DISSERTATION

TECHNICAL AND ECONOMIC EVALUATION OF TRIGLYCERIDE GASOLINE BLENDS AS AN ALTERNATIVE FUEL FOR DIESEL ENGINES

Submitted by

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ABSTRACT

TECHNICAL AND ECONOMIC EVALUATION OF TRIGLYCERIDE GASOLINE BLENDS AS AN ALTERNATIVE FUEL FOR DIESEL ENGINES.

Developing viable and sustainable alternative fuels is critical in addressing future energy needs. Existing fossil fuels, being limited in nature, are depleting, contribute to climate change, health effects and their markets are volatile resulting in price fluctuations. Liquid fuels comprise a significant portion (about 40%) of a nation's total energy demand and production. Transportation sector being a key contributor national growth and security consumes almost 24% of the liquid fuel, while farming consumes about 15% to 17% of the liquid fuels. Bio diesel and bio ethanol are the two most widely used alternative, renewable fuels available.

This work presents the technical and economics of using Triglyceride gasoline blends (TGBs) in a diesel engine. Canola straight vegetable oil (SVO) is highly viscous and has poor flow ability in cold weather. Consequently, it cannot be used in diesel engines without modification to the fuel system. Blending regular unleaded gasoline (10% by volume) to unrefined canola oil results in the specific gravity of the blend being similar to that of diesel. This enables it to be used in off road diesel engines in cold weather without modifications to the fuel system. A series of studies were performed to examine the viability of using TGBs to fuel diesel engines.

Engine experiments were conducted on a 4.5L, turbocharged, intercooled Tier-III diesel engine. Lower heating value, higher mass based fuel consumption and slightly higher

thermal efficiencies were recorded using TGB10 compared to diesel. The cylinder pressure traces and location of 50% mass fraction burnt for TGB10 and diesel were similar in most load points of the ISO 8178 8-mode test cycle. The average peak pressure of TGB10 was within ±4.5% to that of diesel. The combustion duration of TGB10 was about 12% to 15% shorter than diesel. Increased weighted NO_X emissions (+9.8%), slightly lower weighted PM emissions (-5.5%), significantly lower weighted CO emission (-51.7%) and higher metal content (various orders of magnitude) were observed when using TGB10 as fuel in comparison to diesel.

Additional engine experiments included varying the gasoline percentage in the TGB, evaluating combustion statistics, engine ECU parameters like start of injection, turbocharger speed and emissions analysis. Overall for blends containing up to 25% gasoline, most of the combustion parameters were identical to 100% triglyceride. As the gasoline content increased up to 55%, the combustion parameters were similar to diesel. For blends containing gasoline greater than 60% the combustion parameters were significantly different than diesel.

A durability study (250 hours) on three fuels – (i) off road diesel, (ii) canola based bio diesel, and (iii) canola based TGB10 was conducted on a single-cylinder, naturally aspirated Yanmar diesel engine operating at constant load. Oil samples, injector spray patterns and carbon buildup from the injector and cylinder surfaces for the three fuels were analyzed and compared. Biodiesel had a cleansing effect on the injector tip. TGB10 left behind thick sludge on piston crown while diesel fuel had the least impact on lubricating oil quality.

Finally, an economic business case model was analyzed for a complete lifecycle for TGB10. The model includes growing the canola crop, setting up a crushing facility to extract unrefined canola oil to converting it to TGB10 and the cost of ownership for a farm tractor over four different lifespans. The results show that though the cost of producing TGB10 can be lower than diesel, the cost of ownership can significantly vary on the lifespan of engine and its components. Expensive diesel prices and higher engine lifespans are the key to making TGB10 economically viable.

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KEYWORDS

Alternative fuels, biofuels, biodiesel, diesel, gasoline, straight vegetable oils, triglycerides, triglyceride gasoline blends (TGB), fuel properties, density, viscosity, calorific value, heat release, pressure trace, engine ECU, start of injection (SOI), mass fraction burnt (MFB), emissions, nitrogen oxides (NO_X), particulate matter (PM), carbon monoxide (CO), durability testing, lubricating oil, soot, sulfation, nitration, oxidation, wear metals, additives, farm economics, fuel storage, capital expenditure, operating costs cost of ownership, sensitivity analysis, payback period, return on investment.

1. INTRODUCTION, BACKGROUND AND MOTIVATION FOR RESEARCH

Continuous increase in the global population and economic development has resulted in an increased energy demand. Limited energy resources and higher demand has resulted in higher energy prices. These circumstances have placed industries under social and political pressure to produce and use cleaner energy and highly efficient equipment. However, technologies that promote clean energy are too expensive, which outweighs the benefits of using them. Hence, it is important to maximize localized energy production that is economical and relatively independent of political influences across borders.

To ensure adequate supply of energy, countries around the world are introducing policies to promote renewable and alternative energy sources. It is projected that the world energy consumption will grow by 28% on an average between years 2015 to 2040, and Asia will account for an energy consumption of more than 60%[1].

As for liquid transportation fuels, in 2016 alone, 19.7 million barrels per day of liquid fuel was consumed in the US[2]. The US government has introduced Energy Independence and Security Act to promote biofuels and bio energy [3]. Renewable Fuel Standards have been established to encourage and gradually replace the fossil fuels[4]. Currently, biodiesel and bio-ethanol are the two major alternative fuels being produced. These fuels are blended in small percentages (up to 10%) with diesel or gasoline that are being sold in gas stations across the US and many countries across the world.

1.1 BACKGROUND

One main drawback of using 100% biodiesel is its cost. Figure 1-1 shows the average national price of biodiesel and diesel in the US. Even in an industrial scale biodiesel production, the cost of producing biodiesel is higher than the cost of diesel available in the market, making it economically unfit for consumers, especially farmers. The use of unrefined vegetable oils produced from crushing oil seeds has been of great interest to the community due to its lower cost of production compared to diesel. However, it is known to have higher viscosity, lower energy density and poor flowability in cold weather, making it difficult to use in all year round[5-7]. To overcome this some farmers in Rocky Ford - Colorado, formed a consortium named Big Squeeze LLC. Where they blend straight vegetable oils with gasoline and used it in their farm equipment. Anecdotal claims are that the engines worked fine, produce lower emissions (less black smoke), have better gas mileage, and have more power.

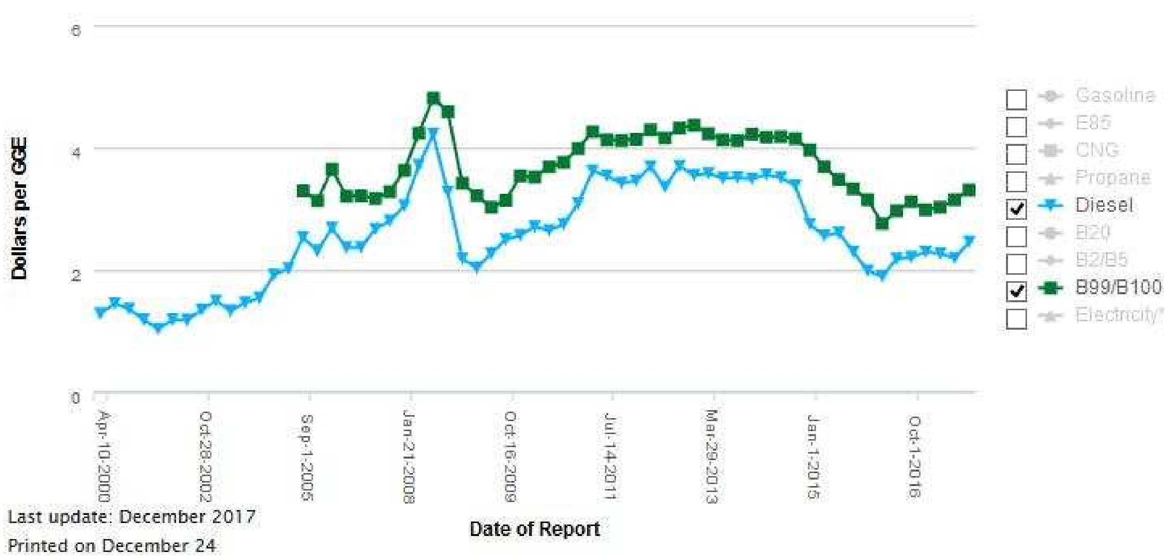

Figure 1-1-1: Average Retail Fuel Prices in the US[8]

1.2 MOTIVATION

To verify the claims of the farmers, the researchers visited their farm and conducted experiments on a farm tractor as shown in Figure 1-2. The engine throttle of the tractor (Figure 1-3) was fully open and the power take-off (PTO) shaft (Figure 1-4) from a tractor was coupled to a dynamometer (Figure 1-5). The dynamometer displayed the speed and the load on the engine. One tractor was rated at 158 HP at 2000 rpm and the other at 144 HP at 2000 rpm. Since there is a 2:1 gear reduction, the rpm at which the horse power readings were taken was 1000 rpm, displayed on the dynamometer.

Figure 1-2: On Farm Experimental Tractor

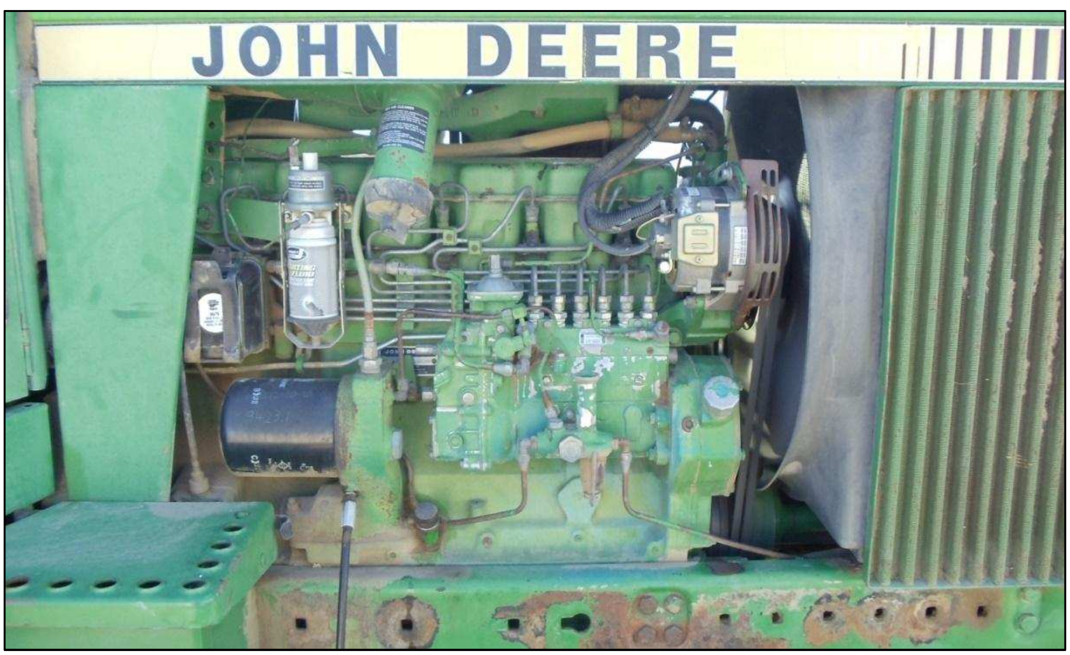

Figure 1-3: On Farm Tractor Engine

Figure 1-4: Tractor PTO Shaft coupled to the dynamometer

Figure 1-5: On field dynamometer

Five different fuels were tested for maximum power achievable for each of the fuels. The results are shown in Table 1-1 and Table 1-2.

1. Diesel (DSL) – Off road red diesel
2. Blend #1 – (67% SVO +33% Regular Unleaded Gasoline)
3. Blend #2 - 50% DSL + 50% Blend #1
4. Big Squeeze Fuel (BSF) - (90% SVO + 10% Regular Unleaded Gasoline)
5. Blend #3 – 50% DSL + 50% BSF

Table 1-1 shows the Maximum Power that was produced by a tractor rated for 158 HP. The maximum power achieved by diesel fuel was 158 HP. Blend #1 produced a maximum power of 151 HP, which is about 5% lower than diesel.

Table 1-1 Max Power, Tractor #1, 158 HP at 1000 rpm

Dynamometer Speed (rpm)	Diesel	Blend #1
1000 rpm	158 HP	151 HP
620 rpm	98 HP	94 HP
535 rpm	85HP	80 HP

Table 1-2 shows the Maximum Power that was produced by a tractor rated for 144 HP. The maximum power achieved by diesel fuel was 144 HP. Blend #1 produced a maximum power of 134 HP, which is about 9.3% lower than diesel. Blend #2 produced a maximum power of 141 HP, which is about 2% lower than diesel. BSF produced a maximum power of 130 HP, which is about 10% lower than diesel. Blend #3 produced a maximum power of 134 HP, which is just about 1% lower than diesel.

Table 1-2 Max Power, Tractor #2, 142 HP at 1000 rpm

Dynamometer Speed (rpm)	Diesel	Blend #1	Blend #2	BSF	Blend #3
1000 rpm	144 HP	134 HP	141 HP	130 HP	142 HP
620 rpm	88 HP	84 HP	87 HP	80 HP	88 HP
535 rpm	74 HP	71 HP	74 HP	67 HP	75HP

From these tests, it was concluded that the alternative fuels produced lower power than diesel fuel. Since the alternative fuels have a large content of straight vegetable oil (SVO), their calorific value would be 10% to 15% lower than diesel. Consequently, due to the lower calorific value of the alternative fuels, the mass based fuel consumption is likely higher than diesel. Changes in fuel-specific engine efficiency can also impact fuel consumption.

1.2.1 FARM ECONOMICS

The farmer's land was adjacent to an animal feed lot. Oil cake is in great demand in cattle feedlots because of their high protein content. To increase cash flow, the farmers sell oil cakes to the feedlot. Also, in the years leading up to 2012-2013, the farmers of Big Squeeze LLC were buying diesel fuel at almost $4.0 per gallon. Driven by high diesel prices, the farmers began growing canola and sunflower on their farms during the fallow periods. The seeds were then crushed in a rudimentary crushing facility set up nearby their farm. The oil from the oil seeds were then converted into TGBs and used on their farm tractors while the meal/cake was sold off to an adjacent animal feedlot for a nominal price. Between the cost of making TGBs and the price of the meal, the farmers believed they had a viable economic model.

1.3 RESEARCH OBJECTIVES

This research is aimed at further understanding the triglyceride gasoline blends as a diesel fuel alternative. Engine experiments are carried out in a controlled environment at the laboratory to understand the performance and emissions. Durability testing is performed to evaluate engine durability on TGBs. A business economic model is developed to understand the cost of equipment ownership and operation on TGBs. Research objectives are specified below.

1.3.1 RESEARCH OBJECTIVE #1: Preliminary Laboratory Experiments

Repeat the field experiments in a controlled laboratory environment. For this, fuel samples from the farm were transported to the laboratory. A Tier -II and Tier- III engine were used to test these fuels. Engine emissions and fuel physical properties were measured.

1.3.2 RESEARCH OBJECTIVE #2: TGB10 Laboratory Experiments

Conduct engine experiments with TGB10 as a fuel in controlled laboratory environment. Analyze engine stack emissions and combustion statics following the ISO 8178 8 mode off road load profile.

1.3.3 RESEARCH OBJECTIVE #3: Percentage Gasoline Bend Experiments

Conduct engine experiments by blending gasoline of various quantities (5% to 80% by volume) and raw, unrefined triglycerides as a fuel in controlled laboratory environment. Analyze engine stack emissions and combustion statics following the ISO 8178 8 mode off road load profile. In addition to this, the Engine Control Unit (ECU) parameters like start of injection, turbocharger speed and Indicative mean effective pressure (IMEP) were recorded and analyzed.

1.3.4 RESEARCH OBJECTIVE #4: Durability Testing

To conduct engine durability experiments with TGB10, biodiesel and diesel fuels. Qualitative comparison of the injector spray pattern, carbon buildup and oil degradation analysis with respect to diesel baseline.

1.3.5 RESEARCH OBJECTIVE #5: Economic Modeling

Create a business case economic model for using TGB10 as fuel. The model includes growing canola oil seed crop, setting up a crushing facility and extracting oil, blending it with gasoline to get TGB10, and cost of ownership based on various life expectancies of the equipment using on TGB10 as fuel.

1.4 ORGANIZATION OF DISSERTATION

The dissertation content is presented primarily as five independent technical papers in Chapters 2, 3, 4, 5 and 6. Chapter 7 is a summary with broad conclusions and future recommendations drawn from the work as a whole.

1.5 REFERENCES

[1] U.S.EIA, Today in Energy. 2017.

[2] U.S.EIA, FAQ-How much oil is consumed in the United States. 2017.

[3] U.S.Government, ENERGY INDEPENDENCE AND SECURITY ACT OF 2007. 2007, 110th Congress Public Law 140.

[4] Christensen, A. and S. Siddiqui, Fuel price impacts and compliance costs associated with the Renewable Fuel Standard (RFS). Energy Policy, 2015. 86(Supplement C): p. 614-624.

[5] Corsini, A., et al., Vegetable Oils as Fuels in Diesel Engine. Engine Performance and Emissions. Energy Procedia, 2015. 81: p. 942-949.

[6] Dwivedi, G. and M.P. Sharma, Potential and limitation of straight vegetable oils as engine fuel – An Indian perspective. Renewable and Sustainable Energy Reviews, 2014. 33: p. 316-322.

[7] Abollé, A., K. Loukou, and P. Henri, The density and cloud point of diesel oil mixtures with the straight vegetable oils (SVO): Palm, cabbage palm, cotton, groundnut, copra and sunflower. Biomass and Bioenergy, 2009. **33**(12): p. 1653-1659.

[8] U.S.DoE, Alternative Fuel Price Report. 2017.

2. PERFORMANCE AND EMISSION EVALUATION OF TRIGLYCERIDE GASOLINE BLENDS IN AGRICULTUTAL COMPRESSION IGNITION ENGINES [1]

2.1 OVERVIEW:

This article details the approach of using untreated oilseed triglycerides (plant oil) that can be produced at local and regional scales to supply fuel for farming operations. The main objective of this research was to conduct fuels and engines testing on triglyceride gasoline blends, congruent with practices already adopted at farm scales. Most farm equipment is powered by diesel engines. One of the major drawbacks of substituting triglycerides for diesel fuel is their density and viscosity in cold conditions. By blending triglycerides with 10% to 30% gasoline, however, their density and viscosity can be lowered, thus allowing the blended fuel substitute to be consumed in an unmodified diesel engine. Blended and unblended triglycerides were tested in 4.5LI EPA Tier-2 and EPA Tier-3 diesel engines at the CSU Engines & Energy Conversion Laboratory. Maximum power testing was conducted in the field on a tractor. The Cold Filter Plug Point and Cloud Point of these blends were tested. The values differed significantly when compared to diesel. The viscosities were 7 times greater than that of diesel. Phosphorous, sulfur, sodium, and potassium contents were greater compared to diesel but within the ASTM 6751 Biodiesel standard limits. The emission testing on the 4.5L Tier-3 engine showed that NO_X levels were within ±5% of diesel and PM was within ±10% of diesel for the triglyceride blend. The thermal efficiency was close to diesel while the mass based fuel consumption was approximately 10% higher than that of diesel. Reduction in the peak power was observed due to a reduction in lower heating value.

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[1] Manuscript published in *Applied Engineering in Agriculture 30(4):523-534* (2014) by A Lakshminarayanan et.al.

2.2 INTRODUCTION

The need for alternative fuels development in agriculture is clear in light of increased fuel demand and costs. Because fuel costs comprise a major share of farm enterprise budgets, farmers are looking more closely at alternative fuels. Biofuels are being promoted to reduce greenhouse gas emissions and move towards achieving U.S. energy security (United States DOE, 2012). Agricultural rural communities are tied to energy supplies that vary year after year in an economic climate that needs greater predictability in the cost of farming inputs. Fuel costs represent one of the most significant and steadily-growing costs supported by farming operations [2, 3] Shifts in fuel prices require adaptation in agricultural sectors, as these shifts also affect food and biofuel feedstock production. Plant oil, or triglycerides, can be produced by crushing oilseed crops. Innovative farmers are currently evaluating oilseed crops (e.g., canola, sunflower, camelina, carinata) that appear viable under various climatic and irrigation water supply conditions [4]. These evaluations are needed to help guide those focused on the use of triglycerides in rural machinery used for farming[5, 6] Keske et al., (2013)[7], for example, concludes that oilseeds (camelina, in particular) can offset on-farm diesel use, making it economically feasible for farmers to grow their own fuel.

In some parts of the country, farmers are using oilseeds as a feedstock for triglyceride-gasoline blends (TGBs) and ultimately used as biofuel for diesel engines. The famer-collaborators in this study are producers in Rocky Ford, Colorado, where they have taken significant steps to establish a small-scale crushing facility and refinery to produce filtered oil primarily from canola and sunflower crops. The core aspect of the refinery is an advanced sequential pressing-centrifugation process that is unique compared to most operations of similar size and scope. Another unique aspect of this refinery is the cooperative model that it represents. The crushing facility is integrated on-site with the infrastructure of an animal feeding operation (AFO). After oilseeds are delivered by local farmers to the AFO for processing, the solids byproduct (“cake”) generated during the crushing step is purchased from the AFO for meal, thus generating an additional revenue stream back to the farmer. The clean oil is also retrieved by the farmer, some of whom use it as the basis for TGBs or a feedstock for another biofuel.

Potential users of TGBs as biofuels need a fuller understanding of its long-term impacts on their machinery. Currently, the discussion of TGBs occurs on various internet blogs and web sites that promulgate largely anecdotal evidence, un-replicated research, and opinions both positive and negative. Previous claims of favorable experience with triglyceride fuel blends, however, do exist [8-11]. No peer reviewed literature is found on TGBs, while there is an abundance of published work on other biofuels[12-18]. There is a substantial body of work on the practice of blending diesel fuel with triglycerides [10, 19-21]. One of the major drawbacks of using triglycerides directly as fuel is the density and viscosity of the oil, which can generally cause problems for the fuel delivery system, especially in cold conditions [22]. Triglycerides also contain metals, which can affect long-term engine and exhaust after treatment system performance.

The collaborators on this project are located in southern Colorado, but the practice of blending triglycerides with petroleum products occurs in scattered areas throughout the United States. The research presented in this article summarizes an evaluation of the engine performance of a simplified biofuel that farmers can use as a means of reducing the economic insecurity associated with volatile and increasingly expensive fuel supplies.

Nevertheless, because this approach is contrasted with the more standardized use of diesel and biodiesel, many farmers are interested but understandably have questions regarding the impact of TGBs on their vehicles, tractors, and generator engines. This research addresses many of these questions by conducting testing on an expanded suite of fuels and engines.

2.3 OBJECTIVES AND EXPERIMENTAL SET UP

The main objective of this research project was to conduct fuels and engines testing on several TGBs, congruent with practices already adopted at farm scales. This work was carried out in three different phases, which correspond to resource availability. As resources became available, TGB fuels were blended and testing was performed on available engines. Consequently, three different engines and different TGBs were utilized for the different phases of work. The TGBs were prepared in the same manner for each phase of testing, which was to match the specific gravity of typical diesel fuel. The objective of the engine testing was not to compare the performance of different engines running on TGBs, or to compare the performance of different TGBs on the same engine. Rather, it was to evaluate the performance and emissions of TGBs prepared in a consistent manner relative to diesel fuel in diesel engines. The objectives of this work are summarized in the list below.

- Test and evaluate TGBs produced using the same methodology currently being used in the field.
- Analyze fuel properties of TGB fuels and compare to diesel.
- Perform TGB fuel testing on agricultural engines to assess differences relative to diesel fuel in power, emissions, fuel consumption, and efficiency.

The typical approach to triglyceride blending is to use a thinning agent such as regular unleaded gasoline (RUG) in order to achieve a blended specific gravity (SG) comparable to that of diesel (DSL) fuel burned in conventional compression ignition engines. This blending process is intended to produce a simple miscible fluid in the range of 0.865 to 0.870, similar to diesel fuel. The farmers collaborating on this project will either mix the fuel volumetrically for sake of convenience or gravimetrically by measuring SG using an off-the-shelf hydrometer, Precision Hydrometer Model Cat#6602-4 (Kirkland, Wash.). For the gravimetric process, Regular Unleaded Gasoline is added to the triglyceride source to form a TGB with a specific gravity ≈ 0.87.

A complete summary of the fuels and TGBs tested is provided in Table 2-1. The composition of each TGB blend varies since the properties of triglycerides vary for different harvests and oilseed types. Different amounts of RUG are required to achieve a target specific gravity close to 0.87, which is a representative value for diesel fuel at approximately 60°F. The most common approach is to measure the SG of diesel fuel supplied locally and then to match that value. Each TGB is designated by a subscript that correlates to a specific composition in the table. For example, TGB_2 corresponds to 32% RUG and 68% sunflower oil by volume. TGB/DSL blends are designated by subscripts.

The triglycerides used to develop the blends originated from an on-farm oilseed crushing facility. Harvested oilseeds are trucked to this facility, located at an AFO in Rocky Ford, Colorado, and later crushed and filtered onsite. The seed is first crushed using rough presses, which produces meal for the AFO. The produced oil is then run through a modified screw-press designed by the farmer-cooperators and finally a 2-micron high-speed centrifuge manufactured by Servizi Industriali® to super-clean the oil. The TGB and

TGB/DSL blends were blended and stored at room temperature in capped containers out of direct sunlight. They were agitated daily to ensure good mixing until the day of testing.

2.3.1 FUEL ANALYSIS

TGB_1 and diesel fuels were tested at the EECL fuels laboratory for measuring the physical properties, including density and viscosity (ASTM D7042), metal content (ASTM 6751), cold flow plug point (CFPP – ASTM 6371), cloud point (CP –D2500), and the calorific value. These values for TGB_1 were then compared to that of diesel fuel. Instruments used were Anton Parr for physical properties, Lawler Manufacturing Company's cold flow property tester (Edison, N.J), Ametek-Spectro for metals (Kleve, Germany), and a bomb calorimeter (IKA C200, Wilmington, N.C) for calorific value.

2.3.2 LABORATORY ENGINE SET UP

Maximum power, fuel consumption and thermal efficiency assessments were performed on a turbocharged and intercooled 4.5 L EPA Tier 2 John Deere 4045 test engine (Moline, Illinois) rated at 175 hp. The 100% load value for this program is de-rated to 154 hp (115 kW) due to high altitude (5000 ft/1530 m), test cell cooling limitations, and reduced LHV for TGB. Additional assessments of fuel consumption, thermal efficiency and emissions were performed on a 4.5 L Tier 3 John Deere 4045 test engine (Moline, Illinois) rated at 175 hp. The engine is turbocharged and intercooled, with a variable geometry turbocharger and exhaust gas recirculation. Both engines have electronically controlled common rail fuel injection.

Table 2-1 Summary of fuels tested

Engine Configuration	Fuels Tested	Fuel Composition (by volumetric percentage)				Specific Gravity
		% Triglyceride				
		Sunflower	Canola	% RUG[a]	% DSL[b]	
John Deere Tier 3 4045 Laboratory Test	DSL[b]				100	0.84
	TGB_1		90.0	10.0		0.89[c]
John Deere Tier 2 4045 Laboratory Test	DSL				100	Not measured
	TGB_2	68		32.0		0.87
	TGB/DSL_1	35		15.0	50.0	0.87
	TGB/DSL_2	23.1		10.9	66.0	0.87
John Deere Tier 2 4400 Field Test	DSL				100	Not measured
	TGB_3	66.7		33.3		0.87
	TGB/DSL_3	33.5		16.5	50.0	0.87
	TGB/DSL_4		45.0	5.0	50.0	0.87
	TGB_1		90.0	10.0		0.89[c]

[a] Regular Unleaded Gasoline (RUG).
[b] Diesel (DSL).
[c] Summer blend with higher specific gravity.

The test engines at the Engines & Energy Conversion Laboratory (EECL) are connected to a 175 hp Eddy current dynamometer (Mid West Induction Dynamometer Model 1014A, Jackson, Wis.). Two different probes extracted exhaust for emissions measurements. An averaging probe was used for gaseous emissions and an isokinetic probe was used for particulate measurement. Heated sample lines carry exhaust gas to gas analyzers and a dilution tunnel.

The laboratory engine test schematic is shown in Figure 2-1. Engine performance and emissions were tested at 8 modes Table 2-2 per ISO 8178-4 (European Commission, 1998) test cycle C1. Data at each mode was recorded for 5 min once the engine was at steady state. Two fuels were tested at all eight modes to permit comparison of ISO weighted average emissions representing the full operating range of the engine. This is necessary in order to compare emissions with regulatory limits. Most fuels were not tested at all eight modes, in which case comparisons were made at individual operating modes. The fuel from each tank was delivered to the engine with a lift pump. A three-way valve was used to divert the return fuel to the waste tank or back to the engine. A Micro Motion flow meter (Model Number 2700R11BBCEZZZ, St. Louis, Mo.) was used to measure the net mass flow rate of fuel. The Micro Motion flow meter was the standard approach to measure net fuel flow rate. However, an electronic scale was used in two different scenarios. (1) It was used when fuel quantities were limited. (2) For some TGBs unstable flow meter readings were experienced, presumably due to gasoline vaporization in the return line. For those cases, the fuel was retested using the electronic scale. When the electronic scale was used a small container of fuel was placed on the scale, with supply and return lines located in the fuel container with ends approximately 2 cm from the bottom of the container. The net fuel flow rate was calculated from the rate of change of the electronic scale readings. The electronic scale was a Pelouze Model 4010 (Bridgeview, Illinois).

Oxides of nitrogen (NO_X), carbon monoxide (CO), total hydrocarbons (THC), carbon dioxide (CO_2), and oxygen (O_2) are determined with a Rosemount 5-gas emissions bench. A Peltier-type condenser removes water from the exhaust sample before the gas enters the analyzers. Chemiluminescence, infra-red absorption, flame ionization, and paramagnetic gas detection methods are used for NO_X, CO and CO_2, THC, and O_2, respectively.

A partial flow dilution tunnel is used to measure PM in the exhaust. A small portion of exhaust is discharged from the exhaust pipe through an isokinetic probe, through a heated sample line, and to the dilution tunnel via a venturi on the dilution air inlet. The dilution air flowrate is measured with a turbine meter. The exhaust flowrate is measured using differential pressure across the venturi as it flows into the dilution air. The mixture is passed through a residence chamber to simulate particulate mixing with ambient air. Then a portion of the flow is pulled from the base of the residence chamber a Teflon filter where PM is collected downstream of the PM10 cyclone, which eliminates particulates larger than 10 μm. The filter collects all particulate matter that passes through the cyclone. The filters are weighted before and after the test using a precision balance, accurate to 1 microgram. A complete description of the gas analyzers and the dilution tunnel can be found in [24].

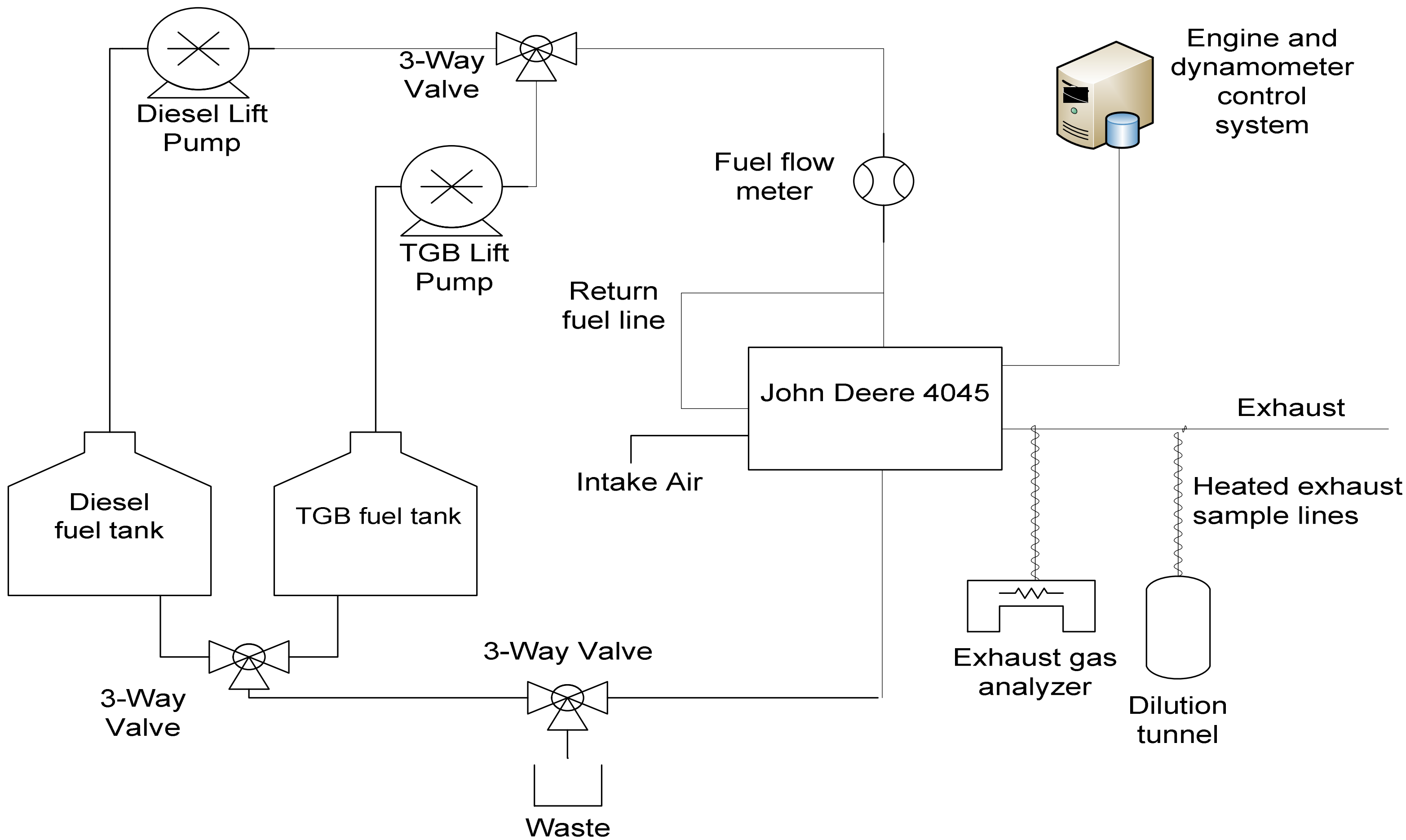

Figure 2-1 2 1 Laboratory engine test schematic for 4.5 L 175 hp John Deere 4045 Tier 2 and Tier 3 engines

Table 2-2 Test conditions of 8-mode map for engine performance and emissions per ISO 8178-4[23]

Mode Number	Speed	Torque (%)
1	Rated	100
2	Rated	75
3	Rated	50
4	Rated	10
5	Intermediate	100
6	Intermediate	75
7	Intermediate	50
8	Low	0

Measurements of maximum power, fuel consumption, brake thermal efficiency, and pollutant emissions were carried out on three different engines. The maximum power developed by an engine with a certain fuel is determined by running the engine at a set speed and increasing the load on the engine until it is unable to maintain the set speed. This assessment was performed on the John Deere-EPA Tier 2 laboratory engine and the John Deere 4440 tractor engine. In general, laboratory testing was performed by first bringing the engine to a desired operating point. Key parameters such as pollutant emissions, coolant temperature, air manifold temperature, and fuel flow rate were observed. Once key parameters were stable, 5 min of data was recorded at approximately 1 Hz. Average values over 5 min were calculated. Brake thermal efficiency and brake specific emissions were computed from average parameters. The laboratory TGB data is presented as percent of the diesel baseline.

2.3.3 FIELD ENGINE

Field testing was carried out on a John Deere Model 4440 tractor (Moline, Ill) at a farm in Rocky Ford, Colorado. The tractor had a John Deere 7.6l engine, Model 6466T, rated at

142 hp at 2000 rpm. This tractor engine was manufactured prior to the implementation of the EPA multiple tier emissions standards. It can be considered Tier 0. The fuel system was a pump-line-injector type. Four fuels were used, which were (1) off road red diesel, (2) TGB_1, (3) TGB_3, and (4) 50% red diesel and 50% TGB_1. The primary purpose of this testing was to measure maximum power output for different fuels.

The power take-off (PTO) shaft of the tractor was coupled to a Hydra Gauge Dynamometer manufactured by M&W Gear Company (Gibbson City, Ill). The PTO shaft had a gear ratio of 2:1; hence readings displayed on the dynamometer were at 1000 rpm when the engine speed was 2000 rpm. The engine rack position was set to maximum and load was applied with the dynamometer. The dynamometer load was increased until the engine speed was reduced to 2000 rpm. The dynamometer power was recorded at this point, which corresponded to the maximum power at 2000 rpm.

2.4 TEST RESULTS

2.4.1 FUEL PROPERTIES

The result of mixing the triglyceride source with RUG at the volumetric ratios described in Table 2-1 above is a miscible fluid characterized by a pale yellow color. A sample of TGB_1 was stored in a capped class container at room temperature. There has been no visible separation of triglyceride and gasoline after approximately 1 year of storage with no external mixing. Thus, qualitatively the mixture appears to be stable.

The fuel property test results are presented in tables 3-5. Phosphorous content in TGB_1 was 10 times greater than diesel but only ~1 ppm above the ASTM D6751 Biodiesel standard. Sulfur content is more than 9 times than that of diesel and the ASTM 6751

Biodiesel standard. Sodium and potassium contents were higher by orders of magnitude compared to diesel but still well within the ASTM 6751 Biodiesel limit. The elevated levels of sulfur and potassium are of concern for newer engines with after-treatment systems. These metals can poison catalysts, leading to accelerated degradation and reduced catalyst life. High sulfur level could lead to an increase in the SO_2 emissions, though it is not likely to significantly impact NO_X emissions [25]. It should be noted that the triglycerides used for this study were processed only by filtration. With additional processing steps, such as de-gumming and de-waxing, the metal levels could be decreased [26, 27].

The cold filter plugging point (CFPP) of TGB_1 is much higher compared to diesel. Elevated CFPP may result in difficulties running this TGB_1 at extremely low temperatures. The cloud point (CP) of TGB_1 is close to that of diesel, while the kinematic viscosity of TGB_1 is approximately 7 times higher than diesel. The differences in CFPP, CP and kinematic viscosity could impact the ability of TGB_1 to be pumped through the fuel system at lower temperatures. The difference in the cold flow properties is most likely due to the fact that the saturated fuels have a higher melting point than unsaturated fuels[28]. Because TGB_1 exhibits high viscosity, low volatility and poor cold flow properties, it is possible that its use may cause injector coking, combustion chamber deposits and sticking of piston rings [22]. On-going durability testing is being conducted to evaluate these effects. It is possible that the RUG contained in TGBs may act as a solvent and counteract these effects. Note that the measured densities are very different. The density of TGB_1 is higher than the target value of 0.87, and the diesel density is significantly lower than the assumed value of 0.87. TGB_1 is a summer blend with a larger specific gravity, intended to have higher percent triglycerides. The assumed specific gravity for diesel of 0.87 is a representative value; specific values in different parts of the country are expected to deviate above and below this value.

Calorific value, or lower heating value (LHV), of TGB_1 is ~8.7% lower than diesel. Reduced LHV is expected as triglycerides exhibit LHVs 10% to 15% lower than diesel. The LHV for RUG is slightly higher than diesel.

Table 2-3 Fuel test results for comparison of diesel and TGB1 against ASTM D6751-12 for biodiesel

	Metal Species Concentration (ppm)				
Fuels Tested	P	S	Na	K	Na + K
ASTM standard	10	15			5
Diesel (DSL)	1.15	14.4	< 0.098	0.858	0.858
TGB_1	11.3	133	3.54	0.895	4.43

Note: Multiple runs performed for each measurement and R value was between 0.93 and 0.97.

Table 2-4 Physical properties of diesel and TGB1

		ASTM Standard			
		D1298	D6371	D2500	D7042
Fuels Tested	Sound Velocity @ 20°C ($m\ s^{-1}$)	Density @ 20°C ($g\ cm^{-3}$)	Cold Filter Plugging Point (CFPP) (°C)	Cloud Point (CP) (°C)	Kinematic Viscosity (v) @ 40 °C ($mm^2\ s^{-1}$)
Off road diesel	1370.8 ± 0.1	0.838 ± 1E-6	-19.0 ± 0.5	-18.0 ± 0.5	2.57 ± 0.01
TGB_1	1426.8 ± 0.1	0.893 ± 1E-6	-13.0 ± 0.5	-17.0 ± 0.5	15.7 ± 0.1

Table 2-5 Calorific Value of Diesel and TGB1

	Calorific Value (LHV MJ kg^{-1})
Off Road Diesel	42.8 ± 0.2
TGB_1	37.0 ± 0.2
RUG[a]	40.5 ± 0.2

[a] *Regular Unleaded Gasoline (RUG).*

Note: The accuracy/uncertainty values are calculated from the specification sheet for the bomb calorimeter.

2.4.2 MAXIMUM POWER

Figure 2-2 shows the average percent variation in the maximum power output on the John Deere-EPA Tier 2 laboratory engine relative to diesel. The uncertainties (0.1% to 0.25%) were calculated by visually observing the analog rpm meter pointer over the test and the percent error was deduced. The data show TGB_2 exhibited ~11% reduction in maximum power compared to diesel while the maximum power output for TGB/DSL_1 and TGB/DSL_2 were lower than diesel by 7% and 6%, respectively. The maximum power increased with increasing percentage of diesel in the blends due to an increase in the LHV of diesel fuel compared to TGB_2. Maximum power field test results are plotted in Figure 2-3. The uncertainties (3.3%) were deduced by calculating the coefficient of variance over the averaging time of the data point. The variations in the peak power correspond to variations of LHVs of the fuels. The power of TGB/DSL_3 fuel is reduced to 141 HP, a 3.2% reduction compared to DSL. This reduction is attributed to a smaller LHV of this fuel (40,500 kJ/kg), which is ~5% lower than that of DSL. The maximum horsepower of the TGB_3 fuel was ~134 hp, a 7% reduction compared to DSL. This corresponds to a LHV approximately 9% lower than diesel. The horsepower of TGB/DSL_4 fuel was ~142 HP, which was ~3% lower than that of diesel. This reduction is attributed to a smaller LHV (40,200 kJ/kg), which is

~5.5% lower than that of diesel. The TGB_1 fuel gave a maximum horsepower of 130 hp, which was 10% lower than that of diesel. The LHV of this fuel (37,700 kJ/kg) is approximately 11% lower than that of diesel.

Note that in each case the percent reduction in LHV is greater than the percent reduction in peak power observed. This is indicative of higher brake thermal efficiency for the blends. This outcome may be due to the lower compressibility of the TGB fuels. TGB_1 exhibits 13.4% lower compressibility as compared to diesel. The relationship is similar for biodiesel. This observation could explain why the engines running on triglycerides and biodiesel have advanced combustion phasing, which can increase NO_X emissions[29, 30] The field engines are pump-line-injector systems. Compared to common-rail injection systems, pump-line-injector systems are likely more sensitive to compressibility effects due to pressure transients in the line between the injector pump and the injector. Another possible factor is the cetane number of the fuel. Fuels with higher cetane numbers have shorter ignition delays and earlier combustion phasing, which can increase the brake thermal efficiency of the engine.

2.4.3 FUEL CONSUMPTION AND THERMAL EFFICIENCY

Figure 2-4 presents the average fuel consumption relative to diesel for three engine operating conditions. The uncertainties (1%) were deduced by calculating the coefficient of variance over the averaging time of the data point. On average, the fuel consumption rates for TGB/DSL_1 and TGB_3 were about 5% and 12%, respectively, greater than diesel. These increases are primarily due to the variation in the LHV differences of the blends.

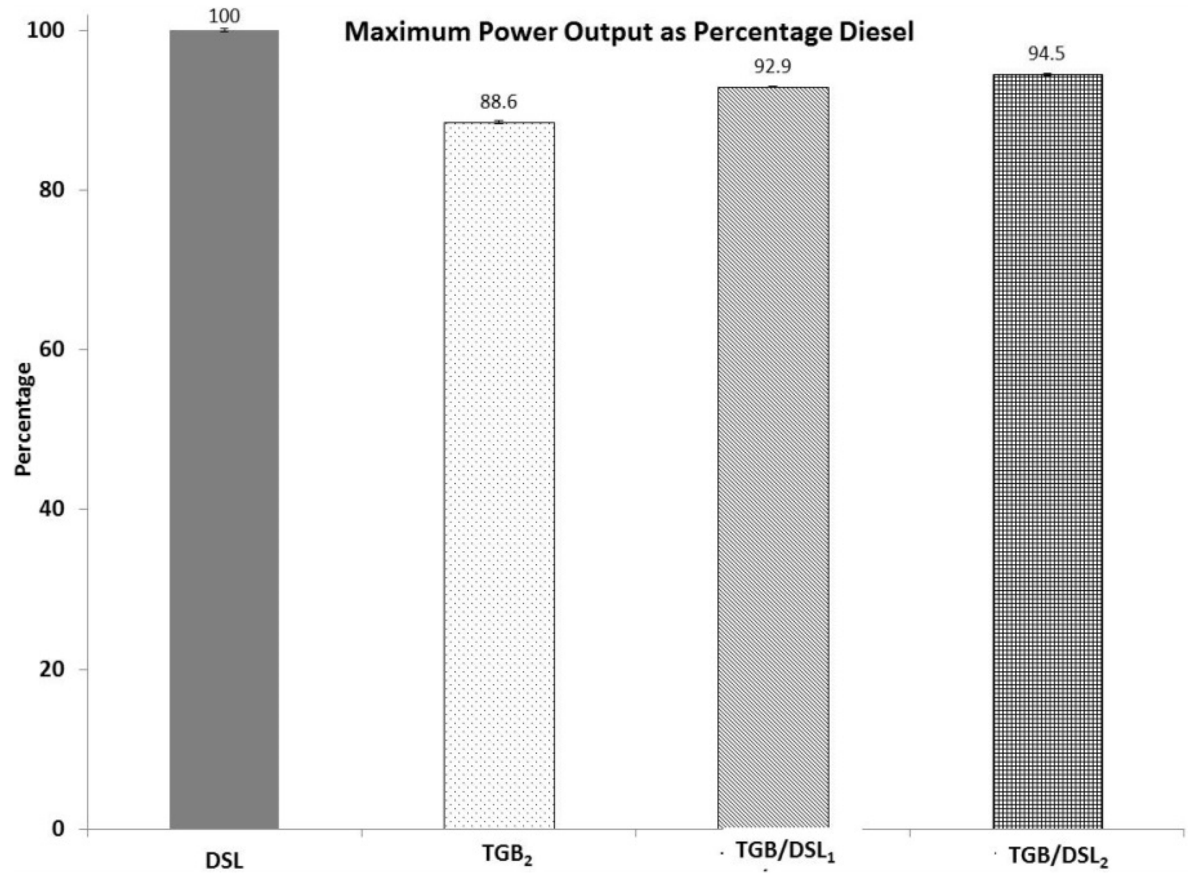

Figure 2-2 Maximum power test John Deere 4.5 l Tier 2 engine

The brake thermal efficiency for the fuels is plotted in Figure 2-5. In general, thermal efficiency for the 80% load 1700 rpm data point was the highest, followed by 100% load 1700 rpm and then the 80% load 2200 rpm data. Thermal efficiency normalizes the variations in LHV. TGB/DSL_1 produced a thermal efficiency of 0.05% to 0.30% higher than diesel. TGB_3 has a thermal efficiency approximately the same (within ±0.1%) as diesel fuel. The uncertainties of the primary measurement (0.057% to 0.28%) were evaluated by calculating the coefficient of variance over the averaging time of the data point. For this comparison, the uncertainties are generally large compared to differences in brake thermal efficiency. Thus, the differences in brake thermal efficiency are not statistically significant.

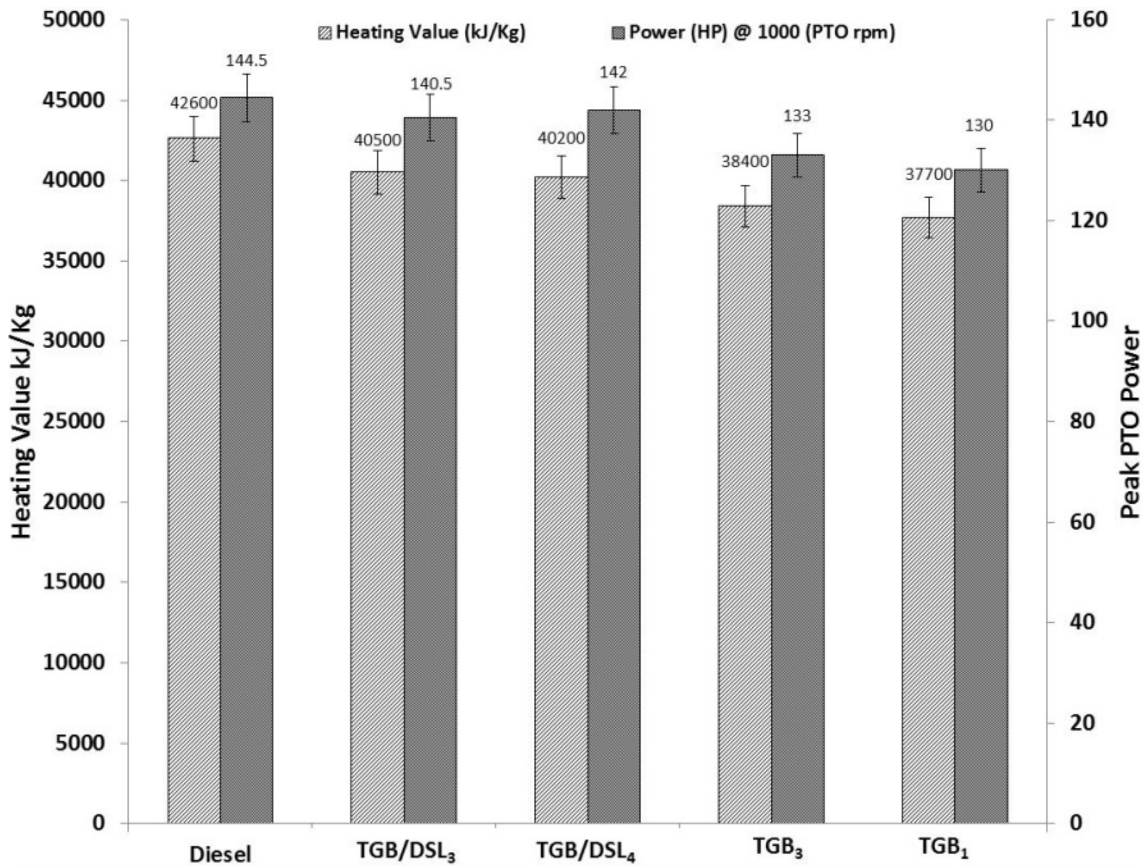

Figure 2-3 Peak power for John Deere 4440 tractor engine and heating value of fuels

Mass based fuel consumption is presented in Figure 2-4 as a percent of diesel for the John Deere 4.5 l EPA Tier 3 engine for the 8-mode map. The 8-mode test data was collected by running a diesel point, followed by a TGB_1 point, then a final diesel point for each mode. This approach gave a more direct comparison with diesel performance. The results in figure 6 are similar to those for the John Deere 4.5 l Tier 2 engine.

Higher fuel consumption is observed with TGB_1 for most data points. However, the trend reverses when the fuel consumption is expressed on a volumetric basis (Fig 2-7). The volume-based fuel consumption is generally lower for TGB_1 compared to diesel with exceptions for the low load data points where it was higher than diesel by 2% to 10%.

The thermal efficiency was calculated and plotted against diesel (Fig 2-8). The thermal efficiency of the TGB_1 blend was generally higher than diesel by approximately 2% to 3%. This result is consistent with previous research by Faletti et al. (1984) who reported higher brake thermal efficiencies in various hybrid fuels consisting of partial vegetable oils.

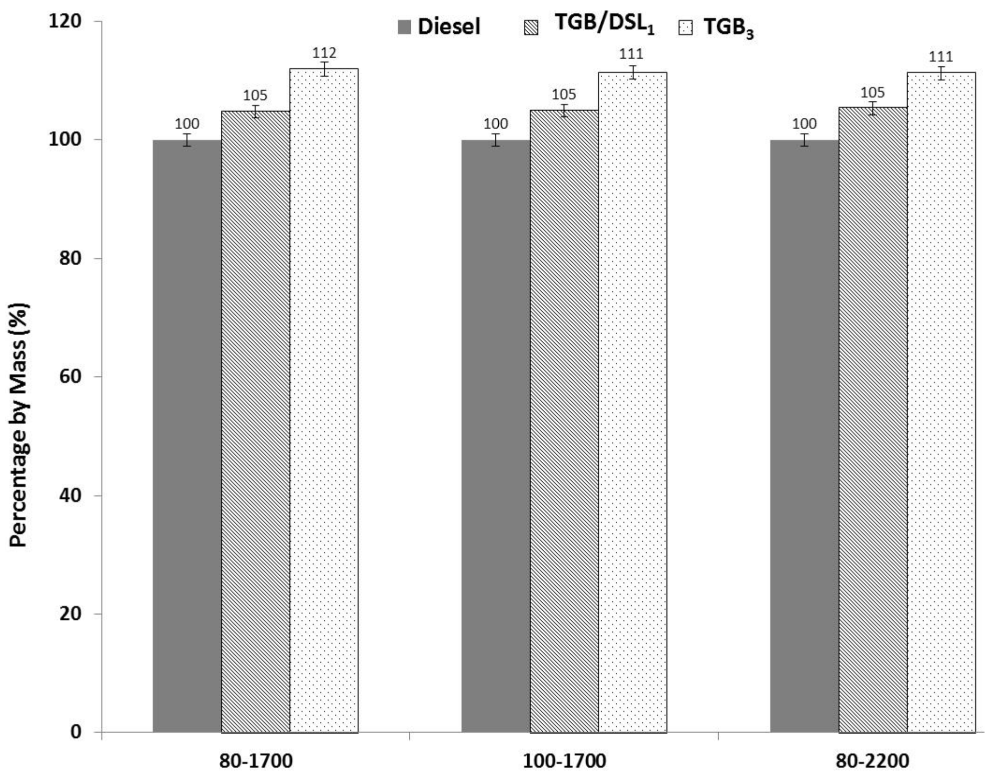

Figure 2-4 Fuel consumption by mass as percentage as diesel for the John Deere 4.5 l Tier 2 engine2

The results indicate that end users would observe improved fuel consumption for TGB_1, since fuel economy for on-road vehicles and farm machinery is normally expressed in miles per gallon and gallons per hour, respectively. TGB_1 is approximately 7% denser than diesel. The density difference in addition to slightly higher thermal efficiencies explains the volumetric fuel consumption benefit of using TGB_1.

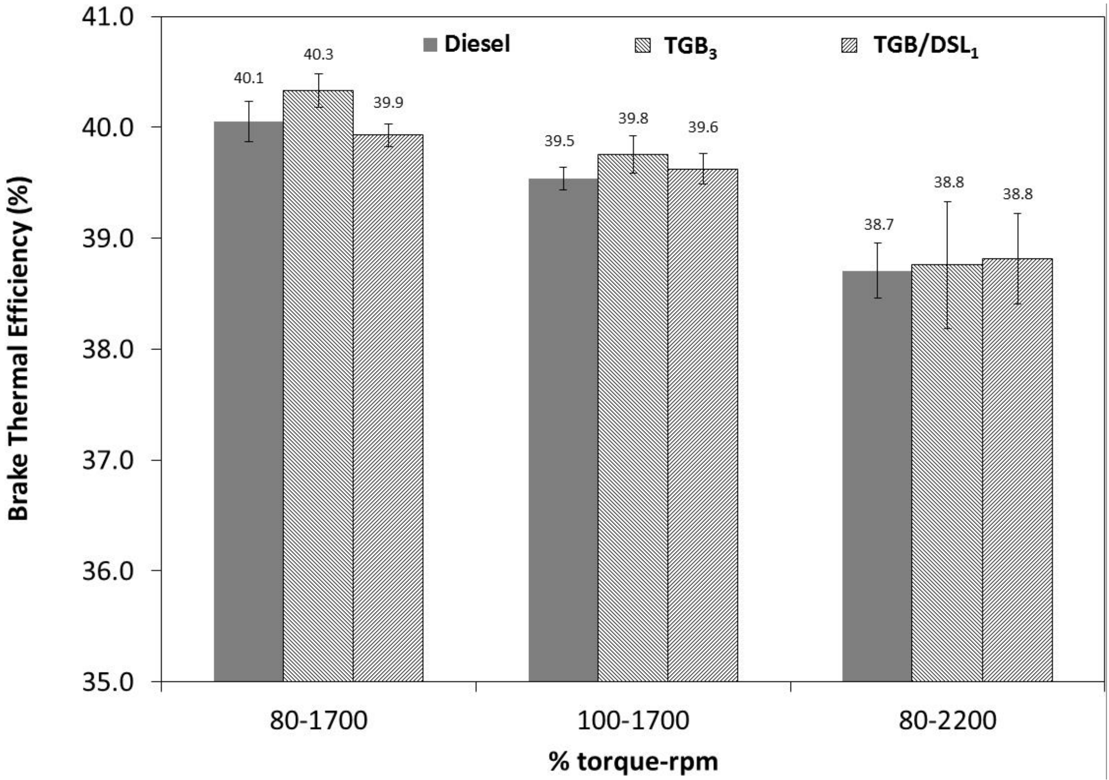

Figure 2-5 Brake thermal efficiency for the John Deere 4.5 l Tier 2 engine

2.4.4 POLLUTANT EMISSIONS

Exhaust emissions THC, CO, and NO_X are plotted with respect to diesel in Figures 2-9 to Figure 2-11 for three engine operating conditions. The THC emissions are significantly higher for TGBs but display an inconsistent trend. Carbon monoxide decreases as the amount of TGB increases. Triglycerides are oxygenated, which may help promote more effective oxidation of carbon monoxide. Emissions of NO_X display an increasing trend with increasing levels of TGB. This is similar to behavior sometimes observed with biodiesel.

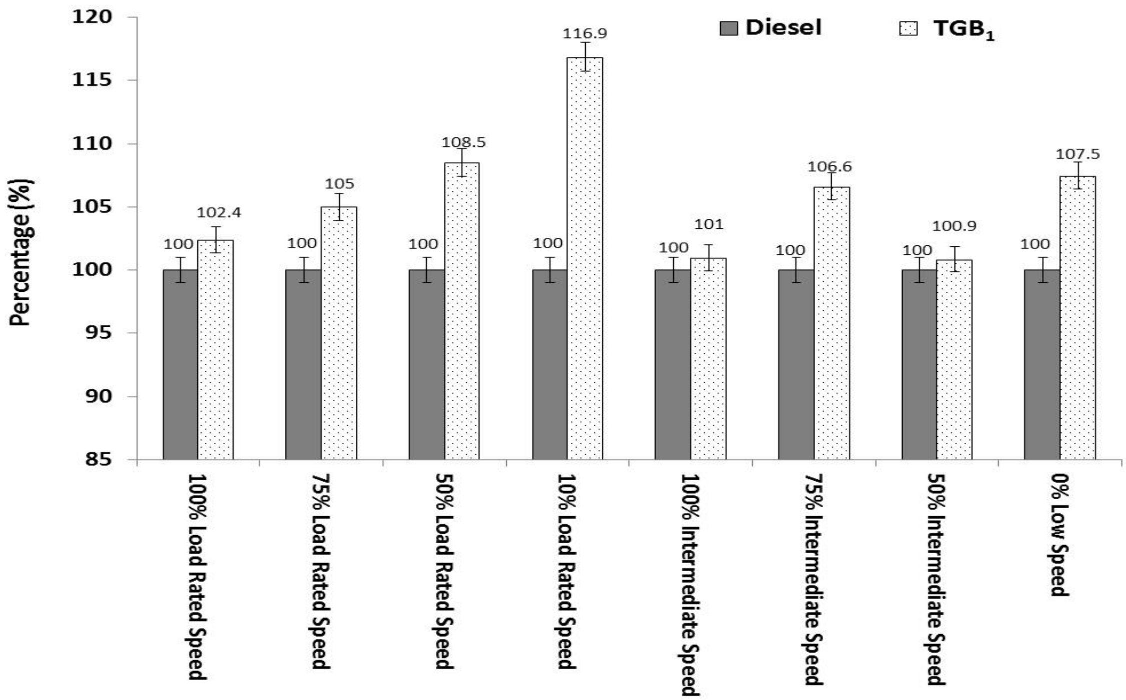

Figure 2-6 Mass based fuel consumption as percentage of diesel for the John Deere 4.5 l Tier 3 engine

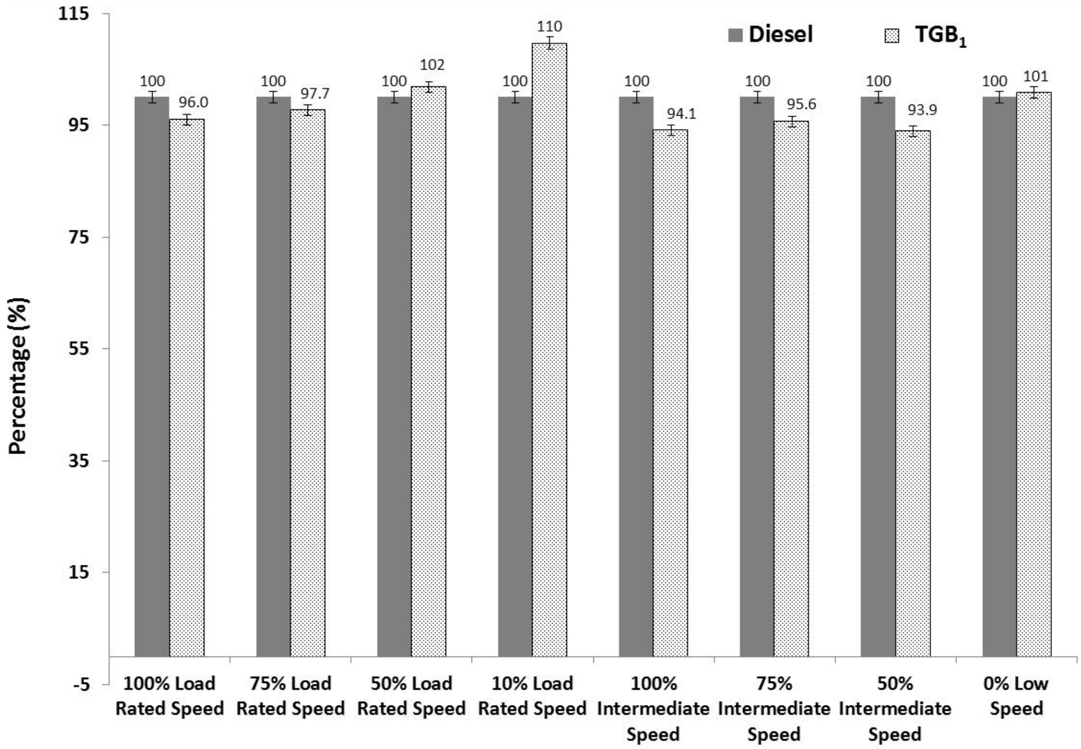

Figure 2-7 Volume based fuel consumption as percentage of diesel for John Deere 4.5 l Tier 3 engine

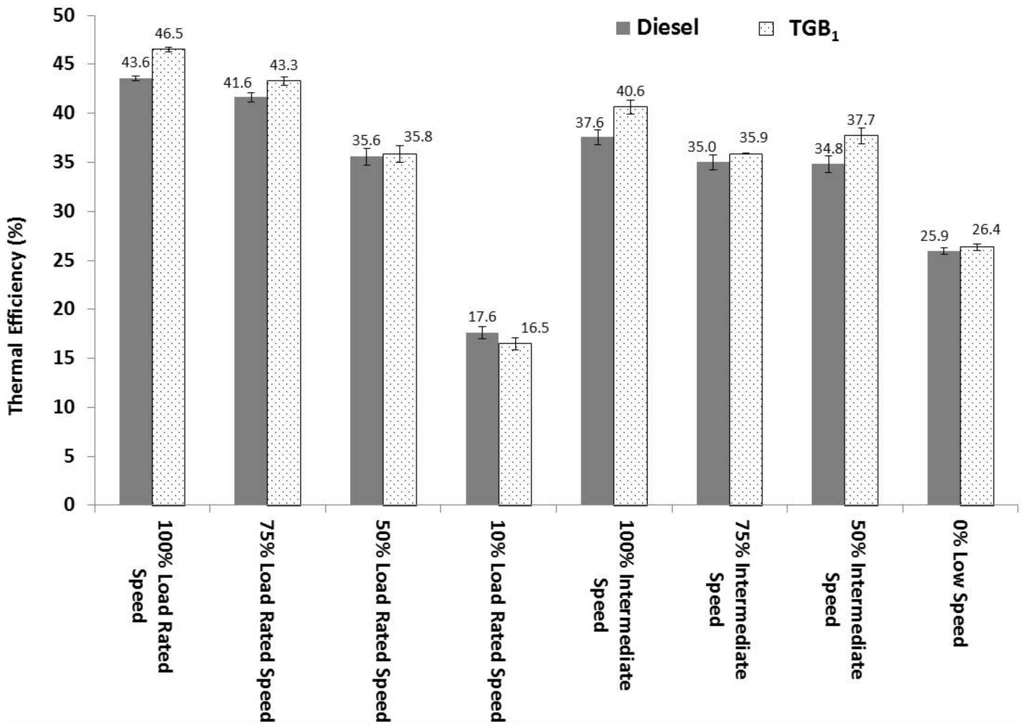

Figure 2-8 Thermal efficiencies as percentage of diesel for the John Deere 4.5 l Tier 3 engine

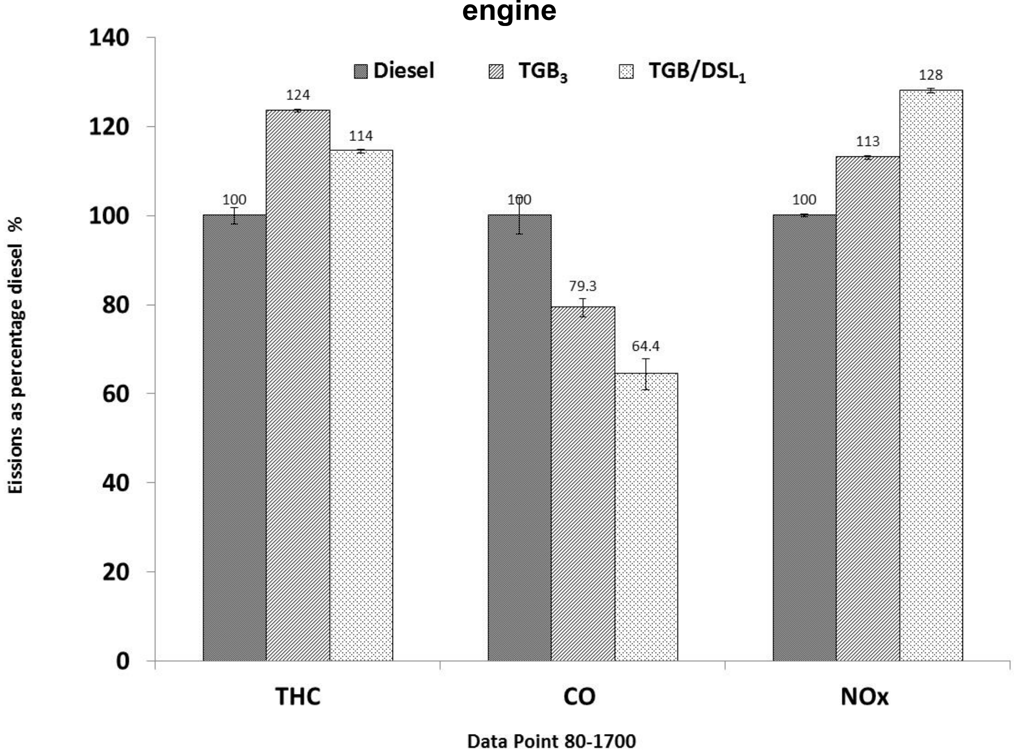

Figure 2-9 Emissions at 80% load and 1700 rpm as percentage diesel for the John Deere 4.5 l Tier 2 engine

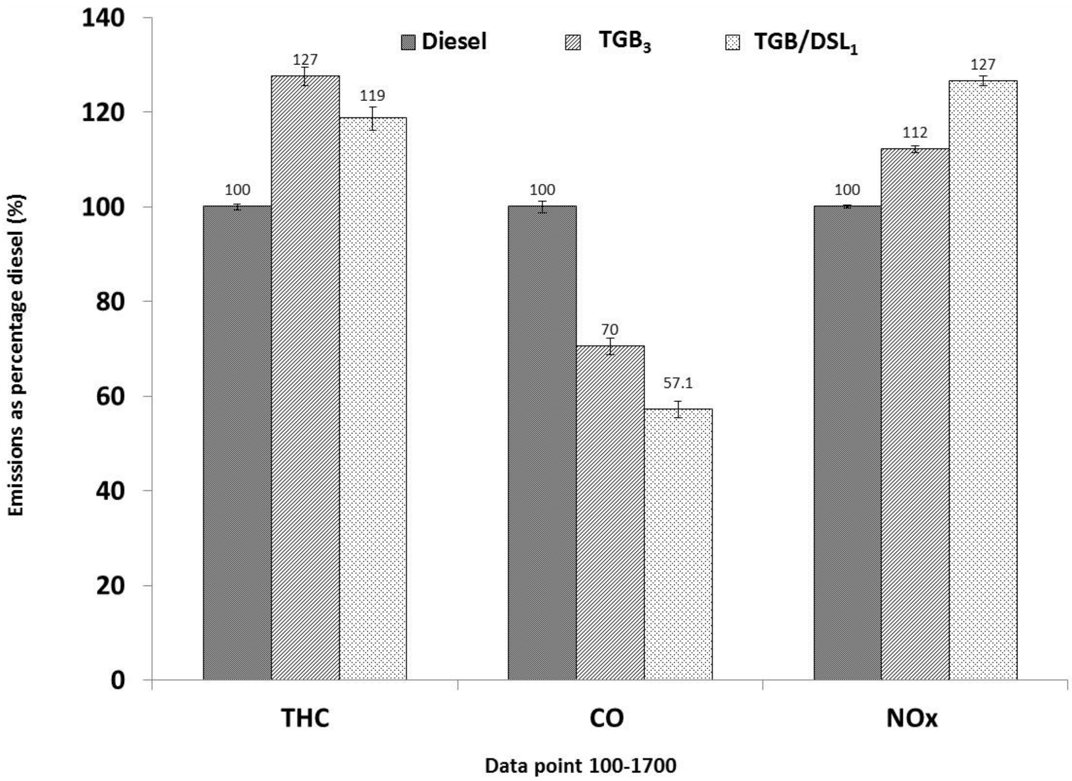

Figure 2-10 Emissions at 100% load 1700 rpm as percentage diesel for the John Deere 4.5 l Tier 2 engine

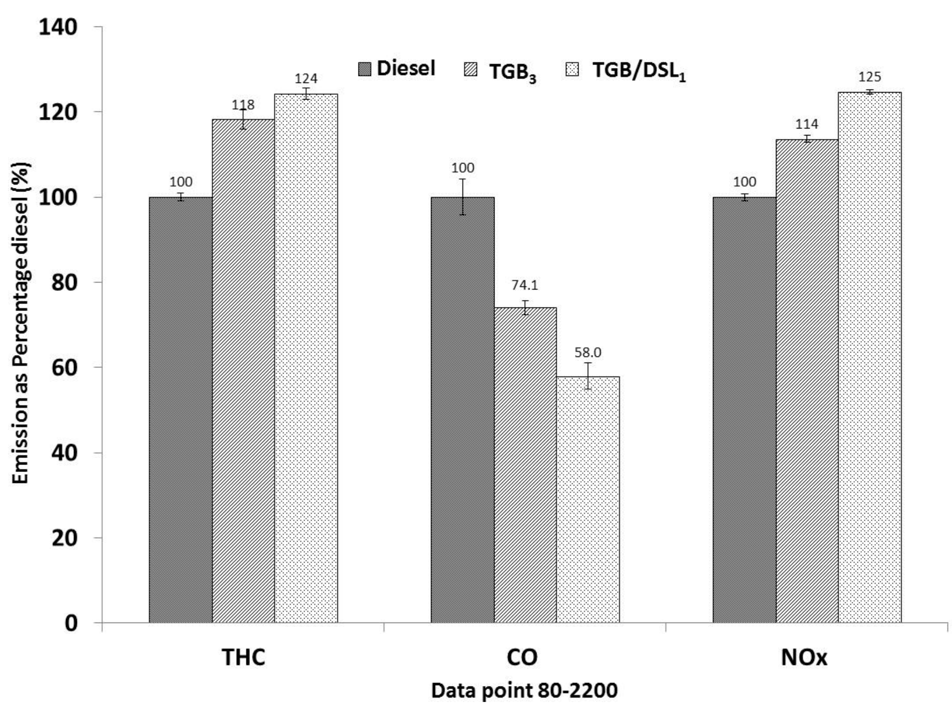

Figure 2-11 Emissions at 80% load 2200 rpm as percentage diesel for the John Deere 4.5 l Tier 2 engine

Two possible explanations are: (1) faster combustion rates lead to higher cylinder temperatures that accelerate NO_X formation, and (2) oxygenated fuel combustion contains additional kinetic paths for NO_X formation.

Emissions of NO_X and PM for the TGB_1 test on the John Deere 4.5 l Tier 3 engine are shown in Figure 2-12. These values are computed based on ISO 8178 8-mode weighting factors. The NO_X emissions for TGB_1 is about 3.5% higher than diesel while PM was about 8% lower than diesel. Emissions of NO_X and PM typically trend in opposite directions, which is consistent with the data. For example, if the rate of combustion is faster for TGB_1, then the combustion pressure peak occurs earlier and cylinder average temperature is higher, producing more NO_X. Conversely, higher combustion temperatures tend to consume PM more completely prior to exhaust valve opening when combustion products are emitted into the exhaust system. The data is also consistent with the data presented above for the John Deere 4.5 l Tier 2 engine. Injection timing retard could be implemented to bring PM and NO_X closer to diesel levels.

EPA Tier 3 weighted average emission limits are 4.0 g/bkW-h for NOx + Non Methane Hydrocarbons (NMHC) and 0.3 g/bkW-h for PM. However, the engine is only required to meet these limits within a range of atmospheric conditions. This testing is performed at 1530 m (5000 ft) above sea level where the atmospheric pressure is approximately 84 kPa. The emissions limits are not applicable at this altitude based on a criterion defined in ISO 8178-1.

Thus, it is not possible to clearly determine whether the engine meets the EPA Tier 3 emissions limits operating on TGB_1 using this test data and the data must be interpreted with this caveat.

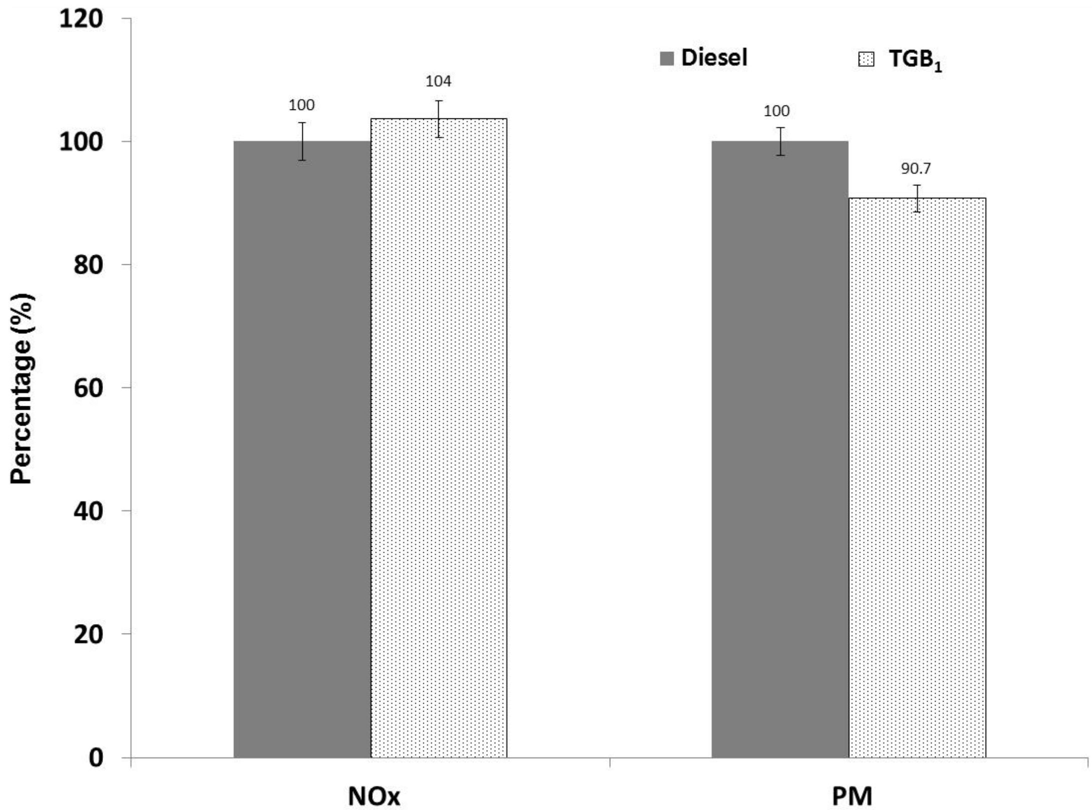

Figure 2-12 Percentage comparison of TGB1 to diesel for ISO weighted average NOx and PM emissions for the John Deere 4.5 l Tier 3 engine

The brake specific diesel emissions are 5.4 and 0.21 g/bkW-h for NOx + NMHC and PM, respectively. Note that NMHC emissions are not presented graphically, although they were measured during testing.

The diesel emissions meet the PM tier 3 limit, but do not meet the (NOx + NMHC) limit. At sea level where the boost pressure would be higher the engine would meet the emissions limits with margin. The brake specific TGB_1 emissions are 6.6 and 0.19 g/bkW-h for NOx + NMHC and PM, respectively. Similar to diesel the TGB_1 NOx + NMHC emissions are above the Tier 3 limit and PM emissions are below the Tier 3 limit. This small shift of NOx + NMHC and PM emissions could be compensated for by retarding timing, which would reduce NOx + NMHC and increase PM. However, it is possible that at sea level where the turbocharger provides higher boost pressure the margins for NOx + NMHC and PM emissions would be large enough so that the engine timing adjustments would not be necessary.

2.5 CONCLUSION

Though regarded as a somewhat crude approach to biodiesel, TGBs are a simple alternative for farmers who operate older machinery that is likely no longer under warranty by manufacturers. The diesel engines used in this study were capable of burning TGBs without modification. While the initial testing suggests modestly favorable applications of TGBs in specific engines, research in this area requires long-term durability testing to assess the impact of using TGBs in the combustion chamber, fuel system, and after-treatment components.

Based on this research, some specific observations and conclusions about the engine performance and fluid properties of TGBs can be provided. The overall thermal efficiencies under various engine operating conditions when using TGB were slightly higher than for diesel, suggesting a slightly more efficient energy conversion. High viscosity (~7X diesel) and poor cold flow properties were measured for the TGB containing 90% canola-triglyceride and 10% regular unleaded gasoline (TGB_1). These properties will likely affect engine performance and reliability in colder temperatures. The lower heating value (LHV) of TGBs is lower than diesel. The LHV will vary with the percent gasoline in the blend, but for TGB_1, the LHV was approximately 9% lower than that of diesel fuel baseline.

The metal content of TGBs is generally higher than diesel. Although this is a concern for catalysts in after-treatment systems, it could be addressed by adding additional triglyceride processing steps. Engines running on TGBs produced higher levels of NO_X but lower levels of CO and PM compared to diesel. Emissions of NO_X increased by less than 5% and PM decreased by less than 10%. Injection timing could be adjusted to shift emission back closer to diesel levels.

2.6 REFERENCES

[1] Uri, N.D. and K. Day, Energy efficiency, technological change and the dieselization of agriculture in the United States. Transportation Planning and Technology, 1992. 16(3): p. 221-231.

[2] Skalsky, S.A., et al., Impact of Fuel and Nitrogen Prices on Profitability of Selected Crops: A Case Study. 2008.

[3] Johnson, J., et al., Completion Report No. 211: Development of oilseed crops for biodiesel production under colorado limited irrigation conditions. 2009: Fort Collins, Colorado: Colorado Water Institute.

[4] Fuls, J., C.S. Hawkins, and F.J.C. Hugo, Tractor engine performance on sunflower oil fuel. Journal of Agricultural Engineering Research, 1984. 30(0): p. 29-35.

[5] Paulsen, H.M., et al., Use of straight vegetable oil mixtures of rape and camelina as on farm fuels in agriculture. 2011: Biomass and Bioenergy 25, 4015-4024.

[6] Keske, C.M.H., et al., Is it economically feasible for farmers to grow their own fuel? A study of Camelina sativa produced in the western United States as an on-farm biofuel. Biomass and Bioenergy, 2013. 54(0): p. 89-99.

[7] Goering, C.E., et al. Evaluation of soybean oil-aqueous ethanol microemulsions for diesel engines. in ASAE Proceedings of the International Conference of Plant and Vegetable Oils as Fuels. 1982. ASAE

[8] Zubik, J., S.C. Sorenson, and C.E. Goering. Diesel engine combustion of sunflower oil fuels. 1984. Trans. ASAE, .

[9] Dorado, M.P., et al. The effect of a waste vegetable oil blend with diesel fuel on engine performance. 2002. ASAE.

[10] Drenth, A.C., et al., Compression ignition engine performance and emission evaluation of industrial oilseed biofuel feedstocks camelina, carinata, and pennycress across three fuel pathways. Fuel, 2014. 136: p. 143-155.

[11] Allen, C.A.W., et al., Predicting the viscosity of biodiesel fuels from their fatty acid ester composition. Fuel, 1999. 78(11): p. 1319-1326.

[12] Miers Scott A, K.A.L., El-Hannouny Essam M, Longman Douglas E. AN EXPERIMENTAL INVESTIGATION OF BIODIESEL INJECTION CHARACTERISTICS USING A LIGHT-DUTY DIESEL INJECTOR. in ASME Internal Combustion Engine Division 2007 Fall Technical Conference. 2009. Charleston, South Carolina, USA.

[13] Thornton Matthew J, A.T.L., Luecke Jon, Robert L. McCormick, Impacts of Biodiesel Fuel Blends Oil Dilution on Light-Duty Diesel Engine Operation, in 2009 SAE International. 2009.

[14] Bartoli, Y., et al. 1000 Hour Durability Evaluation of a Prototype 2007 Diesel Engine with Aftertreatment Using B20 Biodiesel Fuel. in SAE International. 2009. SAE International.

[15] Shonnard.David R, W., Kalnesc Tom N Camelina-Derived Jet Fuel and Diesel: Sustainable Advanced Biofuels. 10 June 2010.

[16] Bezergianni, S., A. Kalogianni, and A. Dimitriadis, Catalyst evaluation for waste cooking oil hydroprocessing. Fuel, 2012. 93(0): p. 638-641.

[17] Lapuerta, M., et al., Blending scenarios for soybean oil derived biofuels with conventional diesel. Biomass and Bioenergy, 2013. 49(0): p. 74-85.

[18] Baker, H.W. and R.L. Sweigert, A comparison of various vegetable oils as fuels for compression ignition engines, in ASME Oil and Gas Power Meeting. 1947, ASME: New York. p. 1-5.

[19] Peterson, C.L., G.L. Wagner, and D.L. Auld. Vegetable oil substitutes for diesel fuel. 1983. ASAE.

[20] M., Z., Vegetable oils as a potential alternate fuel in DI diesel engines. 1983, Society of Automotive Engineers.

[21] Srivastava, A. and R. Prasad, Triglycerides-based diesel fuels. Renewable and Sustainable Energy Reviews, 2000. 4(2): p. 111-133.

[22] Directive 97/68/EC of the European Parliament and of the Council of 16 December 1997 on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery. Official Journal of the European Communities ;, in 41:L 59/86.-. 27 February 1998.

[23] S., M.A., Effect of fuel additives on performance and emissions of industrial diesel engines, in Department of Mechanical Engineering. 2009, Colorado State University: Fort Collins.

[24] Tan, P.-Q., Z.-Y. Hu, and D.-M. Lou, Regulated and unregulated emissions from a light-duty diesel engine with different sulfur content fuels. Fuel, 2009. 88(6): p. 1086-1091.

[25] Lambelet, P., et al., Formation of modified fatty acids and oxyphytosterols during refining of low eurcic acid rapeseed oil. Journal of Agriculture and Food Chemistry, 2003. 51(15): p. 4284-4290.

[26] Tasan, M. and M. Devirc, Trans FA in Sunflower oil at different steps of refining. Journal of American Oil Chemists' Society, 2003. 80(8): p. 825-828.

[27]. Knothe, G., Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters. Fuel Processing Technology, 2005. 86(10): p. 1059-1070.

[28] Mueller, C., A. Boehman, and G. Martin, An experimental investigation of the origin of increased nox emissions when fueling a heavy-duty compression-ignition engine with soy biodiesel. SAE Intl. J. of Fuels and Lubricants, 2009. 2(1): p. 789-816.

[29] Ye, P. and A.L. Boehman, An investigation of the impact of injection strategy and biodiesel on engine NOx and particulate matter emissions with a common-rail turbocharged DI diesel engine. Fuel, 2012. 97(0): p. 476-488.

3. EFFECTS OF TRIGLYCERIDE GASOLINE BLENDS ON COMBUSTION and EMISSIONS IN A COMMON RAIL DIRECT INJECTION DIESEL ENGINE [2]

3.1 OVERVIEW

This study presents the combustion and emission results using a blend of unrefined triglycerides (straight vegetable oils) and regular unleaded gasoline in a compression ignition engine typically used in farming machinery. Most farm equipment is powered by diesel engines. A sizable cost of producing a crop on a farm can be attributed to fuel - diesel in such cases. Farmers and researchers have been interested in the use of alternative fuels, especially triglycerides, which could potentially bring down the fuel cost portion of the farm input costs.

One of the major drawbacks of using unrefined triglycerides is poor cold flow properties due to high density and viscosity. To overcome this, the triglycerides can be blended with gasoline to lower the density and viscosity. This blend has been used in existing diesel engines without the need for any modification to the engine or its control system.

The experiments were conducted on a 4.5L Tier-III Engine. The fuel used was a blend of unrefined canola triglyceride and regular unleaded gasoline (10% by volume). Measurements include mass fraction burned combustion pressure, fuel consumption, and pollutant emissions. The fuel consumption of TGB10 was lower than most SVOs found in literature, but higher than diesel. The peak pressure of TGB10 was slightly higher than diesel and occurred earlier than diesel. The brake specific NOx was lower than diesel at lower and no load points. Particulate matter emissions of TGB10 were higher than diesel

[2] Manuscript published in *International Journal of Engine Research*, (10.1177/14680874177403162017) by A. Lakshminarayanan et.al.

at rated speed. THC emissions were generally higher than diesel. CO emissions were lower than diesel except at low or no load points where they were significantly higher.

3.2 INTRODUCTION

The continued development of biofuels is important to the expansion of renewable energy and US energy security. Using biofuels to substitute for diesel fuel is attractive when they can be used in compression ignition engines with little or no modification. Biofuels are renewable and contribute to government initiatives [1] to reduce greenhouse gas emissions and the dependency on fossil fuels. Most biofuels contain oxygen which helps reduce particulate matter (PM) growth reactions by promoting oxidation of the unsaturated hydrocarbon (HC) species[2]. The oxygen in the fuel influences combustion via local air/fuel ratio and affects pollutant emissions [3]. Emissions from combustion of fossil fuels are believed to be linked to global warming, resulting in the increase of sea-levels and disappearing coastlines across the globe [4]. Use of biofuels are shown to mitigate greenhouse gas emissions [5, 6].

Biodiesel is a biofuel that can be substituted for diesel fuel. It is made from straight vegetable oils and animal fats by transesterification [7]. The main impediments to the widespread use of biodiesel are high cost and insufficient infrastructure to process a wide range of feedstocks [8]. The cost of producing biodiesel is greater than the cost of producing straight vegetable oils (SVOs) since SVO production does not require transesterification. However, use of SVOs has technical barriers to its widespread use as an engine fuel. Many SVO engine studies indicate that the use of SVO leads to reduced engine life [9-11] caused by carbon deposit buildup in the combustion chamber and acceleration of lubricating oil degradation. These issues can be attributed to high viscosity and boiling point relative to diesel fuel [12-15].

To overcome the SVO limitation of high viscosity, some farmers [16] blend regular unleaded gasoline with SVO to match the specific gravity of diesel (~0.865 to 0.870). Gasoline is used as a thinner for two reasons: (i) it is readily available, and (ii) gasoline is also a fuel. This blend of SVO and gasoline is defined as a Triglyceride Gasoline Blend (TGB). Gasoline, is characterized by a high volatility and a low cetane number [17, 18]. Gasoline also evaporates quickly due to its low boiling point, which results in a shorter liquid spray penetration[19]. Faster evaporation of the fuel could lead to accelerated fuel-air mixing, which in turn leads to an increase in ignition delay. This results in intensified premixed heat release and, hence, resulting in less smoke and higher nitrogen oxide NOx emissions [20-22].

The potential users of TGBs need a better understanding of the combustion process and the long term impacts on the machinery. There is very little peer reviewed literature [16, , 23, 25] available on the TGBs while there are many publications on diesel blends with triglycerides and other oxygenates [26-29]. These publications discuss in detail the physical properties and exhaust emissions from diesel engines.

TGBs are similar to standardized fuels like diesel and biodiesel and do not require engine modification for their use. However, questions regarding the impact of TGBs on the vehicle, tractor, and generator engine components remain unanswered. This research aims to address many of these questions by experimentally characterizing diesel engine performance operating on a TGB.

The main objective of this research was to characterize diesel engine performance using a blend of unrefined canola triglyceride (90% by volume) and gasoline (10% by volume) as fuel, designated as TGB10.

The stock program in the engine control unit (ECU) was used. This ECU was programmed and calibrated by the engine manufacturer with diesel as the primary fuel. The engine ECU was not modified to adapt it to the alternative fuel used in these experiments. The results are interpreted with this caveat.

3.3 EXPERIMENTAL SET UP

3.3.1 FUEL

The fuel used was a blend of canola SVO (triglyceride) and regular unleaded gasoline in a 9:1 ratio by volume. Gasoline was added to the SVO such that the specific gravity of the resulting blend would be in the range of 0.865 to 0.870, similar to that of diesel fuel available at fueling stations. This blended fuel (TGB10) was then stored in containers for about 3 days before being used in experiments. The fuel blend did not show any separation of the triglyceride and gasoline and remained stable throughout the duration of the engine test program.

The fuel property details for TGB10 are discussed in previous work [16]. The kinematic viscosity of diesel is 2.57mm^2/s and 15.7 mm^2/s for TGB10, about 6 times larger than diesel. The calorific value of TGB10 is 39 MJ/kg which is about 6% lower than diesel. Metals and mineral content of TGB10 is orders of magnitude higher than diesel and exceeded the ASTM D6751 limits for biodiesel as shown in Table 1[16].

Table 3-1 Metal Species Concentration

Fuels	P	S	Na	K	Na+K
ASTM standard	10	15			5
Diesel	1.15	14.4	<0.098	0.858	0.858
TGB10	11.3	133	3.54	0.895	4.43

3.3.2 ENGINE

Engine performance and emission analysis is conducted on a 4-cylinder, 16 valve, turbocharged, intercooled, 4.5L, 175 hp (129 kW), John Deere 4045 PowerTech Plus, Tier 3 test engine. The engine is configured with a variable geometry turbine (VGT) turbocharger, exhaust gas recirculation (EGR) and a high pressure common rail electronically controlled fuel injection system. The engine is coupled to an eddy current dynamometer (Midwest Inductor Dynamometer 1014A). The dynamometer and its controller (Dynesystems Dyn-LocIV) are used to load the engine and maintain constant speed for each test point.

Diesel and TGB10 were stored in two different fuel tanks. Each fuel tank had a dedicated fuel lift pump which supplied the fuel to the engine mounted high pressure fuel pump. The fuel return line for diesel operation was connected back to the fuel supply line downstream of the Coriolis fuel meter (Micro Motion 2700R11BBCEZZZ), so it directly read the net fuel consumption. The TGB10 fuel tank was placed on an electronic scale and the lift pump supplied fuel from the tank to the engine. The TGB10 fuel return line from the injectors was routed directly to the fuel tank. The difference in the readings of the electronic scale before and after the data point gave the net fuel consumption.

The high speed in-cylinder pressure was recorded by a Kistler Instrument Corporation PiezoStar pressure sensor (6056A41) with a glow plug adaptor (6542Q128) that was installed in the glow plug port of cylinder 1. A custom system developed at the laboratory using National Instruments PXI-1002 was connected to a charge amplifier (Kistler type 5010) to record combustion pressure data from the in-cylinder pressure transducer. Crankshaft position and instantaneous engine speed were provided by an incremental encoder connected to the crankshaft. Pressure data was taken at 0.50 crank angle degree intervals for 1000 cycles, then averaged and smoothed using LABView software. The engine ECU operated as per the stock programming and hence parameters such as the injection timing and injection pressure were controlled according to stock ECU maps.

3.3.3 EXHAUST GAS SAMPLING AND MEASUREMENT

Two different probes extracted exhaust for emissions measurements. An averaging probe was used for gaseous emissions and an isokinetic probe was used for PM. The gas analysis was performed with a 5-gas analyzer. Table 3-1 shows a summary of exhaust gas analyzer specifications.

A dilution tunnel was used to measure PM emissions. The laboratory air was drawn into the system by a pump and made to pass through a High Efficiency Particulate Air (HEPA) filter to purify it. The exhaust sample entered the dilution tunnel where it was mixed with the purified air. A PM10 cyclone removed all particles larger than 10 micron in diameter.

Table 3-1 Exhaust composition measurement techniques

	Device	Measurement Technology	Min. Conc. Range	Max. Conc. Range	Linearity
CO	Ultramat 6	IR	0 – 10.0 ppm	0 – 10000 ppm	< 0.5%
CO_2	Ultramat 6	IR	0 – 5.0 ppm	0 – 30 %	< 0.5%
THC	Fidamat 6	FID	0 – 10 ppm	0 – 99999 ppm	< 1%
NO_x	NOx MAT 600	Chemi-luminescence	0 – 1.0 ppm	0 – 3000 ppm	< 0.5%
O_2	OXYMAT6E	Paramagnetic	0 – 5 %	0 – 100 %	0.1%

from the mixture. A portion of the mixture was then extracted by a pump and made to flow through the filter assembly Teflon filters designed to collect particulate matter were held by filter cassettes. Particulate samples were collected onto pre-weighted Teflon filters which were then weighed again to give mass of the sample collected.

3.4 EXPERIMENTAL PROCEDURE

The 8-mode engine testing was carried out as per the ISO8178 [30]. Table 2 shows the speed and load of the 8 modes. The engine was warmed up to steady conditions. Average temperatures of coolant and lubricating oil were kept at 85°C and 87°C, respectively. At each of the 8 modes, a five-minute average for emissions and fuel consumption was recorded. Diesel fuel was first tested for each of the 8 modes. Then the fuel supply system was purged and flushed with TGB10 to ensure that there was no residual diesel fuel. The 8 modes were then repeated with the TGB10 as the fuel. The fuel system was then flushed with diesel and another set of 8 modes was tested with diesel. The two diesel cycles were evaluated independently and then the averaged to give us the average exhaust emissions and engine performance for diesel. TGB10 was available in limited quantity enough to carry out one set of experiment.

Table 3-2: Engine Modes according to ISO8178

M	Speed	Torque
1	2200	100%
2	2200	75%
3	2200	50%
4	2200	10%
5	1700	100%
6	1700	75%
7	1700	50%
8	800	0%

Table 3-3: Engine performance and emission data

ISO 8178 Modes	Fuel Type	**BSFC (g/kWh)**	**NO_X (g/kWh)**	**PM (g/kWh)**	**THC (g/kWh)**	**CO (g/kWh)**
Mode 1	Diesel	193.1	4.28	0.173	0.073	0.453
	TGB10	198.4	4.82	0.196	0.115	0.292
Mode 2	Diesel	204.0	4.26	0.111	0.075	0.734
	TGB10	213.1	5.01	0.176	0.115	0.415
Mode 3	Diesel	234.6	4.68	0.225	0.121	1.311
	TGB10	257.6	5.67	0.237	0.175	0.859
Mode 4	Diesel	476.6	6.01	0.572	1.35	17.239
	TGB10	560.0	5.67	0.997	3.14	25.55
Mode 5	Diesel	217.6	5.76	0.156	0.067	1.349
	TGB10	227.1	6.22	0.037	0.108	0.297
Mode 6	Diesel	228.2	5.85	0.187	0.073	1.073
	TGB10	257.3	8.06	0.123	0.102	0.571
Mode 7	Diesel	249.7	5.91	0.098	0.106	1.007
	TGB10	244.8	6.81	0.121	0.145	0.764
Mode 8	Diesel	341.6	9.79	0.605	1.36	5.41
	TGB10	350.3	6.13	0.233	3.24	13.192

Table 3-4: In-cylinder combustion data

ISO 8178 Modes	Fuel Type	Peak Pressure (kPa)	Location of Peak Pressure (^{O}ATDC)	Location of 50% MFB (^{O}ATDC)	Location of 10% MFB (^{O}ATDC)
Mode 1	Diesel	148	8.93	20.6	8.64
	TGB10	154	7.18	20.4	9.97
Mode 2	Diesel	122	8.54	20.0	11.1
	TGB10	125	6.39	19.9	11.2
Mode 3	Diesel	103	12.3	18.7	10.4
	TGB10	108	8.96	18.3	10.4
Mode 4	Diesel	88	0.281	18.1	12.4
	TGB10	80	0.536	19.3	13.1
Mode 5	Diesel	134	16.3	20.7	11.3
	TGB10	127	15.1	21.7	12.4
Mode 6	Diesel	115	16.2	18.4	9.90
	TGB10	116	17.3	18.2	10.4
Mode 7	Diesel	85	0.378	23.9	17.1
	TGB10	106	13.7	16.3	8.4
Mode 8	Diesel	64	4.81	-14.9	-19.4
	TGB10	64	5.67	-14.2	-19.2

Table 3-5: Weighted Emissions over the 8 mode cycle[46]

	NOx (g/kwh)	PM (g/kwh)	THC (g/kwh)	CO (g/kWh)
Diesel	5.71	0.281	0.405	3.25
TGB10	5.92	0.255	0.897	4.93

3.5 TEST RESULTS

A summary of brake specific fuel consumption and exhaust emissions – NO_X, PM, CO and THC for TGB10 and diesel fuel at the 8 modes are shown in Table 4. Table 5 shows the combustion statistics of peak pressure, location of peak pressure and the location of 50% mass fraction burned. Table 3-3 shows the average brake specific weighted emissions over the 8 modes. A detailed discussion of these data are in subsequent sections of this chapter.

Figure 3-1 shows the average brake specific fuel consumption of TGB10 as a percent deviation relative to diesel[16] that has been adapted from a previous publication by the authors. The uncertainty bars for each mode were calculated as the ratio of the standard deviation to the average value (Coefficient of Variance) of fuel consumption for two runs of diesel. In general, there was an increase in fuel consumption for TGB10, which could be attributed to the lower calorific value of the triglyceride-gasoline blend. Triglycerides, (straight vegetable oils) typically have about 20% to 30% lower calorific values than diesel [31, 32] and gasoline has a calorific value of 47MJ/kg. The calorific value of TGB10 used in this testing was 39 MJ/kg and diesel has an average calorific value of 42 MJ/kg.

At rated speed and 100% load (mode 1), TGB10 consumed about 2.8 % more fuel than diesel. As the load decreases at rated speed, the brake specific fuel consumption increased. At mode 4 (rated speed, 10% load) the TGB10 fuel consumption was about 18% larger than diesel. Thus, the increase in fuel consumption of TGB10 relative to diesel got larger as load decreased at rated speed. Mode 7 shows that TGB10 had about 2% lower fuel consumption. This was the only mode where TGB10 had lower fuel consumption than diesel. However, the difference is within the uncertainty bars.

Figure 3-2 shows the average brake thermal efficiency for TGB10 and diesel fuel at each of the 8 tested points[46] that has been adapted in a previous publication by the authors. The uncertainty bars are based on the standard deviation over two distinct diesel cycles

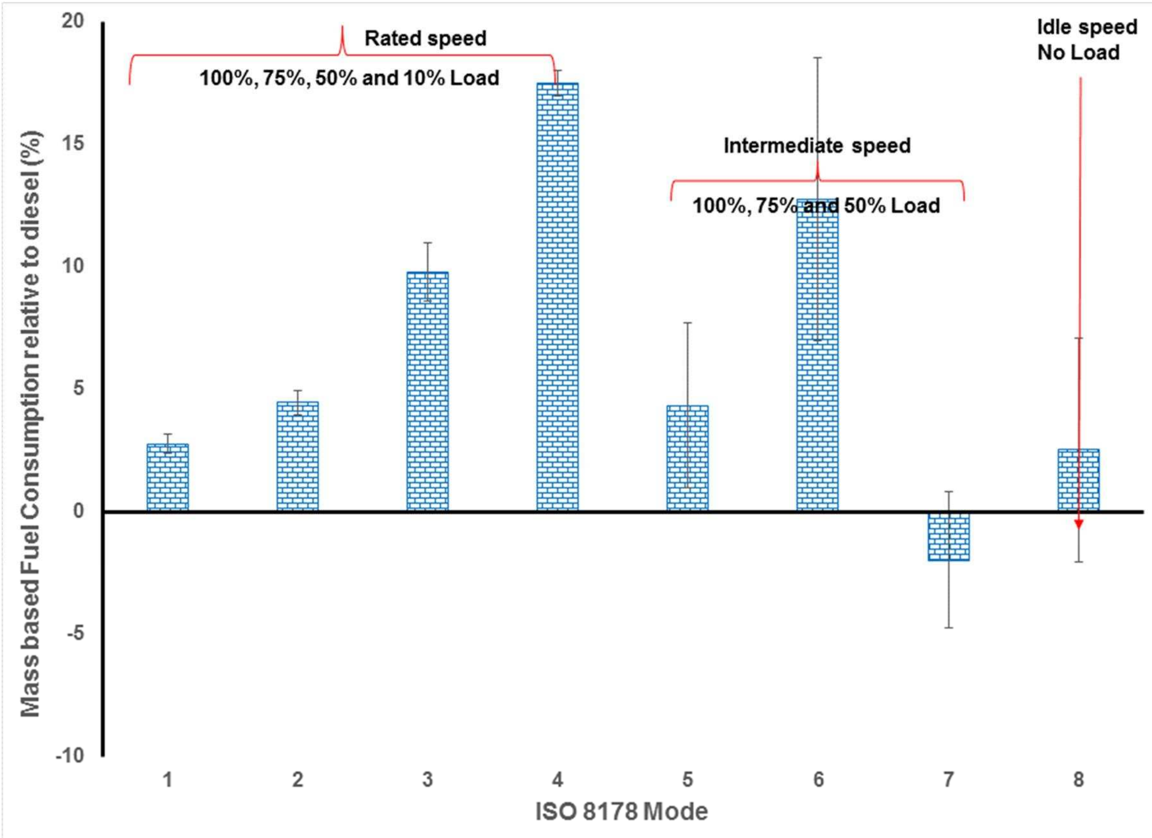

Figure 3-1: Mass based fuel consumption relative to diesel (error bars represent the variance)

for each of the 8 modes. The thermal efficiency of TGB10 was generally higher than diesel. This is consistent with previous research that reported higher thermal efficiencies using fuels containing partial vegetable oils. Detailed explanation of the higher thermal efficiency and the fuel consumption are found in another research that tested varieties of Straight Vegetable Oil, gasoline and diesel blends [16, 23, 25, 33].

Figure 3-3 shows average pressure traces over a 1000 cycles for TGB10 and diesel at four different modes. Figure 3-3(a) represents mode 1 (100% load and rated speed). The pressure trace of TGB10 has a higher peak pressure than diesel. The peak pressure of

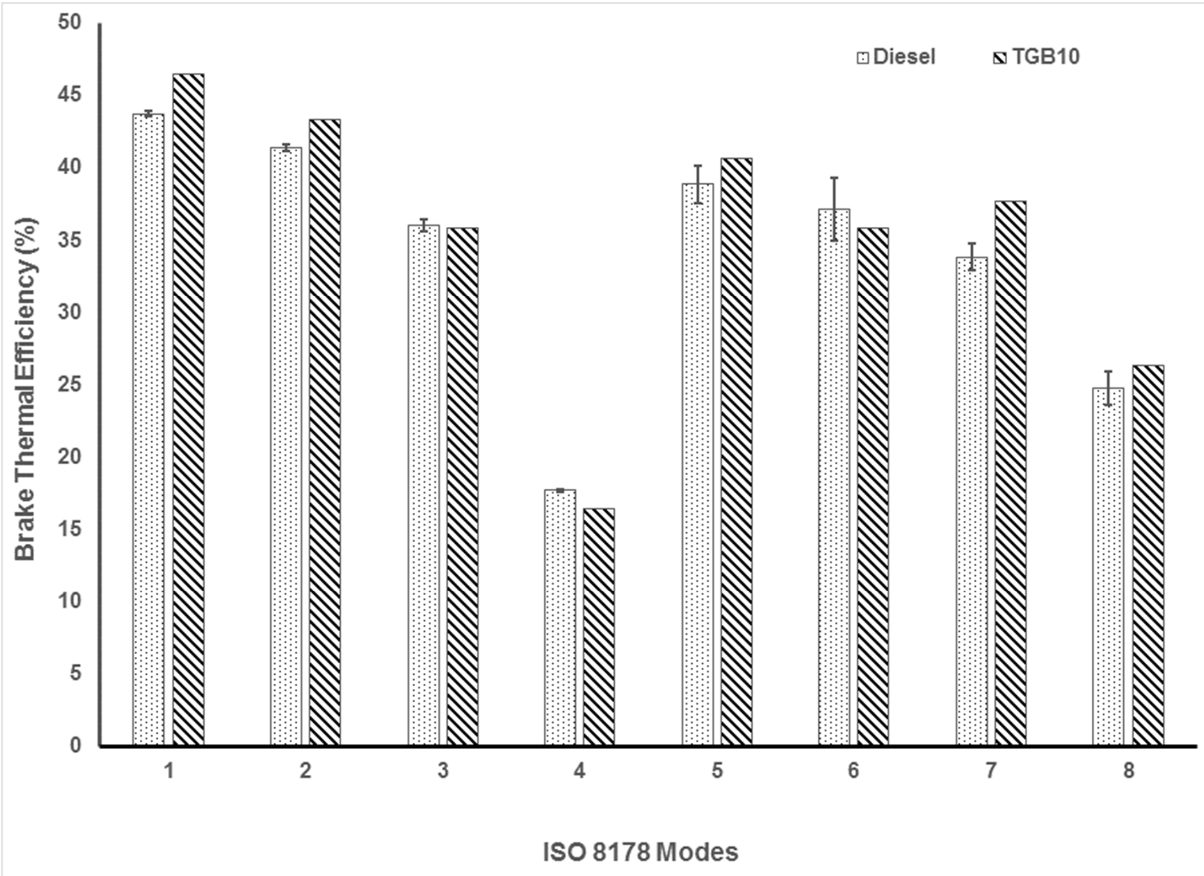

Figure 3-2: Brake Thermal Efficiency of TGB10 and Diesel (the error bars represent one standard deviation)

TGB10 is earlier than diesel by approximately 1.75 CAD (crank angle degrees) over the cycle. Generally, earlier peak pressures result in larger peak pressure values, which may explain why the peak pressure is larger for TGB10. Figure 3-3(b) represents mode 4 (10% load, rated speed). Diesel has a larger peak pressure than TGB10, but the location of peak pressure is about the same for both the fuels. Figure 3-3(c) represents mode 7 (50% load, intermediate speed). The pressure trace for diesel shows a "double hump" which is usually associated with two distinct injection periods. The first hump, also higher than the second, for diesel could be the result of pilot injection and the second hump could be the result of main injection.

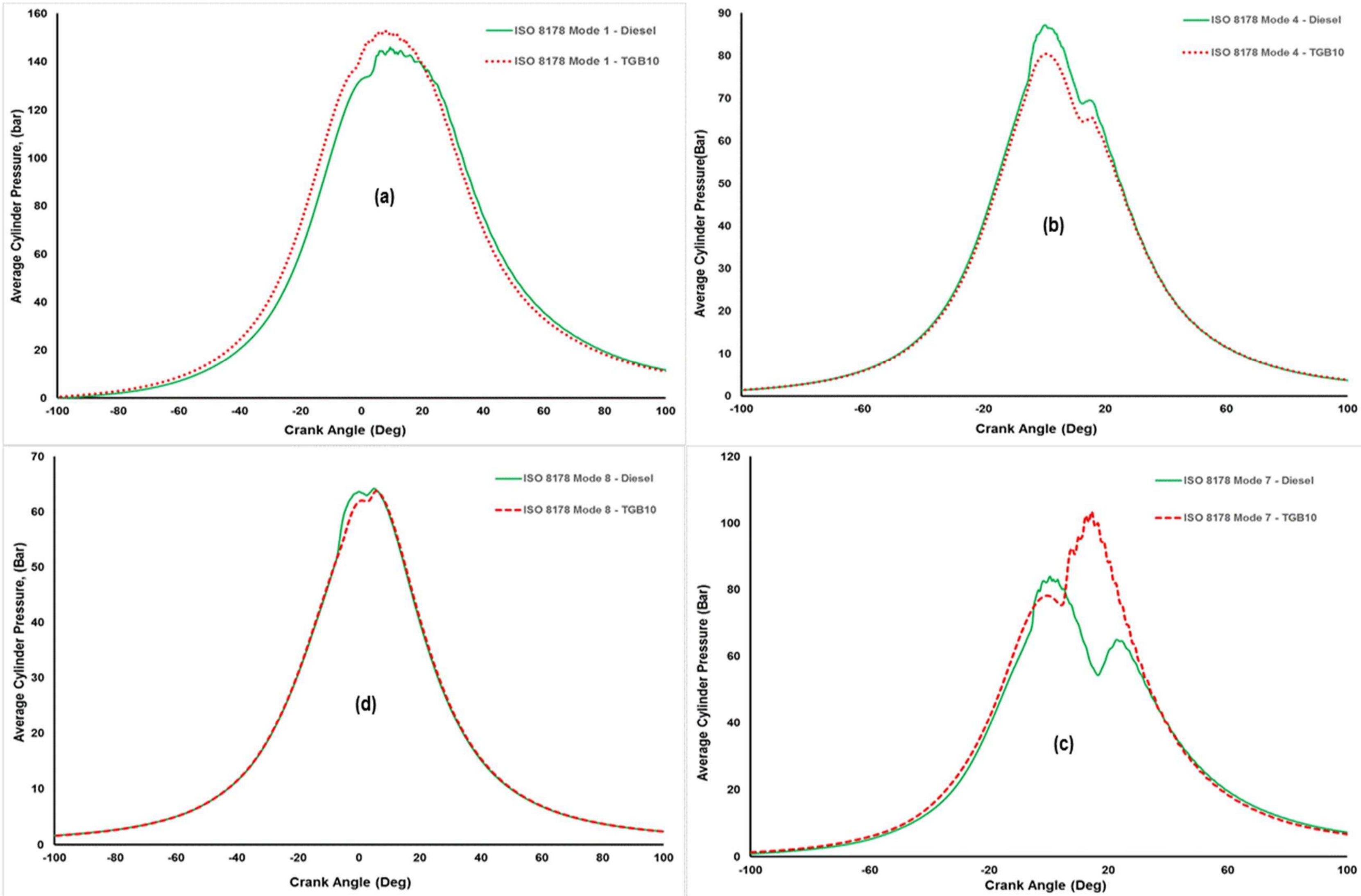

Figure 3-3: Pressure Trace. (a) Mode 1: 100% Load, rated speed, (b) Mode 4: 10% Load, rated speed, (c) Mode 7: 50% Load, intermediate speed, (d) Mode 8: 0% Load, idle speed.

This engine is usually connected to a power take-off (PTO) shaft on a tractor or combine. This mode is usually calibrated to aid in the power transfer. The pressure trace for TGB10 by contrast had only one pressure peak. This suggests, that while using TGB10 as a fuel at mode 7, the engine ECU interprets a point different than that for diesel on the engine calibration map. The engine calibration map for fuel injection is dependent on engine load, engine speed, temperature and physical properties of the fuel being supplied. TGB10 has significantly different properties than diesel[16], which could lead to the ECU reading a different point on the map. Figure 3-3(d) shows mode 8 (no load, idle speed). Diesel and TGB10 have similar pressure traces. Both diesel and TGB10 pressure traces overlap each other and peak pressure locations are about the same. No load and idle speed (mode 8) requires a relatively small amount of fuel, resulting in the lowest peak pressure over all of the 8 ISO-8178 modes.

Figure 3-4 shows the average peak pressures over 1000 cycles at each of the 8 modes for TGB10 and diesel. The uncertainty bars indicate the standard deviation over the 1000 cycles. The maximum pressure in the cylinder during a cycle is termed as peak pressure. Generally, the peak pressure occurs after the start of combustion, usually near, but after top dead center (TDC). For mode 1, at 2200 rpm and 100% load the average peak pressure for diesel was 148kPa while for TGB10 it was 154kPa. The peak pressure for mode 4 at 2200 rpm and 10% load was 88kPa for diesel and 80.5kPa for TGB10.

The TGB10 fuel could have a longer ignition delay due to the presence of gasoline. This delay allows more time for mixing of the fuel with combustion air inside the cylinder. At higher speeds and higher loads the cylinder temperature is higher, which results in more rapid combustion. At intermediate speeds, modes 5, 6 and 7, a slight decrease in peak pressure was observed due to the lower load at each of the modes. At idle speed and no load, mode 8, the average peak pressures for TGB10 and diesel were about the same.

The power output at modes 2 and 5 are similar to each other and can be seen by the average peak pressures for these modes which are similar to each other. Mode 5 has a slightly larger peak pressure value since the speed is lower. Similar trends can be seen in modes 3 and 6 where the power output are similar.

For mode 4, the load is 10%, so the amount of fuel demanded by the engine ECU is relatively lower. At this operating condition much of the energy released occurs late in the cycle and does not cause the pressure to rise above motored pressure (see Figure 3-3(b)). Hence the peak pressures for TGB10 and diesel are approximately the same and occur very close to top dead center. The pressure trace for diesel at mode 7 conditions is similar (See Figure 3-3(c)) to mode 4, so the average peak pressure location is at TDC. Overall, the peak pressures for TGB10 and diesel are close to each other and within a range of ± 2.5% to ±4.5% of each other.

The Figure 3-5 shows the location of peak pressure in Crank Angle Degrees (CAD) for diesel and TGB10 at each of the 8 modes. The uncertainty bars indicate the standard deviation of the location of peak pressures over 1000 cycles. For higher speed and higher load, the peak pressure of TGB10 occurs before diesel, while for intermediate and low speeds, peak pressure of TGB10 occurs later than diesel.

For modes 1 and 2 (rated speed and high load), the location of peak pressure for TGB10 was about 2 CAD earlier than diesel. For mode 3, which has a lower temperature owing

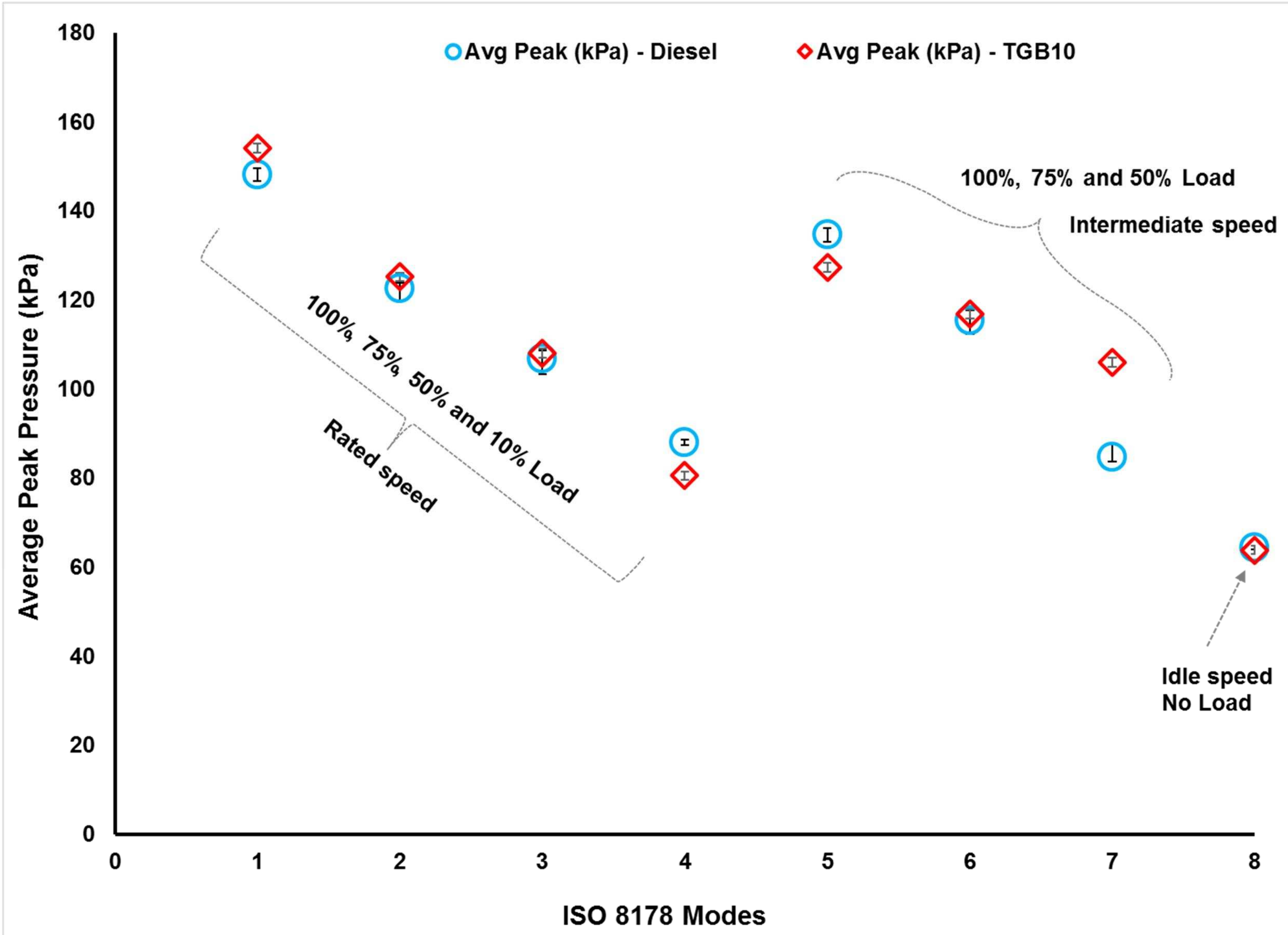

Figure 3-4: Average Peak Pressures (kPa) (error bars represent standard deviation)

to a lower load than modes 1 and 2, the location of peak pressure for TGB10 was ~3.5 CAD earlier than diesel. At mode 4, the location of peak pressure for TGB10 and diesel were close to top dead center at 0.3°ATDC and 0.5°ATDC, respectively.

Figure 3-6 shows the crank angle location of 50% mass fraction burned for TGB10 and diesel at each of the 8 modes. The 50% mass fraction burned indicates the point where half of the heat release has taken place. Generally, at each of the 8 modes, location of 50% mass fraction burned for diesel and TGB10 are close to each other, within ±0.75 CAD with the exception of mode 7.

At mode 1 and mode 2, the location of 50% mass fraction burned for TGB10 and diesel is about 20° ATDC. At mode 4 the location of 50% mass fraction burned, is 18°ATDC for diesel and ~19°ATDC TGB10. At mode 5 (intermediate speed, 100% load) the location of 50% mass fraction burned is ~ 20.6°ATDC for diesel and ~21.7°ATDC for TGB10. At mode 8, idle speed and no load, the 50% mass fraction burned occurred ~14.5°BTDC for both diesel and TGB10.

At mode 7 (intermediate speed, 50% load), the location of 50% mass fraction burnt for diesel was 24°ATDC while that for TGB10 was 16°ATDC. This difference can be explained by the difference in average pressure profile, presented earlier in Figure 3-3 (c).

Figure 3-7 shows the crank angle location of 10% mass fraction burned for TGB10 and diesel at each of the 8 modes. The 10% mass fraction burned indicates the point where the start of combustion has taken place. Generally, at each of the 8 modes, location of 10% mass fraction burned for TGB10 was slightly later than diesel, with the exception of mode 7. This indicates that TGB10 might have had a slightly longer ignition delay as compared to diesel.

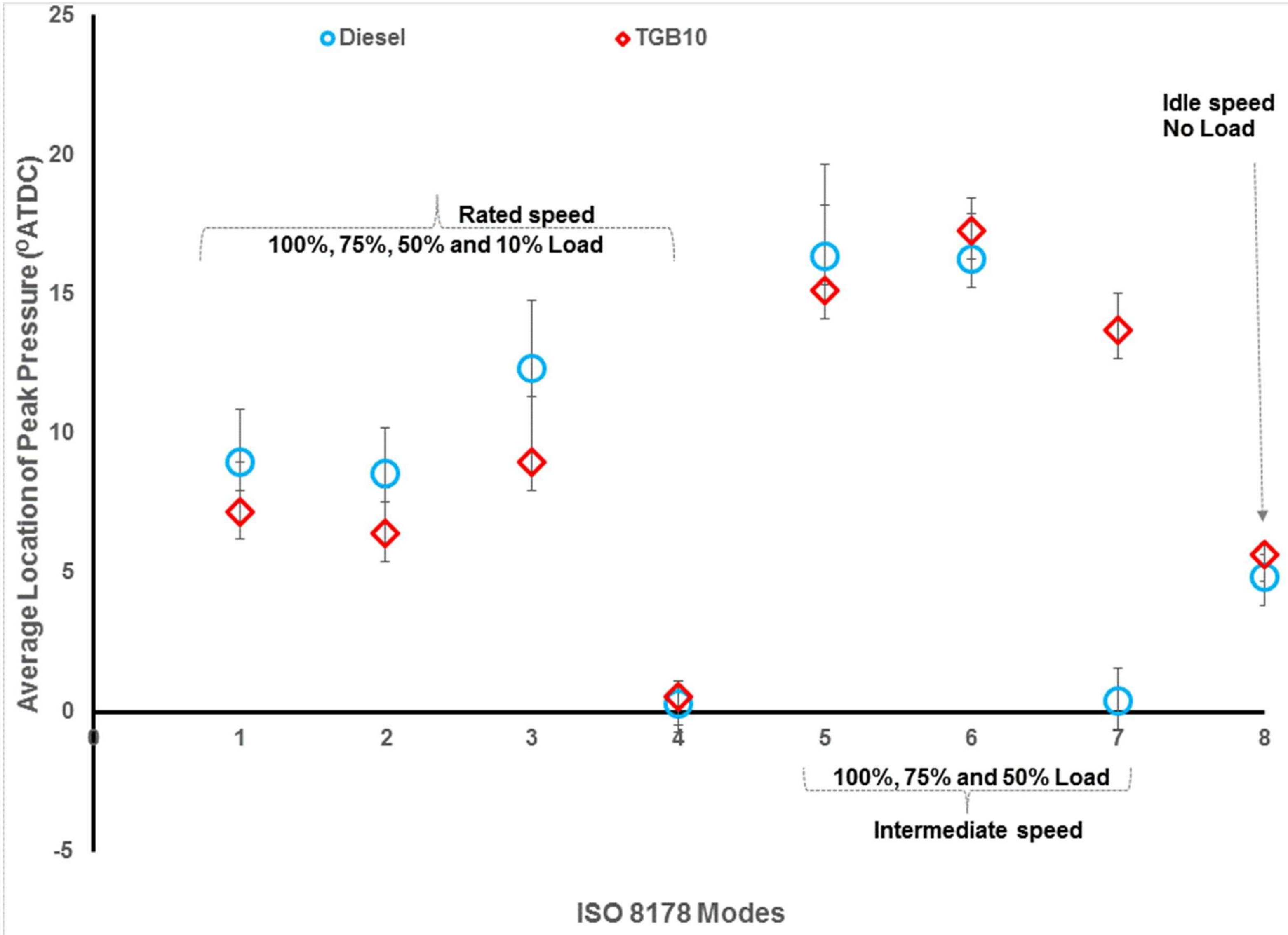

Figure 3-5: Location of Peak Pressure (Error bars represent standard deviation)

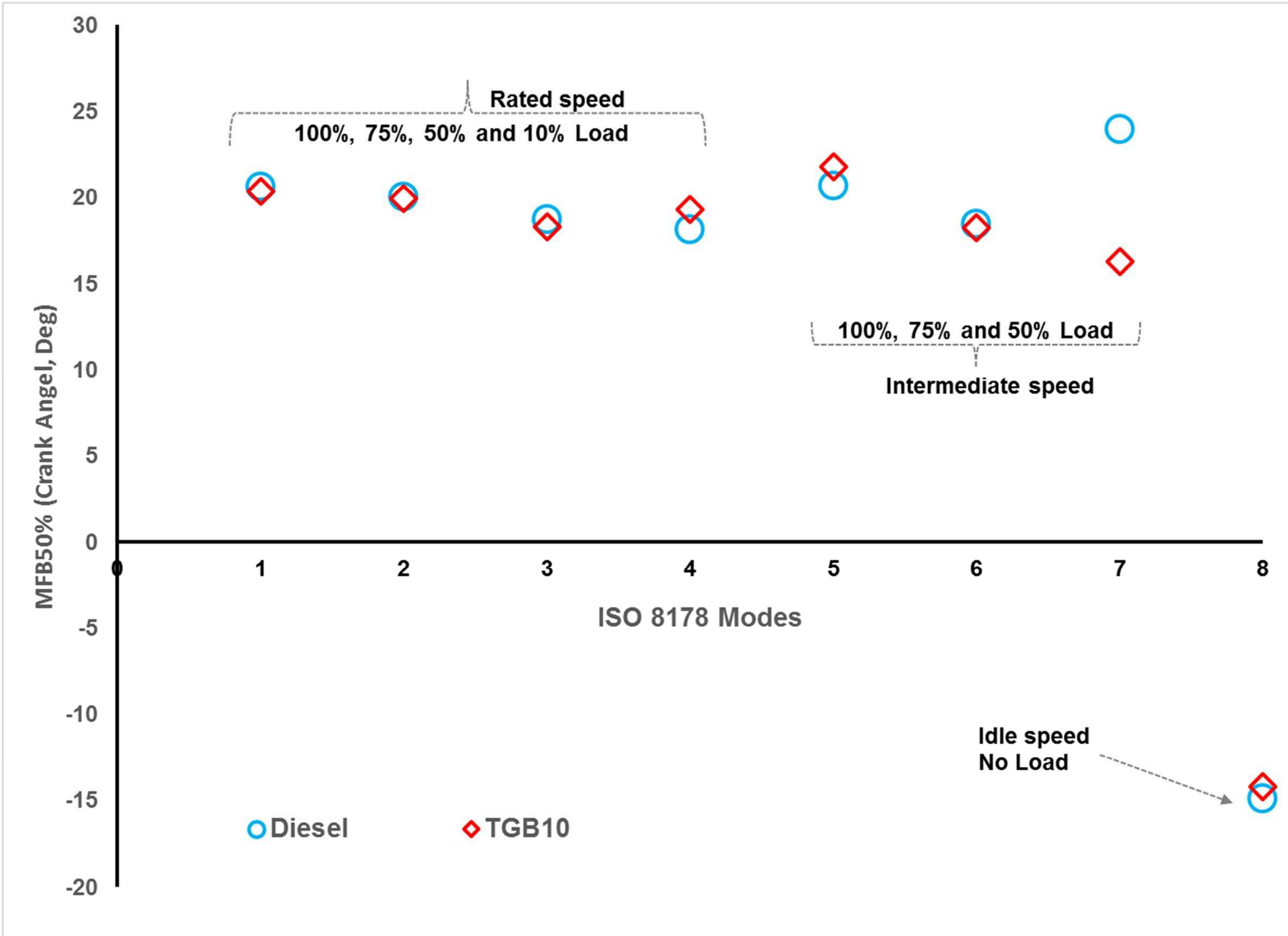

Figure 3-6: Location of 50% Mass fraction burned

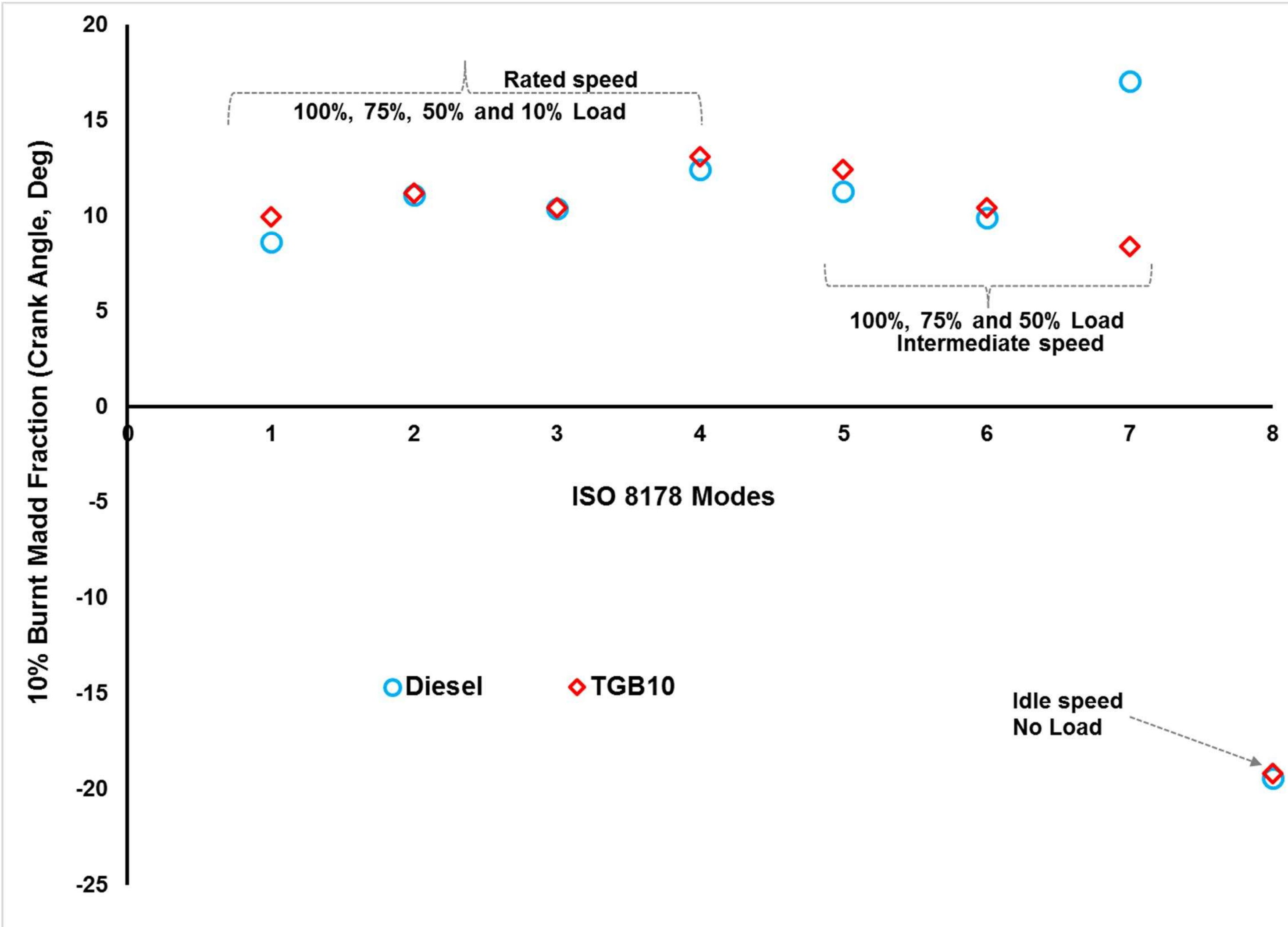

Figure 3-7: Location of 10% Mass Fraction Burnt

Figure 3-8 shows the 10% to 90% mass fraction burned duration which is a good indicator of the rate of the combustion process. The remaining 10% (90-100%) is usually excluded from combustion analysis due to difficulties in quantifying the location of 100% burned.

At mode 1, rated speed and 100% load, the burn duration of diesel and TGB10 was about 26.6 CAD. At mode 4 (rated speed and 10% load) the burn duration of diesel was about 20.0 CAD and that of TGB10 was 20.5 CAD. At mode 5 (intermediate speed and 100% load) the burn duration for TGB10 and diesel was about 28 CAD and at mode 8 (idle speed and no load) the burn duration for diesel was about 8.3 CAD and for TGB10 was about 10 CAD. Overall TGB10 had a shorter combustion duration than diesel by about 12 to 15%. This is in agreement with the average peak pressures and the location of peak pressures in Figure 3-3 and Figure 3-4, respectively. Overall the rate of heat release after the beginning of combustion was faster for TGB10 than diesel.

Figure 3-9 shows the THC emissions in the exhaust as percent deviation from the diesel baseline. In general, there was an overall increase in the unburned hydrocarbons. The uncertainty bars represent the percentage standard deviation for repeated diesel points at the respective test modes. It is assumed that the uncertainty will be the same for diesel and TGB10 for a given test mode. At rated speed points, modes 1, 2 3, THC emissions showed a decreasing trend as load decreased. Similar trend is observed at intermediate speed modes 5, 6 and 7. Note that the trend in Figure 9 is the percent deviation from the diesel baseline. In general the magnitude of THC emissions increases with decreasing load for both fuels, which can be seen in Table 3 presented earlier. The low load and no load points, modes 4 and 8, had significantly higher THC emissions relative to diesel, 130% and 138%, respectively.

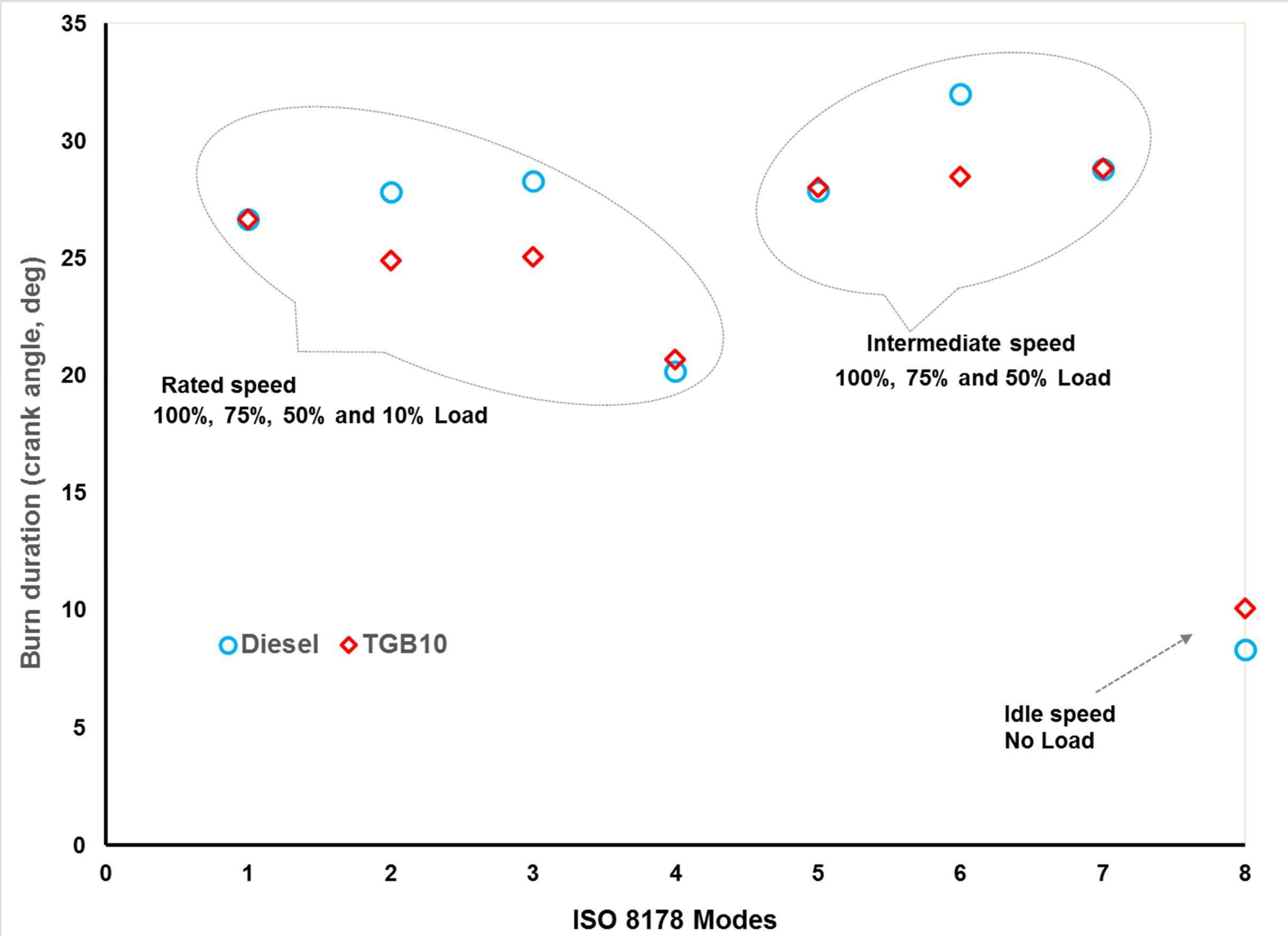

Figure 3-8: 10% to 90% Burn duration

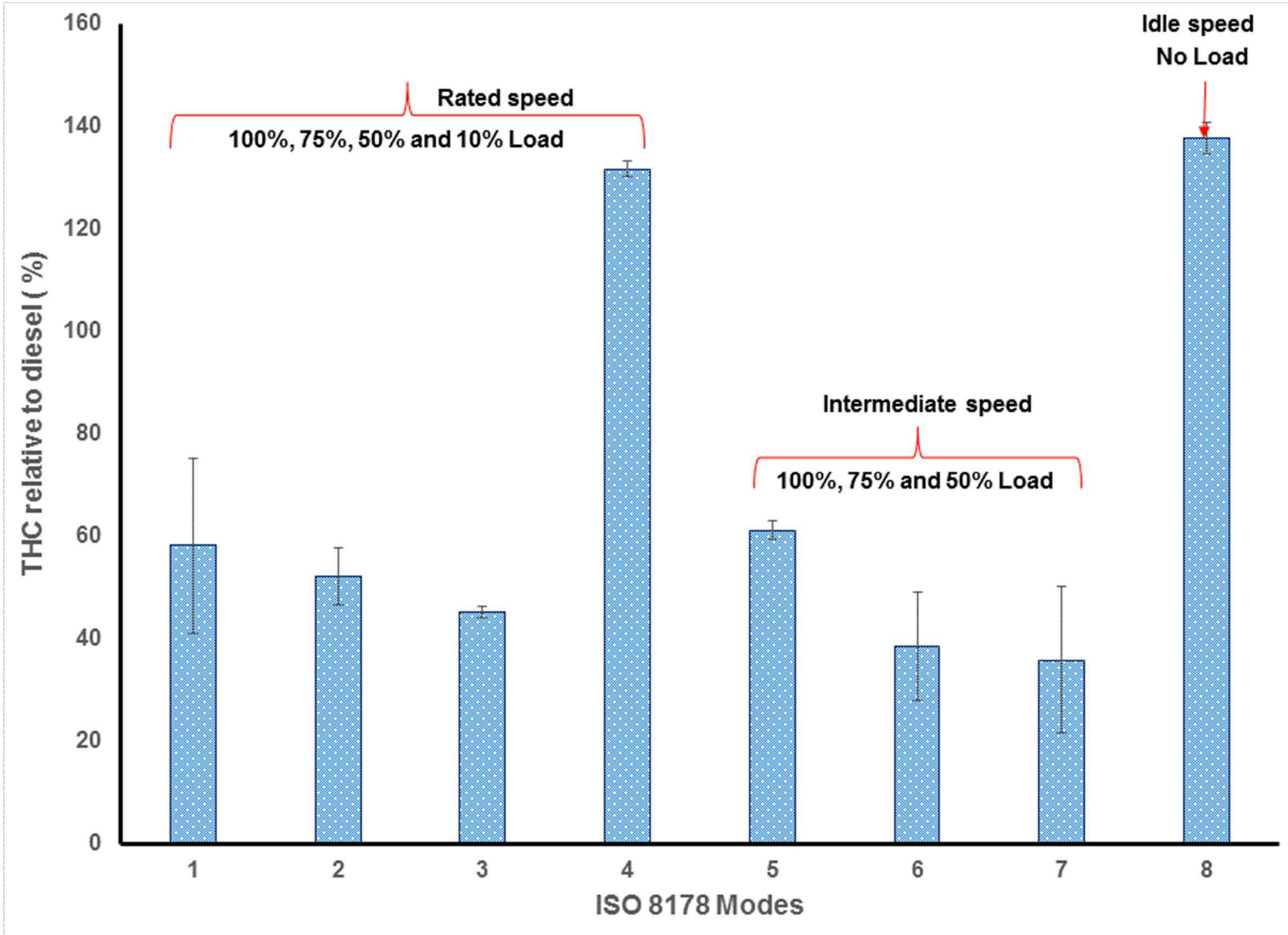

Figure 3-9: Total Hydro-carbon emissions as percentage deviation from diesel (Error bars represent standard deviation)

One possible explanation for higher THC emissions for TGB10 is a larger ignition delay. Ignition delay causes localized over lean mixtures which result in higher THC emissions[33, 34, 35]. The Cetane number of TGB10 is lower than diesel due to the inherent property of SVOs [36] and addition of gasoline. Consequently, ignition delay is longer and the fuel has more time to mix with surrounding air and form localized pockets of over lean mixture. Localized pockets of over lean mixture are less likely to burn because they cannot propagate a flame and are separated from the main diffusion flame jet. If a pocket of over lean mixture escapes combustion the hydrocarbons in that region flow into the exhaust during the exhaust stroke and increase THC emissions.

Figure 3-10 shows the NOx emissions in the exhaust as percentage deviation from the diesel baseline. In general, TGB10 had a higher NOx emission compared to diesel with the exception of modes 4 and 8 where it was lower. The uncertainty bars represent the percent standard deviation for diesel at the respective test modes. It is assumed that the variations in diesel and TGB10 modes will be the same for diesel and TGB10 for a given test mode. Table 3 shows the absolute values of NOx emissions for TGB10 and diesel at each of the test modes. At modes 1, 2 and 3, the NOx emissions were higher than diesel by 12.5%, 17.5% and 21%, respectively. Figures 2 ,3 and 4 show higher peak pressure and earlier location of peak pressure stemming from a shorter burn duration and faster heat release compared to diesel. These factors result in higher in-cylinder temperatures which accelerate the formation of NOx and result in higher NOx emissions. At intermediate speed points, modes 5, 6 and 7, the TGB10 NOx emissions were 8%, 37.5% and 15% higher than the diesel baseline, respectively.

At lower load points (modes 4 and 8) NOx emissions were about 5.8% and 38% lower than diesel. At these low load points, the amount of fuel injected is low and the cylinder temperatures are low. These factors do not support the formation of NOx. Modes 4 and 8 showed substantially larger increases in THC emissions (see Figure 9). In the discussion above, elevated THC emissions are linked to potential over lean zones in the combustion chamber. This also implies the existence of premixed lean zones since the fuel originates in the jet, a fuel rich zone. An explanation for lower NOx emissions at modes 4 and 8 is that a high fraction of the overall heat release comes from lean premixed zones, which inherently have lower NOx formation rates.

Figure 3-11 shows the weighted average NOx + NMHC emissions over the 8 mode cycle for diesel and TGB10 [46] that has been adapted from a previous publication by the authors. The uncertainty bars on diesel are evaluated based on the standard deviation of duplicate diesel data points.

Figure 3-12 shows the PM emissions for each of the 8 modes. In general, there are no definitive trends in the PM data. The uncertainty bars represent the percent standard deviation for duplicate diesel points at the respective test modes. It is assumed that the uncertainty of diesel and TGB10 will be the same for a given test mode. At rated speed, the PM emissions are generally higher than the diesel baseline. At intermediate speed and idle, PM emissions are 35% to 76% lower than diesel with the exception of mode 7 that emitted 23% more PM then diesel.

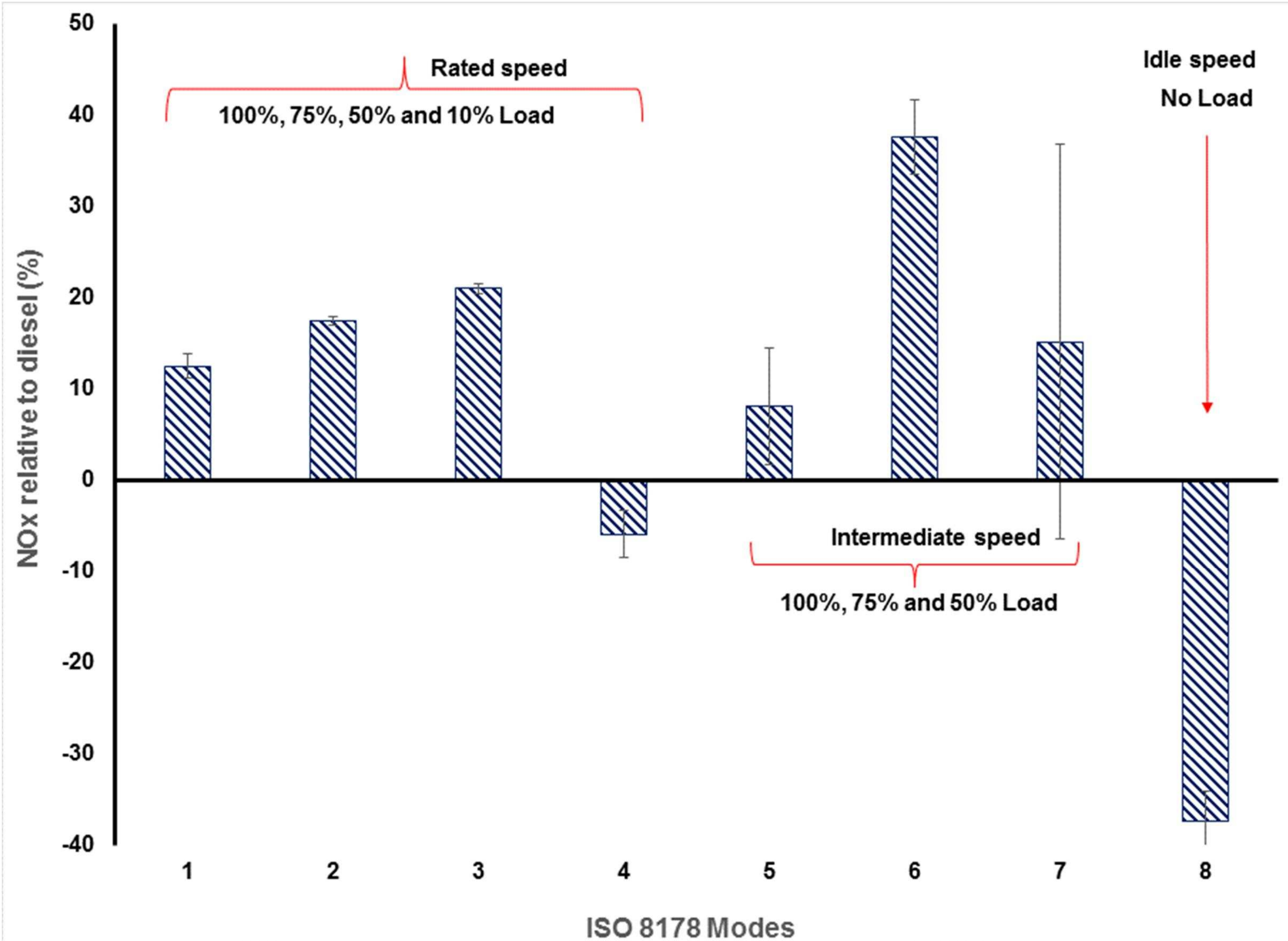

Figure 3-10: NOx emissions as percentage deviation from diesel (Error bars represent standard deviation)

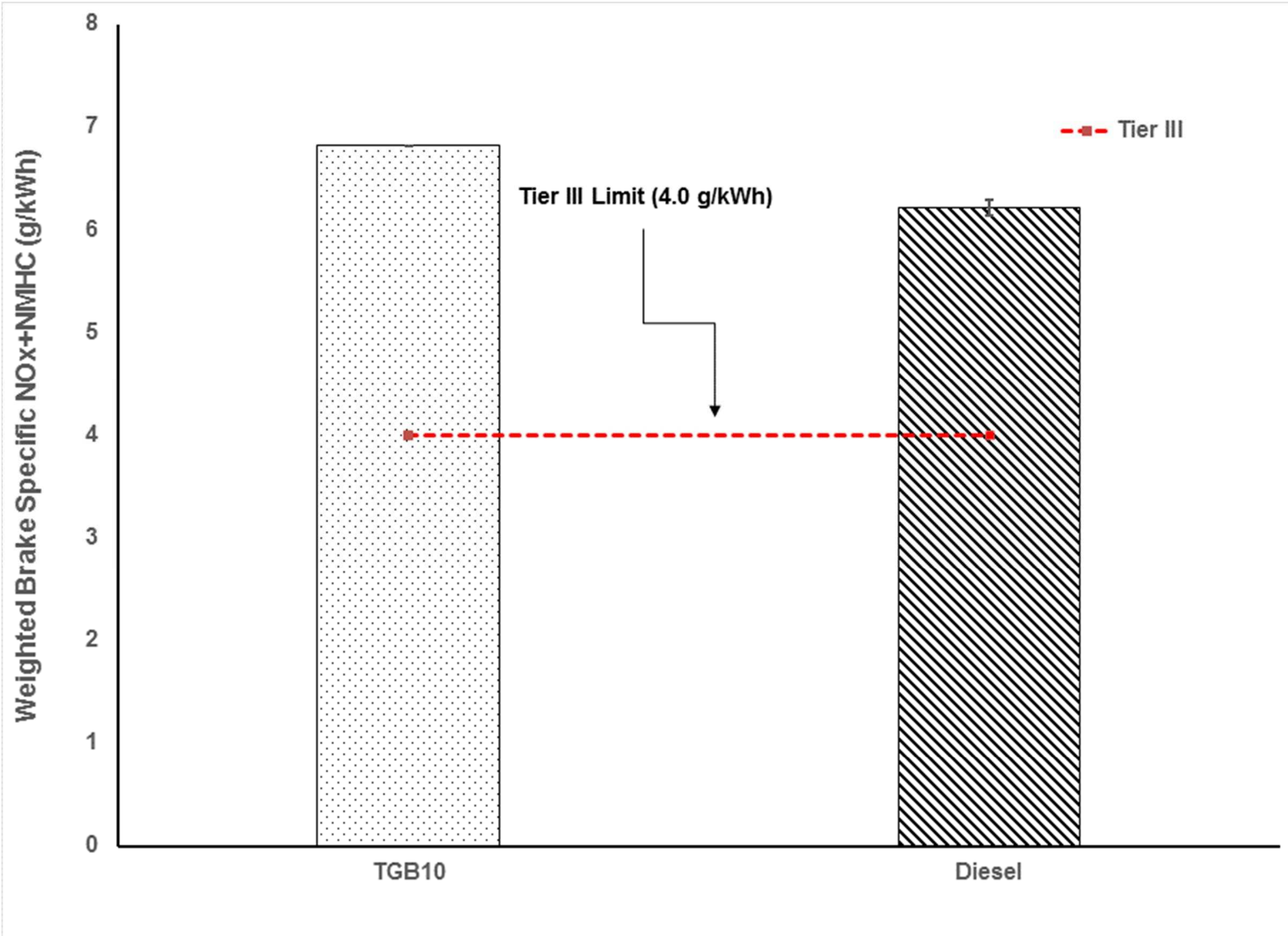

Figure 3-11: Weighted NOx+NMHC Emission (Error bars represent standard deviation)

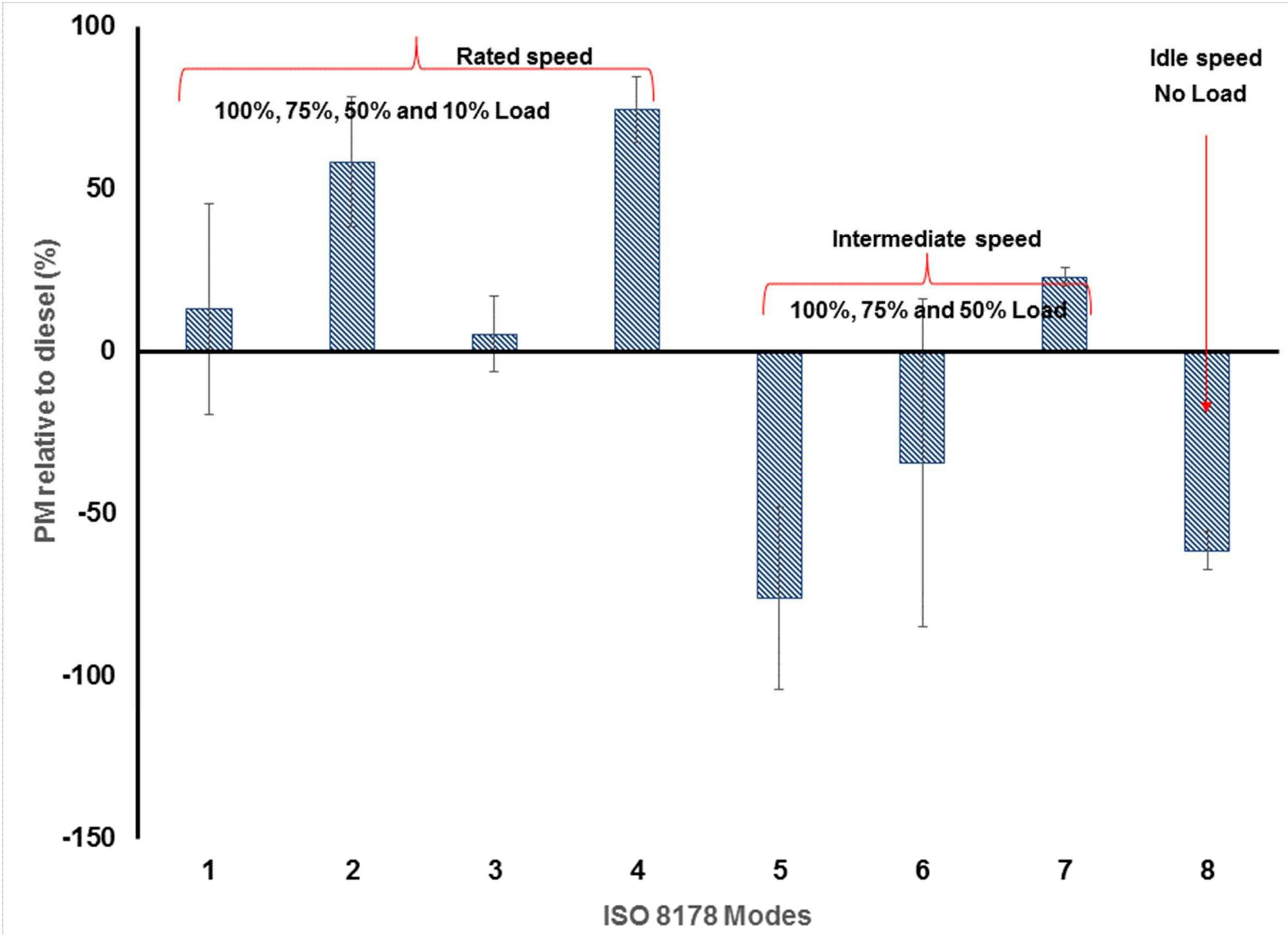

Figure 3-12: Particulate Matter (PM) emissions as percentage deviation from diesel (Error bars represent the standard deviation)

PM are carbonaceous particles generated during combustion. Incomplete combustion of the fuel in an engine is the primary mechanism for PM exhaust emissions while lubricating oil contributes a small portion of it [37]. In general, straight vegetable oils have about 15% to 25% higher PM emissions than diesel [33]. The high choking index of straight vegetable oils 1.4 [38]as compared to diesel could lead to deposit formations on the injector resulting in improper fuel spray characteristics[9, 39,]. Since 90% of TGB10 is Straight Vegetable Canola oil, this could be one of the factors contributing to the higher PM at rated speed modes. Conversely, the addition of gasoline, a lower molecular weight, more volatile hydrocarbon is likely to decrease PM. These are competing effects and tend to offset. Further studies and investigation will be helpful to understand the different mechanisms that affect emission formation for such triglyceride-gasoline blend.

Figure 3-13 shows the weighted average PM emissions for TGB10 and diesel [16] that has been adapted from a previous publication by the authors. PM emissions for diesel and TGB10 are 0.27 g/kWh and 0.25 g/kWh, respectively. Overall there is no substantial difference in PM between diesel and TGB10.

Figure 3-14 shows the brake specific carbon monoxide emission relative to diesel at each of the 8 modes. The uncertainty bars indicate the standard deviation for diesel at each of the 8 modes. Since the TGB10 and diesel were tested one after the other, it is assumed that the uncertainty in the measurement equipment is the same for both fuels. TGB10 had a lower CO emission value compared to diesel except at low load points, mode 4 and 8. TGB10 had 48.2% and 143% higher CO compared to diesel at modes 4 and 8, respectively.

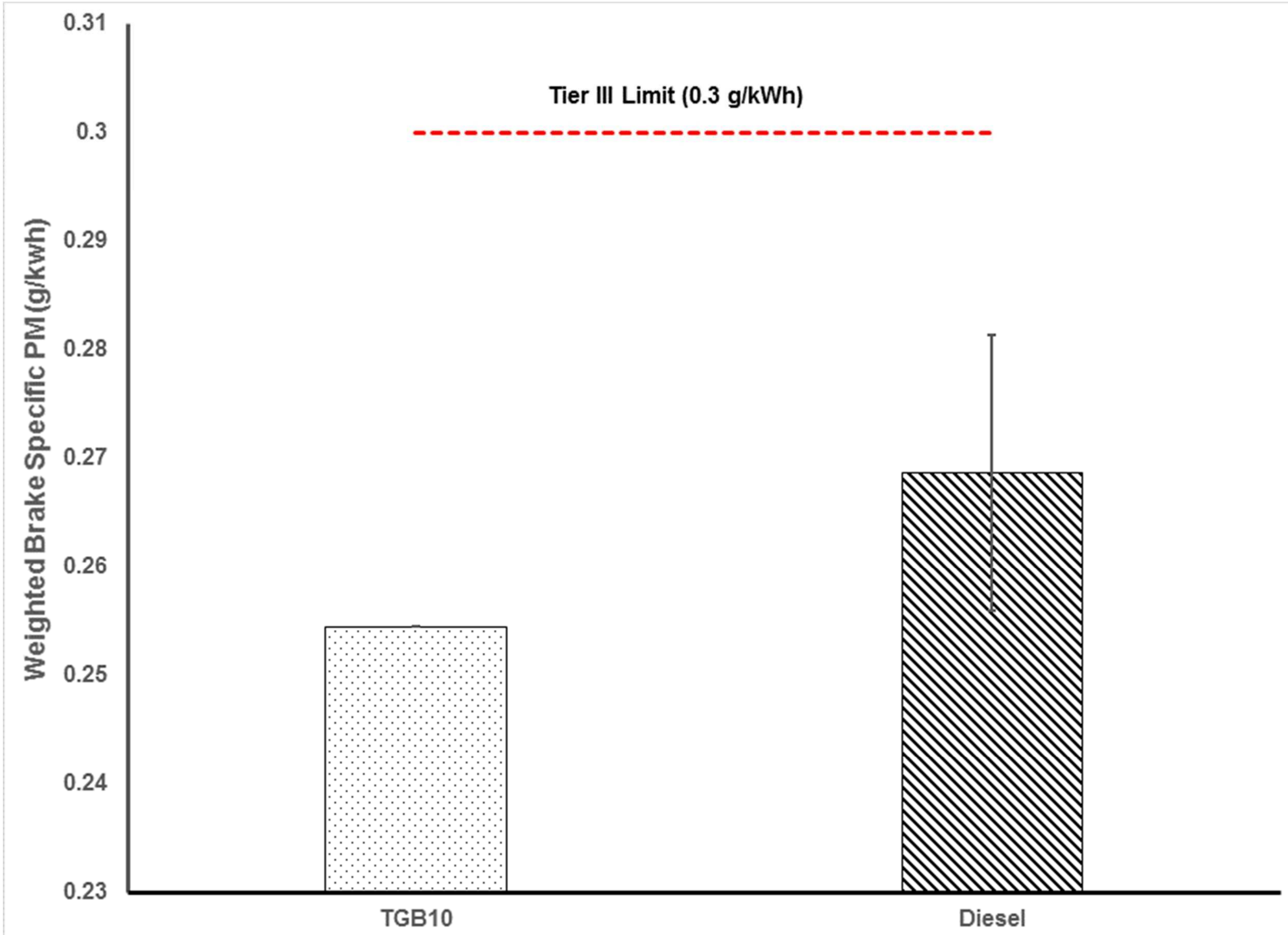

Figure 3-13: Weighted PM Emission (Error bars represent standard deviation)

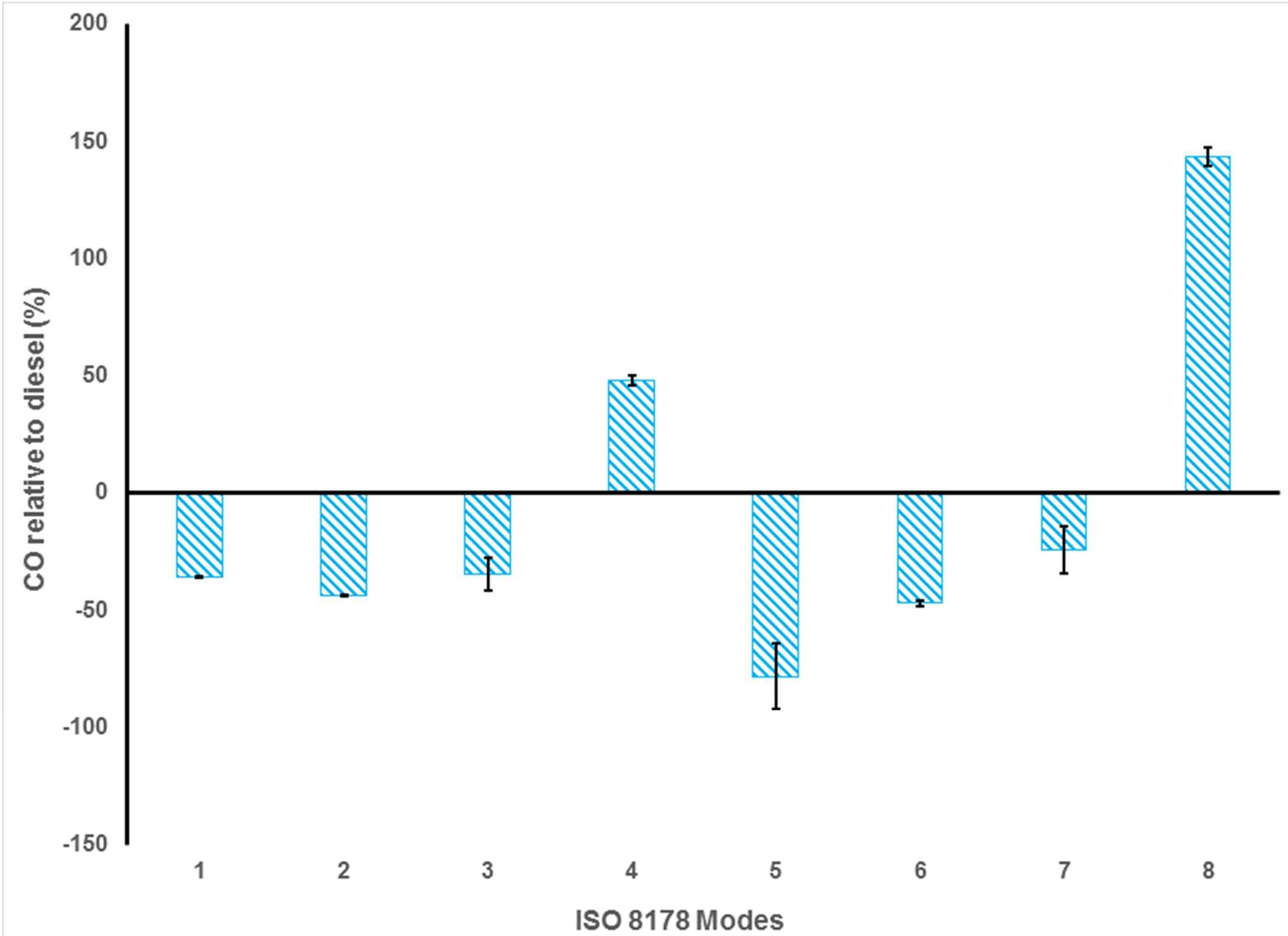

Figure 3-14 Brake specific Carbon monoxide emissions relative to diesel (Error bars represent standard deviation)

The brake specific weighted carbon monoxide emissions over all the 8 modes were 3.25 g/kWh and 4.93 g/kWh for diesel and TGB10, respectively as shown in Figure 15. Lower carbon monoxide emissions are common with the use of straight vegetable oils and biodiesel [11, 54] straight vegetable oils contain oxygen, which helps in effective oxidation of carbon monoxide [11, 46].

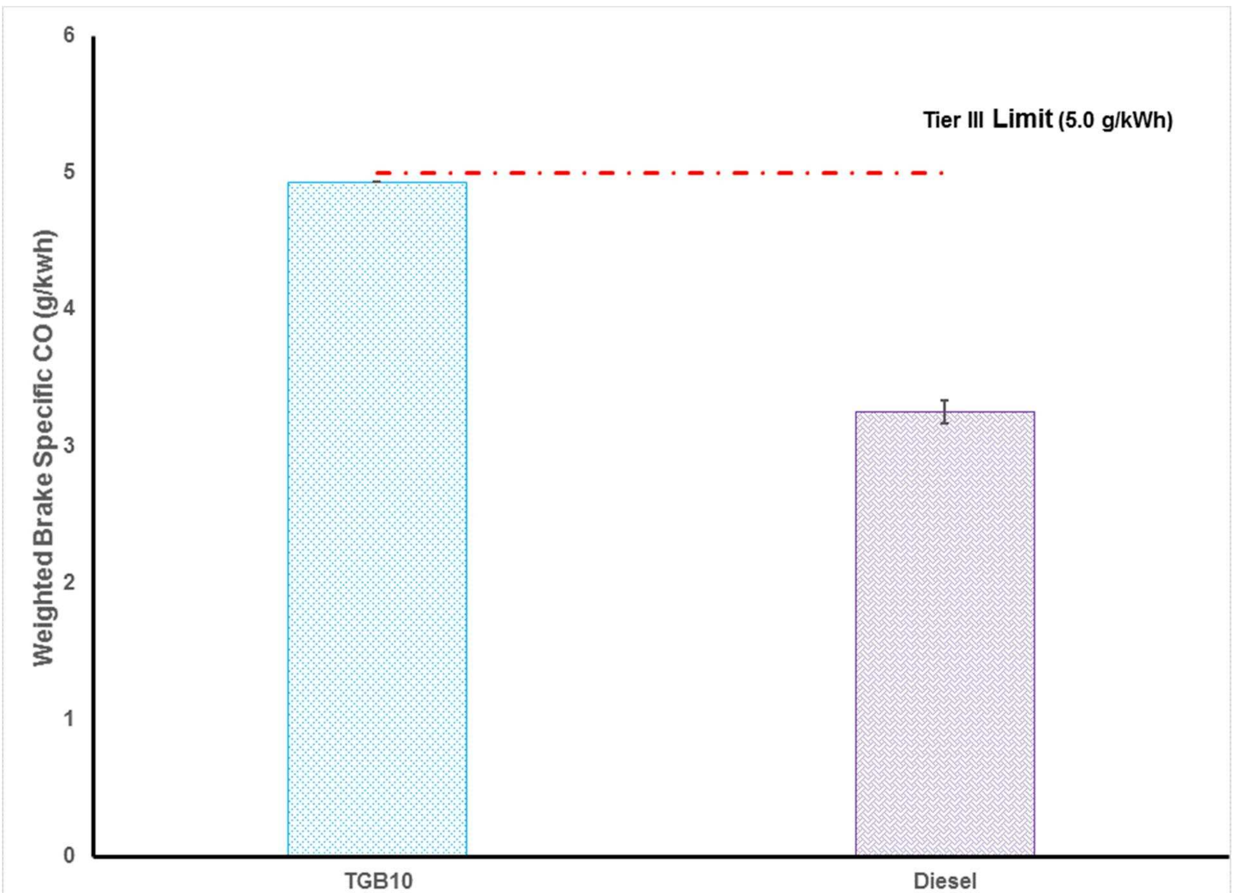

Figure 3-15: Weighted Brake Specific Carbon Monoxide emission (Error bars represent standard deviation)

3.6 CONCLUSIONS

In this study the performance of a blend of 90% triglyceride (canola oil) and 10% gasoline, designated as TGB10, was evaluated. Combustion pressure statistics and pollutant emissions were compared to diesel over an 8 mode test cycle. The data were analyzed for individual modes and as weighted averages.

The mass based fuel consumption of TGB10 was generally higher than diesel. This is likely due primarily to the fact that the calorific value of TGB10 is lower than diesel. The average cylinder pressure traces of TGB10 followed a pattern similar to diesel in most cases with the exception of mode 7, where the TGB10 and diesel combustion pressure traces were significantly different. This suggests that the use of TGB10 could potentially result in the engine ECU reading a different point on the calibrated map compared to diesel though the dynamometer torque and engine speed was the same. The average peak pressures of TGB10 and diesel at most test points were within the ±2.5% to ± 4.5% of each other. The location of peak pressures for TGB10 and diesel were close to each other. The location of 50% Mass fraction burnt for TGB10 and diesel were close to each other at most test modes. Overall TGB10 had a shorter combustion duration (10% to 90% burn duration) than diesel by about 12 to 15%.

TGB10 THC emissions at each of the 8 modes were higher than diesel. NOx emissions were generally higher than diesel except for low load points. The weighted NOx emissions of TGB10 was 9.8% higher than diesel. PM emissions were generally lower than diesel at intermediate and low speeds but higher at rated speeds. Weighted PM emission of TGB10 was 5.5% lower than diesel. The carbon monoxide emissions for lower load modes were significantly higher than diesel while at higher load points were lower than diesel due to the presence of oxygen in the fuel. The weighted CO emissions over the 8 mode cycle for TGB10 was 51.7% higher than diesel.

The results from this work are promising. They show relatively minor combustion and pollutant emission differences between TGB10 and diesel for the specific engine application using stock engine control maps. Additional work is needed. A separate evaluation of the engine performance on a calibration-control map that is optimized for TGB10 as the fuel would be beneficial. A long-term study that quantifies the life of engine components would identify potential durability problems with using TGB10 as a fuel. Finally, TGBs will likely require a different fuel storage system. The presence of gasoline in TGBs makes it necessary to have a Class I type storage system, similar to gasoline. Proper fuel classification and storage needs to be addressed.

3.7 REFERENCES

[1] US Department of Energy, Program FEM. Energy Independence and Security Act. 2007.

[2] Glaude PA, Pitz WJ, Thomson MJ. Chemical kinetic modeling of dimethyl carbonate in an opposed-flow diffusion flame. Proceedings of the Combustion Institute. 2005;30(1):1111-8.

[3] Rakopoulos CD, Dimaratos AM, Giakoumis EG, Rakopoulos DC. Investigating the emissions during acceleration of a turbocharged diesel engine operating with bio-diesel or n-butanol diesel fuel blends. Energy. 2010;35(12):5173-84.

[4] Winkelmann R, Levermann A, Ridgwell A, Caldeira K. Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet2015; 1(8):[e1500589–e pp.].

[5] Menten F, Chèze B, Patouillard L, Bouvart F. A review of LCA greenhouse gas emissions results for advanced biofuels: The use of meta-regression analysis. Renewable and Sustainable Energy Reviews. 2013;26:108-34.

[6] Gnansounou E, Dauriat A, Villegas J, Panichelli L. Life cycle assessment of biofuels: Energy and greenhouse gas balances. Bioresource Technology. 2009;100(21):4919-30.

[7] National Biodiesel Board USA. Chapter 2 - Introduction to Biodiesel and Glossary of Terms A2 - Dahiya, Anju. Bioenergy. Boston: Academic Press; 2015. p. 37-40.

[8] Go AW, Sutanto S, Ong LK, Tran-Nguyen PL, Ismadji S, Ju Y-H. Developments in in-situ (trans) esterification for biodiesel production: A critical review. Renewable and Sustainable Energy Reviews. 2016;60:284-305.

[9] Sidibe SS, Blin J, Vaitilingom G, Azoumah Y. Use of crude filtered vegetable oil as a fuel in diesel engines state of the art: Literature review. Renewable and Sustainable Energy Reviews 14,; 2010. p. 2748-59.

[10] Dhar A, Agarwal AK. Effect of Karanja biodiesel blend on engine wear in a diesel engine. Fuel. 2014;134:81-9.

[11] Mofijur M, Masjuki HH, Kalam MA, Atabani AE, Shahabuddin M, Palash SM, et al. Effect of biodiesel from various feedstocks on combustion characteristics, engine durability and materials compatibility: A review. Renewable and Sustainable Energy Reviews. 2013;28:441-55.

[12] Dwivedi G, Sharma MP. Potential and limitation of straight vegetable oils as engine fuel – An Indian perspective. Renewable and Sustainable Energy Reviews. 2014;33:316-22.

[13] Hellier P, Ladommatos N, Yusaf T. The influence of straight vegetable oil fatty acid composition on compression ignition combustion and emissions. Fuel. 2015;143:131-43.

[14] Department of Energy OoEEaREUS. Chapter 11 - Straight Vegetable Oil as a Diesel Fuel? A2 - Dahiya, Anju. Bioenergy. Boston: Academic Press; 2015. p. 189-92.

[15] Atabani AE, Silitonga AS, Ong HC, Mahlia TMI, Masjuki HH, Badruddin IA, et al. Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renewable and Sustainable Energy Reviews. 2013; 18:211-45.

[16] Arunachalam L, Daniel BO, Perry EC. Performance and Emission Evaluation of Triglyceride-Gasoline Blends in Agricultural Compression Ignition Engines. 2014;30(4).

[17] Ma S, Zheng Z, Liu H, Zhang Q, Yao M. Experimental investigation of the effects of diesel injection strategy on gasoline/diesel dual-fuel combustion. Applied Energy. 2013;109:202-12.

[18] Benajes J, Molina S, Novella R, De Lima D. Implementation of the Partially Premixed Combustion concept in a 2-stroke HSDI diesel engine fueled with gasoline. Applied Energy. 2014;122:94-111.

[19] Kim K, Kim D, Jung Y, Bae C. Spray and combustion characteristics of gasoline and diesel in a direct injection compression ignition engine. Fuel. 2013;109:616-26.

[20] Du J, Sun W, Guo L, Xiao S, Tan M, Li G, et al. Experimental study on fuel economies and emissions of direct-injection premixed combustion engine fueled with gasoline/diesel blends. Energy Conversion and Management. 2015;100:300-9.

[21] Lu X, Qian Y, Yang Z, Han D, Ji J, Zhou X, et al. Experimental study on compound HCCI (homogenous charge compression ignition) combustion fueled with gasoline and diesel blends. Energy. 2014;64:707-18.

[22] Han D, Ickes AM, Bohac SV, Huang Z, Assanis DN. Premixed low-temperature combustion of blends of diesel and gasoline in a high speed compression ignition engine. Proceedings of the Combustion Institute. 2011;33(2):3039-46.

[23] Drenth AC, Olsen DB, Cabot PE, Johnson JJ. Compression ignition engine performance and emission evaluation of industrial oilseed biofuel feedstocks

camelina, carinata, and pennycress across three fuel pathways. Fuel. 2014;136:143-55.

[24] Drenth AC, Olsen DB, Denef K. Fuel property quantification of triglyceride blends with an emphasis on industrial oilseeds camelina, carinata, and pennycress. Fuel. 2015;153:19-30.

[25] Aaron CD, Karolien D, Perry EC, Daniel BO. Evaluation of Industrial Corn Oil as an On-Farm Biofuel Feedstock. 2015;31(5).

[26] Chauhan BS, Singh RK, Cho HM, Lim HC. Practice of diesel fuel blends using alternative fuels: A review. Renewable and Sustainable Energy Reviews. 2016;59:1358-68.

[27] Al-Hamamre Z, Al-Salaymeh A. Physical properties of (jojoba oil + biodiesel), (jojoba oil + diesel) and (biodiesel + diesel) blends. Fuel. 2014;123:175-88.

[28] Mwangi JK, Lee W-J, Chang Y-C, Chen C-Y, Wang L-C. An overview: Energy saving and pollution reduction by using green fuel blends in diesel engines. Applied Energy. 2015;159:214-36.

[29] Abollé A, Loukou K, Henri P. The density and cloud point of diesel oil mixtures with the straight vegetable oils (SVO): Palm, cabbage palm, cotton, groundnut, copra and sunflower. Biomass and Bioenergy. 2009;33(12):1653-9.

[30] ISO 8178 1-11 Reciprocating internal combustion engines — Exhaust emission measurement. International Organization for Standardization, Geneva, Switzerland.

[31 Emberger P, Hebecker D, Pickel P, Remmele E, Thuneke K. Ignition an combustion behaviour of vegetable oils after injection in a constant volume combustion chamber. Biomass and Bioenergy. 2015;78:48-61.

[32] Corsini A, Marchegiani A, Rispoli F, Sciulli F, Venturini P. Vegetable Oils as Fuels in Diesel Engine. Engine Performance and Emissions. Energy Procedia. 2015;81:942-9.

[33] Lakshminarayanan A. Testing and performance measurement of straight vegetable oils as an alternative fuel for diesel engines. Fort Collins: Colorado State University; 2014.

[34] Greeves G, Khan IM, Wang CHT, Fenne I. Origins of Hydrocarbon Emissions from Diesel Engines. SAE International; 1977.

[35] Kwon H, Min K. Modified one-step reaction equation for modeling the oxidation of unburned hydrocarbons in engine conditions. International Journal of Automotive Technology. 2010;11(5):637-50.

[36] D'Alessandro B, Bidini G, Zampilli M, Laranci P, Bartocci P, Fantozzi F. Straight and waste vegetable oil in engines: Review and experimental measurement of emissions, fuel consumption and injector fouling on a turbocharged commercial engine. Fuel. 2016;182:198-209.

[37] Lee KB, Thring MW, Beér JM. On the rate of combustion of soot in a laminar soot flame. Combustion and Flame. 1962;6:137-45.

[38] National Renewable Energy Laboratory(NREL) anlotUSDoE, Office of Energy Efficiency and Renewable Energy. Straight Vegetable Oil as a Diesel Fuel ? 2010.

[39] Babu AK, Devaradjane G. Vegetable Oils And Their Derivatives As Fuels For CI Engines: An Overview. SAE International; 2003.

4. EFFECT OF GASOLINE CONTENT IN TRIGLYCERIDE GASOINE BLENDS ON THE COMBUSTION & EMISSIONS IN A COMMON RAIL COMPRESSION IGNITION ENGINE[3]

4.1 OVERVIEW

This study presents the combustion and emission results using a blend of unrefined triglycerides (straight vegetable oils) with varying percentages of regular unleaded gasoline in a compression ignition engine typically used in farming machinery. About 27% of energy used on a farm can be attributed to diesel fuel as most farm equipment is powered by diesel. Triglycerides as an alternative fuel, produced locally, could potentially bring down farm input costs.

Poor cold flow properties due to high density and viscosity is one of the major drawbacks of using unrefined triglycerides. Triglycerides can be blended with gasoline to lower its density and viscosity. Such blends are being used in existing diesel engines without the need for any modification to the engine or its control system.

The experiments were conducted on a 4.5L Tier-III Engine at 1700 rpm and 50% torque. The fuel used was a blend of unrefined canola triglyceride and regular unleaded gasoline in varying ratios. Physical properties, including density, viscosity and bulk modulus, were measured. In-cylinder measurements include pressure, heat release and mass fraction burned. Exhaust pollutants NOx, PM, CO and THC were measured. Engine electronic control unit values for intake pressure, start of injection, turbocharger speed and fuel quantity demand were also recorded.

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For blends containing lower gasoline content, up to 25% by volume, the start of injection, specific fuel consumption, heat release rates and combustion duration were similar to 100% triglyceride (straight vegetable oil). For blends containing gasoline content from 25% to 55% by volume, the start of injection, turbocharger speed, brake specific fuel consumption, heat release rates and combustion duration were similar to diesel. Blends containing gasoline content greater than 55% by volume, the start of injection, turbocharger speed, brake specific fuel consumption, heat release rates and combustion duration were significantly different than diesel or pure triglyceride.

The exhaust emissions for blends containing low gasoline content had values similar to pure triglyceride. As the gasoline content increased to about 55% by volume the trends were similar to diesel. However, for blends containing more than 55% gasoline, the trends were significantly different than diesel or pure triglyceride.

4.2 INTRODUCTION:

The US has mandated the use of biofuels to alleviate some of the energy shortfall (energy trade deficit) in the transportation sector. Using plant based triglycerides, also known as straight vegetable oils (SVOs) as an alternative to diesel fuel is not a new concept. Some studies have predicted that second-generation biofuels could fill the void for both personal consumption and powering generation industry by balancing the need to grow more food crops while also their biomass could be used for producing fuels. This reduces some of the dependence on fossil fuel [1, 2].

Producing crops on farm consumes a significant amount of energy in the agricultural sector. Approximately 17 to 20% % of liquid fuel consumption in the US is used for agriculture and allied activities[3]. Fuel costs roughly translate to about 6.6 % of the total farm production costs in 2005. The costs have since then gone up three times [4, 5]. Increases in the prices of fuel and energy directly affect the cost of producing a crop which in turn affects the farmer’s net farm profitability which affects the prices of food commodities.

Vegetable oils apparently have good potential as alternative fuels for maintaining crop production during periods of fuel shortages. Among the advantages of vegetable oils as fuels are their physical nature as liquids and, hence, their portability, their heat content (88% of diesel oil), their availability, and the fact that they are renewable resources [6, 7]. However, vegetable oil fuels that have been used on farm tractors introduced a large number of problems that can be attributed to their high viscosity, low volatility and the oxidative stability of the unsaturated hydrocarbon chains [8].

To overcome the SVO limitation of high viscosity, some farmers [9, 10] blend regular unleaded gasoline with SVO to match the specific gravity of diesel (~0.865 to 0.870). Gasoline is used as a thinner for two reasons as follows: (i) it is readily available, and (ii) gasoline is also a fuel. This blend of SVO and gasoline is defined as a Triglyceride Gasoline Blend (TGB). Gasoline, is characterized by a high volatility and a low cetane number [11, 12]. Gasoline also evaporates quickly due to its low boiling point, which results in a shorter liquid spray penetration [13-15]. Faster evaporation of the fuel could lead to accelerated fuel-air mixing. The low cetane number may lead to an increase in ignition delay. This results in intensified premixed heat release, less smoke and higher NOx emissions [15-17].

The potential users of TGBs need a better understanding of the combustion process and the long term impacts on the engines. There is very little peer reviewed literature [10, 18-20] available on the TGBs while there are many publications on diesel blends with gasoline and other oxygenates [21-25]. These publications discuss in detail the physical properties and exhaust emissions from diesel engines.

TGBs are similar to standardized fuels like diesel and biodiesel in that they do not require engine modification for their use. However, questions regarding the impact of TGBs on the vehicle, tractor, and generator engine components remain unanswered. It is also unclear what blend ratio should be used and what trade-offs exist with varying blend ratios. his research aims to address many of these questions related to blend ratio by experimentally characterizing diesel engine performance operating on varying triglyceride-gasoline blend ratios.

The stock program in the engine control unit (ECU) was used. This ECU was programmed and calibrated by the engine manufacturer with diesel as the primary fuel. The engine ECU was not modified to adapt it to the alternative fuel used in these experiments. The results are interpreted with this caveat.

4.3 EXPERIMENTAL SET UP

4.3.1 FUEL

The fuels used were a blend of unrefined canola oil (triglyceride) and various percentages regular unleaded gasoline by volume. All specified blend percentages in this paper are by volume. The blended fuels were then stored in containers for about 5 days before being used in experiments. The fuel blends did not show any separation of the triglyceride and gasoline and remained stable throughout the test program.

Density Meter Anton Paar density meter (DSA 5000 M) [26] was used to measure the density and the speed of sound in the fuel sample with a repeatability of $1x10^{-6}$ g/cm^3 . It is equipped with a density and sound velocity cells. The fuel sample is introduced into the Anton Paar oscillating U Tube made of borosilicate glass which is then excited to vibrate electronically at its characteristic frequency. This frequency is a function of the density of the fuel. The density is then deduced using mathematical co-relation.

Viscosity meter: Anton Paar Viscosity Meter (SVM 3000) [27] was used to measure the viscosity of the fuel sample with an accuracy of ±0.35% and a repeatability of ±0.2%.A tube is filled with the sample fuel rotates at a constant speed. This tube is suspended in a hollow measuring rotor made of Titanium. This measuring rotor is centered in the heavier liquid by buoyancy forces due to its low density. A permanent magnet is used to guide the rotor axially and deliver the speed using eddy currents. The difference in the torque due to the shear stress influences the rotor speed which can then be used to calculate the viscosity of the sample.

Calorimeter An IKA-200C was used to measure the heating value of the fuel sample within a repeatability of ±0.1%. A known weight of the sample in taken in a crucible and is placed in a steel container. This container also called the bomb is filled with 99.95% oxygen at 30 bar. The sample is then ignited with a cotton thread of known heating value and allowed to burn. This burning of the sample heats up the known quantity of water surrounding the bomb at a known temperature. This temperature rise is measured and the heating value of the sample is measured.

4.3.2 ENGINE

Engine performance and emission analysis are conducted on a 4-cylinder, 16 valve, turbocharged, intercooled, 4.5L, 175 hp (129 kW), John Deere 4045 PowerTech Plus, Tier 3 test engine. The engine is configured with a variable geometry turbine (VGT) turbocharger, exhaust gas recirculation (EGR) and a high pressure common rail electronically controlled fuel injection system. The engine is coupled to an eddy current dynamometer (Midwest Inductor Dynamometer 1014A). The dynamometer and its controller (Dynesystems Dyn-LocIV) are used to load the engine.

Diesel and test fuels were stored in two different fuel tanks. Each fuel tank had a dedicated fuel lift pump which supplied the fuel to the engine mounted high pressure fuel pump. The fuel return line for diesel operation was connected back to the fuel supply line downstream of the Coriolis fuel meter (Micro Motion 2700R11BBCEZZZ), so it directly read the net fuel consumption. The test fuel tank was placed on an electronic scale and the lift pump supplied fuel from the tank to the engine. The test fuel return line from the injectors was routed directly to the fuel tank. The difference in the readings of the electronic scale before and after the data point gave the net fuel consumption.

The high speed in-cylinder pressure was recorded by a Kistler Instrument Corporation PiezoStar pressure sensor (6056A41) with a glow plug adaptor (6542Q128) that was installed in the glow plug port of cylinder 1. A custom system developed at the laboratory using National Instruments PXI-1002 was connected to a charge amplifier (Kistler type 5010) to record combustion pressure data from the in-cylinder pressure transducer. Crankshaft position and instantaneous engine speed were provided by an incremental encoder connected to the crankshaft. Pressure data was taken at 0.50 crank angle degree intervals for 1000 cycles, then averaged and smoothed using LABView software. The engine ECU operated as per the stock programming and hence parameters such as the injection timing and injection pressure were controlled according to standard Engine Control Unit maps.

4.3.3 EXHAUST GAS SAMPLING AND MEASUREMENT

Two different probes extracted exhaust for emissions measurements. An averaging probe was used for gaseous emissions and an isokinetic probe was used for PM. The gas analysis was performed with a 5-gas analyzer [9, 10].

A dilution tunnel was used to measure PM emissions. The laboratory air was drawn into the system by a pump and made to pass through a High Efficiency Particulate Air (HEPA) filter to purify it. The exhaust sample entered the dilution tunnel where it was mixed with the purified air. A PM10 cyclone removed all particles larger than 10 micron in diameter from the mixture. A portion of the mixture was then extracted by a pump and made to flow through the filter assembly. Teflon filters designed to collect particulate matter were held by filter cassettes. Particulate samples were collected onto pre-weighted Teflon filters which were then weighed again to give mass of the sample collected.

4.3.4 EXPERIMENTAL PROCEDURE

Engine testing was carried out at an engine speed of 1700 rpm and load of 50% for all test points. The engine was warmed up to steady conditions. Average temperatures of coolant and lubricating oil were kept at 85°C and 87°C, respectively. A five-minute average for emissions and fuel consumption was recorded. Diesel fuel was first tested followed by each of the test fuels. Then the fuel supply system was purged and flushed with the test fuel to ensure that there was no residual fuel from the recently concluded test. Each of the test fuels were available in limited quantity just enough to carry out one set of experiment.

4.4 TEST RESULTS

A summary of brake specific fuel consumption and exhaust emissions – NO_X, PM, CO and THC for fuels tested are shown in Table 3. Table 4 shows the combustion statistics of peak pressure, location of peak pressure and the location of 50% mass fraction burned. Table 5 shows the average brake specific weighted emissions over the 8 modes. A detailed discussion of these data are in subsequent sections of the paper.

Figure 4-1 shows the densities of the triglyceride gasoline blends. 100% triglyceride and diesel have densities of 0.900 g/cm^3 and 0.838 g/cm^3, respectively. The densities of the TGBs decrease with increased gasoline fraction. Triglyceride blended with 45% gasoline and 50% gasoline had densities 0.837 g/cm^3 and 0.835 g/cm^3, respectively, which are approximately the same as diesel. Triglyceride blended with 5 and 10% gasoline had densities 0.908 g/cm^3 and 0.902 g/cm^3, respectively, which are approximately the same as 100% triglyceride. Variations in density is also known to affect the fuel spray characteristics and hence can impact exhaust emissions [28-30].

Table 4-1 Engine performance and emission data

Fuel Type	BSFC (g/kWh)	NO_X (g/kWh)	PM (g/kWh)	THC (g/kWh)	CO (g/kWh)
Diesel	237.6	5.73	0.110	0.278	1.35
Triglyceride	252.6	6.63	0.101	0.295	0.98
5% gasoline blend	247.3	6.49	0.099	0.289	0.96
10% gasoline blend	250.4	7.04	0.051	0.291	0.90
15% gasoline blend	242.5	6.59	0.041	0.306	0.96
20% gasoline blend	243.7	6.79	0.044	0.308	0.94
25% gasoline blend	234.4	6.61	0.034	0.314	0.95
35% gasoline blend	225.4	6.23	0.058	0.322	1.00
40% gasoline blend	226.9	6.36	0.014	0.325	1.04
50% gasoline blend	230.4	6.87	0.048	0.323	1.08
55% gasoline blend	231.5	7.13	0.035	0.315	1.11
60% gasoline blend	238.2	4.58	0.055	0.544	1.71
70% gasoline blend	250.6	5.03	0.077	0.598	1.97
80% gasoline blend	232.8	5.00	0.126	0.541	2.06

Table 4-2: In-cylinder Combustion Data

Fuel Type	Start of Injection (°CAD)	Peak Pressure (kPa)	Location of Peak Pressure (°ATDC)	Location of 50% MFB (°ATDC)
Diesel	3.34	8140	12.6	19.4
Triglyceride	1.71	7454	15.3	21.1
5% gasoline blend	1.92	7477	14.7	20.8
10% gasoline blend	1.92	7624	15.2	20.8
15% gasoline blend	2.10	7582	14.5	20.7
20% gasoline blend	2.14	7641	14.4	20.7
25% gasoline blend	2.28	7649	15.1	19.1
35% gasoline blend	2.48	7685	15.0	19.1
40% gasoline blend	2.67	7755	14.5	18.9
50% gasoline blend	2.96	7884	13.6	18.7
55% gasoline blend	3.04	7973	13.3	18.6
60% gasoline blend	2.76	5873	24.0	27.4
70% gasoline blend	2.75	5765	24.0	27.4
80% gasoline blend	3.13	5627	24.0	26.9

Figure 4-2 shows the viscosities of the TGBs. 100% triglyceride and diesel had viscosities of 39.01 mm^2/s and 2.57 mm^2/s, respectively. Viscosities for TGBs containing up to 40% gasoline were measured using Anton Parr equipment. TGBs containing gasoline percentages in excess of 40% could not be measured at the lab due to the design and functional limitation of the measuring device. Hence the viscosities of triglyceride blends containing 45%, 50%, 55%, 60%, 65%, 70%, 75% and 80% gasoline were extrapolated with the data available from 0 % to 40% gasoline blends. The viscosity of gasoline ranges from 0.418 mm^2/s to 0.634 mm^2/s[13, 31]. TGB viscosity decreases with increased gasoline fraction. TGB with 55% gasoline had an extrapolated viscosity of 2.537 mm^2/s, which is nearly the same as diesel. TGB with 5% gasoline has a viscosity of 28.03 mm^2/s. Thus, by blending just 5% gasoline to triglyceride the viscosity is reduced by nearly 29%.

Figure 4-3 shows the bulk modulus of the triglyceride gasoline blends. 100% triglyceride, diesel and gasoline had a bulk modulus of 1.96E12 N/m^2, 1.57E12 N/m^2 and 1.09 N/m^2, respectively. The bulk modulus of the TGBs decreases with an increase in the blended gasoline. TGBs with 35% and 40% gasoline had bulk moduli of 1.58 N/m^2 and 1.56 N/m^2, respectively, which are nearly the same as diesel. TGBs with 5% and 10% gasoline had densities 0.908 g/cm^3 and 0.902 g/cm^3, respectively, which are approximately the same as 100% triglyceride.

The calorific value, or lower heating value (LHV) of the TGBs are shown in Table 4-3. LHVs of diesel, triglyceride and 5, 10, 15, 20, 25 and 35% gasoline TGBs were measured using the calorimeter. The calorific values of the remaining TGBs were extrapolated because the calorimeter was unavailable.

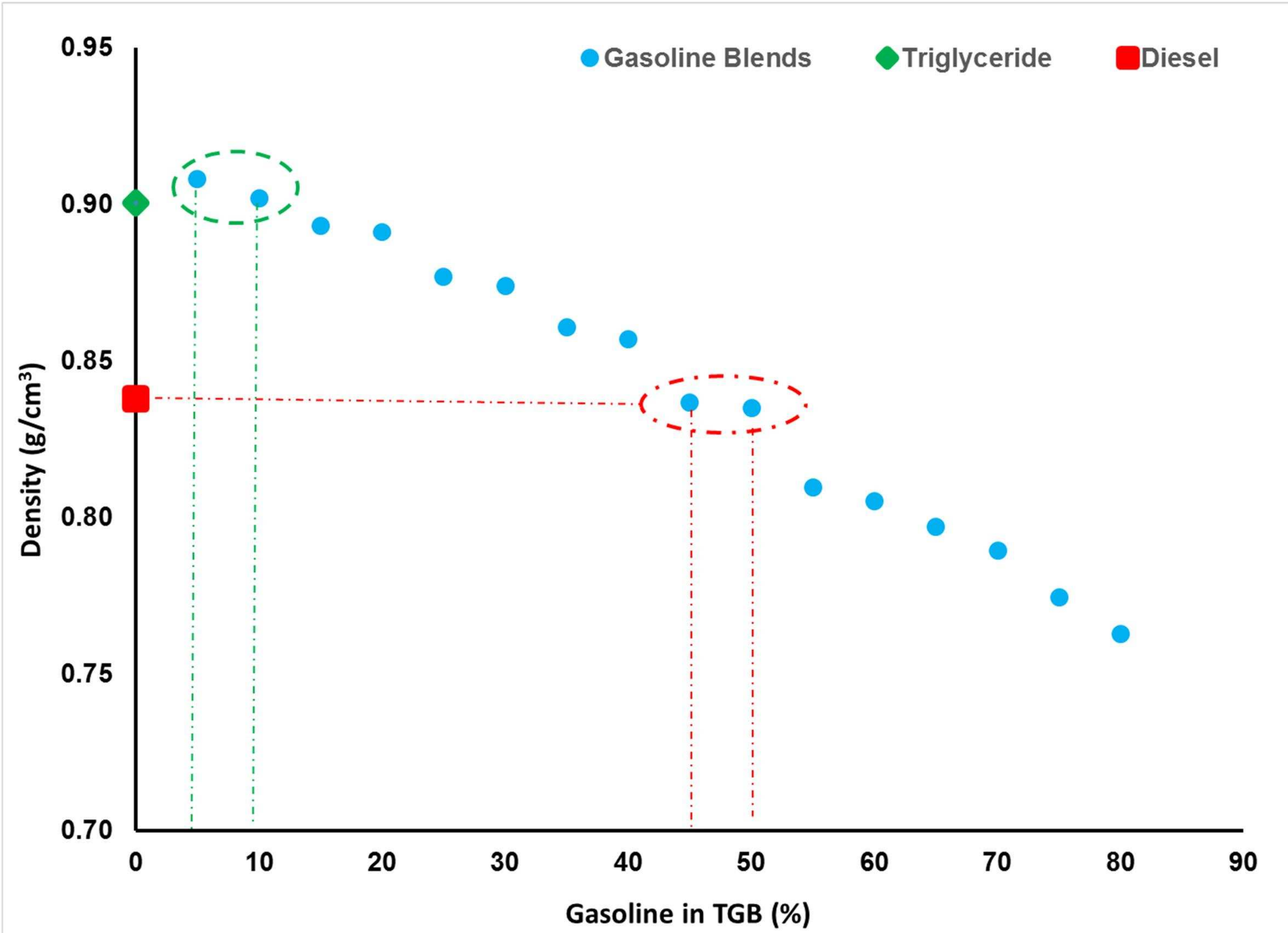


Figure 4-1: Density of Triglyceride Gasoline Blends

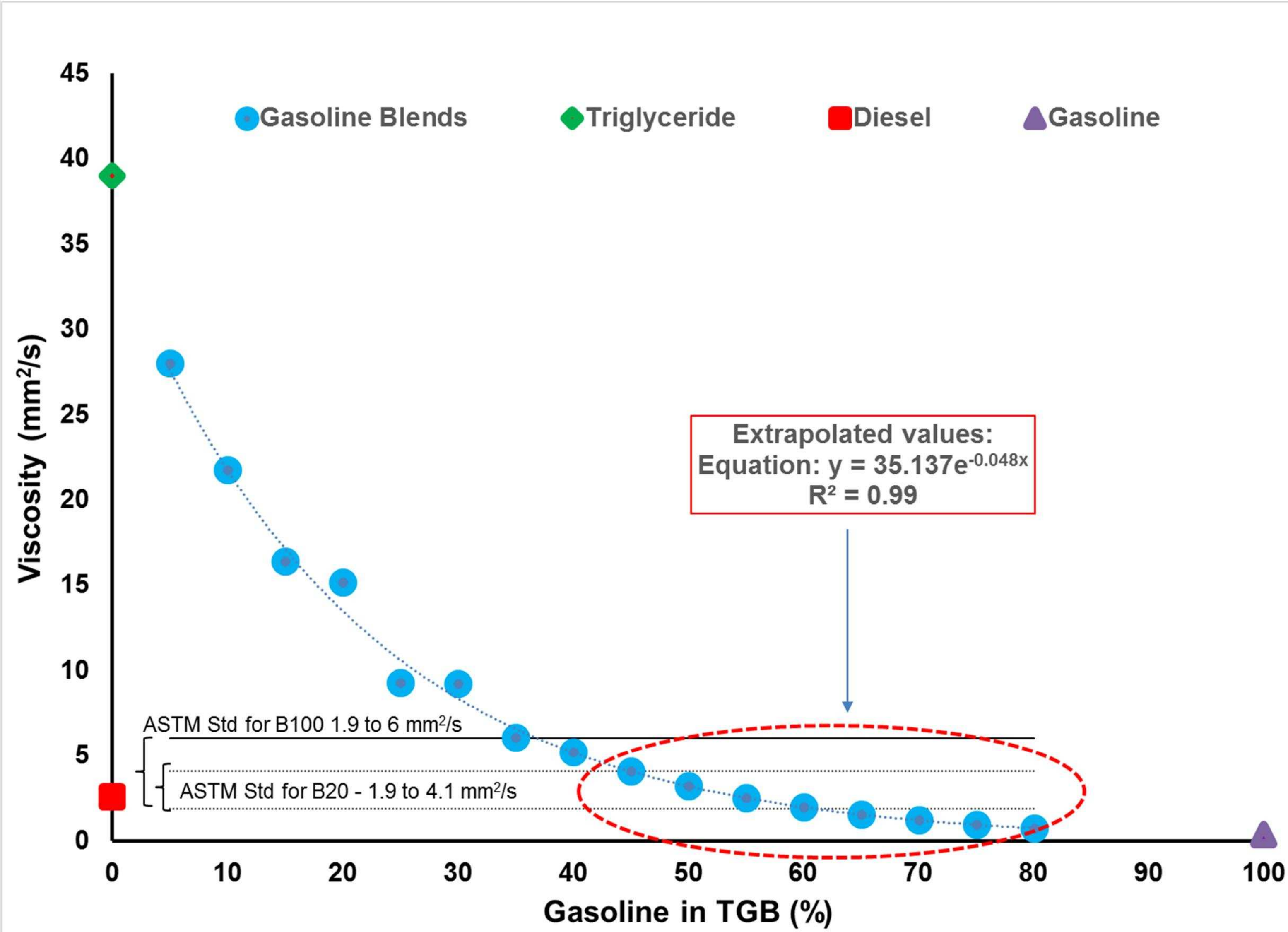


Figure 4-2: Viscosity of Triglyceride Gasoline Blends

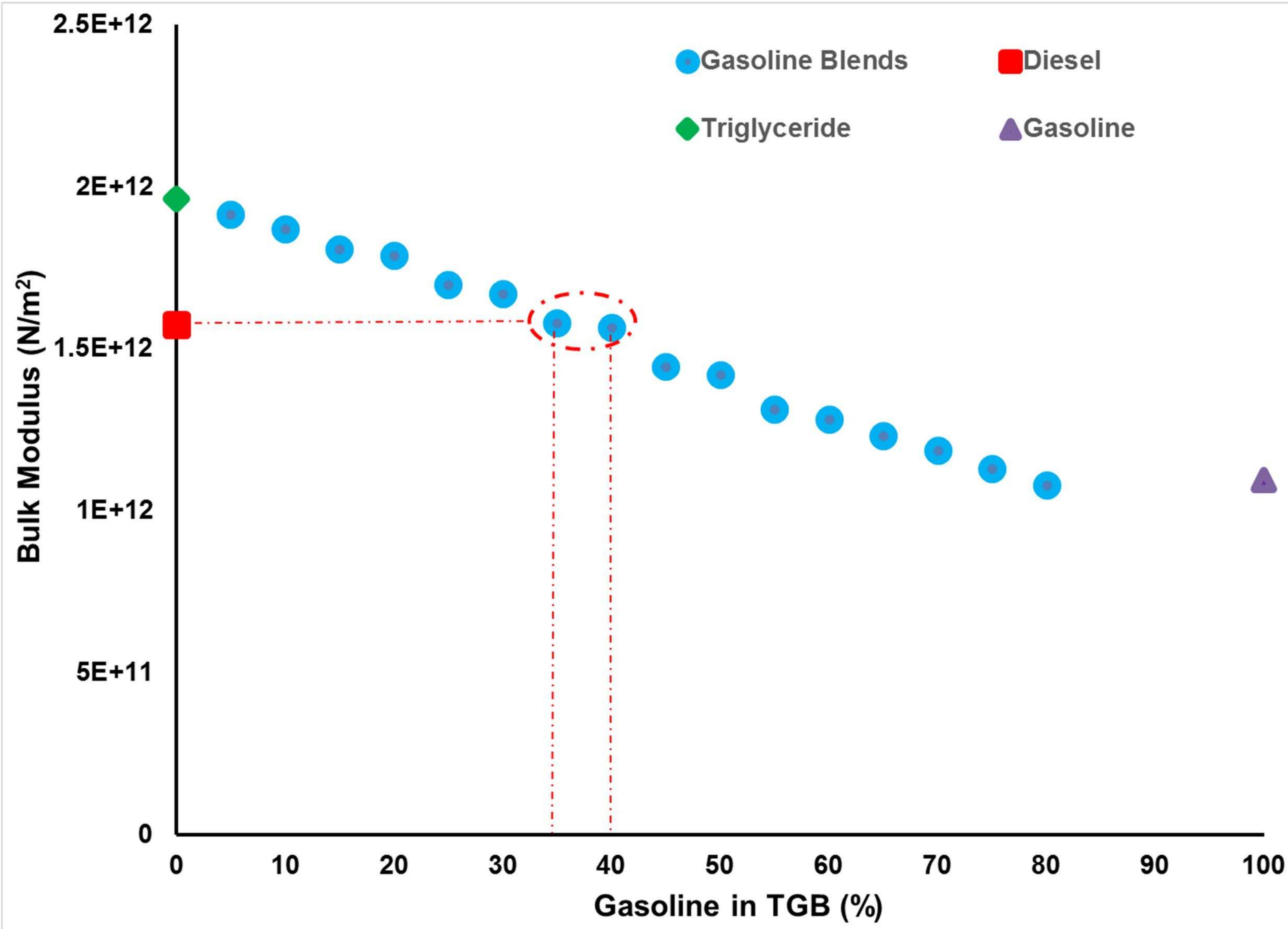


Figure 4-3 Bulk Modulus of Triglyceride Gasoline Blends

Diesel fuel had an LHV of about 42600 kJ/Kg and triglyceride had a value of about 36800 kJ/Kg. The calorific value of the TGBs increased linearly with the amount of gasoline blended with the triglyceride.

Table 4-3: Lower Heating Value of Triglyceride-Gasoline Blends

Fuel Type	**LHV (KJ/Kg)**
Diesel	42600
Triglyceride	36800
5% gasoline blend	37130
10% gasoline blend	37460
15% gasoline blend	37790
20% gasoline blend	38120
25% gasoline blend	38450
35% gasoline blend	38780
40% gasoline blend	39110 *
50% gasoline blend	40100 *
55% gasoline blend	40430 *
60% gasoline blend	40760 *
70% gasoline blend	41420 *
80% gasoline blend	42080 *
* Extrapolated values since equipment was unable for use after the first few points	

Figure 4-4 shows the Start of Injection (SOI) of the TGBs from the engine ECU. 100% triglyceride and diesel had SOI values of 1.71 and 3.34° bTDC, respectively. Generally, as the percentage of gasoline that was blended increased, the SOI of the fuel also increased. For a 5% gasoline TGB, the SOI was 1.92 bTDC while for a 55% gasoline TGB, the SOI was 3.04 deg bTDC. This is due to the programmed ECU calibrations by the manufacturer. The engine calibrations co-relate the engine speed, demanded load/torque, and the quantity of fuel required to calculate the start of injection. Some studies have shown that injection timing and combustion sensitivity of gasoline blended fuels can be improved to achieve better combustion [32].

Figure 4-5 shows the Desired Fuel (mL/stroke) commanded by the engine ECU. 100% triglyceride and diesel had desired fuel values of 69 and 50.5 mL/Stroke, respectively. Since triglyceride has a lower energy density than diesel, the engine ECU commands more triglyceride as fuel to maintain the same load and speed as that of diesel. Blending of gasoline to triglyceride increases the calorific value of the blend, hence decreasing the amount of fuel desired to maintain engine load and speed. The amount of fuel injected is controlled by the injector open duration. Longer durations result in more fuel injected into the combustion chamber.

Figure 4-6 shows the turbocharger speed from the ECU. 100% triglyceride and diesel had a turbocharger speed of 92,000 and 76,700 rpm, respectively. Generally, the turbocharger speed decreases as % gasoline increases. The turbocharger speed for 5% gasoline TGB was 90,400 rpm and that for 80% gasoline TGB was 80,200 rpm. The change in turbocharger speed likely results in ECU operating point shifts as the fuel command changes (Figure 4-5). EGR valve position and turbocharger vane angle are controlled by the ECU and can impact turbocharger speed.

Figure 4-7 shows the Intake air pressure from the ECU. 100% triglyceride and diesel had an intake air pressures of 141.8 and 120.8 kPa, respectively. In general, the intake air pressure decreases as TGB % gasoline increases. The intake air pressure for a 5% gasoline TGB was 139.6 kPa and for 80% gasoline TGB was 125 kPa. The trend is similar to turbocharger speed (Figure 4-6); higher intake air pressure is generated by higher turbocharger speeds.

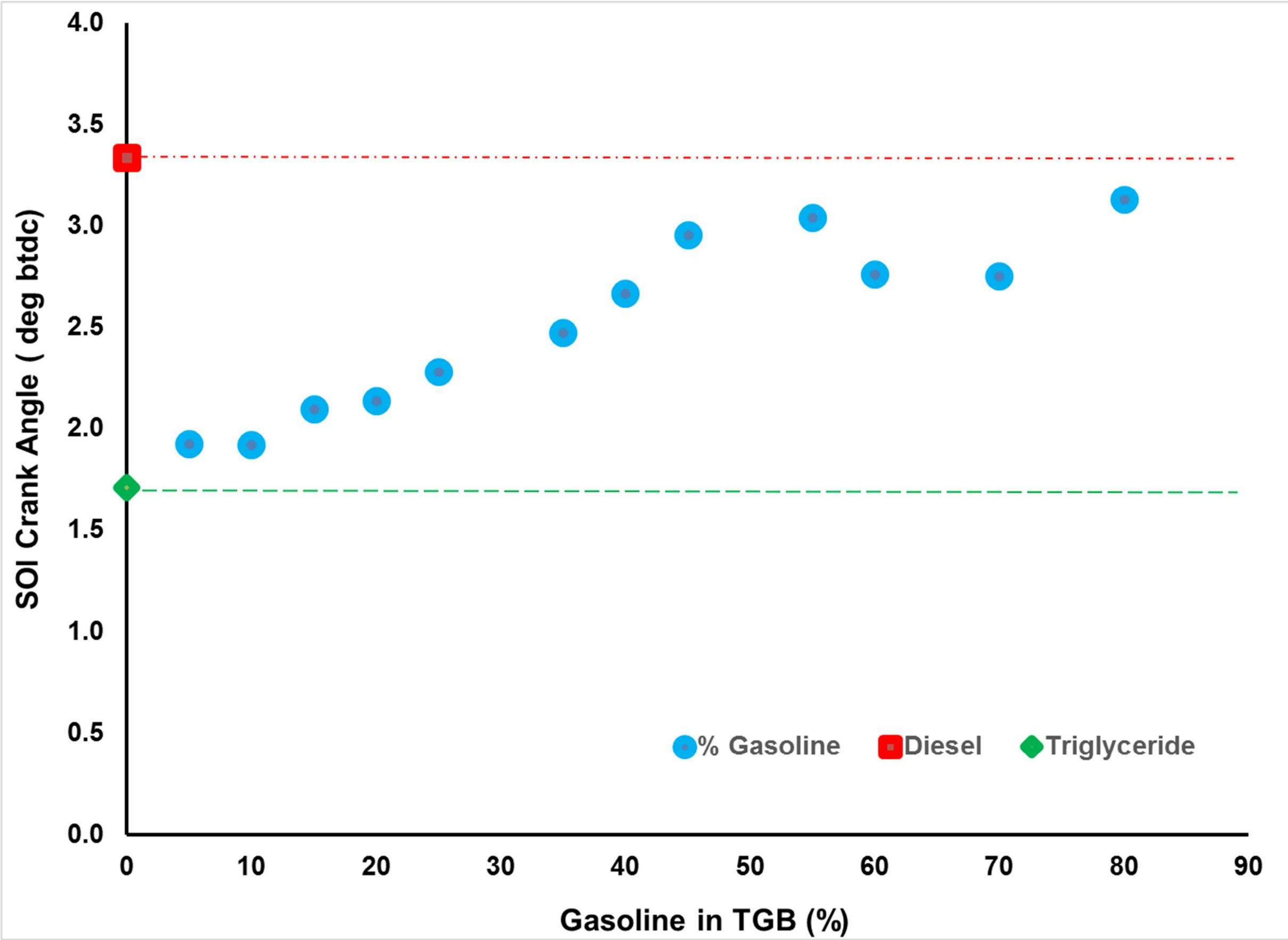


Figure 4-4 Start of Injection for Triglyceride Gasoline Blends

Since the desired fuel for triglyceride gasoline blends is higher than diesel (see Figure 4-5), the engine requires more air for effective combustion. Hence a higher turbocharger speed occurs and results in higher intake air pressure (see Figure 4-7). Higher intake air pressure means that the engine is being supplied with more air. The higher intake air pressure and a start of fuel injection closer to TDC than diesel (see Figure 4-4), suggests higher in-cylinder pressure for triglyceride gasoline blends than diesel.

As the percentage of gasoline blended to the triglyceride increases, the calorific value of the blend increases to get closer to diesel (see Table 4-4). As the calorific value of the fuel blend increases, the amount of desired fuel decreases and turbocharger speed decreases, which reduced the intake air pressure and results in start of injection closer to a diesel fuel like operation.

Figure 4-8 shows the cylinder pressure traces for different TGBs compared to diesel and triglyceride. The maximum in-cylinder pressure for diesel fuel was around 7,600 kPa while that for 100% triglyceride was around 7,350 kPa. Figure 4-8A shows the pressure traces of 5% and 10% gasoline in TGBs. Since the percentage of gasoline blended is low, the cylinder pressure traces are closer to 100% triglyceride and are generally higher than diesel. The maximum in-cylinder pressure for 5% gasoline TGB was around 7,300 kPa while that for 10% gasoline TGB was around 7,480 kPa. Similar result are observed in research using Jatropha oils [33].

Figure 4-8B shows the pressure traces for 25% and 35% gasoline TGBs. The pressure traces are lower than 100% triglyceride but generally higher than diesel. The maximum

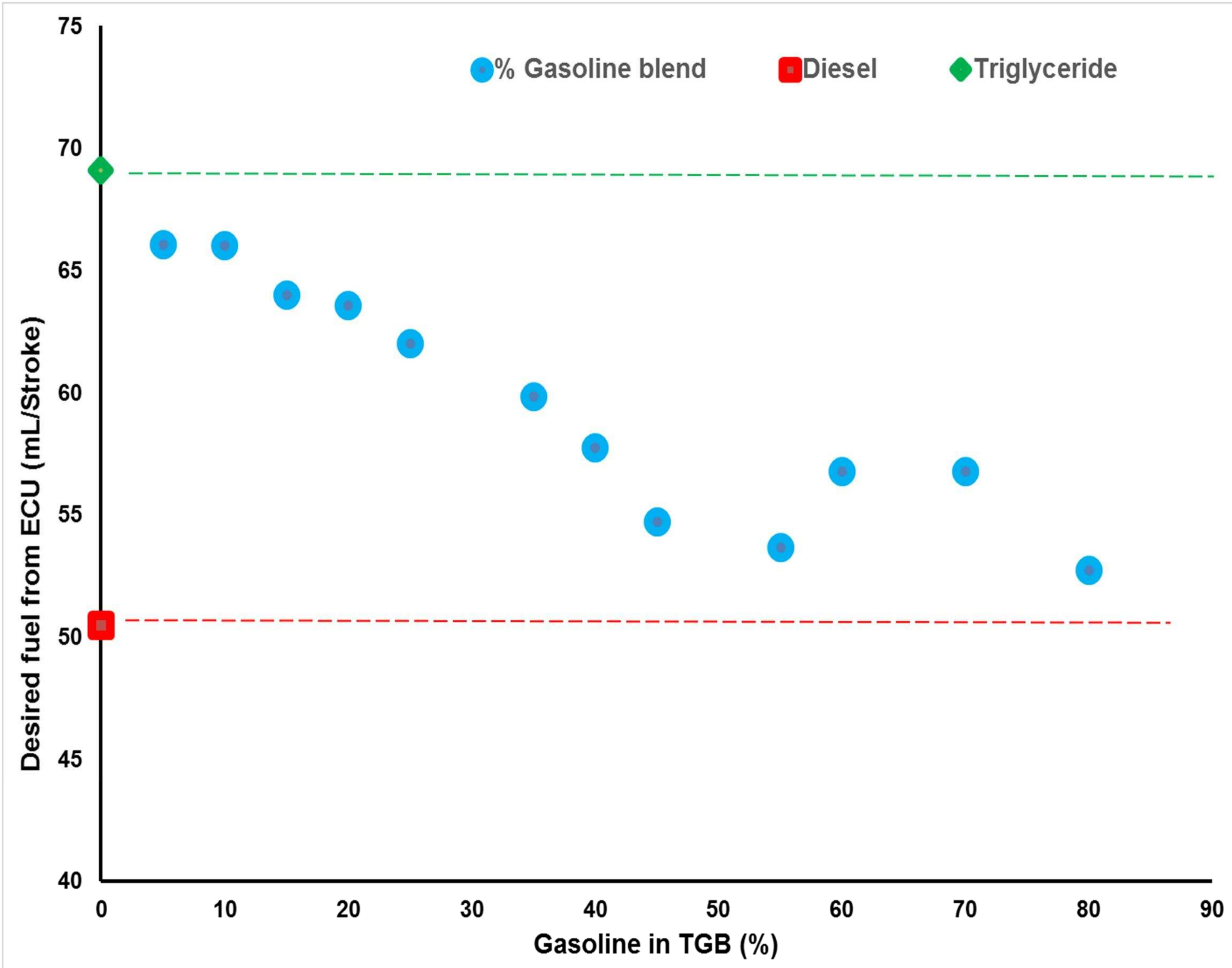


Figure 4-5 Desired fuel as requested by the engine ECU for Triglyceride Gasoline Blends

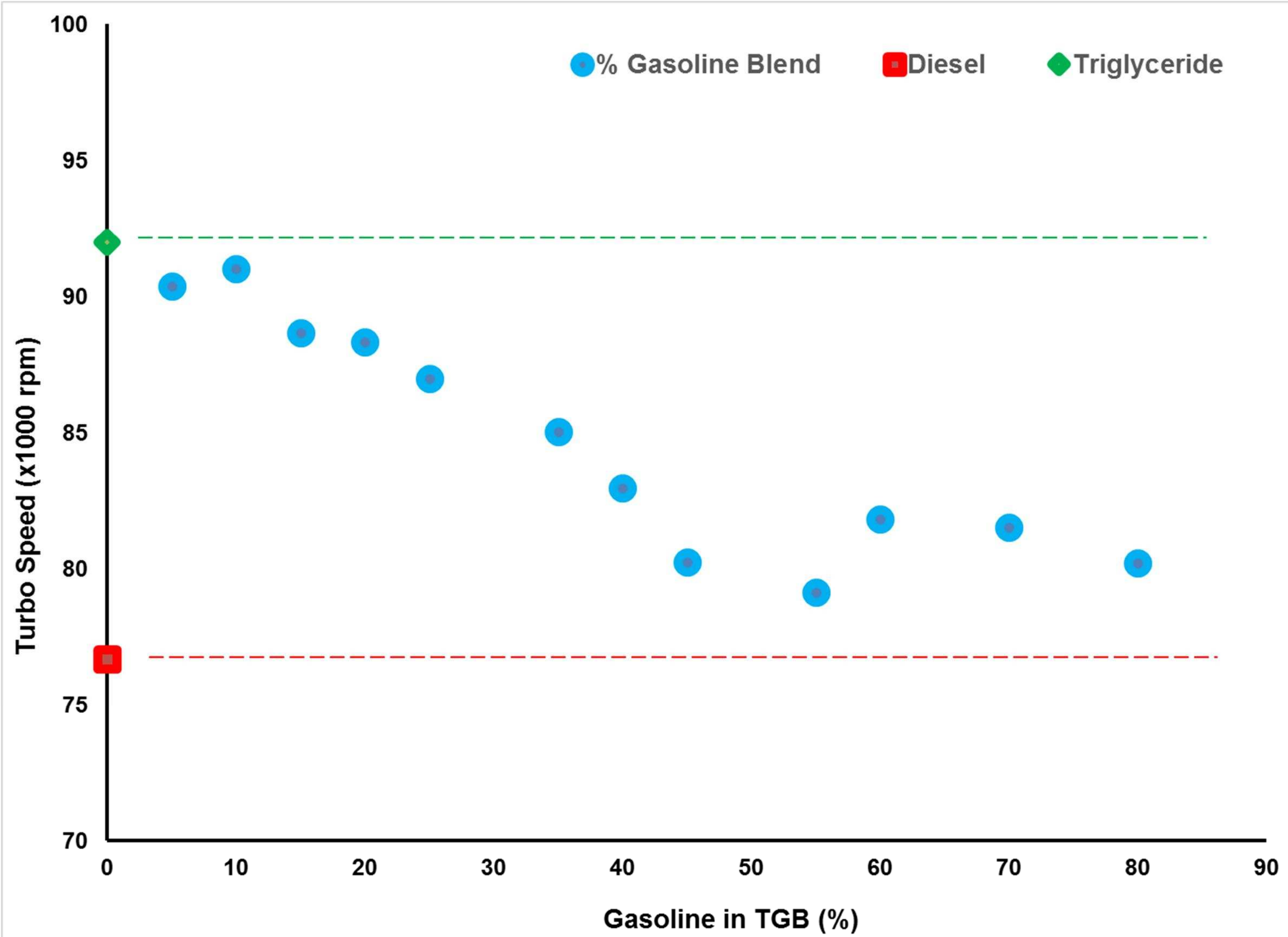


Figure 4-6 Turbocharger speeds for Triglyceride Gasoline Blends

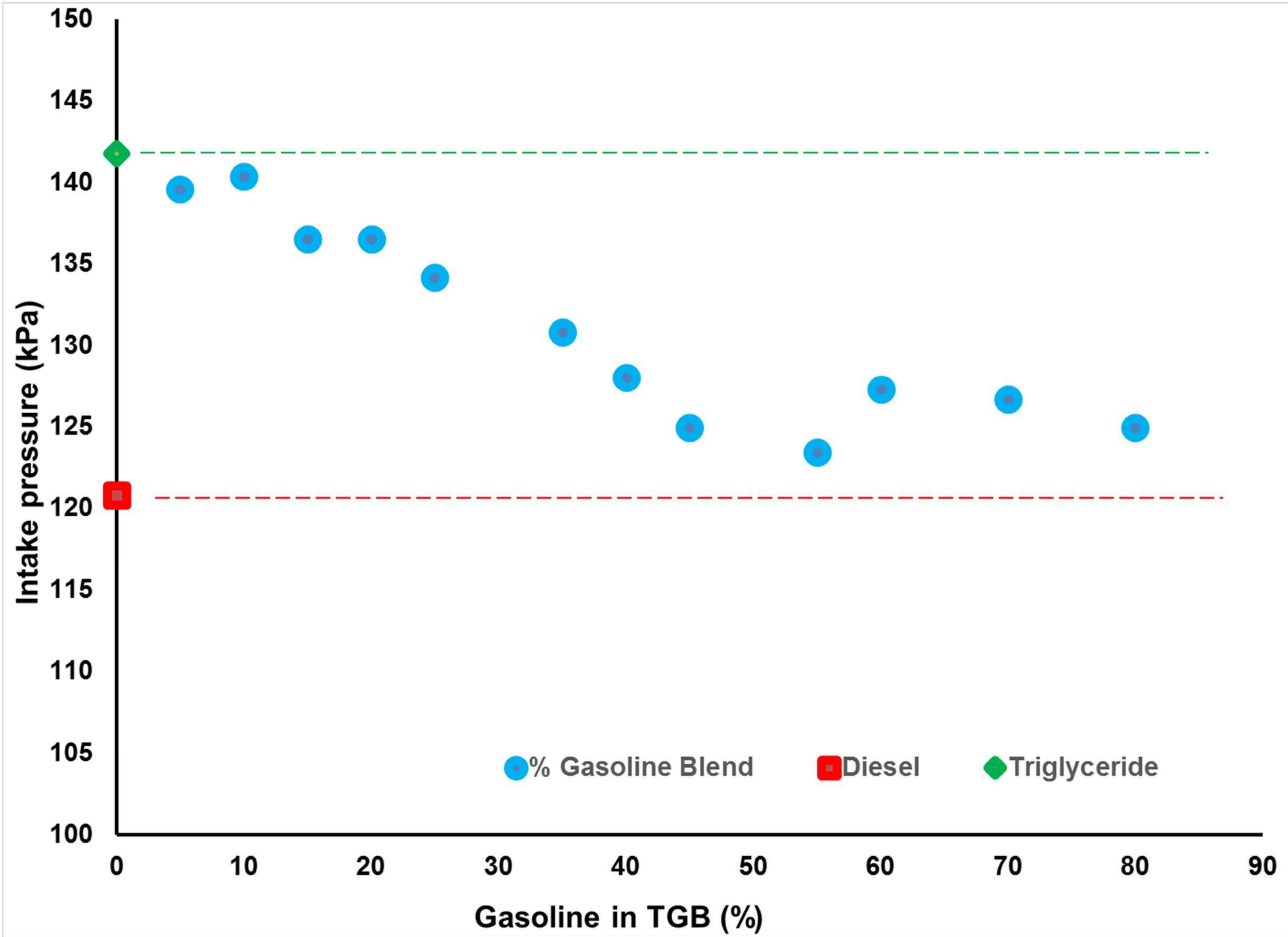


Figure 4-7 Intake Air Pressure for Triglyceride Gasoline Blends

pressure for 25% gasoline TGB was around 7,380 kPa, while that for 35% triglyceride gasoline blend was around 7,420 kPa.Figure 4-8C shows the pressure traces of 50 and 55% gasoline. TGBs. The pressure traces are lower than 100% triglyceride but generally closer to diesel. The maximum pressure for 50% gasoline TGB was around 7,580 kPa, while that for 55% gasoline TGB was around 7,620 kPa.

Figure 4-8D shows the pressure traces of 60%, 70% and 80% triglyceride gasoline blends. The pressure traces show a distinct "double hump" characteristic. The first hump occurs at top dead center is that of the motoring pressure. The second hump around 24 CAD after TDC is due to combustion. This suggests that the fuels start the combustion later than diesel. The maximum in-cylinder pressure after the start of combustion (about 24 CAD) was 4,717 kPa for 60% gasoline TGB, 4,690 kPa for 70% gasoline TGB, and 4,684 kPa for 80% gasoline TGB.

Figure 4-9 shows the location of peak pressure in crank angle degrees after start of injection (aSOI). The data is plotted relative to start of injection to remove the impact of varying injection timing. The error bars are ± one standard deviation over 1000 cycles. Diesel fuel had a peak pressure location at 12.6 degrees aSOI and 100% triglyceride had the peak pressure located at 15.35 degrees aSOI. The triglyceride gasoline blends had a peak pressure closer to 100% triglyceride at lower gasoline blends and shifted closer to diesel as the gasoline percentage increased up to 55%.

The 60%, 70% and 80% gasoline TGBs had peak pressure location at about 24 degrees aSOI, which is significantly higher than diesel and 100% triglyceride. This can be attributed to the later combustion and the double hump phenomena (Figure 8D).

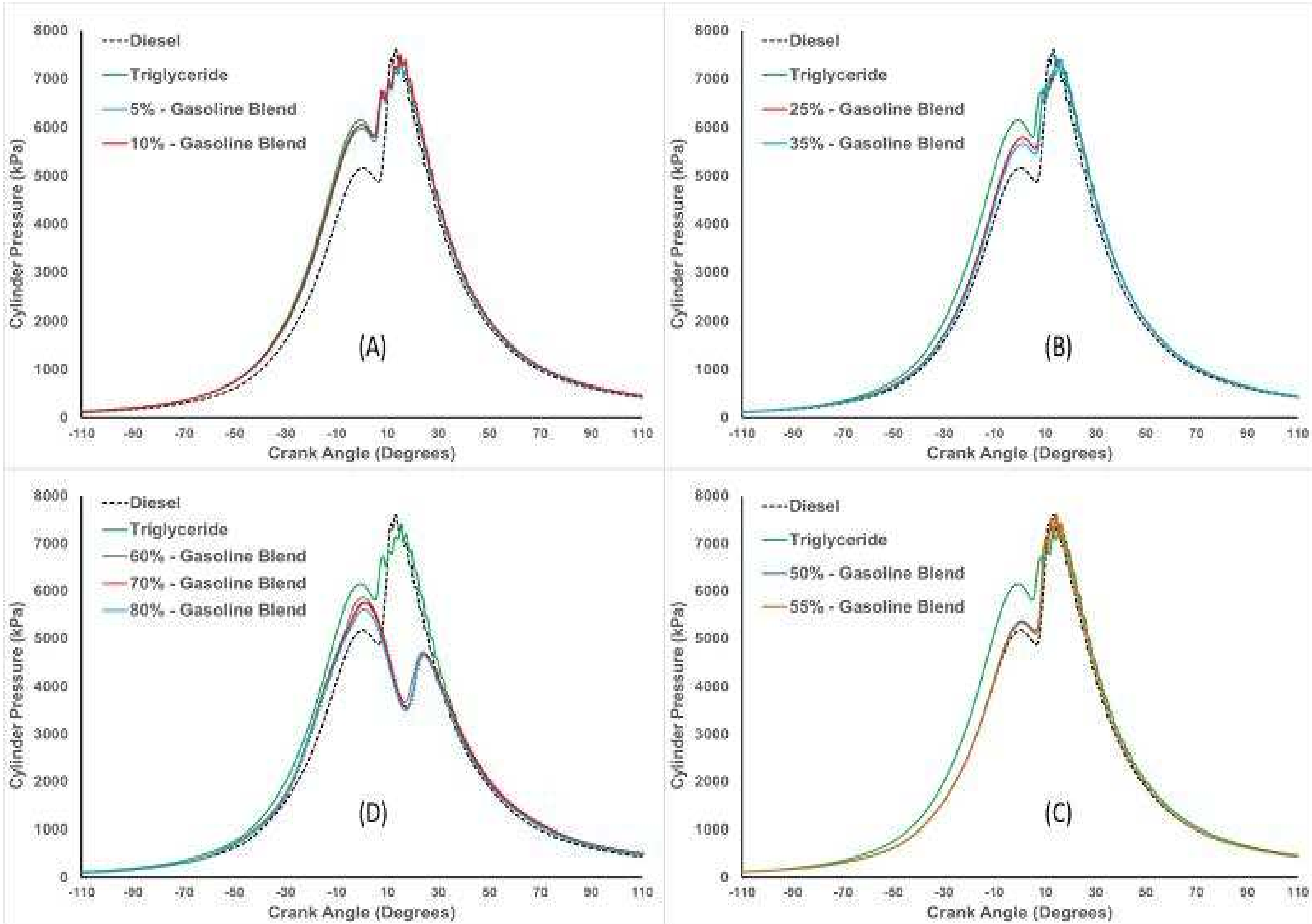


Figure 4-8 Cylinder pressure traces at 1700 rpm and 50% load

Some researchers have observed opposite results than observed in this study. The main reason for this is the fuels used in these studies have higher density and viscosity, which does not atomize satisfactorily resulting in incomplete combustion [33].

Figure 4-10 shows the indicated mean effective pressure (IMEP) and pumping mean effective pressure (PMEP) for TGBs compared to diesel and 100% triglyceride. The left axis represents the IMEP and the right axis shows the PMEP. The error bars are ±one standard deviation over 1000 cycles.

Diesel fuel had a IMEP of about 1267 kPa while 100% Triglyceride had an IMEP of about 1210 kPa. The TGBs had IMEP values closer to 100% triglyceride at lower gasoline blend and increased closer to diesel as the gasoline percentage increased until 55%. The 60%, 70% and 80% gasoline TGBs had IMEP values of 1071 kPa, 1069 kPa and 1042 kPa, respectively, which are significantly lower than 100% triglyceride.

Diesel fuel had a PMEP of about -16.5 kPa while 100% Triglyceride had an IMEP of about -33.3 kPa. The triglyceride gasoline blends had IMEP values closer to 100% triglyceride at lower gasoline blend and increased closer to diesel as the gasoline percentage increased up to 55%. The 60%, 70% and 80% gasoline TGBs had PMEP values of -8.28 kPa, -7.04 kPa and -8.00 kPa, respectively, which are significantly lower in magnitude than diesel. This is likely related to the change in the engine operation and control parameters in the stock calibration fed into and read by the Engine Electronic Control Unit maps. The engine might be reading a different point in the calibration map for the various blends of TGBs and diesel.

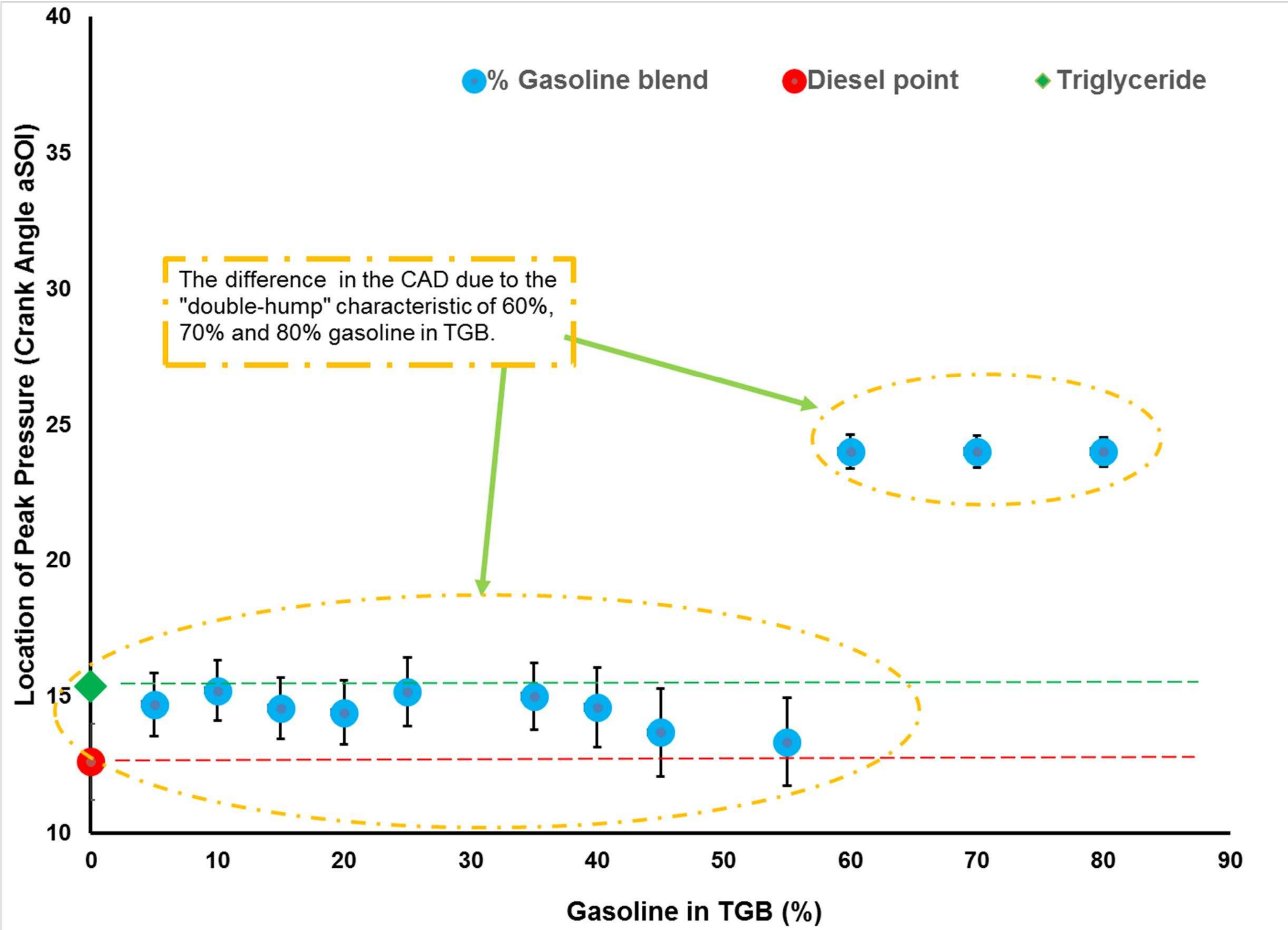


Figure 4-9 Location of Peak Pressure for Triglyceride Gasoline Blends

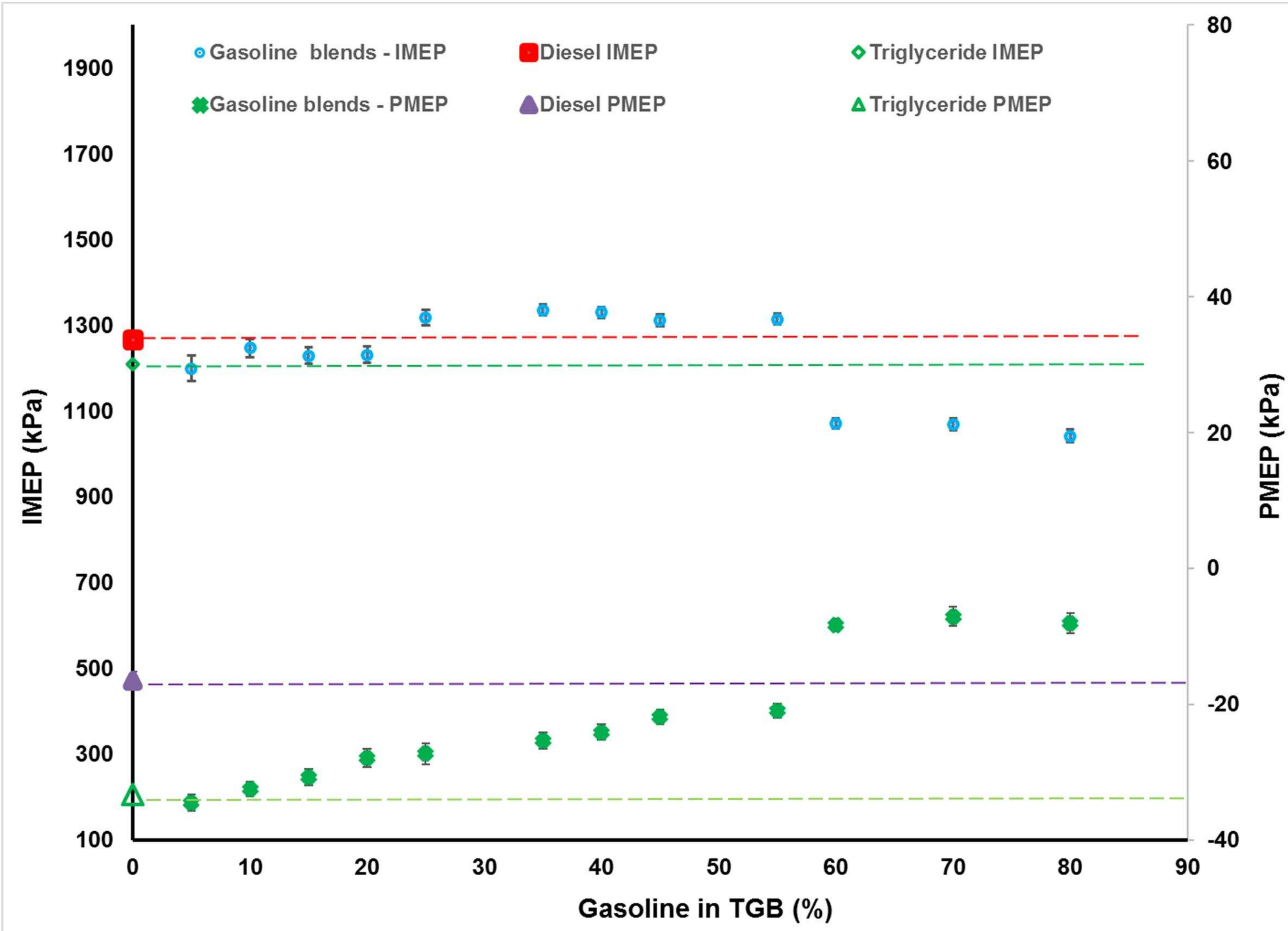


Figure 4-10 IMEP and PMEP for Triglyceride Gasoline Blends

Figure 4-11 shows the cylinder heat release rate averaged over 1000 cycles for different TGBs compared to diesel and triglyceride. 100% triglyceride and its gasoline blends in general had the distinct “double-hump” characteristic for the heat release rate.Diesel fuel had a maximum heat release rate of 0.088 kJ/Deg at about 9.5 degrees aTDC while 100% triglyceride a 1^{st} maximum heat release rate of 0.062 kJ/Deg at about 6.5 degrees aTDC and a 2^{nd} peak heat release rate of about 0.071 kJ/deg at 14.5 degrees aTDC.

Figure 4-11A shows the heat release rates of 5 and 10% gasoline TGBs. Since the percentage of gasoline blended is low, the heat release rates exhibit the same trends as 100% triglyceride and are slightly higher than diesel. For 5% gasoline TGB, the 1^{st} heat release rate peak was around 0.088 kJ/Deg at 6.5 degrees aTDC and the second peak at 0.070 kJ/degrees at 12.5 degrees aTDC. The 10% gasoline TGB had 1^{st} heat release rate peak around 0.062 kJ/Deg at 6.0 degrees aTDC and the second peak at 0.073 kJ/degrees at 14 degrees aTDC.

Figure 4-11B shows the heat release rates of 25% and 35% gasoline TGBs. The heat release rates show a more pronounced double hump with higher peaks than 100% triglyceride but lower than diesel. pressure traces are lower than 100% triglyceride but generally higher than diesel. For 25% gasoline blend, the 1^{st} heat release rate peak was around 0.080 kJ/Deg at 8.0 degrees aTDC and the second peak at 0.082 kJ/Deg at 13 degrees aTDC. The 35% gasoline TGN had the 1^{st} heat release rate peak about 0.083 kJ/Deg at 8.0 degrees aTDC and the second peak at 0.084 kJ/Deg at 13 Deg aTDC.

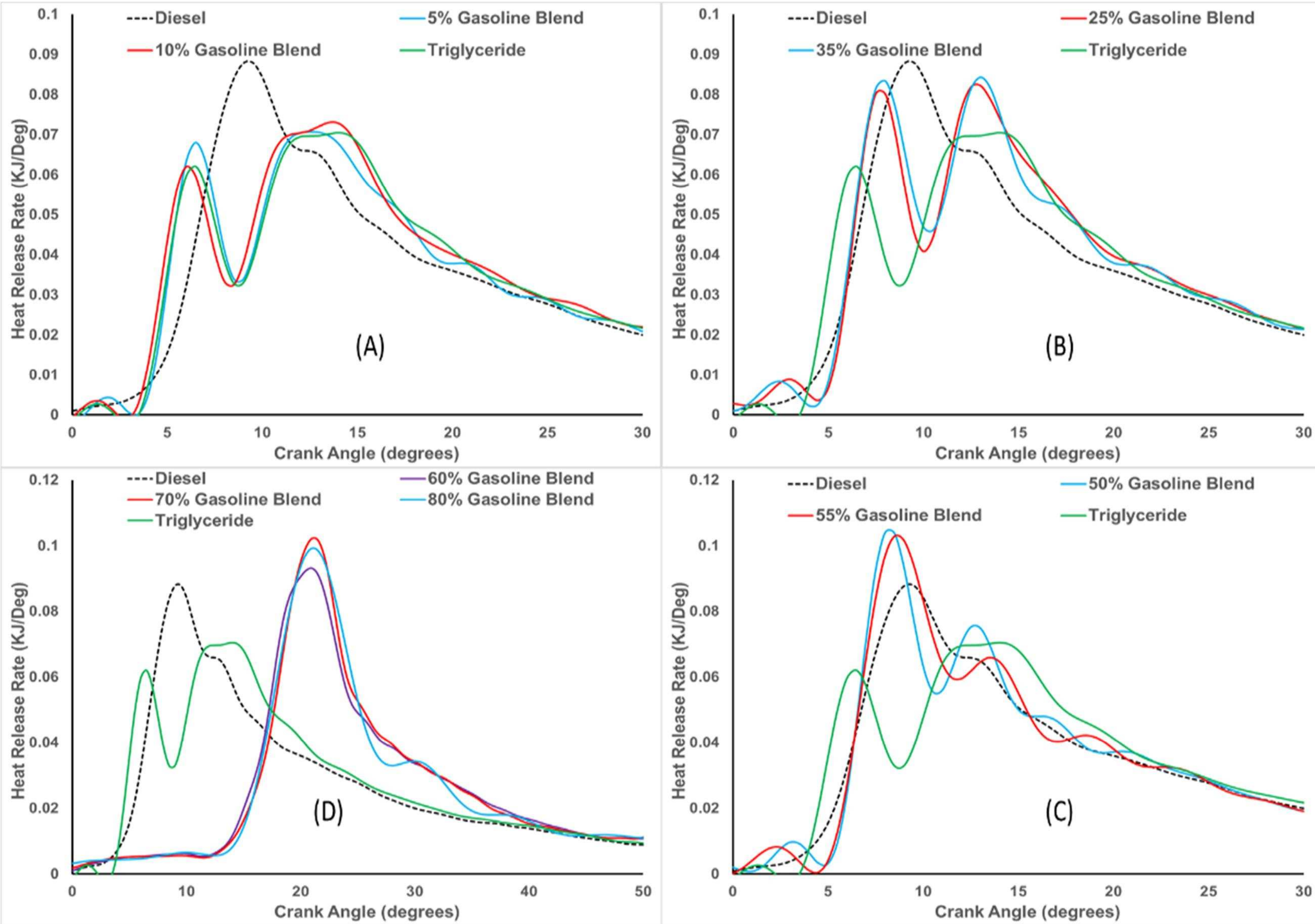


Figure 4-11: Heat Release Rate at 1700 rpm and 50% Load

Figure 4-11C shows the heat release rates of 50% and 55% gasoline TGBs. The heat release rate contours are similar to that of diesel. The 1st of the double humps are significantly higher than diesel, while the second is a lot lower than the 1st. For 50% gasoline blend, the 1st heat release rate was around 0.104 kJ/Deg at 8.0 degrees aTDC and the second at 0.075 kJ/degrees at 13 Deg aTDC. The 55% gasoline TGB had the 1st heat release rate peak around 0.101 kJ/Deg at 9.0 Deg aTDC and the second peak at 0.064 kJ/Deg at 14 Deg aTDC.

Figure 11D shows the heat release rates of 60, 70 and 80% gasoline TGBs. The heat release rate has one maximum peak similar to that of diesel, is higher than diesel and occurs at a much later stage in the cycle. For 60% gasoline blend, the maximum heat release rate was around 0.093 kJ/Deg at 21.5 degrees aTDC, 0.101 kJ/Deg at 21.5 degrees aTDC for 70% gasoline and 0.099 kJ/Deg at 21.5 Deg aTDC for 80% gasoline blend. Similar trends are observed in other researches involving triglycerides[94] The double hump characteristics and the delayed heat release can been seen in the presure traces and the location of peak pressures as discussed in Figure 4-8 and 4-9.

Figure 4-12 shows the mass fraction burnt rate averaged over 1000 cycles for different TGBs compared to diesel and triglyceride. Diesel fuel had a location of 10% mass fraction burnt at about 8 degrees aTDC and a 90% mass fraction burnt at around 55 degrees aTDC. 100% triglyceride had a start of combustion at around 7.5 degrees aTDC and a 90% mass fraction burnt at approximately 54 degrees aTDC.

Figure 4-12A shows the mass fraction burnt of 5 and 10% gasoline TGBs. Since the percentage of gasoline blended is low, the mass fraction burnt data exhibit the same trends as 100% triglyceride. It takes a little longer in terms of crank angle degrees for the triglyceride gasoline blends to achieve about 60% mass fraction burned as diesel, after which it follows the same trend as diesel.

Figure 4-12B shows the mass fraction burnt of 25 and 35% gasoline TGBs. The gasoline blends generally burn faster than 100% triglyceride. From the start of combustion to about 45% mass fraction burnt, the TGBs were slower than diesel, but after 45% mass burnt fraction, the TGBs burnt faster than diesel.

Figure 4-12C shows the mass fraction burnt of 50 and 55% gasoline TGBs. The TGBs generally burnt faster than diesel. From the start of combustion to about 45% mass fraction burnt, the TGBs were similar to diesel, but after 45% mass burnt fraction, the TGBs burnt faster than diesel.

Figure 4-12D shows the mass fraction burnt of 60, 70 and 80 gasoline TGBs. The start of combustion for these blends were about 17.5 degrees aTDC, which indicates a much slower start of combustion than diesel and 100% triglyceride. However, after the start of combustion, the triglyceride gasoline blends burnt much faster to complete combustion around the same time as diesel.

Figure 4-13 shows the average 0 to10% and 10 to 90% burn durations over 1000 cycles. The average 0-10% burn durations for diesel and triglyceride are 5.6 and 9.4 crank angle degrees, respectively. The average 10-90% burn durations for for diesel and triglyceride are 44.7 and 42.8 crank angle degrees, respectively.

For a mass fraction burn duration of 0 to 10%, the TGBs were generally higher than diesel. For lower percentage of gasoline (5% to 20%), the 0-10% burn duration was closer to triglyceride. As the percentage of gasoline increases (35 to 55%), the 0-10% burn duration was shorter and closer to diesel.

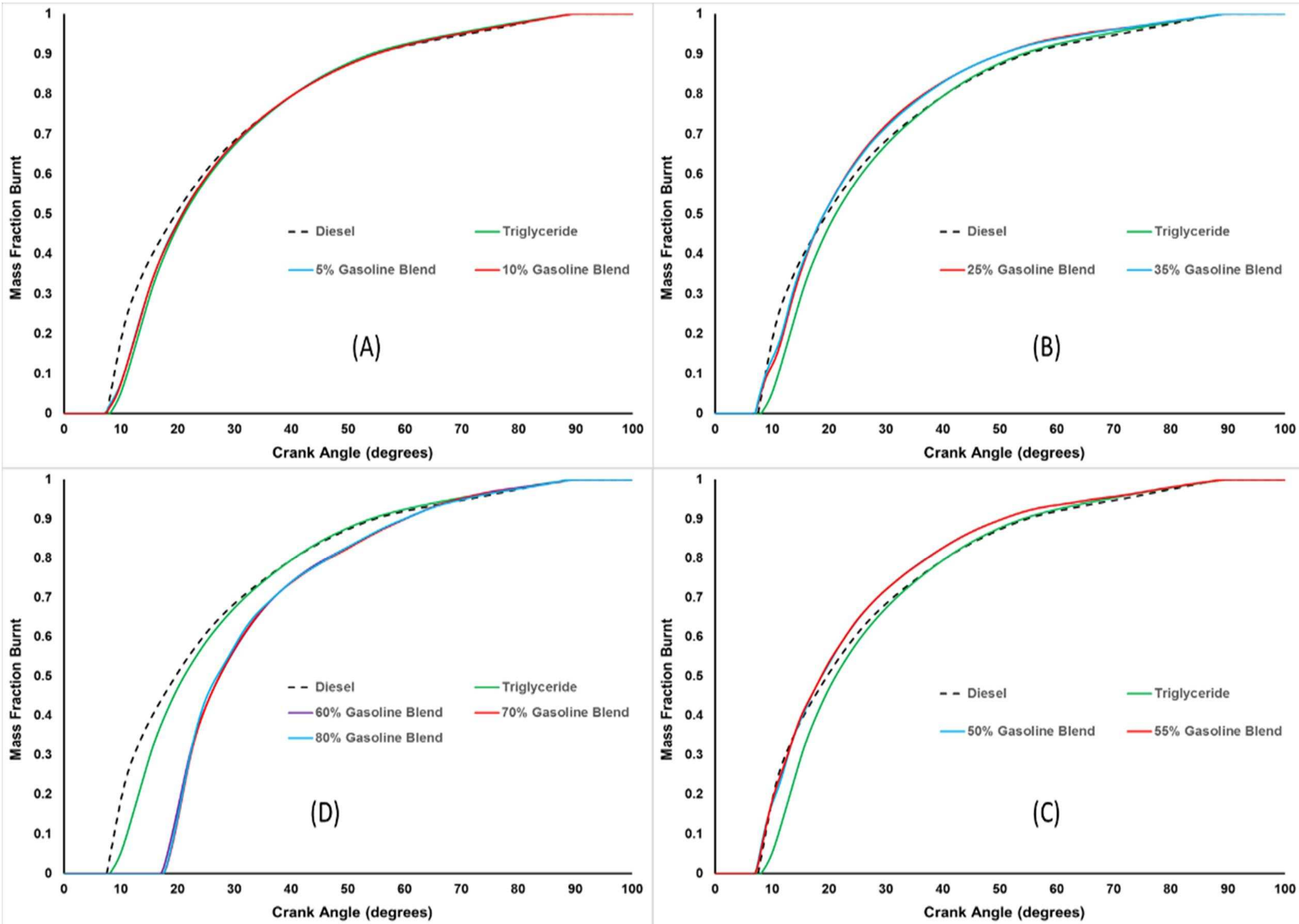


Figure 4-12: Mass Fraction Burnt at 1700 rpm and 50% Load

For higher percentage gasoline, 60, 70 and 80%, the 0-10% burn duration was around 16 crank angle degrees, which is significantly larger than diesel and triglyceride. For a mass fraction burn duration of 10 to 90%, the TGBs were generally lower than diesel. For lower percentage of gasoline (5 to 20%), the burn duration was closer to diesel. As the percentage of gasoline increases the burn rate increases resulting in shorter duration to reach 90% mass fraction burnt. Triglycerides containing more than 35% gasoline content had a burn duration less than 100% triglyceride and diesel.

Figure 4-14 shows the average location of 50% mass fraction burnt (BMF) in crank angle degrees after the start of injection over 1000 cycles. The error bars are the coefficient of variation from data recorded for location of peak pressures. Since the equipment used to measure both are the same, it is assumed that the error in readings will also be the same. The average location of 50% mass fraction burnt for diesel fuel was 19.4 degrees aTDC while that for 100% triglyceride was 21.17 degrees aTDC.

The average location of 50% mass fraction burnt for TGBs can be divided in three zones. (i) Zone 1 - TGBs containing up to 20% gasoline. The location of 50% mass fraction burnt were closer to 100% triglyceride. (ii) Zone 2 - TGBs containing more than 30% but less than 55% gasoline. The location of 50% mass fraction burnt were closer to diesel. (iii) Zone 3 - TGBs containing 60% or more gasoline. These TGBs had a location of 50% mass fraction burnt around 27 degrees aTDC which is significantly later than diesel and 100% triglyceride. This can be attributed to the later combustion, the double hump phenomena, later location of peak pressure and lower IMEP.

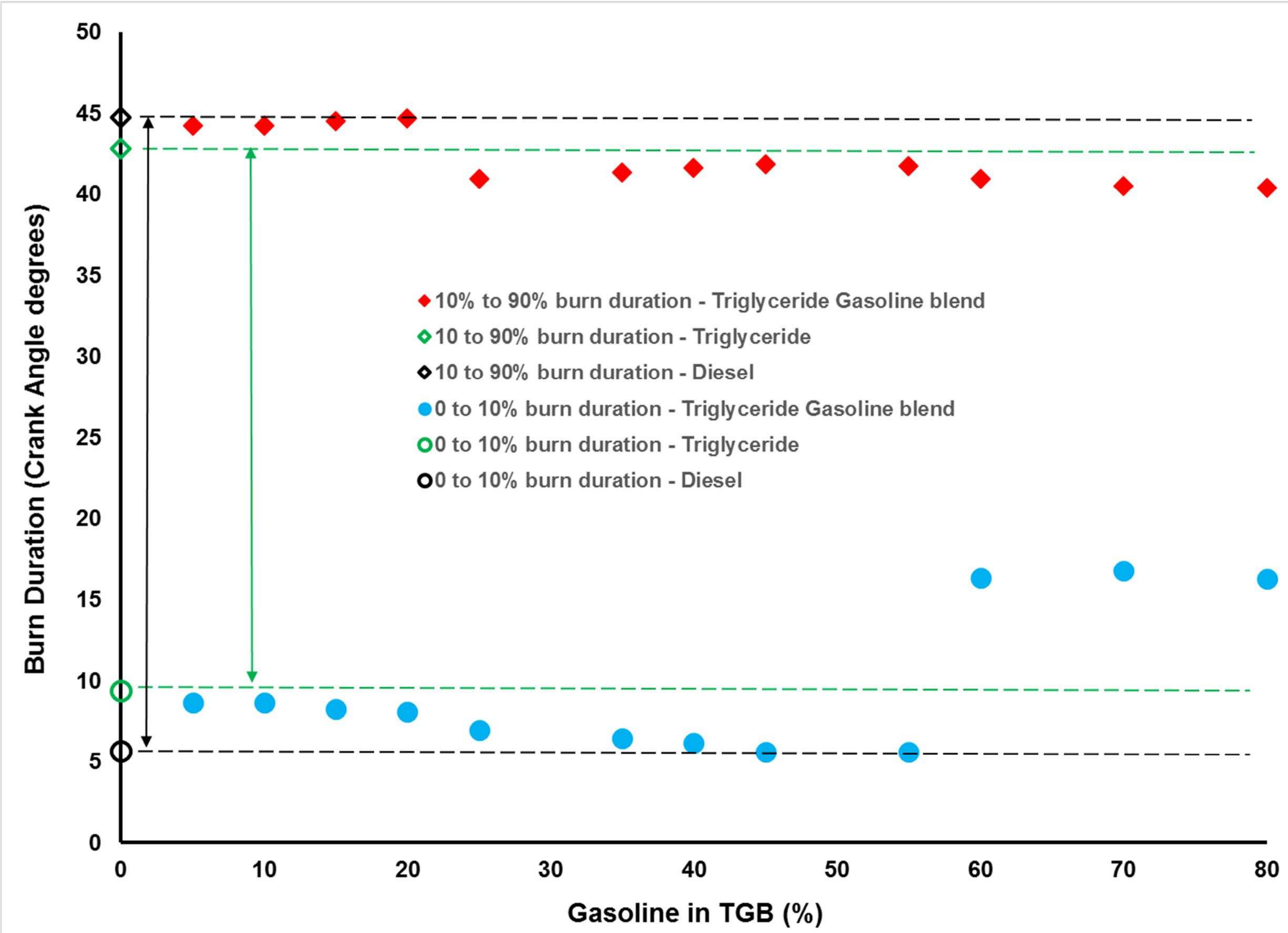


Figure 4-13 Burn duration of Mass Fraction Burnt for Triglyceride Gasoline Blends

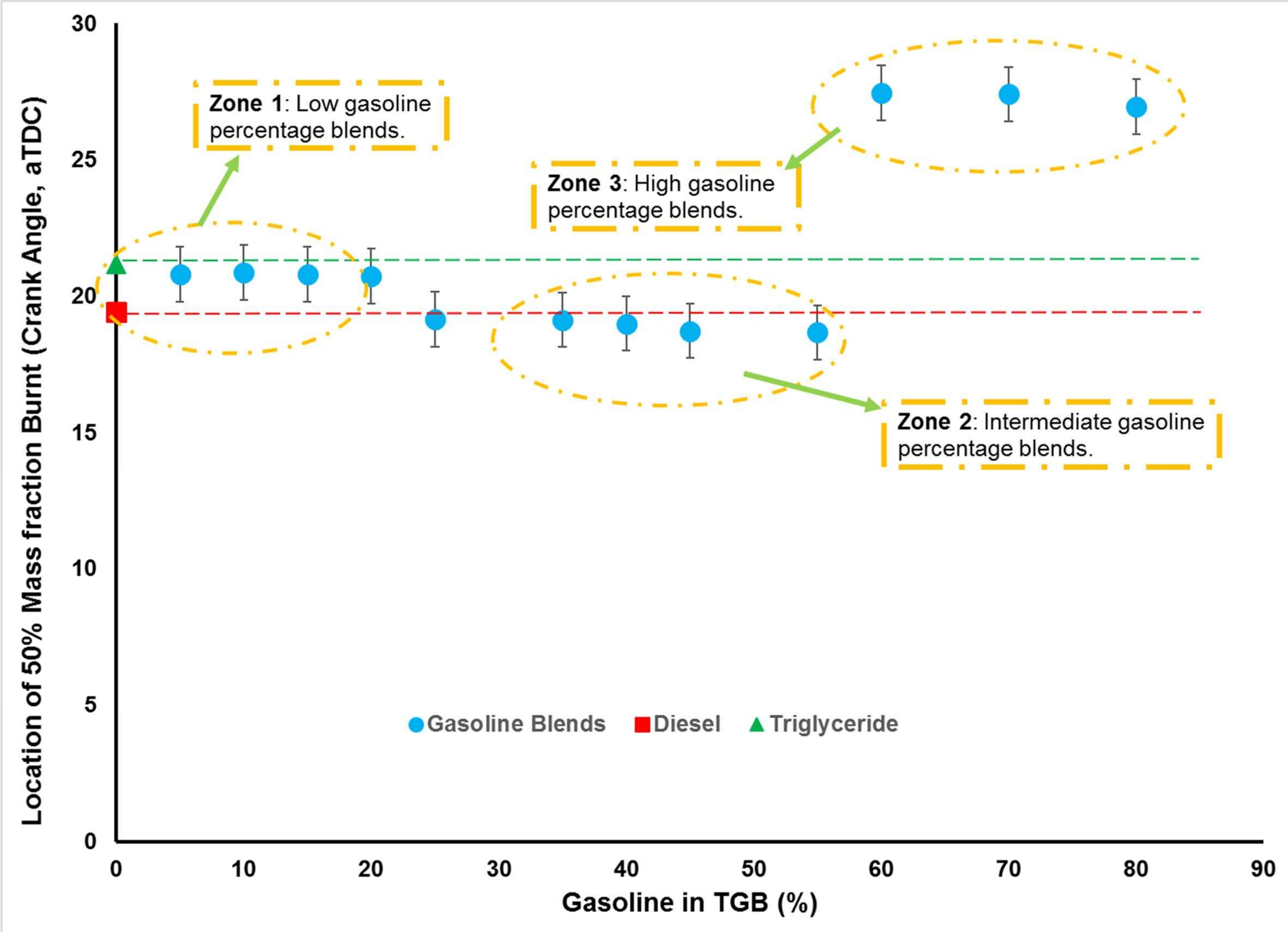


Figure 4-14 Location of 50% Mass Fraction Burnt of Triglyceride Gasoline Blends

Figure 4-15 shows the average actual brake specific fuel consumption and amount of fuel demanded by the engine's ECU. The uncertainty bars for the brake specific fuel consumption correspond to ± one standard deviation. The engine ECU consists of various parameters and maps that are optimized for diesel operation. Over the complete engine operation points (speed and torque), the ECU directs the electronically controlled injector to inject a predetermined quantity of fuel injected. This is normally done by controlling the time for which the injector opens (usually in milli-seconds). Depending on the fuel and its density, the engine autocorrects the injector open duration via a feedback loop to meet the speed setpoint. The brake specific fuel consumption of diesel was 237 g/kW and 100% triglyceride 253 g/kwh. Triglycerides typically have about 20% to 30% lower calorific values than diesel [35, 36]. Gasoline has a calorific value higher than diesel.

As the percentage of gasoline increased in the blend, the brake specific fuel consumption decreased. This trend was observed up to about 35% gasoline, at which the fuel consumption was 225 g/kWh, less than diesel. As gasoline percentage increased beyond 35%, the fuel consumption showed an increasing trend in a range closer to diesel.

Figure 4-16 shows the average brake thermal efficiency of the diesel, 100% triglyceride and the TGBs. The uncertainty bars are ± one standard deviation over the duration of measurement. Thermal efficiency, unlike BSFC, is based on fuel energy and normalizes LHV differences. The thermal efficiency of triglyceride and its gasoline blends were generally higher than diesel. The thermal efficiency of diesel and 100% triglyceride were 35.6% and 38.7%, respectively. The triglyceride-gasoline blends generally had thermal efficiency closer to 100% triglyceride and are consistent with other literatures [10, 18, 19]

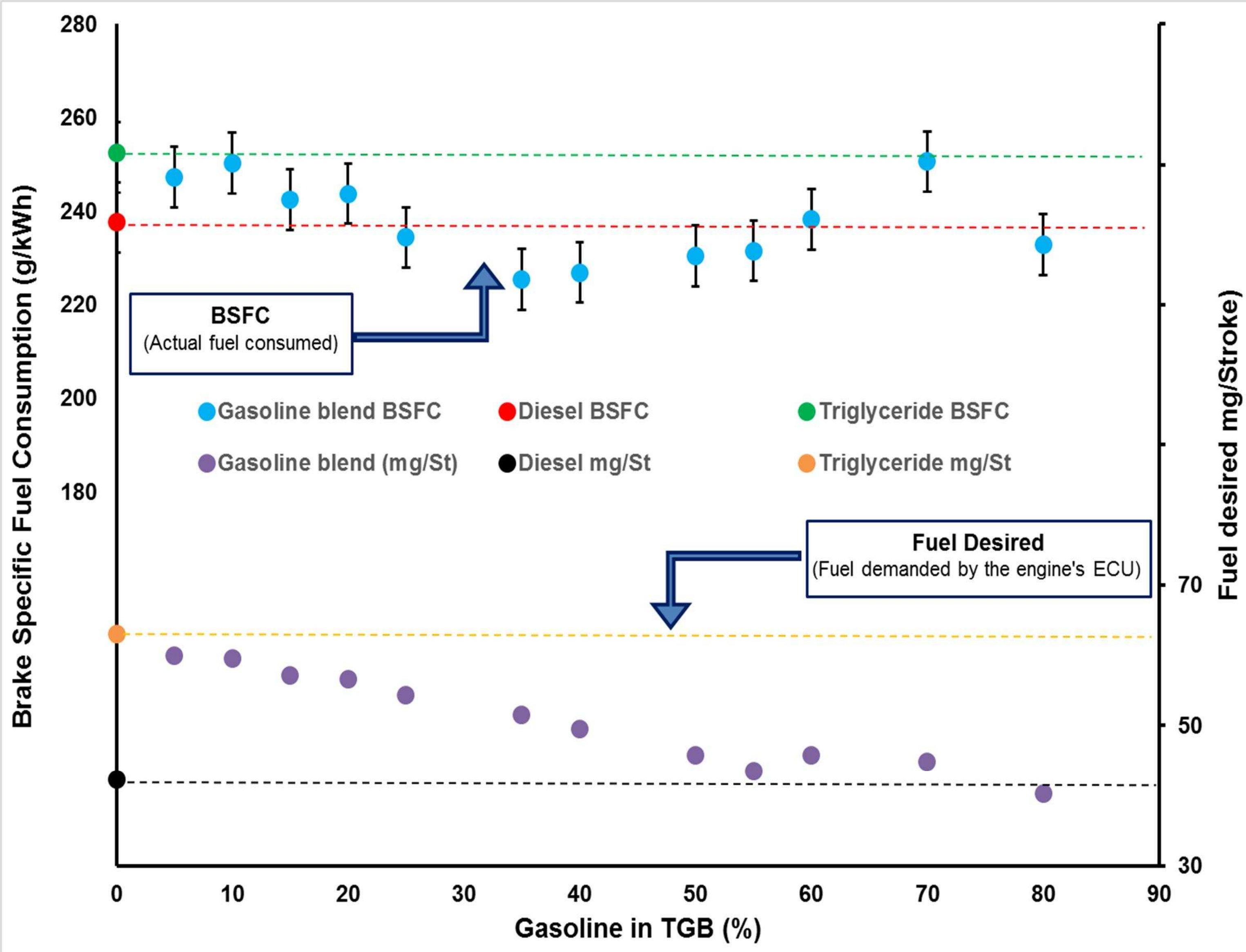


Figure 4-15 Brake specific fuel consumption and ECU fuel demand

Figure 4-17 shows the brake specific THC emissions in the exhaust. In general, for triglyceride and its gasoline blends, there was an overall increase in the unburned hydrocarbons. The uncertainty bars correspond to ± the coefficient of variation for diesel points repeated twice, applied as a percent uncertainty to TGB data. Error bars on subsequent emissions plots are calculated with the same approach. It is assumed that the uncertainty will be the same as diesel for triglyceride and its blends. Diesel fuel and triglyceride had a brake specific THC of 0.277 g/kWh and 0.295 g/kWh, respectively. At the lower gasoline blends (5 and 10%) the THC emissions were closer to triglyceride at 0.289 g/kWh and 0.291 g/kWh, respectively. As the percentage of gasoline the TGB increased, there was an increase in the THC emissions. Both 50 and 55% gasoline TGBs had THC emissions about 0.32 g/kWh.

At higher percent gasoline TGBs, the THC emissions were significantly higher by roughly a factor of 2 compared to both diesel and pure triglyceride. The TGBs containing 60, 70 and 80% gasoline had THC emissions of 0.544, 0.598 and 0.541 g/kWh, respectively. Larger ignition delay is one possible explanation for higher THC emissions for triglyceride gasoline blends. Ignition delay causes localized over-lean mixtures that result in higher THC emissions [37, 38]. Triglycerides and gasoline generally have a lower Cetane numbers [39] compared to diesel. The low Cetane number fuel results in a long ignition delay. The fuel has more time to mix with surrounding air and forms localized pockets of over lean mixture. Localized pockets of over-lean mixture cannot propagate a flame and are separated from the main diffusion flame jet and hence are less likely to burn. If a pocket of over lean mixture escapes combustion the hydrocarbons in that region flow into the exhaust during the exhaust stroke and increase THC emissions.

Figure 4-18 shows the brake specific NOx emissions. In general, triglyceride and its gasoline blends yield a higher NOx emissions compared to diesel with the exception of 60, 70 and 80% gasoline TGBs. Table 4-3 (presented earlier) shows the values of NOx emissions for the fuels at each of the test modes.

Diesel and 100% triglyceride had a brake specific NOx emission of 5.73 and 6.60 g/kWh, respectively. The average NOx emissions for the TGBs up to 55% gasoline were closer to triglyceride and the difference is not very significant compared to the uncertainty bars. For blends containing higher gasoline content (60, 70 and 80%), the NOx emissions were slightly lower than diesel at about 5.0 g/kWh. Figures 8, 9, 12 and 13 show a higher and earlier location of peak pressure, shorter burn duration and faster heat release for diesel. These factors result in higher in-cylinder temperatures, which accelerate the formation of NOx and result in higher NOx emissions[34, 40].

At higher gasoline blend percentages, the heat release occurs much later in the cycle, resulting in lower in-cylinder temperatures at lower peak pressures than diesel as seen in Figure 11. These low in cylinder temperatures do not aid NOx formation. Figure 18 shows substantially larger THC emissions for the higher gasoline blends. In the discussion above, elevated THC emissions are linked to potential over lean zones in the combustion chamber. This also implies the existence of premixed lean zones since the fuel originates in the jet, a fuel rich zone. An explanation for lower NOx emissions at is that a high fraction of the overall heat release comes from lean premixed zones, which inherently have lower NOx formation rates.

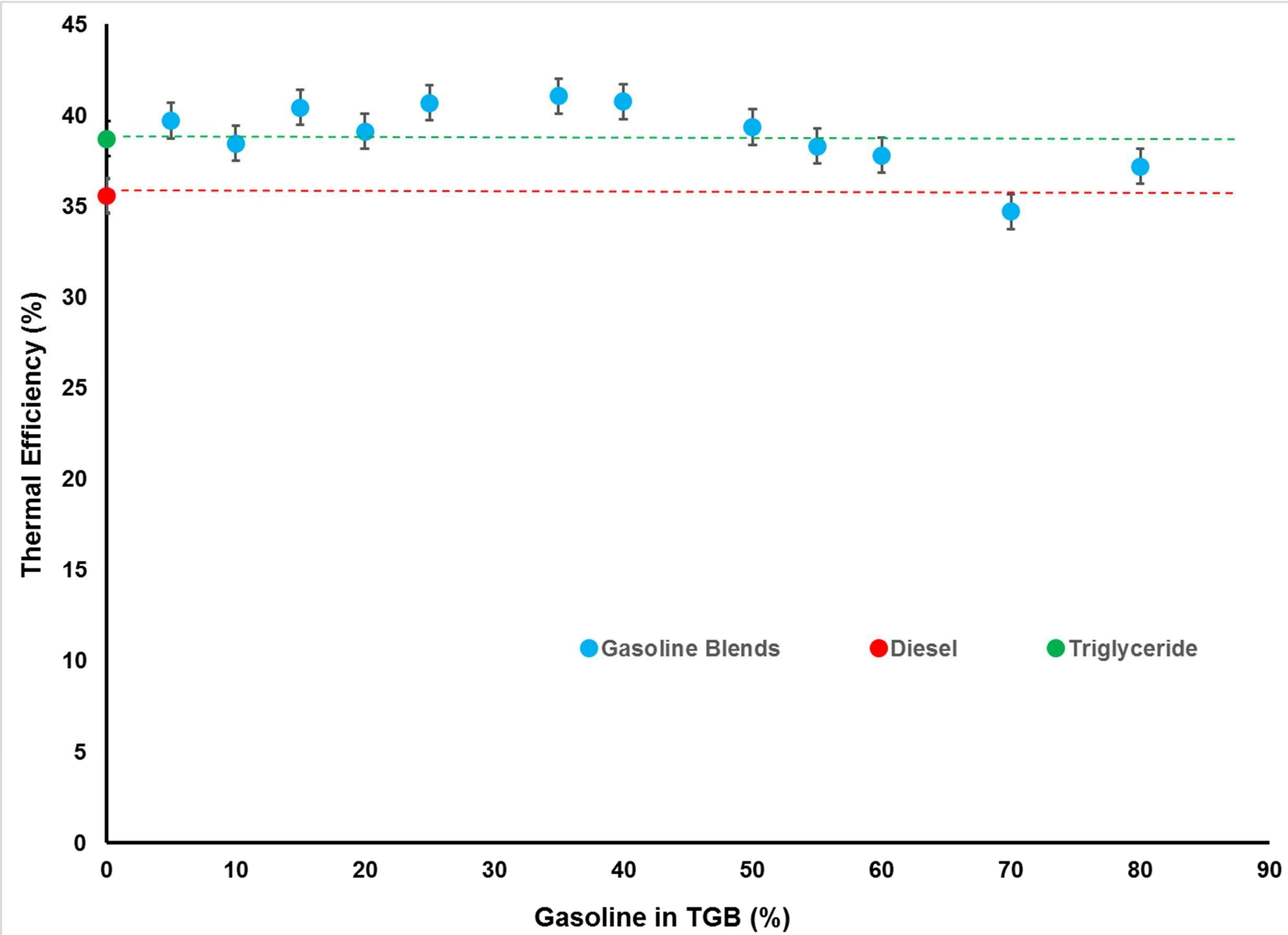


Figure 4-16: Brake Thermal Efficiency of Triglyceride Gasoline Blends

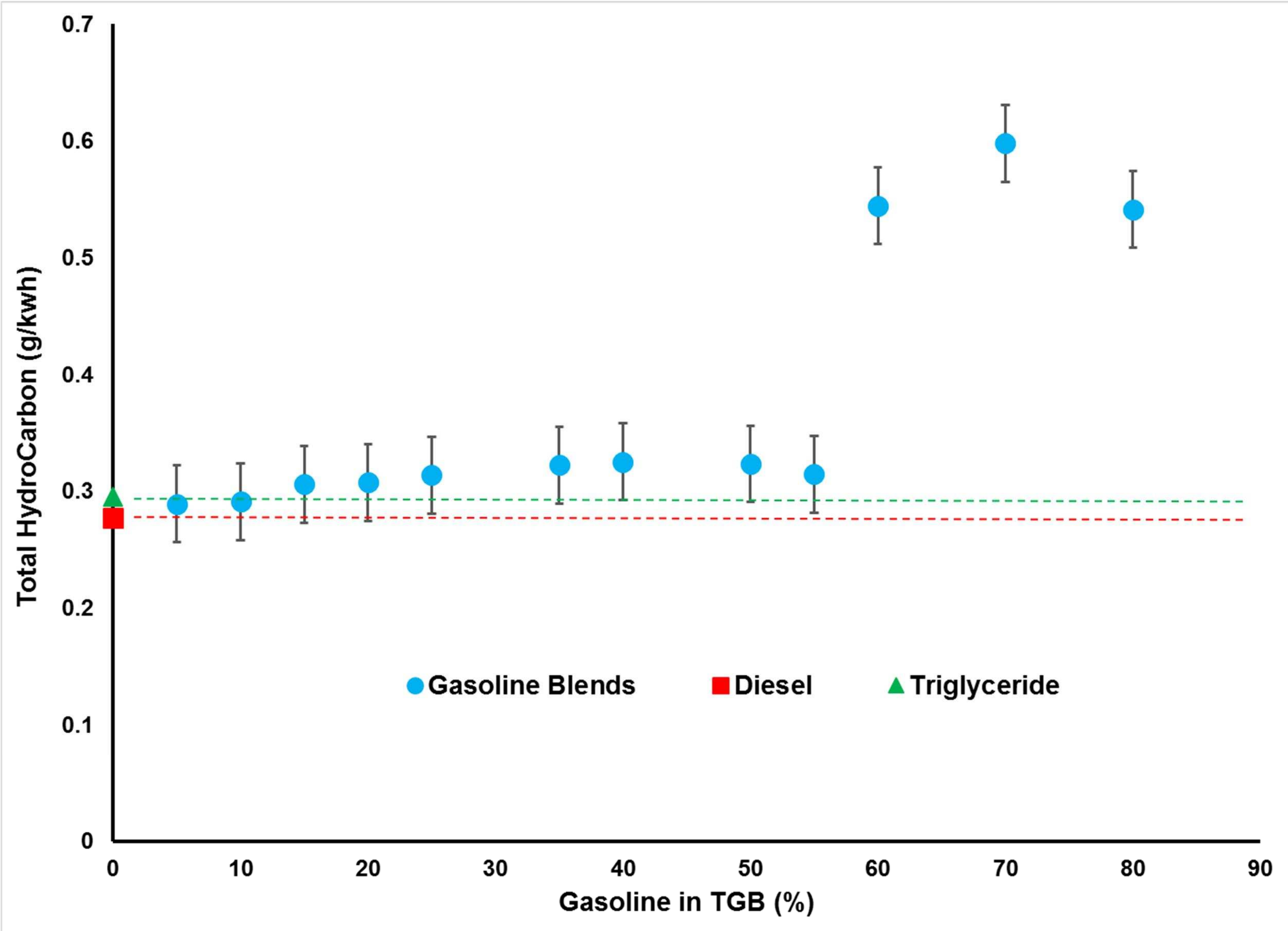


Figure 4-17: Brake Specific Total Hydrocarbon emissions for Triglyceride Gasoline Blends

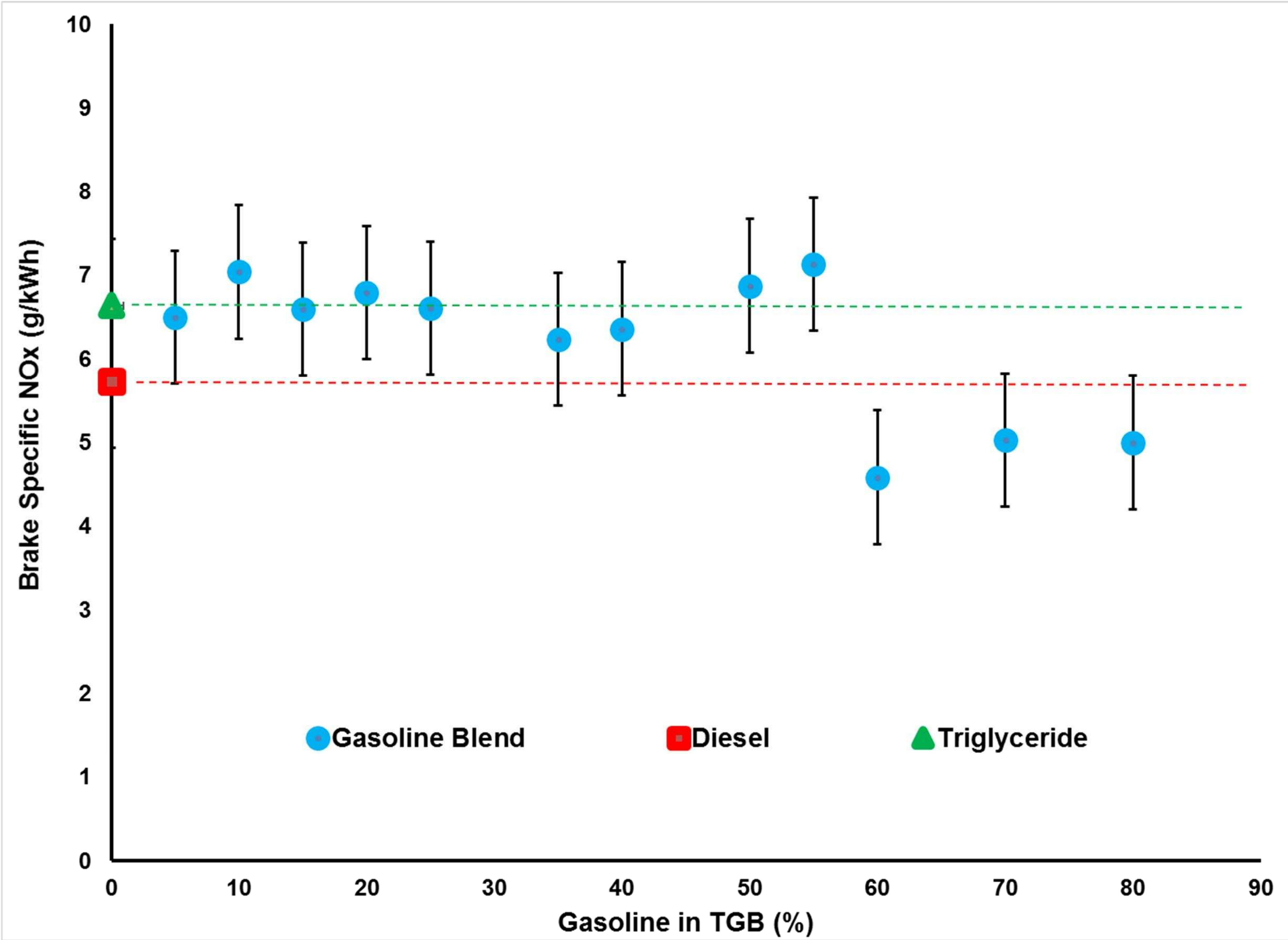


Figure 4-18: Brake specific NOx for Triglyceride Gasoline Blends

Figure 4-19 shows the brake specific particulate (PM) emissions for diesel, triglyceride and its gasoline blends. In general, the PM for triglyceride and its gasoline blends were lower than diesel. Diesel had a brake specific PM emission of 0.11 g/kWh while triglyceride had a PM emission of 0.10 g/kwh.

The 5% gasoline TGB had a PM of 0.099 g/kWh, which is nearly the same as triglyceride. As the percentage of gasoline in the blend increased, a gradual decrease in PM was observed until about 40% gasoline where the PM emissions were 0.014 g/kWh. With further addition of gasoline, the PM emission increased with 70% gasoline blend having an emission 0.77 g/kWh. The 80% gasoline blend had a slightly higher PM emission than both triglyceride and diesel of about 0.13 g/kWh.

Carbonaceous particles generated during combustion are the major constituents of PM. The primary PM generation mechanism is incomplete combustion; lubricating oil contributes a small portion [41]. In general, triglycerides have about 15% to 25% higher PM emissions than diesel [9]. The addition of gasoline, which has a lower molecular weight and is highly volatile hydrocarbon tends to decrease PM, except at high % gasoline TGBs where significant incomplete combustion occurs.

Figure 20 shows the brake specific carbon monoxide emission for diesel, triglyceride and its gasoline blends. In general, triglyceride and its gasoline blends had lower CO emissions compared to diesel with the exception of blends containing more than 55% gasoline. Diesel had a CO emission of 1.34 g/kWh and triglyceride had an emission of 0.982 g/kWh. Triglyceride blends containing gasoline up to 25% gasoline had CO emissions lower than diesel and similar to triglyceride. Blends containing 35% gasoline up to 55% gasoline saw a slight increase in CO emissions compared to triglyceride but were insignificant relative to the uncertainty bars.

Blends containing gasoline above 55% had higher CO emissions than diesel and triglyceride. Triglycerides blended with 60, 70 and 80% gasoline had a CO emission of 1.71, 1.96 and 2.05 g/kWh, respectively. Similar to THC emissions for these points, the increased CO emissions can be attributed to incomplete combustion of over-lean regions. Lower carbon monoxide emissions are commonly observed with the use of triglycerides and biodiesel [18, 19]. Triglycerides contain oxygen, which helps in effective oxidation of carbon monoxide [10, 19].

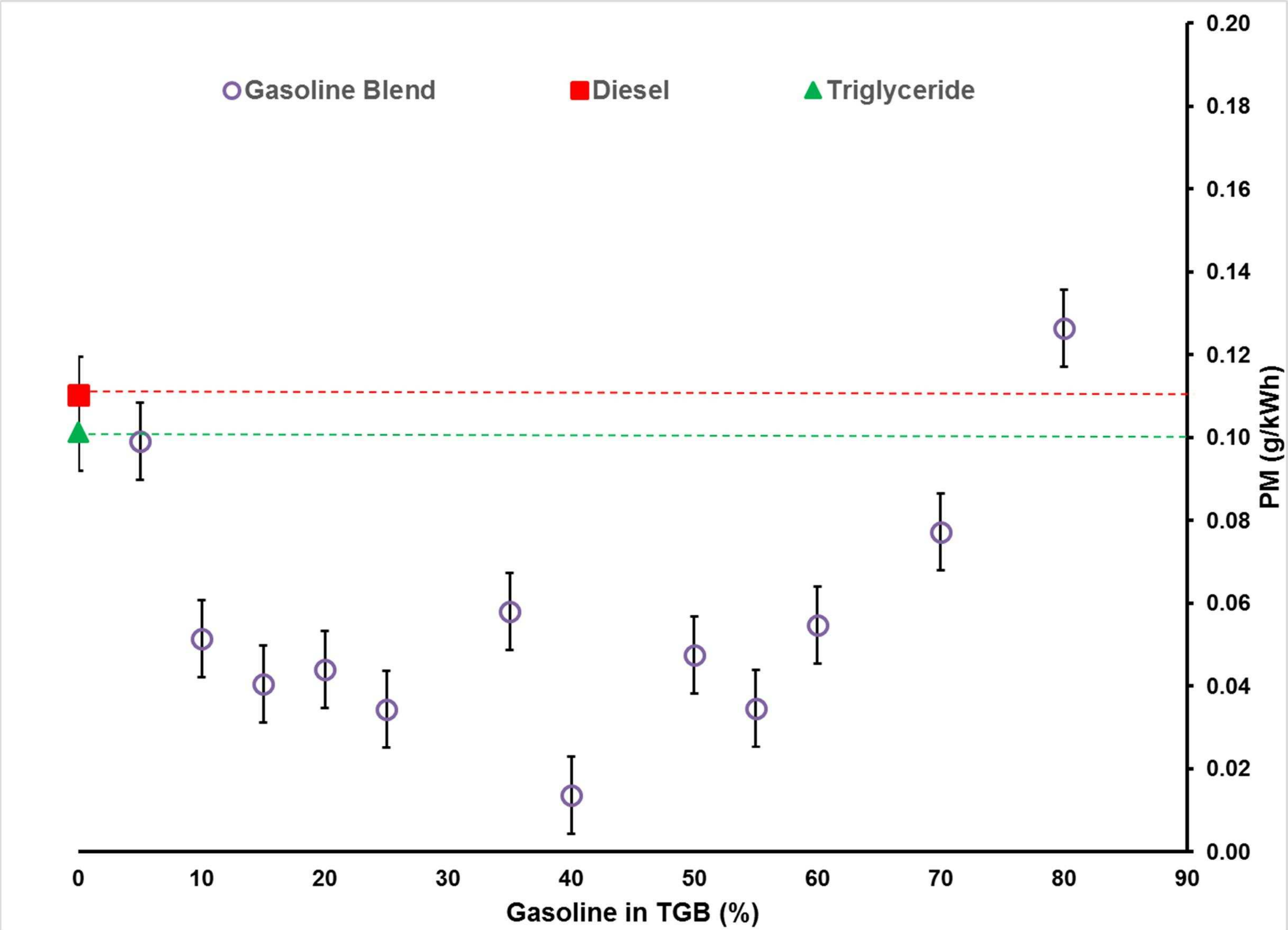


Figure 4-19: Brake Specific Particulate (PM) emissions for Triglyceride Gasoline Blends

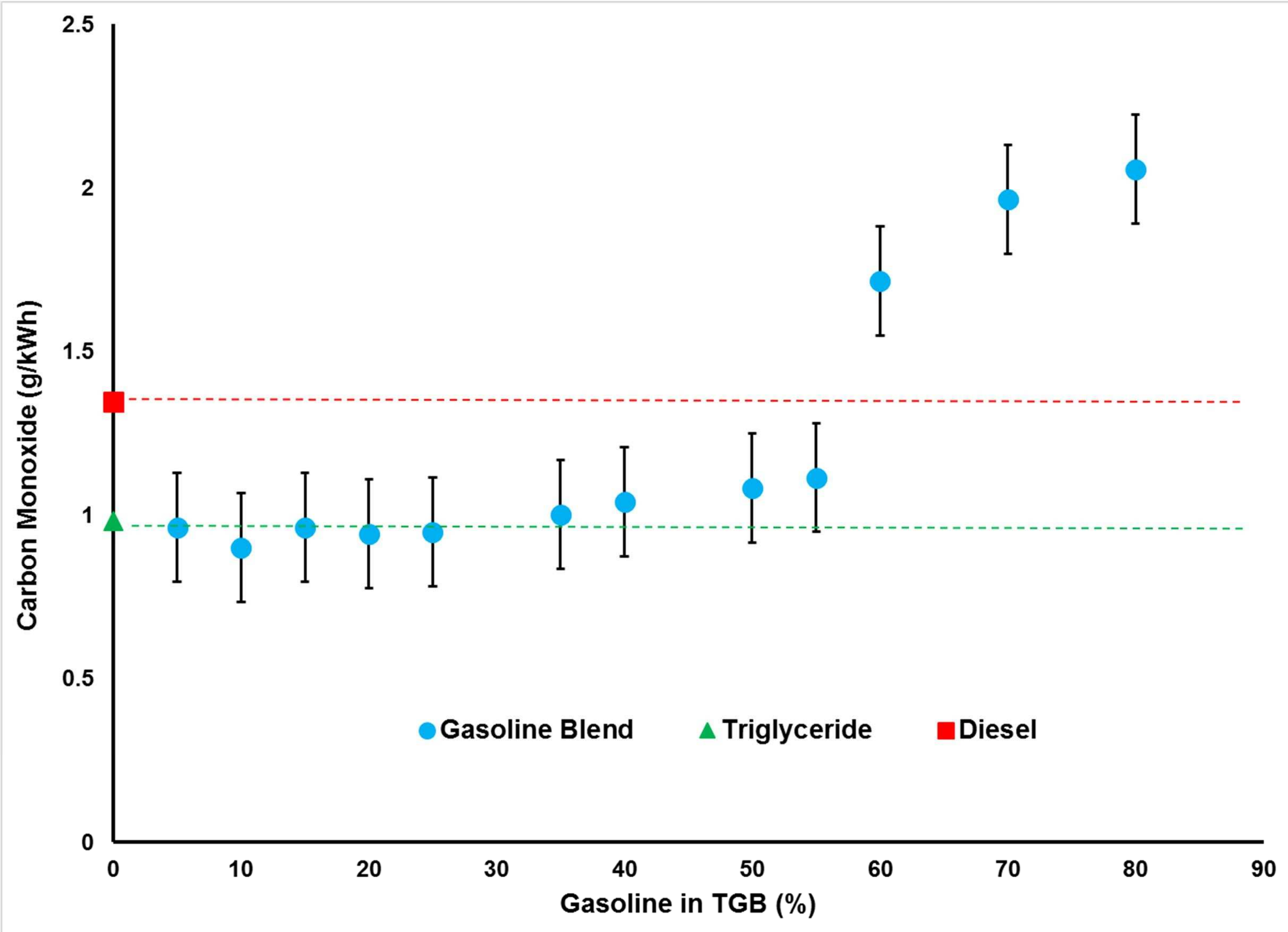


Figure 4-20: Brake Specific carbon monoxide (CO) emissions for Triglyceride Gasoline Blends

4.5 CONCLUSION

In this study, the performance of a blend of untreated triglyceride (canola oil) and regular unleaded gasoline in various percentages, was evaluated. The engine was operated at a speed of 1700 rpm and 50% load for all data points. Nitrogen oxides, particulate matter, carbon monoxide, unburnt hydrocarbons and combustion statistics, including in-cylinder pressure, heat release rate, mass fraction burnt, location of peak pressure, were analyzed and compared to diesel. Engine ECU data for start of injection (SOI), turbocharger speed, intake air pressure and desired fuel quantity were recorded for each fuel blend and compared to diesel. Fuel physical properties including density, viscosity and bulk modulus were also measured.

The physical properties of pure triglyceride can be improved with the addition of gasoline. By blending pure triglyceride with 25 to 35% gasoline by volume diesel-like physical properties were observed. The engine ECU specified engine operating parameters differently for the triglyceride blends than diesel. The turbocharger speed, start of injection and injection duration varied for different triglyceride gasoline blends.

The combustion parameters and exhaust emissions for fuel blends containing lower gasoline content (10% to 20%) were similar to that of 100% triglyceride. As the percentage of gasoline content in the blends increased (25% to 55%), the combustion parameters and exhaust emissions trended closer to that of diesel. Blends containing 60% and higher gasoline content had combustion and exhaust emissions significantly different than diesel. The combustion process occurred with delayed heat release. This explains the difference in exhaust emissions, marked by low NOx emissions and elevated CO and THC emissions.

The results from this work are promising. However, additional work is needed. An ECU calibration could be developed for a select TGB, which would allow a more appropriate comparison with diesel. A long-term study that quantifies the life of engine components would identify potential durability problems with using triglyceride gasoline blends as a fuel. Finally, triglyceride gasoline blends will likely require a different fuel storage system. Proper fuel classification and storage needs to be addressed.

4.6 REFERENCES

[1] F. Cherubini, "The biorefinery concept: Using biomass instead of oil for producing energy and chemicals," *Energy Conversion and Management,* vol. 51, no. 7, pp. 1412-1421, 7// 2010.

[2] R. Saidur, E. A. Abdelaziz, A. Demirbas, M. S. Hossain, and S. Mekhilef, "A review on biomass as a fuel for boilers," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 5, pp. 2262-2289, 6// 2011.

[3] U. S. E. I. A. (EIA), "Sales of Distillate Fuel Oil by End Use,"

U.S. Department of Energy (DOE), Washington, DC, 2012," ed.

[4] S. A. Skalsky, J. J. Jacobs, D. J. Menkhaus, and W. B. Stevens, "Impact of Fuel and Nitrogen Prices on Profitability of Selected Crops: A Case Study," 2008.

[5] M. Hanna, J. H. and, and J. Flammang, "How Much Energy is Used on Your farm?," ed. Iowa State University (ISU) Extension, Ames, IA, 2009.

[6] B. L. Salvi, K. A. Subramanian, and N. L. Panwar, "Alternative fuels for transportation vehicles: A technical review," *Renewable and Sustainable Energy Reviews,* vol. 25, no. 0, pp. 404-419, 9// 2013.

[7] R. D. Misra and M. S. Murthy, "Straight vegetable oils usage in a compression ignition engine—A review," *Renewable and Sustainable Energy Reviews,* vol. 14, no. 9, pp. 3005-3013, 12// 2010.

[8] A. Abollé, K. Loukou, and P. Henri, "The density and cloud point of diesel oil mixtures with the straight vegetable oils (SVO): Palm, cabbage palm, cotton, groundnut, copra and sunflower," *Biomass and Bioenergy,* vol. 33, no. 12, pp. 1653-1659, 12// 2009.

[9] A. Lakshminarayanan, "Testing and performance measurement of straight vegetable oils as an alternative fuel for diesel engines.," Mechanical Engineering, Colorado State University, Fort Collins, 2014.

[10] L. Arunachalam, B. O. Daniel, and E. C. Perry, "Performance and Emission Evaluation of Triglyceride-Gasoline Blends in Agricultural Compression Ignition Engines," vol. 30, no. 4, 2014.

[11] L. M. Rodríguez-Antón, F. Gutíerrez-Martín, and Y. Doce, "Physical properties of gasoline, isobutanol and ETBE binary blends in comparison with gasoline ethanol blends," *Fuel,* vol. 166, pp. 73-78, 2/15/ 2016.

[12] I. Nita, O. Iulian, E. Geacai, and S. Osman, "Physico-chemical Properties of the Pseudo-binary Mixture Gasoline + 1 - Butanol," *Energy Procedia,* vol. 95, pp. 330-336, 2016/09/01 2016.

[13] K. Kim, D. Kim, Y. Jung, and C. Bae, "Spray and combustion characteristics of gasoline and diesel in a direct injection compression ignition engine," *Fuel,* vol. 109, pp. 616-626, 7// 2013.

[14] Y. Liu *et al.*, "Spray development and droplet characteristics of high temperature single-hole gasoline spray," *Fuel,* vol. 191, pp. 97-105, 3/1/ 2017.

[15] W. Yu, W. Yang, and F. Zhao, "Investigation of internal nozzle flow, spray and combustion characteristics fueled with diesel, gasoline and wide distillation fuel (WDF) based on a piezoelectric injector and a direct injection compression ignition engine," *Applied Thermal Engineering,* vol. 114, pp. 905-920, 3/5/ 2017.

[16] X. Li, H. Zhou, L. M. Zhao, L. Su, H. Xu, and F. Liu, "Effect of split injections coupled with swirl on combustion performance in DI diesel engines," *Energy Conversion and Management,* vol. 129, pp. 180-188, 12/1/ 2016.

[17] H. Watanabe *et al.*, "Spray combustion simulation including soot and NO formation," *Energy Conversion and Management,* vol. 48, no. 7, pp. 2077-2089, 7// 2007.

[18] C. D. Aaron, D. Karolien, E. C. Perry, and B. O. Daniel, "Evaluation of Industrial Corn Oil as an On-Farm Biofuel Feedstock," vol. 31, no. 5, 2015.

[19] A. C. Drenth, D. B. Olsen, P. E. Cabot, and J. J. Johnson, "Compression ignition engine performance and emission evaluation of industrial oilseed biofuel feedstocks camelina, carinata, and pennycress across three fuel pathways," *Fuel,* vol. 136, pp. 143-155, 11/15/ 2014.

[20] A. C. Drenth, D. B. Olsen, and K. Denef, "Fuel property quantification of triglyceride blends with an emphasis on industrial oilseeds camelina, carinata, and pennycress," *Fuel,* vol. 153, pp. 19-30, 8/1/ 2015.

[21] M. E. Baumgardner *et al.*, "Combustion of Lignocellulosic Biomass Based Oxygenated Components in a Compression Ignition Engine," *Energy & Fuels,* 2015/09/29 2015.

[22] B. Rajesh Kumar, S. Saravanan, B. Sethuramasamyraja, and D. Rana, "Screening oxygenates for favorable NOx/smoke trade-off in a DI diesel engine using multi response optimization," *Fuel,* vol. 199, pp. 670-683, 7/1/ 2017.

[23] H. K. Imdadul *et al.*, "Evaluation of oxygenated n-butanol-biodiesel blends along with ethyl hexyl nitrate as cetane improver on diesel engine attributes," *Journal of Cleaner Production,* vol. 141, pp. 928-939, 1/10/ 2017.

[24] L. Zhou, M. D. Boot, B. H. Johansson, and J. J. E. Reijnders, "Performance of lignin derived aromatic oxygenates in a heavy-duty diesel engine," *Fuel,* vol. 115, pp. 469-478, 1// 2014.

[25] M. Zhu, Y. Ma, Z. Zhang, Y. L. Chan, and D. Zhang, "Effect of oxygenates addition on the flame characteristics and soot formation during combustion of single droplets of a petroleum diesel in air," *Fuel,* vol. 150, pp. 88-95, 6/15/ 2015.

[26] A. Paar, "Density Meter Instruction Manual DSA 5000 M," ed.

[27] A. Paar, "Viscosity Meter Instruction Manual SVM 3000," ed.

[28] M. Gülüm and A. Bilgin, "Measurements and empirical correlations in predicting biodiesel-diesel blends' viscosity and density," *Fuel,* vol. 199, pp. 567-577, 7/1/ 2017.

[29] B. Tesfa, R. Mishra, F. Gu, and N. Powles, "Prediction models for density and viscosity of biodiesel and their effects on fuel supply system in CI engines," *Renewable Energy,* vol. 35, no. 12, pp. 2752-2760, 12// 2010.

[30] E. Alptekin and M. Canakci, "Determination of the density and the viscosities of biodiesel–diesel fuel blends," *Renewable Energy,* vol. 33, no. 12, pp. 2623-2630, 12// 2008.

[31] D. Kim and C. Bae, "Application of double-injection strategy on gasoline compression ignition engine under low load condition," *Fuel,* vol. 203, no. Supplement C, pp. 792-801, 2017/09/01/ 2017.

[32] J. Liu *et al.*, "Investigation on partially premixed combustion fueled with gasoline and PODE blends in a multi-cylinder heavy-duty diesel engine," *Fuel,* vol. 193, pp. 101-111, 4/1/ 2017.

[33] Y. Jiotode and A. K. Agarwal, "In-cylinder combustion visualization of Jatropha straight vegetable oil and mineral diesel using high temperature industrial endoscopy for spatial temperature and soot distribution," *Fuel Processing Technology,* vol. 153, pp. 9-18, 12/1/ 2016.

[34] S. Bari, T. H. Lim, and C. W. Yu, "Effects of preheating of crude palm oil (CPO) on injection system, performance and emission of a diesel engine," *Renewable Energy,* vol. 27, no. 3, pp. 339-351, 11// 2002.

[35] A. Corsini, A. Marchegiani, F. Rispoli, F. Sciulli, and P. Venturini, "Vegetable Oils as Fuels in Diesel Engine. Engine Performance and Emissions," *Energy Procedia,* vol. 81, pp. 942-949, 2015/12/01 2015.

[36] P. Emberger, D. Hebecker, P. Pickel, E. Remmele, and K. Thuneke, "Ignition and combustion behaviour of vegetable oils after injection in a constant volume combustion chamber," *Biomass and Bioenergy,* vol. 78, pp. 48-61, 7// 2015.

[37] G. Greeves, I. M. Khan, C. H. T. Wang, and I. Fenne, "Origins of Hydrocarbon Emissions from Diesel Engines," 1977. Available: http://dx.doi.org/10.4271/770259

[38] H. Kwon and K. Min, "Modified one-step reaction equation for modeling the oxidation of unburned hydrocarbons in engine conditions," *International Journal of Automotive Technology,* vol. 11, no. 5, pp. 637-650, 2010// 2010.

[39] B. D'Alessandro, G. Bidini, M. Zampilli, P. Laranci, P. Bartocci, and F. Fantozzi, "Straight and waste vegetable oil in engines: Review and experimental measurement of emissions, fuel consumption and injector fouling on a turbocharged commercial engine," *Fuel,* vol. 182, pp. 198-209, 10/15/ 2016.

[40] F. G, M. G, and S. Z, "Experimental evaluation of cottonseed oil-diesel blends as automotive fuels via vehicle and engine measurements," ed. SAE paper 07NAPLES-151. SAE ICE2007 8th International Conference on Engines for Automobile, September 2007.

[41] K. B. Lee, M. W. Thring, and J. M. Beér, "On the rate of combustion of soot in a laminar soot flame," *Combustion and Flame,* vol. 6, pp. 137-145, 1962/01/01 1962.

5. DURABILITY TESTING OF BIODIESEL AND TRIGLYCERIDE GASOLINE BLEND IN A COMPRESSION IGNITION ENGINE

5.1 OVERVIEW

The volatile fossil fuel international markets and the need for energy security has provided a motivation to research alternative transportation fuels. Biodiesel has already been established as an alternative to diesel fuel, but the search continues for cheaper and more readily available diesel substitute. Using untreated oils from freshly crushed oil seeds has gained interest because such oils, unlike biodiesel, do not need refinement and do not undergo any chemical processes. Though oil seeds like canola and sunflower are readily available in the US markets, their untreated oils are highly viscous, exhibit poor flowability and cold start in a diesel engine. Previous studies involved examining the in-cylinder pressure, heat release and exhaust emissions of using untreated SVOs and SVOs blended with diesel and gasoline in varying quantities in an off-road engine. However, little is known about the long-term effects of these compounds on engine durability issues such as the impact on fuel injection, in-cylinder carbon buildup, and engine oil degradation. In this study, three fuels – (i) off road diesel, (ii) canola based bio diesel, and (iii) a canola based triglyceride-gasoline blend were tested. The durability testing protocol devised for this work consisted of 250 hours of testing in a stationary, single-cylinder, Yanmar diesel engine operating at constant load. Oil samples, injector spray patterns, and carbon buildup from the injector and cylinder surfaces were analyzed and compared for the three fuels.

5.2 INTRODUCTION

Fuel costs comprise of a major portion of farm enterprise budget, turning farmers to look for alternative fuels that are lower cost and compatible with their farm equipment.

Internationally, many countries have mandated the gradual replacement of fossil fuels with renewable energy. In the US alone, Renewable Fuel Standard – II mandates the substitution of 22 billion gallons of transportation fuel by alternative renewable fuels[1]. Plant based straight vegetable oils (SVOs) can be produced by crushing oil seeds.

Biodiesel is produced by processing SVOs chemically known as transesterification. This process requires chemical and thermal energy input, hence making the localized production of biodiesel in rural settings challenging and cost ineffective. Studies evaluating the use of untreated SVOs from canola, sunflower and camelina as fuel are generating wide interests amongst the farming and research communities. For example, a study showed that camelina could be used as an oil seed crop that could offset the use of on farm diesel thus making it economically feasible for farmers to use their own crop[2].

In our previous work[3-8] different fuels – diesel, various SVOs, triglyceride gasoline blends were tested in tier 2 and tier 3 diesel engines uses for off road farm machinery. Detailed analysis of the physical properties, in-cylinder combustion statistics, heat release rates and exhaust emissions were conducted. For these fuels, the performance and emission results indicated a variety of results ranging from being poor to being almost the same when compared to the standard baseline diesel fuel. Also, the physical properties of such fuels were significantly different than diesel and biodiesel and the amount of contamination in the fuels exceeded the limits set by ASTM D6751-12[6].

The concluding results of these engine tests showed that the physical properties of triglycerides could be improved by blending small amounts of fossil fuels and the exhaust emissions from such engines can be lowered by calibrating the engine differently.

However, there is a lack of information about the long-term effects of these compounds on engine durability issues such as the impact on fuel injection, in-cylinder carbon buildup, and engine oil degradation.

While little information is available on the durability impact of pure triglycerides derived from crushing oil seeds, there have been several studies done assessing the long-term durability effects of using biodiesels or its blends with diesel. The results of such studies showed higher wear metals than diesel[9, 10] in some cases while others showed lower wear metals than diesel[11, 12]. Similarly, deterioration of lubricating oils and effects on the injector spray pattern have been observed and studied[13-15]

5.3 FUEL PREPARATION

For this study, off road diesel was procured from a local gas station in 55 gallon drums. Canola based biodiesel was procured from a farmer in Stratton, Colorado. The farmer has an on-site biodiesel production facility where he makes his own biodiesel from canola oil seed crop. Canola based triglyceride was procured from farmers in Rocky Ford, Colorado, who have been using a blend of canola triglyceride and gasoline in their farm equipments. More information on the fuels can be found in previous sections chapter 2, chapter 3 and chapter 4 and in literatures[6, 8].

5.4 EXPERIMENTAL METHODS

Each of the three fuels were tested in a single-cylinder Yanmar TF140E engine coupled to a 3-phase 240 VAC generator at 60 Hz as shown in Figure 5-1. This engine is naturally-aspirated with a displacement of 0.76 liters, a compression ratio of 17.7:1, a mechanical fuel injector, and a sea-level rating of 9.2 kW at 2400 rpm. For the current testing, the engine was de-rated to 4.5 kW at 1800 rpm for continuous operation at high-altitude; the laboratory is at an elevation of 5000 ft above sea-level.

Engine specifications are listed in Table 5-1, while further details can be found in other publications [16-18]. Each fuel was tested for 10-15 hr intervals on consecutive days for a total of 250 hrs. This process allowed for multiple start-up and shutdown events, which simulates the engine operation on a farm. The specific gravity, viscosity, and LHV of the blended fuel, are shown in Table 5-2.

At the start of each test the engine was filled with fresh Shell Rotella 15W40 oil. A lubricating oil sample was collected every 50 hr and analyzed by a local Caterpillar dealer (www.wagner equipment.com) laboratory. The oil was tested for viscosity (ASTM D445), oxidation, sulfation, as well as a comprehensive wear metals analysis (ASTM D5185). After each sample was taken, the engine crankcase was topped-off with fresh Shell Rotella 15W40 oil.

Once each test was completed, the fuel injector and cylinder head were removed. Photographs were taken of both the injector and piston face for qualitative analysis of carbon deposits. The camera was focused on the injector tip so as to get a clear image of the injector nozzle holes and the carbon build up around them. The injector was then subjected to a spray test with the respective test fuel via a manual diesel injector pop-tester under ambient conditions. Spray image sequences were taken with a high-speed 10 bit CMOS camera (PCO 1200s) operating at 1000 fps as seen in Figure 5-2.

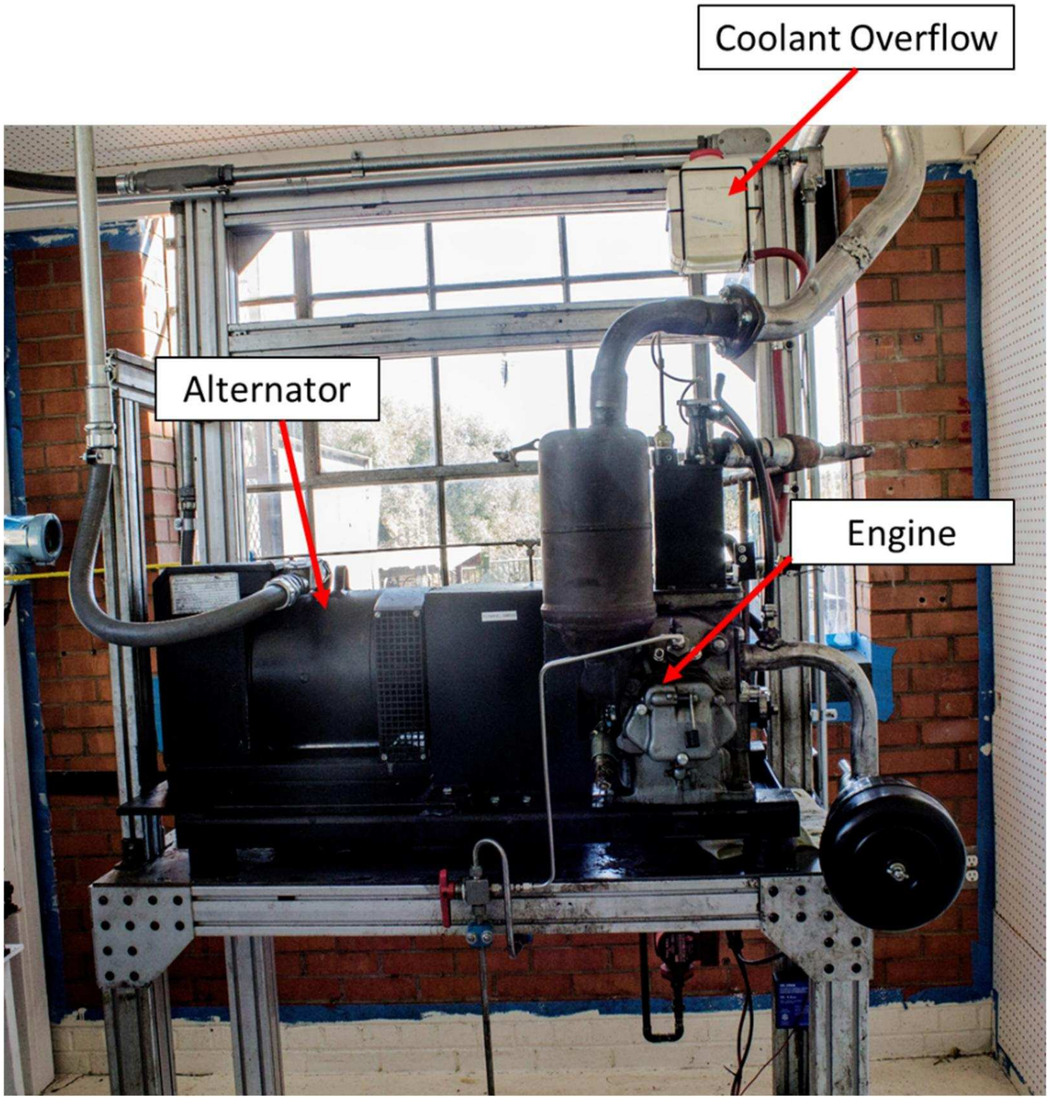


Figure 5-1: Engine-Generator Set Up

Table 5-1: Engine Specifications

No. Cylinders	1
Cylinder orientation	horizontal
Bore x Stroke [mm]	96 x 105
Displacement [L]	0.76
Continuous Output (derated) [kW]	4.5
Speed [rpm] / frequency (Hz)	1800 / 60 Hz)

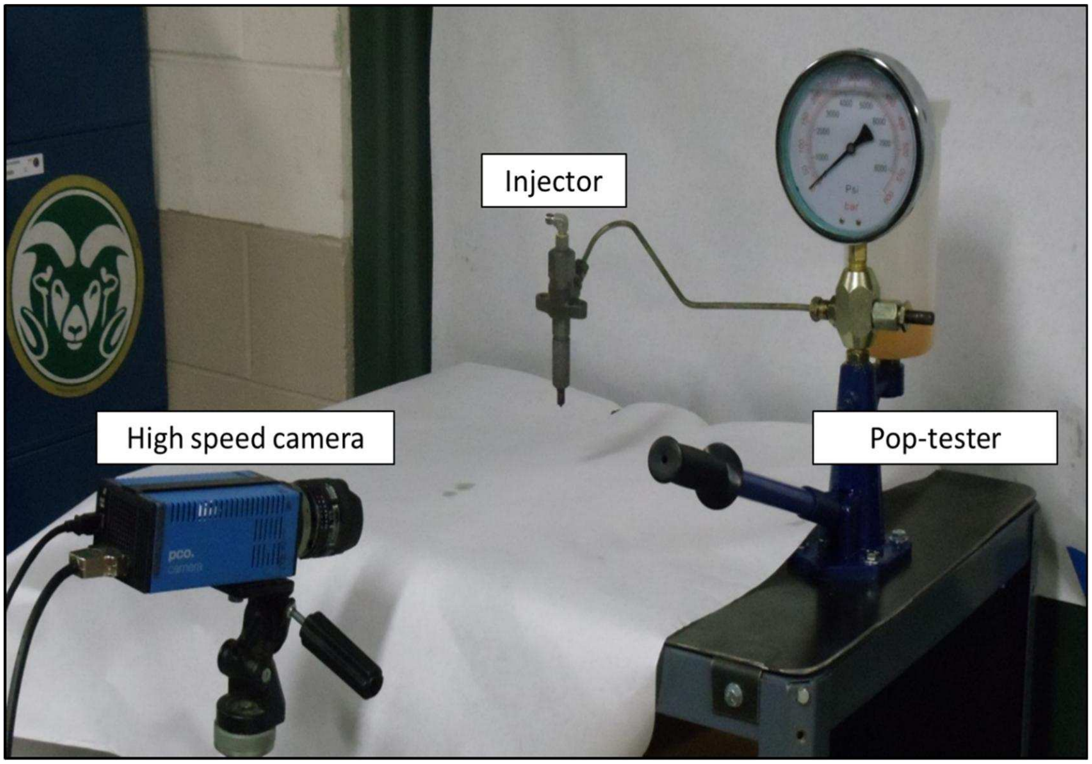


Figure 5-2: Injector pop tester

5.5 DURABILITY RESULTS

The images of the carbon buildup and injector spray are showed in Figure 5-3. It should be noted that the results of canola triglyceride and diesel fuels have been adapted from a previous study done by researchers from the same research group [17, 18]

5.5.1 INJECTORS

Internal deposits in diesel injection systems have been widely studied[19-22]. The internal deposits on fuel injectors reduce the flow of the fuel and distort the designed spray pattern which then impacts the behavior and durability of the injector. In Figure 3 biodiesel seemed to have the least of surface deposition, followed by diesel and canola triglyceride fuels. This is consistent with other studies[23, 24].

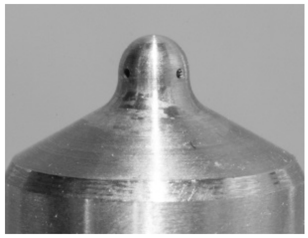
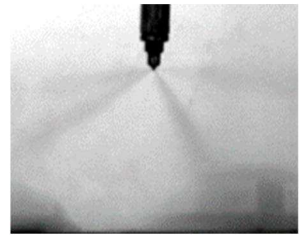
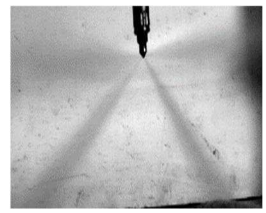
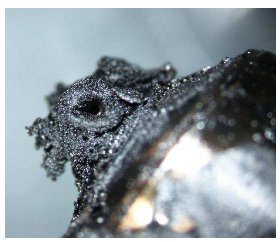
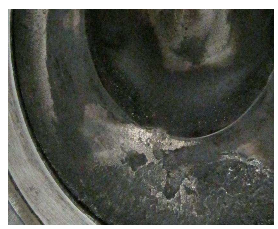
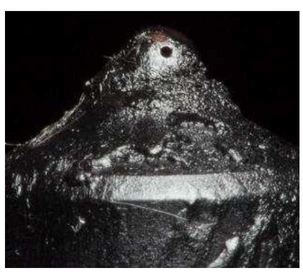
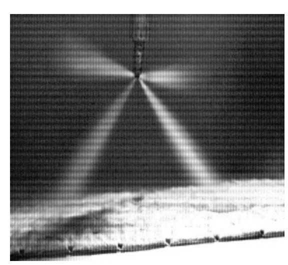
	Injectors	Piston	Spray
Clean			
Diesel			
Canola Triglyceride			
Bio Diesel			
TGB10			

Figure 5-3: Qualitative Analysis: injector, piston crown and injector spray

The TGB10 fuel had significant surface deposition, almost forming a tunnel shape around the nozzle holes. This buildup affects the overall engine performance, noise and durability of other components. The impact of fuel stability along with several physical and chemical parameters can have a significant influence on the nozzle surface condition. The pathways of such formation have not been properly understood though various studies [25-27] have tried to address this. Hence extensive studies are still needed to help understand the buildup and to provide solutions

5.5.2 PISTON CROWN

Carbon deposits on vital components of engine such as cylinder head, piston crown, and injector tip occur due to partial combustion of the fuel and oxidative degradation of lubricants. These deposits result in reduced engine performance, and often lead to an increase in the maintenance cost. Engine failure has also occurred due to a large carbon build up in the piston and cylinder heads. Similar studies have recorded that biodiesel has had less deposition on piston crown[11, 24]. The carbon deposits of the test using diesel fuel was evenly distributed throughout the piston surface and had a smooth texture. The usage of biodiesel rendered a matt type surface on the piston crown and the deposits were also evenly distributed. TGB10 fuel left an impression of dried sludge formation on the piston crown, which peeled off like paint during the cleaning process. Canola triglycerides constitutes for 90% of TGB10. Canola triglycerides, contains about 11% saturated fatty acids, 41% mono unsaturated fatty acids and 48% polyunsaturated fatty acids. These fatty acid compounds, in addition to being viscous, do not combust efficiently in the combustion chamber and could be the cause of deposit formation. [7, 24]

5.5.3 INJECTOR SPRAY PATTERN

A good spray pattern is essential for efficient combustion of the fuel. Fuel properties like density and viscosity strongly affect the operation of the injectors and their spray pattern. In Figure 3, the spray pattern of TGB10, diesel and clean injectors look similar to the naked eye, but the spray cone angle for biodiesel seems to be a smaller. Similar results have been observed in other researches who concluded that the injector body temperature, viscosity and lower surface tension of biodiesel could potentially result in broken spray pattern and affect the injection [28] [29, 30].

5.6 LUBRICATING OIL ANALYSIS

The lubricating oil of engines plays an important role in keeping the engine in good operating condition by cooling engines, reducing abrasion of engine components due to friction and eliminating corrosive agents [31, 32]. The lubricating oil degradation is one of the major contributor for engine wear and tear. The combustion gases in the combustion chamber contaminate the lubricating oil by leaking past the piston rings and coming in contact with the lube oil in the crankcase. This causes the lube oil to oxidize and form solid deposits over a period of time, which changes its viscosity and impairs the engine performance in the long run[16-18].

In this study, lubricating oil samples were taken every 50 hrs and sent to a local Caterpillar Dealer, Wagner Equipment, for elemental analysis. Wear metals and trace elements were reported in parts per million (ppm) for copper, iron, chromium, aluminum, lead, tin, silicon, sodium, potassium, boron, molybdenum, nickel and silver using an Inductively Coupled Plasma Spectrometer ICP and ASTM method D5185. The engine soot, oxidation, sulfation, and nitration levels were tested using the JOAP method for FTIR, ASTM E2412.

The kinematic viscosity tests were run at 100 degrees Centigrade, ASTM method D445. Fuel dilution was determined by gas chromatography, using ASTM method D7593 while Water contamination was determined by a crackle test[33].

5.6.1 PHYSICAL PROPERTIES OF LUBE OIL

Figure 5-4 shows the variation of lubricating oil viscosity, soot concentration, lube oil sulfation and oxidation over the duration of the test run. For canola triglyceride testing, only the 250-hour lubricating oil analysis was available. In general, a 20 ct/ml increase in oxidation, sulfation and soot levels in lube oil signals the time to change the oil[34]

Figure 5-4 (a) shows the kinematic viscosity of the lube oil over a period of 250 hours. The kinematic viscosity is one of the most essential factors in evaluating the life of engine lubricating oil. Higher viscosities indicate lubricating oil deterioration from either oxidation or contamination, while a decrease in viscosity suggests dilution of the lubricating oil with liquids such as fuel or engine coolant. For a lubricating oil, the viscosity increase by 20%, or decrease by 10% signals the time to replace the oil[13]. To enhance the lubricating properties and prolong life, antioxidant and anti-corrosion additives are added to it. These additives activate at different times during the engine operation depending on the combined effect of pressure, temperature on friction components.

Lubricants are known to undergo tribochemical reactions rather than creating the protecting film using the additives, which results in faster viscosity degradation compared to rest of the operating period[9, 35]. The kinematic viscosity of fresh lube oil was 12.3 cSt. At the end of 250 hours of diesel fuel test run, the viscosity of the lube oil was about 14.4 cSt, which was a slight increase. The viscosity of lube oil during the TGB10 run was slightly lower than fresh lube oil.

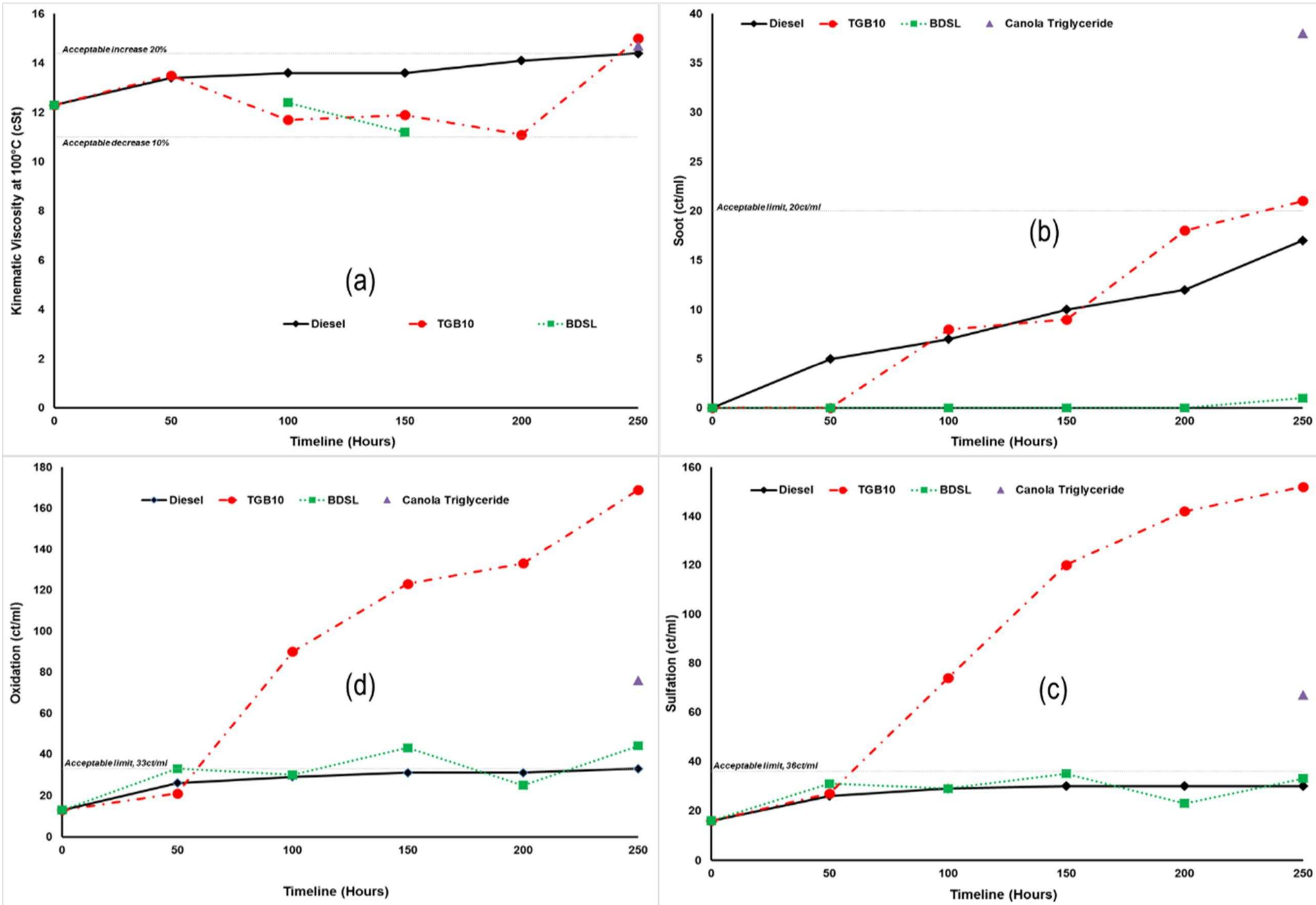


Figure 5-4: Physical properties of lube oil over 250 hours

One possible explanation could be a potential contamination by fuel passing through the combustion chamber to the crankcase. At the end of 250 hours of testing on TGB10, the lube oil had a viscosity of 15 cSt while that for canola triglyceride was 14.7 cSt which was slightly higher than the viscosity for a diesel run. For biodiesel runs, not all measurements of viscosity were possible due to technical difficulties at the laboratory. This suggests that lube oil changes are due at 200 hours instead of 250 hours when using TGB10 as fuel, a 20% reduction in life of lube oil.

Figure 5-4 (b) shows the soot concentration in particle counts per milliliter. Contamination of the engine lubricating oil by diesel soot is one of the major causes of increased engine wear and tear. The diesel soot from the combustion chambers escapes to the crankcase along with blow by gases and interacts with the lubricating oil in the crankcase. These soot particles then travel through the engine components with the lube oil and result in wear and tear of various engine components, especially the piston polished surfaces due to weakening of the antiwear lube oil film and abrasion[36, 37]. Type of fuel has an important role in defining the type of surface the soot, chemical and physical forms of soot and the degradation of the lube oil. Presence of soot in the lube oil tends to increase its viscosity causing lube oil circulation problems[38]. Fresh lube oil would have no soot contamination. For diesel fuel, there was a steady rise in the soot concentration of the lube oil over the period of testing. At the end of 250 hours, the soot concentration was around 17 ct/ml. For fuel TGB10, there was no soot contamination in lube oil for the first 50 hours. A rapid rise in soot concentration in the lube oil was then observed and was around 21 ct/ml at the end of 250 hours. For biodiesel, no soot contamination was recorded for almost 200 hours of operation and very little trace around 1ct/ml was found at the end of 250 hours. For canola triglyceride, the soot concentration in lube was the highest at 30 ct/ml.

Figure 5-4 (c) shows the sulfation levels of the lube oils over a period of 250 hours in counts per milliliter (ct/ml). The sulfation level in the lube oil for diesel and biodiesel were similar to each other. Canola triglyceride fuel resulted in a lube oil sulfation that was twice that of diesel while TGB10 resulted in a lube oil sulfation five times greater than that of diesel. TGB10 is an untreated oil, and contains sulfur almost 9 times higher than diesel and biodiesel. During engine operation, the reaction between oxygen (air), heat, water and sulfur from diesel fuel results in formation of sulfurous compounds. These compounds are usually expelled through exhaust; however, some of these compounds make their way into the crankcase due to blow-by through piston rings and contaminate the lube oil. Presence of sulfur in the lube oil results in the formation of sludge and sedimentation that increases the viscosity of the lube oil and can harm the engine.

Figure 5-4 (d) shows the oxidation levels of lube oil over a period of 250 hours in counts per milliliter (ct/ml). Oxidative stability is the resistance to reaction with oxygen. Oxidation ages the lubricating oil sooner. It is undesirable because it increases the viscosity, reduces anti-corrosion property and increases deposit formation of lubricant. For a fresh oil, the oxidation level was 13 ct/ml. At 50 hours of diesel operation, the oxidation count doubled to 26 ct/ml and at 250 hours, the oxidation level had a very slight increase to about 33 ct/ml. For biodiesel, the oxidation level showed inconsistent increasing and decreasing trends. Biodiesel molecules contains small levels oxygen which could be responsible for such an inconsistent behavior. The oxidation levels for lube oil using canola triglyceride as fuel was 76 ct/ml. The oxidation levels for lube oil using TGB10 as fuel was 169 ct/ml at 250 hours which is significantly higher than diesel, Biodiesel and canola triglyceride. TGB10 and canola triglycerides contains untreated plant based oil contains close to 90% unsaturated fatty acids which could have resulted in the steep increase in oxidation values[7, 17]

5.6.2 WEAR METALS IN LUBE OIL

Engine consists of many components that works harmoniously to deliver power. In the process, there is friction between components which can lead to wear. Dust and dirt from external sources like coolant leakages, air intake system and fuel system can contaminate the lubricating oil and harm the engine components and thereby reducing the "time before overhaul" and the life of the engine. Figure 5 shows the presence of wear metals – copper, iron aluminum and chromium in the lube oil over a period of 250 hours. For canola triglyceride testing, only the 250-hour lubricating oil analysis was available. As a rule of thumb, a concentration of 50 ppm of copper, 80 ppm of iron, 30 ppm of aluminum and 25 ppm of chromium in the lube oil indicates time for the oil change[34]

Figure 5-5 (a) shows the concentration of copper present in lube oil over the duration 250 hours. Copper is a primary metal used in the manufacture of bearings, heat exchangers and bushings made from brass and bronze. Presence of copper in the lube oil could also indicate a small leak in the cooling water system that could contaminate the engine block and lube oil system. For diesel fuel, the copper content in the lube oil was ~ 3 to 9 ppm which is small. Similar copper content was observed with the use of canola triglyceride as fuel. Elevated copper content ~86ppm was recorded with the use of biodiesel.

Figure 5 (b) shows the concentration of iron present in the lube oil over 250 hours. Presence of iron in the lubricating oil indicates wear and tear of cylinder liner and piston skirt. Iron is used in cylinder head, cylinder liners, piston rings, crankshaft, bearings and valves[39]. In general, there was an increase of iron content in the lube oil over the course of the experiments. Lubricating oil used for canola triglyceride, Bio diesel and TGB10 fuels had lower iron contamination than diesel fuel. Canola triglyceride and TGB10 and have 15 times and 11 times higher viscosities than diesel respectively. They also contain higher unsaturation fatty acids[40] as compared to diesel and biodiesel thus offering better lubricating properties resulting in less wear and tear on the engine components.

Figure 5 (c) shows the concentration of aluminum present in the lube oil over 250 hours. Source of aluminum in lubricating oil can be piston crown, cylinder head and the main bearings. Higher wear has also been reported for Al by several researchers[41, 42]. Common dirt and dust that enters the combustion chamber through air intake system can contain abrasive elements that result in aluminum wear from the engine components. Over the period of tests, the presence of aluminum on the lube oil showed a steady increase for diesel and TGB10 while the use of biodiesel seemed to have had an insignificant impact on the aluminum content. Aluminum content in lube oil using canola triglyceride as fuel was 80 ppm which is almost twice than that of TGB10.

Figure 5 (d) shows the concentration of chromium present in the lube oil over 250 hours. Chromium is an alloy metal used in making cylinder wall/liner, piston, ring, valve, shaft and gears. Lubricating oil used for canola triglyceride, Bio diesel and TGB10 fuels had lower chromium contamination than diesel fuel. One possible explanation is that canola triglyceride, TGB10 and biodiesel offer better lubricating properties compared to diesel.

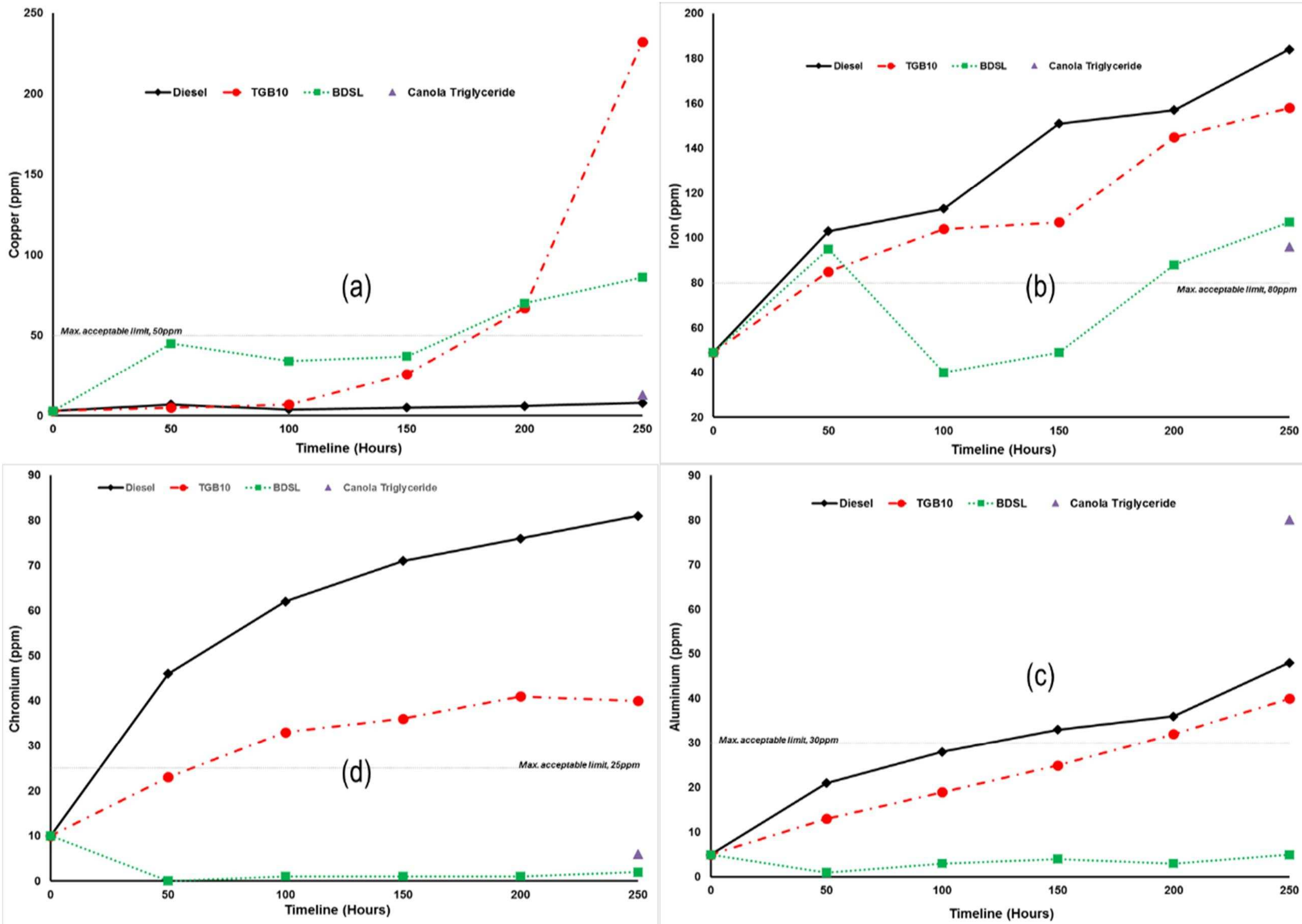


Figure 5-5: Wear metals in lube oil

5.6.3 ADDITIVES IN LUBRICATING OIL

Most lubricating oils contain a mixture of base oil (90%) and additives (10%). The function of the base oil is to act as a lubricant and to be the carrier of additives. The function of additives is to enhance the property of base fluid such as viscosity, oxidation resistance, suspending ability, antiwear and corrosion inhibitors.

Figure 5-6 shows the concentration elements found in some of the most common additives used - calcium, molybdenum, phosphorus and zinc in lube oil over 250 hours.In general, the additive concentration in lube oils when using TGB 10 and biodiesel were less than that of regular diesel over the 250 hours. This means that the lubricating oil loses its anti-corrosion and anti-wear properties sooner with the use of biodiesel and TGB10 compared to diesel. This leads to greater wear of engine components which can be confirmed with the wear metal concentration shown in Figure 5-5. This indicates two things (i) The lubricating oil available in the market and used for these experiments is not effective with biodiesel and TGB10. (ii) The lubricating oil must be changed at a shorter interval when using biodiesel and TGB10.

5.7 CONCLUSIONS

Three fuels – diesel, canola based biodiesel and canola based triglyceride gasoline blend (TGB10) were tested for 250 hours in a single-cylinder, naturally aspirated Yanmar diesel engine at a constant load of 4.5 kW and 1800 rpm. Qualitative analysis of the carbon buildup on injector and cylinder surface, injector spray patterns, and lube oil sample deterioration over the length of the test were analyzed.

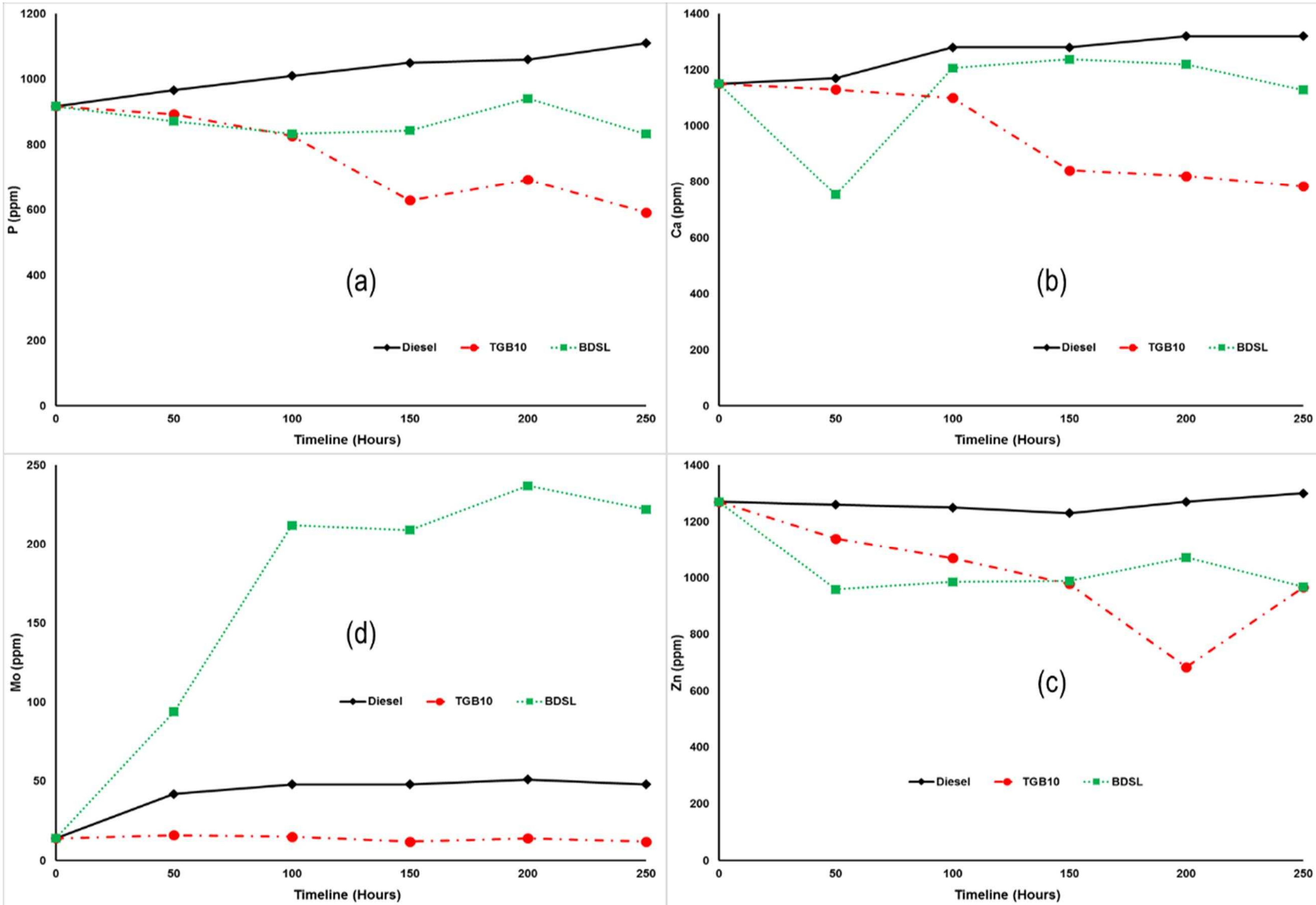


Figure 5-6: Additives in Lube Oil

— The injector tip with biodiesel had the least carbon buildup while that on TGB10 had the maximum buildup – almost a tube-like structure. Biodiesel, being a good dissolver of carbon deposits, could potentially have a cleansing effect on the injector.

— The piston crown surface had a smooth layer of fine carbon deposit with diesel fuel and a slightly rough and matt finish like surface with the use of biodiesel. The use of TGB10 had a thick and sludgy layered deposition on the piston crown. A visual comparison of the spray testing for these fuels indicated the biodiesel may have a larger spray cone angle and a greater spray penetration depth than diesel, while the use of TGB10 had a shorter spray penetration than diesel.

— The kinematic viscosity of the lube oil did not seem to change much with the use of the three different fuels. The soot content in the lube oil for biodiesel was the least, almost nonexistent while that for TGB10 showed a steady increase in the concentration and higher than diesel. The sulfation and oxidation of biodiesel and diesel where similar to each other, but for TGB10 they were orders of magnitude higher than the other two fuels.

— The copper content in lube oil for Biodiesel and TGB10 increased beyond the 50ppm limit around the 200 hours. The iron content for TGB10 and was consistently higher than the 80ppm limit, a chromium limit of 30 ppm with TGB10 was recorded at 100 hours and aluminum limit of 30 ppm for TGB10 was recorded at 300 hours. These results indicate that the lube oil life is reduced by at least 80% while using TGB10 as fuel, indicating a frequent oil change schedule.

— The concentration of lubricating oil additives for biodiesel and TGB10 were lower than diesel and close to the recommended oil change interval at 200 hours. This could indicate a 20% to 40% reduction in life of lube oils and the need for a lube oil change twice as frequent as diesel when using these fuels.

- For future work, SEM/EDS elemental testing of the deposits is recommended that would the composition of elements associated with lube oil on the carbon deposits and hence gain a deeper understanding to the contaminations.
- Detailed study on carbon build up and component wear mechanisms will help in understanding the long-term impacts of alternative fuels on the wear and tear of engine components.

5.7 REFERENCES

[1] ENERGY INDEPENDENCE AND SECURITY ACT OF 2007. Available: http://www.gpo.gov/fdsys/pkg/PLAW-110publ140/html/PLAW-110publ140.htm

[2] C. M. H. Keske, D. L. Hoag, A. Brandess, and J. J. Johnson, "Is it economically feasible for farmers to grow their own fuel? A study of Camelina sativa produced in the western United States as an on-farm biofuel," *Biomass and Bioenergy,* vol. 54, no. 0, pp. 89-99, 7// 2013.

[3] A. C. Drenth, D. B. Olsen, P. E. Cabot, and J. J. Johnson, "Compression ignition engine performance and emission evaluation of industrial oilseed biofuel feedstocks camelina, carinata, and pennycress across three fuel pathways," *Fuel,* vol. 136, pp. 143-155, 11/15/ 2014.

[4] C. D. Aaron, D. Karolien, E. C. Perry, and B. O. Daniel, "Evaluation of Industrial Corn Oil as an On-Farm Biofuel Feedstock," vol. 31, no. 5, 2015.

[5] A. C. Drenth, D. B. Olsen, and K. Denef, "Fuel property quantification of triglyceride blends with an emphasis on industrial oilseeds camelina, carinata, and pennycress," *Fuel,* vol. 153, pp. 19-30, 8/1/ 2015.

[6] L. Arunachalam, B. O. Daniel, and E. C. Perry, "Performance and Emission Evaluation of Triglyceride-Gasoline Blends in Agricultural Compression Ignition Engines," vol. 30, no. 4, 2014.

[7] A. Lakshminarayanan, "Testing and performance measurement of straight vegetable oils as an alternative fuel for diesel engines.," Mechanical Engineering, Colorado State University, Fort Collins, 2014.

[8] A. Lakshminarayanan, D. B. Olsen, and P. E. Cabot, "Effects of triglyceride gasoline blends on combustion and emissions in a common rail direct injection diesel engine," *International Journal of Engine Research,* p. 1468087417740316, 2017.

[9] A. M. Liaquat, H. H. Masjuki, M. A. Kalam, and I. M. Rizwanul Fattah, "Impact of biodiesel blend on injector deposit formation," *Energy,* vol. 72, pp. 813-823, 2014/08/01/ 2014.

[10] P. R. Wander, C. R. Altafini, A. L. Colombo, and S. C. Perera, "Durability studies of mono-cylinder compression ignition engines operating with diesel, soy and castor oil methyl esters," *Energy,* vol. 36, no. 6, pp. 3917-3923, 2011/06/01/ 2011.

[11] A. K. Agarwal *et al.*, "Field Trials of Biodiesel (B100) and Diesel Fuelled Common Rail Direct Injection Euro-III Compliant Sports Utility Vehicles in Indian Conditions," 2008-01-09, 2008.

[12] A. K. Agarwal, T. Gupta, and A. Kothari, "Particulate emissions from biodiesel vs diesel fuelled compression ignition engine," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 6, pp. 3278-3300, 2011/08/01/ 2011.

[13] A. Sharma and S. Murugan, "Durability analysis of a single cylinder DI diesel engine operating with a non-petroleum fuel," *Fuel,* vol. 191, pp. 393-402, 2017/03/01/ 2017.

[14] M. D’Amico, M. Zampilli, P. Laranci, B. D’Alessandro, G. Bidini, and F. Fantozzi, "Measuring Injectors Fouling in Internal Combustion Engines through Imaging," *Energy Procedia,* vol. 82, no. Supplement C, pp. 9-16, 2015/12/01/ 2015.

[15] A. Ben Amara *et al.*, "Experimental Study of the Impact of Diesel/Biodiesel Blends Oxidation on the Fuel Injection System," *SAE International Journal of Fuels and Lubricants,* vol. 7, no. 3, pp. 849-860, 2014-10-13 2014.

[16] S. Nettles-anderson, D. B. Olsen, J. J. Johnson, and J. Enjalbert, "Performance of a Direct Injection IC Engine on SVO and Biodiesel from Multiple Feedstocks," ed: J Power Energy Eng, pp. 1–13, 2014.

[17] S. Nettles-Anderson and D. Olsen, "Survey of straight vegetable oil composition impact on combustion properties," ed: SAE, 2009.

[18] S. Nettles-anderson, D. B. Olsen, J. Johnson, and N. Enjalbert, "Engine Durability Testing of Unrefined Straight Vegetable Oil," ed.

[19] K. Yamane, K. Kawasaki, K. Sone, T. Hara, and T. Prakoso, "Oxidation stability of biodiesel and its effects on diesel combustion and emission characteristics," *International Journal of Engine Research,* vol. 8, no. 3, pp. 307-319, 2007/06/01 2007.

[20] J. Barker, P. Richard, C. Snape, and W. Meredith, "Diesel Injector Deposits - An Issue That Has Evolved with Engine Technology," 2011. Available: https://doi.org/10.4271/2011-01-1923

[21] T. Omori, A. Tanaka, K. Yamada, and S. Bunne, "Biodiesel deposit formation mechanism and improvement of Fuel Injection Equipment (FIE)," 2011. Available: https://doi.org/10.4271/2011-01-1935

[22] J. Barker, C. Snape, and D. Scurr, "A Novel Technique for Investigating the Characteristics and History of Deposits Formed Within High Pressure Fuel Injection Equipment," *SAE Int. J. Fuels Lubr.,* vol. 5, no. 3, pp. 1155-1164, 2012.

[23] H. Raheman, P. C. Jena, and S. S. Jadav, "Performance of a diesel engine with blends of biodiesel (from a mixture of oils) and high-speed diesel," *International Journal of Energy and Environmental Engineering,* vol. 4, no. 1, p. 6, 2013/01/22 2013.

[24] M. S. Reddy, N. Sharma, and A. K. Agarwal, "Effect of straight vegetable oil blends and biodiesel blends on wear of mechanical fuel injection equipment of a constant speed diesel engine," *Renewable Energy,* vol. 99, no. Supplement C, pp. 1008-1018, 2016/12/01/ 2016.

[25] J. Ullmann, M. Geduldig, H. Stutzenberger, R. Caprotti, and G. Balfour, "Investigation into the Formation and Prevention of Internal Diesel Injector Deposits," 2008. Available: https://doi.org/10.4271/2008-01-0926

[26] P. Lacey, S. Gail, J. M. Kientz, G. Benoist, P. Downes, and C. Daveau, "Fuel Quality and Diesel Injector Deposits," *SAE Int. J. Fuels Lubr.,* vol. 5, no. 3, pp. 1187-1198, 2012.

[27] J. Bouilly, A. Mohammadi, Y. Iida, H. Hashimoto, S. Geivanidis, and Z. Samaras, "Biodiesel Stability and its Effects on Diesel Fuel Injection Equipment," 2012. Available: https://doi.org/10.4271/2012-01-0860

[28] S. Moon, "Novel insights into the dynamic structure of biodiesel and conventional fuel sprays from high-pressure diesel injectors," *Energy,* vol. 115, no. Part 1, pp. 615-625, 2016/11/15/ 2016.

[29] J. M. Desantes, R. Payri, A. García, and J. Manin, "Experimental Study of Biodiesel Blends' Effects on Diesel Injection Processes," *Energy & Fuels,* vol. 23, no. 6, pp. 3227-3235, 2009/06/18 2009.

[30] B. Wang, T. Badawy, Y. Jiang, H. Xu, A. Ghafourian, and X. Zhang, "Investigation of deposit effect on multi-hole injector spray characteristics and air/fuel mixing process," *Fuel,* vol. 191, no. Supplement C, pp. 10-24, 2017/03/01/ 2017.

[31] S. Zzeyani, M. Mikou, J. Naja, and A. Elachhab, "Spectroscopic analysis of synthetic lubricating oil," *Tribology International,* vol. 114, pp. 27-32, 2017/10/01/ 2017.

[32] R. Q. Aucélio, R. M. de Souza, R. C. de Campos, N. Miekeley, and C. L. P. da Silveira, "The determination of trace metals in lubricating oils by atomic

spectrometry," *Spectrochimica Acta Part B: Atomic Spectroscopy,* vol. 62, no. 9, pp. 952-961, 2007/09/01/ 2007.

[33] W. E. C. Marianne Long, ed.

[34] M. Holloway, "The Oil Analysis Handbook - A Comprehensive Guide to Using and Understanding Oil Analysis,"

[35] Y. Y. Wu, W. C. Tsui, and T. C. Liu, "Experimental analysis of tribological properties of lubricating oils with nanoparticle additives," *Wear,* vol. 262, no. 7, pp. 819-825, 2007/03/15/ 2007.

[36] P. R. Ryason, I. Y. Chan, and J. T. Gilmore, "Polishing wear by soot," *Wear,* vol. 137, no. 1, pp. 15-24, 1990/04/01/ 1990.

[37] I. Berbezier, J. M. Martin, and P. Kapsa, "The role of carbon in lubricated mild wear," *Tribology International,* vol. 19, no. 3, pp. 115-122, 1986/06/01/ 1986.

[38] C. Kim, C. A. Passut, and D. M. Zang, "Relationships Among Oil Composition, Combustion-Generated Soot, and Diesel Engine Valve Train Wear," 1992. Available: http://doi.org/10.4271/922199

[39] A. S. M. A. Haseeb, M. A. Fazal, M. I. Jahirul, and H. H. Masjuki, "Compatibility of automotive materials in biodiesel: A review," *Fuel,* vol. 90, no. 3, pp. 922-931, 2011/03/01/ 2011.

[40] L. Gardynski and J. Kaldonek, "Comparative Study of Selected Lubricating Properties of Biofuels," *Advances in Science and Technology Research Journal,* vol. 7, 20, pp. 75-79, 2013.

[41] S. Raadnui and A. Meenak, "Effects of refined palm oil (RPO) fuel on wear of diesel engine components," *Wear,* vol. 254, no. 12, pp. 1281-1288, 2003/11/01/ 2003.

[42] S. J. Clark, L. Wagner, M. D. Schrock, and P. G. Piennaar, "Methyl and ethyl soybean esters as renewable fuels for diesel engines," *Journal of the American Oil Chemists Society,* vol. 61, no. 10, pp. 1632-1638, 1984/10/01 1984.

6. ECONOMIC AND BUSINESS CASE OVERVIEW OF USING TRIGLYCERIDE GASOINE BLENDS AS AN ALTERNATIVE TO DIESEL FUEL

6.1 OVERVIEW:

This paper provides an overview of the economic lifecycle feasibility of growing and using the oil from Canola oilseed crops as a diesel fuel substitute for off road applications. Using untreated oils from oil seeds like canola, jatropha and sunflower as a diesel substitute has gained much interest over the last few decades. Though there are many studies available on the economics of growing an oil seed, few publications are available on the durability studies of such fuels in diesel engines and cost of ownership of equipment running on such fuel. In this analysis, the economics of growing Canola oil seed crop, unrefined oil extraction and its subsequent conversion to a triglyceride gasoline blend with 10% gasoline by volume (TGB10) is considered. Growing a crop over 2000 acres during a fallow season, setting up an oil crushing facility and utilizing a nearby animal feeding lot to sell the canola meal formed the basis of this analysis. Finally, the cost of ownership of the diesel engine using TGB10 as a fuel over four different engine life assumptions, 80%, 70%, 60% and 50% as that of diesel, was analyzed. An alternative fuel that is lower cost than diesel fuel does not necessarily result in cost savings. Value proposition for a business case scenario using of TGB10 as a fuel is also discussed.

6.2 INTRODUCTION

Interest in biofuels has been driven by many factors, including energy policy goals, reduction in the emissions of greenhouse gases, increased energy independence objectives and the emergence of new energy markets [1-4]. In the liquid fuel sector, many studies on biodiesel and straight vegetable oils as an alternative to diesel have been conducted. Such studies have focused on the engine and emission performance of such diesel fuel alternatives [5-7], some have studied the cost of biofuel and biomass crop cultivation [8-10]. In the agricultural sector, there has been a lot of interest in crop rotation schedule and farm cost economics for growing oilseed crops.

This study analyses the economic feasibility of producing and using one such alternative fuel in farm equipment by growing an oilseed crop. Canola oil seed crop has been grown in eastern Colorado[11]. Farmers have been blending canola oil (90%) with gasoline (10%) on a volume basis to form a triglyceride gasoline blend (TGB10) and using it in their farm equipment [12, 13]. Previous studies by our research group have shown that using such a blended fuel in an off road Tier III diesel engine can produce comparable results to diesel with regards to engine performance and emissions [14-18], while durability studies of using such fuels have yielded mixed results[19-21].

6.3 ECONOMIC ANALYSIS

In this study, it is assumed that 2000 acres of land at a given time (which is the average size of a farm in Colorado) is available to grow a canola crop in the fallow season and each acre of land produces approximately 30 bushels (1500 lb) of canola crop. Diesel is the primary fuel used in the farm equipment for all farm activities. The baseline cost of growing canola crop is adapted from a previous studies [22, 23] and is shown in Table 6-1. The impact due to inflation and interest on machinery has not been considered as it is assumed that those costs are covered during the primary farming season and crop.

The total cost of growing a canola crop per acre is $219.48. The fixed cost and variable cost of canola crop production are 17.3% and 82.7% of the total cost, respectively. The cost of storage and transportation to market is not considered. It is assumed that the canola crop will be directly transported to the seed crushing facility on the farm to produce canola oil and hence there will be no cost of storage and transportation. It is also assumed that the labor required for farming is done by the farmer himself and he pays himself $20.00 per hour.

The total cost for the farmer to produce canola crop is $7.34 per bushel or roughly $0.15 cents per pound of canola. It is assumed that the farmer will not be selling the canola crop, but will crush it at the farm to produce canola oil and convert into fuel for farm machinery.

6.3.1 SEED CRUSHING AND OIL PRODUCTION

The farmer is assumed to crush all the canola crop grown on 2000-acres of farming land in 30 days. Two screw type seed crushers, two centrifugal oil separators, two shifts per day of operation (each of 8 hours), one operator per shift are considered. In addition to this, the canola cake left over from the crushing process is sold as meal to an adjacent animal feeding lot.

Table 6-2 shows the design and sizing considerations for the canola seed crushing facility. The 2000-acre canola crop yields about 3,000,000 pounds of canola oil seed. Each of the two oil seed crushers operate at a capacity of 35 tons per day. The canola oil seed crop, on an average contains 40% oil by weight[24, 25]. About 4% of the oil is not harvested during the crushing process and remains with the cake.

Table 6-1: Baseline Canola Crop Production Costs

Item	Quantity per Acre	Unit	Cost/ Unit	Cost/ Acre	Cost as % of total cost
Variable Costs					
Seed:				**$17.50**	8.0%
Canola Seed	*5*	*lb*	*$3.50*	*$17.50*	
Fertilizer:				**$84.25**	38.4%
Nitrogen	*75*	*lb*	*$0.77*	*$57.75*	
Phosphorus	*15*	*lb*	*$0.66*	*$9.90*	
Sulfur	*15*	*lb*	*$0.56*	*$8.40*	
Boron	*1*	*lb*	*$8.20*	*$8.20*	
Pesticides:				**$19.73**	9.0%
Glyphosate	*24.00*	*oz*	*$0.20*	*$4.80*	
Ammonium sulfate	*1.70*	*lb*	*$0.42*	*$0.71*	
Spodnam	*1.00*	*pt*	*$14.22*	*$14.22*	
Machinery:				**$44.53**	20.3%
Fuel	*1*	*acre*	*$14.45*	*$14.45*	
Lubricants	*1*	*acre*	*$2.18*	*$2.18*	
Machinery Repairs	*1*	*acre*	*$7.90*	*$7.90*	
Machinery Labor	*1*	*hour*	*$20.00*	*$20.00*	
Crop insurance				**$14.60**	6.7%
Crop insurance	1	acre	$14.60	*$14.60*	
Total Variable Costs				**$180.61**	82.3%
Fixed Costs:					
Machinery depreciation	*1*	*acre*	*$13.48*	*$13.48*	
Machinery interest	*1*	*acre*	*$10.95*	*$10.95*	
Machinery insurance, taxes, housing, licenses	*1*	*acre*	*$5.72*	*$5.72*	
Interest on capital	*1*	*acre*	*$8.72*	*$8.72*	
Total Fixed Costs				**$38.87**	17.7%
Total Costs per Acre				**$219.48**	
Total Cost per pound				$0.146	

The total canola oil harvested is 18, 386 liters per day and has a density of 0.89 kg/l. The canola oil from the seed crusher, is collected in a 500 gallon day tank. Two self-cleaning centrifugal separators, each with a capacity of 600 liters per hour (lph) then draw oil from the day-tank and pump the clean oil to a 4,500 gallon storage tank.

After the seed crushing process in the screw crusher, the canola oil seed cake is then transported via a conveyer belt to the animal feed lot as a high protein meal. The cost of transporting and storing the meal is assumed to be the responsibility of the feedlot owner. About 29 tons of canola meal is produced per day from the crushing facility totaling to roughly 873 tons for the 30 day crushing period.

The capital expenditure (CAPEX) to set up the crushing facility and the operating expenditure (OPEX) to get canola oil are shown in Table 6-3. The initial capital investment required is about $102,000. A straight-line depreciation [26, 27] is used, with a salvage value of 10% and a useful life of 10 years. The operating expenditure over the period of 30 days is calculated to be $13,523 that includes electricity, water and labor for 16 hours of operation a day.

The balance sheet for canola oil extraction is shown in Table 6-4. The cost of growing canola over 2000 acres is $438,968 as shown in Table 6-1. The CAPEX and OPEX totaling to $22,700 per growing and crushing cycle are shown in Table 6-3. Building and equipment maintenance costs are assumed to be 2.5% of the total operating costs per cycle. The high protein canola meal is sold to the feeding lot after oil extraction at a rate of $292/Ton. Around 115,400 gallons of canola oil and 873 tons of canola meal are extracted from growing canola oil seed crop for 2000 acres. The cost of producing Canola oil on-farm is $1.79 per gallon.

Table 6-2: Design and Sizing of Canola Oil Extraction Facility

Harvested Canola crop per acre	1,500	lb.
Total Canola crop for 200 acres	3,000,000	lb.
Number of crushing days	30	days
Canola crop to be crushed	100,000	lb. per day
	45,455	kg per day
Number of operating hours per day	16	hours
Number of crushers	2	
Target crushing for each crusher	22,727	kg per day
	23	Tons per Day (TPD)
Design Size of each crusher	**35**	**Tons per Day**
Oil content of Canola Crop	40%	per batch of crushing
Residual oil content after crushing	4%	per batch of crushing
Oil harvested after crushing	36%	per batch of crushing
Density of crushed Canola oil	0.89	kg/l
Total oil harvested per day	**18,386**	**Liters**
Total quantity of oil passing through separators	18,386	Liters per Day
Number of separators	2	
Quantity of oil passing through separators	9,193	Liters per day
	575	Liters per hour
Design capacity of each separator	**600**	**Liters per hour**
Storage tank to store 1 day's oil harvest	18,386	Liters
Design capacity of Day Tank	**500**	**Gallon**
Design capacity of storage tank	**4,500**	**Gallon**
Canola meal after crushing	64%	per batch of crushing
Total canola meal produced per day	29,091	kg per day
	29	Tons per Day (TPD)
Total canola meal produced for 2000 acres of canola harvest	**873**	**Tons**

Table 6-3: CAPEX and OPEX for the Oil Extraction Facility

CAPITAL EXPENDITURE					
Item	**Capacity**	**Quantity**	**Cost/unit**	**Total cost**	
Screw type oil seed crusher	*35 TPD*	*2*	*$35,000*	*$70,000*	
Centrifugal Separator	*600 lph*	*2*	*$2,000*	*$4,000*	
Day Tank	*500 Gallons*	*1*	*$550*	*$550*	
Storage Tank	*4500 Gallons*	*1*	*$4,500*	*$4,500*	
Erection and Commissioning	*10% of cost of supply*	*1*		*$7,905*	
Building & Set up cost		*1*	*$15,000*	*$15,000*	
			Total Capital Cost	**$101,955**	
Assuming a salvage value of 10% and a useful life of 10 years, the depreciation of the capital expenditure per year is				**$9,175.95**	
OPERATING EXPENDITURE					
Item	**Capacity**	**Quantity**	**Hours/Day**	**Total consumable/day**	
Electricity					
Seed Crusher	*56 kW*	*2*	*16 hours*	*1792*	*kWh*
Centrifuge	*5 KW*	*2*	*16 hours*	*160*	*kWh*
Building Lighting	*0.5 KW*		*16 hours*	*8*	*kWh*
Total Electricity Cost at 6.5 cents per unit for 30 days				***$3,822***	
Water Cost					
Separator usage	*10 gallons per hour*	*2*	*16 hours*	*320*	*Gallons*
Building usage	*1 gallons per hour*	*1*	*16 hours*	*16*	*Gallons*
Total Water Cost at 1 cent per gallon for 30 days				***$101***	
Labor					
Labor	*1 per shift*	*2*	*8 hours*	*16*	*hours*
Total Labor Costs for 30 days at $20/hour				***$9,600***	
Total Operating Expenditure over 30-day period				**$13,523**	

Table 6-4: Balance Sheet for Canola Oil Extraction Facility

Cost of growing Canola	*See Table 1*	*$438,968*	
CAPEX and OPEX	*Building and Machinery*	*$22,699*	
Building and Equipment Maintenance	*2.50% of OPEX*	*$338*	
Return from selling canola meal	*$292 per Ton*	*$254,836*	
Cumulative cost of canola oil production		***$207,168***	
Canola oil harvested per day		*18386*	*Liters*
Total Canola oil harvested	*30 Days*	*551583*	*Liters*
		115394	*Gallons*
On Farm Canola oil production		**$1.79**	**per Gallon**

Budgeting for canola oil production as shown in Table 6-4 contains many variables. The cost of growing canola and the return on selling canola meal to the nearby feed lot are the two main drivers in the economics of canola oil production. Any change in the main drivers, will have an impact in the cost of oil produced. Table 6-5 shows the sensitivity analysis for the cost of canola oil production. Historical data show that the cost of canola farming and selling price of meal fluctuates between 1.5% and 11% on an average over the years[28, 29]. Depending on the demand and supply, prices have often varied over 20 to 35% in a few cases[30, 31]. For sensitivity analysis, a standard range [32] of (-5% to +5%) change in the cost of growing canola and the selling price of canola meal has been considered.

The cost of oil production from Table 6-4 is $1.79 per gallon. With a 5% increase in the cost of growing canola and a 5% reduction in the selling price of canola meal, the breakeven cost of canola oil is $2.10, a 31-cent increase. Conversely, a 5% reduction in the growing cost of canola and 5% increase in the selling price of canola will reduce the overall breakeven price of canola oil by 30 cents to $1.49 per gallon.

Table 6-5: Sensitivity Analysis for Canola Oil Production Cost per gallon

		% Change in the cost of growing Canola										
		-5	-4	-3	-2	-1	0	1	2	3	4	5
% Change in the selling price of Canola meal	-5	$1.71	$1.75	$1.79	$1.83	$1.87	$1.91	$1.94	$1.98	$2.02	$2.06	$2.10
	-4	$1.69	$1.73	$1.77	$1.81	$1.84	$1.88	$1.92	$1.96	$2.00	$2.04	$2.07
	-3	$1.67	$1.71	$1.75	$1.78	$1.82	$1.86	$1.90	$1.94	$1.98	$2.01	$2.05
	-2	$1.65	$1.69	$1.72	$1.76	$1.80	$1.84	$1.88	$1.91	$1.95	$1.99	$2.03
	-1	$1.63	$1.66	$1.70	$1.74	$1.78	$1.82	$1.85	$1.89	$1.93	$1.97	$2.01
	0	$1.60	$1.64	$1.68	$1.72	$1.76	**$1.79**	$1.83	$1.87	$1.91	$1.95	$1.98
	1	$1.58	$1.62	$1.66	$1.70	$1.73	$1.77	$1.81	$1.85	$1.89	$1.92	$1.96
	2	$1.56	$1.60	$1.64	$1.67	$1.71	$1.75	$1.79	$1.83	$1.86	$1.90	$1.94
	3	$1.54	$1.58	$1.61	$1.65	$1.69	$1.73	$1.77	$1.80	$1.84	$1.88	$1.92
	4	$1.52	$1.55	$1.59	$1.63	$1.67	$1.71	$1.74	$1.78	$1.82	$1.86	$1.90
	5	$1.49	$1.53	$1.57	$1.61	$1.65	$1.68	$1.72	$1.76	$1.80	$1.84	$1.87

6.3.2 TGB10 PRODUCTION

Once the canola oil is extracted from the oil seed, it is then blended with gasoline to reduce its viscosity. Previous research has shown that the specific gravity of canola oil can be matched to that of diesel by blending approximately 10% gasoline by volume. This allows the fuel to be used in the engine without fuel system modifications, which are required for viscous fuels like straight vegetable oil. From the previous section, a total of 115400 gallons of canola oil can be harvested. To create a TGB10 blend, 10% gasoline, 12,822 gallons is added to produce a cumulative 128,216 gallons of TGB10.

Table 6-6 shows the budgetary estimate of TGB10 production. A storage tank capacity of 150,000 gallons would be needed with a useful life of 10 years and it is assumed that it has no salvage value at the end of it life. The depreciation cost of the storage tank is 13 cents per gallon of TGB10 fuel over its lifespan of 10 years. The cost of gasoline is assumed to be $2.70 per gallon. It is assumed that the farmer himself will blend gasoline with the canola oil, which requires minimal work and effort and hence no labor cost included. The cumulative cost of TGB10 production is around $2.01 per gallon. This price of TGB10 fuel amounts to a saving of $1.19 or 37% over the average diesel price in the US between 2014 and 2016[33].

For TGB10 to be an economically viable alternative to diesel fuel, it must be substantially lower cost than diesel. Two main drivers define the economic viability of using TGB10, the cost of producing TGB10 and the cost of diesel fuel.

Table 6-6: Budgetary Estimation of TGB10 production

Budgetary Estimate for TGB10 production				
TGB10 Quantification				
TGB10: proportion of constituents	*90%*	*Canola Oil*	*10%*	*Gasoline*
Canola Oil harvested	*1*	*Day*	*18386*	*Liters*
Total Canola Oil Harvested			*115394*	*Gallons*
Total Gasoline required			*12822*	*Gallons*
Total TGB10 Produced			*128216*	*Gallons*
Capacity of Storage Tank			*150000*	*Gallons*
TGB10 Cost Estimation				
Cost of Canola Oil			*$1.80*	*per gallon*
Cost of Gasoline			*$2.70*	*per Gallon*
Total Cost of TGB10 Blended			*$241,786.65*	
			$1.89	*Per Gallon*
Cost of Storage tank	*$1.10*	*per Gallon*	*$165,000*	
Useful life of storage tank	*10*	*years*		
Salvage Value of storage tank	*$0.00*			
Depreciation of storage tank			*$16,500*	*Per year*
			$0.13	*Per gallon*
Cumulative Cost of TGB10			**$2.01**	**Per Gallon**
Cost of diesel			*$3.20*	*per gallon*
Fuel cost savings of TGB10 over diesel			**$1.19**	per gallon
			37%	over diesel

Table 6-7 shows the sensitivity analysis for cost savings per gallon of TGB10 produced and the retail price of diesel over a range of ±5%. If the cost of TGB10 production increases by 5% and cost of diesel decreases by 5%, a net savings of $0.92 per gallon, or 30% of diesel cost is predicted. For a scenario where the cost of diesel increases by 5% and the cost of TGB10 production decreases by 5%, a net savings of $1.45 per gallon, or 43% of diesel cost is predicted.

Table 6-7: Cost savings per gallon of TGB10 produced and retail price of diesel

% Change in the cost of diesel	% Change in the cost of blending TGB10: -5	-4	-3	-2	-1	0	1	2	3	4	5
-5	$1.13	$1.11	$1.09	$1.07	$1.05	$1.03	$1.01	$0.99	$0.97	$0.94	$0.92
-4	$1.16	$1.14	$1.12	$1.10	$1.08	$1.06	$1.04	$1.02	$1.00	$0.98	$0.96
-3	$1.19	$1.17	$1.15	$1.13	$1.11	$1.09	$1.07	$1.05	$1.03	$1.01	$0.99
-2	$1.22	$1.20	$1.18	$1.16	$1.14	$1.12	$1.10	$1.08	$1.06	$1.04	$1.02
-1	$1.25	$1.23	$1.21	$1.19	$1.17	$1.15	$1.13	$1.11	$1.09	$1.07	$1.05
0	$1.29	$1.27	$1.25	$1.23	$1.21	$1.19	$1.17	$1.15	$1.13	$1.10	$1.08
1	$1.32	$1.30	$1.28	$1.26	$1.24	$1.22	$1.20	$1.18	$1.16	$1.14	$1.12
2	$1.35	$1.33	$1.31	$1.29	$1.27	$1.25	$1.23	$1.21	$1.19	$1.17	$1.15
3	$1.38	$1.36	$1.34	$1.32	$1.30	$1.28	$1.26	$1.24	$1.22	$1.20	$1.18
4	$1.41	$1.39	$1.37	$1.35	$1.33	$1.31	$1.29	$1.27	$1.25	$1.23	$1.21
5	$1.45	$1.43	$1.41	$1.39	$1.37	$1.35	$1.33	$1.31	$1.29	$1.26	$1.24

The canola oil, like other vegetable oils, has a lower calorific value than diesel. Previous experiments with canola oil at our lab showed that the TGB10 has about a 15% lower calorific value than diesel [14]. This results in higher fuel consumption on a mass basis by about 15%, assuming the engine efficiency does not change. On an energy density basis, TGB10 had 27% to 30% lower fuel consumption cost as compared to diesel. (Appendix, Exhibit D Table 8-1 shows the sensitivity analysis of TGB10 on the basis of energy density and fuel consumption compared to diesel baseline.)

Figure 6-1 shows the cost savings in using TGB10 over diesel on a farm. With a current diesel fuel price of $3.20 per gallon (as seen in this article) and a cost of production of TGB10 at $2.01 per gallon, a total savings of $1.19 per gallon on the cost of fuel at the farm could be achieved. An increase in the price of diesel or a decrease in the cost of TGB10, results in greater savings per gallon of fuel.

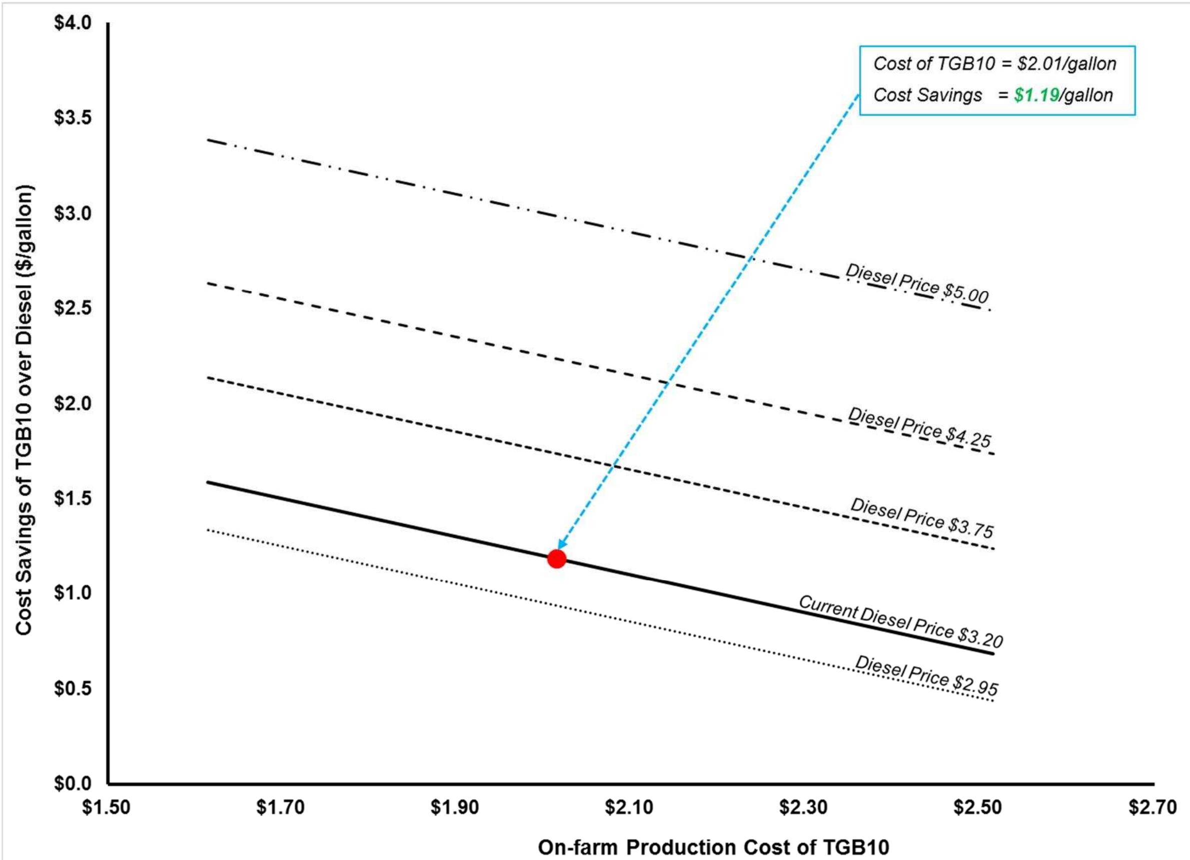


Figure 6-1: Cost savings of TGB10 over Diesel

6.3.3 COST OF OWNERSHIP OF FARM EQUIPMENT USING TGB10

To consider whether an alternative fuel is an economically viable alternative to diesel, it is necessary to analyze the operating and maintenance cost of the engine operating on the alternative fuel in addition to the fuel cost itself. Previous durability engine testing has shown more carbon deposits on piston head, coking of injectors and buildup on injector tip affecting the spray pattern for alternative fuels compared to diesel fuel [19-21]. These factors contribute to accelerate the engine and component aging, lower the engine performance and shorten the engine lifespan.

In this study, a diesel engine for off-road applications, similar to the one in tractors and combines is considered. Depending on the engine load profile and its intended application, the engine manufacturer will provide and recommend a maintenance schedule. Depending on the number of hours the engine has been in operation, a complete overhaul of the engine and its components may be necessary. This time period from a new engine to its complete overhaul is defined as “Time Before Overhaul” or TBO. For economic purposes, TBO signifies the end of the engine’s useful life, requiring significant amount of component changes, time and money to get the engine to its optimum performance level.

Table 6-8 shows a typical load profile for an agricultural engine. The engine operates at 100% load for 10% of the time, 75% load for 40% of the time, 50% load for 30% of the time, 25% load for 10% of the time and 10% load for 10% of the time. The time before overhaul (TBO) for this engine is usually defined by the manufacturer. Table 6-9 shows the maintenance schedule for an engine whose TBO is 10,000 hours that has been adapted from personal and professional communications with industry experts[34-36].

Table 6-8: Load profile for Agricultural Engine

Typical Load Profile for Agricultural Engines			
Engine Load %	**Time %**	**Load Factor %**	**TBO (hours)**
100	10		
75	40		
50	30	58.5	10000
25	10		
10	10		

Table 6-9: Typical engine maintenance schedule using diesel as fuel

Maintenance Item	Engine Operating hours										
	500	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**10000**
Lube oil & filter	X	X	X	X	X	X	X	X	X	X	X
Fuel filter	X	X	X	X	X	X	X	X	X	X	X
Valve gear			X		X		X		X		X
Air filters						X					X
Belt drive						X					X
NOx sensor										X	
Lambda sensor										X	
Humidity sensor										X	
Crankcase breathers						X					X
Fuel injectors						X					X
Exhaust gas recirculation						X					X
Intercooler						X					X
Cylinder heads						X					X
Component maintenance						X					X
HP fuel pump											X

For further analysis, we consider an off-road farm equipment with the diesel engine power rating of 130 kW, with a TBO of 10,000 hours, costing $200,000[37], and fuel consumption[14] as shown in Table 6-10. Two types of fuel are considered – diesel and TGB10. For engine operating on diesel fuel, the TBO is 10,000 hours.

For the engine operating of TGB10, four TBO timeframes (8,000 hours, 7,000 hours, 6,000 hours and 5,000 hours) are considered. Each of these four TBO periods represent scenarios where in the effect of using TGB10 has a rapid deteriorating effect on the engine and its components as discussed in Chapter 5 on the engine durability testing and lubricating oil analysis. Table 6-11 shows the engine maintenance schedule for a reduced TBO of 8000 hours when using TGB10 as fuel. Table 6-12 shows the cumulative time the engine operates at a different load over the TBO lifespan as a factor of operating load profile as shown in Table 8.

Table 6-10: Engine Fuel Consumption

Engine Load	Engine Power (kW)	Diesel Fuel Cons. (g/kWh)	TGB10 Fuel Cons. (g/kWh)
100%	130	193	198
75%	97.5	204	213
50%	65	234	258
25%	32.5	215	236.5
10%	13	249	245

Table 6-11: Engine maintenance schedule using TGB10 as fuel (TBO 8000 hours)

Maintenance Item	Engine Operating hours										
	400	800	1600	2400	3200	4000	4800	5600	6400	7200	8000
Lube oil & Filter	X	X	X	X	X	X	X	X	X	X	X
Fuel filter	X	X	X	X	X	X	X	X	X	X	X
Valve gear			X		X		X		X		X
Air filters						X					X
Belt drive						X					X
NOx sensor										X	
Lambda sensor										X	
Humidity sensor										X	
Crankcase breathers						X					X
Fuel injectors						X					X
Exhaust gas recirculation						X					X
Exhaust gas recirculation						X					X
Intercooler						X					X
Cylinder heads						X					X
Component maintenance						X					X
HP fuel pump											X

Table 6-12: Cumulative hours at a given load point over the span of TBO

Hours at each load point before TBO					
Load	**10000**	**8000**	**7000**	**6000**	**5000**
100%	1000	800	700	600	500
75%	4000	3200	2800	2400	2000
50%	3000	2400	2100	1800	1500
25%	1000	800	700	600	500
10%	1000	800	700	600	500

Table 6-13 shows the total cost of fuel and equipment invested for each of the fuel and TGB scenarios aligned to the diesel's TBO of 10,000 hours. Cost of Diesel fuel considered is $3.20 per gallon and TGB10 is $2.01 per gallon, as calculated from the previous section. For TGB10 fuel with a TBO of 8,000 hours, additional cost of a new reman engine pro-rated and TGB10 fuel consumption for remaining 2000 hours is considered. A complete replacement of the farm equipment is not considered necessary because it is assumed that only the engine lifespan is affected by the use of TGB10 as fuel. The other TBOs for TGB10 have been standardized in a similar way. The maintenance cost for each TBO are assumed to be the same.

The cumulative investment is $327,161 for using diesel fuel until a TBO of 10,000 hours. Overall, the cost of ownership of the farm equipment for all scenarios was less than diesel. If using TGB10 fuel and considering a TBO of 8,000 hours, the cumulative investment was close to that of diesel at $255,532 while using TGB10 fuel with a TBO of 5,000 hours would have cost almost 50% more than using diesel fuel even though the cost of TGB10 was 33% lower than diesel.

Table 6-13: Cost of ownership of farm equipment, standardized to a TBO of 10,000 hours

Cumulative Investment until TBO					
	Diesel TBO (hours)	**TGB10 TBO (hours)**			
	10000	**8000**	**7000**	**6000**	**5000**
Fuel Consumed in Kg	160505	135993	118994	101995	84996
Fuel Consumed in Liters	189946	160938	140821	120704	100587
Fuel Consumed in Gallons	39738	33669	29460	25252	21043
Fuel consumed in $	$127,161	$67,826	$59,347	$50,869	$42,391
Additional cost of fuel and equipment to TBO diesel baseline	$0	$20,706	$31,863	$43,913	$57,391
Total cost of ownership over 10,000 hours	**$327,161**	**$288,532**	**$291,210**	**$294,782**	**$299,782**

Tables 6-15 shows the sensitivity analysis on the ownership cost savings for a farm equipment using TGB10 as fuel for a TBO of 8,000 hours for different fuel prices. For a TBO of 8,000, a lower TGB10 price by roughly $1.5 per gallon compared to diesel yields a same cost of ownership as that of a TBO 10,000 hours operating on purely diesel fuel.

For a TBO of 7,000, a lower TGB10 price by roughly $2.5 per gallon compared to diesel yields a same cost of ownership as that of a TBO 10,000 hours operating on purely diesel fuel. For a TBO of 6,000, a lower TGB10 price by roughly $3.75 per gallon compared to diesel yields a same cost of ownership as that of a TBO 10,000 hours operating on purely diesel fuel. For a TBO of 5,000, a lower TGB10 price by roughly $4.80 per gallon compared to diesel yields a same cost of ownership as that of a TBO 10,000 hours operating on purely diesel fuel. Appendix, Exhibit D shows the sensitivity analysis for TBO 6k, 7k and 5k in Tables 8-2, 8-3 and 8-4 respectively.

Table 6-14: Ownership Cost Savings for farm equipment using TGB10 as a fuel over diesel (TBO of 8,000 hours)

Diesel Price	TGB10 Price $1.5	$2	$3	$4	$5	$6	$7
$2.5	$32,465	$10,812	-$31,274	-$73,361	-$115,447	-$157,533	-$199,620
$3.2	$60,281	$38,629	-$3,458	-$45,544	-$87,631	-$129,717	-$171,803
$4.0	$92,071	$70,419	$28,332	-$13,754	-$55,840	-$97,927	-$140,013
$5.0	$131,809	$110,157	$68,070	$25,984	-$16,103	-$58,189	-$100,276
$6.0	$171,547	$149,894	$107,808	$65,721	$23,635	-$18,451	-$60,538
$7.0	$211,284	$189,632	$147,545	$105,459	$63,373	$21,286	-$20,800
$8.0	$251,022	$229,370	$187,283	$145,197	$103,110	$61,024	$18,938

Figure 6-2 shows the trends in potential cost savings by using TGB10 over diesel in a farm engine. The lifespan of the engine in this scenario is 8000 hours. With an estimated cost of production of TGB10 at $2.01 per gallon and diesel cost at $3.20 per gallon, the farmer stands to lose $7,621. However, the ability to produce TGB10 at a cost of $1.90 per gallon or an increase in diesel price to $3.60 per gallon will result in cost savings for the farmer by using TGB10 as fuel. Similarly, for the following combination of fuel prices (TGB10: Diesel) $1.25:2.5, $2.5:4.0, $3.5:5.0 will be favorable for using TGB10 as a fuel in farm equipment. Similarly, as the cost of producing TGB10 increases, the cost of ownership of farm engines increases making it unfavorable to use TGB10 as an alternative to diesel fuel.

6.3.4 MORTGAGE AND PAYBACK ANALYSIS

The total Capital Expenditure (CAPEX) required to set up the oil extraction and TGB10 production facility is $266,955, shown in Table 15. It is assumed that the farmers will own 50% equity stake in the TGB10 production facility and the remaining 50% will be financed through loans at a rate of interest of 2.875% [38] per annum from financial institutions.

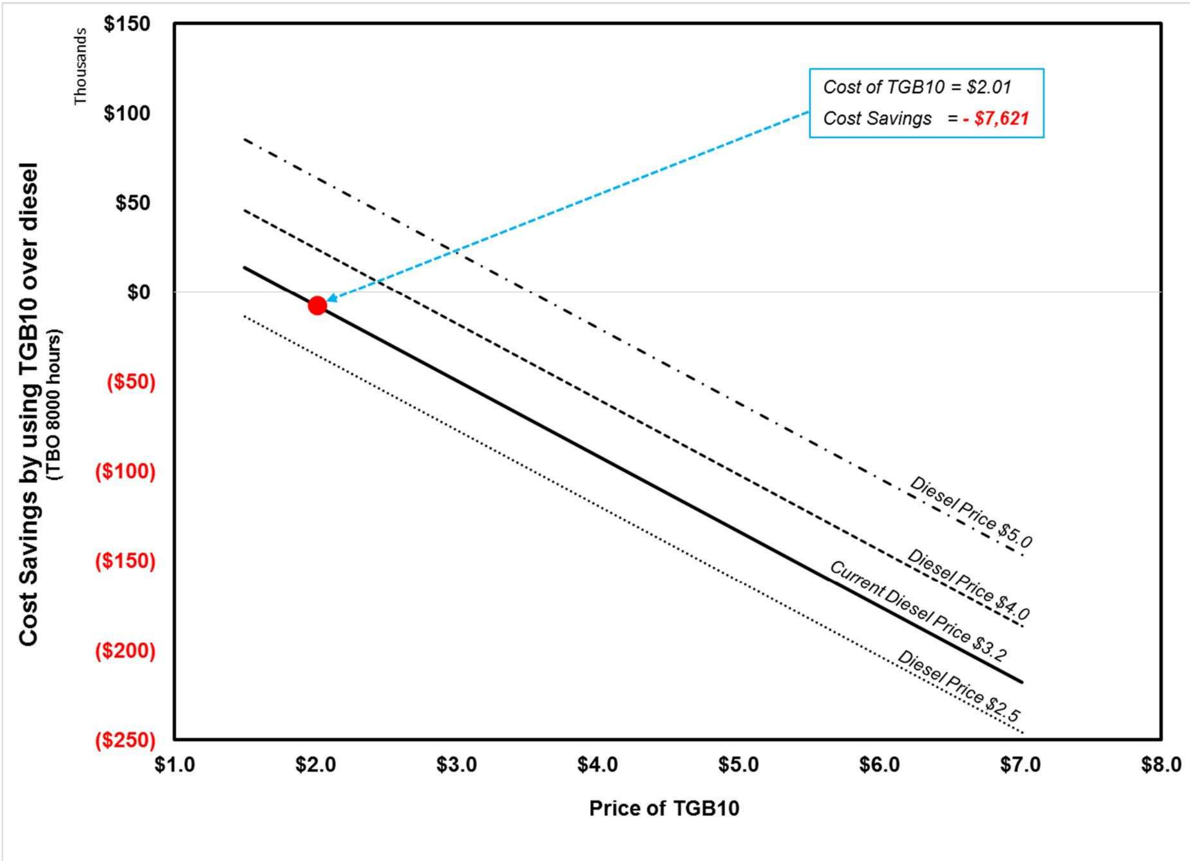


Figure 6-2: Cost savings over the lifetime of farm equipment using TGB10 as fuel (TBO 8000 hours)

Assuming the quantity of TGB10 fuel produced and consumed per year (128,216 gallons) and cost savings of $1.19 per gallon as compared to diesel, a 12-month loan payment duration after the beginning of TGB10 production is considered. The payment schedule over 12 months is shown in Table 6-16 and the Figure 6-3 shows the loan amortization (Principal and Interest).

The CAPEX investment payback analysis is shown in Table 6-17. The interest incurred over 12 months on the loan is $2,893. The interest cost apportioned to each gallon of TGB10 is $0.02 only for the first year of production after which the loan is paid off. A cost of insurance valued at $0.01 is apportioned to each gallon of TGB produced. The total cost of TGB10 production is $2.04.

To calculate the payback period, it is important to analyze the cost savings in using TGB10 for the same energy requirement as diesel. The calorific value of TGB10 is about 15% lower than diesel (Chapter 3). Hence the cost savings in using TGB10 over diesel to do the same amount of work is $0.84 per gallon. For a TGB10 production of 121,682 gallons per year, a total cost savings would be $107,729 per year and it would take about 2.5 years to payback the total CAPEX investment of $266,955.

Figure 6-4 shows the Return on Investment (ROI) on the CAPEX on the basis of on-farm TGB10 production at a cost $1.19 lower than the retail price diesel. After the payback at 2.5 year mark, the total ROI at the end of 3rd year is roughly $56,000. At the 10 year mark, ROI would $810,000 where the salvage value of the facility would be $27,000 - 10% of the CAPEX as assumed in this analysis.

Table 6-15: Mortgage Payment

CAPEX	$266,955
Equity	50%
Loan Amount	$133,477.50
Loan Duration (Years)	1
Loan Duration (months)	12
Interest Rate Per Annum	2.875%
Interest Rate per Month	0.004107143
Payment per month	$11,422.30

Table 6-16: Mortgage Payment Schedule

Month	Beginning Balance	Payment	Interest	Principal	Ending Balance
1	$133,477.50	$11,422.30	$548.21	$10,874.09	$122,603.41
2	$122,603.41	$11,422.30	$503.55	$10,918.75	$111,684.65
3	$111,684.65	$11,422.30	$458.70	$10,963.60	$100,721.05
4	$100,721.05	$11,422.30	$413.68	$11,008.63	$89,712.43
5	$89,712.43	$11,422.30	$368.46	$11,053.84	$78,658.58
6	$78,658.58	$11,422.30	$323.06	$11,099.24	$67,559.34
7	$67,559.34	$11,422.30	$277.48	$11,144.83	$56,414.51
8	$56,414.51	$11,422.30	$231.70	$11,190.60	$45,223.91
9	$45,223.91	$11,422.30	$185.74	$11,236.56	$33,987.35
10	$33,987.35	$11,422.30	$139.59	$11,282.71	$22,704.64
11	$22,704.64	$11,422.30	$93.25	$11,329.05	$11,375.58
12	$11,375.58	$11,422.30	$46.72	$11,375.58	$0.00

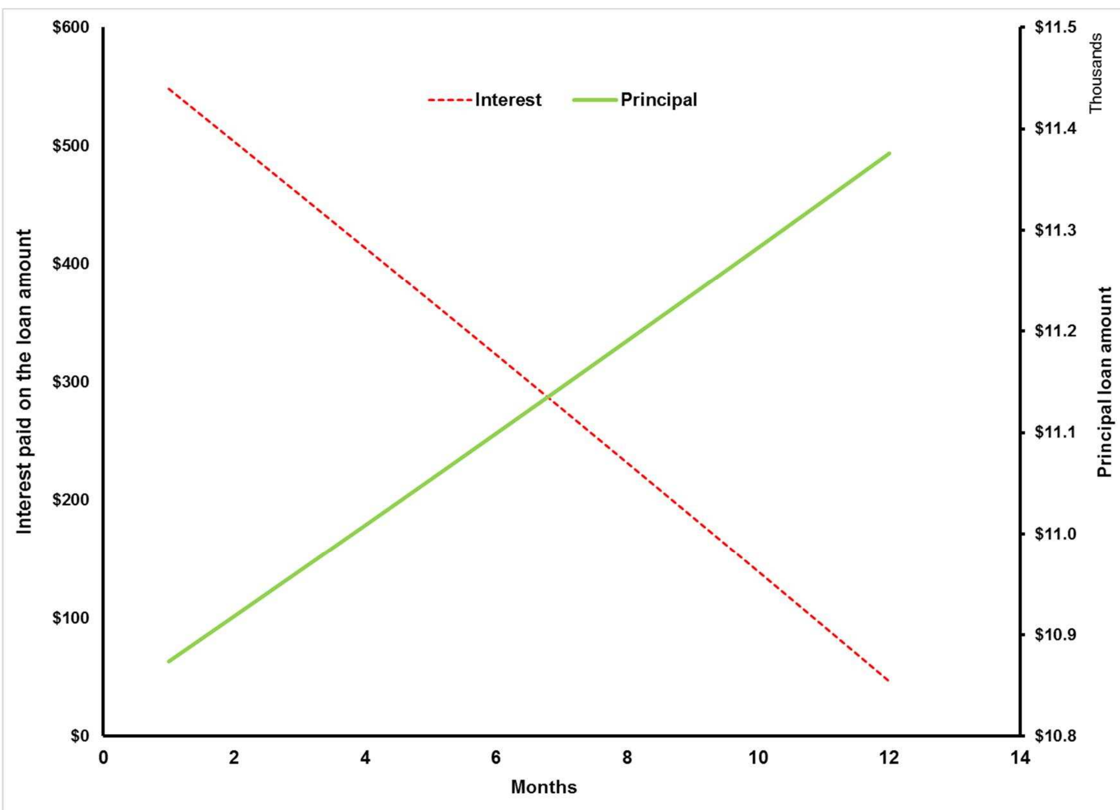


Figure 6-3: Principal and Interest over the duration of loan

Table 6-17: CAPEX Payback Time

TGB10 produced per year	128,216	Gallons
Cumulative Interest Payed over loan duration	$2,893	
Interest per Gallon of TGB10	$0.02	
Small Business Premium	$960	
Insurance per Gallon TGB10	$0.01	
Additional Cost of TGB10 (1st year Only)	$0.03	
Additional Cost of TGB10 (every year)	**$0.01**	
Calorific Value of Diesel	42.8	MJ/Kg
Calorific Value of TGB10	37.0	MJ/Kg
Cost of Diesel on Energy Density of 42.8 MJ/Kg	$3.20	per gallon
Cost of TGB10 for Energy Density of 37 MJ/Kg	$2.04	per gallon
Cost of TGB10 for Energy Density of 42.8 MJ/Kg	$2.36	per gallon
Cost Savings by using TGB10 for Energy Density of 42.8 MJ/Kg	$0.84	per gallon
Total Cost Savings by using TGB10	**$107,729**	per year
CAPEX Investment Payback time	**2.5**	**years**

Figure 6-5 shows the Payback Period on the CAPEX on the basis of cost of ownership of farm equipments using TGB10 produced on-farm at a cost of $2.01 and various retail prices of diesel fuel. At the diesel price of $3.2 a gallon, the payback period for farm equipments at a TBO of 8000 hours is 9 years while that for a TBO of 5000 hours is about 11 years. For a diesel retail price of $5 per gallon, the payback period was more lucrative around 3 years for TBOs of 8000 hours, 7000 hours, 6000 hours and 5000 hours. As the price of diesel increases, the cost of ownership of using TGB10 decreases and the payback period is more lucrative and largely remains unaffected by the TBO hours.

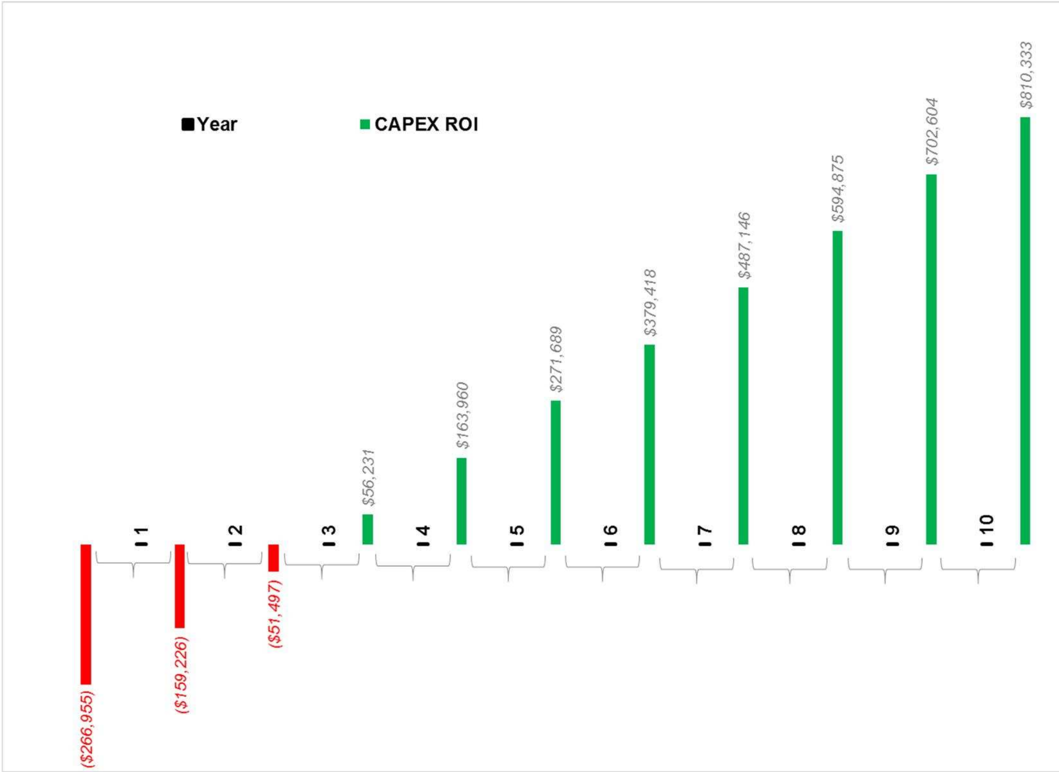


Figure 6-4: Return on Investment on CAPEX over 10 years

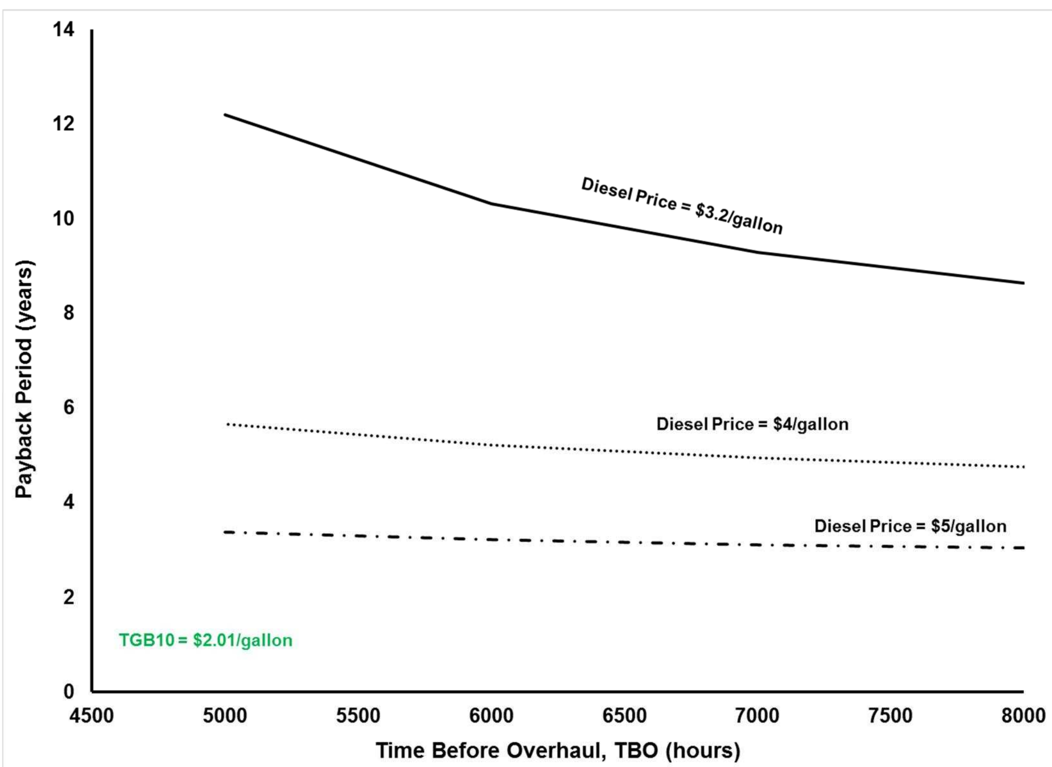


Figure 6-5: Payback Period (Cost of ownership basis)

6.4 VALUE PROPOSITION FOR TGB10

The main value of using TGB10 is that it could result in major cash savings for customers shifting from using diesel as fuel. The target customers are people who own and operate off road equipment that use diesel as fuel. Farming, backup power generation and mining industries are the major customers who are always looking for cheaper fuel. The cost of fuel prices has a major share in the way they do business and directly affects their balance sheet bottom line.

This fuel production service should be out in the market slowly capturing the market in about 18 months. This can be done in 3 stages, each of 6 months. The first 6 months can be used to obtain necessary approvals from government, initiate negotiations with customers and partners. The next 6 months could be used to set up infrastructure, grown canola crop and launch TGB10 production. The last 6 months can be used to make improvements and upgrades in the service in this dynamic market.

The cost sharing structure can be in three tiers – (i) Tier-I customers who also are partners and hold some equity in Big Squeeze LLC. (ii) Tier -II customers who buy fuel in bulk quantities, periodically and (iii) Tier-III customers who buy fuel in small quantities whenever the need arises. Each of these tiers should have a different pricing strategy which is competitive to the nearest diesel producing corporation. Refer Appendix, Exhibit D for more analysis on value proposition.

6.5 CONCLUSIONS:

This paper presents the economics of using TGB10 as an alternative to diesel fuel for off-road applications. The cost of growing canola oil seed, processing it into TGB0 fuel and the maintenance costs of the engine for a TBO of 8000, 7000, 6000 and 5000 hours was normalized and compared to a diesel TBO of 10,000 hours.

- 37% lower cost of TGB10 as compared to diesel can be produced. The cost of growing canola and facility for crushing it are the main drivers for the price of canola TGB10.
- A further reduction in the cost of processing canola seeds into TGB10 can be achieved if pre-used or refurbished equipment are procured. Similarly, effective distribution of canola TGB10 can reduce the storage cost resulting in lower CAPEX and on farm TGB10 production cost.
- A fuel cost savings of $108,000/year and a 2.5-year payback on CAPEX based on fuel cost savings is possible when 50% of the CAPEX is financedA return of investment of $810,000 over a period of 10 years can be possible for an on-farm TGB10 production facility.
- Lower cost of an alternative fuel compared to diesel need not necessarily result in cash savings for the user. A complete lifecycle analysis of alternative fuel – from cost production to cost of equipment ownership needs to be considered to evaluate the potential savings of using an alternative fuel.
- TGB10 can potentially replace diesel and result in cash savings for the daily user provided the cost of maintenance and operation of equipment using TGB10 is not greater than 20% of diesel, and the price of diesel is significantly higher than TGB10.

6.6 REFERENCES

[1] C. Hunsberger, L. German, and A. Goetz, "“Unbundling” the biofuel promise: Querying the ability of liquid biofuels to deliver on socio-economic policy expectations," *Energy Policy,* vol. 108, no. Supplement C, pp. 791-805, 2017/09/01/ 2017.

[2] A. Baumber, "Enhancing ecosystem services through targeted bioenergy support policies," *Ecosystem Services,* vol. 26, no. Part A, pp. 98-110, 2017/08/01/ 2017.

[3] K. Koponen, S. Soimakallio, K. L. Kline, A. Cowie, and M. Brandão, "Quantifying the climate effects of bioenergy – Choice of reference system," *Renewable and Sustainable Energy Reviews,* vol. 81, no. Part 2, pp. 2271-2280, 2018/01/01/ 2018.

[4] J. Abrams, D. Becker, J. Kudrna, and C. Moseley, "Does policy matter? The role of policy systems in forest bioenergy development in the United States," *Forest Policy and Economics,* vol. 75, no. Supplement C, pp. 41-48, 2017/02/01/ 2017.

[5] A. Corsini, G. Fanfarillo, F. Rispoli, and P. Venturini, "Pollutant Emissions in Common-rail Diesel Engines in Extraurban Cycle: Rapeseed Oils vs Diesel Fuel," *Energy Procedia,* vol. 82, no. Supplement C, pp. 141-148, 2015/12/01/ 2015.

[6] A. Corsini, A. Marchegiani, F. Rispoli, F. Sciulli, and P. Venturini, "Vegetable Oils as Fuels in Diesel Engine. Engine Performance and Emissions," *Energy Procedia,* vol. 81, pp. 942-949, 2015/12/01 2015.

[7] H. Li, P. Biller, S. A. Hadavi, G. E. Andrews, G. Przybyla, and A. Lea-Langton, "Assessing combustion and emission performance of direct use of SVO in a diesel engine by oxygen enrichment of intake air method," *Biomass and Bioenergy,* vol. 51, no. Supplement C, pp. 43-52, 2013/04/01/ 2013.

[8] C. M. H. Keske, D. L. Hoag, A. Brandess, and J. J. Johnson, "Is it economically feasible for farmers to grow their own fuel? A study of Camelina sativa produced in the western United States as an on-farm biofuel," *Biomass and Bioenergy,* vol. 54, no. 0, pp. 89-99, 7// 2013.

[9] S. Akao, D. Yasutake, K. Kondo, H. Nagare, M. Maeda, and T. Fujiwara, "Effects of cultivation period on catch crop chemical composition and potential for bioenergy production," *Industrial Crops and Products,* vol. 111, pp. 787-793, 1// 2018.

[10] T. Maaz *et al.*, "Economic, policy, and social trends and challenges of introducing oilseed and pulse crops into dryland wheat cropping systems," *Agriculture, Ecosystems & Environment,* vol. 253, no. Supplement C, pp. 177-194, 2018/02/01/ 2018.

[11] R. F. Meyer. Canola Production Guide Summary [Online].

[12] D. G. Fuels. (2008). *Regarding the ridiculous crap "Diesel Secret"*.

[13] C. Piatt, "Energy Independence: From Crop to Tank,"

[14] A. Lakshminarayanan, D. B. Olsen, and P. E. Cabot, "Effects of triglyceride gasoline blends on combustion and emissions in a common rail direct injection diesel engine," *International Journal of Engine Research,* p. 1468087417740316, 2017.

[15] L. Arunachalam, B. O. Daniel, and E. C. Perry, "Performance and Emission Evaluation of Triglyceride-Gasoline Blends in Agricultural Compression Ignition Engines," vol. 30, no. 4, 2014.

[16] A. C. Drenth, D. B. Olsen, P. E. Cabot, and J. J. Johnson, "Compression ignition engine performance and emission evaluation of industrial oilseed biofuel feedstocks camelina, carinata, and pennycress across three fuel pathways," *Fuel,* vol. 136, pp. 143-155, 11/15/ 2014.

[17] C. D. Aaron, D. Karolien, E. C. Perry, and B. O. Daniel, "Evaluation of Industrial Corn Oil as an On-Farm Biofuel Feedstock," vol. 31, no. 5, 2015.

[18] A. C. Drenth, D. B. Olsen, and K. Denef, "Fuel property quantification of triglyceride blends with an emphasis on industrial oilseeds camelina, carinata, and pennycress," *Fuel,* vol. 153, pp. 19-30, 8/1/ 2015.

[19] S. Nettles-anderson, D. B. Olsen, J. Johnson, and N. Enjalbert, "Engine Durability Testing of Unrefined Straight Vegetable Oil," ed.

[20] S. Nettles-anderson, D. B. Olsen, J. J. Johnson, and J. Enjalbert, "Performance of a Direct Injection IC Engine on SVO and Biodiesel from Multiple Feedstocks," ed: J Power Energy Eng, pp. 1–13, 2014.

[21] S. Nettles-Anderson and D. Olsen, "Survey of straight vegetable oil composition impact on combustion properties," ed: SAE, 2009.

[22] J. R. Connolly, V. McCracken, and K. Painter. Enterprise Budgets: 3-Year Wheat and Canola Rotations in Eastern Washington Intermediate Rainfall Regions (12" to 16") [Online].

[23] Aaron Smith and I. o. A. University of Tennessee Extension. 2017/18 Wheat/Soybean, Wheat, and Canola Budget Spreadsheet (Fall Amendment) [Online].

[24] K. Sun, F. Jian, D. S. Jayas, and N. D. G. White, "Quality changes in high and low oil content canola during storage: Part I – Safe storage time under constant temperatures," *Journal of Stored Products Research,* vol. 59, no. Supplement C, pp. 320-327, 2014/10/01/ 2014.

[25] K. G. Moore and C. L. Jones, "Impact of a polyethylene liner on the storage of winter canola seed in unaerated steel bins," *Journal of Stored Products Research,* vol. 73, no. Supplement C, pp. 125-128, 2017/09/01/ 2017.

[26] R. Rajapakse, "Chapter 13 - Equipment Depreciation," in *Construction Engineering Design Calculations and Rules of Thumb*: Butterworth-Heinemann, 2017, pp. 263-269.

[27] S. B. Jackson, X. Liu, and M. Cecchini, "Economic consequences of firms' depreciation method choice: Evidence from capital investments," *Journal of Accounting and Economics,* vol. 48, no. 1, pp. 54-68, 2009/10/01/ 2009.

[28] C. C. o. Canada. Historic Canola Average Prices [Online].

[29] U. Economic Research Service. Canola Oil: Price, disappearance and supply, U.S [Online].

[30] S. Margaret. (2017). *Canola Profile*.

[31] U. Economic Research Service, "Canola Meal: Price, disappearance and supply, U.S," ed, 2016.

[32] M. A. Food and Rural Development, "Guidelines for estimating crop production costs," ed, 2016.

[33] E. I. Administration. Weekly US no 2 Ultra Low Sulfur (0-15ppm) Diesel Retail Prices [Online].

[34] J. D. Inc. Service Intervals: Servicing your machine. [Online].

[35] D. P. S. Group, Operation and Maintenance Manual, 1996. [Online]. Available.

[36] A. Laksminarayanan, I. Experts., and E. D. a. Distributors., "Diesel engine maintenance achedule," ed, 2017.

[37] M. Pete. *https://*www.machinerypete.com/media_posts.

[38] F. S. A. USDA. Farm Loan Program [Online].

[39] A. Osterwalder and Y. Pigneur, *Business Model Generation*. 2010.

7. RESEARCH CONCLUSIONS AND RECOMENDATIONS

To supplement their agricultural income, the farmers at Rocky Ford, Colorado, began to grow canola during a fallow season and sell the meal to a nearby animal feeding lot. The oil extracted from the Canola seeds was then used in their diesel-powered farm equipment. To overcome the poor physical properties of the canola oil like high viscosity, the farmers started blending a combination of gasoline and diesel to the oil to match the specific gravity of diesel. The farmers believed that this blend of canola oil and gasoline gave them better gas mileage, produced lower emissions and the engines produced more power and worked fine.

To verify the claims of the farmers, the researchers from this study visited the farmers at their farm and conducted tests on the farm equipments using blends that the farmer prepared. The experiments concluded that the engine produced lower power and had higher fuel consumption. There were no emission measurements taken on the farm.

The researchers conducted detailed tests on the fuel physical properties, engine and emission tests at their research facility. To explore the limits of gasoline blending in canola oil, the researchers prepared and tested fuel blends containing canola oil and various percentages of gasoline content ranging from 5% to 80%. The combustion statistics, engine ECU parameters and exhaust emissions were recorded and analyzed.

Further, to better understand the impact of canola TGB10 and canola biodiesel on engine components, a durability test for 250 hours was conducted on a Yanmar engine. Injector spray pattern, carbon build up and lubricating oil analysis formed the basis of the Chapter 5 section of the study.

Finally, an economic analysis on the lifecycle ownership costs of producing and using TGB10 on a farm was considered. TGBs could be considered as a simple, yet crude approach to biodiesel, especially for off-road applications like farming. The specific observations from each section of this study are summarized below.

Fuel Properties: - High viscosities (~7 times of diesel) and poor cold flow properties of TGB10 could affect engine performance and reliability in extremely cold climates. The calorific value of TGB10 was about 9% lower than diesel. Blending of gasoline to achieve the viscosity range similar to B100 (1.9 mm^2/s to 6.0 mm^2/s) and B20 (1.9 mm^2/s to 4.1 mm^2/s) will help define the acceptable limits for a variety of feedstocks. The metal content like Sulphur and Phosphorus were higher than the ASTM D6751-2 limits for biodiesel diesel which is a concern for engine after-treatment catalysts. Refining and purifying of TGB10 to meet ASTM standards may result in additional costs and will need to be considered for economic analysis.

Engine performance for TGB10: - Higher mass based fuel consumption and slightly higher thermal efficiencies were recorded using TGB10 compared to diesel. The cylinder pressure traces and location of 50% mass fraction burnt for TGB10 and diesel were similar in most load points of the ISO 8178 8-mode test cycle. The average peak pressure was within ±4.5% to that of diesel. The combustion duration of was about 12% to 15% shorter than diesel. the use of TGB10 resulted in a 9.8% increase in weighted NOX emissions, 5.5% decrease in weighted PM emissions and 51.7% lower CO emissions in comparison to diesel.

Engine performance for TGB gasoline variation: - The engine performance for TGBs containing 5% to 80 % gasoline content can be separated into three groups – (i) Low gasoline percentage blends (≤ 25% gasoline content), (ii) Intermediate gasoline percentage blends (30% ≤ gasoline content ≥ 55%) and High gasoline percentage blends (60% ≤ gasoline content ≥ 80%). For low gasoline percentage blends, most of the combustion parameters were identical to 100% triglyceride. For intermediate gasoline percentage blends, the combustion parameters were similar to diesel and for high gasoline content blends, the combustion parameters were significantly different than diesel as the base fuel.

Engine durability performance: - A durability study (250 hours) on three fuels – (i) off road diesel, (ii) canola based bio diesel, and (iii) canola based TGB10 was conducted on a single-cylinder, naturally aspirated Yanmar diesel engine operating at constant load. TGB10 seemed to have a greater build up on the injector tip and a thick sludge like deposit on the piston crown. Biodiesel seemed to have a cleansing effect on the tip of the injector. A visual comparison of the injector spray indicated TGB10 had the shortest penetration depth. The kinematic viscosity of the lube oil did not seem to change much with the use of the three fuels, soot content in lube oil for TGB10 showed a steady increase over the period of time. The sulfation and oxidation levels of lube oil for TGB10 as a fuel were orders of magnitude higher than diesel and biodiesel. The content of wear metals in lube oil for TGB10 were significant, indicating a reduced lifespan of engine component, frequent oil and component changes as compared to diesel and biodiesel.

Economic and business case: - The analysis showed that it is possible to produce TGB10 at a cost lower than that of diesel in both – volume and energy density basis. Farming techniques to reduce cost of crop production and using refurbished equipment in crop processing could significantly bring down the cost of TGB10. Lower cost of alternative fuel may not guarantee cost savings for the user. A comprehensive life cycle modeling from growing canola crop to using TGB10 as fuel should be considered. The cost of ownership can significantly vary on the lifespan of engine and its components. Expensive diesel prices and higher engine lifespans are the key to making TGB10 economically viable.

Recommendations for future work: - The use of TGB10 as an alternative to diesel is interesting. A detailed and quantifiable analysis about the effect of alternative fuels on engine and machinery components will help in developing alternative fuels. The following recommendations will help investigate, understand and further the research:

- Blending triglycerides with gasoline to match diesel's density is recommended rather than using specific gravity. For Canola feedstock, blending gasoline with around 50% gasoline will help match the physical properties of the TGB closely to diesel. It will be helpful to then compare the TGBs to diesel more accurately.
- A process and method to refine, purify and enhance the physical properties of TGB10 to meet ASTM standard 6517 D will be helpful to achieve biodiesel like properties for TGB10.
- A complete engine calibration using industry techniques for TGB10 is recommended to understand whether an efficient combustion and lower emissions could be achieved.
- A study on carbon build-up mechanisms will help in understanding the wear and tear, and predict accurately the lifespan of engine components when using TGBs.

APPENDIX

8. APPENDIX

8.1 EXHIBIT A: FOR CHAPTER 2

8.1.1 ENGINE DATA – JD4045 Tier-II

Table 8-1: Engine Operating Condition and Tailpipe Emissions

	JD Tier-II 4045											
	80% 2400rpm				80% 1700 rpm				100% 1700 rpm			
	DSL	Blend A	Blend B	Blend C	DSL	Blend A	Blend B	Blend C	DSL	Blend A	Blend B	Blend C
Compressor Diff Pressure [psi]	0.03	0.03	0.02	0.03	0.03	0.03	0.02	0.03	0.03	0.02	0.02	0.02
Intake Manifold Pressure [psig]	19.3	18.7	18.8	18.8	15.9	15.5	15.6	15.8	20.0	16.9	18.0	18.6
Exhaust Manifold Pressure [psig]	16.6	16.9	14.3	12.5	8.27	9.48	9.49	9.66	10.2	10.2	10.9	11.3
Exhaust Back Pressure [in H2O]	0.36	0.35	0.41	0.23	0.17	0.20	0.18	0.18	0.21	0.18	0.20	0.20
Engine Oil Pressure [psig]	66.0	65.4	64.0	67.6	52.8	56.0	56.1	54.4	52.1	53.5	53.2	51.8
Fuel Supply Flow [kg/hr]	51.1	49.3	56.4	59.5	45.5	42.2	44.9	46.6	49.0	41.6	47.7	49.7
Fuel Return Flow [Lpm]	0.52	2.08	1.35	0.68	0.51	1.56	0.87	0.58	0.51	2.01	1.09	0.64
Inlet Air Temp [°C]	22.2	26.1	52.1	45.9	21.2	37.1	38.8	50.4	21.7	38.1	44.7	45.6
Inlet Air Temp [°F]	71.9	78.9	126	115	70.1	98.8	102	123	71.0	101	113	114
ntake Air- Pre Intercooler Temp [°C]	197	190	194	195	154	151	154	155	177	162	170	173
Intake Manifold Air Temp [°C]	38.3	38.3	38.5	37.8	37.3	36.0	35.7	36.2	37.6	36.8	36.8	37.1
Exhaust Cyl 1 Temp [°C]	531	514	522	523	555	552	550	553	595	569	578	585
Exhaust Cyl 1 Temp [°F]	987	957	972	974	1030	1025	1022	1028	1103	1057	1073	1085
Exhaust Cyl 2 Temp [°C]	566	551	564	568	598	586	597	596	625	607	624	630
Exhaust Cyl 3 Temp [°C]	560	542	550	552	592	576	582	579	620	595	609	615
Exhaust Cyl 4 Temp [°C]	512	501	511	512	543	530	541	536	563	550	567	573
Stack Temp [°C]	438	425	435	434	513	500	508	505	520	511	520	521
Engine Oil Temp [°C]	75.2	73.9	77.2	68.6	78.5	71.2	68.3	74.2	79.4	74.3	73.9	77.1
Intercooler Inlet Water Temp [°C]	6.92	6.92	6.92	6.93	6.91	6.96	6.96	6.93	6.90	6.93	6.94	6.92
Fuel Inlet Temp [°C]	25.2	76.5	82.7	74.8	23.1	73.2	73.4	77.0	23.9	79.3	79.8	82.0
Fuel Inlet Temp [°F]	77.3	170	181	167	73.6	164	164	171	75.0	175	176	180
Jacketwater Out Temp [°C]	86.2	86.3	89.9	82.4	89.8	80.3	80.6	83.7	90.1	86.6	87.0	89.6
Jacketwater In Temp [°C]	83.0	83.2	86.7	79.4	86.4	77.5	77.9	80.8	86.6	83.7	83.9	86.3
Dyno Out Temp [°C]	23.6	23.8	24.0	24.2	21.2	21.3	21.4	21.6	23.4	22.2	22.9	23.3
Dyno In Temp [°C]	7.1	7.1	7.3	7.4	7.0	7.2	7.3	7.4	7.0	7.2	7.3	7.4
Speed [RPM]	2400	2400	2400	2400	1700	1700	1700	1700	1700	1700	1700	1700
Power [kW]	108	109	108	110	95	95	95	96	113	100	105	107
Power [hp]	145	146	145	147	127	127	127	128	151	134	141	143
Torque [N-m]	430	432	431	436	532	534	534	537	634	560	588	599
THC [ppm dry]	31.8	34.4	27.9	27.5	31.6	31.2	28.9	28.1	30.1	29.3	27.3	25.9
O2 [% dry]	13.2	13.3	13.2	13.1	12.0	11.9	11.9	11.9	11.5	11.9	11.8	11.7
NOx [ppm dry]	311	384	368	356	549	595	587	576	548	604	594	587
CO2 [% dry]	5.78	5.62	5.62	5.64	6.42	6.67	6.60	6.56	6.84	6.64	6.69	6.68
CO [ppm dry]	127	72.3	90.4	101	154	72.3	110	127	284	72.3	87.2	103

8.2 EXHIBIT B: FOR CHAPTER 3

8.2.1 ENGINE DATA – JD4045 Tier-III

Table 8-2: Engine Operating Condition and Tailpipe Emissions

	Diesel								TGB10							
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
Intake Manifold Pressure [psig]	5.52	3.98	2.27	0.80	3.06	2.17	2.01	0.16	5.22	3.56	1.92	0.67	2.96	2.16	1.33	0.17
Exhaust Manifold Pressure [psig]	19.6	14.2	10.9	15.0	13.3	10.4	4.81	5.13	22.3	17.7	14.6	13.1	16.4	9.52	8.00	5.35
Exhaust Back Pressure [in H2O]	1.92	1.39	0.91	0.63	1.55	1.07	0.49	0.11	2.00	1.54	1.10	0.57	1.67	0.98	0.64	0.12
Engine Oil Pressure [psig]	57.9	60.8	62.9	64.6	51.8	56.3	55.5	44.8	59.7	59.7	60.3	65.0	52.7	52.4	54.4	46.9
Torque [N-m]	499	375	250	52	499	375	250	7	499	375	250	52	499	375	250	7
Power [kW]	115	86.9	57.6	12.0	89.6	70.1	44.5	1.00	115	86.2	57.6	12.0	89.0	67.0	44.2	1.00
Speed [RPM]	2205	2205	2200	2202	1714	1783	1699	1100	2202	2201	2200	2202	1706	1700	1697	1102
Dyno In Temp [C]	12.3	12.0	12.0	12.1	12.1	12.2	12.2	12.2	12.4	12.4	12.4	12.3	12.4	12.3	12.3	12.4
Dyno Out Temp [C]	47.8	38.9	30.2	16.5	40.4	33.7	26.1	13.0	46.5	38.4	30.1	16.6	39.0	32.7	26.1	13.3
Jacketwater In Temp [C]	87.6	81.0	78.0	79.8	89.9	83.1	77.7	82.3	83.7	82.3	82.9	75.7	82.4	83.6	79.4	73.0
Jacketwater Out Temp [C]	83.9	78.0	75.6	78.5	86.5	80.2	75.3	82.0	80.4	79.5	80.4	74.1	79.5	80.8	77.2	72.6
Intercooler Inlet Water Temp [C]	11.8	11.6	11.6	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.6	11.7
Engine Oil Temp [C]	62.5	50.5	45.6	43.0	61.0	50.4	48.1	40.6	49.7	48.9	56.3	50.6	51.8	58.3	52.7	43.4
Stack Temp [C]	429	394	348	202	457	424	438	151	386	361	320	206	418	427	358	163
Exhaust Cyl 4 Temp [C]	519	465	409	275	516	471	480	171	499	449	389	271	504	474	403	171
Exhaust Cyl 3 Temp [C]	569	509	432	276	580	522	519	169	541	488	422	274	559	526	434	173
Exhaust Cyl 2 Temp [C]	568	498	405	274	566	501	481	166	547	471	388	269	549	485	391	168
Exhaust Cyl 1 Temp [C]	585	1194	405	279	840	n/a	588	166	755	872	n/a	279	n/a	n/a	n/a	169
Intake Manifold Air Temp [C]	27.2	22.5	19.0	17.3	22.0	19.6	15.9	13.6	26.1	22.9	20.4	17.1	21.7	18.3	16.4	13.9
Charge Air - Pre Intercooler Temp [C]	32.3	29.0	27.3	26.5	30.2	28.1	27.5	30.7	30.7	30.0	29.0	27.1	29.7	29.1	28.1	29.9
Inlet Air Temp [C]	184	149	118	96.6	157	134	89.7	53.9	194	163	134	96.4	162	122	97.4	52.9
THC [ppm dry]	21.3	21.7	27.8	74.9	23.1	23.4	34.2	66.9	39.2	32.0	34.2	152.1	35.3	29.0	35.5	151.8
O2 [% dry]	9.79	10.8	12.2	16.7	8.66	9.75	9.86	18.4	10.2	11.5	13.0	16.7	9.28	9.38	11.4	18.3
NOx [ppm dry]	532	451	371	116	715	606	451	156	570	487	382	94.5	699	792	578	98.8
CO2 [% dry]	7.98	7.24	6.28	2.98	8.80	8.05	7.93	1.78	7.89	6.96	5.84	3.07	8.57	8.49	6.98	1.83
CO [ppm dry]	91.0	128	182	521	222	177	145	281	56.8	66.2	95.3	700	54.8	92.1	107	698

8.2.2 ENGINE IN-CYLINDER COMBUSTION DATA – JD4045 Tier-III

Table 8-3: In-Cylinder Combustion Statistics over 8 modes

	DSL								TGB10							
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
Avg. Peak [kPa]	148	123	107	88	135	115	85	64	154	125	108	81	127	117	106	64
Peak Std. Dev.	1.6	2.8	3.4	0.7	1.6	3.1	1.0	0.4	1.3	1.3	1.9	0.6	1.3	2.3	2.8	0.4
Peak COV	1.1	2.3	3.2	0.8	1.2	2.7	1.1	0.6	0.8	1.0	1.7	0.7	1.0	2.0	2.6	0.7
Max Peak [kPa]	156	142	122	91	140	127	89	66	158	132	116	82	131	126	121	65
Min Peak [kPa]	144	116	100	86	130	108	82	63	149	122	103	79	124	110	98	63
Avg. Peak Loc.	8.9	8.5	12.3	0.3	16.3	16.2	0.4	4.8	7.2	6.4	9.0	0.5	15.1	17.3	13.7	5.7
Peak Loc. Std. Dev	1.9	1.6	2.5	0.8	1.8	1.6	1.2	0.9	1.8	1.6	2.9	0.6	4.6	1.2	1.3	0.4
Peak Loc. COV	21.1	19.2	20.3	29.9	11.2	10.0	316.9	17.8	24.8	25.8	32.9	10.4	30.1	6.9	9.9	6.8
AVG IMEP [kPa]	36.5	23.8	17.6	7.4	29.7	22.7	16.1	2.9	31.0	24.3	17.7	7.4	29.7	23.3	17.1	3.0
IMEP STD DEV	0.3	0.2	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1
IMEP COV	0.8	0.9	1.0	1.4	0.8	0.9	1.2	2.5	0.8	0.8	1.2	2.0	0.7	0.8	1.4	2.3
AVG NIMEP [kPa]	36.2	23.5	17.1	6.1	29.8	22.7	16.1	2.4	30.4	23.6	17.0	6.2	29.6	23.2	16.8	2.5
NIMEP STD DEV	0.3	0.2	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1
NIMEP COV	0.8	0.9	1.1	1.7	0.8	0.9	1.2	3.0	0.8	0.8	1.2	2.4	0.7	0.8	1.4	2.7
AVG PIMEP [kPa]	-0.4	-0.4	-0.5	-1.4	0.1	0.0	0.0	-0.5	-0.6	-0.6	-0.8	-1.2	0.0	-0.1	-0.3	-0.5
PIMEP STD DEV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PIMEP COV	-5.6	-7.0	-6.2	-1.8	15.7	40.7	-18.5	-1.2	-3.9	-3.3	-4.7	-2.5	-51.9	-18.4	-5.8	-1.3
MFB 10% [CAD]	8.6	11.1	10.4	12.4	11.3	9.9	17.1	-19.4	10.0	11.2	10.4	13.1	12.4	10.4	8.4	-19.2
MFB 50% [CAD]	20.6	20.1	18.7	18.2	20.7	18.4	24.0	-14.9	20.4	19.9	18.3	19.3	21.8	18.3	16.3	-14.2
MFB 90% [CAD]	35.3	39.0	38.7	32.6	39.1	41.9	45.9	-11.1	36.6	36.1	35.5	33.8	40.5	38.9	37.2	-9.1

8.3 EXHIBIT C: FOR CHAPTER 4

8.3.1 ENGINE DATA – JD4045 Tier-III

Table 8-4 Engine Operating Conditions and Tailpipe Emissions (75% Load, 1700 rpm)

	DSL	95-05	90-10	85-15	80-20	75-25	65-35	60-40	50-50	45-55	40-60	30-70	20-80
Intake Manifold Pressure [psig]	5.58	7.61	7.87	7.28	7.23	6.91	6.49	6.09	5.56	5.35	5.9	5.8	5.5
Exhaust Manifold Pressure [psig]	4.99	10.21	10.21	9.52	9.25	8.93	8.23	7.63	6.87	6.57	5.8	5.7	5.6
Engine Oil Pressure [psig]	46.5	46.3	45.8	45.8	45.4	45.6	45.7	45.8	45.8	45.9	45.3	45.2	45.4
Precooler Pressure [psig]	6.11	8.27	8.52	7.93	7.89	7.55	7.07	6.62	6.06	5.86	6.5	6.4	6.1
Torque [N-m]	252	247	255	249	255	249	250	248	247	246	249	253	247
Power [kW]	44.8	44.0	45.2	44.5	45.5	44.2	44.8	44.0	44.0	44.0	44.2	45.0	44.0
Speed [RPM]	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700
Dyno In Temp [C]	13.7	13.8	13.9	14.0	14.2	14.0	14.0	14.1	14.0	14.0	13.7	13.6	13.7
Dyno Out Temp [C]	21.9	22.0	22.2	22.1	22.5	22.3	22.3	22.3	22.3	22.2	22.0	22.1	22.0
Jacketwater In Temp [C]	65.8	65.2	67.3	66.5	67.6	67.6	67.5	67.3	67.5	67.1	67.6	67.6	67.6
Jacketwater Out Temp [C]	68.9	68.0	70.0	69.2	70.3	70.3	70.3	70.1	70.4	70.0	70.4	70.4	70.3
Fuel Inlet Temp [C]	23.2	18.3	19.2	20.3	21.5	21.1	22.2	23.3	24.0	24.0	24.6	26.0	28.4
IC Water Inlet Temp [C]	13.3	13.3	13.3	13.3	13.4	13.4	13.5	13.5	13.4	13.4	13.3	13.2	13.2
Engine Oil Temp [C]	89.7	89.7	90.0	89.9	90.6	90.5	90.5	90.4	90.6	90.9	89.9	90.2	90.0
Exhaust Cyl 4 Temp [C]	490	383	393	385	390	400	406	407	421	424	483	492	488
Exhaust Cyl 3 Temp [C]	533	412	425	416	427	422	425	426	427	427	506	515	505
Exhaust Cyl 2 Temp [C]	493	384	395	387	391	383	386	385	386	386	460	473	469
Exhaust Cyl 1 Temp [C]	446	372	385	379	376	364	372	374	374	376	449	454	445
Charge Air Pre-IC Temp [C]	88.5	102.2	103.2	98.6	98.0	96.3	94.2	91.9	88.7	87.4	87.9	88.6	87.6
Inlet Air Temp [C]	32.1	31.3	31.0	30.5	30.2	30.6	31.4	32.1	32.5	32.9	29.2	30.5	31.3
Fuel Supply Flow [g/min]	171	185	188	182	183	176	169	170	173	174	179	188	175
THC [ppm dry]	79.4	66.2	67.9	72.8	74.2	77.7	85.1	86.5	87.4	85.7	147.1	157.2	151.4
O2 [% dry]	9.8	12.0	11.7	11.8	11.6	11.7	11.5	11.3	11.0	10.8	10.5	10.3	10.3
NOx [ppm dry]	473	515	569	543	567	567	570	586	643	672	428	458	484
NO [ppm dry]	416	454	501	475	497	494	496	511	564	588	374	396	411
NO2 [ppm dry]	56.5	61.1	67.5	68.1	70.2	72.9	73.8	74.7	79.5	83.9	54.9	62.0	72.5
CO2 [% dry]	8.0	6.6	6.8	6.7	6.8	6.8	6.9	7.0	7.2	7.3	7.5	7.6	7.5
CO [ppm dry]	190	125	120	130	129	134	151	157	166	173	263	294	327
Pre DPF Temp [C]	441	327	335	332	339	335	341	345	348	350	419	429	425
Post DPF Temp [C]	380	292	297	294	300	296	301	304	306	308	366	375	373
Charge Air Post-IC Temp [C]	33.8	28.0	36.8	29.7	29.5	28.8	26.5	25.7	25.2	25.6	23.9	23.6	23.4
IC Water Outlet Temp [C]	15.9	15.2	15.3	15.4	15.5	15.8	16.0	16.3	16.8	16.8	17.0	17.6	18.3
Pre DPF Pressure [psig]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2

8.3.2 ENGINE IN-CYLINDER COMBUSTION DATA – JD4045 Tier-III

Table 8-5 In-Cylinder Combustion Statistics (75% Load, 1700 rpm)

	DSL	95-05	90-10	85-15	80-20	75-25	65-35	60-40	50-50	45-55	40-60	30-70	20-80	TGB100
Avg. Peak [kPa]	8141	7477	7624	7581	7641	7649	7685	7755	7884	7973	5873	5765	5627	7455
Peak Std. Dev.	362	160	159	168	162	193	203	230	275	290	21	26	32	163
Peak COV	4	2	2	2	2	3	3	3	3	4	0	0	1	2
Max Peak [kPa]	10033	8094	8426	8373	8264	8558	8520	8785	8964	9243	5932	5870	5746	8085
Min Peak [kPa]	7396	7066	7244	7177	7194	7207	7254	7264	7336	7341	5799	5664	5488	7068
vg. Peak Loc.[CAD]	13	15	15	15	14	15	15	15	14	13	24	24	24	15
Peak Loc. Std. Dev	1	1	1	1	1	1	1	1	2	2	1	1	1	1
Peak Loc. COV	11	8	7	8	8	8	8	10	12	12	259	99	63	7
AVG IMEP [kPa]	1267	1200	1247	1230	1232	1318	1336	1330	1312	1314	1071	1070	1042	1210
IMEP STD DEV	14	30	22	19	19	17	13	13	14	13	12	13	15	22
IMEP COV	1	3	2	2	2	1	1	1	1	1	1	1	1	2
AVG NMEP [kPa]	1250	1165	1215	1199	1204	1291	1311	1306	1290	1293	1063	1063	1034	1177
NMEP STD DEV	14	30	22	19	19	17	13	13	14	13	12	13	15	22
NMEP COV	1	3	2	2	2	1	1	1	1	1	1	1	1	2
AVG PMEP [kPa]	-17	-35	-33	-31	-28	-27	-25	-24	-22	-21	-8	-7	-8	-33
PMEP STD DEV	1	1	1	1	1	1	1	1	1	1	1	1	1	2
PMEP COV	-8	-3	-3	-4	-5	-5	-5	-5	-5	-5	-11	-20	-18	-6
MFB 10%[CAD]	9	11	11	10	10	9	9	9	9	9	19	20	19	11
MFB 50%[CAD]	19	21	21	21	21	19	19	19	19	19	27	27	27	21
MFB 90%[CAD]	54	55	55	55	55	50	50	50	50	50	60	60	60	54
SOI[CAD]	3	2	2	2	2	2	2	3	3	3	3	3	3	2
Turbo speed[rpm]	77	90	91	89	88	87	85	83	80	79	82	82	80	92

8.4 EXHIBIT C: FOR CHAPTER 6

8.4.1 FUEL COST SAVINGS (ENERGY DENSITY BASIS)

Table 8-6: Fuel Cost Savings of TGB10 on Energy Density Basis as Compared to Diesel

		% Change in the cost of blending TGB10										
		-5	-4	-3	-2	-1	0	1	2	3	4	5
% Change in the cost of diesel	-5	33%	33%	32%	32%	31%	30%	30%	29%	29%	28%	27%
	-4	34%	33%	33%	32%	32%	31%	30%	30%	29%	29%	28%
	-3	35%	34%	33%	33%	32%	32%	31%	30%	30%	29%	29%
	-2	35%	34%	34%	33%	33%	32%	32%	31%	30%	30%	29%
	-1	36%	35%	34%	34%	33%	33%	32%	32%	31%	30%	30%
	0	36%	36%	35%	34%	34%	33%	33%	32%	32%	31%	31%
	1	37%	36%	36%	35%	34%	34%	33%	33%	32%	32%	31%
	2	37%	37%	36%	36%	35%	34%	34%	33%	33%	32%	32%
	3	38%	37%	37%	36%	36%	35%	34%	34%	33%	33%	32%
	4	38%	38%	37%	37%	36%	36%	35%	34%	34%	33%	33%
	5	39%	38%	38%	37%	37%	36%	36%	35%	34%	34%	33%

8.4.2 COST OF EQUIPMENT OWNERSHIP FOR A TBO OF 7,000 HOURS

Table 8-7 Cost Savings in using TGB10 as fuel and equipment TBO of 7,000 hours

		TGB10 Cost						
		$1.5	$2.0	$3.0	$4.0	$5.0	$6.0	$7.0
Diesel Price	$2.5	$29,786	$8,743	-$33,344	-$75,430	-$117,516	-$159,603	-$201,689
	$3.2	$57,602	$36,559	-$5,527	-$47,614	-$89,700	-$131,786	-$173,873
	$4.0	$89,393	$68,349	$26,263	-$15,823	-$57,910	-$99,996	-$142,083
	$5.0	$129,130	$108,087	$66,001	$23,914	-$18,172	-$60,259	-$102,345
	$6.0	$168,868	$147,825	$105,738	$63,652	$21,565	-$20,521	-$62,607
	$7.0	$208,606	$187,562	$145,476	$103,390	$61,303	$19,217	-$22,870
	$8.0	$248,343	$227,300	$185,214	$143,127	$101,041	$58,954	$16,868

8.4.3 COST OF EQUIPMENT OWNERSHIP FOR A TBO OF 6,000 HOURS

Table 8-8 Cost Savings in using TGB10 as fuel and equipment TBO of 6,000 hours

Diesel Price		$1.5	$2.0	$3.0	$4.0	$5.0	$6.0	$7.0
	$2.5	$26,215	$5,171	-$36,915	-$79,001	-$121,088	-$163,174	-$205,261
	$3.2	$54,031	$32,988	-$9,099	-$51,185	-$93,271	-$135,358	-$177,444
	$4.0	$85,821	$64,778	$22,692	-$19,395	-$61,481	-$103,568	-$145,654
	$5.0	$125,559	$104,516	$62,429	$20,343	-$21,744	-$63,830	-$105,916
	$6.0	$165,297	$144,253	$102,167	$60,080	$17,994	-$24,092	-$66,179
	$7.0	$205,034	$183,991	$141,905	$99,818	$57,732	$15,645	-$26,441
	$8.0	$244,772	$223,729	$181,642	$139,556	$97,469	$55,383	$13,297

8.4.4 COST OF EQUIPMENT OWNERSHIP FOR A TBO OF 5,000 HOURS

Table 8-9 Cost Savings in using TGB10 as fuel and equipment TBO of 5,000 hours

		TGB10 Price						
Diesel Price		$1.5	$2.0	$3.0	$4.0	$5.0	$6.0	$7.0
	$2.5	$21,215	$171	-$41,915	-$84,001	-$126,088	-$168,174	-$210,261
	$3.2	$49,031	$27,988	-$14,099	-$56,185	-$98,271	-$140,358	-$182,444
	$4.0	$80,821	$59,778	$17,692	-$24,395	-$66,481	-$108,568	-$150,654
	$5.0	$120,559	$99,516	$57,429	$15,343	-$26,744	-$68,830	-$110,916
	$6.0	$160,297	$139,253	$97,167	$55,080	$12,994	-$29,092	-$71,179
	$7.0	$200,034	$178,991	$136,905	$94,818	$52,732	$10,645	-$31,441
	$8.0	$239,772	$218,729	$176,642	$134,556	$92,469	$50,383	$8,297

8.4.5 BUSINESS CASE STRATEGY (PRELIMNARY MODEL)

Analysis Plan / Data Used / Key Assumptions – The assumption is that TGB10 has been approved as a fuel by the governmental authorities and that the market opportunity is large. The company is assumed to have 2000 acres of farm land, 50% of the equity is owned by farmers while the remaining 50% is through micro loans from financial institutions. An estimation for the cost of growing canola, crushing the seeds and TGB10 production, storage and its transportation has been considered. The lifecycle cost of ownership of farm equipment using TGB10 as fuel is considered for a useful life that is 80% of the equipment using diesel fuel. To answer these questions, the economic analysis in the previous sections of this article has been used.

Data Interpretation –With the current set up, the cost of producing TGB10 is $2.01 per gallon for 128,216 gallons over a 30-day period. The cost of insurance and interest as a combined surcharge is $0.03 per gallon of TGB10 as shown in Chapter 6, Table 6-17. To maintain a modest profit of $0.05 per gallon of fuel, the maximum cost of production should be $2.09 per gallon. For breakeven costs over an equipment's life, price of diesel should be $1.41 per gallon higher than TGB10. Any additional costs in transportation, storage and distribution is assumed to be in the scope of customer.

Business Statement – There is a narrow window of opportunity to capitalize on consumers' and government's desire to use and promote alternative fuels. They can make use of existing farm land in the fallow season to grow canola crop and convert the oil into TGB10 – an alternative fuel to diesel. In order for this, there is a need to develop and deliver on a Value Proposition which provides substantial cost savings to consumers using TGB10 as fuel. The opportunity for such a case will be unfavorable as (i) the price of production of TGB10 increases, (ii) the price of diesel decreases and/or (iii) the lifespan of equipment using TGB10 decreases sharply.

Recommendation to Management - Management could explore a few opportunities. The first one could be to identify the drivers to grown canola crop at a cheaper price. For this, they could explore farming on additional land by either buying or leasing farm lands. Secondly, the cost of operation and production of TGB10 could be made more efficient by allowing for greater running time per year. Leasing the crushing facility to crush other oil seed crops could be considered. Alternatively, a redesign of crushing process and/or increasing the operating time per day from 16 hours to 24 hours could also help in reducing CAPEX and OPEX. Thirdly, a strategic decision to keep the plan in operation only when the price of diesel is $1.41 greater than the production of TGB10 can help the company remain sustainable.

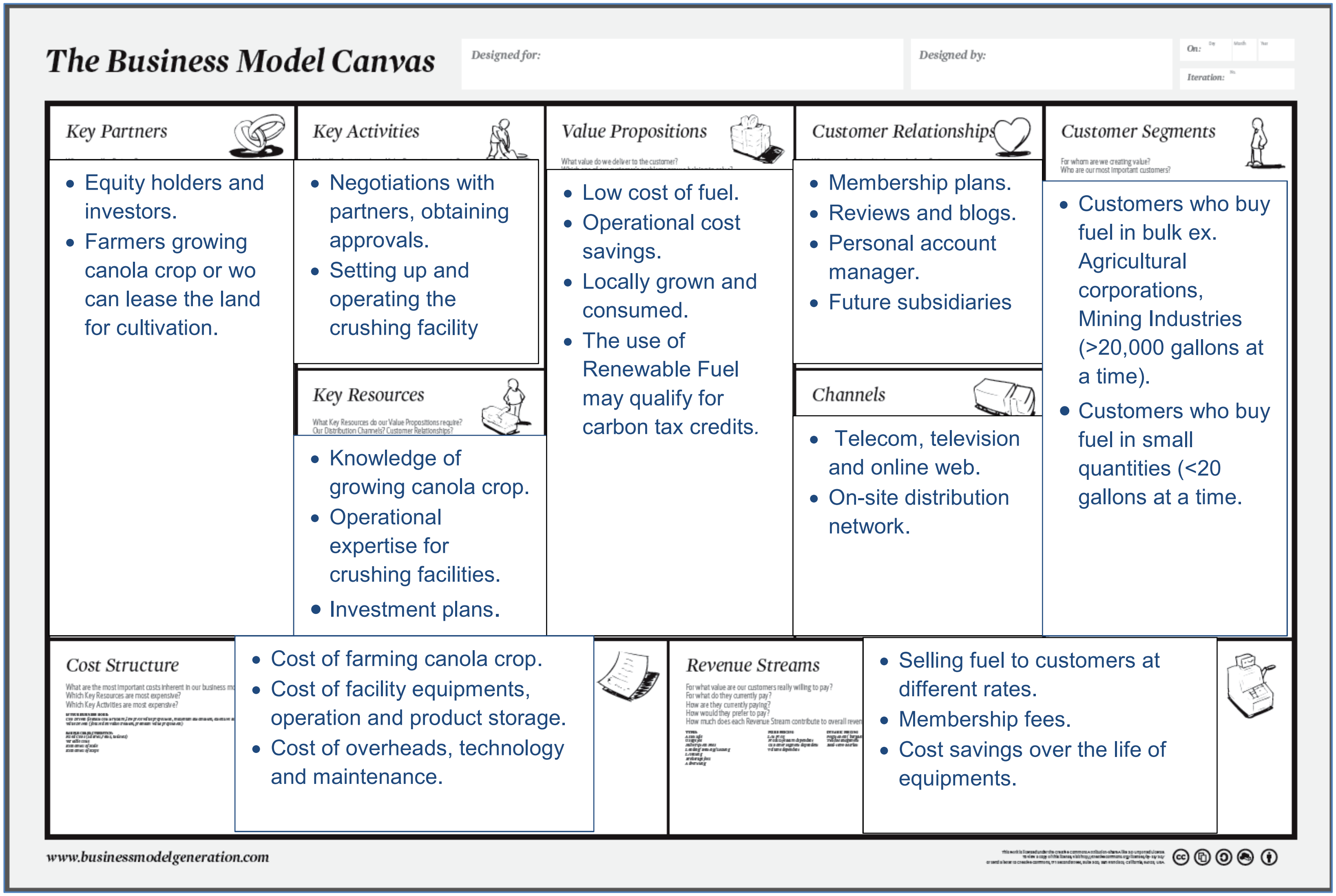


Figure 8-1: Business Model Canvas

LIST OF ABBREVIATIONS

°aTDC – Degree After Top Dead Center

°bTDC – Degree Before Top Dead center

°aSOI – Degree After Start Of Injection

ASTM – American Society for Testing and Materials

BSFC – Brake Specific Fuel Consumption

CAD – Crank Angle Degrees

DAQ – Data Acquisition

ECU – Electronic Control Unit

EISA – Energy Independence and Security Act

EGR – Exhaust Gas Recirculation

EPA – Environmental Protection Agency

FAME – Fatty Acid Methyl Ester

FID – Flame Ionization detection

FTIR – Fourier Transform Infrared

GDP – Gross Domestic Product

GHG – Greenhouse Gas

IR – InfraRed Radiation

NMHC – Non Methane Hydrocarbons

PM – Particulate Matter

PTO Shaft – Power Take-Off shaft

SOI – Start of Injection

SVO – Straight Vegetable Oils

THC – Total Hydrocarbons

TGB – Triglyceride Gasoline Blend

TGB10 – Blend of 90%Triglyceride and 10% gasoline (volume basis)

ULSD – Ultra Low Sulfur Diesel

US – United States