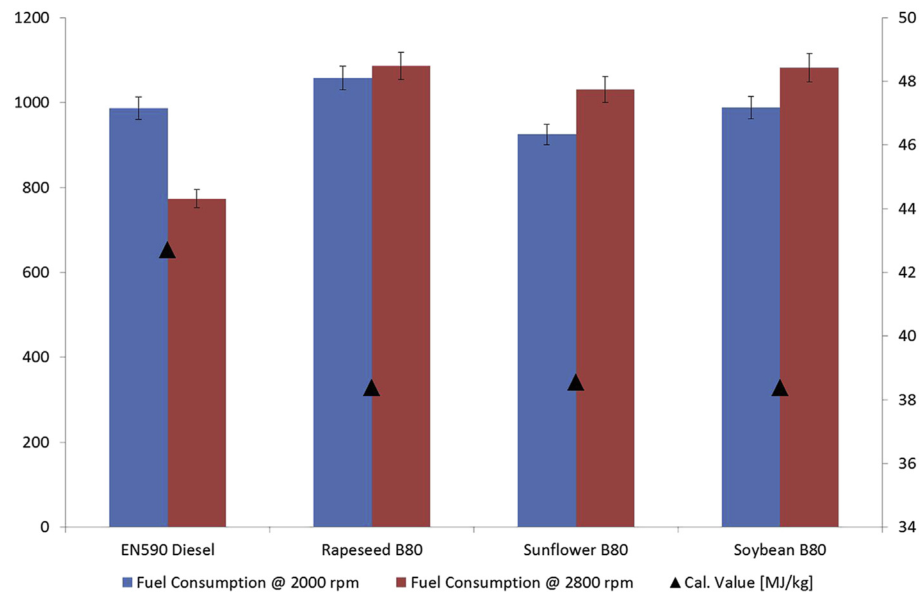

Fig. 1. Comparison of fuel consumption and gross calorific values.

4.2. Ignition delay

When looking to assess the performance, it was noted that there was delay between the start of injection and the start of combustion (*vide infra*) Values for the ignition delay can be obtained by using the difference between start of combustion and start of injection points from the data to calculate the delay in degrees of crankshaft rotation. Start of combustion can be identified by differentiating the pressure with respect to crankshaft angle and identifying the point at which the rate of pressure increase rises. This method of identifying start of combustion has previously been reported (Luján et al., 2010).

When applying this method, the engine speed was set at 2000 rpm (and therefore rotational speed of the crankshaft is known), hence the ignition delay in seconds can be calculated. The ignition delays of each fuel are given below in Table 5.

Based purely on the cetane number of the fuels (Table 2) which indicates ignition quality and therefore the length of ignition delay, it would have been expected for B100 to have the shortest ignition delay, followed by B50 and EN 590 diesel. The results in Table 6 show that B100 had an ignition delay 0.02 ms longer than B50. Previous work in the literature suggests that this can be attributed to the viscosities of the biodiesel fuels tested; the kinematic viscosity of B100 was more than 15% higher than that of B50, while its cetane number was only 3.12% higher. Wang et al. studied the fuel injection spray patterns of diesel, palm oil B100 and used cooking oil (UCO) B100 fuels (Wang et al., 2010). Higher viscosities led to a smaller spray angle and reduced air entrainment, and hence poor fuel atomization and concluded that at higher injection pressures the spray quality of used cooking oil biodiesel was similar to that of diesel, but the higher viscosity of palm oil B100 resulted in poor atomisation.

Increased viscosity due to poor atomisation has previously been suggested as a reason for extended ignition delay (Rodríguez et al., 2011). The longer ignition delay of B100 can therefore be attributed to its higher viscosity. Despite being longer than expected, the ignition delay of B100 was 0.08 ms (7.7%) shorter than that of diesel. Even though diesel fuel has a lower viscosity, it has a longer ignition delay due to the difference in chemical composition (aromatics vs. aliphatic fatty acids).

A 0.1 millisecond ignition delay may seem insignificant, but at 2000 rpm the crankshaft is rotating at a rate of 12° per millisecond. Therefore the start of combustion for EN 590 diesel occurs 1.2° nearer to TDC than B50 biodiesel. As has been established above, biodiesel vaporizes faster but takes more time to achieve near-to-complete combustion as the pathway to small combustible molecules is longer. Thus it would make sense to vary the SOI point in order to give the vaporized fuel the longest residency time possible in the cylinder in order to achieve the maximum possible pressure.

4.3. B50 biodiesel with varying SOI timing

Fig. 2 shows the effect of varying start of injection on the in cylinder pressure generated by using B50 biodiesel from beef tallow. Peak pressures for SOI of 10 and 11° before top dead centre (BTDC) were almost identical. All SOI timings for B50 resulted in a similar rate of pressure increase at the start of combustion which reduced until peak pressure. The timing of peak pressure was delayed with an increase in retardation of SOI timing.

The lowest peak pressure of 64.77 bar was recorded at a start of injection of 7° BTDC (see Table 6). Peak torque of 135.85 Nm was

Table 4
Biodiesel and diesel fuel properties.

Test	Standard	EN 590 diesel	Beef tallow B50	Soybean B100
Kinematic Viscosity ($mm^2\ s^{-1}$)	EN ISO 3104	2.80	3.62	4.27
Gross Calorific Value ($MJ\ kg^{-1}$)	–	44.8	43.24	40.50
Cetane Number	EN ISO 5165	52.0	63.9	64.1

Table 5
Calculated ignition delays of biodiesels and EN 590 diesel.

Fuel	Ignition Delay (ms)
EN 590 diesel	1.04
B50	0.94
B100	0.96

Table 6
In–cylinder pressures and torques for B50.

Fuel	Start of injection [degrees BTDC]	Peak in–cylinder pressure [bar]	Torque at 2000 rpm [Nm]
B50	7	64.77	133.14 ± 0.27
B50	9	71.51	135.85 ± 0.27
B50	10	75.62	135.58 ± 0.27
B50	11	75.59	132.19 ± 02.6

generated by injecting fuel at 9° BTDC. This maximum torque corresponded to an in–cylinder pressure 5.4% lower than peak. The higher torques produced in comparison to those in Section 4.2 are a result of the change in engine size.

4.4. B100 biodiesel with varied SOI timing

Fig. 3 shows the effect of varying start of injection timing on the in–cylinder pressure when using B100 biodiesel manufactured from Soybean oil. The figure clearly shows that advancing the start of injection results in increased peak in–cylinder pressures.

The peak pressures achieved within the cylinder at different start of injection points and the corresponding output torques are shown in Table 7.

By understanding the chemistry involved in the combustion process, it allows the injection point to be modified to account for the differences in chemical structures and therefore crucial to the successful implementation of biodiesel as a fuel for motorsport.

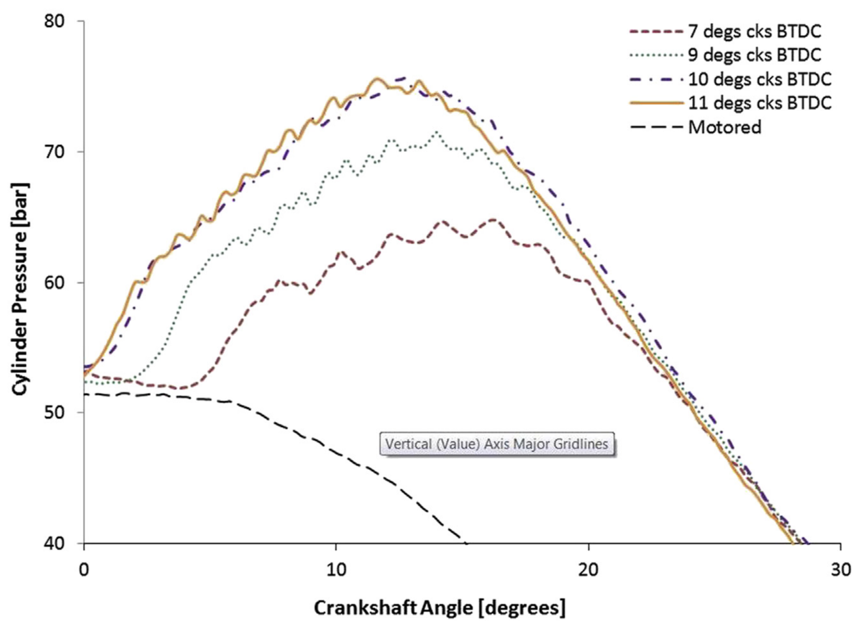

Fig. 2. In–cylinder pressure for beef tallow B50 with varied start of injection timing.

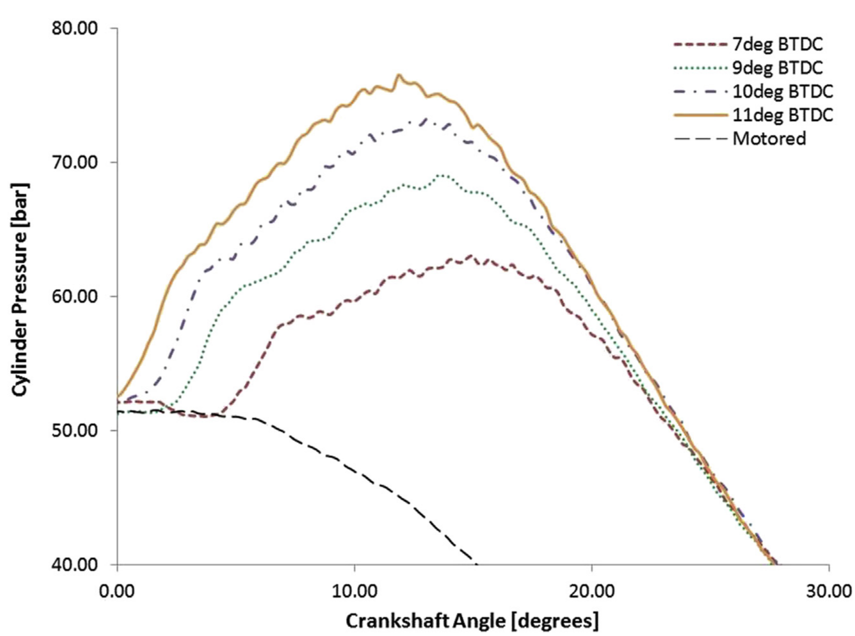

Fig. 3. In–cylinder pressure for soybean B100 with varied start of injection timing.

Table 7
In–cylinder pressures and torques for B100.

Fuel	Start of injection [degrees BTDC]	Peak in–cylinder pressure [bar]	Torque at 2000 rpm [Nm]
B100	7	63.04	124.46 ± 0.25
B100	9	69.04	124.06 ± 0.25
B100	10	73.26	126.63 ± 0.25
B100	11	76.51	126.57 ± 0.25

5. Conclusions

Methyl esters from rapeseed, soybean and sunflower oils were tested alongside EN 590 diesel fuel in a single cylinder generator engine. Variations in fuel consumption, output torque and power were observed between the fuels, confirming research that has previously been presented in the literature. To develop results relevant to motorsport, further tests were carried out on an automotive diesel engine to evaluate the in–cylinder pressures for soybean B100, beef tallow B50 and EN 590 to gain understanding of the reasons behind the performance differences noted in the initial tests.

Retarding the start of injection for B50 biodiesel by two degrees from standard resulted in a 2.8% increase in peak torque accompanied by a 5% reduction of in–cylinder pressure. Best torque for B100 was observed when retarding SOI by 1° from standard. This timing resulted in a negligible torque increase but a 4.4% reduction in in–cylinder pressure.

The torque outputs at all injection timings when using tallow B50 and soybean B100 were significantly lower than diesel fuel; this was attributed to the lower calorific value of biodiesel. The amount of fuel injected was varied for each biodiesel to compensate for the lower energy content of the fuel until the same torque as EN 590 diesel was produced at an engine speed of 2000 rpm. The shorter ignition delays of B50 and B100 resulted in lower peak in–cylinder pressures for the same torque, with B50 giving the lowest in–cylinder pressure due to its low ignition delay and hence the ability to begin injection later than either B100 or EN 590 diesel. The rate of pressure change using both B50 and B100 was lower than for diesel, the implication of which is reduced engine wear, or in motorsport terms, the potential to increase the output of the engine before critical failure occurs.

By altering the timing of the start of injection and increasing fuelling to allow for their lower calorific value, tallow B50 and soybean B100 are able to produce equal torque at the same engine speed compared to EN 590 but with lower peak in–cylinder pressure and a shorter ignition delay. The application of this to motorsport is the potential to achieve higher peak power outputs; the shorter ignition delay and more rapid combustion has the potential to be used to raise the maximum engine speed and therefore the peak power output of diesel engines for motorsport. Reduction in in–cylinder pressures for the same torque output allows for further potential performance increases by allowing more fuel to be injected and therefore more torque to be generated before the engine reaches its maximum in–cylinder pressure.

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