PERFORMANCE APPRAISAL OF A DIESEL GENERATOR POWERED BY BIODIESEL

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B. ENG (HONS) MECH

Submitted in fulfilment of the requirements for the degree of

Masters of Engineering Science

University of Tasmania

June 2007

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Acknowledgements

First, thanks go out to my supervisor Vishy Karri whose enthusiasm got this project started and whose guidance was instrumental in its completion. Thanks also to my co-supervisor, Alan Henderson; your critiques and comments along the way were greatly appreciated.

To all those who helped out in the workshop and at the university, thanks; particularly to Nathan Smith, John McCulloch and Steve Avery, your assistance in setting up the test rig was indispensable.

At South Australia Farmer's Fuel I would like to thank Mike Jureidni and Mark Connole for providing the biodiesel and consultation.

Finally, to James for supporting me, encouraging me and putting up with me; you were a continual source of motivation. Without you this thesis would still be a work in progress.

Abstract

This project conducts a performance appraisal of a new Tasmanian grown biodiesel as compared with a commercially available Australian biodiesel. The innovation patent recipe for the Tasmanian blend is a fuel that is derived from canola oil and poppy seed oil, both of which grow plentifully in Tasmania; the oils are transformed into a fuel through a transesterification reaction. The second biodiesel, commercially produced by South Australian Farmers Fuel, will be tested in conjunction with the Tasmanian biodiesel. The tests planned are to assess the commercial competitiveness of the Tasmanian fuel against a leading Australian biodiesel. As part of this work, both biodiesels will be analysed against a baseline of petroleum diesel to compare the relative advantages and disadvantages of implementing biodiesel as a diesel substitute.

The performance appraisal involves the study of emissions of carbon monoxide, hydrocarbons, carbon dioxide and nitrous oxide, as well as the opacity and fuel consumption of a generator. To conduct the tests a generator unit is proposed that will be fitted with instrumentation including: emissions analyser, smokemeter, temperatures probes, load bank, power meter, rpm sensor and flow board. The load applied to the generator is varied at levels of 10%, 25%, 50%, 75% and 100% of the rated power.

The results will be benchmarked against published literature. The observations of this study have highlighted that the emissions of carbon monoxide decrease with the use of biodiesel due to the higher oxygen content. The hydrocarbon emissions were reduced for nearly all biodiesels and blends because of the biodiesels superior combustion characteristics. The tailpipe exhaust emissions for biodiesel of carbon dioxide were relatively consistent with those of diesel fuel; however, biodiesel decreases carbon dioxide emissions over its life cycle when the plants absorb carbon dioxide during their growth period. The nitrous oxide emissions were increased, as expected, due to the nature of the oils from which the biodiesel had been derived. The opacity showed only minor increases for most biodiesels, which is consistent with other recent work. The fuel consumption increased as well with the use of neat biodiesel, again this is consistent with current literature. The results indicate that biodiesel may be used in an unmodified diesel generator and provide some improvement in the exhaust emissions.

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Chapter 1: Introduction

Fossil fuels are at the forefront of current politics because, not only are they a finite resource, which is being quickly depleted, but are also responsible for releasing harmful compounds into the atmosphere when burned. One the most important fossil fuels is petroleum because many products that are integral to the world today are derived from crude petroleum; such products include tar, asphalt, plastics, synthetic rubbers and numerous fuels including petrol, kerosene and diesel fuel. The problem is that the world's economies are intricately bound with petroleum and its derivatives; worldwide demand of oil is approximately 84 million barrels per day [1]. This high level of demand is compounded with the issue that nearly all of the world's oil has been discovered and that if the current rate of consumption of oil continues, than estimates state the supplies will run out as soon as the year 2040 [2]. Approximately 50% of the world's demand of oil is consumed by the transportation sector and about 75% of that is consumed by passenger cars and trucks [1, 3]. In developed countries such as Australia and the United States the rate of car ownership is high, approximately 500 and 780 vehicles per 1000 persons respectively in 2004 [3, 4]. Figure 1.1 shows the past and projected car ownership rates for Australia; most developed countries follow a similar trend.

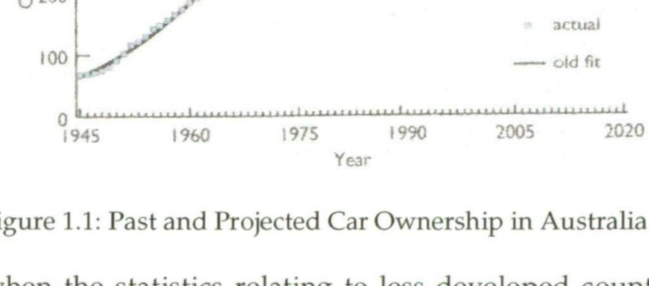


Figure 1.1: Past and Projected Car Ownership in Australia [3]

Concern arrises when the statistics relating to less developed countries such as China and India are examined; they report rates of car ownership to the order of 12 and 9 cars per 1000 persons respectively in 2004 [4]. While the levels are currently low, their economies are undergoing an intense growth period and the demand for items such as cars are growing at astronomical rates. Along with this increased demand for cars comes an increase in the demand for fuel and, consequently, an increase in emissions related to transportation; this demand for fuel and cars is not likely to decrease.

Vehicles powered by diesel fuel are particularly problematic in terms of their emissions as these vehicles are typically large trucks with older engines, which burn dirtier than small petrol powered cars; these diesel trucks make up approximately 28% of the transportation fuel demand in Australia [3]. The emissions due to transportation consist of carbon dioxide, carbon monoxide, hydrocarbons, nitrous oxides, sulphur and particulate matter. These emissions are harmful not only to the environment but they are harmful to humans as well. The United States Environmental Protection Agency published a report in 2002 which stated that long term inhalation exposure to diesel exhaust emissions was likely to pose a lung cancer hazard; short term exposure caused irritation and inflammation of the respiratory system and any exposure can aggravate pre-existing allergies and asthma symptoms [5].

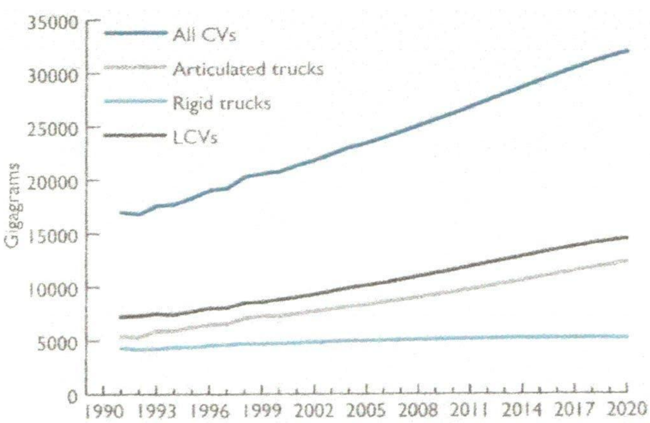


Figure 1.2: Commercial Vehicle Base CO_2 Equivalent Emissions 1990-2020 from [3]

Carbon dioxide is one of the most important greenhouse gases and is partially responsible for keeping the earth's atmosphere at a liveable temperature; however, as humans burn fossil fuels and release carbon trapped in the earth back into the atmosphere, the concentration of carbon dioxide is increasing unnaturally. Figure 1.2 shows the CO_2 emissions for commercial vehicles in Australia from 1990 and projected to 2020.

It can be seen that there has been significant increase in the carbon dioxide emissions even over the last ten years. Since carbon dioxide is a major greenhouse gas, the increased concentration of CO_2 is being primarily blamed for changes the earth is experiencing in its climate; pressure is being mounted world wide to reduce carbon dioxide emissions before irreversible damage to the environment is caused.

Another transportation emission, carbon monoxide or CO, is an extremely toxic gas which can rapidly kill at concentrations as low as 1% [6]. Haemoglobin is the component of blood which carries oxygen from the lungs to the vital organs; however, haemoglobin has an affinity for carbon monoxide which is over 200 times stronger than its affinity for oxygen. Consequently, if CO is present in the lungs, the haemoglobin will attach to it and not the oxygen, thus depleting the blood of its oxygen carrying capability and causing a large decrease, or complete block of oxygen that is transported to the vital organs [6]. This is known as carbon monoxide poisoning and can be fatal in minutes.

Hydrocarbons emissions are a generic term for the hydrogen and carbon compounds released during combustion of diesel fuel. The health effects on humans vary with concentration, length of exposure and type of hydrocarbon. At low levels symptoms can include fatigue, headaches, nausea and drowsiness which will dissipate once the person has been removed from the source of the pollutant; however more extreme cases have been seen to affect the immune system, liver, kidneys and lungs.

Nitrous oxides are extremely toxic; symptoms of acute NO_2 poisoning can include coughing chest pain, pulmonary oedema, irritation of the eye, nose and throat. The lungs may become inflamed causing slight pain; however the resulting oedema may be fatal several days later. Nitrous oxides may also cause respiratory distress particularly in elderly or children or those with asthma or other respiratory illnesses [6].

Exposure to sulphur oxides can cause irritation to the eyes, nose and throat causing choking, coughing, bronchoconstriction and burns [6]. In addition to human health effects sulphur emissions will also affect the atmosphere and are one of the main components in acid rain [7]. As a result, stringent limitations are being implemented on the level of sulphur in the fuel as this level is directly related to the amount of sulphur oxides that is released after combustion. However, these levels are not consistent world wide; the California regulations states a level of 500 ppm as the maximum while the World Wide Fuel Charter states a limit of 300 ppm [8].

Finally, the particulate matter causes both health and environmental issues; health issues are mainly respiratory problems as the particulates can be small enough to penetrate far into the lungs and prevent full transfer of the oxygen to the blood. Additionally, the particulate matter can be made up of various toxic components, including hydrocarbon, sulphur particulates, soot etc. each of which pose additional health risks [7]. Environmentally, particulate matter is a major component of smog, particularly in urban areas.

Due to the finite nature of fossil fuels, as well as their environmental and health risks there is an obvious benefit to finding a substitute fuel. Ideally, this fuel would be derived from a renewable source that is not damaging to the earth; additionally this fuel should reduce the level of emissions released that are harmful to both humans and the environment. As a result, much effort needs to be placed in developing alternative, and particularly renewable, energies that can reduce the world's dependence on fossil fuels.

This work concerns the alternative fuel commonly referred to as biodiesel and its application in a diesel generating set. Chapter 2 provides a brief introduction into the workings and applications of internal combustion engines with a focus on diesel engines. Typical biofuels used for transportation applications are discussed while comparing their relative advantages and disadvantages. Additional detail has been provided relating to biodiesel in terms of its production, properties compared to diesel fuel and the relevant standards. A review of current literature is also presented with a specific focus on the emissions, opacity and fuel consumption of engines powered by biodiesel or a biodiesel blend.

Chapter 3 outlines the experimental test rig and instrumentation as well as the testing conditions and procedures. The results and their analysis are presented in Chapter 4 along with an evaluation of the results compared to previous work.

Chapter 2: Literature Survey

This work focuses on a transportation fuel that is both renewable and which promises to reduce some of the harmful emissions. This fuel, biodiesel, can also be substituted directly into a diesel engine, and other existing diesel infrastructure, without requiring major modifications. This chapter introduces the diesel engine and petroleum based diesel fuel as well as three types of biofuels: straight vegetable oils, ethanol and methanol, and biodiesel. Full background on biodiesel will be provided since this is the fuel tested; as well current research will be analysed and expected outcomes of the experimentation conducted will be discussed.

2.1 Internal Combustion Engine

An Internal Combustion Engine (ICE) is a type of heat engine that is characterised by the ignition of the fuel within the engine in a combustion chamber. The useful work of the engine is produced by the conversion of the energy released during combustion into mechanical work using pistons, rotors etc. There are many variations of the basic ICE one differences is the method in which the fuel is ignited; two methods are Spark Ignition (SI) and Compression Ignition (CI). The difference is that the SI engine requires a spark to ignite the air-fuel mixture while in the CI engine the mixture is compressed such that its temperature rises to the point of combustion [9].

Two or four stroke cycles are commonly used in internal combustion engines; although four stroke cycles are the most popular due to the higher thermal efficiencies and lower emissions. The strokes of the four stroke cycle are intake, compression, combustion/power and exhaust. The cycle takes place over two complete revolutions of the crankshaft as illustrated in Figure 2.1.

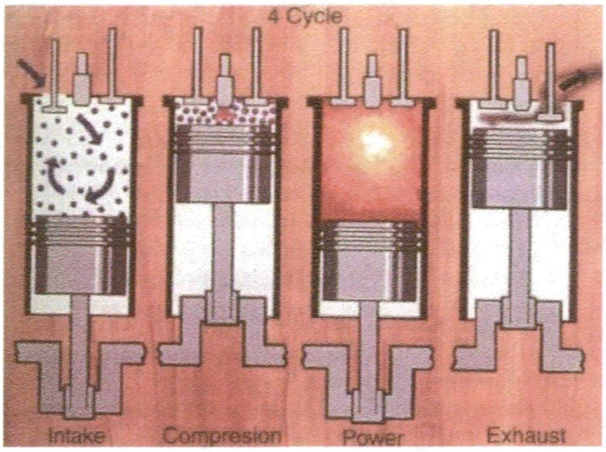


Figure 2.1: Four Stoke Cycle of a Compression Ignition Engine [9]

During the intake stroke the inlet valves are opened while the exhaust valves are closed when the piston is near top dead centre (TDC). As the piston travels down the cylinder air is drawn in. During the compression stroke both intake and exhaust valves are closed and as the piston travels upwards in the cylinder, the air is compressed causing it to heat to between 500°C and 650°C. As the piston approaches top dead centre, fuel is injected into the combustion chamber by an atomizer. In a CI engine, when the atomized fuel comes into contact with the heated air ignition takes place [10]; this combustion forces the piston down during its power stroke; in an SI engine the fuel air mixture is ignited by a spark. This combustion stroke is the drive of the engine as the power developed though forcing the piston downwards is transferred to the crankshaft through the connecting rod. The exhaust stroke is the final step in the process. In this step the exhaust valve opens and the piston begins to move upwards pushing the exhaust out of the cylinder [9].

2.1.1 Diesel Engine

The diesel engine is a type of compression ignition engine. While Rudolph Diesel was working on his engine, other internal combustion engines were already in existence such as the Silent Otto Engine which was one of the first four stroke engines in operation; however, there was much room for improvement. The theories behind the operation of the engine were not new and work on them had begun in the early 1800s by scientists such as Carnot and Otto. The originality in his work was the way in which Diesel planned to control the combustion in the cylinder [9]. Diesel proposed to draw in more air than was required for combustion, compress it to raise a temperature which is higher than required for combustion then inject a small amount of fuel which would burn instantaneously. The theory was that less heat would be produced which would result in a more efficient engine. After a series of prototypes and working models, the first diesel engine for practical use was developed in 1897 and produced 20 horsepower at 175 rpm [11] and is shown in Figure 2.2. At the time of development there was no specific fuel used to feed the engine and at the 1900 World Fair in Paris, Diesel showcased the engine by fuelling it with peanut oil [12]. When a petroleum derivative emerged as an inexpensive and accessible fuel the diesel engine was able to be used in many applications; however, the inherent operation of the compression ignition engine has changed little from Diesel's prototype and as a result there is no need to make modifications to the engine or the combustion chamber to allow the engine to run on vegetable oils again [9].

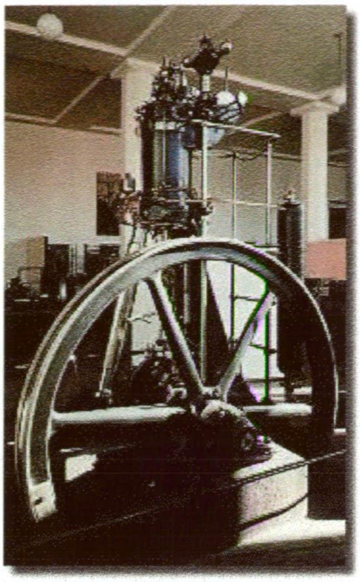


Figure 2.2: Diesel's First Engine [13]

The diesel engine is one of the most widely used internal combustion engines in the world because of its high efficiency and fuel economy. Diesel engines are used in a variety of applications e.g. cars and heavy goods vehicles as well as construction and agricultural machinery, railway locomotive, marine engines and generators. However, diesel engines have drawbacks as well. One such drawback is that the injector pumps and injectors must be built to highly precise tolerances which add to the initial cost of production [10]. Secondly, when compared with a gasoline engine, the gasoline engine is capable of delivering useful torque though a wider range of RPMs; the diesel engine's lack of ability to match these RPMs results in heavy duty trucks being equipped with 18 or 20 speed transmissions. Another advantage of gasoline engines over diesel engines is that gasoline engines runs quieter and cleaner; the exhaust emissions of an old or poorly maintained diesel engine will contain high amounts of soot and other toxins [10].

However, modern diesel engines are competitive with petrol engines through technology related to emissions reduction, improvements in performance of the power output and by installing turbochargers or superchargers.

The purpose of superchargers or turbochargers is to increase the amount of combustion air supplied to the engine and thus to increase the engine power output. Additional air is supplied by compressing the air to a higher density than ambient prior to injection into the engine, along with more air more fuel can be injected resulting in higher levels of more complete combustion and thus more power [14]. Turbochargers have become common in modern diesel engines as they utilize some of the previously wasted exhaust gas energy. As shown in Figure 2.3, a turbocharger consists of a compressor that is driven by a turbine via a common rod; the turbine is powered by the exhaust exiting the engine. The supercharger is mechanically driven and utilises a series of gears as a connection between the compressor and the engine.

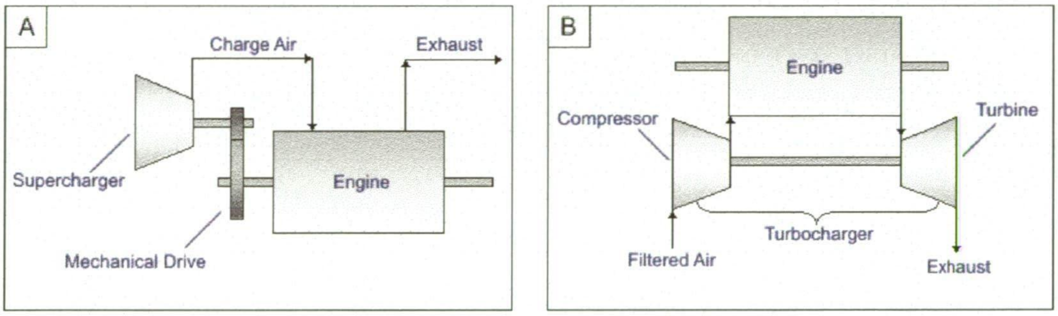


Figure 2.3: A – Supercharger driven mechanically by the engine
B – Turbocharger where a turbine drives a compressor through a common shaft [14]

Turbochargers are one of the devices being implemented to make diesel engine competitive with petrol engines in the general transportation market as they allow the diesel engine to operate more efficiently at a wider range of speeds. One reason automotive manufacturers are considering diesel engines as a possibility in the passenger market is due to the cost benefits, particularly in Europe and North America, of diesel fuel over petrol; as well as the superior fuel economy of the diesel engine.

2.1.2 Diesel Fuel

The commonly used fuel in a diesel engine is derived from crude oil or petroleum which has been named 'diesel' fuel after the inventor of the engine Rudolf Diesel. Petroleum is consists of hydrocarbons, or molecules of hydrogen and carbon joined in chains of varying lengths and structures; the physical properties of the substance depend on the length of the chain [15]. The shortest chains: methane, ethane, propane and butane (CH_4, C_2H_6, C_3H_8 and C_4H_{10} respectively) are the lightest petroleum derivatives and are gases at room temperature. As the length of the chain increases, the density of the product and its boiling point increases as well. Chains in the range of C_7H_{16} through $C_{11}H_{24}$ are used to produce petrol while heavier chains ranging from $C_{15}H_{32}$ to $C_{20}H_{42}$ are used to produce diesel fuel [15]. The different weights of petroleum products are separated in an oil refinery with the use of the varying boiling points through distillation Figure 2.4 shows a schematic of a modern oil refinery.

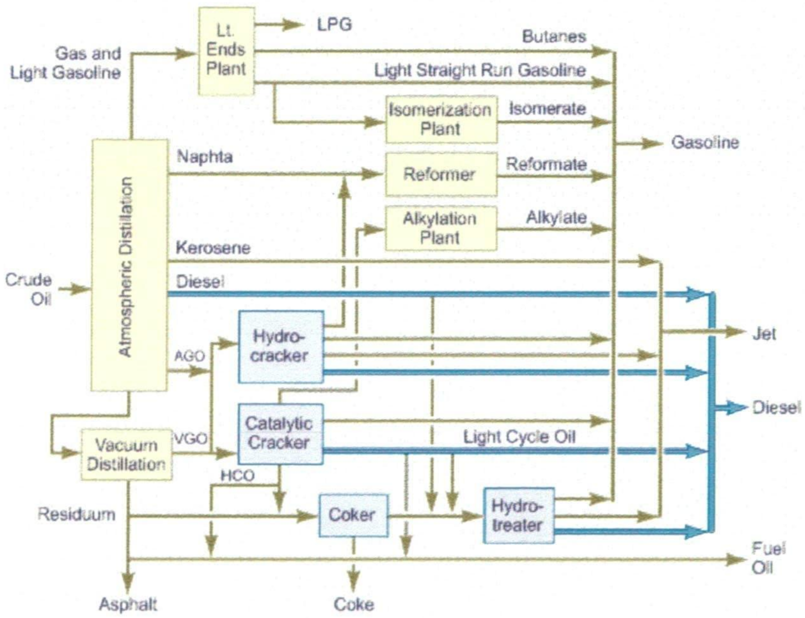


Figure 2.4: Schematic of Oil Refinery; Diesel Streams Highlighted in Blue [16]

One of the core differences between a diesel fuel and a petrol fuel used in transportation is the octane number. The octane rating is a measure the fuels resistance to autoignition and is particularly used in rating petrol. The octane number is measured by comparing the combustion characteristics of a specific fuel relative to two fuels which have defined octane numbers; n-heptane and iso-octane have defined octane numbers of 0 and 100 respectively. Autoignition is not a desirable property in spark ignition engines as it may cause the fuel to ignite before the piston is in the correct position and will result in knocking and damage to the engine [17]; high octane numbers correspond to high levels of autoignition inhibition. Conversely, Diesel fuels are heavier and are designed to ignite due to high temperatures without assistance from a spark or other flame source and as a result autoignition is a desired property; diesel fuels are classified on a separate scale, called the cetane number, where high numbers indicate a propensity to autoignite [18]. These differences will cause potentially serious problems if the wrong type of fuel is used in the wrong engine.

Diesel engines are surprisingly versatile when it comes to their fuel; they are designed to run on a fuel with similar physical properties to petroleum diesel, such as the density and viscosity, which are important for the fuel injection systems. In addition to the physical properties, diesel engines also require a fuel that has a tendency to autoignite under high temperature and high pressure situations; however, petroleum based diesel is not the only substance with these properties. Various oils are a possible substitution due to their similar combustion characteristics and physical properties, as previously stated Rudolph Diesel first showcased his engine by running it on peanut oil. Due to the current state of crude oil resources today as well as the rising fuel costs, these oils, known as biofuels or biodiesels, are being explored as a viable substitute for petroleum based products. Biofuels are derived from biological sources and may be implemented directly into compression ignition engines or may undergo a chemical process called transesterification prior to their use as a fuel. These differences and their associated advantages and disadvantages are discussed in the following section.

2.2 *Biofuel and Biodiesel*

Biofuels are fuels which are derived from biological sources; while petroleum may be considered to be derived from biological sources, its life span is in the order of millions of years. Consequently, biofuels are generally concerned with fuel sources that are CO_2 neutral with a relatively short life cycle, meaning that they do not add to the carbon dioxide in the atmosphere. With this consideration, examples of biofuels are: various plant oils (corn, soy, palm etc), animal tallow, cow manure or wood. The focus of this paper is biofuels used in transportation and generation applications and as such three types of biofuels, Straight Vegetable Oil (SVO), ethanol and methanol, and biodiesel which are applicable to transportation will be discussed in the following subsections.

2.2.1 Straight Vegetable Oils

Pure vegetable oils, such as canola, corn, or palm oils can be used as a fuel in diesel engines; these fuels, in their neat form are referred to as Straight Vegetable Oils (SVO). SVOs have similar properties to diesel fuel except that they have a higher viscosity and lower oxidative stability [19]; however, these differences can be overcome and as a result vegetable oil can be used as a substitute fuel for diesel in home heaters or engines.

While it is possible for vegetable or used cooking oils to be used as a fuel, engine modifications are required to overcome the issues relating to the viscosity and oxidative stability. Unless altered, these issues will result in poor atomisation of the fuel which leads to incomplete combustion. Other problems that can occur in the engine with the use of straight vegetable oils are substantial carbon deposits in the combustion chamber and pistons, injector coking and piston ring sticking [20]. All of these issues lead to long term engine damage and must be prevented if the fuel is to be used.

Traditionally, straight vegetable oil (SVO) is used in a dual fuel arrangement where one tank contained petroleum based diesel, and a second tank contains straight vegetable oil. The engine was started and warmed up using regular diesel and then manually switched over to SVO when a satisfactory temperature in the SVO tank has been reached; to reduce the viscosity of the fuel, the SVO must be preheated. Studies have shown that vegetable oil must be heated up to 150°C before it obtains a viscosity comparable to standard diesel fuel [21]. Once heated to a sufficient temperature, the user would then be able to drive solely using SVO; however, before stopping, the engine had to be switched back over to petroleum diesel for a long enough period of time to flush the engine and fuel lines of SVO. Failure to flush the engine could result in the vegetable oil congealing and clogging the fuel lines preventing the engine from running or starting [22]. The schematic of a system produced by Frybrid which incorporates a

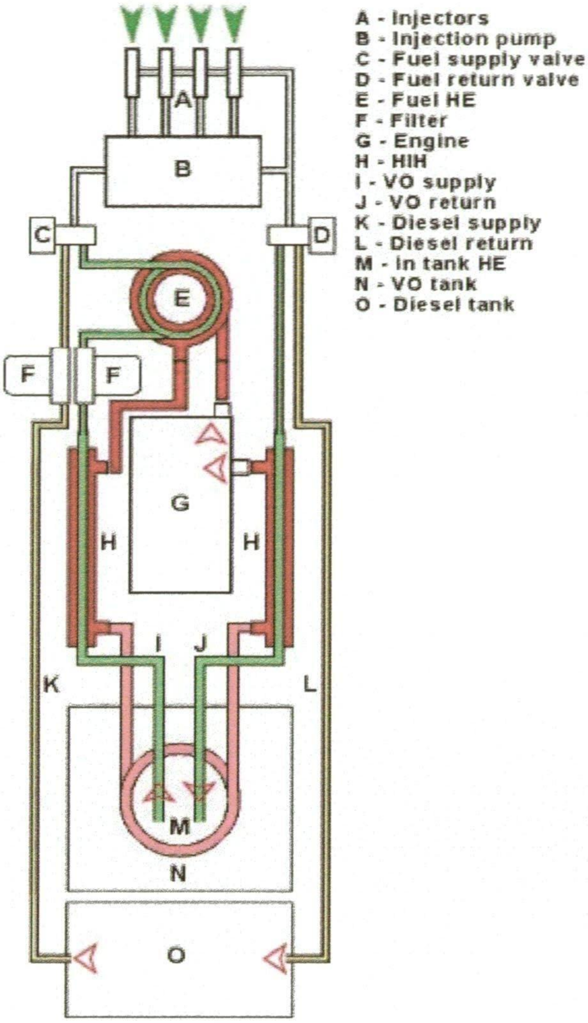


Figure 2.5: Schematic of Frybrid's Basic System with two tanks [23]

microprocessor for system control, an in tank heating element and the ability to purge the system of vegetable oil in seconds, is shown in Figure 2.5. This type of system, with an external heating source for the fuel prior to injection is extremely similar to the system which was originally used by Rudolph Diesel in his compression ignition engine in the early 1900s [11].

Another solution is a single tank system where there is no waiting for the fuel to heat, no switching over or purging prior to turning off the engine. The key aspects to a single tank system are an increased injection pressure, stronger glow plugs, which heat the fuel in the combustion chamber, and an electric preheating ability within the fuel tank [24].

Conversion kits are available from a wide variety of companies such as Frybrid, Greasecar and VegPower to name a few; these kits provide the means of converting a regular diesel car or truck to run on straight vegetable oils. Many of these kits have been developed with the use of computers or microcontrollers to minimise the responsibility placed on the driver; temperature sensors prevent switching to vegetable oil before a sufficient temperature is reached, high efficiency heat exchangers allow the switch to vegetable oil to occur sooner during the drive regardless of the diving conditions and alarms will sound if the car is stopped with SVO in the fuel lines or engine [23].

In general, when vegetable oils are used as a fuel they are referred to as Straight Vegetable Oil (SVO), derived from vegetable oils, or Waste Vegetable Oil (WVO), derived from used cooking oils, to distinguish them from biodiesel which is distinctly different. Vegetable oils are not the only source of biologically available fuels; some alcohols may also be used. The two alcohols which are currently undergoing extensive research are ethanol and methanol; these two alcohols and their advantages and disadvantages will be discussed further in the following section.

2.2.2 Ethanol & Methanol

Ethanol is a type of alcohol that can be used as a transportation fuel that can be blended with gasoline and used in an unmodified engine at low percentage blends, 10-30% or at higher blends with some modifications [25]. Ethanol is created by the fermentation of starches and sugars; because of breakthroughs in biotechnology ethanol can now be derived not only from the traditional corn or sugar cane but also from switchgrass, wood chips, corn husks or other agricultural waste. The production of ethanol involves grinding the feedstock in to a powder then mixing the powder with water and alpha-amylase and heating it to turn the starch into a liquid mash. The mash is cooled and another enzyme is added to transform the starch into sugars; the sugars are fermented using yeast, and then distilled creating ethanol and carbon dioxide. The ethanol is then separated and the water removed from it leaving a pure ethanol of around 200 proof. The main by-products of this process are distillers grain and carbon dioxide. Distillers grain is a highly nutritious livestock feed and carbon dioxide can be collected and sold for industrial use [26].

Ethanol is typically used in blends of E10, 10% ethanol and 90% gasoline, and E85, 85% ethanol and 15% gasoline. Some of the benefits of E10 are that no engine modifications are required and it is already covered under warranty by manufactures of all makes of all cars [26]. E85 is generally used in flex-fuel cars; flex-fuel cars are capable of running on either E85, gasoline or any blend in between. Regardless of the level of ethanol in the fuel, any blend is beneficial as it is reducing the amount of fossil fuels being burned and as it is a high-octane fuel it promotes full and complete combustion thereby reducing emissions due to improper or incomplete combustion.

Methanol is also considered an alternative fuel which is generally used in conjunction with gasoline; however, it has generally received less attention than ethanol as it has a few inherent problems. Methanol is more corrosive to engine components than ethanol and its calorific energy per litre is 55% lower than that of petrol, while ethanol's energy per litre is only 75% that of petrol. However, the use of higher compression ratios and corrosion resistant materials can overcome these issues, albeit significant engine modifications are required. Another issue with the use of methanol is the higher levels of toxicity; extensive exposure can cause serious and lasting health damage [27].

Methanol also has its advantages; it can easily be produced from abundant sources such as methane. Methane is a large component of natural gas, but is also available from renewable resources such as the decomposition of organic materials. Another advantage is demonstrated through race car organisations such as Indy Car is that methanol does not burn as hot as gasoline and consequently it is safer during a collision than petrol; as a result methanol is the fuel used during races despite the lower energy content [27].

Alcohols are typically used in spark ignition engines as they have higher autoignition inhibition; however, there is still a large sector of transportation which does not operate using a spark ignition engine. Compression ignition engines require a fuel that has a high tendency to autoignite; for this application, the focus of research has been on a fuel called biodiesel. This fuel is derived from straight vegetable oils and is discussed further in the following section.

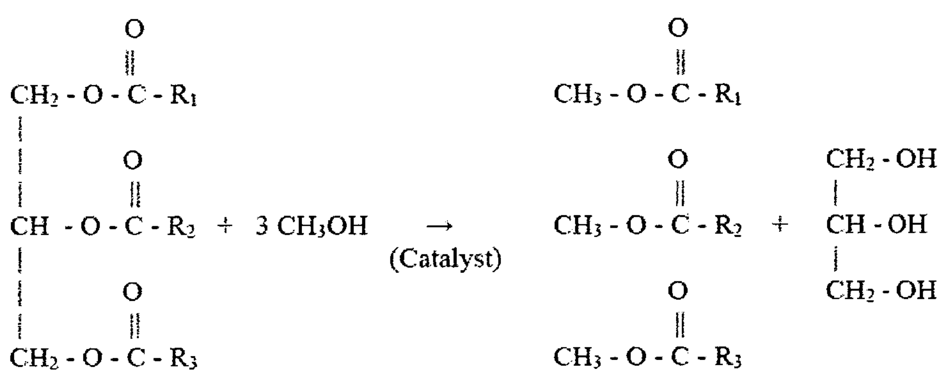
2.2.3 Biodiesel

Biodiesel can be derived from various renewable sources such as plant oils (e.g. coconut, palm, soy, rape seed, eucalyptus to name only a few), animal tallow or waste cooking oil. These oils are transformed into fuel through a process called transesterification. Transesterification is the process of changing one type of ester into another type of ester; esters are an organic compound formed through the combination of an acid and an alcohol.

2.2.3.1 Production Process

At a molecular level, vegetable oil consists of three esters attached to one molecule of glycerine; this is known as a triglyceride. Transesterification involves removing the glycerine component from the vegetable oil to reduce the viscosity and replacing it with a molecule of alcohol; ethanol or methanol are the typical alcohols used. Methanol is typically the alcohol of choice for use in biodiesel production; the reason is that the reaction to produce methyl esters is a faster and more reliable reaction. If ethanol is used, the resulting ethyl esters are much more likely to create emulsifiers in the fuel as a result of water present in the oil; this causes the secondary issue of separating the emulsifiers from the biodiesel [2].

The triglycerides are broken by the addition of a catalyst to the vegetable oil; typical catalysts are sodium hydroxide or potassium hydroxide. Once the triglyceride is broken up each of the esters attaches itself to an alcohol resulting in three alkyl ester molecules (molecules made from alcohol and vegetable oil) and one glycerine molecule. An example of a transesterification reaction can be seen in Figure 2.6.



triglyceride methanol mixture of fatty esters glycerol

Figure 2.6: Transesterification Reaction [28]

In Figure 2.6 R_1, R_2 and R_3 refer to long chains of carbons and hydrogen atoms called fatty acid chains. When the reaction is complete, it must be allowed to settle for at least eight hours to allow the esters to separate from the glycerine. Once the glycerine and esters have separated the glycerine can be removed and used to make, amongst other things, soap leaving the esters behind to be used as fuel [2, 28]. A typical reaction creating biodiesel from fats and oils can be predicted by the following relationship:

100 kg oil + 10 kg methanol → 100 kg biodiesel + 10 kg glycerol

The actual process of biodiesel production can be summarised in a flow chart as created by Joshua Tickell in his book, From the Fryer to the Fuel Tank. This flow chart is shown below in Figure 2.7

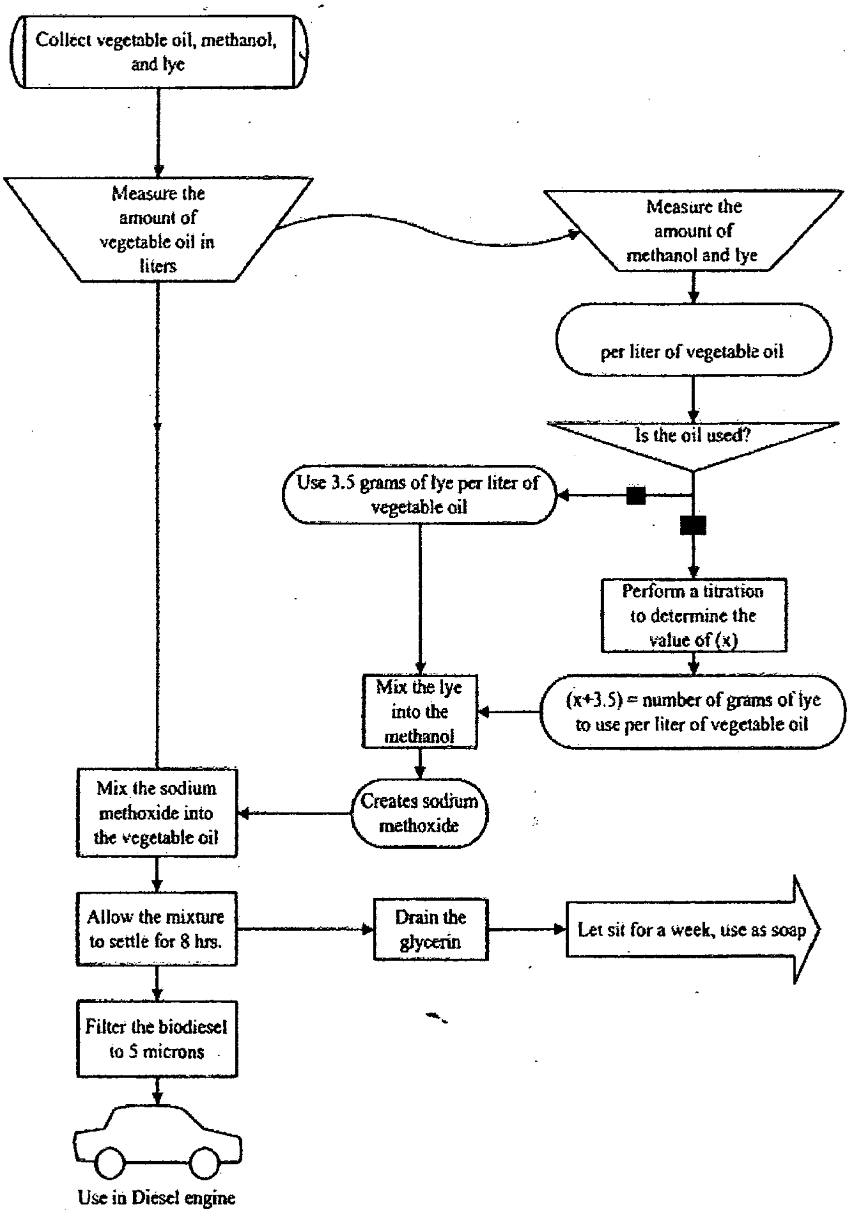


Figure 2.7: Biodiesel Production Flowchart from [2]

2.2.3.2 Diesel and Biodiesel Properties

There are a number of properties of diesel fuel which are essential to its effective operation in an engine; these properties are governed by standards dictated by a local authority. These properties can be divided into physical (density, viscosity or sulphur content) and non physical properties (cetane number, flash point or lubricity); physical properties can be measured whereas non physical properties are determined through the interaction of a fuel with a standardised measurement device. The following is a discussion of the key properties of a diesel fuel and how biodiesel compares.

One of the primary properties of a diesel fuel is its ignition quality; this is usually quantified as the cetane number. The cetane number is an important quality in a diesel fuel as it is a measure of the fuels combustive quality; it measures how quickly a fuel starts to burn under CI engine conditions. High cetane numbers relate to superior ignition quality and result in the fuel igniting quickly after being injected into the cylinder while a fuel with a low cetane number will result in an ignition delay. A high cetane number is desirable as the improved combustion will provide better cold starts and reduce the associated white smoke as well as decrease the noise [16]. A minimum level for the cetane number is defined in local standards and range from 40 in the USA and Canada to 51 in the European Union. It can be noted that standards typically require biodiesel to possess a higher cetane number than petroleum based diesels with the USA requiring biodiesel to have a cetane number of 47 [20] while Australia and the EU require a minimum cetane number of 51. However, biodiesels tend to have inherently higher cetane numbers ranging near 55 [29].

The density is the mass per unit volume and for a fuel it is a regulated property; this is because the density is related to the calorific value of the fuel and thus plays a role in the rate of fuel consumption and power output. Heavier fuels have higher levels of associated risk in terms of operational problems that can arise such as knocking, afterburning, variation in ignition delay; these factors lead to increased engine fatigue, excessive thermal loading and higher levels of exhaust emissions [18]. Biodiesels tend to have higher densities; diesel fuel tends to have densities ranging from 820 - 860 kg/m^3 as per Australian standards while biodiesels have a standard defined density of 860 – 890 kg/m^3 by the same standards body [30].

The heating value of a fuel is a measure of the energy content and is quantified by the heat released during combustion when a unit of the fuel is burned. The heating value is also called the calorific value and is related to the density of the fuel; higher density fuels have lower calorific values, while less dense fuels have higher calorific values. Consequently, it can be expected that biodiesel will have a lower calorific value to that of diesel fuel. Diesel fuel typically has a (lower) calorific value of 42.6 MJ/kg [16] while biodiesel has a value of approximately 39.4 MJ/kg [29]. As the calorific value is correlated with the fuel consumption it is expected that biodiesel will have higher rates of fuel consumption since less energy is released during combustion thus more fuel must be burned to meet the demand.

Viscosity is a measure of the resistance of the fuel to flow. The viscosity of a fuel is important in the operation of the fuel injection apparatus as this equipment must accurately measure and disperse small quantities of the fuel. A fuel with a high viscosity may distort the fuel pump through the high shear stresses and associated heat generated [16]; in this way, very viscous fuels can lead to poor combustion and cause deposits to form within the cylinder. A fuel with a low viscosity has potential to cause power loss due to leakage of the injection pump and injectors [31]. As a result, upper and lower limits have been set for the viscosity of a fuel. Since the requirements for viscosity are determined by the ability of the engine to run on the fuel, the limits defined for the viscosity of biodiesel and diesel fuel are the same.

The cold flow properties of a fuel are an important consideration as diesel fuels contain a paraffin component including waxes which can crystallise at low temperatures resulting in clogged fuel filters that will stall the engine. This issue is apparent with both diesel and biodiesel fuels; however, it is more pronounced with the biodiesels. There are three standard points where are used to define the cold flow properties of a fuel:

- Cloud Point: This point is the temperature at which visible crystals begin to form in the clear fuel resulting in a cloudy appearance. Most fuels can still operate effectively below this point provided the temperature remains above the cold filter plug point [31].

- Cold Filter Plug Point (CFPP): The CFPP is the temperature at which the fuel has crystallised sufficiently such that the crystals have joined into groups large enough to plug the fuel filter. This point is indicative of the cold flow properties of a fuel as it is the point at which engine operation becomes an issue [32].
- Pour Point: The pour point is the temperature at which the crystals have joined such that the fuel is essentially a gel and cannot flow. This measure is not generally applicable to practical circumstances as once the fuel has reached the pour point the engine has long stopped running [32].

Accordingly, precautions must be taken in colder climates, particularly in the winter; for diesel fuel it may be sufficient to select the fuel that has been refined or treated for cold conditions as there are a variety of diesel fuels available. The biodiesels have inherently worse cold flow properties which are highly dependent on the type of fuel they were derived from; in particularly cold climates neat biodiesel is not an ideal fuel due to these poor cold flow properties and as a result many biodiesel users convert to a diesel-biodiesel blend such as B20 during the colder months of the year.

The flash point is the lowest temperature at which a liquid produces a concentration of vapour above the liquid in adequate quantities such that it can mix with the air and be capable of ignition; flash points are regulated to ensure safe handling of the fuel. A minimum flashpoint, between 60°C and 80°C, has been defined for petroleum diesel as a safety precaution. The flashpoints of biodiesels are much higher, minimum of 120°C. The reason for the higher flash points is to ensure that the manufacturer has removed any excess alcohol which was used in the manufacturing process; excess alcohol in the biodiesel will cause additional safety issues. Even small quantities of alcohol will significantly reduce the flashpoint and thus increase the risk of fires. Within the engine, the alcohol will affect fuel pumps, seals or other rubber components and will result in poorer combustion characteristics [31]. Since biodiesel has a high flash point, it is considered non flammable and thus is far simpler to transport and store as it is not classified as a hazardous substance.

Engine wear properties are related to the lubricity, cleanliness and acidity of the fuel used. The fuel injection equipment relies primarily on the fuel for local lubrication as a result, should the fuel not posses the necessary lubricative properties or contain contaminates it will cause wear and ultimately failure of the injection devices. Prior to regulations on sulphur content this was not an issue; however sulphur is removed from the fuel through hydrotreating. The process of hydrotreating not only removes the sulphur from the fuel but it also removes the poly aromatics and polar impurities of the diesel fuel which influence the lubricity of the fuel. The hydrotreating process also removes the organic acids which contribute to the fuels acidity [16]. Maintaining a minimum lubrication level of the fuel will significantly aid in the prevention of engine wear of the fuel injection systems such as oxidation, adhesive wear, scuffing, fatigue, corrosion and erosion. The cleanliness and acidity of the fuel also affect the wear through abrasive wear and corrosive wear respectively. Biodiesel has natural lubricative properties as well as low natural sulphur content; consequently, it is a fuel that is low in sulphur and requires no additives to prevent damage to the fuel injection systems or engine.

Petroleum diesel fuels contain sulphur elements within their chemical structure and as previously discussed high sulphur fuels tend to have high lubricative properties. However, the sulphur in diesel fuels has multiple negative impacts on the emissions, corrosion and exhaust aftertreatment systems. Most of the sulphur in the fuel is converted during combustion into sulphur dioxide which is a major constituent of acid rain. Sulphur condensates corrode the exhaust systems and are particularly an issue when exhaust gas recirculation systems are in place. Additionally, in catalytic converters more sulphate particles can be generated than the carbon based particulates which are being destroyed thus increasing overall particulate emissions; as well, sulphur will deactivate NO_X absorbers in exhaust aftertreatment systems [16]. As previously stated the biodiesels inherently have near zero sulphur content and as a result have lower levels of sulphur oxide emissions and will not cause sulphate particulate problems in exhaust systems.

Iodine number is a property that is particularly important to biodiesel fuels but is not typically recorded for diesel fuels. The iodine number predicts the tendency of the fuel to be unstable; the iodine number measures the presence of double carbon-carbon bonds (C=C) bonds that are prone to oxidation; it is a measure of the level of saturation of the fuel. The stability of the fuel is important to know as poor stability (low number of C=C bonds) can lead to high acid number, increased viscosity and the formation of sediments which will clog engine filters [32]. The iodine number also correlates to the level of NO_X emissions. Iodine numbers around 38 will produce a fuel that is NO_X neutral when compared with conventional diesel fuel while biodiesel with an iodine number lower than 38 will produce significantly less NO_X emissions than diesel fuel; however, the trade-off is that these fuels with low numbers of C=C bonds also produce fuels that have very poor cold flow properties [33].

It can be seen that biodiesel and diesel fuel possess similar physical and combustive characteristics. Because of these similarities of viscosity, density and autoignition tendencies it is possible for biodiesel to be an unobtrusive substitute for petroleum derived diesel fuel.

2.2.3.3 Pros & Cons of Biodiesel

Biodiesel offers a renewable source of fuel with similar properties to diesel fuel which also has the potential to decrease harmful emissions associated with burning diesel fuel. In addition to this, biodiesel possesses an abundance of other advantages including:

- Biodiesel is biodegradable and non hazardous (with a flash point above 120°C) [34]
- The methyl esters (biodiesel) produced by transesterification contains virtually no sulphur (less than 0.001%) which is a primary cause of acid rain [2, 35]
- The production of biodiesel can assist in the revitalisation of depleted agricultural sectors in developing countries by giving value to a crop that has traditionally been uneconomical to produce.
- Biodiesel can be used as a neat fuel or blended with regular petroleum based diesel.
- Biodiesel can be used with the current diesel infrastructure.
- Biodiesel has higher inherent lubrication abilities than diesel fuel and thus does not require additives to increase the lubricity [32].

While the fact that biodiesel is a mild solvent which will clean out the fuel tank and fuel lines of the engine may be considered an advantage, it also poses a few problems. One issue is that the fuel filter may become clogged when the engine is running on the first few tanks of biodiesel and as a result need to be changed at least once; however, once the diesel deposits have been removed this is no longer an issue. Another issue is that experience has shown biodiesel has a tendency to deteriorate parts of the fuel system that are made from natural rubber [36]. When running an engine on neat biodiesel it is recommended that all rubber hoses and seals be replaced with a synthetic material.

Another issue surrounding biodiesel is that in warm weather biodiesel is more susceptible to the growth of bacteria in the fuel tank than petroleum based diesel [37]; however, this can be corrected with antibacterial additives if necessary.

One of the main concerns with the use of biodiesel is its performance at low temperatures. As with petroleum based diesel fuels, freezing or gelling occurs as the temperature decreases. When the fuel gels, it can clog the filters and will eventually become too thick to pump from the fuel tank to the engine. Consequently, the cloud point of biodiesel must be reported so the user can take precautions should the ambient temperature drop too low [9].

For any particular fuel the three cold flow temperatures the cloud point, cold filter plug point and the pour point, will lie within a close range of approximately 3°C or 4°C; thus once the fuel begins to cloud, it can gel with a slight drop in temperature.

The cold flow properties are largely dependant on the type of oil that is used to create the biodiesel; however, the type of oil also affects other factors such as the combustion characteristics. Highly saturated oils such as animal tallow or used cooking oils produce a biodiesel which can have a cetane number as high as 70; by comparison, the cetane number for petroleum diesel is around 40. If the biodiesel is produced from polyunsaturated oils such as soy, sunflower, corn or canola a fuel with a cetane number closer to the defined standard of 51 is produced. However, while the saturated oils have superior combustion characteristics they have much poorer cold flow properties; similarly the polyunsaturated oils which produce a biodiesel with a lower cetane number result in a fuel that is better capable of tolerating cold temperatures. As a result, it is common to use combinations of various oils in the production of biodiesel to obtain a fuel with desirable combustion and cold flow properties [31].

Studies, such as the study conducted by Wyatt et al, have investigated the effect of blending biodiesel with petrol diesel on the cold flow properties of the fuel. This work has shown that the blending with petroleum diesel resulted in the improvement of the cold flow properties of biodiesel such that they are comparable to neat conventional diesel fuel up to a biodiesel content of 20% [38].

2.2.3.4 Biodiesel Standards

All Biodiesel that is produced and is to be used in diesel engines by the public must adhere to standards set out by the local authority. Standards may vary from country to country but their purpose is to ensure that quality is maintained regardless of manufacturer. As biodiesel is a growing industry, not all standards organisations have defined specific standards relating to neat biodiesel and its use; however, for some regions these standards do exist.

The American Society of Testing and Materials (ASTM) have approved a standard which was developed through the involvement of companies which manufacture the vehicles, engines and fuel injection equipment. It is to be noted that this standard, ASTM D6751 titled: Standard Specification for Biodiesel Fuel (B100) Blend Stock for Distillate Fuels specifies that it is for neat biodiesel which will be used in blends of up to 20% by volume [7]. The table summarising the specifications outlined in ASTM D6751 can be found in Appendix A.

The European Committee for Standardisation has developed a standard for biodiesel as well, EN 14214: 2003 Automotive Fuels – Fatty Acid Methyl Esters (FAME) for Diesel Engines; however, it is limited to biodiesel produced by rapeseed stock i.e. rapeseed methyl esters. A summary of EN 14214 specifications can be found in Appendix A.

Australia has recently developed its own biodiesel standard, based off the existing European and United States standards shown in Tables 2.1.

Table 2.1 Australian Biodiesel Standards [39]

Parameter	Standard
Sulphur	100 ppm (effective February 1 2006)
Density	860-890 kg/m^3
Distillation T90 max	360° C
Sulphated Ash max	0.020% mass
Viscosity @ 40°C	3.5-5.0 mm^2/s
Flashpoint min	120°C
Water and Sediment max	0.050% vol
Ester Content min	96.5%
Phosphorus max	10 mg/kg
Acid Value max	0.80 mg KOH/g
Total Contamination max	24 mg/kg
Free Glycerol max	0.020 % mass
Total Glycerol max	0.250 % mass
Oxidation Stability min	6 Hrs @ 110°C
Metals	≤5mg/kg Group I (Na, K) ≤5mg/kg Group II (CA, Mg)
Methanol Content	<0.20% (m/m)
Copper Strip Corrosion	Class 1
Cetane Number min	51.0

Each of the properties governed by the standards contributes to the effectiveness and cleanliness of the fuel. In order to be classed as a fuel for commercial use it must adhere to all the above specifications and be tested on a regular basis. Regular testing is required because minor changes can have a large impact on the fuels operational ability; for example, if the viscosity was too high in one batch of biodiesel, the engine may have problems pumping it into the cylinder, the injectors will not atomise it effectively, thus the fuel will not combust properly resulting in lower power output and higher emissions due to incomplete combustion. Since these properties vary between biodiesels and by the type of oil from which they have originated, the effects of biodiesel use on engine performance has been tested and analysed by many researchers. This work also investigates the quantitative trends that result from biodiesel use in a diesel generator.

2.3 Engine Performance with Biodiesel

This work evaluates the benefits and detriments of substitution of biodiesel for petroleum based diesel fuel in a generator unit. The focus is on several aspects of engine performance: the exhaust emissions, the opacity, the fuel consumption as the applied load is varied. The following sections provides details on the investigated emissions, opacity and fuel consumption and outlines previous research in each of the areas studied as related to biodiesel and its impact on diesel engines.

2.3.1 Emissions

Apart from the reduction in fossil fuel consumption, one of the major benefits of switching to a renewable fuel such as biodiesel is the reduction in harmful exhaust emissions. This is particularly significant in urban areas in both the developed and developing world as well as in regions that have sensitive ecosystems. In urban areas a reduction in exhaust emissions could significantly improve the quality of air and reduce related health issues. The following section introduce the main exhaust emissions providing details on their mechanisms of formation and discusses the recent work conducted on the five main components of diesel exhaust emissions: carbon dioxide, carbon monoxide, hydrocarbons, nitrous oxides and sulphur oxides.

2.3.1.1 Carbon Monoxide

Carbon monoxide, CO, is a poisonous gas which contributes to the formation of ozone and smog at low levels. Carbon monoxide is generally a result of incomplete combustion when carbon is burned in oxygen with an excess of carbon present [40] CO is also considered a greenhouse gas. Carbon monoxide is capable of reacting photochemically with aldehydes; aldehydes are common in urban areas where the concentration of exhaust emissions from automobiles and industrial actions are high.

Carbon monoxide is formed during the intermediate combustion stages of hydrocarbon fuels; as combustion occurs the oxidation of CO to CO_2 takes place through recombination reactions between CO and various oxidants. However, if there is insufficient oxidants present or if the gas temperature is too low, more carbon monoxide will be left un-reacted in its current form to be emitted as CO. As the applied load increases, the temperature of the exhaust gases increase as well, this promotes the oxidation reaction that shifts CO to CO_2 by increasing the speed at which the reaction occurs resulting in lower emissions of CO and higher emissions of CO_2 at high loads [41]. At light loads more air, and hence oxygen, is available for reaction; however, the temperatures are too low to drive the reaction of CO to CO_2 resulting in high levels of CO at low loads. As the load is increased, the temperature increases as well resulting in larger amounts of CO eliminated. At high loads there is little air available for the elimination reaction to take place; as a result, despite the high temperatures, less CO is eliminated. Consequently, there is an optimal load at which to operate the engine, which varies for different engines, that produces a minimum amount of carbon monoxide emissions [41].

Existing research tends to concur that the use of biodiesel reduces carbon monoxide emissions. Ulusoy et al. [42] performed tests comparing the performance of biodiesel derived from used frying oil to standard diesel fuel and reported a reduction of 8.59%. However, other studies such as the one conducted by Canakci [20] which tested the emissions of a soybean derived biodiesel reported a much larger reduction of 18%; a graph illustrating this study can be found in Figure 2.8. Biodiesel blends of B20, 20% biodiesel and 80% diesel, reported slightly lower levels of carbon monoxide reductions of between 7% and 11% for the studies conducted by Canakci and Environment Australia respectively [20, 43]. Although, one study prepared by the Environmental Protection Agency (EPA) in the United States quoted a decrease of up to 20% [7]. A study conducted in Ireland by Gomez et al actually reported an increase in CO emissions in the order of 7.5% [44]; however, this was attributed to insufficient air in the engine at a specific testing speed.

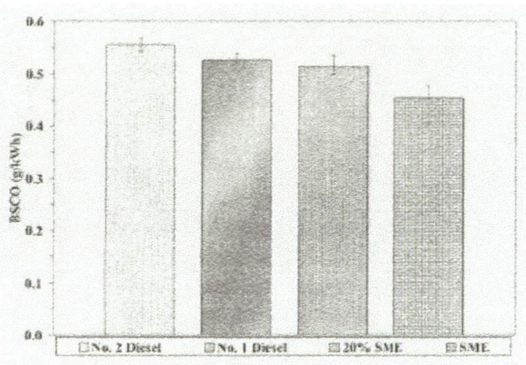


Fig. 1 Comparison of brake specific CO emissions

Figure 2.8: Comparison of brake specific CO emissions for two diesel fuels, B20 and B100 [20]

Biodiesel blends reduce CO emissions since biodiesel has higher oxygen content than petroleum diesel. Higher oxygen content assists in achieving a more complete combustion and causes more oxygen to be available for carbon monoxide elimination reactions.

2.3.1.2 Hydrocarbons

In general terms, hydrocarbons, HC, are any chemical compound that consist exclusively of carbon and hydrogen. When hydrocarbons are extracted from a geological source in a liquid form they are labelled as petroleum; in gaseous form, they are called natural gas. In relation to exhaust emissions, the presence of hydrocarbons generally indicates incomplete combustion as some of the fuel is simply being exhausted without being burned [45]. This release of hydrocarbons by vehicle exhaust results in pollution which, along with NO_x emissions and sunlight will form low level ozone and smog [7].

Ozone forms at low levels through a variety of complex chemical reactions between nitrous oxides, carbon monoxide and hydrocarbons. The main issues with the low level formation of ozone are health related. Ozone is known to cause many types of health problems including irritation of the respiratory system, reduced lung capacity, aggravation of asthma, increased susceptibility to respiratory infections and the inflammation of and damage to the lining of the lungs [45].

The level of unburned hydrocarbons are a result of factors relating to the operating conditions of the engine such as the fuel spray characteristics, and the interaction between the fuel spray and the air in the combustion chamber as well as the properties of the fuel [20]. The cetane number is one property which can predict the amount of HC in the exhaust. A high cetane number promotes superior combustion characteristics and as a result the combustion that takes place is more complete and thus hydrocarbon emissions decrease [44]. Since biodiesel is required to have a higher cetane number than petroleum based diesel, it is not surprising that biodiesel produces lower hydrocarbon emissions.

The primary source of hydrocarbons which are present in the exhaust emissions originate from the fuel molecules initially injected into the cylinder for combustion;

however, some may be due to recombined intermediary compounds. The appearance of hydrocarbons in the exhaust generally indicates that the fuel was not ignited successfully; however, the physical properties and chemical composition of the fuel play also play an important role in the concentration of HC in the exhaust as well as the engine operating parameters such as the engine speed, load and AFR [46].

The reasons why hydrocarbons may be emitted in the exhaust are related to the air-fuel mixture in the cylinder. The engine speed, load and air-fuel ratio all influence the combustion and swirl patterns within the cylinder; it is possible that the local mixture in a particular region of the cylinder is so rich, or so lean, that the oxidation reactions (which occur prior to full combustion) are extremely slow and as a result the ignition cannot occur since too much heat has been lost [41]. Another possible situation is that within elements of the air fuel mixture the surface to volume ratio may be too large and cause high levels of heat loss thus preventing ignition. Finally, heat losses can also occur if the air fuel mixture is adjacent to a comparatively cool surface, such as that of the piston or cylinder wall, which would cause heat loss within the mixture and inhibit combustion [46].

Studies have shown that the use of biodiesel will reduce the level of hydrocarbon emissions. One study, performed by Ulusoy et al, that was conducted on biodiesel derived from used fryer oil determined that the emissions of HC decreased by 30.66% [42]. When testing B20, studies generally show a reduction of 20-30% [7, 43]; however, one study performed by Canakci et al reported a decrease of as small as 2.9% for a 20% volumetric blend of biodiesel derived from soybeans [20]. The same study reported a decrease of hydrocarbon emissions by 42.5% with the use of B100; the results may have more to do with the type of diesel fuel that was used in the blend, as well factors such as load and engine speed

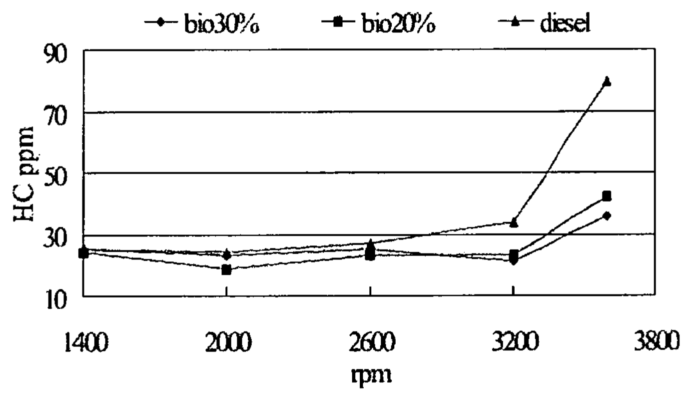


Figure 2.9: Hydrocarbon emissions for B20 and B30 blends with respect to engine speed [44]

which play a significant role in hydrocarbon emissions. A study performed by Lue et al [44] determined that at low rpm, 1400-2600, there was a small decrease in HC emissions, however when the speed was increased to between 2600 and 3000 rpm there was a significant benefit in the use of biodiesel in terms of reducing the emissions of hydrocarbons; this relationship is shown on the previous page in Figure 2.9.

In general the level of hydrocarbons is expected to decrease with an increase in biodiesel concentration due to the superior combustion characteristics of biodiesel fuel over diesel fuel.

2.3.1.3 Carbon Dioxide

Carbon Dioxide, CO_2, is classified as a green house gas and as such measures are being taken to reduce its emissions. While it is generally accepted that the levels of CO_2 are rising and that the overall temperature of the earth is increasing as well, it is yet unclear how much human activities have affected this. Regardless, the disruption to the carbon cycle by burning tonnes of fossil fuels which took millions of years to store cannot have anything but a negative impact; thus there is a necessity to restore balance to the environment [25].

The emissions of carbon dioxide are related to those of carbon monoxide since the reaction that eliminates CO produces CO_2. Thus, it can be expected that there will be an inverse relationship between the two emissions as a result of the mechanisms discussed in Section 2.3.1.1.

Many studies have already been conducted relating to the effect biodiesels have on the performance of the engine, particularly relating to the exhaust emissions. When comparing the emissions performance of biodiesel and petroleum diesel studies have shown varying results. Gomez et al cited a reduction of 7.5% CO_2 emissions when comparing diesel to waste cooking oil methyl esters [48]. However, Ulusoy et al reported an increase of 2.62% when measuring the CO_2 emissions of biodiesel produced from used frying oil as compared to regular diesel fuel [42]. Canakci also indicated a slight rise, less than 1% in CO_2 emissions of a biodiesel sourced from soybeans [20]. In general, biodiesel is not expected to make significant effects on the emissions of carbon dioxide in terms of tailpipe emissions. The benefit of biodiesel use related to CO_2 stems from the production of biodiesel which involves growing massive amounts of crops; these crops require carbon dioxide during their growth period. This means that biodiesel is CO_2 neutral whereas petroleum based diesel fuels simply adds to the net emissions[49].

The use of B100 reduces net CO_2 emissions by 78.45% compared to petroleum diesel; for B20, net CO_2 emissions dropped by 15.66%. The chart for which is shown in Figure 2.10. This figure does not have a 100% reduction rate for B100 because it includes the fossil fuels burned during the harvesting of the crops and the production of biodiesel.

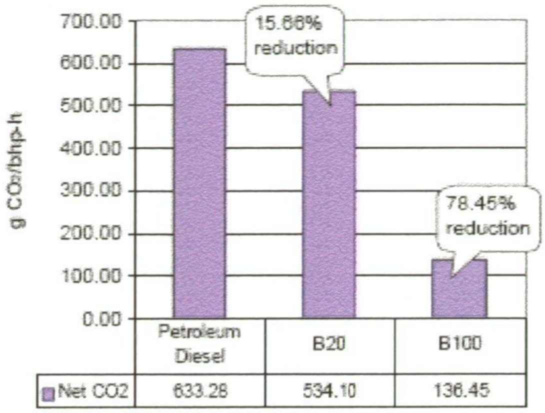


Figure 2.10: Comparison of Net CO_2 Life Cycle Emissions for Petroleum Diesel and Biodiesel Blends [47]

2.3.1.4 Nitrous Oxides

In many instances, when implemented in CI engines, the use of biodiesel results in an increase in NO_X emissions; however if used in a boilers or for home heating applications the NO_X emissions tend to decrease [31]. This change in emissions is a result of the varying ways in which the fuel is burnt in these applications. In boilers it is burned with an open flame, where as in an engine it is ignited under a high pressure spray; it is this burning at high temperatures and pressures that promotes the formation of NO_X.

There are three mechanisms that typically contribute to the formation of nitrous oxides during combustion, these are: prompt NO, NO from the fuel and thermal NO formation [46]. The first two, prompt and fuel formation do not play a large role in the overall amount of NO which is formed. Prompt NO formation is a two step process in which carbon and hydrogen radicals attack nitrogen and form cyanide (HCN). This step is followed by the oxidation of HCN which results in NO; this process is only significant in extremely fuel rich flames. Nitrous oxides can also form as a result of the oxidation of the nitrogen contained within the fuel; however, only a small portion of the nitrogen in the fuel undergoes this process and as a result is not a major contributor to the final amount of nitrous oxides produced. The final method, thermal formation is the main mechanism by which nitrous oxides are formed within a diesel engine. This type of formation occurs when the high temperatures during combustion cause oxygen in the air to dissociate into atoms. These atoms dissociate nitrogen molecules from the air to form NO; the degree of conversion is dependant on the concentration of atomic oxygen within the air [50].

The amount of nitrous oxides formed will be determined by the rate of formation and the time available for reaction. One factor that affects the rate of formation is the peak temperature reached during combustion which depends on a number of factors such as the equivalence ratio, fuel composition and the initial temperature of fuel-air mixture [50]. Additionally, the rate of formation is dependant on the concentration of oxygen present during combustion [41].

Since the rate of formation speeds up at higher temperatures it is expected that the amount of NO_X emitted will increase with an increased load because of the associated temperature increase.. Additionally, as the amount of NO formed is impacted by the amount of oxygen in the fuel it is not surprising that biodiesels tend to produce higher levels of NO_X emissions since they inherently contain higher levels of oxygen. This effect is amplified at low loads since the maximum NO formation occurs in a fuel and air mixture which is slightly lean as there is more oxygen available for reaction [41].

Studies have shown that the source of the biodiesel can play a significant role in the NO_X emissions. Specifically, increasing number of double bonds between the carbon atoms, quantified as the iodine number, correlates with increaseing NO_X emissions [33]. Waste cooking oil has a high number of double bonds and consequently a study by Gomez produced increased nitrous oxide emissions of 20% when compared with petroleum diesel [48]. However, an experiment performed by Ulusoy studying used fryer oil reported an increase of only 5.03% [42]. Figure 2.11 shows a chart produced by the U.S. Department of Energy that compares the level of NO_X emissions for various biodiesels with the NO_X emissions of standard diesel fuel.

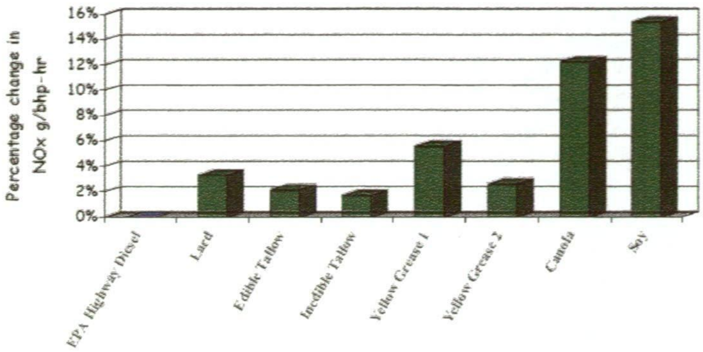


Figure 2.11: Increase in NO_X emissions from a CI engine using various B100 fuels [31]

The use of B20 is common as it balances the positive aspects of the emissions with minor issues regarding the engine as well as causing only minor increases of NO_X emissions. For B20, the typical levels of NO_X emissions are between two and three percent greater than petroleum diesel [38, 43].

As an illustration of the impact of the source oil on the NO_X emissions, a study conducted by Whyatt et al, tested emissions for soy methyl esters, animal fats, and tallow. NO_X emissions from B20 soy methyl ester increased by 6.2% while the emissions from B20 derived from animal fat (chicken fat, lard) increased by 3.0% and B20 from tallow was, within error, the same as petroleum based diesel [38].

In general, studies have shown that the use of biodiesel increases the emissions of nitrous oxide; the higher the level of biodiesel in the blend, the higher the nitrous oxide emissions. This is because of the shorter delay in the ignition time of the biodiesel blends which result in peak pressures and temperatures that enhance NO_X formation [44]. Another reason for the increase in nitrous oxide emissions is the higher levels of oxygen in biodiesel which leads to better oxidation of the available nitrogen [51].

Although the use of biodiesel increases the level of harmful nitrous oxide emissions, there are steps that can be taken to minimise the impact of this increase. For example, previous research has stated that delaying the timing of the injection of the fuel can help reduce NO_X emissions [52, 53]. As well, techniques such as exhaust gas recirculation (EGR) or the installation of a catalytic converter have proven successful. Additionally, many fuel additives have been research in an effort to reduce the emissions of nitrous oxide.

2.5.1.5 Sulphur and Sulphur Oxides

Sulphur is one of the main contributing factors to acid rain. New restrictions on petroleum diesel fuels are limiting the allowable sulphur content of fuel. However, this causes problems related to lubrication in the engine as ultra low sulphur fuels have much lower lubricity than regular diesel [7]. In this instance biodiesel can be beneficial in more than one way; firstly, biodiesel has much higher lubricity than diesel fuel and when mixed, even in small quantities, with petroleum diesel it can increase the lubricity. Secondly, it is sulphur free and as a result can be added to ultra low sulphur fuels to increase the lubricity without breaking sulphur limitations.

Biodiesel typically contains less than 15 ppm sulphur, as a result nearly all sulphur oxides in exhaust emissions are eliminated. In this work it was not possible to monitor the emissions of sulphur and sulphur oxides. However, this is not necessary as the level of sulphur emitted is directly related to the level of sulphur in the fuel [54]; consequently, it is known that since biodiesel contain very low levels of sulphur it can be deduced that the sulphur oxide emissions will decrease as a function of biodiesel content. Figure 2.12 illustrates the relationship between the sulphur content of the fuel and the resulting SO_2 emissions.

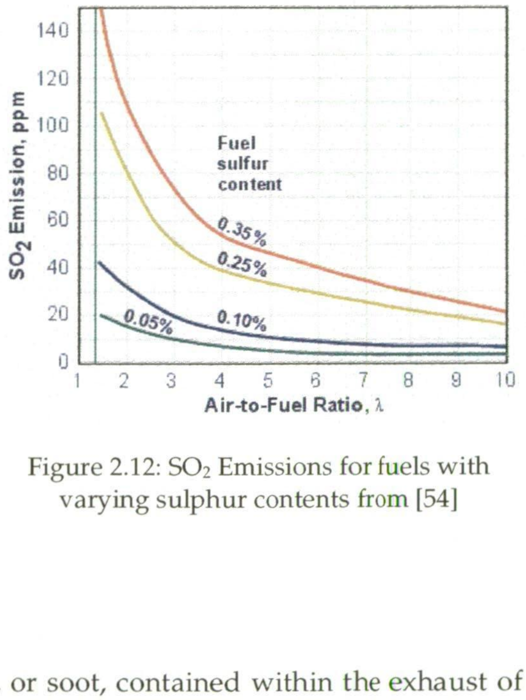


Figure 2.12: SO_2 Emissions for fuels with varying sulphur contents from [54]

2.3.2 Opacity

Opacity is a measure of the particulate matter, or soot, contained within the exhaust of the engine. Particulate matter (PM) is classified in terms of its size; PM_{10} refers to a particle that is smaller than 10 micrometers. Particles larger than PM_{10} are not considered a human health risk as these particles may be filtered by hairs in the nose and throat; however, PM_{10} is small enough to enter the bronchi and lungs and settle there causing health problems. The next level down is $PM_{2.5}$, particulate matter smaller than 2.5 micrometers in diameter; this size of particle can penetrate deep into the lungs

[55]. Studies have shown that the presence of $PM_{2.5}$ can lead to heart attacks and other cardiovascular problems as well as respiratory disease [7].

Opacity is a result of the amount of soot formed during combustion of diesel fuels. During complete combustion, the fuel is sprayed into the cylinder where it diffuses, evaporates and mixes with the air before combusting due to the high temperatures. However, due to the high cycle temperatures within the cylinder, there is insufficient time for the evaporation and mixing to fully complete; consequently, pyrolysis occurs and soot is formed during this period. Additionally, if some of the spray begins to combust in a locally fuel rich area, due to the lack of oxygen, pyrolysis of the hydrocarbons occurs, creating soot. In the post combustion period some of the soot formed may be burned, and eliminated, as it is exposed to oxygen present thus reducing the net soot output [46]. Once the soot particles have formed, they grow through agglomeration and coagulation resulting in black smoke made up of particles of varying sizes. More soot is produced at higher loads as there is less oxygen available to burn the soot particles in the post combustion period resulting in an increase in the net soot emitted [41]. Lower levels of soot are produced when the size of the fuel particle injected is minimised; this is because it allows quicker diffusion, evaporation and mixing and reduces the amount of fuel burned in a fuel rich region.

Since the formation of opacity is largely dependent on the engine and operating conditions, there are varying reports as to whether or not biodiesel causes a reduction in the opacity. Leu et al found a decrease of 4% for B20 and 10% for B30 [44] while Environment Australia showed a decrease of 10.1% with the use of B20 [43]. The National Biodiesel Board (NBB) cited a 30% decrease of particulate matter through the use of biodiesel [7], while Gomez et al stated a reduction of 48% based on a comparison of waste cooking oil methyl esters and petroleum diesel [48]. These studies show that higher levels of biodiesel produce larger reductions of opacity; however, not all studies agree. In one study conducted by Durbin et al [56] four engines were tested with four types of fuel: a standard diesel, synthetic diesel, a B20 and a B100. Figure 2.13 should the result for the particulate matter emissions for the four engines; and increase as a result of biodiesel use is shown for the 1990 Dodge while the 1996 Dodge reported a decrease in opacity. This graph also illustrates the advancement in emission reduction technology since the newer engines produce significantly lower emissions overall.

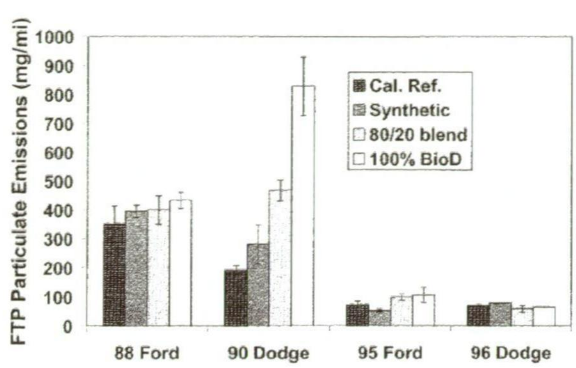


Figure 2.13: Particulate Emissions for four types of fuels in four different engines [56]

In general, smoke emissions may decrease with biodiesel use; but it is possible they will increase as well since the most significant engine factors that contribute to the formation of particulate matter are the engine load and its speed [44].

2.3.3 Fuel Consumption

Fuel consumption is an important factor to consider when studying the performance of an engine. The fuel consumption can be considered in two ways; the first is the basic fuel consumption as measured in volume per time. The second method is to consider the specific fuel consumption which provides and indication of the efficiency of the engine to burn the fuel; the specific fuel consumption (SFC) is reported in g/kW-hr.

When considering the fuel consumption of biodiesel as related to petroleum based diesel, it is generally considered that biodiesel will result in a higher rate of fuel consumption [57].

The rate of fuel consumption of an engine is related not only to the structure of the engine in terms of the number and size of cylinders etc. but is also a result of the properties of the fuel it is running on. The properties of the fuel that determine the rate of consumption are all interconnected and closely related; namely the density, calorific value and the cetane number [18]. Biodiesel has a lower calorific value, typically around 39.4 MJ/kg [29] as compared to 42.6 MJ/kg [16] for diesel fuel. However, as previously discussed, biodiesels also tend to have a higher cetane number. The higher cetane number promotes superior combustion when biodiesel is used but the lower calorific value indicates that less energy is release during combustion of an equal volume of biodiesel than diesel fuel; as a result, more biodiesel is required to be burned to produce an equal amount of energy resulting in higher fuel consumption for biodiesels [31].

In a study conducted by Krahl et al. the effect of rapeseed oil methyl ester as compared with low sulphur diesels was investigated in terms of emissions and specific fuel consumption. The result, as related to the specific fuel consumption was that there was an increase of 12% when biodiesel was used as compared to the low sulphur diesel fuels [58]. A study by Labeckas et al looked at biodiesel in concentration up to B35; it was found that at maximum torque the SFC had increased by 18.7% and at the maximum rated power, the SFC had increased by 23.3% over the specific fuel consumption of petrol-diesel at the same conditions [59].

A study conducted in 2005 by Cetinkaya and Karaosmanoğlu at Istanbul Technical University investigated the performance of a diesel generator run on biodiesel derived from used cooking oil. Regarding the fuel consumption, Cetinkaya and Karaosmanoğlu found a 4% increase when using B20 and a 10% increase when the generator was operating on B100. A graph illustrating their results can be found in Figure 2.14.

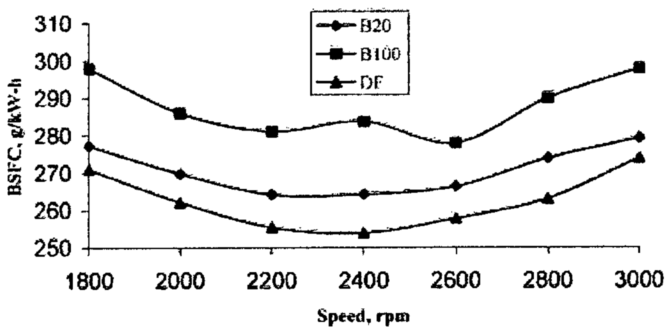


Figure 2.14: Brake specific fuel consumption of B20, B100 and Diesel Fuel [60]

In 2003 Dorado et al. conducted a study that investigated the performance of waste olive oil methyl esters as a fuel operating at steady state conditions. This study concluded that biodiesel results in higher specific fuel consumption; however, this increase is 8.5% above that of the diesel fuel which was deemed acceptable based on the benefits to the exhaust emissions provided by the use of biodiesel [49].

In general it can be determined that the fuel consumption for biodiesel, or blend, is higher than that of petroleum based diesel; this is a result of the lower calorific value.

2.4 Concluding Remarks

This chapter has presented a brief introduction to internal combustion engines and investigated the background of biodiesel as well as the need for it in the world today. The benefits and detriments of the use of biodiesel as a fuel have been discussed and concluded that with a few minor precautions there is very little that needs to be done for biodiesel to be used as a fuel by the general population.

Previous studies were discussed with particular focus on the emissions, opacity and fuel consumption. From the study of these previous works, it can be expected that as the concentration of biodiesel increases and the concentration of conventional diesel fuel decreases, there will be a resulting decrease of CO and HC emissions. An increase in NO_X emissions is expected, as is a slight rise in the fuel consumption. Carbon dioxide emissions will remain relatively neutral while the opacity may increase or decrease.

This work will investigate the performance of a diesel generator unit operating on two different types of biodiesel, one produced locally and one purchased through a commercial supplier. These will be compared to a baseline of standard diesel fuel. The comparison will include investigations into any change in emissions of CO, CO_2, HC, NO_x and opacity as well as changes in the fuel consumption as the load on the generator unit is varied.

Chapter 3: Experimental Test Rig and Instrumentation

This chapter describes the instrumentation, test engine and the methods of data acquisition. The chapter also details the specific biodiesels that were tested as well as the particular blends used. Further, this chapter also outlines the testing procedure used during experimentation.

3.1 Generator Set & Instrumentation

The following section provides a description of the testing equipment used in this work as well as the instrumentation and data acquisition systems required to obtain the necessary information to conduct the performance appraisal. Below, Figure 3.8 shows a schematic of the generating unit used during testing.

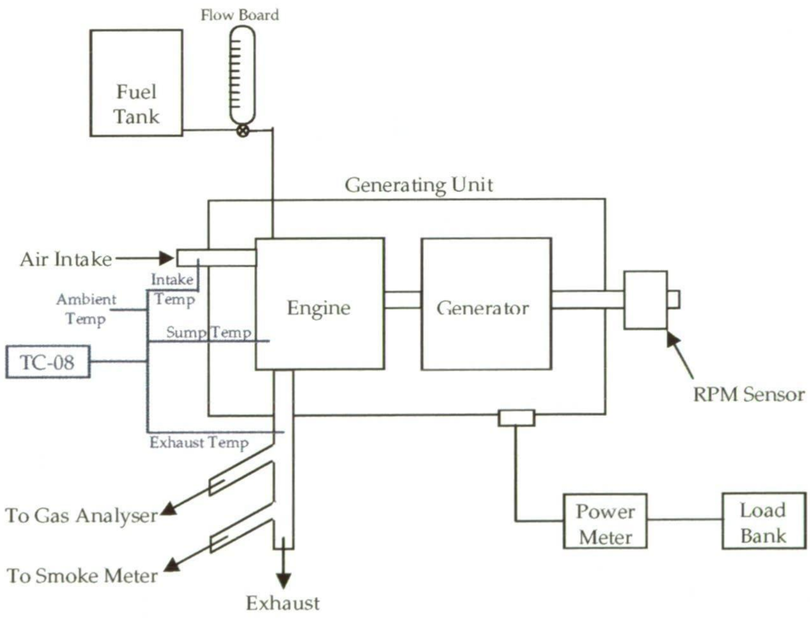


Figure 3.8 Generating Unit Schematic

The schematic is not to scale and does not contain connection details; as such it should be used a guide only for understanding the general methods of data acquisition and set up of the test rig.

3.1.1 Generator Description

The Scorpion 178F, shown in Figure 3.1 consists of a standard diesel engine coupled to an HDY3000L generating unit. This 3.3 kVA silenced diesel generator unit was chosen as a typical generator that consumers may already have in use powered by regular diesel fuel. This generator can represent other diesel engines currently in use in various applications whether they are stationary or mobile applications. The unit is used in testing consists of a single cylinder, vertical 4 stroke direct injection engine which is cooled by forced air. Table 3.1 contains further details of the generator unit.

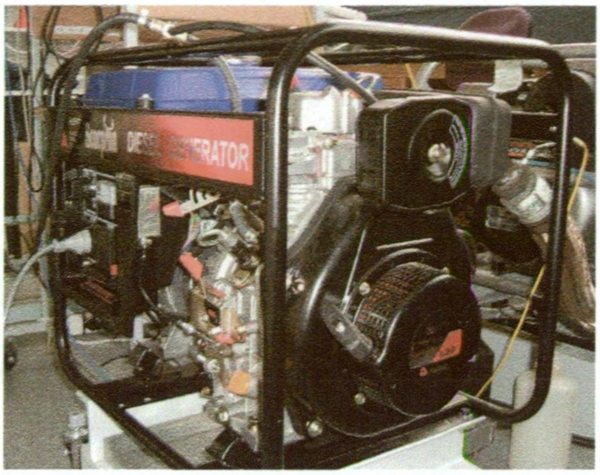


Figure 3.1: Scorpion 178F Diesel Generator

Table 3.1: 178F Technical Specifications [61]

Item	Technical Specification
Bore x Stroke (mm)	78 x 62
Displacement (cc)	296
Nominal Speed(rpm)	3000-3600
Normal Power kW (PS)	5-5.5
Mean Effective Pressure (kPa)	540.5-496.6
Generator Frequency (Hz)	50-60
Net Weight (kg)	78
Engine Rated Output (hp)	5.5
Generator Rating (KVA)	2.8-3.3

This generator was chosen to be a generic, multipurpose generator, suitable for use in a Remote Area Power System (RAPS). These systems are designed for areas that are too remote to be connected to the standard electricity grid. These systems typically have a renewable source, such as wind power, which supplies the load; should there be excess energy generated it is stored in the form of hydrogen or batteries. If the system load exceeds the energy generated when the reserve storage is exhausted, an auxiliary diesel generator is connected to supply the load. Ideally the generator would be run on biodiesel to create a closed system powered by renewable energies.

3.1.2 Load Bank

A variable load bank was used to apply load to the generator. The load may be varied between 1 and 9 kW in 0.250 kW increments; as the generator is rated to 3 kW this was deemed to provide a sufficient range for testing. The electricity drawn is dissipated through resistors as heat; the unit is shown in Figure 3.2

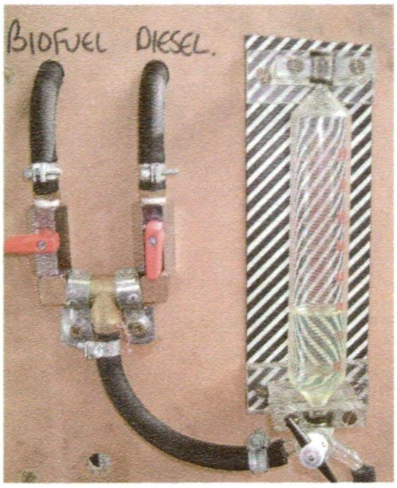
Figure 3.2 – Load Bank

A power meter was used in conjunction with the load bank in order to obtain a reading of the actual power being drawn by the load bank. The device available for use was a single phase 3184 Degital Power Hi Tester produced by Hioki Corp.

There is uncertainty in the readings obtained from the load bank and power meter. The uncertainty in the load bank is dependent on the combination of load resistors used. For example, a switch designed to draw 1 kW will, in reality, draw power ranging from 0.900 kW ± 0.01 kW to 1.150 kW ± 0.01 kW. Variability in the applied load due to error stacking can be minimised by consistency during testing of which switches, or resistors, are applied for each load. The power meter has an uncertainty relating to the resolution; the power meter measured accurate to 0.001 kW; however due to fluctuations and the accuracy of the instrument this must be adjusted to 0.01 kW.

3.1.3 Fuel Flow Rate Measurement

A flow board was used to measure the volumetric flow rate of fuel. The unit consisted of a sight glass, a fuel tank, fuel lines and valves mounted on a mobile stand. The sight glass was labelled with graduations in 1 mL marks ranging from 0-80 mL. As the fuel was consumed the time for a particular displacement, with a minimum of 15 mL displacement, was noted thus providing the information required to perform flow rate calculations. The flow board was grounded to prevent static build up. A photograph of the flow board is shown in Figure 3.3.



Since multiple types of fuel of varying blends were being tested, it was decided that a removable tank system would be implemented to allow easier transition between fuels. The tanks used were made of high density polyethylene (HDPE) bottles with an aspirator, or tap. Crown Scientific Pty Ltd. determined the tanks to be a low risk for wear or failure for the liquids in use in this project [62]. The existing aspirator including valve attachment was discarded as it was deemed not durable enough to undergo the testing. The bottles were connected to the flow board using a device designed to connect the existing threaded section of the aspirator to a valve and spigot. This system, allowed the fuel tank to be switched without requiring the full tank to be used up.

Regarding the uncertainty, the resolution of the glass vial is 1 mL marks and the timing is done manually by an operator. Consequently, the flow rate is accurate to ±0.5 mL/s.

3.1.4 Temperature Measurement and Acquisition

Figure 3.4: TC-08 Thermocouple Data Logger [63]

Engine temperature is an important variable to monitor the engine while performing tests. It is essential for the life of the engine, as well as other instrumentation on the engine that the temperatures remain within the limits specified by the manufacturer. When measuring the emissions of the exhaust it is also important to monitor the temperature as NO_X emissions are closely related to the temperature of the engine. For the purposes of this testing, four locations were monitored for temperature: intake air, exhaust air, ambient and the oil sump temperature. These were monitored using Type K thermocouples. The temperatures from the four thermocouples were connected to a TC-08 Thermocouple Data Logger from Pico Technology Ltd. The TC-08 can record temperatures ranging from -270°C to 1820°C [63] while the thermocouples are capable of reading temperatures ranging from -100°C to 1380°C. Further technical specifications can be found in Table 3.2 and a photograph of the TC-08 can be seen in Figure 3.4.

Table 3.2: TC-08 Technical Specifications

Number of channels	8
Conversion time	100 ms (thermocouple and cold junction compensation)
Temperature accuracy	Sum of ±0.2 % of reading and ±0.5 °C
Voltage accuracy	Sum of ±0.2 % of reading and ±10 µV
Overload protection	±30 V
Maximum common mode voltage	±7.5 V
Input impedance	2 MΩ
Input range (voltage)	±70 mV
Resolution	20 bits
Noise free resolution	16.25 bits
Thermocouple types supported	B, E, J, K, N, R, S, T
Input connectors	Miniature thermocouple
Output connector	USB — cable supplied
PC connection	USB 1.1

The error in the temperature measurement is partially due to the accuracy of the thermocouples. According to the National Institute of Standards and Technology (NIST), a type K thermocouple contains an expected bias error of ± 2.2°C or 0.75% [64].

3.1.5 Engine Speed

It is important to accurately measure the engine speed during testing since variations in engine speed can influence the other quantities being measured. It is also important to ensure that the generator unit is running within its capabilities.

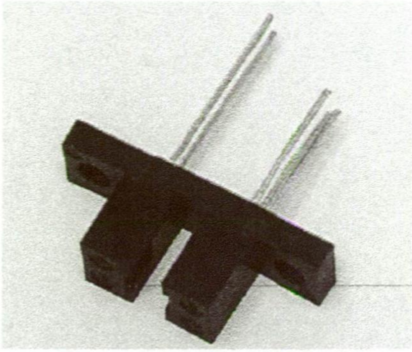


Figure 3.5: HOA2001 [65]

An HOA2001 transmissive Optoschmitt sensor, shown in Figure 3.5 was purchased from Honeywell and installed on the crankshaft of the generating unit as shown in Figure 3.6.

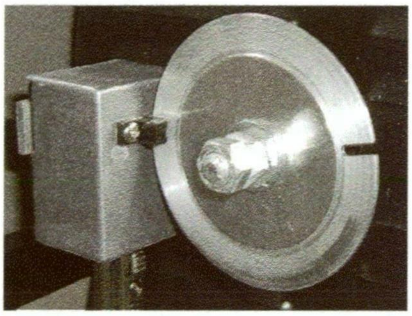


Figure 3.6: HOA2001 as installed

The HOA2001 features direct TTL interface, buffer logic, 1.52 mm diameter detector aperture, 3.05 mm slot width and 1.27 mm offset pin circle detector ends. This sensor operates using an infrared emitting diode facing an Optoschmitt detector encased in black plastic. The buffer logic provides a high output when the optical path is clear and a low output when the path is interrupted [65]. This output is a pulse which is translated in to rpm and acquired using a N16025E board using the LabView software.

A disc with a 3 mm notch cut out was directly coupled to main shaft. The HOA2001 was installed such that the notched disc would pass through the slot of the sensor. As the disc rotates and the notch passes though the sensor, the output of the sensor changes from high to low resulting in a pulse that is counted for each revolution of the shaft.

3.1.6 Emissions Measurement

To measure the emissions of the generating set a TECPAC II 5 Gas Analyser was used. This analyser measured hydrocarbons, carbon monoxide, carbon dioxide, oxygen and nitrous oxide. The HC, CO and CO_2 were measured using non dispersive infrared technology while an electrochemical cell was implemented for the measurement of oxygen and nitrous oxide. A triple filtration device and Delphi HDF296 water trap were installed on the analyser to remove excess particulate matter and moisture which are commonly associated with diesel exhaust. The moisture and particulate matter need to be removed since they impair the analyser from accurately measuring the emissions required. The analyser, water trap and filters are shown in Figure 3.7. Further technical specifications can be found below in Table 3.3.

Figure 3.7: TECPAC II, Water Trap and Filtration system

Table 3.3: Specifications for TECPAC II

Emission	Range	Accuracy
HC	0 – 2000 ppm	± 4 ppm absolute
CO	0.00 – 10.00%	± 0.02% absolute
CO_2	0.00 – 16.00%	± 0.30% absolute
O_2	0.00 – 25.00%	± 0.10% absolute
NO	0000 – 4000 ppm	± 25 ppm absolute

3.1.7 Opacity Measurement

The device used to measure the opacity of the exhaust was a LCS 2100 manufactured by Sensor Inc. and is shown in Figure 3.7. The LCS is a Smokemeter designed to measure the emissions of diesel cars and trucks using the partial-stream measuring technique. This instrument measures the amount of light transmitted using a scale that ranges from zero to 100%: zero means that all light has been transmitted and thus represents zero opacity, 100% indicates that all light has been blocked, 100% opacity represents completely black smoke. The light source used in the analyser is a green LED which pulses with a peak at 560 nm [66]. Further specifications can be found in Table 3.3 and a photograph of the device in Figure 3.8.

Figure 3.8: LCS 2100 Smoke Meter [66]

Table 3.3: LCS 2100 Product Specifications [66]

Operational Temperature	5°C – 40°C
Response Time	1 msec
Humidity	0 – 95%
Pneumatic Stability	± 1.0 %
Acoustic Noise	53 dba
Opacity Accuracy	± 2 % relative
Pressure	0 … 10 kPa ± 0.2 kPa
Communication	Via RS-232 async

The level of accuracy stated by the manufacturer is ± 2 % of the reading. However, in practice, readings of exhaust gas opacity tend to fluctuated significantly. For a given load and operating conditions the opacity readings will fluctuate resulting in an overall uncertainty of ± 4 % at steady state conditions.

3.2 Test Fuels

Three types of fuel were tested during this work: a petroleum based diesel was tested as a baseline for comparison, and two biodiesels with varying blends. The first biodiesel tested was a fuel developed by the University of Tasmania using locally grown plant oils, the second was a commercially obtainable biodiesel produced by South Australian Farmers Fuel (SAFF).

3.2.1 Blends Tested

Testing of a petroleum diesel was conducted to allow comparison with the various biodiesel blends. Three blends of each biodiesel were tested in the same manner: B5, B20 and B100. These were chosen as representatives of typical blends in which biodiesel is used. The mixing of all biodiesel and blends was conducted in house.

Low levels of biodiesel mixed with diesel can be particularly beneficial in diesel fuels which have been produced to conform to the new ultra low sulphur regulations as these ultra low sulphur diesels have serious lubrication problems. The addition of even small quantities of biodiesels can alleviate these problems by providing increased lubricity without increased sulphur. As a result B5 was tested as it is a common additive to reduce sulphur and increase lubricity[31].

B20 was chosen, as it is the most common blend of biodiesel currently in use. B20 has been favoured as it has proven to be a reliable fuel which is practical since few precautions or modifications are required for its implementation. This is because B20 has very similar properties to that of conventional diesel and studies have shown that it balances performance and emissions benefits with the cost [31]. It can also be used in conventional diesel engines with minimal risk of failure or serious complications.

It is important to consider B100 as well, as this would be the ideal fuel to use as it contains no fossil fuels and is 100% renewable. However, care must be taken when operating an engine on B100 as modifications such as the use of heaters, changing seals, hoses or gaskets that encounter the fuel may or may not be required.

3.2.2 Tasmanian Biodiesel

The first biodiesel to be tested was a fuel created by the University of Tasmania and is derived from locally grown oils. The types of oil used in the Tasmanian fuel are canola (75%), poppy seed (25%); methanol was used as the alcohol and potassium hydroxide was the catalyst. The innovation patent recipe used was developed by Vishy Karri [67] as part of a project within the School of Engineering. The biodiesel was produced onsite using a Catalyst Reactor CR-102, a Biodiesel Reactor BR-103, a Settling Tank ST 105 and Washing Tank WT-107.

The Tasmanian biodiesl was tested by an external source to ensure its adherence to the defined Australian Standards. The company which performed the tests was Oilcheck Pty Ltd based in New South Wales; a summary of the results and testing methods are shown in Table 3.4 as well as a comparison to the prescribed standard limits.

Table 3.4: Results of TasFuel Testing and Adherence to Standards

SCH Biodiesel	**Results**	**Limits**	**Test Method**
Clarity	Clear & Bright		ASTM D4176
Visible Particulates	Nil		ASTM D4176
Visible Free Water	Nil		ASTM D4176
Test Result	Pass		
Test Temperature	23 °C		
Moisture (Coulometric KF)	0.05 % w/w		ASTM D6304
Particulate Contamination	8.5 mg/L	Max 24 mg/L	ASTM D5452
Density at 15°C	0.8858 kg/L	0.860 – 0.890 kg/L	ASTM D 4052/D1250
Flash Point	174.0°C	Min 120.0 °C	ASTM D93
Sulphated Ash Content	0.005 % Mass	Max 0.020 % mass	ASTM D874
Sulphur	< 5 µg/g	Max 10 µg/g	ASTM D5453
Copper Corrosion of Oil	1A	Max 3A	ASTM D130
Carbon Residue-Micro	0.060 % m/m	Max 0.050 % m/m	ASTM D4530
Acid Number	0.23 mg KOH/g	Max 0.8 mg KOH/g	ASTM D664
Kinematic Viscosity at 40°C	4.655 mm^2/s	3.5 – 5.0 mm^2/s	ASTM D 445
Ester Content	96.3 % (m/m)	Min 96.5 % (m/m)	EN 14103
Alcohol Content	0.053 %	Max 0.20 %	OL 1097
Phosphorous	< 1 mg/kg	Max 10 mg/kg	ASTM D4951
Metals: Group I (Na, K)	1, 1 mg/kg	Max 5 mg/kg	ASTM D5185
Metals: Group II (Ca, Mg)	2, < 1 mg/kg	Max 5 mg/kg	ASTM D5185
Oxidation Stability: Test Result (hrs)	0.3 hrs	Min 6 hrs	EN 14112
Oxidation Stability: Test Temperature	110°C		EN 14112
Glycerine – Free	0.003 mass %	Max 0.020 mass %	ASTM D6584
Glycerine – Total	0.247 mass %	Max 0.250 mass %	ASTM D6584

It can be noted that some specifications do not match the standard: carbon residue, ester content and oxidation stability. The carbon residue is 0.010 % m/m higher than specified; this value corresponds to the level of glycerides, free fatty acid, catalyst or other impurities remaining in the fuel. A higher value means the Tasmanian biodiesel will have a higher tendency to form engine deposits. The ester content is a measure of how complete the transesterification reaction has been. The ester content for the Tasmanian fuel is 0.2 % (m/m) lower than expected; however when accounting for the repeatability factors related to the machine use, and the lab in which it was tested, the fuel does fall within the specified range. Finally the oxidation stability is significantly lower than the standard specifies; 0.3 hrs as opposed to 6 hrs. The oxidative stability is determined by the level of unsaturation; oxidation of biodiesel results in aldehydes and acids which increases the formation of sediments and gums [68].

3.2.3 South Australian Farmers Fuel

The biodiesel produced by SAFF is derived from used cooking oil and canola oil. This biodiesel was obtained in order to carry out a comparison of a commercial biodiesel with the new recipe developed by the University of Tasmania. SAFF is based in South Australia and was the first government approved and operating biodiesel retailer in Australia. Currently SAFF sells their biodiesel at more than fifty retailers within Australia. SAFF highlighted two common problems reported with their biodiesel; one is that shortly after switching to SAFF biodiesel customer's fuel filters required changing. This is a result of the previously discussed solvency properties of biodiesel in Section 2.2.3.3. The second problem reported was the softening of rubber hoses and seals [69]. Incidentally, both these problems are common to all biodiesel use and should be considered prior to the use of biodiesel as a fuel [70].

3.3 *Experimental Procedure*

This testing portion of this study will be conducted in a similar manner to the standards specified by the international body ISO. Adhering to standard testing method allows comparison of results between different testing bodies. The following sections describe the procedures used during the testing in this project as well as the methods of taking measurements.

3.3.1 Testing Standards

The test cycle used in this work was based on the standard ISO 8178 Part 4: Reciprocating Internal Combustion Engines – Exhaust Emission Measurement Part 4: Test Cycles for Different Engine.

3.3.1.1 Test Cycle

The standard ISO 8178-4 defines various test cycles to be used depending on the type of engine and its application. Cycles D1 and D2 refer to engines run at a constant speed and are applicable for generators. The Two cycles were conducted consecutively to allow data acquisition at a wider range of operating conditions [71].

The chart below, Table 3.5, outlines test cycles D1 and D2; the torque figures are percentage values of the Torque corresponding to the continuous and prime power ratings as defined in ISO 1878-1

Table 3.5: ISO 8178 – 4 Test Cycles D1 and D2 [71]

Mode No.	1	2	3	4	5
Cycle D1					
Torque %	100	75	50		
Cycle D2					
Torque %	100	75	50	25	10

The cycles, D1 and D2, may be added to make a single test cycle by performing the cycles consecutively to create an eight mode test cycle. Consequently the sequence of applied loads during the test cycle was 100%, 75%, 50%, 100%, 75%, 50%, 25% and 10%.

3.3.2 Test Conditions

Prior to testing the engine must undergo a preconditioning phase to warm the engine and to obtain steady state conditions. The length of the preconditioning phase was determined by running the engine from a cold start, first with no load as specified by the manufacturer, and monitoring the temperature and emissions until all had reached a plateau.

It was also necessary to determine the stabilisation time for each test mode after adding a load. This was done by simply adding the loads as specified in the test cycle after the preconditioning period and then monitoring the emissions and temperature readings until stabilised. It was found that a 5 minute mode length provided sufficient time for both stabilisation and measurements. As a result, the mode length was determined to be five minutes, with the final two minutes used for data acquisition.

Testing was conducted following the provisions of a minimum length of test mode of 5 minutes; exhaust emissions measured and recorded for the last 2 minutes of the mode; sampling of particulate matter was coincident with the sampling of the gaseous emissions and must not commence prior to engine stabilisation [71]. The mode length is defined as the time between leaving the speed/torque of the previous mode and the beginning of the following mode.

3.3.3 Testing Procedure

The steps used during testing are listed below:

Step 1: Preconditioning Period
Run Engine at No Load for 15 minutes

Step 2: Test Cycle
- a) Add Load as specified
- b) Stabilisation period: 3 minutes
- c) 2 minutes data acquisition
  - a. To be logged automatically:
    - i. Gas Analyser
    - ii. Opacity
    - iii. RPM
    - iv. Air Intake Temperature, Exhaust Temperature, Sump Temperature and Ambient Temperature
  - b. To be logged manually:
    - i. Power – make note of actual power drawn from generator
    - ii. Fuel Consumption
- d) Change Load: Return to start of step c) and repeat for each mode

Step 3: When test cycle complete store data for further analysis

This process is summarised below in Figure 3.9 as a flow chart.

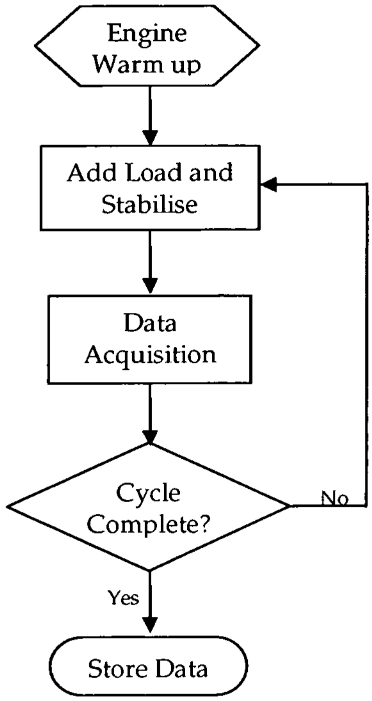


Figure 3.9: Flow chart of testing process

This process will be repeated a minimum of three times for each fuel tested to ensure the testing data is accurate and repeatable. In order to switch between the different types of fuels, it is necessary to purge the fuel lines of the system to ensure that the fuel delivered to the engine is the same as the fuel in the tank to be tested. To do this, it is necessary to determine the approximate volume of the fuel delivery system and then flush the system three times using the determined volume as a minimum volume for each flush. The system was flushed in this way three times with the new fuel before the test cycle began.

3.4 Concluding Remarks

This section has described the test rig used during the experimentation. The instrumentation and equipment described in this chapter were used under the methods as outlined in Section 3.3 to conduct the required testing. The following chapter presents the results obtained and discusses the relevance to current literature.

Chapter 4: Results and Analysis

The tests as outlined in Chapter 3 were conducted and the data relating to the performance of the engine was collected for each fuel. This data was complied into an experimental matrix. The matrix summarises all data obtained including the load applied, emissions and opacity, rpm, fuel consumption and temperatures at the air inlet, exhaust outlet, sump and ambient. The load was applied as a percentage of the rated power at levels of 10%, 25%, 50%, 75% and 100%. This chapter presents the results obtained focusing on the emissions, opacity and fuel consumption presented as a factor of the applied load. This chapter also contains a discussion of the observed results and how they relate to current literature.

It will be noted in the following results that there is a marked change in the data obtained between 75% and 100% of the rated power. This is because the maximum rated output of the engine is stated as 2.8 - 3.3 KVA. The upper limit of 3.3 KVA was chosen in order to investigate the performance of the engine when operating at the extreme limit of its capability. The results indicate that the upper limit of the rated power is not a preferred operating level as all the results showed a sharp increase from the previous level of 75%.

This chapter presents the emissions data obtained during experimentation. The testing procedure was first carried out using straight diesel fuel; this was done to create a baseline with which to compare the performance of the biodiesels and the blends. The data is presented showing the emissions as a function of the load applied beginning at a low load of 10% of the rated power and increasing to 100% of the rated power for each of the four analysed emissions, the opacity and the fuel consumption.

4.1 Emissions

The emissions measurements were collected using the gas analyser and smoke meter as detailed in sections 3.1.6 and 3.1.7 respectively. This section discusses the trends observed for each of the four exhaust emissions

4.1.1 Carbon Monoxide

As the load is increased, the emissions of carbon monoxide decreased. At low loads, the emissions of carbon monoxide decreased with an increase in biodiesel content of the fuel. At the lowest applied load, 10% of the rated power, the largest decrease of CO emissions resulted from the South Australian B100, which resulted in a decrease of 19.9%; the Tasmania B100 also showed a large decrease at this load with a decrease of 12.3%. The blends of B20 proved to have moderate impact on CO emissions showing a decrease of 3.0% and 8.9% for SAFF and Tasmania respectively, while the blends of B5 showed minor changes of +0.1% and -1.8% for SAFF and Tasmania respectively when compared with petroleum based diesel. Figure 4.1 shows the emissions of carbon monoxide as a percentage composition of the exhaust compared with the applied load, while Figure 4.2 summarises the percentage change of CO emissions for each fuel, at each load, relative to the CO emissions of pure diesel fuel.

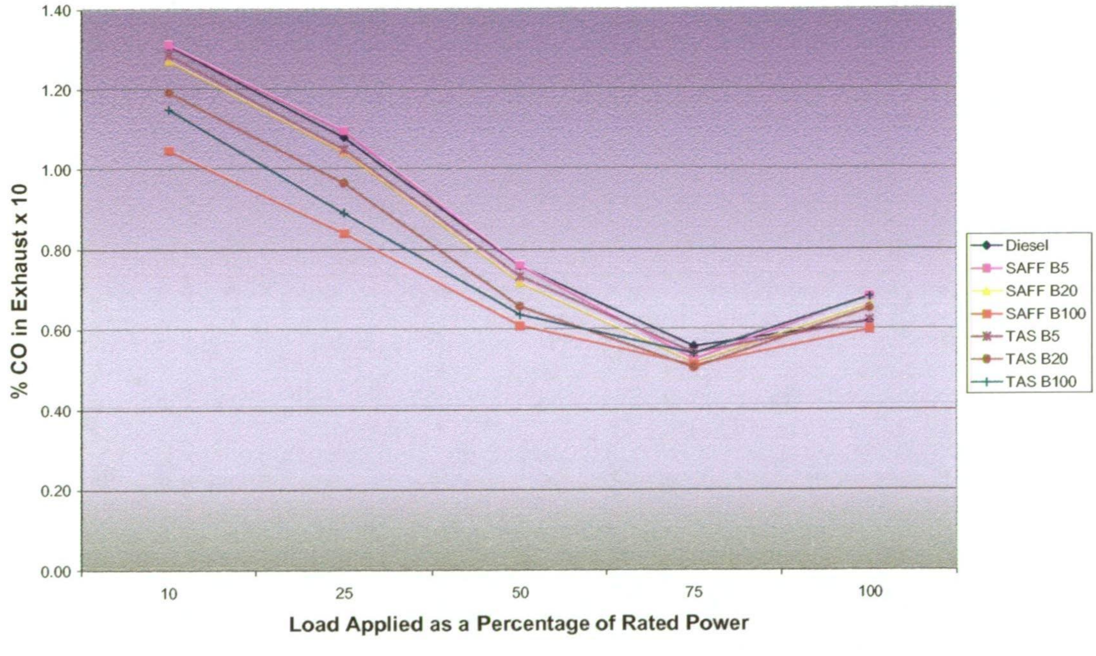


Figure 4.1: Variation of %CO in the Exhaust related to Load Applied

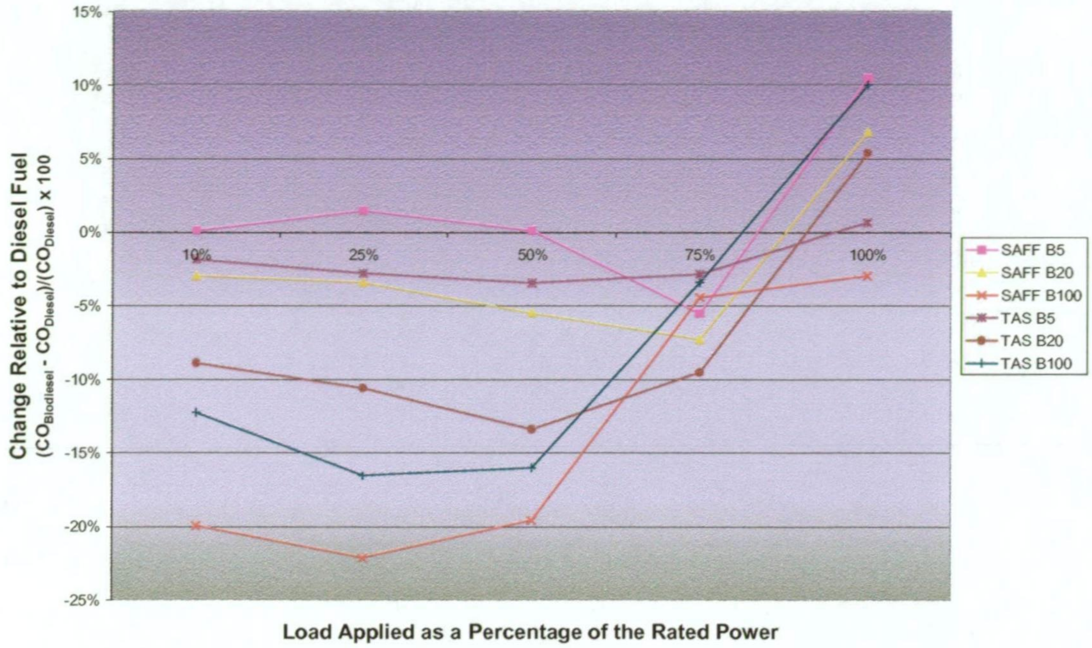


Figure 4.2: Carbon Monoxide Emissions Relative to Diesel Fuel related to Load Applied

As the load increases past 50% of the rated power, the relative difference between the CO emissions of the biodiesel blends and the diesel fuel decreases; when the applied load is 75% of the rated power, the relative difference between the CO emissions of diesel fuel and biodiesel is at a minium. At this point, all blends showed a decrease in CO emissions with the largest decreases belonging to the blends of B20 which produced reductions of 7.3% and 9.5% for the South Australian and Tasmanian fuels respectively.

When operating the generator unit at 100% of the rated power all emissions increased from when the load applied was 75% and all but SAFF B100 surpassed the diesel emissions of CO. The blends of biodiesel and diesel fuel, as well as the Tasmanian B100, produced an increase in the level of CO emissions. The largest increase was SAFF B5 blend which resulted in a 10.5% increase, closely followed by the Tasmanian B100 which resulted in a rise in CO emissions of 10.0% over diesel fuel; a graphical summary is shown in Figure 4.2.

The trends demonstrated in Figures 4.1 and 4.2 followed the expected pattern of a reduction of CO emissions over most loads because of biodiesel use. The cause of the patterns can be explained through the processes of carbon monoxide formation and elimination reactions which occur during and after combustion within the engine; details of these reactions can be found in Section 2.5.1.1. The visible increase between the applied load of 75% and 100% power is an expected occurrence due to the decrease in the air available fro reaction. This lack of air results in higher levels of CO in the exhaust despite the elevated temperatures because of the low concentration of oxidants and shortened reaction time. Consequently, there is an optimal load at which to operate the engine that would produce minimal emissions of carbon monoxide [41]. For this engine the load which would produce the lowest levels of CO emissions is near 75% of the rated power; however, further testing is required to accurately specify the optimal point.

The reason that biodiesel and blends of biodiesel and petroleum diesel produce lower levels of carbon monoxide emissions is that the rate of elimination of CO is related to the amount of oxygen present. Biodiesel, as a fuel, contains inherently higher levels of oxygen therefore, when combustion occurs there is more available oxygen which can react with the carbon monoxide allowing more elimination reactions to occur and thus decrease the amount of CO which is emitted in the exhaust [44, 72]. This situation is more prevalent with higher concentrations of biodiesel.

These results are consistent with current literature which all report a decrease in the emissions of carbon monoxide regardless of the type of oil used to create the biodiesel. Dorado et al. showed a significant decrease in the CO emissions measuring 58.9% below that of the diesel emissions when using a biodiesel derived from waste olive oil methyl esters [49]; while this is a decrease in the level of emissions it is significantly larger than the result obtained during this work, it is also significantly larger than other tests which have been conducted. Gomez et al., Last et al. and Ulusoy et al. all showed more moderate decreases in CO emissions; the largest decrease of these three was presented by Ulusoy et al. which reported a decrease of 8.59% compared to diesel fuel [42, 48, 73]. One study conduced by Lue et al. confirmed the results that increased at high loads; Lue et al. reported minor decreases in the emissions of CO over various speeds with a sharp increase at the maximum load [44].

The results showed higher levels of CO emissions at low loads; however, the use of biodiesel provided a more significant reduction in the CO emissions at these same low loads. As the load increased the benefit, in terms of emissions reduction, with the use of biodiesel decreased. At the maximum rated load the CO emissions showed a slight increase over the emissions at 75% of the rated power and the majority of the biodiesel fuels and blends resulted in an increase of CO emissions relative to diesel fuel. These results are the expected outcome of the testing and are consistent with current literature.

4.1.2 Hydrocarbon Emissions

The emissions of hydrocarbons did not show a strong correlation with the load applied; most of the fuels produced consistent levels of HC regardless of load which fluctuated within a range of 10 ppm HC or less. The Tasmanian B100 showed the most consistent and largest amount of reduction at all loads, ranging from 12.5% to 25.2% reduction for power levels of 100% and 75% respectively. Figure 4.3 shows a graphical representation of the data relating to the amount of hydrocarbons present in the exhaust while Figure 4.4 shows the increase or decrease in emissions relative to the emissions of diesel fuel.

The two blends of the Tasmanian fuel, B5 and B20, as well as SAFF B20 all showed consistent reductions in HC emissions. The Tasmanian B20 showed a decrease of approximately 20% of HC emissions when operating at 10%, 25% and 50% loads then moving to a reduction of 10.1% and 8.1% for loads of 75% and 100% respectively. Tasmanian B5 HC emissions were fairly consistent with an 8% reduction while the SAFF B20 emissions fluctuated resulting in percentage changes ranging from +0.5% to -17.9% relative to diesel fuel.

Two fuels, SAFF B5 and B100 showed consistent increases in hydrocarbon emissions relative to diesel emissions. SAFF B5 emissions were consistently higher and ranged from 9.7% increase at low load to 15.3% at 75% load. SAFF B100 showed a decrease of 2.3% when at low load; however, the emissions jumped to an increase of 9.5% over diesel fuel when running at 50% of the rated power. The emissions then decreased to a reduction of -0.1% when the generator was operating at 100% of the rated power.

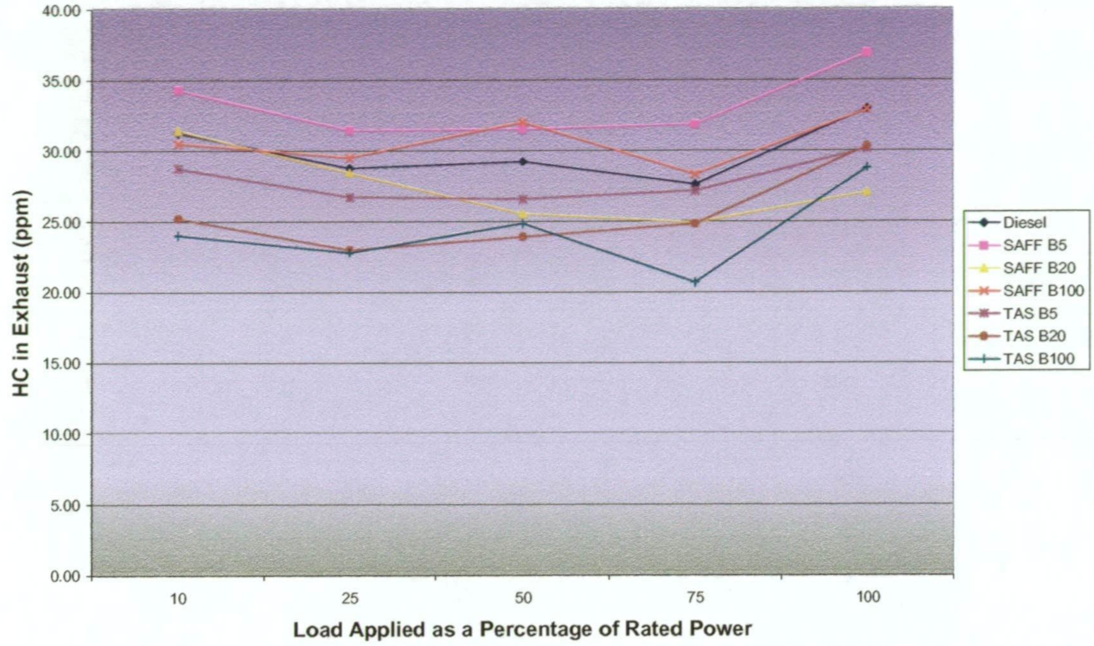


Figure 4.3: Hydrocarbon Content in the Exhaust related to Load Applied

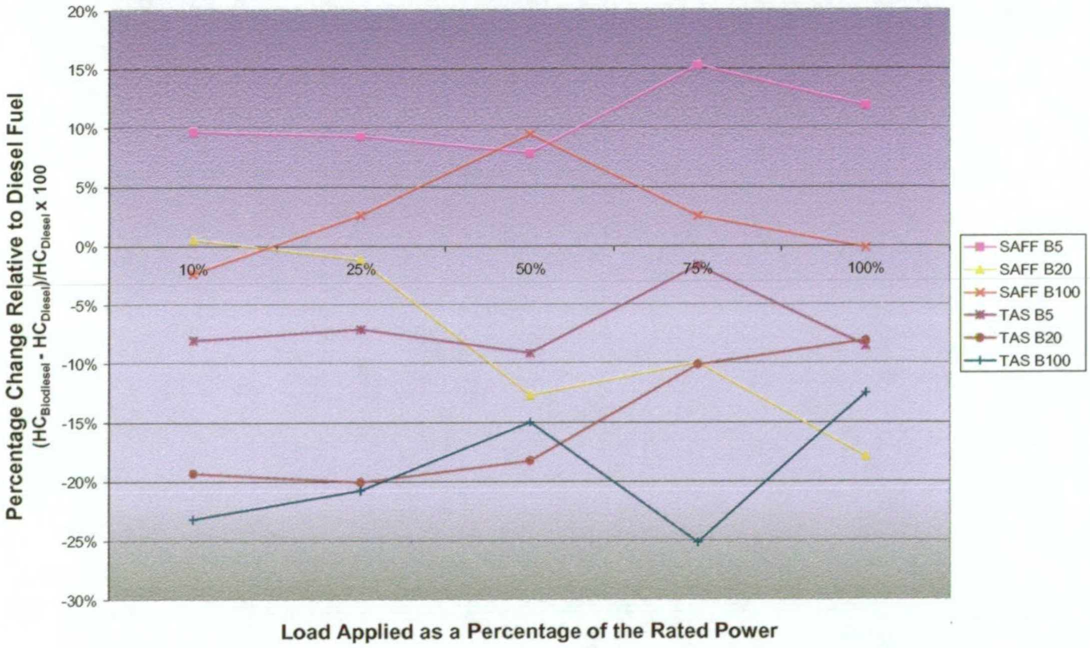


Figure 4.4: Hydrocarbon Emissions relative to Diesel Fuel related to Load Applied

The chemical composition and physical properties of the fuel play a large role in determining the propensity a fuel has to hydrocarbon emission. Without detailed information on the composition of the fuel and quantitative indicators such as the cetane number, it is difficult to determine the reasons for the trends. For example, no such information is available on the South Australian fuel unless an extensive analysis is carried out; however, it was not possible to conduct this analysis due to lack of resources and equipment. As a result, it is difficult to speculate the reasons behind why the B5 and B100 blends produced an increase in HC emissions while the B20 blend resulted in a decrease. Typically, biodiesels produce fewer HC emissions because they possess superior combustion characteristics such as a higher cetane number which promote more complete combustion within the cylinder. This is consistent with the results obtained for all fuels except for the SAFF B5 and B100; which, without information regarding the composition of the fuel, is not possible to determine reasons behind this occurrence.

The results for the Tasmanian biodiesel are consistent with current literature which reports a decrease in hydrocarbon emissions through using biodiesel due to improved combustion. Canakci et al. produced a larger reduction in hydrocarbon emissions of 42.5% compared with diesel fuel for B100; the same tests showed amore moderate reduction of 2.9% for B20 for a soy based biodiesel [20]. Ulusoy et al. and Last et al. showed similar results in which there was a reduction in hydrocarbon emissions of 30.66% and 28% respectively as compared to diesel fuel [42, 73]. Krahl et al. studied the effect of rapeseed oil methyl esters and determined that the hydrocarbon emissions were reduced by 30-50% depending on engine settings [58]. Additionally, in a study conducted by Ali et al. which investigated the effect of methyl soyate as compared to diesel fuel showed that there was no affect on the emissions of hydrocarbons as the speed was varied [74].

In general, the emissions of hydrocarbons showed little dependence on the load applied and more dependence on the type of fuel used. Four of the six biodiesels and blends tested showed a decrease in hydrocarbon emissions as compared to diesel fuel while two blends, SAFF B5 and SAFF B100 caused the HC emissions to increase. The four fuels which resulted in a decrease of HC emissions conform to current literature which concludes that biodiesels will reduce the levels of hydrocarbons emitted because of superior combustion characteristics. The two fuels which resulted in an increase were obtained from South Australian Farmers Fuel; consequently there was no information regarding the chemical composition of the fuel, thus it was not possible to determine the reasons behind the increase.

4.1.3 Carbon Dioxide Emissions

Carbon dioxide emissions were affected by the load applied but were not influenced by the biodiesel content of the fuel. At 10% of the rated power, the exhaust emissions contained approximately 2.5% carbon dioxide. As the load applied increased, the carbon dioxide emissions increased as well, with the highest CO_2 levels being approximately 6.75%. Regardless of the load applied, there was very small deviation from the carbon dioxide emissions of diesel fuel. At all loads the largest deviation was a 4.2% increase for SAFF B100 at a load of 75%; The next largest deviation occurred when the engine was operating at the upper limits of its capability at 100% of the rated power fuelled by the Tasmanian B100 which resulted in an increase of 2.1% over diesel emissions of CO_2.

Figure 4.5 shows a graphical representation of the effect of load on the emissions of carbon dioxide. It can be seen that all emissions of carbon dioxide followed the same trends yielding nearly identical results regardless of the fuel being tested. When the load applied was equal to 100% of the rated power the results can be seen to diverge slightly and show a higher variation from diesel fuel. Figure 4.5 presents the percentage change of the biodiesel emissions relative to those of diesel emissions.

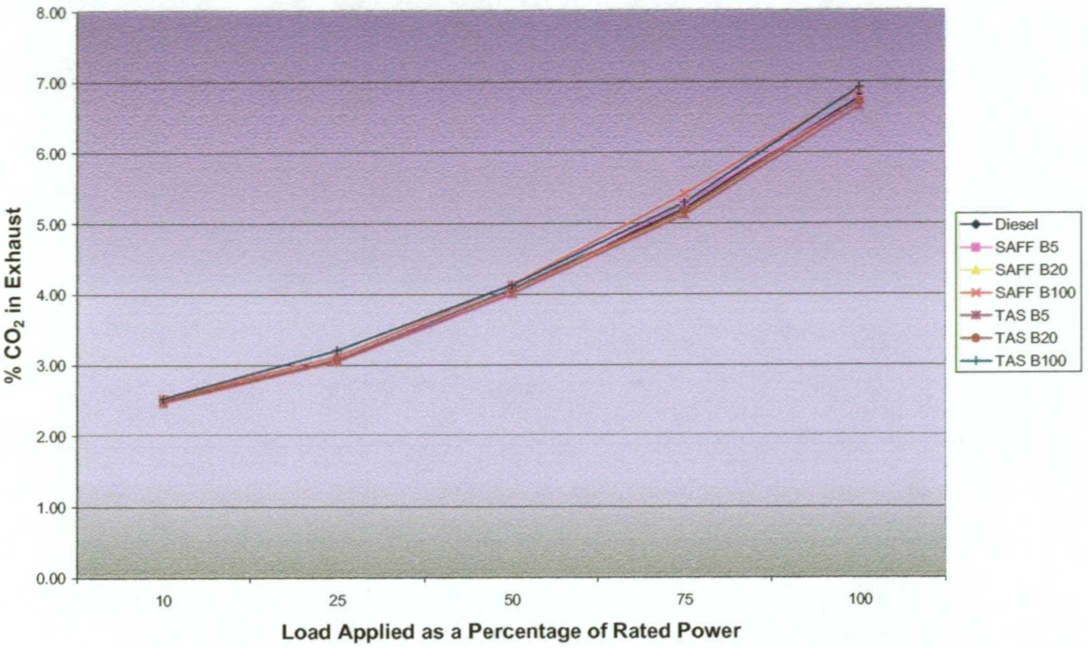


Figure 4.5: Carbon Dioxide Content in Exhaust Emissions related to Load Applied

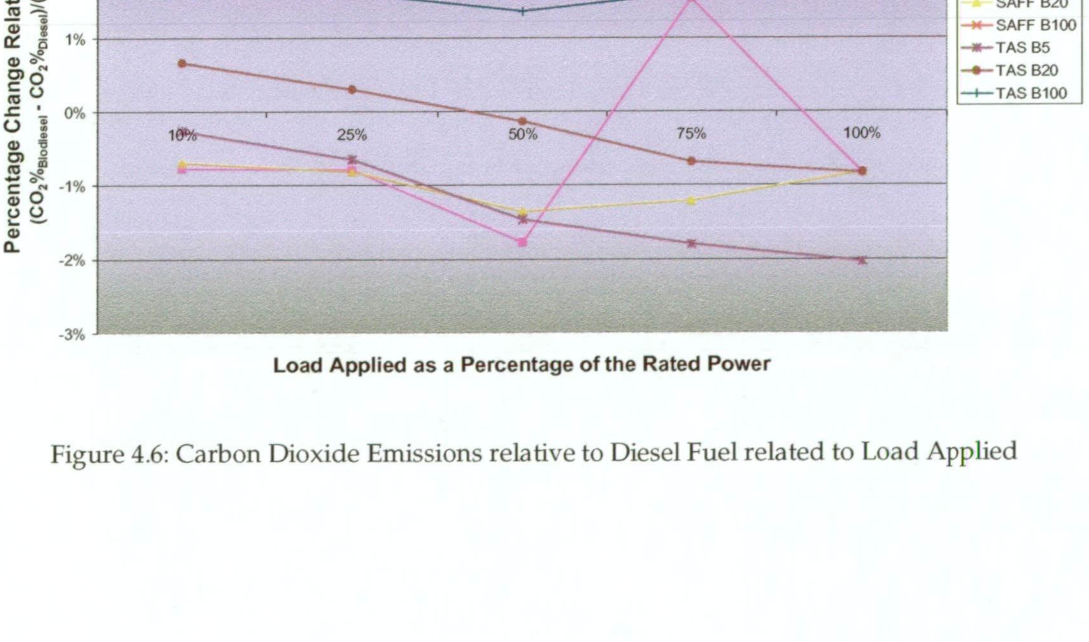


Figure 4.6: Carbon Dioxide Emissions relative to Diesel Fuel related to Load Applied

These results are consistent with current literature, which report a variety of minor increases and decreases in the emissions of carbon dioxide. Canacki reported an increase of 0.5% and 0.1% for B100 and B20 respectively [20]. Gomez et al. tested waste cooking oil based biodiesel; the biodiesel resulted in higher levels of CO_2 emissions at low loads and lower emissions at high loads relative to petroleum based diesel fuel [48]. Finally, Ulusoy et al. reported an increase in carbon dioxide emissions of 2.62% as compared with diesel fuel [42]. These results are within range of what is expected as the benefit biodiesel presents in relation to carbon dioxide is not a decrease in tailpipe exhaust emissions but in an over all reduction during the life cycle of the fuel.

The emissions of carbon dioxide increased with increasing load and little variation was observed because of biodiesels use. These results performed as expected based on current literature and according to the combustion processes which occur within the engine.

4.1.4 Nitrous Oxide Emissions

The emissions of NO are directly related to the load applied; as the load is increased, the emissions of nitrous oxide increase as well. At low loads, the impact of biodiesel use is greater than at higher loads. When the applied load is 10% of the rated power the NO emissions range from 84 ppm (diesel) to 108 ppm (SAFF B100). The two fuels which showed minor increases of NO emissions over diesel fuel were SAFF B5 and B20 with increases of 0.7% and 7.9% respectively. All other fuels showed a significant increase in the emissions of NO over diesel fuel. The Tasmanian fuel showed increases of 19.5%, 22.9% and 26.4% for B5, B20 and B100 respectively while the South Australian B100 produced the highest levels of emissions with a 29.8% increase when compared with conventional diesel fuel.

As the applied load increased, the level of NO emissions increased as well but the difference between diesel and biodiesel decreased. At 100% of the rated power, the emissions due to biodiesel generally increased by approximately 2.5% with the largest increase being SAFF B20 blend showing an increase of 3.9%; the lowest change reported was the SAFF B100 with a decrease of 0.2%. A graphical representation of the results can be seen in Figure 4.7 while Figure 4.8 shows the percentage change in NO levels relative to diesel fuel.

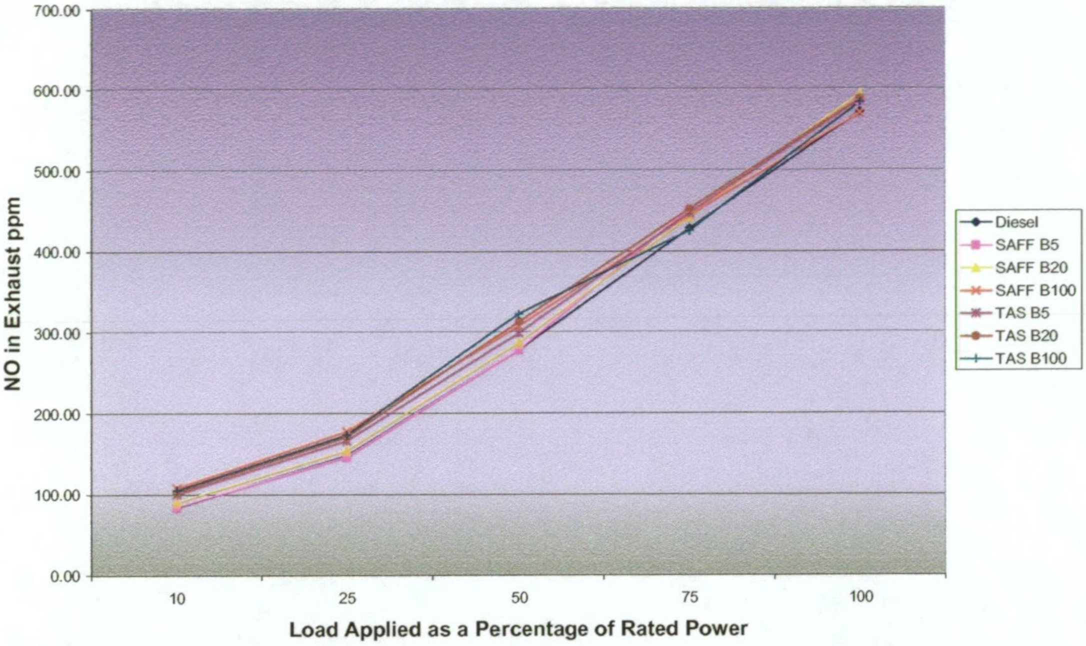


Figure 4.7: Nitrous Oxide Content in the Exhaust Emissions related to Load Applied

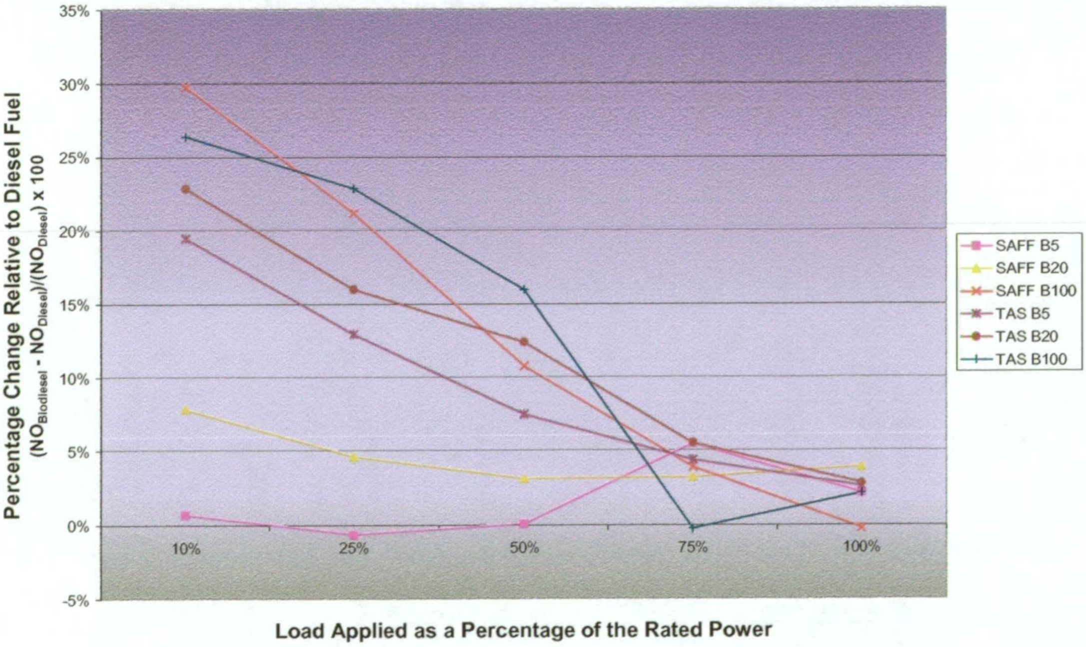


Figure 4.8: Nitrous Oxide Emissions relative to Diesel Fuel related to Load Applied

Nearly all studies conducted on the impact of biodiesel use conclude that biodiesel use results in an increase in the level of NO emissions. The study conducted by Ulusoy et al. determined that the increase in NO emissions was equal to 5.03% [42]; as well, a study by Krahl et al. in Germany concluded that rapeseed oil methyl esters resulted in an increase in NO emissions [58]. One study, conducted by Leung et al. showed similar results to those obtained in this work; the nitrous oxide emissions had a significant increase at the low loads, however, when the load was increased, the NO emissions of biodiesel become comparable to the emissions of diesel fuel [52].

The fuels performed as expected during testing; the levels of nitrous oxide emissions increased with increasing load and biodiesel consistently caused higher emissions than diesel fuel. As previously discussed, one of the few detrimental effects of biodiesels is their tendency to cause an increase in the emissions of nitrous oxides. Amongst other reasons, discussed in Section 2.3.1.4, biodiesels have a higher number of double carbon bonds in the fuel which directly related to the levels of NO emitted by that fuel. This is particularly important with the Tasmanian biodiesel since it contains 25% poppy seed oil which has a high iodine number; thus the overall fuel has a higher iodine number than the SAFF blend which, according to literature, predicts that it will emit higher levels of nitrous oxide.

4.2 Opacity

The level of opacity present in the exhaust is impacted by the amount of load applied. At low loads, the level of opacity was approximately 1% for diesel fuel and the biodiesel blends; however, levels were slightly higher for both the Tasmanian and SAFF B100s with the SAFF producing a level of 2% and Tasmanian biodiesel producing approximately 3% opacity. As the applied load increased, the level of opacity increased as well; the amount of increase was steady between loads up to 75% of the rated power, but showed a drastic rise for the load equal to 100% of the rated power.

At low loads, the difference between biodiesel blends and diesel fuel is significantly larger than at high loads. When the load applied was equal to 10% the increase in opacity due to biodiesel use ranged from 28.5% for SAFF B5 to 337.3% for Tasmanian B100; one fuel, Tasmanian B5, showed a minor decrease of -0.3%. As higher loads are applied this relative increase of opacity decreases; when the load applied is 100% of the rated power the increases range from 14.5% for SAFF B20 to 43.7% for Tasmanian B20, the SAFF B100 was the only fuel to produce a reduction in opacity. The load that showed the optimal performance in terms opacity emissions is when the load applied is equal to 50% of the rated power. At this load all fuels, except for the Tasmanian B100 showed a decrease in the level of opacity emitted. The amount of decreases ranged from -2.7% for SAFF B100 to -15.0% for SAFF B5; however, the Tasmanian B100 produced a significant increase of 29.4%. Figure 4.9 shows a graphical representation of the opacity level in the exhaust while Figure 4.10 presents the percentage change between the opacity of each fuel and the opacity of diesel fuel.

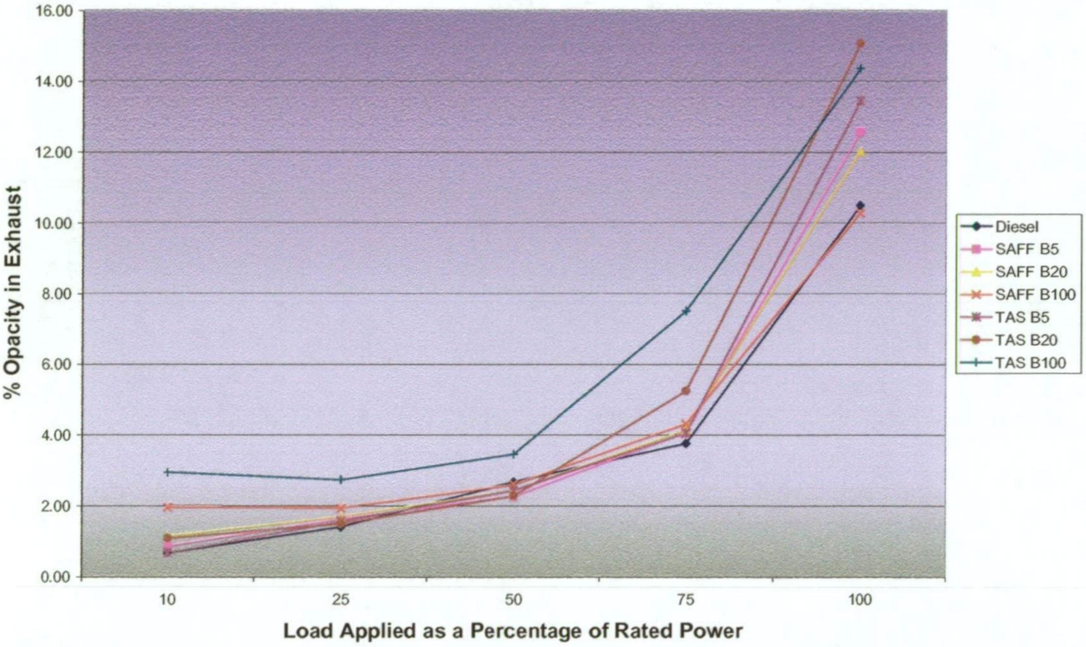


Figure 4.9: Opacity Level of Exhaust Emissions related to Load Applied

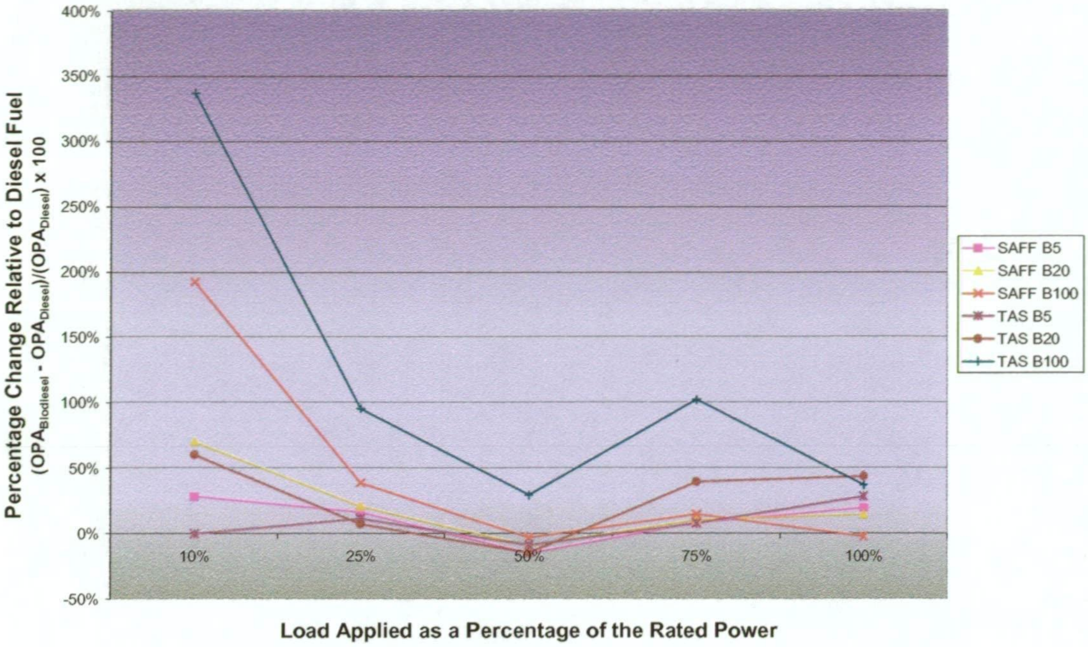


Figure 4.10: Opacity Level Relative to Diesel Fuel Opacity related to Load Applied

Previous work has documented both increases and decreases in the opacity because of biodiesel use. Lue et al. studied particulate matter which was 2 µm, PM_2, or less in size as these cause significant health problems; they determined that a diesel engine fuelled with biodiesel blends emits more PM_2 than the same engine run on pure diesel fuel and that the PM_2 concentration increased with an increase in biodiesel content [44]. In a study on palm oil biodiesel Lin et al. measured the opacity in terms of particulate matter; they concluded that PM emissions decreased for biodiesel blends of B0-B10 but increased from B20-B100 for a palm oil based biodiesel [75]. Their result is consistent with this work as the blends of B5 produced opacity readings equivalent to diesel emissions at most loads while the blends of B20 and B100 produced significantly higher levels of opacity. Additionally, Durbin et al. tested neat biodiesel, B20, a synthetic diesel fuel and a standard diesel fuel against emissions etc. From their results it can be seen that the opacity depends on both the engine and the fuel; older engines tend to produce higher levels of opacity. Additionally, the neat biodiesel, followed by the B20 blend, produced the highest level of opacity out of the fuels for all engines but one. The one engine where biodiesel was not the highest emitter was the newest engine which produced the same low level of emissions regardless of fuel [56].

There are various possible explanations for the increase in opacity shown by the use of biodiesel. Firstly, there have been studies conducted which show a relationship between higher cetane numbers and the increased tendency to produce soot [41]. It is also possible that the injectors in this generating unit are not suited to the use of a more viscous fuel and as a result are spraying larger droplets of fuel which promotes the formation of soot.

Overall, the level of opacity increased as the load increased; however the relative difference between the opacity of biodiesel and the opacity of diesel fuel decreased with increasing load. One fuel, the Tasmanian B100 produced a substantial increase of opacity compared to the opacity of diesel fuel regardless of load. The results observed during this work complement previously conducted studies.

4.3 Fuel Consumption

The level of fuel consumption is directly related to the amount of load applied to the engine. At low loads, the engine consumed 0.470 L/hr when run on diesel fuel. The fuel consumption was relatively constant when biodiesel was blended with the diesel fuel; however, when biodiesel was used as a neat fuel there was a marked increase in the consumption with SAFF B100 increasing by 6.2% and the Tasmanian biodiesel increasing the rate of consumption by 5.1%. As the applied load increased the fuel consumption increased as well. The SAFF blend of B5 showed no change in fuel consumption regardless of the load applied, while the Tasmanian B5 showed a slight decrease for all loads except for 100% power where the consumption increased by 0.4%.

As the biodiesel content increased, the fuel consumption increased as well, the blends of B20 showed slight increases over the consumption of diesel fuel. SAFF B20 showed increases in consumption ranging from 0.2% at 10% of the rated power to a maximum of a 2.5% increase when the applied load was 25%. The increase in fuel consumption due to the use of the Tasmanian biodiesel blend of B20 ranged from 0.6% increase at 25% of the rated power to 1.7% increase when the load was 75% of the rated power; the Tasmanian B20 showed a minor decrease in fuel consumption of -0.1% when the applied load was equal to 10%. The B100s showed a marked increase in fuel consumption at all loads; this increase ranged from 6.2% at the lowest load to 11.3% at 100% power for the

South Australian blend. The Tasmanian B100 produced slightly lower increases relative to diesel fuel which ranged from 5.1%, at 10% load, to 8.8% increase at both 25% and 100% of the rated power. Figure 4.11 shows a plot of the fuel consumption related to the applied load while Figure 4.12 shows the percentage difference between the fuel consumption for each biodiesel as compared with the fuel consumption of diesel fuel.

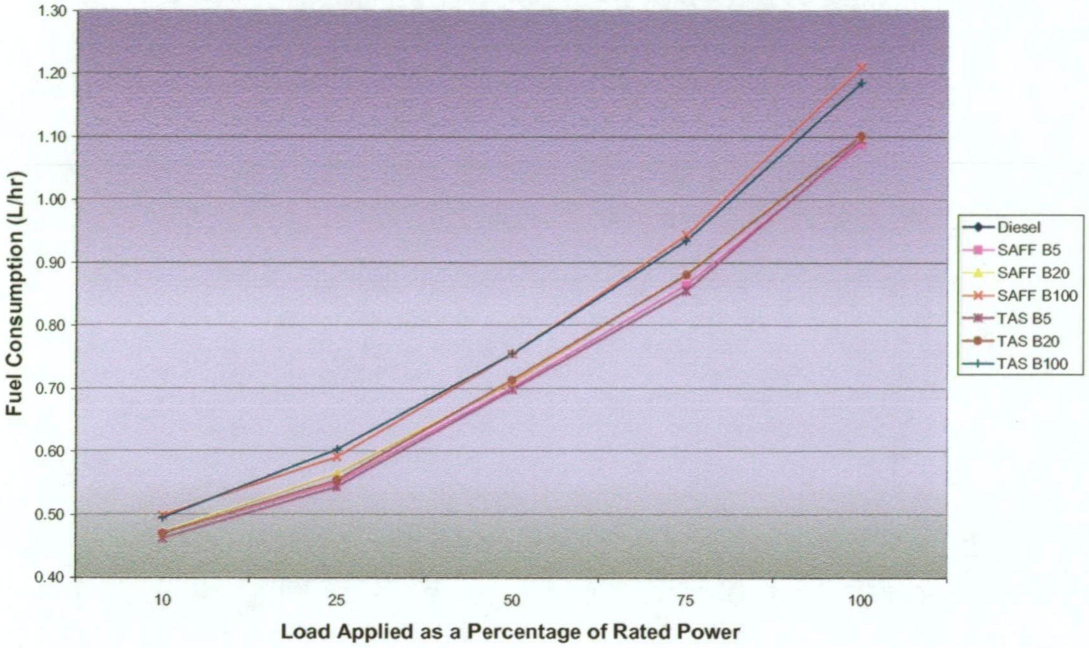


Figure 4.11: Volumetric Fuel Consumption related to Load Applied

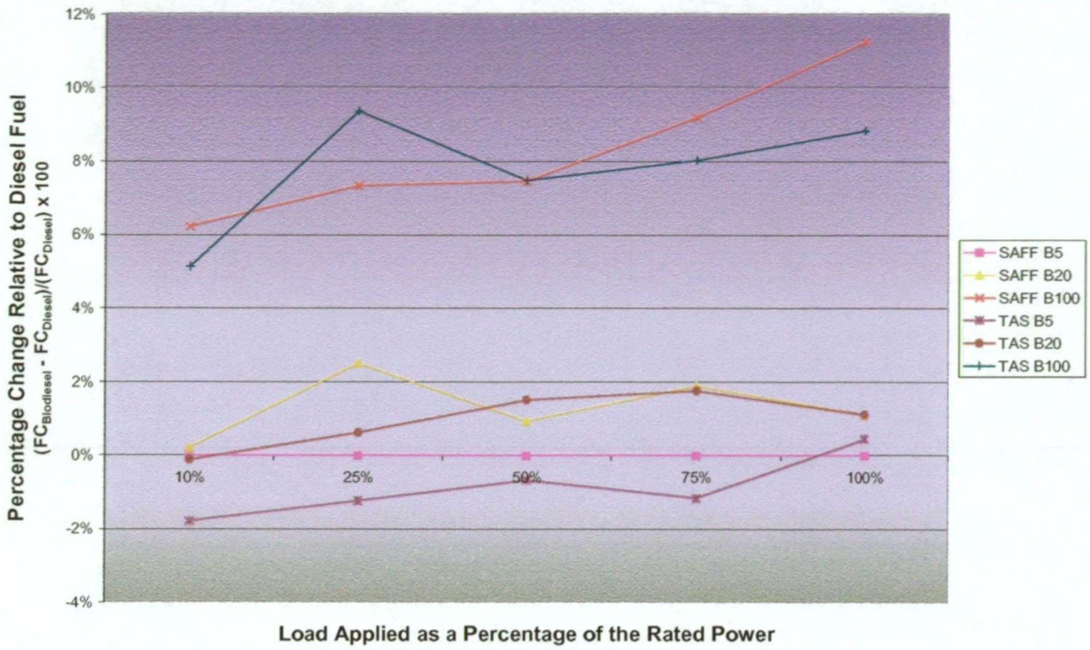


Figure 4.12: Fuel Consumption Relative to Diesel Fuel Consumption related to Load Applied

The results obtained in this work are consistent with current literature. Previous works have reported increases in fuel consumption as a result of biodiesel use; the results all show the largest increase for neat biodiesel regardless of the source oil [49, 51, 57, 58]. The increase in fuel consumption it typically in the order of 6-8% more fuel burned compared with diesel fuel.

The cause of the increase in fuel consumption is generally attributed to the higher oxygen content of biodiesel and the lower calorific value compared to diesel fuel. The higher oxygen relates to the cetane number and promotes more complete combustion; however the lower calorific value indicates that there is a lower energy content in the fuel and as a result, more fuel must be burned in order to produce an equivalent power output to diesel fuel [31].

As discussed, the rate of fuel consumption increases with increasing load and is highly dependent on the properties of the fuel which is powering the engine. Higher biodiesel content causes higher rates of fuel consumption regardless of the fuels composition.

4.4 Qualitative Analysis

From the results obtained it is possible to draw conclusions around the fuels tested to assess their operating performance. As the carbon dioxide remained relatively constant, the most benefit will be gained form the fuel that provided the maximum decrease in carbon monoxide and hydrocarbon emissions while creating the lowest increase in nitrous oxides, opacity and fuel consumption.

4.4.1 Recommendation

Based on the results presented in Section 4.1 – 4.3 it is possible to ascertain which fuel/load combination would provide the optimal performance. The optimal performance is defined as decreasing the maximum amount CO and HC emissions while causing a minimal increase in the emissions of NO and Opacity and causing a minimal increase in the fuel consumption.

When examining the above results, it is apparent that without modifications to the engine such as a delay in the injection timing or the addition of a catalytic converter, EGR or filters, biodiesel as a neat fuel does not produce the optimal change in emissions. While the Tasmanian B100 produced significant reductions in carbon monoxide and hydrocarbons as well as providing the maximum benefit to the carbon dioxide cycle, it also creates an increase in the nitrous oxide emissions as well as a substantial increase in the opacity. Similarly, while the South Australian blend resulted in the maximum decrease of carbon monoxide emission, it also produced an increase in the hydrocarbon emissions, which along with the increase in nitrous oxide emissions and opacity does not make it a viable fuel to be used as B100. Accordingly, out of the fuels tested in this work, the optimal fuel will be a blend. Specifically the blend of B20 since the blend of B5 did not offer significant emissions advantage; the blends of B20 provided a reduction in emissions of CO and HC while causing minor increases in NO_X and opacity.

The Tasmanian B20 blend produced the lowest emissions of carbon monoxide apart from the neat biodiesels; these emissions were significantly lower than the emissions for the SAFF B20 blend. In regards to the emissions of hydrocarbons the Tasmanian blend produced significant advantages compared to diesel fuel at all loads particularly at loads up to 50% of the rated power. The emissions of carbon dioxide were not greatly impacted by the type of fuel used and actual difference between either B20 and diesel fuel was less than 2%. Both fuels caused the emissions of nitrous oxide to increase; however due to the oils from which it was derived the Tasmanian fuel produced significantly higher levels than the South Australian recipe. In terms of the opacity, it was determined that a blend is preferable to neat biodiesel as both biodiesel, particularly the Tasmanian blend, resulted in an increase in the opacity. The Tasmanian blend of B20 resulted in smaller increases of the fuel consumption compared with the SAFF blend at all loads except for the load of 50% power where the Tasmanian fuel consumed slightly more fuel than the South Australian blend.

From the results obtained it can be recommended that when operating at loads up to and including 50% of the rated power, the Tasmanian biodiesel blend of B20 provides the maximum benefit in terms of emissions reduction without causing significant detrimental effects in relation to the NO_X and opacity emissions and the fuel consumption. When the load is increased to either 75% or 100% of the rated power the South Australian blend has superior performance and thus would be the preferred fuel.

4.4.2 Tasmanian Biodiesel Appraisal

Since the purpose of this project is to conduct a performance appraisal on the new Tasmania biodiesel, this section provides a summary of the performance characteristics of the Tasmanian fuel as determined during this work.

The Tasmanian biodiesel performed well concerning the emissions of carbon monoxide; while the South Australian B100 still provided a larger decrease, the Tasmanian blends tested resulted in superior performance than the SAFF B20 and B5 blends, as well they caused a decrease in emissions compared with petroleum diesel. Regarding the emissions of hydrocarbons the Tasmanian recipe for biodiesel showed vast improvements over the performance of the SAFF blend. All three of the Tasmanian fuels reduced the emissions of hydrocarbons when compared with diesel fuel regardless of the applied load.

Concerning, the carbon dioxide emissions, the Tasmanian fuel showed a mixture of increases and decreases relative to the emissions of diesel fuel; however, as the largest deviation was only 2.1% they are generally considered insignificant. As with all biodiesels, the advantage in their use is in the net life cycle of the fuel; as the canola and poppy plants grow, carbon dioxide is absorbed from the atmosphere. Further research would be required before this benefit could be quantified. An investigation into the crop harvesting and oil extraction techniques would be necessary, as well as an examination of the sources of heat and electricity that are required during biodiesel production before it is possible to ascertain the overall reduction of carbon dioxide compared with petroleum diesel.

As a fuel, the Tasmanian biodiesel did produce some unsatisfactory results in relation to the emissions of nitrous oxide and the opacity. The significant increase in the nitrous oxide emissions is largely due to the oils from which the fuel is derived. Twenty five percent of the oil used is poppy seed oil which is grown plentifully in Tasmania; however, poppy seed oil inherently has an extremely high iodine number which causes the resultant biodiesel to possess a high iodine number as well. As discussed in Section 2.3.1.4 the iodine number is directly correlated to the level of NO_X emissions; higher iodine numbers result in higher NO_X emissions. It would be possible to reduce the level of these emissions through either a modification to the recipe of the biodiesel or through modifications to the engine. The first option is not ideal as the current recipe has been created and tested until it has met the standards dictated relating to the properties and content of the fuel as described in Section 2.2.3.5. The opacity emitted as a result of the use of the Tasmanian biodiesel typically showed significant increases over the straight diesel fuel. These results indicate that it would be necessary to fit an engine running on Tasmanian biodiesel with a device to reduce the soot emissions. Various techniques such as gravity settlers, cyclones, electrostatic precipitators or fabric filters could be investigated to reduce the level of opacity [50]. Additionally, the effectiveness of the fuel injector should be investigated since the change in viscosity of the Tasmania fuel compared to diesel fuel may be causing the injector to operate ineffectively.

Finally, regarding the fuel consumption the Tasmanian blend performed competitively against both the South Australian blends tested and conventional diesel. When operating on blends with a high level of biodiesel present, there is an increase in the fuel consumption up to a maximum of 8.8% more fuel consumed than if the engine was run on standard diesel fuel. In order to reduce the fuel consumption slight modifications to the engines injection system may be made to optimise the combustion within the cylinder; however, this increase consumption is a small price to pay for a renewable fuel.

4.5 Concluding Remarks

The results obtained during the testing of this work were presented and their trends relative to diesel fuel have been examined. The results relating to the emissions of carbon monoxide showed higher level emissions at low loads; however, higher biodiesel content caused a larger reduction in the CO emissions at low loads. As the load increased, the benefit caused by the use of biodiesel decreased. At the maximum applied load the CO emissions showed an increase in emissions compared those observed at 75% of the rated power; at 100% rated power, the majority of the biodiesel fuels and blends resulted in an increase of CO emissions relative to diesel fuel. This pattern conformed to the expected pattern as predicted by literature.

The emissions of hydrocarbons showed little dependence on the load applied and more dependence on the type of fuel used. Two fuels resulted in an increase of hydrocarbon emissions compared to diesel fuel, while four of the biodiesels and blends tested showed a decrease in hydrocarbon emissions. This decrease is expected due to the superior combustion characteristics of biodiesel.

The emissions of carbon dioxide increased with increasing load and little variation was observed because of biodiesels use. This was the anticipated performance as literature concurs that biodiesel reduces carbon dioxide emissions through the net life cycle and not through the exhaust emissions.

Nitrous oxide emissions increased with increasing load; biodiesels consistently caused an increase in the level of NO emissions compared with diesel fuel. As the applied load increased the difference between biodiesel and diesel emissions decreased. This increase of NO emissions was predicted, as biodiesels have inherently higher iodine numbers which are directly related to higher levels of NO emissions.

Overall, the level of opacity increased as the load increased; however the relative difference between the opacity of biodiesel and the opacity of diesel fuel decreased with increasing load. One fuel, the Tasmanian B100 produced a substantial increase of opacity compared to the opacity of diesel fuel regardless of load.

The rate of fuel consumption increased with an increase in applied load; it is also highly dependent on the properties of the fuel which is powering the engine. Higher biodiesel content causes higher rates of fuel consumption regardless of source of the fuel. This is a result of the higher oxygen content and lower calorific value of biodiesel as compared with diesel fuel.

The results obtained during this work complement previous studies which have been conducted and published in current literature. Carbon monoxide and hydrocarbons were found to decrease with the use of biodiesel, while the nitrous oxides, opacity and fuel consumption increased. Carbon dioxide emissions were consistent with the emissions produced from straight diesel fuel.

Chapter 5: Final Concluding Remarks & Proposed Future Work

A brief study into the background of biodiesel has been conducted and the potential role of biodiesel in the world today has been discussed. The benefits and detriments of the use of biodiesel as a fuel were examined and it was concluded that with a few minor precautions there is very little that needs to be done for biodiesel to be used as a fuel by the general population.

Through the course of a literature review, previous studies relating to the implementation of biodiesel in compression ignition engines were discussed with particular focus on the emissions, opacity and fuel consumption. From examinations of these works, it was determined that as the concentration of biodiesel in the fuel increased, there will be a resulting decrease of CO and HC emissions. An increase in NO_X emissions is expected, as is a slight rise in the fuel consumption. It was also expected that there would be very little change in the emissions of CO_2, and that the opacity may increase or decrease.

This work has investigated the performance of a diesel generator unit operating on two different types of biodiesel: one produced locally in Tasmania and one purchased through a commercial supplier. These two biodiesels were compared against a baseline of standard diesel fuel in blends of B5, B20 and B100. The comparison included examinations of changes in the emissions of CO, CO_2, HC, NO and opacity as well as changes in the rate fuel consumption as the load on the generator was varied.

To conduct the testing a diesel generator and various instrumentation was used and the testing was conducted as outlined in Section 3.3. The results obtained during this work have complemented current literature and have provided the expected results.

The emissions of carbon monoxide showed the largest reductions at low loads. The South Australian and Tasmanian B100s caused decreases of 19.9% and 12.3% respectively, relative to the emissions of petroleum diesel. This decrease is a result of the higher oxygen content of the biodiesels. The hydrocarbon emissions were reduced for nearly all biodiesels and blends because of higher cetane numbers and thus superior combustion characteristics. The largest reductions were caused by the Tasmanian B100 which had an average reduction of 19.3% followed by the Tasmanian B20 with an average reduction of 15.2% when compared with conventional diesel. The tailpipe exhaust emissions for biodiesel of carbon dioxide were relatively consistent with those of diesel fuel; the relative difference compared to diesel fuel ranged from a maximum reduction of -1.8% for the Tasmanian B5 to a maximum increase of +4.2% for the South Australian B100. These results are not unexpected as biodiesel is known to be a carbon dioxide neutral fuel over the course of its life cycle because the plants, from which the oil is derived, absorb carbon dioxide during their growth period. The nitrous oxide emissions showed the highest levels of increase at low loads. The neat biodiesels reported 26.4% and 29.8% more emissions of nitrous oxide for the Tasmanian and South Australian fuels respectively compared with diesel fuel. As the load was increased the relative difference decreased drastically; at the highest load the use of biodiesel increased the nitrous oxide emissions by an average of 2.3%. This increase is consistent with published literature and is due to the nature of the oils from which the biodiesels have been derived. The opacity produced by the biodiesels varied greatly when compared with the opacity of diesel fuel; the lowest change observed was a decrease of 15.0% which was seen for both the South Australian B5 and the Tasmanian B20. The highest levels of increase were reported for the neat biodiesels; the Tasmanian B100 caused an increase of 337.3% and the South Australian B100 caused an increase of 192.9% compared with regular diesel fuel. While the changes in opacity, particularly for the Tasmanian B100 are large they are not unexpected and still conform to previously published work. This is because the opacity is dependent on many factors that are independent of the fuel composition, such as the size of the droplets in the injection spray and the cetane number. The rate of fuel consumption increased slightly for the blends of biodiesel with the largest increase reported as 2.5% for the South Australian B20. However, the B100s for both fuels caused significantly larger increases with a range of 6.2% - 11.3% increase for South Australia and 5.1% - 9.4% for the Tasmanian biodiesel as compared with petroleum diesel. These observations are also consistent with current literature and the use of neat biodiesel.

These results show that biodiesel can be used in an unmodified diesel generator and provide some improvement in the exhaust emissions. While biodiesel may not be the full answer to the problems surrounding the depletion of fossil fuel resources due to the amount of arable land required to grow the crops, it is certainly a source of fuel which is available now and can be implemented into current infrastructure to provide a bridge between fossil fuels as an energy source and the future of renewable and sustainable energy sources.

This work is only the first step in understanding biodiesels and how they maybe used; in this work it was shown that the nitrous oxide emission and opacity were increased due to biodiesel use. Future work should concentrate on reducing these emissions; NO_X emissions may be reduced by using additives in the fuel, delayed injection timing or the implementation of exhaust gas recirculation. The opacity may be decreased by the use of gravity settlers, electrostatic precipitators or by installing a filter in the exhaust system. Before commercial use, each of these options need to be tested and analysed to determine what effects, positive and negative, they have on the overall performance and emissions of the engine. Another effect that is worth investigating is the effect of the temperature of the fuel on the emissions; heating the fuel would reduce the viscosity of the biodiesel and improve the flow and create a finer injection spray into the combustion chamber which would improve the combustion characteristics. While this work was restricted in the control of the rpm it would also be useful to conduct testing at a wide range of rpm which would simulate reality more closely.

Finally, work should be done to investigate the possibility of using a hydrogen and biodiesel blend in a diesel engine; this could be particularly applicable in Remote Area Power Systems which store hydrogen for use in compression ignition engine. The use of biodiesel and hydrogen blends would be a further step in the direction of a cleaner, renewable fuel source.

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Appendix A: Biodiesel Standards

Table A1 presents the standards specified by the American Society for Testing and Materials (ASTM). This standard is only applicable for biodiesel fuels which will be used as a blend stock; it is not for fuels which are intended to be used in neat, B100 form.

Table A1 ASTM D 6751-02 [20]

Table 1 Standard specification for biodiesel fuel (B100) blend stock for distillate fuels (ASTM D 6751-02)

Property	ASTM method	Limits	Units
Flash point (closed cup)	D 93	130.0 min	°C
Water and sediment	D 2709	0.050 max	% vol.
Kinematic viscosity, 40 °C	D 445	1.9–6.0	mm^2/s
Sulphated ash	D 874	0.020 max	% mass
Sulphur	D 5453	0.05 max	% mass
Copper strip corrosion	D 130	No. 3 max	–
Cetane number	D 613	47 min	–
Cloud point	D 2500	Report*	°C
Carbon residue, 100% sample	D 4530	0.050 max	% mass
Acid number	D 664	0.80 max	mg KOH/g
Free glycerin	D 6584	0.020 max	% mass
Total glycerin	D 6584	0.240 max	% mass
Phosphorus content	D 4951	0.001 max	% mass
Distillation temperature, (atmospheric equivalent temperature, 90% recovered)	D 1160	360 max	°C

*Cloud point of biodiesel is generally higher than petrodiesel and should be taken into consideration when blending.

Table A2 presents the specifications set for European biodiesels; however, the standard specifies it applies to biodiesels created from Rapeseed oil Methyl Esters (RME) only.

Table A2 - Generally Applicable Requirements European Biodiesel Standards (RME)

Property	Unit	Minimum	Maximum
Ester Content	% (m/m)	96.5	
Density @ 15°C	kg/m3;	860	900
Viscosity @ 40°C	mm2/s	3.5	5.0
Flash Point	°C	Above 101	
Sulphur Content	ppm		100
Carbon Residue (10% Bottoms)	% (m/m)		0.3
Cetane Number		51.0	
Sulphated Ash Content	% (m/m)		0.02
Water Content	mg/Kg		500
Total Contamination	mg/Kg		24
Copper Strip Corrosion(3hr @ 50°C)	rating	Class 1	Class 1
Thermal Stability			
Oxidation Stability, 110°C	hours	6	
Acid Value	mg KOH/g		0.5
Iodine Value			120
Linolenic acid methyl ester	% (m/m)		12
Polyunsaturated (>= 4 double bonds) methyl esters	% (m/m)		1
Methanol Content	% (m/m)		0.2
Monoglyceride Content	% (m/m)		0.8
Diglyceride Content	% (m/m)		0.2
Triglyceride Content	% (m/m)		0.2
Free Glycerol	% (m/m)		0.02
Total Glycerol	% (m/m)		0.25
Alkaline Metals (Na + K)	mg/Kg		5
Phosphorus Content	mg/Kg		10