Effects of Various Additives on Regulated Emissions of Modern Diesel Engines

By

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Abstract

Increasingly strict emissions regulations along with man-made global warming has peaked interest in clean burning diesel engines. Renewable biofuels such as biodiesel are being investigated to reduce carbon monoxide (CO), unburned hydrocarbon (HC), and smoke opacity, while slightly increasing nitrogen oxides (NO_x). Two modern diesel engines, a light-duty engine and heavy-duty engine, were investigated with various biodiesel blends. The heavy-duty engine was a Cummins 4-cylinder direct injection (DI) diesel engine, which was run at three idling conditions: low, medium and high idling states operated at 800 revolutions per minute (rpm), 1000 rpm, and 1200 rpm respectively. The engine was fueled with biodiesel-diesel blends with two additives. Two additives, ethanol and diethyl ether (DEE) at 5% and 15% were mixed with biodiesel-diesel blends B20, B50 and B100. B100 was produced from canola oil. The engine was tested from cold start to warm up in real world conditions. The light-duty engine was a HATZ 2-cylinder diesel engine, which was fueled with biodiesel blends with dissolved expanded polystyrene (EPS) and fuel stabilizer additive acetone. The light-duty engine was tested at three speed conditions 1000 rpm, 2100 rpm, and 3000 rpm. Each speed condition had 4 load conditions: 0%, 20%, 50%, and 80% load. EPS was dissolved at 50g/l of biodiesel and the acetone additive was tested at 100ml/l of biodiesel and 250ml/l of biodiesel. Emissions analysis was conducted for carbon monoxide (CO), carbon dioxide (CO2), nitric oxide (NO), nitrogen dioxide (NO2), oxides of nitrogen (NOx), smoke opacity and unburned hydrocarbons (HC). Investigation results demonstrate that for the heavy-duty engine at idle conditions, diesel-biodiesel blends with additives produce lower CO emissions than neat diesel. Ethanol and DEE additives can also reduce NOx emissions in diesel-biodiesel blends, and increasing biodiesel content reduced HC emissions. For the light-duty engine at all loading conditions biodiesel-diesel blends produced lower CO emissions, higher NO_x emissions and higher smoke opacity. EPS content overall decreased CO and NO_x emissions, but increased smoke opacity. At 100ml/l of biodiesel acetone decreased CO emissions, acetone at 250 ml/l of biodiesel increased CO emissions. Acetone increased NO_x emissions and decreased smoke opacity.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Meaning
CO	Carbon Monoxide
CO_2	Carbon Dioxide
UHC, THC, HC	Unburned Hydrocarbons
NO_x	Nitrogen Oxides
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
PM	Particulate Matter
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
DEE	Diethyl Ether
EPA	Environmental Protection Agency (U.S.)
EPS	Expanded Polystyrene
PS	Polystyrene
RPM	Revolutions Per Minute

Nomenclature

Diesel-Biodiesel Series

Fuel	Diesel Content vol%	Biodiesel Content vol%
Diesel	100	0
B5	95	5
B20	80	20
B50	50	50
B100	0	100

Ethanol Series

	Diesel Content vol%	Biodiesel Content vol%	Ethanol Additive ml/L
B20E5	80	20	50
B20E15	80	20	150
B50E5	50	50	50
B50E15	50	50	150
B100E5	100	0	50
B100E15	100	0	150

Diethyl Ether (DEE) Series

	Diesel Content vol%	Biodiesel Content vol%	Diethyl Ether Additive ml/L
B20DE5	80	20	50
B20DE15	80	20	150
B50DE5	50	50	50
B50DE15	50	50	150
B100DE5	100	0	50
B100DE15	100	0	150

Expanded Polystyrene Series (EPS)

	Diesel Content vol%	Biodiesel Content vol%	Dissolved EPS g/L of Biodiesel	Acetone g/L of Biodiesel
BPS5	95	5	50	0
BPS5A100	95	5	50	100
BPS5A250	95	5	50	250
BPS20	80	20	50	0
BPS20A100	80	20	50	100
BPS20A250	80	20	50	250
BPS50	50	50	50	0
BPS50A100	50	50	50	100
BPS50A250	50	50	50	250
BPS100	0	100	50	0
BPS100A100	0	100	50	100
BPS100A250	0	100	50	250

1.0 Introduction

Automobile manufactures have been caught using “cheat devices” to circumvent EPA and Euro6 regulations have increased public interest in the regulation of diesel emissions. Thompson et. al. [1] found that real world driving emissions of NO_x greatly exceeded EPA regulations, leading the EPA to investigate and substantiate this study.

Diesel engines are used worldwide as the primary workhorse for ground transportation, mining, construction, agriculture, and remote power generation[2]. The discovery of man-made climate change has increased the push for cleaner diesel engines. Diesel engines typically have better fuel economy, which mean less CO_2 gets released into the atmosphere. While countries and industries try to wean off fossil fuels and combustion engines, emissions improvements can be made by including renewable content in fuel blends.

Biodiesel and other renewable fuels are being mandated by governments around the globe for these reasons. Biodiesel has a net zero effect on CO_2 emissions due to photosynthesis of crops required to make biodiesel [3]. Biodiesel is a promising alternative fuel due to increasing ability to be used in compression ignition engines with few modifications [4]. Biodiesel feedstock can include over 350 oil producing crops, animal by-products, waste grease, algal feedstock, and many other sources [3]. Production worldwide has grown from 0.8 to 14.7 billion litres over the last decade [5]. National governments have started to implement policies and research on the potential of renewable content in conventional diesel fuels. China, which produces 5 millions tons of waste cooking oil annually has started to implement regulations on the recycling of said oil [6]. Modern diesel engines now being produced are factory ready for B20 blends of biodiesel. Acceptable biodiesel content in manufacturers standards is only increasing. For this reason biodiesel blends must be explored for immediate use in diesel engines. This study focuses on the emissions of two modern diesel engines

In this study a modern heavy-duty diesel engine typically used in agriculture, construction, or mining will be examined at idle condition. Biodiesel will be blended with diesel to make various biodiesel-diesel blends. Additives, ethanol and diethyl ether (DEE), will be added to biodiesel-diesel blends at 5% and 15% by volume. These fuel blends will be tested at three idling conditions from a cold start ignition. Average regulated emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbons (HC) will be presented and discussed. The performance and emissions of the modern light-duty diesel engine will be examined. These types of engines are also used in agriculture and for small power generation. The engine will be tested at three speeds with 3 load conditions. One more biodiesel blended with diesel to make various biodiesel-diesel blends. Expanded Polystyrene (EPS), a common packing material will be dissolved in biodiesel as a fuel additive. Acetone will then be used as a fuel stabilizer to prevent dissolutions of EPS content. Engines performance of all fuel blends and regulated emissions will be presented and discussed

A literature review will provide background on diesel combustion and emissions, biodiesel production, combustion and emissions, as well as various support information for specific additives used. Literature review will be followed by a method and materials section, details of testing methods, testing equipment, and productions of fuels can be found in this section. Results from tests on both engines will then be discussed in detail.

2.0 Literature Review

2.1 Compression Ignition (CI) Engine

Since the invention of the internal combustion engine in the early nineteenth century fossil fuels have dominated the transportation sector. Compression ignition (CI) or diesel engines have become the prime mover of goods worldwide[4]. The transportation sector has experienced steady growth for the last 30 years and is predicted to continue growing at an average rate of 1.8% year-over-year [3]. Diesel engines are used primarily in shipping, mining and construction industries due to their robust nature and high torque potential. In underground mining CI are used exclusively due to much lower CO emissions than gasoline engines.

2.2 Biodiesel

Extensive use of the compression ignition (CI) engine in mining, construction and transportation as well as new emissions regulations has increased interest in developing cleaner diesel engines. The recent discovery of fossil fuel combustion contributing to climate change has contributed significantly to this trend [7].

Biodiesel has become a promising alternative to conventional diesel fuel due to its ability to run in CI engines with little to no modification [4]. Biodiesel is a non-toxic, low-sulfur and environmentally friendly fuel[8]. Biodiesel feedstock includes up to 350 oil producing crops globally, animal by-products, waste grease, and various other sources [3]. Over the last decade biodiesel output has grown from 0.8 to 14.7 billion litres annually [5]. Primary processes for the conversion of oil producing crops to biodiesel fuel include microemulsion, thermal cracking and transesterification [9].

Transesterification of oil occurs in the presence of short chain alcohol, which is catalyzed using acids and/or bases [10]. Transesterification or alcoholysis is a process by which fat or oil reacts with an alcohol in the presence of a catalyst to form an ester and glycerol [11,12]. These reactions are most commonly catalyzed with an acid or a base, while using ethanol or methanol as the alcohol [11]. Alternative catalysts include enzymes called lipases, carbon-based catalysts and heterogeneous catalysts [12,13]. Costs associated with biodiesel production occur in the selection and purchase of feedstock. The relatively low cost of waste oil is an attractive alternative to primary feedstocks. Waste oil contain large amounts of Free Fatty Acids (FFA), which must be removed for optimal biodiesel production [14].

Pre-treatment of this fuel stock is needed to avoid saponification reactions, yield loss and increased difficulty in the separation process [13,15]. Esterification is the process most often used as a pre-treatment for high FFA content. Acids are a attractive catalyst for these feedstocks because they convert the FFA through esterification while catalyzing the transesterification process. The acids allow for the process to be completed in one step. The drawback of acid catalyst processes is the significant time required for the reaction to take place [13].

2.3 Biodiesel Feedstock

Biodiesel feedstocks include animal by-products, waste grease, and various other potential sources [16]. Biodiesel feedstocks can be categorized and evaluated numerous ways. One categorization method includes the terms first, second, and third generation biofuels. First generation biofuels are obtained by converting food based crops into biofuel, with ethanol often as the end product. First generation biofuels can be viewed as unsustainable due to the carbon footprint of crops and the competition for arable food producing farmland [17] .

Second generation feedstocks are created by the use of non-food-based crops. The advantage of these crops is that many of them can be grown on land not suitable for food based crops. This eliminates competition with food crops and has the potential to reduce deforestation [3].

Third generation feedstocks are derived from eukaryotic microalgae and prokaryotic bacteria. These unicellular organisms can be used to treat waste water and various other disposal processes. Third generation feedstocks have a large potential for production but currently require a considerable initial monetary investment.

Another proposed method to categorize feed stock is to divide them into edible vegetable oils, non-edible vegetable oils, waste and recycled oils, animal fats and by-products [3]. Using this method Table 1-1 was created to examine common feedstocks used globally.

Criteria for evaluation of feedstock include: availability of land, cultivation practices; energy supply and balance, emission and greenhouse gases, injection of pesticides, soil erosion and fertility, contribution to biodiversity value losses, logistical cost; direct economic value of feedstocks taking into account coproducts, creation of maintenance and employment, effect of feedstocks on air quality [3]. Choice of optimum feedstock for biodiesel production varies significantly depending on climate, growing season, and availability of arable land.

Table 2-1 Biodiesel Feedstocks [16,18–22]

Edible Oils	Non-Edible Oils	Animal Products	Other Sources
Babassu	Abutilon muticum	Beef Tallow	Algae (Cyanobacteria)
Barley	Aleurites moluccana	Chicken Fat	Bacteria
Canola	Almond	Fish Oil	Fungi
Coconut	Andiroba	Pork Lard	Latexes
Copra	Brassica carinata	Poultry Fat	Microalgae (Chlorellavulgaris)
Corn (Germ)	Camelina (Camelina Sativa)	Yellow Grease (used cooking oil)	Miscanthus
Groundnut	Castor		Poplar
Laurel	Coffee ground (Coffea arabica)		Switchgrass
Linseed	Cotton Seed (Gossypium hirsutum)		Tarpenes
Oat	Croton megalocarpus		
Olive	Cumuru		
Palm and palm kernal (Elaeis guineensis)	Cynara cardunculus		
Peanut	Jatropa curcas		
Piqui	Jatropha nana		
Rapeseed (Brassica napus L.)	Jojoba (Simmondsia chinensis)		
Rice Brain oil (Oryza sativum)	Karanja or honge (Pongamia pinnata)		
Safflower	Mahua (Madhuca indica)		
Safflower	Moringa (Moringa olefera)		
Sesame (Sesamum indicum L.)	Nagchampa (Calophyllum inophyllum)		
Sorghum	Neem (Azadirachta indica)		
Soybeans (Gycine max)	Pachira glabra		
Sunflower (Helianthus annuus)	Passion Seed (Passiflora edulis)		
Wheat	Pongamia (Pongamia pinnata)		
	Rubber seed tree (Hevca brasiliensis)		
	Salmon oil		
	Tall (Carnegiea gigantean)		
	Terminalia Belerica		
	Tobacco seed		
	Tung		

2.4 Regulated Emissions

Regulated emissions in Canada and the United States include Carbon Monoxide (CO), Unburned Hydrocarbons (HC, UHC), Particulate Matter (PM), and Nitrogen Oxides (NO_x)[23]. In the U.S. the EPA regulates the emissions of road vehicles, Canadian regulations regularly follow the EPA standard due to integration of North American car manufacturing. Table 2-2 illustrates the emissions standards for heavy duty compressions ignition (CI) engines and urban buses from 1974 to present.

Table 2-2 EPA Emissions Standards for Heavy Duty Trucks and Buses [24]

Year	HC (g/bhp-hr)	NMHC (g/bhp-hr)	NMHC + NOx (g/bhp-hr)	NOx (g/bhp-hr)	PM (g/bhp-hr)	CO (g/bhp-hr)
1991-93	1.3	-	-	5	0.25	15.5
1994-97	1.3	-	-	5	0.1	15.5
1998-2003	1.3	-	-	4	0.1	15.5
2004-2006	-	-	2.4	-	0.1	15.5
2007	-	0.14	2.4	0.2	0.01	15.5

2.4.1 Carbon Monoxide (CO) Emissions

Carbon monoxide (CO) is formed primarily in rich fuel air mixtures due to lack of oxygen [25] . Typically spark ignition engines exhibit much higher CO levels due to rich fuel to air mixtures, diesel engines operate leaner then spark ignition engines. CO emissions in diesel engines form over-lean fuel mixtures and over-rich regions while under high load [26]. The CO reaction proceeds as follows.

$$RH >> R >> RO_2 >> RCHO >> RCO >> CO \text{ [27]}$$

Where R is the hydrocarbon Radical. A secondary reaction to convert CO to CO_2 with enough oxygen present is shown below.

$$CO + OH >> CO_2 + H \text{ [26]}$$

Fuel rich areas may produce significant levels of CO. These higher concentrations can be mitigated by post-oxidation occurring as shown above. This second reaction can be frozen due to rapid cooling of the exhaust gas [28].

2.4.2 Unburned Hydrocarbon (HC) Emissions

Unburned Hydrocarbons (HC), also called organic emissions, are caused by incomplete combustion of hydrocarbons fuels. HC can be classified into Paraffin's, Olefins, Acetylene, and Aromatics [25]. Due to a wide range of HC emissions they are further divided into two classes, methane hydrocarbons and non-methane hydrocarbons. This is done because all hydrocarbons with the exception of methane react when enough time is given. The environmental protection agency(EPA) states that hydrocarbons react in the presence of nitrogen oxides and sunlight to form ground level ozone, which attributes to smog [23]. The EPA in the tier 3 emissions requirement actually has two different regulated HC emissions standards categories for heavy duty trucks and buses [24]. Total hydrocarbons were phased out into non-methane hydro-carbons (NMHC) and NMHC+NOx emissions.

The EPA's tier three emissions are also starting to phase in non-methane organic gases (NMOG) which are like NMHC but include oxygenates. Common oxygenates are alcohol and carbonyls such as formaldehyde. This provide some interesting methods in reporting HC emissions as measurement devices are often Flame Ionization Detector (FID) calibrated to propane. The EPA has released a conversion factor for these new categories based on FIC measurement [Table 2-3.]

Table 2-3 EPA Conversion Factor [29]

Engine Type	TOG/THC	NMOG/THC	NMHC/THC	VOC/THC
2-Stroke Gasoline	1.044	1.035	0.991	1.034
4-Stroke Gasoline	1.043	0.943	0.9	0.933
Diesel	1.07	1.054	0.984	1.053
LPG	1.099	1.019	0.92	0.995
CNG	1.002	0.049	0.048	0.004

In Table 2-3 under the diesel section it can be observe that the conversion factor for NMOG Is 1.054. Conversions to NMHC, total organic gases (TOG), and volatile organic compounds (VOC) can also be calculated.

Diesel fuel contains more complex hydrocarbon emissions due to higher boiling point and larger molecules. Generally, diesel idle emissions are lower than SI engines due to high combustion efficiency [30]. Hydrocarbons are typically produced in rich zones of the combustion chamber. Figure 2-1 illustrates the diesel combustion plume where HC are produced at about 1600K.

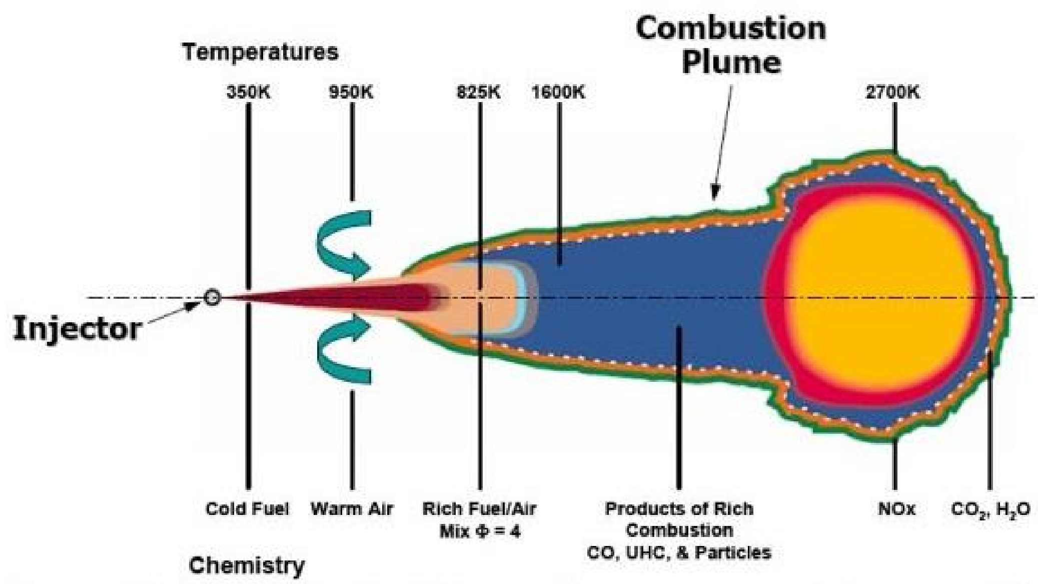

Figure 2-1 Diesel Combustion Plume [31]

Unburned hydrocarbons are produced in the combustion chamber from several sources. These sources include: piston ring is not 100% effective in preventing oil layer in the combustion chamber which traps fuel, carbon deposits build up on valves cylinder and piston crowns, these deposit trap fuel because of their porous structure, fuel content becoming caught in crevices in the combustion chamber, flame quenching, where the flames extinguishes a small distance from the cylinder wall [32]. Figure 2-2 illustrates the mechanisms for incomplete combustion due to fuel injection.

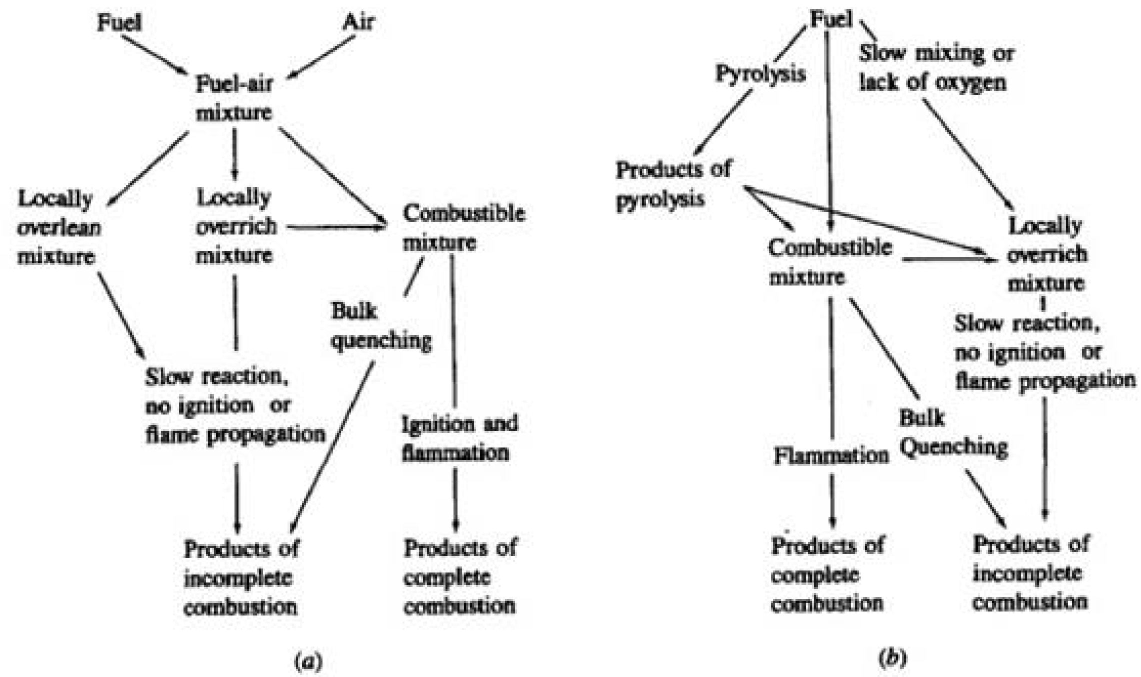

Figure 2-2 HC Mechanism in Diesel Engines a) fuel injected during delay period b) for fuel injected while combustion is occurring [25]

Bulk quenching can occur in low temperature zones and local variation in fuel equivalence ration. Low temperature zones can occur due to heat transfer between fuel charge and combustion chamber walls. Bulk quenching leads to premature flame extinction which allows for unburned hydrocarbons to be released [33]. Figure 6 illustrates the effects of fuel to air mixture on the formation of HC emissions. Figure 2-3 illustrates bulk quenching in a diesel engine cylinder.

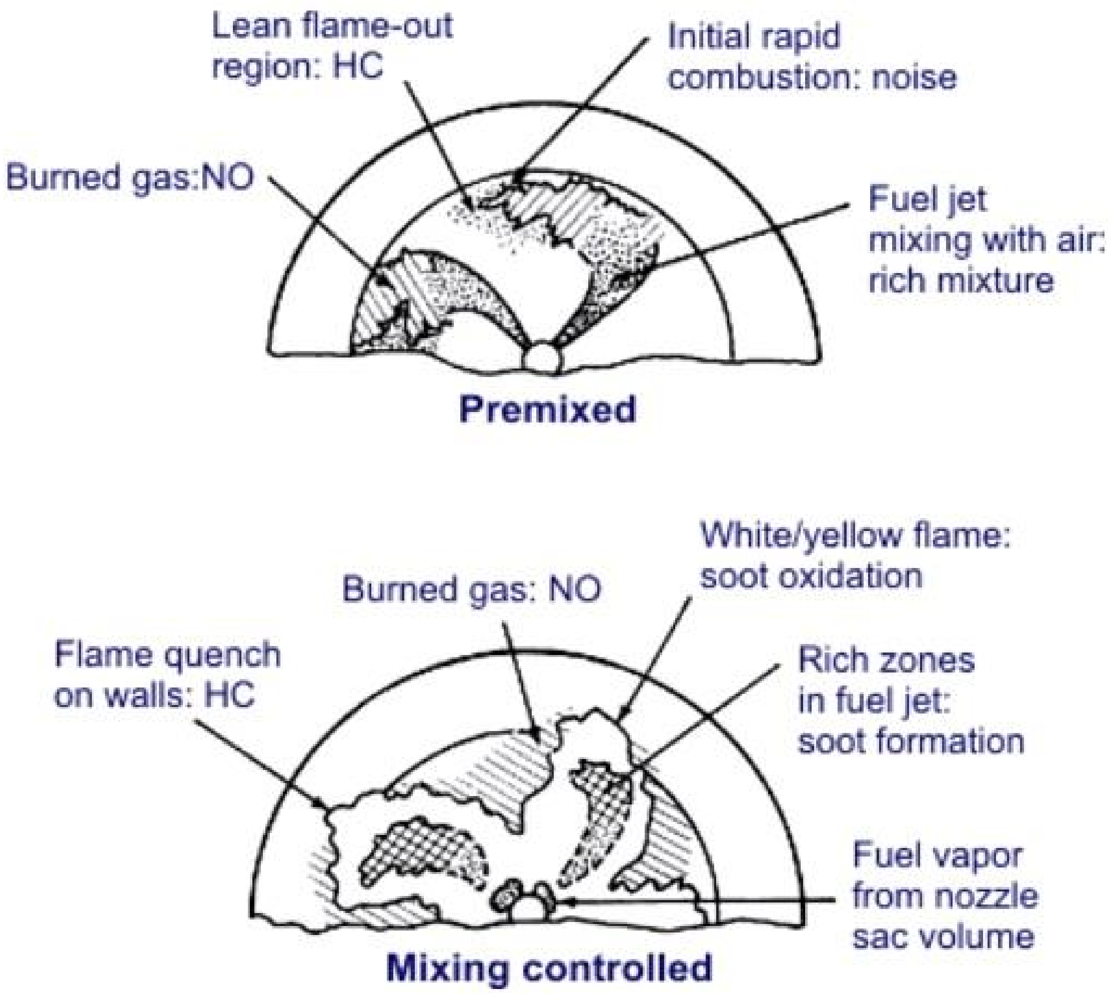

Figure 2-3 HC Formation in Cylinder[34]

2.4.3 Particulate Matter (PM) Emissions

Particulate matter is a mixture of solid particles and liquid droplets found in exhaust than can be visible or invisible to the naked eye. The EPA defines the particulates released by diesel engines into two categories PM10 and PM2.5. The two categories which represent particles smaller than 10 micrometers and 2.5 micrometers respectively[35]. Size is of interest because small particles can be inhaled and causing health problems among local populace. Figure 2-4 illustrates the size distribution of particulate matter compared to a human hair.

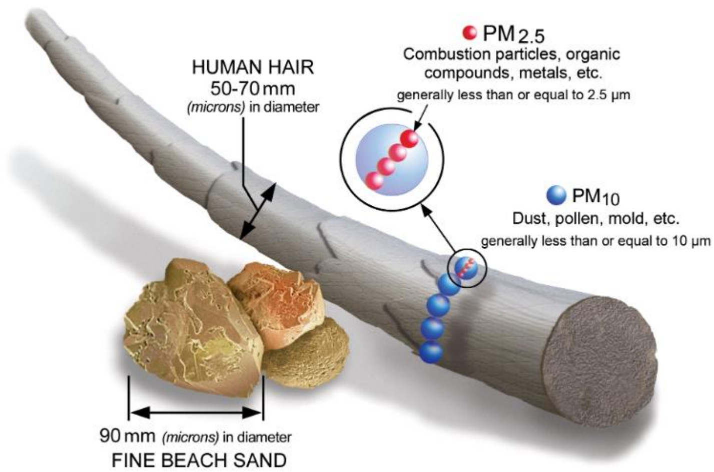

Figure 2-4 Scale of PM sizes [35]

The *Clean Air Act*, which was amended in 1990 requires the EPA to set national ambient air quality standards (NAAQS) for public health protections [36]. Last updated in January 2013, the threshold limit for exposure to PM over a 24-hour period are 35 μg/m^3 and 150 μg/m^3 for PM2.5 and PM10 respectively [37]. Table 2-4 shows the NAAQS table from the EPA for various pollutants.

Table 0-1 2-4 Air Quality Table From EPA [37]

Polluant		Primary/Secondary	Averaging Time	Level	Form
Carbon Monoxide (CO)		Primary	8 hours	9 ppm	Not to be exceeded more than once per year
			1 hours	35 ppm	
Lead (Pb)		Primary and Secondary	1 hour	0.15 μg/m^3	Not to be exceeded
Nitrogen Dioxide (NO_2)		Primary	Rolling 3 month average	100 ppb	98th percentile of 1-hour daily maximum concentrations average over 3 years
		Primary and Secondary	1 hour	53 ppb	Annual Mean
Ozone (O_2)		Primary and Secondary	1 year	0.070 ppm	Annual fourth-highest daily maximum 8-hour concentration, average over 3 years
Particle Pollution (PM	**PM2.5**	Primary	8 hours	12.0 μg/m^3	Annual mean, averaged over 3 years
		Secondary	1 year	15.0 μg/m^3	Annual mean, averaged over 3 years
		Primary and Secondary	1 year	35 μg/m^3	98th percentile, averaged over 3 years
	PM10	Primary and Secondary	24 hours	150 μg/m^3	Not to be exceeded more than once per year on average over 3 years
Sulfer Dioxide (SO2)		Primary	1 hour	75 ppb	99th percentile of 1-hour daily maximum concentrations average over 3 years
		Secondary	3 hours	0.5 ppm	Not to be exceeded more than once per year

Although there are two categories for health effects of PM, only PM2.5 is used in EPA regulation of CI engine emissions. Current regulations are 0.01 g/bhp-hr for heavy duty trucks and buses. Regulations change for different categories of vehicles [24].

Measurements of these levels can be a difficult task in diesel engine research, two methods of wet and dry measurements can be used. Dry measurement collects samples, dries the particles then measures them. This method does not consider liquid particles. Wet measurement cools the exhaust gas and includes all the potential PM. These measurements represent the two extremes of low and high measurement respectively [38]. There are a variety of different detection techniques for wet or dry PM measurement in emissions. These usually fall into the two categories of Concentration of PM and Size distribution of PM. Which measurement system to use is based heavily on conditions of experiments and purpose of study [39]. Table 2-5 illustrates the different methods and devices that can be used in PM emissions research.

Table 2-5 PM Measurement Devices [39]

Instrument	Real Time	Dilution Required	Detection Limit	Size Range (nm)	A (%)	Advantages	Disadvantages
Filter	No	Yes	10 μg/m³	D	5	Simple; reliable; chemical analysis	Lots of work
Scattering	Yes	No (hot)	10 μg/m³	>50	30	-	Measuring large PM
Spotmeter	No	No (hot)	25 μg/m³	All	15	Measuring BC	High response time
PASS; LII	Yes	Yes, No	5 μg/m³	>10	10	Measuring BC	Necessitate calibration
Opacity	Yes	No (hot)	0.1% opacity	>50	20	-	Depends of several factors
TEOM	Yes	Depends sampling site	-	D	-	Agrees well with filter samples	If concentration is high, filter has to be changed
DLPI	No	No	-	30–10,000	-	Large size ranges	Not suitable for smaller particles
SMPS	No	Yes	100 /cm³	3–700	15	Very small particles	Not suitable for larger particles
FMPS	Yes	Yes	1000 /cm³	5–700	25	Fast; Indicates changes in process well	More inaccurate than SMPS
ELPI	Yes	Yes	1000 /cm³	10–10,000	25	Robust and large size range	Wide channels plates may affect the result

PM includes soot, smoke, and various other components. Soot is a solid substance containing on average 8:1 parts carbon to hydrogen. Soot is formed in rich areas of combustion in unburned fuel. Nucleation from vapor phase to solid phase at elevated temperatures causes this formation [40]. Figure 2-5 shows the process for which soot is formed in diesel engines.

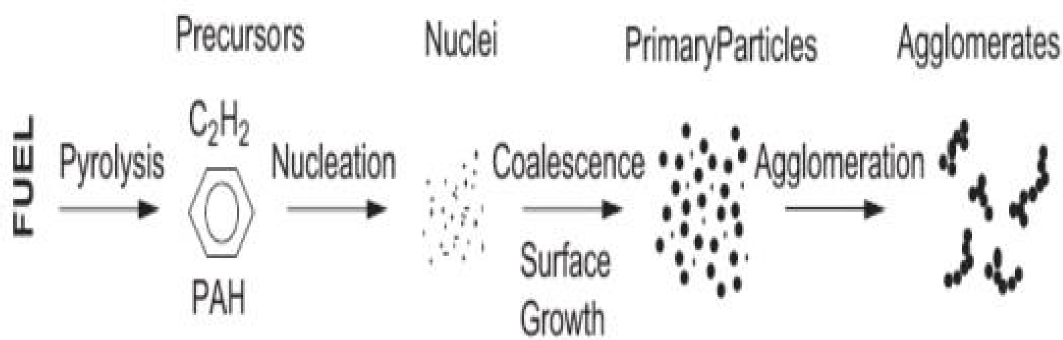

Figure 2-5 Schematic Diagram of Soot Formation [40]

Kittelson [41] examined nanoparticles in engine emissions and found that many were formed by accumulation on existing particles as well as nucleation. He observed that around 1-20% of particles were formed in nucleation where the rest were mostly formed in accumulation.

Particulate matter also includes volatile gas phases that remain in the gas phase during combustion. Figure 2-6 illustrates the portions of PM in a heavy-duty diesel engine.

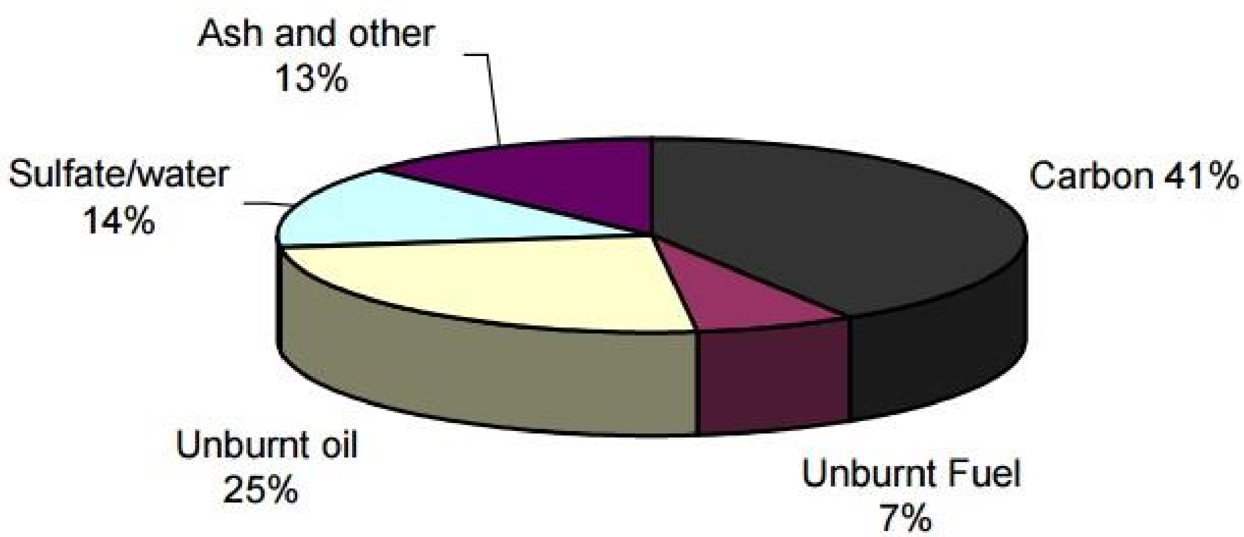

Figure 2-6 Composition of Particle From a Heavy-Duty Diesel Engine [42]

2.4.4 Nitrogen Oxides (NO_x) Emissions

NO_x emissions consist mainly of nitric oxide (NO) and nitrogen dioxide (NO_2) emissions which are grouped together for emissions regulation [25]. Other NO_x components include nitrous oxide (N_2O), dinitrogen dioxide (N_2O_2), dinitrogen trioxide (N_2O_3), dinitrogen tetroxide (N_2O_4), and dinitrogen pentoxide (N_2O_5) [43]. The EPA also regulates NO_x emissions with Non-methane hydrocarbon (NMHC) emissions. This is due to the pair forming ground level ozone which contributes to smog[23]. Figure 1 demonstrates that NO_x emissions standards are 0.2g/bhp-hr for heavy duty trucks and buses, NMHC + NO_x allows for 2.4 g/bhp-hr. In Ontario the Drive Clean Program mandates 984 ppm NO_x at 3000 rpm [32].

Much like other regulated emissions the *Clean Air Act* sets national ambient air quality standards for certain pollutants. NO_x emissions are one of those pollutants. NO_2 ambient levels have decreased by more than 40% since the 1980's in the United States and are expected to fall further [44]. Health effects on human populations are not the only reasons why NO_x emissions standards are becoming more stringent, NO_x also contribute to climate change. The primary green house gas is nitrous oxide which has a lifetime in the atmosphere of 114 years[45]. Transportation emissions of nitrous oxide account for 4% overall emissions in the United States.

The primary source of NO_x emissions in diesel engines is the oxidation of atmospheric nitrogen into NO. The mechanism for NO formation proceeds as follows.

$$O + N_2 = NO + N$$

$$N + O_2 = NO + O$$

$$N + OH = NO + H$$ [25]

In diesel engines NO_2 is observed in higher ratios than spark ignition engines. NO formed in the flame zone can be converted rapidly using the following reactions.

$$NO + HO_2 = NO_2 + OH$$

And then can be converted back using the following mechanism.

$$NO_2 + O = NO + O_2$$

Typically, this occurs in high temperature regions of the combustion chamber. Figure 3 illustrates the diesel combustion plume with related temperatures. NO_x formation occurs at around the 2700K temperature mark. This is often the propagation of the flame front and can happen in various places in the combustion chamber.

Generally, there are three opportunities for NO_x formation; thermal NO_x, fuel NO_x and prompt NO_x. Thermal NOx is controlled by the amount of nitrogen and oxygen and the temperature of combustion. Fuel NOx is formed when ionized nitrogen from the fuel reacts with oxygen. Prompt NOx is the atmospheric nitrogen combining with fuel rich conditions and oxidising with the fuel. Typically, in diesel combustion NO and NO_2 formation happens at the flame front.

2.5 Emissions from Biodiesel Combustion

Vehicle emissions are one of the main sources of air pollutants in modern cities [7]. Increasing number of diesel passenger and heavy duty diesel vehicles have resulted in regulation of CI combustion emissions[8]. From an emissions standpoint biodiesel and biodiesel-blends are attractive because they have the potential to decrease PM, CO, and HC emissions[8]. CO2 emissions can increase or decrease with biodiesel/biodiesel-blends depending on operating conditions and fuel blend.

Karavalakis et al. [46] tested B5 and B10 blends of soybean and animal tallow biodiesel. Two heavy duty diesel engines were tested and found to reduce PM, HC, and CO emissions. NO_x increases were observed with soybean biodiesel blends but not with animal tallow biodiesel blends. Ozener et al. [47] tested soybean biodiesel at B10, B20, and B50 at steady state conditions from 1200-3000 rpm in a single cylinder diesel engine. Biodiesel content was found to decrease CO and HC emission while increasing NO_x emissions. Biodiesel was also found to shorten the ignition delay. Xue [48] reviewed research on biodiesel produced from waste cooking. Xue found that overall CO, PM and HC emissions decreased. Waste cooking oil biodiesel also increased NO_x emissions and decreased ignition delay. Cardenas et al. [49] found that rapeseed, sunflower, and soybean biodiesel blends produce higher fuel specific NO_x, CO and HC emissions, but reduced fuel specific smoke opacity.

The main disadvantage of using biodiesel is that NOx emissions can be significantly increased [7]. It is suggested that this increase is due to advanced timing and higher combustion temperature of biodiesel. Popular methods for reducing NO_x gains from biodiesel combustion can include the use of additives, retarded fuel injection, emulsion with biodiesel and water, and the use of exhaust gas recirculation (EGR) systems [50]. Use of additives will be discussed in more detail in a subsequent section.

Pressure and timing of the injection spray in diesel engines have significant effects on fuel atomization. Controlling to fuel to air mixture in a combustion chamber is important to avoid local over-lean or over-rich regions. Modern diesel engines use injection pressure from 100 MPa to over 300 MPa [51] . Park et al. [52] investigated multiple injection strategies with different timings and pressure to determine their effect on diesel emissions. NOx emissions were found highly dependent on both injection timing and pressure, with injection timings of 20° BTDC to 15° BTDC demonstrated highest NOx emissions. Another study [53] found that injection pressure had significant effect on NOx emissions. Timing was kept constant with increasing load. NOx emissions increased with load, higher injection pressures were found to also increase NOx emissions.

Biodiesel emulsion uses surfactants and additives to suspend and stabilize water content in fuel [54]. Water in biodiesel reduces the kinematic viscosity and lowers the heating value of the fuel. Koc et al. [54], tested biodiesel nanoemulsion fuel at 5%, 10%, and 15% water content. Biodiesel nanoemulsion blends were found to reduce NO_x and soot emissions. Addition of water was found to increase brake specific fuel consumption (BSFC) and slightly increase CO emissions. Anbarasu and Karthikeyan [55] tested canola biodiesel with 15% stable water emulsions. Brake thermal efficiency (BTE), and BSFC were found to increase with B100 emulsified blends. HC emissions and NOx emissions were greatly reduced from diesel fuel.

Exhaust Gas Recirculation (EGR) is a treatment system where a portion of exhaust gas is reintroduced into the air intake. This is done to reduce in-cylinder temperature and oxygen content effectively reducing NO_x emissions. EGR rate is defined by the following equation:

$$Percentage\ EGR = \frac{Volume\ of\ air\ without\ EGR - Volume\ of\ air\ with\ EGR}{Volume\ of\ air\ without\ EGR} \times 100 \qquad \text{(Eq. 2-1)}$$

Two types of EGR exist, hot and cold EGR [56]. Hot EGR simply pulls gases from the exhaust manifold and injects them back into the combustion cylinder. Cold EGR first cools the gas then injects it back into the combustion chamber. Can et al. [57] tested soybean oil B20 biodiesel blends with EGR at 5%, 10%, and 15%. EGR along with biodiesel at 20% was found to be effective at reducing NO_x and HC emissions. CO increases associated with EGR use were reduced and little effect on engine performance was observed. Cardenas at al. [49] tested rapeseed, sunflower and soybean biodiesel blends at 30% by volume. Blends were tested under European test cycles and found to increase specific emissions of NO_x, THC, and CO emissions. No modifications were made to timing of EGR valve opening.

2.6 Diesel Engine in Idling

Due to the extended idling periods that heavy-duty vehicles exhibit, idling emissions have been the subject of increasing laws and regulations from policy makers[30]. In Canada, the Department of Natural Resources has posted idling reductions campaign strategies and by-law strengths/weaknesses for municipalities [58]. Natural Resources Canada has also released a campaign for commercial shipping fleets titled *Fleet Smart*, which is aims to reducing idling time of transport trucks [59]. Regulations are left up to municipalities to develop and enforce. In Ontario (Canada), 37 municipalities have regulated idling to some extent [58]. In the city of Kingston (Ontario), all vehicles must not idle for more than 3 minutes out of every hour, with exceptions for cold weather, parades, emergency vehicles, etc. [60]. In contrast the city of Thunder Bay (Ontario) only regulates idling at gas stations, where in three or more axel vehicles can idle for 5 minutes out of every hour and all other vehicles for 2 minutes out of every hour [61]. Khan et al. [30] compared the emissions of medium duty diesel engines to gasoline trucks, and previously studies heavy-duty diesel engines. As typically reported the study found that the diesel engines exhibited lower fuel use, higher NO_x emissions, and PM emissions while idling. The medium sized diesel engines exhibited lower fuel use and idle emissions than the heavy-duty diesel engines.

While operating in mining, construction, and transportation, diesel engine can experience periods of low operation efficiency. A study [62] examined equipment operational efficiency, which is the ratio of which a piece of equipment is in use vs running idle. Operation efficiency of construction equipment can range from 85% to 41%. As operational efficiency decreased the percentage of unnecessary CO_2 emissions increased [62]. This study only looked at CO_2; unnecessary emissions for other regulated emissions would follow a similar pattern. Another study [63] explored the relationship between emissions from mechanical fuel injection (MFI) and electronic fuel injection (EFI) of idling heavy-duty diesel vehicles. It was found that overall EFI diesel engines emitted less CO, HC, and PM than MFI engines. However, EFI engines emitted higher NO_x emissions due to advanced timing in idle condition. Similarly, transport trucks can idle for extensive periods of time. For example Frey and Kuo [64] examined the use of auxiliary power units (APU) for idling reduction in long haul trucks. Long-haul trucks can idle for more than 2000 hours per year. Idling reduction strategies are especially important in long-haul trucks that experience extreme hot or cold temperatures, where diesel engines are used as power units for cabin air conditioning and heating. The use of APU's was found to significantly decrease fuel use and emissions of CO_2, NO_x, and PM in mild climates.

Since Diesel engines typically experience high periods of idling, biodiesel research must also consider the idle condition. Biodiesel could be used in conjunction with other idling/emission reduction strategies to optimize vehicle fleet use. Rahman at al. [65] examined the effect idling had on Jatropha biodiesel emissions. Biodiesel was found to be an attractive CO and HC emission reduction strategy.

2.7 Performance of Biodiesel Combustion in Diesel Engines

Biodiesel typically exhibit a higher density and viscosity then standard diesel blends. Since many fuel injection systems work on a volumetric system this causes the in-line fuel pressure to rise. Due to the higher inline fuel pressure, spray penetration of fuel also increases. Biodiesels also exhibit Cetane numbers higher that standard diesel blends, this is shown to decrease ignition delay and rated pressure rise [66].

There are many different engine performance parameters that can be examined to determine the quality of combustion. Most papers reviewed focused on Brake Torque (BT), Brake Specific Fuel Consumption (BSFC), and Brake Thermal Efficiency (BTE). Brake torque is the rotating force that can be generated from combustion in the engine. While brake torque is an effective method for comparing performance on a single engine, Brake Mean Effective Pressure (BMEP) may be a better metric for comparing similar engines. BSFC is the amount of fuel used with respect to brake power. Brake thermal efficiency is the measure of the ability of a engine to convert heat produced by a fuel into power output.

Karanja biodiesel blends: B5, B10, B15, B20, B25, B50, and B100 were tested in a four-stroke diesel engine. Engine Torque reduced for all blends, with B50 and B100 exhibiting the highest torque reduction. BSFC was higher for all blends [66]. Canola oil soap stock blends B5 and B10 were tested in a single cylinder diesel engine. Slight reductions in engine torque were examined. B5 was found to have a higher BTE at low to medium load conditions due to the oxygenated nature of biodiesel. B10 was found to have lower BTE and higher BSFC [67].

Blends from Jatropha Curcas feedstock B5, B10, B15, and B20 were tested with and without additives in an inline 4-cylinder diesel engine. Power loss ranged from 0.80%-8.24% for all blends. BSFC increased for all non-additive blends. B10, and B20 with additives produced a reduction in BSFC suggesting reduction in friction from additive[68]. Soybean oil biodiesel blends B10, B20, B50, and B100 were tested in a single cylinder, direct injection, 4-stoke diesel engine. BSFC increased 2-9% for all blends. Torques decreased slightly (1.57-4.7%) for all blends [47]. Five biodiesel blends from canola oil feedstock B5, B10, B20, B50, and B100 were testing with additive Winton XC 30 in a 2 cylinder, 4-stroke, diesel engine. BSFC increased with all blends and additive blends. BTE was found to be higher in both blends due to better combustion from oxygen present [69]. Three Biodiesel blends were tested in a single cylinder diesel engine. Palm oil and coconut oil were used as feedstock for PB30, CB30, and PB15CB15. Torques dropped slightly for all blends. BSFC increased for all blends. BTE was found to be lower for all blends, most likely due to a lower heating value [70]. Soybean, rapeseed, and beef tallow methyl esters were tested on a 200 bhp single cylinder diesel engine to determine effect on torque output. Tallow B50 and soybean B100 were able to produce equal torque to diesel when injection timing was adjusted. Both of these fuels have a potential to create higher peak power outputs for motorsport applications [71].

The majority of studies have found that biodiesel use lowers torque and power output [47,67,68,70]. BSFC was found to be higher than diesel output [47,67,68,70] BTE was found to be similar or lower depending conditions and blend used. Factors affecting these criteria included higher viscosity, density, and lower heating values associated with biodiesel and their blends [48,70] . Carbon deposits and wear for engines using biodiesel blends appeared normal, some researchers have reported that use of additives can improve endurance conditions [16].

2.8 Biodiesel in Canada

In 2010 the Canadian Environmental Protection Act Bill C-33 mandated 5% renewable content in gasoline by 2020 and 2% renewable content in diesel fuel and heating oil by 2012 [5]. Much of renewable content in Canada comes from canola oil ethanol production. Ethanol is then added to gasoline used in SI engines. Seed crops with the highest potential for diesel production in Canada include canola, sunflower, and soybeans [72]. Advantages of canola biofuels include that they are suited better for cold climates and a high percentage of oil can be extracted from crop yields. Disadvantages include high nitrogen fertilization requirements and low livestock meal production as a secondary product. Soybean was found to be a viable option for crops grown in Southern Alberta [20]. Advantages of soybean biofuels include low nitrogen fertilization requirement, larger fractional output of livestock feed, and quality of livestock feed over canola oil. Disadvantages are comparatively lower oil extraction than that of canola oil and reduced performance in cold climate. Other potential crops for Canadian farmland include camelina, flax, rapa canola, and oriental mustard [20].

2.9 Biodiesel Produced from Canola Oil

Since canola oil is the most obvious choice for feedstock in Canada as much research has been conducted on emissions and performance of canola biodiesel and canola biodiesel-diesel blends. An alternative feedstock for canola oil biodiesel is waste canola oil used by the restaurant industry. In [73], Cheikh et al. tested waste oil canola biodiesel blended with diesel. Blends were found to decrease HC, CO, and PM, while slightly increasing all load conditions. Biodiesel was found to increase in-cylinder pressure, decrease ignition delay, and increase BSFC. Tomic et al. [74] tested Canola biodiesel blends on agricultural tractor engines. Biodiesel blends were found to decrease power, increase BSFC, and increase BTE. Emissions of CO and CO_2 were reduced, and NO_x emissions were increased when using biodiesel blends. Aybek at al. [75] also test canola biodiesel blends on a agricultural tractor to determine ideal blend for performance. At 2100 rpm B20 was found to be the ideal biodiesel blend to use in the agricultural tractor engine. Labeckas and Slavinskas [76], tested canola oil biodiesel in a four cylinder direct injection diesel engine. Biodiesel blends were found to increase BSFC at all blends. NO_x emissions increased with increasing biodiesel content and CO emissions decreased with increased biodiesel content in blends. HC emissions were found to be low for all fuels. Ozsezen et al. [77] tested waste palm biodiesel and canola biodiesel in a six cylinder DI diesel engine. Engine torque decreased, BSFC increased, and ignition delay decreased for both biodiesel blends. HC, CO, and smoke opacity decreased while NO_x and CO_2 emissions increased for both fuel blends.

Previous research conducted in the engine laboratory at Lakehead University includes [69,78,79], all of which include emissions from canola oil biodiesel. Roy et al. [69] examined canola oil biodiesel and kerosene biodiesel blends in a two cylinder DI diesel engine. Biodiesel in blends was found to be effective in reducing CO, and HC emissions. NO_x emissions were found to increase with biodiesel content and decrease with kerosene content. In [78], Roy et al. examined biodiesel produced from used and pure canola oil in a two cylinder DI diesel engine. Biodiesel blends from both feedstocks were found to reduce CO, and HC emissions. NO_x were found to increase with biodiesel content over 5%. BSFC decreased when using waste oil as a feedstock when compared to pure canola oil biodiesel. In [79], on the same engine canola oil biodiesel blends were tested at various load conditions. At low load conditions biodiesel blends were effective in reducing CO and HC emissions while significantly increasing NO_x emissions. Medium to high load conditions saw similar reductions in CO and HC emissions, NO_x emissions increases were muted from the low load condition.

2.10 Biodiesel Additives

Biodiesel inherently has some undesirable properties that include; high pour point (PP), high cloud point (CP), corrosion of engine and high NO_x emissions. Additives and diluents can be used to improve or mitigate these effects of biodiesel on wear, performance and emissions. The difference between additives and diluents seems to be subjective, where an additive range is often 0-15vol%, and a diluent can range over 0-80 vol%. Both will be referred to as additives in this paper unless specified by the study. Additives are common not only in the winterization of biodiesel, but are also used to improve emissions. In [80] butanol and pentanol were added to biodiesel blends to determine effect on particulate matter (PM) emissions, Both blends reduced particulate mass and elemental carbon emissions. Some of these additives such as ethanol or kerosene have the added benefit of improving low temperature conditions along with reducing regulated emissions. For example, in [81], the additives kerosene and ethanol were blended with Palm biodiesel-diesel blends to improve cold flow properties. Kerosene and ethanol additives when used in conjunction with biodiesel-diesel blending can help improve the PP by about 92% and 109%, respectively.

2.10.1 Ethanol and DEE Additives

Alcohols can be used in CI engine's as alternative fuels when blended with diesel or biodiesel. Gomez et al.[82], tested ethanol-diesel blends on urban bus fleets to reduce emissions. Ethanol was found to be effective in reducing NO_x emissions and PM emissions. This was found to be dependent on altitude, as high altitudes have lower oxygen content in air. Yilmez et al. [83] tested biodiesel with ethanol as an additive at 3%, 5%, 15% and 25% in a diesel engine. Cooling effects and oxygen content of alcohols were primary factors that affected emission reduction. Test results demonstrated that the blends increased CO emissions compared to diesel for all test conditions. Ethanol blended fuels reduced NOx emissions for all concentrations. HC emissions were found to depend heavily on operating conditions. 2.5%, 5%, and 7.5% ethanol by volume was added to waste pork lard biodiesel [84]. Ethanol addition was found to reduce CO, HC and smoke emissions when compared to neat biodiesel. It was found that HC emission reductions would decrease with increase in ethanol additive. Ethanol was found to increase NO_x emissions for all biodiesel-ethanol blends. Biodiesel with ethanol additive was tested on a supercharged DI diesel engine in [85]. Ethanol blends were found to lower NOx emissions, while supercharging would reduce these improvements. Test results showed that ethanol was able to increase CO and HC emissions, whereas these increases were reduced when supercharged. Ethanol-biodiesel blends were tested in a multi-cylinder diesel engine and a single-cylinder low temperature combustion diesel engine in [86]. The ethanol blended fuels were found to be effective in reducing smoke levels, which allowed for greater use of exhaust EGR system to reduce NOx and PM emissions.

Diethyl Ether (DEE) is an isomer ether of butanol, which is produced from ethanol. DEE exhibits a high cetane number, high oxygen content, high flammability, and mixes well with diesel and biodiesel blends. Rakopolos examined DEE blends at various load conditions in [87]. DEE blends were found to decrease NO_x emissions when compared to ethanol blend emissions. DEE blends were found to decrease CO emissions, and increase unburned hydrocarbons [87]. In [88] Rakopoulos also tested DEE on a light-duty diesel engine. DEE was found to increase ignition delay and reduce NO_x emissions. CO emissions were decreased and HC emissions were increase with DEE. Kannan and Marappan [89] examined DEE blended with biodiesel at 5%, 10%, 15%, and 20% by volume. Satya et al. [90] investigated the effects of addition of DEE to B20 biodiesel blends at 5% and 15% by volume. Due to the higher latent heat of evaporation, DEE was found to reduce emissions of NO_x with increasing effectivity as high volume of DEE is added [89,90]. Additionally, DEE was found to increase HC and CO emissions when compared to neat biodiesel. Higher oxygen content of DEE caused the smoke opacity to exhibit a reduction when compared to biodiesel [89].

2.10.2 Expanded Polystyrene (EPS) in Biodiesel as an additive

Increases in population and quality of life worldwide has increased the demand for plastic products[91]. Duration of life of these plastics is typically less than one month, therefore mechanical and chemical recycling of these plastics must be considered. Expanded polystyrene is produced by the expansions of a styrene plastic pellet and is used in many single use applications. The raw beads are expanded using steam then aged on a storage floor before being cut into various shapes and sizes. Density of EPS varies with application, for example insulation EPS has a much higher density. Polystyrene accounts for 22% by weight for all high volume plastics [92]. Since the density of polystyrene is so low transportation from small municipalities or isolated communities is not feasible. This means that often polystyrene ends up in landfills instead of being recycled. Due to bio solvency properties of biodiesel, polystyrene can be dissolved at room temperature.

A study from Iowa state university [93] on the solubility of biodiesel concluded that polystyrene is completely soluble in biodiesel over a wide range of temperatures. Kuzhiyil and Kong in [92], found that the feasible limit of fuel pump was 10% polystyrene by weight. Polystyrene was found to be able to reduce NO_x emissions, increase CO emissions and soot emissions. Studied also examined the effect of EGR which could reduce NO_x emissions but increased CO and soot emissions. Mohammadi et al [94], studied the performance and emissions of B5 with 25g, 50g, and 75g of dissolved expanded polystyrene. B5EPS50 fuel blend was found to be the best fuel with emission reductions in CO, CO_2, NO_x and soot. Small reduction of 3.6% in brake power and increase in brake thermal efficiency were observed at maximum rated power. Aghbashlo et al. [95] also tested B5 with 25g, 50g, and 75g dissolved polystyrene, and once again found B5PS50 the most desirable fuel blend with similar results to the previous study. In another study by Mohammadi et al. [96] acetone was added to biodiesel to improve cold flow properties and stabilize the fuel.

Various other options for the many types of polymers are also being explored. Suresh et al. [97] converted PES into a partially sulfonated polystyrene which was then used as a catalyst in the production of biodiesel using sunflower oil and rubber seed oil feedstock. Dang et al. [98], used glycerol from the production of waste cooking oil biodiesel to convert PET bottles to polyols and polyurethane (PU) foams.

3.0 Materials and Methods

3.1 Materials

Materials used for experimentation included the following: low sulfur diesel purchased from a local fuel vendor throughout the experiment, pure canola oil purchased from a local supermarket, ethanol, methanol and sodium hydroxide pellets are obtained through Lakehead's Chemical Engineering Lab, diethyl ether, expanded polystyrene, and acetone were all purchased from a local vendor

3.2 Biodiesel production and fuel properties

Transesterification or alcoholysis is the reaction of a fat or oil with an alcohol to form esters and glycerol [90]. Transesterification is considered one of the best approaches to produce biodiesel due to simplicity and relatively low cost. The process of biodiesel production performed was transesterification of canola oil in the presence of methanol [99]. One litre of canola oil produced approximately 1 litre of biodiesel. Glycerol was separated from biodiesel, and then biodiesel was washed twice. Volumetric collection efficiency after washing averaged 80%. Biodiesel production quality was tested per ASTM 6751 standards [Table 3-1].

Table 3-1 Test Results of Biodiesel According to ASTM 6751

Test Name	Test Method	ASTM limit	Results
Free glycerin (mass%)	ASTM D6584	Max. 0.02	0
Total glycerin (mass%)	ASTM D6584	Max. 0.24	0.112
Flash Point, closed cup (^{0}C)	ASTM D93	Min. 130	169
Water & sediment (vol.%)	ASTM D2709	Max. 0.505	0
TAN (mg KOH/g)	ASTM D664	Max. 0.5	0.14
Sim. dist., 50% recovery (^{0}C)	ASTM D2887	N/A	359.8
Cetane index	ASTM D976 (2 variables formula)	N/A	50
Copper corrosion, 3h @ 50^{0}C (rating)	ASTM D130	Max. 3a	1a

Fuel samples were sent to Intertek laboratory in Hamilton (Ontario) to determine cold flow properties using ASTM D5773 standards. Table 3-2 summarizes the related properties of density, viscosity, and cloud point of tested fuels with Ethanol and DEE additives [100,101]. All Ethanol and DEE series samples were found to have higher cloud points than neat winter diesel. All B20 biodiesel diesel blends exhibited cloud point lower than -20°C. Table 3-3 summarizes the same fuel properties as Table 3-2 for biodiesel diesel blends with dissolved expanded polystyrene content.

Table 3-2 Fuel Properties of Diesel-Biodiesel Blends with Ethanol and DEE Additives

	Viscosity (cst)	Density (g/ml)	Cloud Point (˚C)	HHV (kJ/kg)
Diesel	3.90	0.82	-40	45573.00
Ethanol	0.80	0.80		29700.00
Diethyl Ether	0.23	0.71		36892.00
B100	4.32	0.88	-2.6	40296.00
Biodiesel Diesel Blends				
B20	2.68	0.84	-21.2	44517.60
B50	3.20	0.85	-13.2	42934.50
Ethanol Additive Series				
B20E5	1.45	0.84	-26.5	43776.72
B20E15	2.20	0.83	-25.4	42294.96
B50E5	2.58	0.85	-14.8	42272.78
B50E15	2.55	0.84	-14.6	40949.33
B100E5	4.15	0.88	-2.4	39766.20
B100E15	3.92	0.87	-2.8	38706.60
DEE Additive Series				
B20DE5	2.20	0.83	-22.6	44136.32
B20DE15	1.86	0.82	-22.6	43373.76
B50DE5	2.61	0.84	-13.8	42632.38
B50DE15	2.12	0.83	-13.9	42028.13
B100DE5	3.85	0.87	-2.6	40125.80
B100DE15	2.87	0.85	-5.4	39785.40

Table 3-3 Fuel Properties of Blends with EPS content

	Viscosity (cst)	Density (g/ml)	Cloud Point (˚C)	HHV (kJ/kg)
Diesel	3.9	0.82	-40	45573
B100	4.32	0.88	-2.6	40296
BPS100 (50g/L EPS)	11.2	0.894	17.8	40330
Acetone	0.42	0.79		29000
Biodiesel Diesel Blends				
B5	3.92	0.823	-32	45309.2
B20	2.68	0.84	-21.2	44517.6
B50	3.2	0.85	-13.2	42934.5
Dissolved Polystyrene Series				
BPS5	4.148	0.824	-16.8	45310.85
BPS20	5.36	0.835	9.2	44524.4
BPS50	7.55	0.857	15.3	42951.5
Dissolved Polystyrene with Acetone Additive Series				
BPS5A100		0.82	-20	44495.3
BPS5A250		0.81	-22	41233.14
BPS20A100		0.835	8	42971.96
BPS20A250		0.811	7	40643.3
BPS50A100		0.842	10	41556.35
BPS50A250		0.832	9.5	39463.625
BPS100A100		0.872	16	39197
BPS100A250		0.862	15	37497.5

3.3 Selection of fuel and fuel blends

3.3.1 Ethanol and DEE

Both Ethanol and DEE are readily available additives that can immediately be added to diesel biodiesel blends to improve emissions and cold flow properties. Companies and municipalities with large diesel fleets should be able to obtain and use these fuel blends with relative ease. Especially if fleet is already equipped for biodiesel use.

3.3.2 Polystyrene Dissolved in Biodiesel

Polystyrene is commonly used for shipping goods, food packaging, and disposable plates/cups. In 2012, household in the United States produced 2,240,000 tons of Polystyrene and only recycled 20,000 [102]. By volume polystyrene can account for up to 22% of plastic waste [103]. If polystyrene can be recycled simply through addition to biodiesel, small municipalities can start to recycle using their diesel fleets. Expanded polystyrene is a polymer composed of 92% carbon and 8% hydrogen by weight [104]. At

50°C EPS was found be completely dissolved in less than 20 minutes. If fuel blends are left sit, some EPS will dissolve out. Acetone was found to be the best stabilizer by multiple studies [94,96,104]. Acetone has a boiling point of 56°C, latent heat of evaporation of 518 kJ/kg [105], and a viscosity of 0.316 cP.

3.4 Engine and Test Procedure

3.4.1 Engines under study

Two diesel engines were tested, a light-duty and heavy-duty engine. The heavy-duty engine studied was a Cummins QSB4.5 inline 4-cylinder turbocharged engine with high pressure common rail injection system. The QSB4.5 is designed mainly for use in agriculture, mining, and construction. A dual tank fuel system was installed for switching between various test fuels. Specifications of the heavy-duty test engine can be found in Table 3-4.

Table 3-4 Cummins QSB4.5 Specifications

Engine Specification	
Engine Make and Model	Cummins QSB 4.5 T4I
Engine Type	Inline 4-Cylinder
Number of Cylinders	Four
Bore * Stroke	102mm * 138mm
Swept Volume	4.5 l
Compressions Ratio	17.3:1
Rated Power	97KW @ 2300 RPM

The light-duty engine was a HATZ 2G40, 2 cylinder with a common rail injection system. 2G40 was mounted on a engine test apparatus in the thermal lab, exhaust was vented outside through the roof. Exhaust valves for emissions testing machines were installed on the exhaust system. The engine was fitted with a snowmobile water brake dynamometer purchased from Land & Sea DYNO systems. A servo controller was installed on the water load release to control engine load. Data acquisition system and Opacity meter were attached to a Laptop computer to take real time data of tests. Specifications can be found below in Table 3-5.

Table 3-5 HATZ 2G40 Engine Specifications

Engine Specification	
Engine Make and Model	Hat 2G40
Engine Type	Air-cooled 2-cylinder
Number of Cylinders	Two
Bore * Stroke	92mm * 75mm
Swept Volume	0.997 l
Compressions Ratio	20.5:1
Rated Power	17KW @ 3600 RPM

3.4.2 Engine test procedure

Idle Testing Cummins Heavy-Duty Engine

The Cummins QSB4.5 engine was tested at three idling conditions: 800 rpm, 1000 rpm, and 1200 rpm with no engine load. The engine was tested for 30 minutes, starting from a cold start for each test. CO, CO_2, NO, NO_2, HC, O_2, and exhaust temperature readings were taken ending at 2, 5, 10, 20, and 30 minute intervals, respectively. The probe was inserted for 2 minutes for each test. Peak reading of each component was taken for every test. An average cooling period of 8 hours was used between each engine test to ensure 'cold start' conditions. When changing fuel type, engine was run for a short period on neat diesel then fuel was switched to the next test fuel. Fuel consumption was measured by weighing detachable fuel tank before and after each test. The engine was tested in outdoor conditions with a temperature range from 20^0C to 25 ^{0}C.

HATZ 2G40 Engine Testing

The light-duty engine was tested at three different rpm conditions, high idle at 1000 rpm, peak torque condition at 2100 rpm, and high power condition at 3000 rpm. At each rpm condition engine was tested at no load (idle), light load, medium load, and high load, this corresponds with 0%, 20%, 50%, and 80% of the rated peak torque when fueled with neat diesel. Before any test was preformed the engine was warmed up for 10 minutes. Each load condition was tested for 5 minutes to allow for emission levels to stabilize. CO, NO, NO_2, HC, O_2 and opacity meters were tested using a CO meter, a NOVA gas analyzer and a Smart 1500 opacity meter. Engine Power, Torque, RPM, and exhaust gas temperature was measured using a Land & Sea dynamometer data acquisition board. The data acquisition system was connected via USB port to a laptop computer. Data was recorded and analyzed in Dyno Max 2010 software at a rate of 20 Mhz. Engine load condition was also recorded and controlled with the data system, via a servo controller connected to the water load knob. The engine lab was kept at a 22°C. The detachable fuel tank was then measured to determine fuel consumption.

3.5 Exhaust Emissions and Temperature Measurement

Cummins QSB4.5 Heavy-duty Engine

The test apparatus was designed and constructed so that all exhaust measurements were taken 6 inches into the exhaust pipe. The apparatus was held in the middle of the pipes approximately 1 inch from the opening of the catalytic converter. NO, NO_2, HC, O_2 and CO_2 emissions were measured using a NOVA gas 7466K analyzer. NO and NO_2 sensors both have a resolution of 1 ppm. The HC sensor has a resolution of 10 ppm. The CO_2 sensor has a resolution of 0.1% of gas analyzed. CO emissions were measured using a Dwyer 1205A handheld CO analyzer with a resolution of 1 ppm and an accuracy of +/- 5% of reading. Temperature of exhaust gas temp was measured using an EXTech Easyview 10 with a resolution of 0.1 degree Celsius and an accuracy of +/- 0.3% of reading.

HATZ 2G40 Light-duty Engine

During installation of exhaust system, aluminum exhaust pipes were punched so that exhaust lines could be connected to three gas measurement systems. A thermocouple was inserted into the exhaust gas system at the same time. CO emissions were measured using the Dwyer 1205a handheld CO analyzer with a resolution 1ppm and an accuracy of +/- 5% of reading. NO, NO_2, HC, O_2, and CO_2 emissions were measured using a NOVA gas 7466K analyser. NO and NO_2 sensors both have a resolution of 1 ppm. HC sensor has a resolution of 10 ppm. The CO_2 sensor has a resolution of 0.1% of gas analyzed. Opacity was measured using a SMART 2000 with a opacity range of 0-100% and a soot density range of 0-10 mg/m^3 with resolutions of +/- 0.5% for both readings. A summery of equipment used for emissions measurements can be found below in Table 3-6.

Table 3-6 Emission Measurement Devices

Measurement Devices					
Method of Detection	Species	Measured Unit	Range	Resolution	Accuracy
Nova Gas 7466K					
Electro Chemical/Infrared detector	CO	%	0-10%	0.10%	±1%
Infrared Detector	CO2	%	0-20%	0.10%	±1%
Electro Chemical	NO	ppm	0-2000 ppm	1 ppm	±2%
Electro Chemical	NO2	ppm	0-800 ppm	1 ppm	±2%
Electro Chemical	O2	%	0-25%	0.10%	±1%
Infrared Detector	HC	ppm x 10	0-20000 ppm	10 ppm	±1%
Dwyer 1205A					
Electro Chemical	CO	ppm	0-2000	1 ppm	±5%
ExTech EA10					
	Temp	0.1 ^oC	(-)200^oC to 1360^oC	0.1^oC	±0.3%
SMART 2000					
	Opacity	%	0-100%	0.10%	±0.5%
	Soot Density	mg/m^3	0-10 mg/m^3	0.00001	±0.5%

4.0 Results and Discussions

4.1 Light-duty Engine performance

4.1.1 Brake Thermal Efficiency (BTE)

Brake Thermal Efficiency (BTE) is the amount of power produced over energy potential of the fuel. Brake power of the engine is measured in kilowatts (kW), fuel consumption measured in kilograms per hour (kg/h) and higher heating value is measured in kilojoules per kilogram (kJ/kg). Power is multiplied by 3600 second per hour to produce a unit less efficiency.

$$BTE = \frac{3600\left({}^{s}/_{h}\right) \times Power\ (kW)}{Fuel\ Consumption\left({}^{kg}/_{h}\right) \times Higher\ Heating\ Value\left({}^{kJ}/_{kg}\right)} \tag{4-1}$$

1000 rpm (high idle)

Figure 4-1 a, b, c, and d represent the BTE at 1000 rpm of biodiesel blends, biodiesel blends with EPS content, BPS blends with acetone at 100 ml/L of biodiesel and BPS blends with acetone at 250 ml/L of biodiesel. B5 and B50 blends performed well with all additives. BPS5A250 performed exceptional well, due to spray characteristics and the volatility of acetone. BPS100 blends with and without acetone performed poorly when compared to diesel. This was due to high viscosity of BPS100 blends not producing significant power increases. High viscosity causes higher pressure in the fuel line resulting in increased spray penetration and fuel consumption. In small engines overpenetration occurs easily which can result in quenching. B100 as shown in most biodiesel literature performed well with no modification of timing. High cetane number of biodiesel causes shorter ignition delay, therefore better results can be observed if timing were to be advanced.

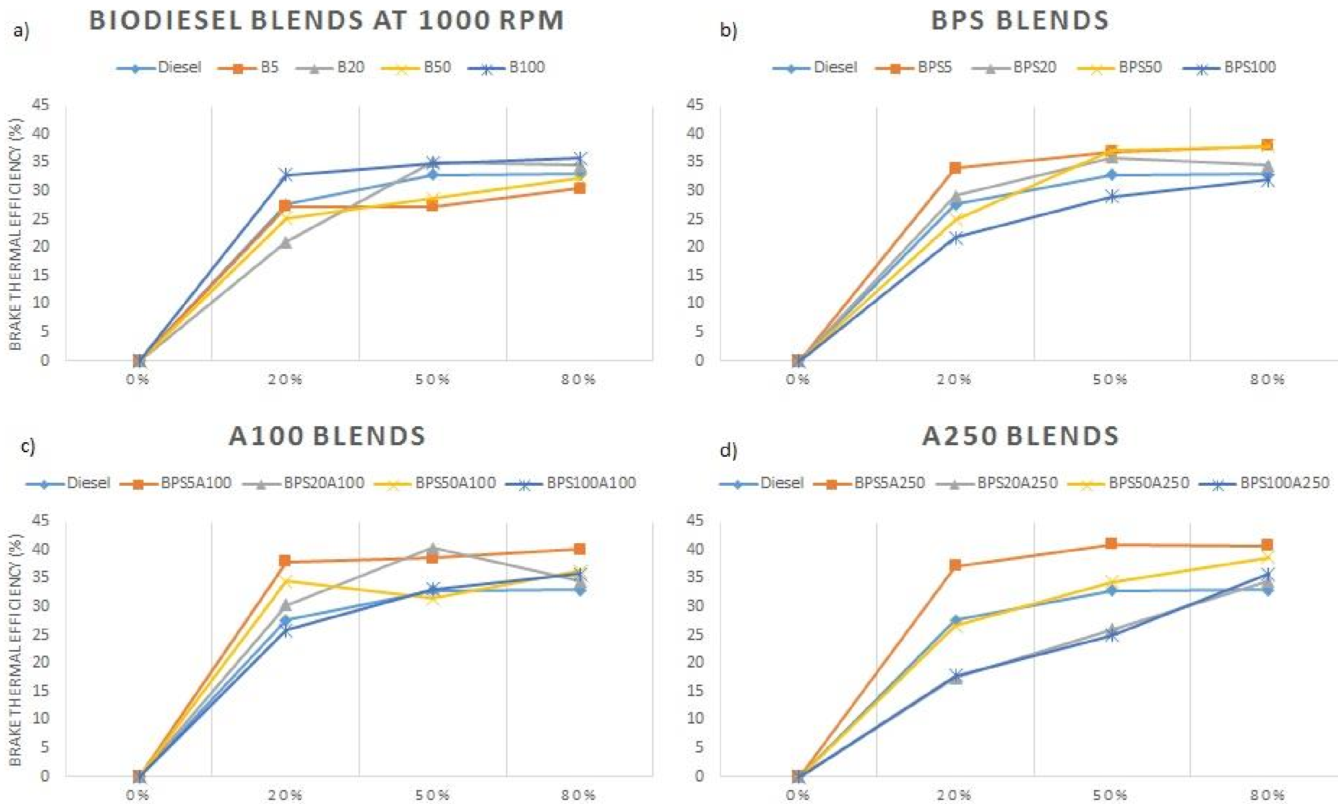

Figure 4-1 EPS Series BTE of Light-duty Engine at 1000 rpm a) Biodiesel Blends b) Blends with EPS Content c) Blends with 100 ml of Acetone d) Blends with 250 ml of Acetone

2100 rpm (Peak Torque)

Figure 4-2 (a, b, c, d) illustrates the BTE for the EPS series at 2100 rpm. Again all B5 and all B50 blends performed well at 2100 rpm, although increases in BTE were diminished from gains at 1000 rpm. BPS100 blends with and without acetone once again performed poorly compared to neat diesel. B100 performed well and overall BTE was increased from 1000 rpm.

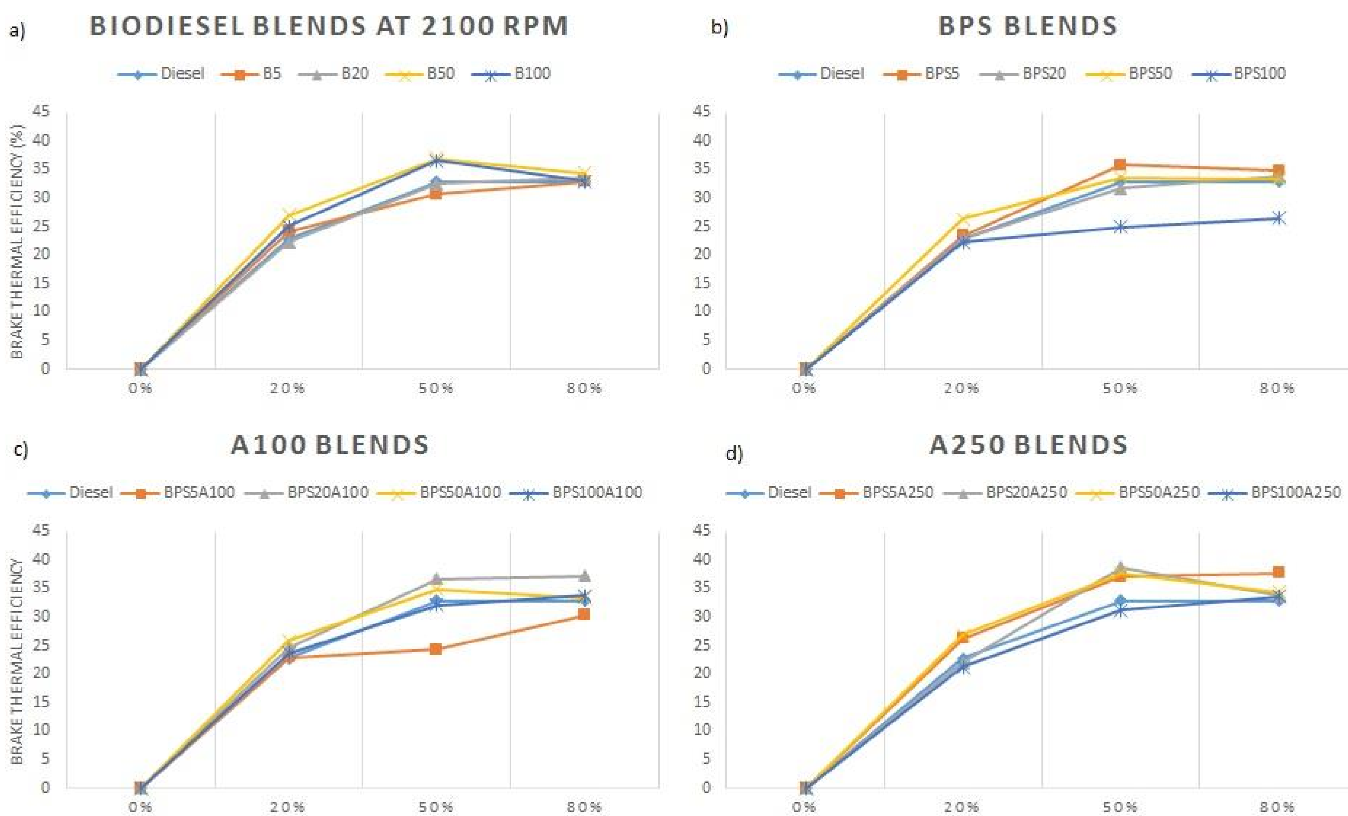

Figure 4-2 EPS Series BTE of Light-duty Engine at 2100 rpm a) Biodiesel Blends b) Blends with EPS Content c) Blends with 100 ml of Acetone d) Blends with 250 ml of Acetone

3000 rpm (High Speed/Power)

Figure 4-3 (a, b, c, d) demonstrates BTE of the EPS series at 3000 rpm. Overall BTE levels are the same as 2100 rpm and greater than 1000 rpm levels. Most fuel blends performed better than neat diesel levels at all load conditions. This may be due to fuel rich regions occurring at high speed, which would allow for oxygen content of biodiesel and volatility of acetone to improve complete combustion.

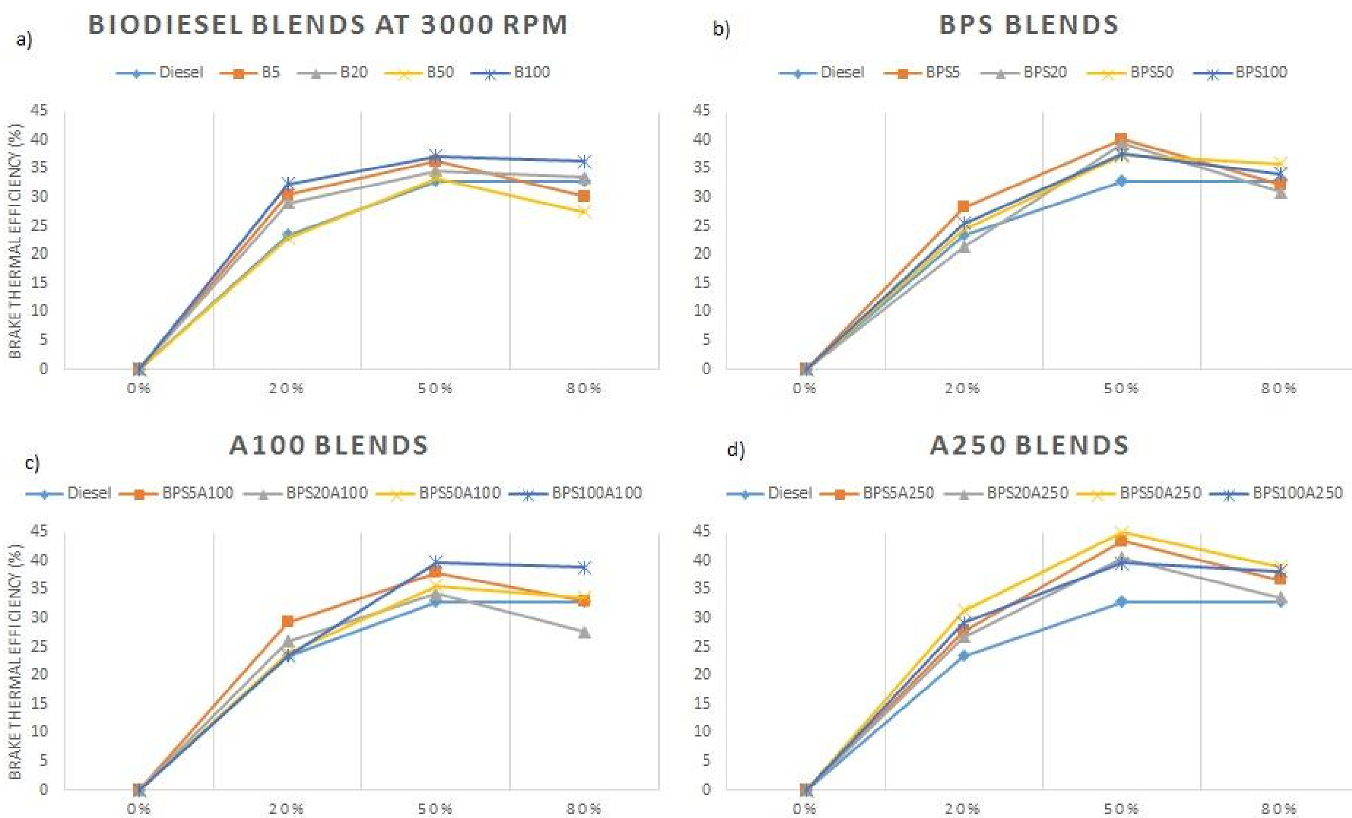

Figure 4-3 EPS Series BTE of Light-duty engine at 3000 rpm a) Biodiesel Blends b) Blends with EPS Content c) Blends with 100 ml of Acetone d) Blends with 250 ml of Acetone

4.1.2 Brake Specific Fuel Consumption (BSFC) in Light-duty Engine

Like BTE, BSFC is a good performance metric when comparing engines because it is also based on performance of fuel. BSFC is often measured in g/kW h or kg/kW h and derived from the following equation.

$$BSFC = \frac{Fuel\ Consumption\ (\frac{g}{h} or \frac{kg}{h})}{Power\ (kW)} \quad (4\text{-}2)$$

1000 rpm (High Idle)

Figure 4-4a shows the BSFC for the EPS series at 100 rpm. Overall trends see BSFC lowering with increasing load. All blends with acetone at 100 ml/L of biodiesel demonstrated a decrease in BSFC due to decreased density of fuel with minimal power drop off. At all conditions BPS5 decreased BSFC due to increased power from oxygen and EPS content. Increased pressure in the fuel line may have also allowed for better spray characteristics. BPS5A100 and BPS5A250 also benefitted from these characteristics. All BPS Blends had lowered BSFC at medium and high load. Increased pressure in fuel line caused better spray penetration and higher energy density of EPS content caused these results. Addition of 100 ml/L of biodiesel to BPS20 decreased BSFC for all load condition. Addition of 250ml/L of acetone in biodiesel improved BSFC for BPS5 Blends.

2100 rpm (Peak Torque)

Figure 4-4b describes the BSFC for EPS blends at 2100 rpm for all load conditions. Overall a decrease in BSFC was observed from 1000 rpm. Once again BSFC was decreasing with increased load. BSP5 consistently proved to be a promising fuel blend at it decreases BSFC at low and medium loads. BPS20, BPS20A100, and BPS20A250 matched or decreased the BSFC consumption at all load conditions.

300 rpm (High Speed/Power)

Figure 4-4c shows the BSFC for EPS blends at 3000 rpm for all load conditions. Compared to 2100 rpm condition there was a significant overall increase in BSFC. This is due to increased fuel consumption without matching power increases. Once again at low and medium load conditions B5 blends perform well with matching or decreasing BSFC of neat diesel. These improvements appear to be from the addition of biodiesel content, which means they may be attributed to better spray characteristics. B20 also decreased BSFC at low and medium load. BPS50A250 decreased BSFC for all load conditions. Once again this is most likely due to increased EPS content contributing to better combustion characteristics.

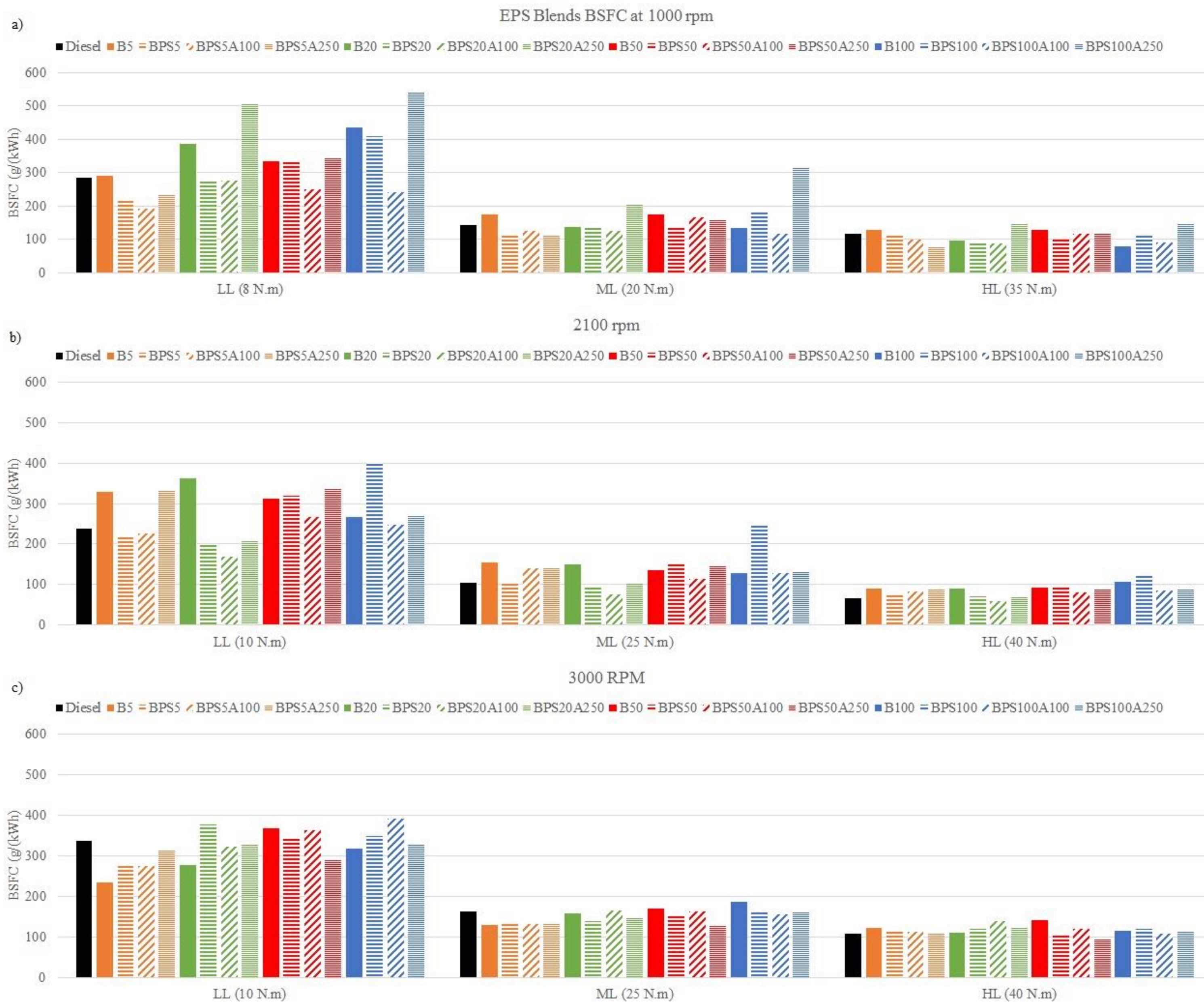

Figure 4-4 EPS Series BSFC for a) 1000 rpm b) 2100 rpm c) 3000 rpm

4.1.3 Average Brake Torque on Light-duty Engine

The average percentage change in brake torque can be found in Figure 4-5. The average percent change was taken across all load conditions for the three speed conditions. Additions of EPS content to B5 Blends was found to increase torque for all blends. At 1000 rpm the torque increase was significant, average increases over 20% with and without acetone content. BPS20 and BPS20A100 improved torque at 1000 rpm and 2100 rpm but decreased torque at 3000 rpm. B50 and BPS50 increased torque from neat diesel at all speed conditions. BPS50A100 performed well at 1000 rpm and 3000 rpm, while decreasing torque by 3.2% at 2100 rpm. B100, BPS100, and BOS100A100 performed well with small reductions at 1000 rpm for BPS100 and 2100 rpm for BPS100A100. BPS100A250 decreased torque significantly at 1000 rpm but then slightly increased torque at higher speeds. Overall all biodiesel-diesel blends with EPS content performed well. B5 and B50 blends with EPS content performed the best.

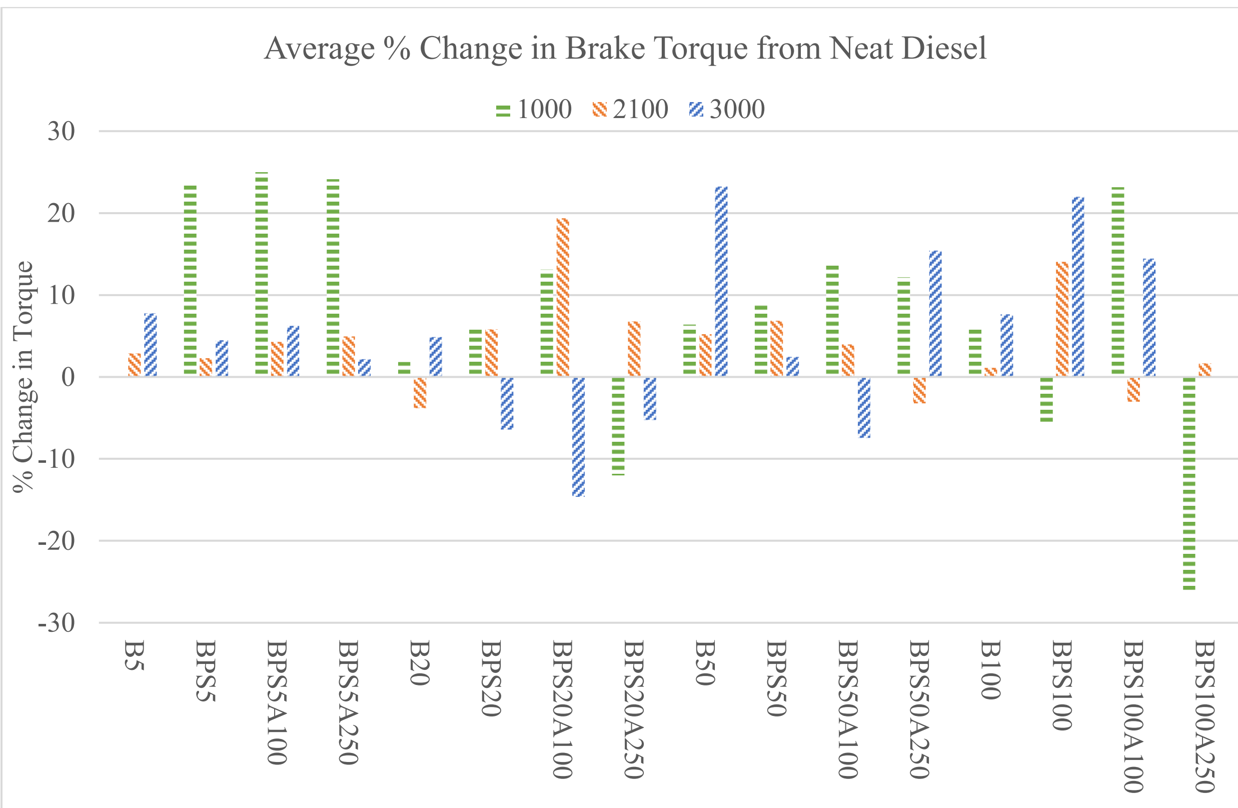

Figure 4-5 Average Percentage Change of Torque at All Load Conditions for 1000 rpm, 2100 rpm, and 3000 rpm

4.2 CO Emissions

4.2.1 Ethanol and DEE in Heavy-duty Engine

Figures 4-6 and 4-7 illustrate CO emissions of different fuel blends for ethanol and DEE series, respectively. Average peak readings of CO emissions over testing period from different blends were compared to those of pure diesel. At low idle condition (Figure 4-6a), CO emissions of B20, B50 and B100 decreased by 4.5%, 6.1% and 32.9%, respectively compared to diesel CO emissions. At 1000 rpm (Figure 15b) or middle idle condition, these reductions increased to 9.5%, 14.8% and 39.4%. As illustrated in Figure 4-6c high idle tests once again increased reductions of CO for B20, B50, and B100 by 26.6%, 30.5%, and 41.8%.

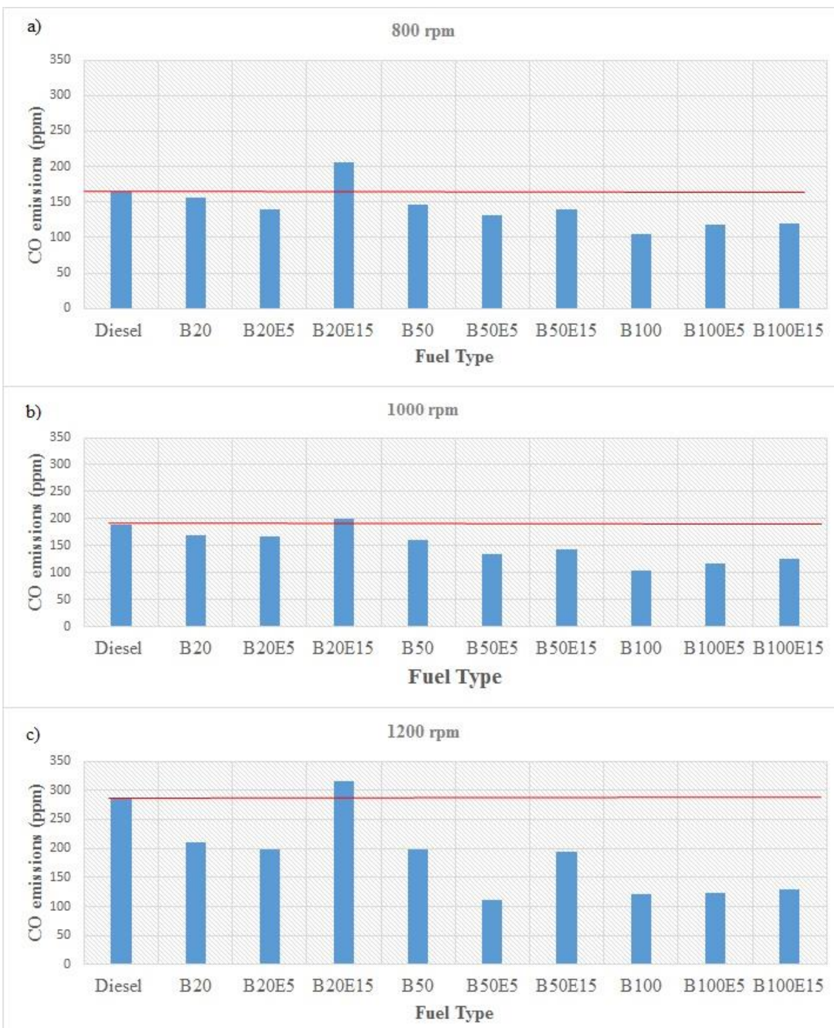

Figure 4-6 Average CO Emissions for Ethanol Series Heavy-Duty Engine a) 800 rpm b) 1000 rpm c) 1200 rpm

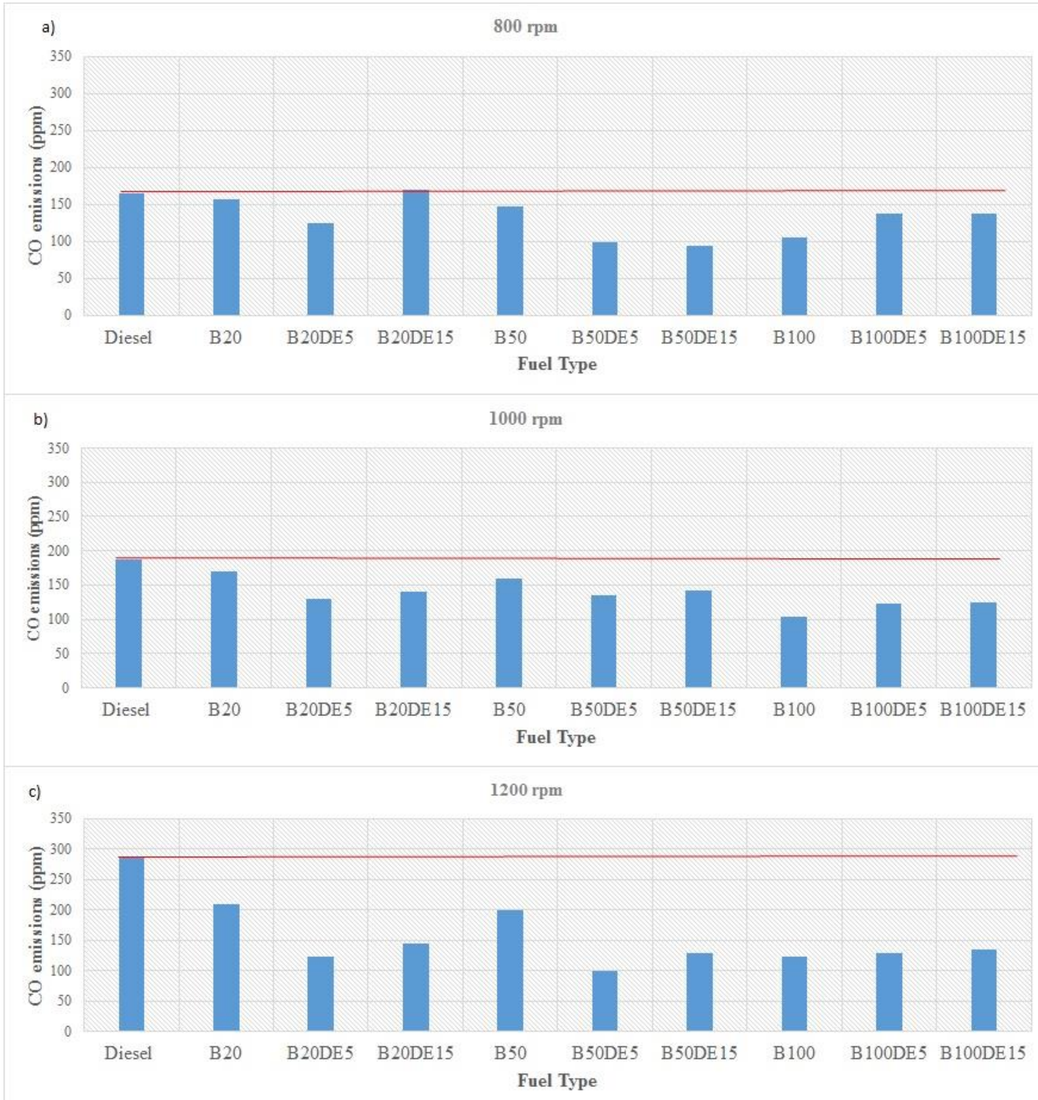

Figure 4-7 DEE Series Average CO Emissions for Heavy-Duty Engine a) 800 rpm b) 1000 rpm c) 1200 rpm

Significant reductions in average CO emissions were observed at all idle conditions in the ethanol series except B20E15. Addition of ethanol to fuel blends has two opposing factors: cooling effect and volatility. Cooling effect of ethanol is attributed to the higher latent heat of vaporization. Ethanol and diesel having a latent heat of vaporization of 921 kJ/kg and 232 kJ/kg, respectively [106]. Increased volatility of ethanol will also affect the combustion profile of a fuel blend. Diesel and biodiesel have boiling point of 180^0C-340^0C, and 350^0C, respectively. Boiling point of ethanol is significantly less than both diesel and biodiesel at 77.8^0C. The addition of 5% ethanol by volume was found to decrease CO emissions for all B20, and B50 blends due to volatility effect of ethanol dominating combustion. 15% ethanol addition by volume to B20 and B50 was found to increase CO emissions from 5% addition probably due to cooling effect of ethanol reducing combustion temperature. At all idling conditions, neat biodiesel with ethanol additive exhibited higher CO emissions with higher ethanol volume percentage. The volatility effect of ethanol additive had a lessened effect on B100 blends due to the high boiling point of biodiesel. Therefore, the cooling effect of ethanol additive lowers the combustion temperature and increases CO emissions for B100 blends.

Figure 4-7 shows CO emissions of DEE series at low, medium, and high idle rpms. Similar to ethanol, DEE has higher volatility and higher latent heat than diesel and biodiesel. The boiling point of DEE is 34.4^{0}C [107] and the latent heat of evaporation is 356 kJ/kg [101]. Compared to ethanol, DEE is more volatile and should have less of a cooling effect due to lower latent heat of evaporation. 5% addition of DEE to B20 and B50 were found to decrease CO emissions due to increased volatility. Addition of 15% DEE to B20 and B50 increased CO emissions from 5% DEE. Again, this can be attributed to cooling effect of DEE dominating combustion profile. Due to reduced cooling effect of DEE when compared to ethanol, increases in CO emission are less pronounced. CO emissions from B100 increased with increased DEE at all idle conditions.

Figure 4-6 indicated that all biodiesel blends from the ethanol series except for B20E15 showed reductions in CO emissions. B100 fuel blends and B50E5 exhibited highest CO reductions across all idle conditions. Similarly, from the DEE series in Figure 3, B100 and B50DE5 showed promising reductions in CO emissions compared to neat diesel. B20DE5 also proved to be effective in CO reduction.

4.2.2 Diesel-Biodiesel Blends with EPS content in Light-duty Engine

Figure 4-8 shows average CO emissions for EPS content series on the light duty engine. With figure 4-8 (a, b, and c) representing CO emissions at 1000 rpm, 2100 rpm, and 3000 rpm respectively. As stated previously these conditions represent high idle (1000 rpm), peak rated torques (2100 rpm), and high speed/power (3000 rpm).

1000 rpm (High Idle)

In Figure 4-8a it can observe the CO emissions for all load conditions at 1000 rpm (high idle). Typically, biodiesel content is expected to lower CO emissions, at 1000 that is true for all loading conditions. B5 was found to be most effective in reducing CO emissions at low load condition. This is due to an increase in oxygen content with little increase in fuel consumption. B50 and B100 both had significant increases in fuel consumption due to higher density. No load, low load, and medium load show decreased CO emissions for all blends. At high load, only B50 increased from diesel due to increases fuel consumption with less reduction in CO emissions than B100 blends. B5 blends with EPS content showed increase from B5 in CO emissions. This is due to increased fuel consumption due to high viscosity, without a significant increase in heating value of the fuel. B20 Blends appear to have allowed enough EPS content to be dissolved to improve CO emissions. Addition of acetone to BPS20 decreased CO emissions due to high volatility from low boiling point of 56°C. BPS50 significantly reduced CO emissions at all load conditions due to an increase in combustion temperature of the engine chamber. B50 blends were not affected positively by the increase in acetone content. Due to high oxygen content a smaller reduction was seen in the addition of EPS for all load conditions. Even so, significant reductions of CO emissions were observed when using acetone as a stabilizer. This is due to decreased fuel consumption and an increased volatility of the fuel blends.

2100 rpm (Peak Torque)

Figure 4-8b shows the average CO emissions for all loads at peak rated torque condition. Peak rated torque is taken from manufacturers specification sheet for the 2G40 run on neat diesel. Lower CO emissions were observed for all B20, B50, and B100 blends at all load conditions. B5 also showed a reduction in CO due to oxygen content in biodiesel. Addition of EPS to B5 blends was found to increase CO emissions. This is due to an increase in fuel consumption caused by added viscosity of fuel. Addition of acetone increased CO emissions further at 100 ml/l, the lower heating value of acetone and high latent heat can be attributed to these increases. At 250 ml/L acetone in BPS5A250 seemed to have increased volatility and decreased fuel consumption by enough to see improvement at low, medium and high load. B20 blends saw a reduction with the addition of EPS and a further reduction with the addition of 100 ml of

Acetone. A slight increase in CO emissions were observed for BPS20A250 at all load conditions due to cooling effect of acetone dominating emission results. B50 and B100 blends both showed reductions in CO emissions with the additions of EPS content. BPS50A100 and BPS50A250 both increased CO emissions for all load conditions. BPS100A100 lowered CO emissions from BPS100 at all load conditions due to the increased EPS content in blend. BPS100A250 showed increases due to possible areas of over-leaning due to acetone addition.

3000 rpm (High Speed/Power)

Figure 4-8c illustrates the average CO emissions of all EPS biodiesel-diesel blends at 3000 rpm. Smaller reductions in CO are observed for all blends when compared to 2100 rpm. B5 Blends and B20 showed an increase in CO emissions for low, medium, and high load conditions. For B5 and B20 this is due to an increase in viscosity with relative little increase in effect of oxygen content. The BPS5 increase is also due to change in viscosity. BPS5A100 and BPS5A250 increase CO emissions due to lower heating value of acetone dominating. Addition of EPS to BPS20, BPS50, and BPS100 decreased emissions for all load conditions. Addition of acetone was once again found to be effective in BPS20A100 for all load conditions but high, where a small increase occurred. For B50 and B100 blends with EPS, acetone seemed to have little effect on CO emissions.

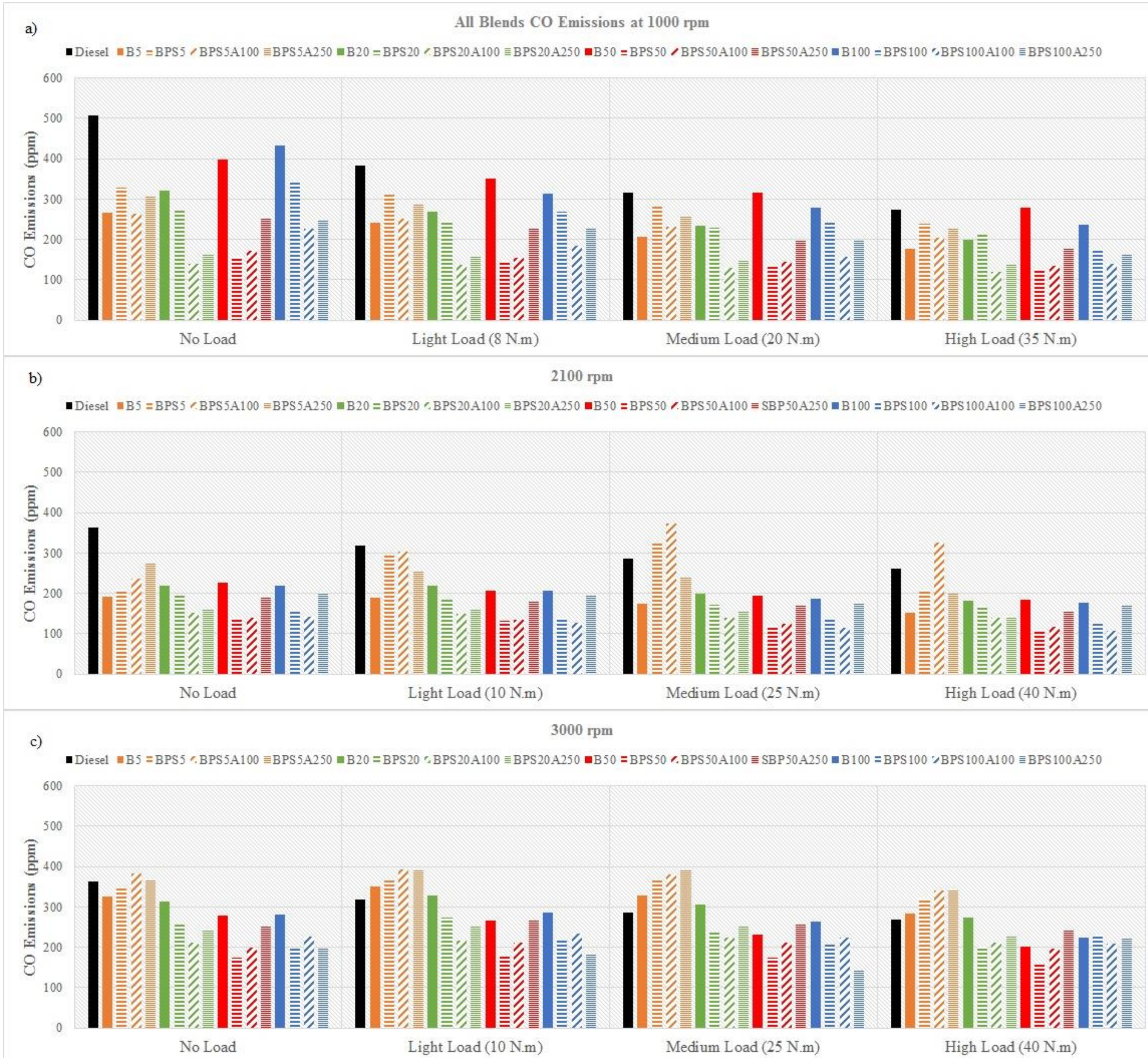

Figure 4-8 Average CO Emissions for All EPS Series Blends on Light-duty Engine a) 1000 rpm b) 2100 rpm c) 3000 rpm

4.3 NO_x Emissions

4.3.1 Ethanol and DEE in Heavy-duty Engine

Figures 4-9 and 4-10 illustrate the average NO, and NO_2 emissions from low, medium, and high idle tests, for ethanol series and DEE series, respectively. NO and NO_2 emissions were combined to examine average NO_x emissions over warm-up period. Average NO_x emissions over testing period were compared to neat diesel NOx emission values. B20, B50, and B100 all emitted higher NO_x emissions than diesel. It was found that increasing volume percentage of biodiesel would increase NOx emissions at all rpms. The average NOx emissions trends for all fuel types tested was that higher idle conditions caused lower average NOx emissions. This may be attributed to over leaning in local areas of combustions due to higher air consumption at high idle speeds. While cylinder temperature increased with rpm, idling condition does not create high enough temperature to facilitate greater NO_x production.

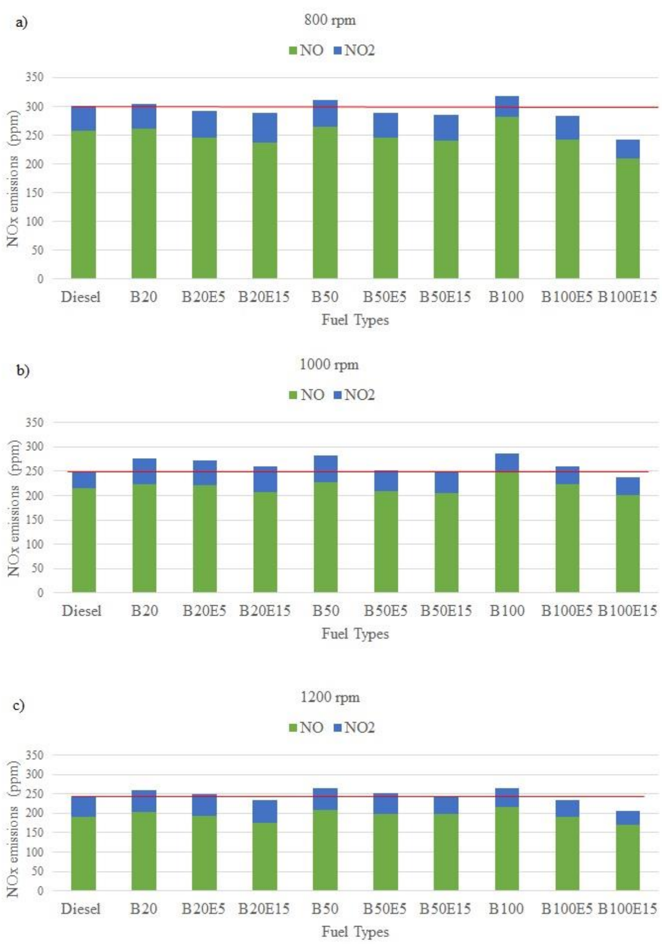

Figure 4-9 Average NOx Emissions for Ethanol Blends, Heavy Duty Engine a) 800 rpm b) 1000 rpm c) 1200 rpm

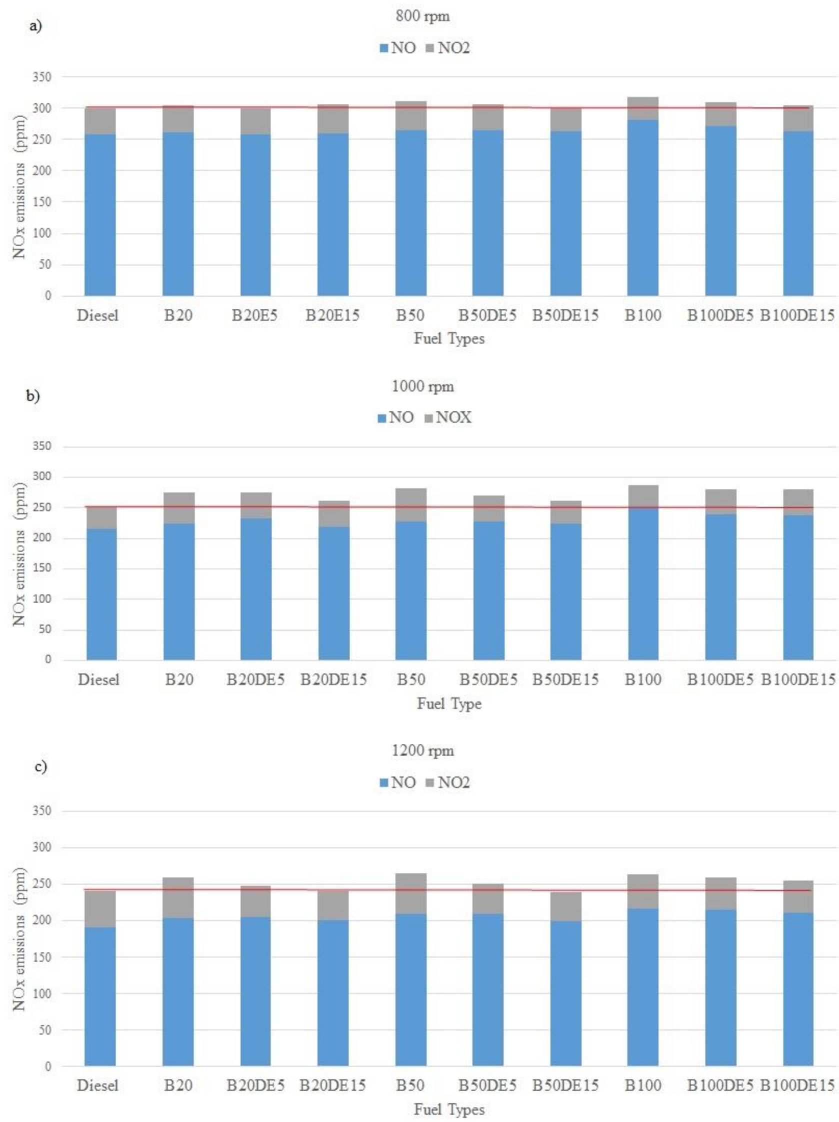

Figure 4-10 Average NOx Emissions for DEE Series, Heavy Duty Engine a) 800 rpm b) 1000 rpm c) 1200 rpm

At low idle, all blends with ethanol produced lower average NOx emissions than neat diesel. As illustrated in Figure 4-9a, B100E15 lowered NOx emissions at medium idle test by 4.8%. In Figure 4-8c, B100E5 and B100E15 reduced NOx emissions by 3.1% and 14.1%, respectively. It was demonstrated that the addition of ethanol to biodiesel-diesel blends could reduce average NOx emissions in all tests. B100E15 was found to be the most effective blend in reducing average NO_x emissions over the test period.

Figure 4-10 demonstrates the average NO_x emissions at different idling conditions for DEE series. No blends generated lower average NOx emissions than neat diesel. Addition of DEE to B20, B50, and B100 caused a slight reduction of average NOx emissions from the biodiesel-diesel blends. Higher volume percent of DEE induced lower NOx emissions. The reduction in NO_x emissions can been attributed to the higher cetane rating associated with DEE, due to lower ignition delay. Cetane number of diesel, biodiesel, and DEE are 48, 50, and 125, respectively [69,108]. Due to very high cetane number of DEE, we expected much higher NOx reduction with higher percentage of DEE in the blend. The results suggest that the effect of high cetane number is less effective to reduce NOx emissions at idling engine running conditions.

4.3.2 Diesel-Biodiesel Blends with EPS content in Light-duty Engine

1000 rpm (High Idle)

Figure 4-11a represents the average NO_x emissions for 1000 rpm at all load conditions. As expected the increase in Biodiesel content caused increases in NO_x emissions. Oxygen content and better spray penetration contribute to a higher combustion temperature resulting in high emissions. For all blends at all load conditions BPS content decreased NO_x emissions. Lower cetane number due to EPS content creates a lower mean combustion temperature. Higher viscosity of the blends with dissolved EPS may have caused overpenetration of the fuel spray, causing quenching on cylinder wall. Addition of 100 ml/L of acetone to biodiesel at no load and light load condition had little effect on NO_x emissions. BPS20A100, BPS50A100, and BPS100A100 all increased NO_x emissions with the addition of 100 ml/L of biodiesel. Acetone increased volatility of the fuel blends reducing the decreased cetane number from EPS content. BPS50A250 saw an increase in NO_x emissions from BPS50A100, this can be attributed to higher volatility and low viscosity of acetone. When 250 ml/L was added to BPS100 NO_x emissions decreased. At high concentration of biodiesel mixed with EPS content 250ml/L was 20%. 20% acetone will significantly decrease the heating value of the fuel.

2100 rpm (Peak Torque)

Figure 4-11b shows the average NO_x emissions at 2100 rpm, which is peak torque conditions. Overall, NO_x emissions decreased from 1000 rpm. Once again biodiesel content increase NO_x emissions due to higher oxygen content and spray characteristics causing better fuel mixing and combustion. BPS5 increase NO_x emissions for no load, low load, and high load conditions. BPS5A100 decreased NO_x emissions from BPS5 for all load conditions. This may be due to small amount of EPS content being overpowered by lower heating value and high volatility of acetone. EPS content appeared to increase combustion temperature for BPS5A250 as NO_x values increased. BPS20 increased emissions for low, medium, and high load conditions. Higher EPS content was not overpowered by bad spray characteristics. BPS20A100 further increased the NO_x emissions due to higher heating values of fuel. B50 and B100 blends lowered NO_x emissions with the addition of EPS content. The addition of 100 ml/L of acetone increased emissions by increasing volatility and reducing viscosity. Once again addition of 250 ml/L of acetone at B50 and B100 blends reduced heating value of fuel allowing for lower NO_x emissions.

3000 rpm (High Speed/Power)

Figure 4-11c illustrates the average NO_x emissions for the final 3000 rpm condition at all loads. Overall NO_x emissions dropped from medium load condition and increased with load. At no load and light load biodiesel content increased NO_x emissions from diesel condition. At medium and high load condition B5 and B20 had no effect on increase in NO_x emissions. B50 and B100 still increases NO_x emissions at medium and high load due to oxygen content and increased spray penetration. BPS5 increases NO_x emissions for all load conditions from B5. BPS content increasing viscosity causing better spray penetration can be attributed to the increase in temperature. BPS5A100 decreased NO_x emissions for all load conditions due to low heating value and the volatility of acetone overpowering EPS content increases. Higher volatility of acetone can be attributed to increases in BPS5A250. BPS20, BPS50, and BPS100 increased NO_x at no and low load conditions due to EPS increasing combustion temperature. Acetone addition seemed to have little effect on most fuels, with the exceptions of B100 blends. High amounts of acetone were effective in reducing heating value of the fuel, thus lowering NO_x emissions significantly.

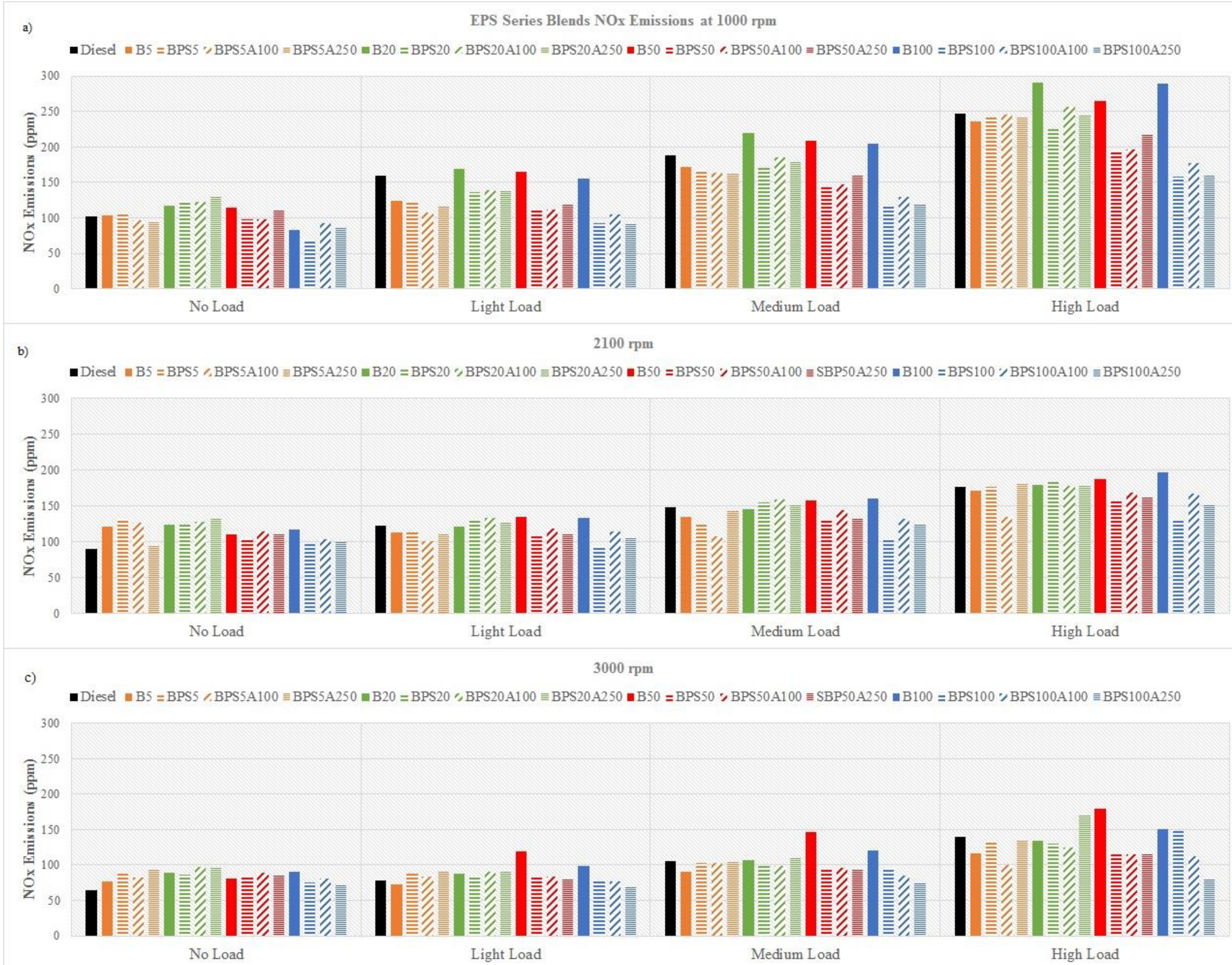

Figure 4-10 EPS Series Average NOx Emissions for a) 1000 rpm b) 2100 rpm c) 3000 rpm

4.4 HC Emissions for Heavy-Duty Engine

4.4.1 Ethanol and DEE series on Heavy-Duty Engine

Figures 4-12 and 4-13 represent the average HC emissions for the ethanol and DEE series blends, respectively. At all tests B20, B50, and B100 produced less HC emissions than diesel. This can be attributed to the higher oxygen content of biodiesel-blends allowing for a more complete combustion.

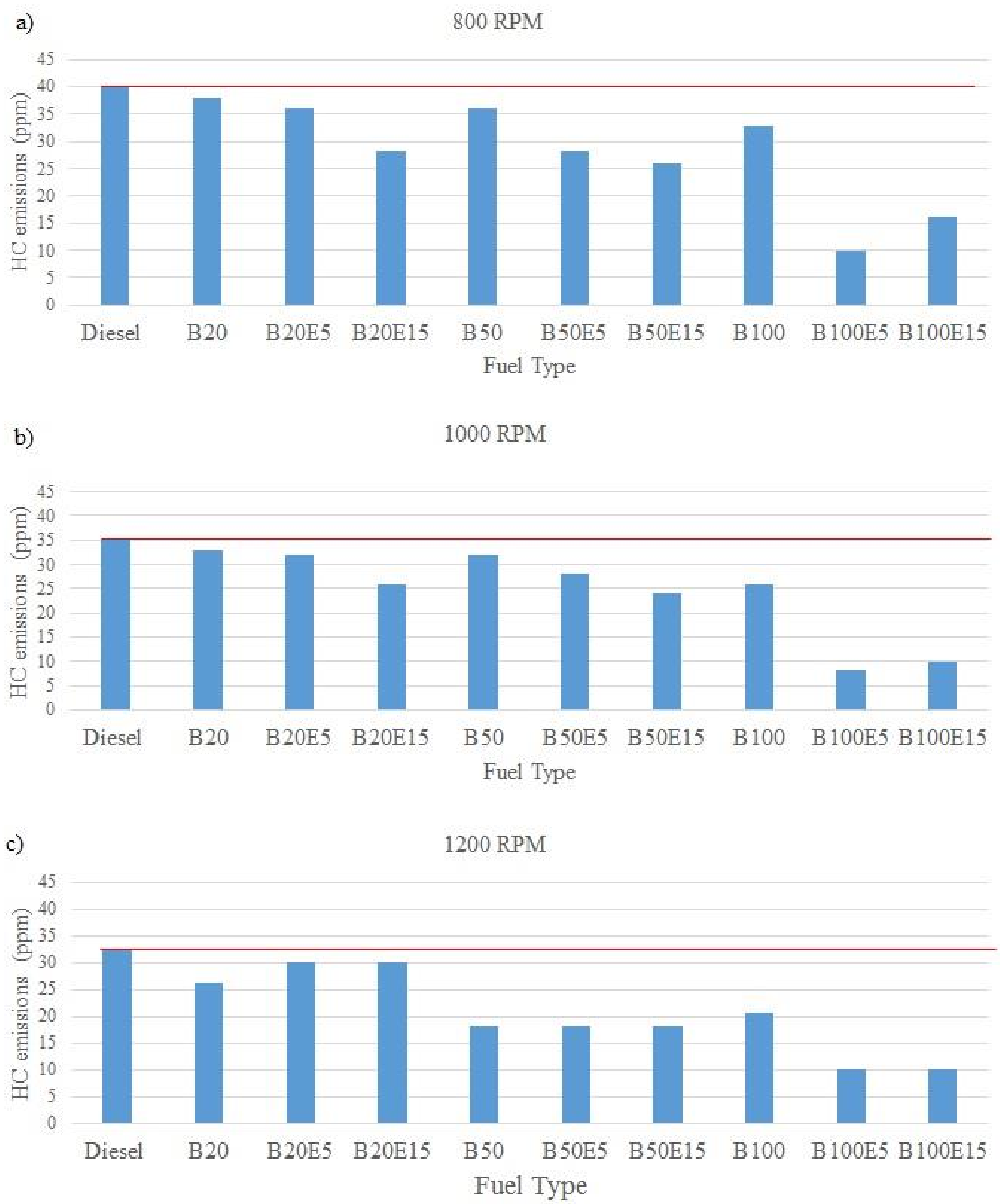

Figure 4-12 Average HC Emissions for Ethanol Series on Heavy-Duty Engine a) 800 rpm b) 1000 rpm c) 1200 rpm

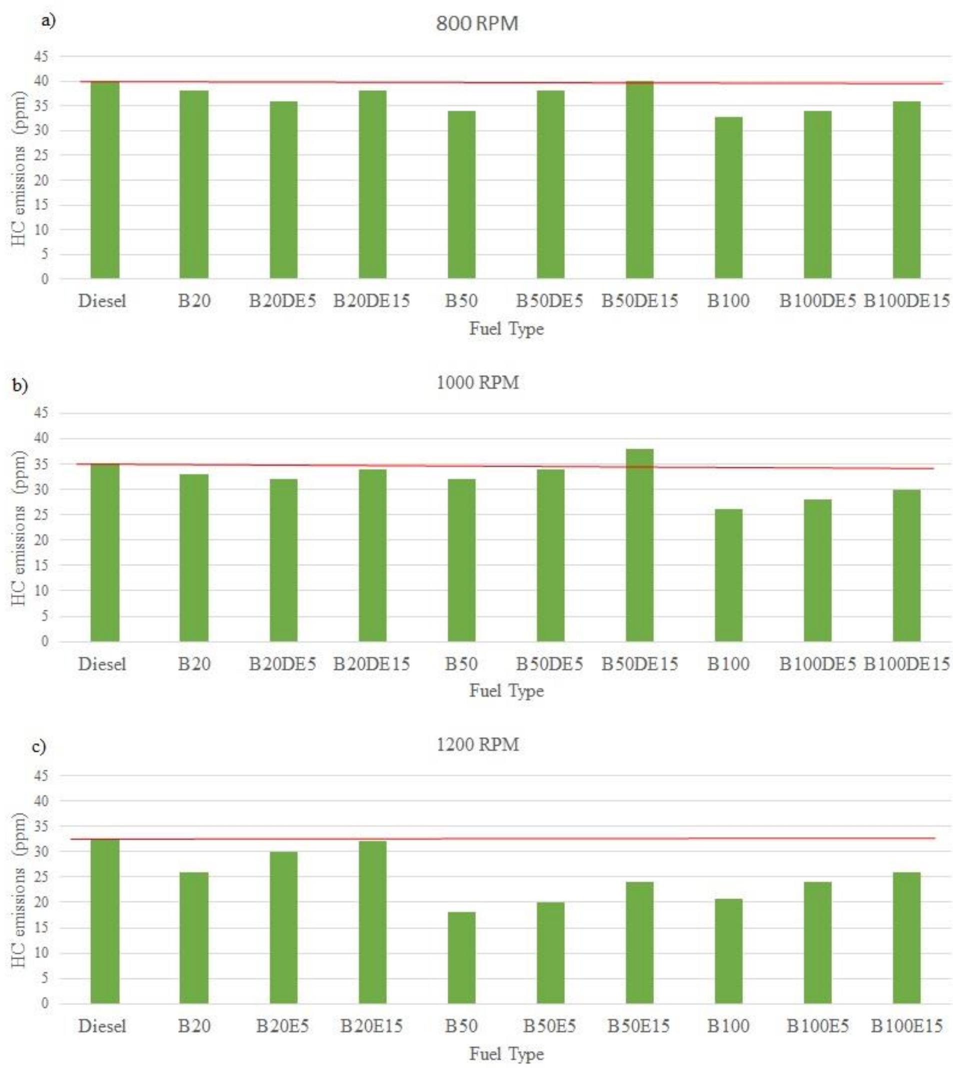

Figure 4-13 Average HC Emissions for DEE Series on Heavy-Duty Engine a) 800 rpm b) 1000 rpm c) 1200 rpm

Figure 4-12 illustrates the average HC emissions of the ethanol series fuel blends. HC emissions are products of incomplete combustions of hydrocarbons in the combustions chamber. At low and medium idle tests, ethanol was found to decrease HC emissions for B20 blends. In all other fuel blends ethanol was found to decrease HC emissions. It was seen that the addition of ethanol to B100 blends would significantly decrease HC emissions, perhaps due to higher O_2 content.

Figure 4-13 illustrates the average HC emissions for the DEE series fuel blends. Increasing DEE percentage by volume was found to increase HC emissions from diesel-biodiesel blends at all idle conditions. This is most likely due to the excessive volatility of DEE which is creating local over-leaning as well as incomplete combustion.

4.4.2 Diesel-Biodiesel Blends with EPS content in Light-duty engine

The HATZ 2G40 exhibited HC emissions during the warm-up period. Once the engine was hot not a single test showed any UHC. Max HC emissions during the warm-up period was 30 ppm, these only occurred if the engine was not run for over a day.

4.5 Smoke Opacity Emissions for Light-Duty Engine

1000 rpm (High Idle)

Figure 4-14a shows the smoke opacity reading for the EPS series at 1000 rpm and all loading conditions. Biodiesel, typically decrease PM content with increased Biodiesel content [109,110]. This has been attributed to oxygen content in fuel helping for a more complete combustion. In the case of the light-duty engine it appears that the trend in smoke opacity increased with an increase in biodiesel content. Other prominent trends included that increased engine speed decreased smoke readings and increased engine load decreased smoke readings. B5, BPS5A100, and BPS5A250 experienced reductions in smoke opacity percentage for all load conditions. The lowest smoke opacity readings were observed when using BPS5A100. Better fuel stability of the EPS content can be attributed to these results. Increase in opacity readings from biodiesel content may be attributed to increased fuel consumption.

2100 rpm (Peak Torque)

Figure 4-14b illustrates the smoke opacity reading for EPS series at 2100 rpm. Note that the y-axis scale for Figure 4-14b and Figure 4-14c is from 0-8% opacity, whereas Figure 4-14a has a y-axis scale of 0-35%. Therefore, one can see a significantly reduction in smoke opacity readings at higher speed. BPS5A100 showed decreased smoke opacity for all load conditions. For B5 and B20 Blends EPS content decreased smoke opacity readings. BPS20A250 also showed decreased smoke opacity when compared to neat diesel. High Volatility of acetone may be attributed to reduced nucleation of smoke particle. B50, and B100 Blends showed increased smoke opacity for all loads due to higher fuel consumption.

3000 rpm (High Speed/Power)

Figure 4-14c illustrates the smoke opacity at 3000 rpm for all load conditions. For no load, low load, and medium load, results are more typical of what is expected. Biodiesel content appears to decrease smoke opacity. B100 increase can be attributed to high fuel consumption and quenching caused by overpenetration of spray characteristics. All Blends except BPS5A250 with acetone content were found to reduce smoke emissions. Increased heating value from EPS content, better mixing, and high volatility of fuels attributed to these decreases in smoke opacity. High viscosity for B100 and BPS100 is the main reason behind increased smoke emissions.

Figure 4-13 Average Opacity Persentage Readings for EPS Series at a) 1000 rpm b) 2100 rpm c) 3000 rpm

5.0 Conclusions

Two modern diesel engines were fueled with biodiesel blends and additives. On the heavy-duty Cummins engines, systematic experimental analysis was conducted to examine the idle emissions of biodiesel blends with ethanol and DEE. Data was taken over a warm-up period from a cold start. Three fuel series were tested: biodiesel-diesel blends, biodiesel-diesel-ethanol blends, and biodiesel-diesel-DEE blends. The light-duty Hatz 2G40 engine was tested with three fuel series. Biodiesel-diesel blends biodiesel-diesel blends with EPS content as an additive, and biodiesel-diesel blends with EPS content as well as acetone as a stabilizer. Light-duty engine was tested at three speeds with an idle and three load conditions.

5.0.1 Conclusions on additions of Ethanol and DEE on Heavy-duty Cummins Engine

(1) All B20 fuel blends exhibited cloud points below -20^{0}C. B20E5, and B20E15 both have cloud points below -25^{0}C.

(2) B20, B50 and B100 blends produced significantly less average CO emissions than neat diesel. All fuel blends with ethanol with the exception of B20E15 generated lower CO emissions results than neat diesel. The addition of 5% ethanol could decrease CO emissions for B20 and B50 fuel blends, whereas the addition of ethanol to B100 would increase CO emissions, while still remaining under neat diesel levels.

(3) Addition of biodiesel content to biodiesel-diesel blends could increase NO_x emissions. Addition of ethanol was found to decrease NO_x emissions with additional ethanol content. NO_x emissions from B100 were affected the most by ethanol content. In high idle tests, B100 blends with ethanol produced less NO_x emissions than neat diesel. It was found that DEE content would reduce NO_x emissions at all idle conditions for all fuel blends. B20DE15 and B50DE15 were the only fuel blends to reduce NOx emissions than average diesel emissions.

(4) Increasing biodiesel content could decrease HC emissions. Ethanol content decreased HC emissions significantly for B100 blends. DEE content was found to increase HC emissions at all test conditions.

(5) On the other hand, no significant increase in aldehyde emissions was found after a warm-up period and no smoke emissions were noticed (via visual inspection) for any fuel blends at idling conditions after engine warm-up.

5.0.2 Conclusions on dissolving EPS content into biodiesel blends with acetone as fuel stabilizer on Light-duty Hatz engine

(1) Increased biodiesel content decreased CO emissions at all conditions. Increased load decreased CO emissions at all speeds. Dissolved EPS content decreased CO emissions for BPS20, BPS50, and BPS100 fuel blends. Additions of Acetone at 100 ml/l of biodiesel was found to decrease CO emissions for BPS20A100, BPS50A100, and BPS100A100 at 1000 rpm and 2100 rpm speed settings. Additions of 250 ml/l acetone increased CO emissions due to cooling effect.

(2) Increased biodiesel content in fuel blends was found to increase NO_x emissions. Dissolving EPS content into biodiesel blends was found to decrease NO_x emissions. Additions of 100 ml/l of acetone was found to increase volatility of fuel blends, thus increasing NO_x emissions. Acetone at 250 ml/l of biodiesel was found to decrease NO_x emissions due to cooling effect. At 3000 rpm, any addition of acetone decreased NO_x emissions.

(3) Increased biodiesel in blends was found to increase smoke opacity readings. Increased load was found to decrease opacity emissions at all speeds. Use of EPS content was found to increase smoke opacity due to larger FAME particles and lower cetane number. Increased acetone content was found to decrease smoke opacity emissions due to higher volatility.

(4) Overall biodiesel blends performed well when considering BTE and BSFC. Result depended heavily on test condition. Blends with EPS and Acetone content did not perform as well due to increased density of fuel overpowering any power increases. 2100 rpm was found to have the best BSFC for the light-duty engine. Blends also performed well with respect to percentage change in brake torque with all B5 and B50 blends performing exceptionally

(5) EPS is an effective additive for reducing NO_x emissions, while recycling waste that would end up in landfills.

6.0 References

[1] Thompson GJ, Carder DK, Besch MC, Thiruvengadam A, Kappanna HK. In-Use Emissions Testing of Light-Duty Diesel Vehicles in the United States. 2014.

[2] Lee KH, Jung HJ, Park DU, Ryu SH, Kim B, Ha KC, et al. Occupational exposure to diesel particulate matter in municipal household waste workers. PLoS One 2015;10:1–18. doi:10.1371/journal.pone.0135229.

[3] Atabani AE, Silitonga AS, Badruddin IA, Mahlia TMI, Masjuki HH, Mekhilef S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renew Sustain Energy Rev 2012;16:2070–93. doi:10.1016/j.rser.2012.01.003.

[4] Agarwal AK, Gupta T, Shukla PC, Dhar A. Particulate emissions from biodiesel fuelled CI engines. Energy Convers Manag 2015;94:311–30. doi:10.1016/j.enconman.2014.12.094.

[5] Sorda G, Banse M, Kemfert C. An overview of biofuel policies across the world. Energy Policy 2010:6977–88.

[6] Zhang H, Xu Z, Zhou D, Cao J. Waste cooking oil-to-energy under incomplete information: Identifying policy options through an evolutionary game. Appl Energy 2017;185:547–55. doi:10.1016/j.apenergy.2016.10.133.

[7] Lopes M, Serrano L, Ribeiro I, Cascao P, Pires N, Rafael S, et al. Emissions characterization from EURO 5 diesel/biodiesel passenger car operating under the new European driving cycle. Atmos Environ 2013;84:339–48. doi:10.1016/j.atmosenv.2013.11.071.

[8] Shahir VK, Jawahar CP, Suresh PR. Comparative study of diesel and biodiesel on CI engine with emphasis to emissions - A review. Renew Sustain Energy Rev 2015;45:686–97. doi:10.1016/j.rser.2015.02.042.

[9] Aransiola EF, Ojumu T V., Oyekola OO, Madzimbamuto TF, Ikhu-Omoregbe DIO. A review of current technology for biodiesel production: State of the art. Biomass and Bioenergy 2014;61:276–97. doi:10.1016/j.biombioe.2013.11.014.

[10] Rabiah Nizah MF, Taufiq-Yap YH, Rashid U, Teo SH, Shajaratun Nur ZA, Islam A. Production of biodiesel from non-edible Jatropha curcas oil via transesterification using Bi2O3-La2O3 catalyst. Energy Convers Manag 2014;88:1257–62. doi:10.1016/j.enconman.2014.02.072.

[11] Bharathiraja B, Chakravarthy M, Kumar RR, Yuvaraj D, Jayamuthunagai J, Kumar RP, et al. Biodiesel production using chemical and biological methods - A review of process, catalyst, acyl acceptor, source and process variables. Renew Sustain Energy Rev 2014;38:368–82. doi:10.1016/j.rser.2014.05.084.

[12] Konwar LJ, Boro J, Deka D. Review on latest developments in biodiesel production using carbon-based catalysts. Renew Sustain Energy Rev 2014;29:546–64.

doi:10.1016/j.rser.2013.09.003.

[13] Rincon LE, Jaramillo JJ, Cardona CA. Comparison of feedstocks and technologies for biodiesel production: An environmental and techno-economic evaluation. Renew Energy 2014;69:479–87. doi:10.1016/j.renene.2014.03.058.

[14] Chai M, Tu Q, Lu M, Yang YJ. Esterification pretreatment of free fatty acid in biodiesel production, from laboratory to industry. Fuel Process Technol 2014;125:106–13. doi:10.1016/j.fuproc.2014.03.025.

[15] Martin M, Grossmann IE. Design of an optimal process for enhanced production of bioethanol and biodiesel from algae oil via glycerol fermentation. Appl Energy 2014;135:108–14. doi:10.1016/j.apenergy.2014.08.054.

[16] Mofijur M, Atabani AE, Masjuki HH, Kalam MA, Masum BM. A study on the effects of promising edible and non-edible biodiesel feedstocks on engine performance and emissions production: A comparative evaluation. Renew Sustain Energy Rev 2013;23:391–404. doi:10.1016/j.rser.2013.03.009.

[17] Scaife MA, Merkx-Jacques A, Woodhall DL, Armenta RE. Algal biofuels in Canada: Status and potential. Renew Sustain Energy Rev 2015;44:620–42. doi:10.1016/j.rser.2014.12.024.

[18] Karmakar A, Karmakar S, Mukherjee S. Properties of various plants and animals feedstocks for biodiesel production. Bioresour Technol 2010;101:7201–10. doi:10.1016/j.biortech.2010.04.079.

[19] Shahid EM, Jamal Y. Production of biodiesel: A technical review. Renew Sustain Energy Rev 2011;15:4732–45. doi:10.1016/j.rser.2011.07.079.

[20] Blackshaw R, Johnson E, Gan Y, May W, McAndrew D, Barthet V, et al. Alternative oilseed crops for biodiesel feedstock on the Canadian prairies. Can J Plant Sci 2011;91:889–96. doi:10.4141/cjps2011-002.

[21] Liu T, McConkey B, Huffman T, Smith S, MacGregor B, Yemshanov D, et al. Potential and impacts of renewable energy production from agricultural biomass in Canada. Appl Energy 2014;130:222–9. doi:10.1016/j.apenergy.2014.05.044.

[22] Singh SP, Singh D. Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: A review. Renew Sustain Energy Rev 2010;14:200–16. doi:10.1016/j.rser.2009.07.017.

[23] U.S. Environmental Protection Agency (EPA). Automobile Emissions : An Overview. US Environ Prot Agency Off Mob Sources 2013:2–5. doi:400-F-92-007.

[24] Environmental Protection Agency (EPA). Heavy-Duty Highway Engine : Clean Fuel Fleet Exhaust Emission Standards 2016:2016.

[25] Heywood JB. Internal Combustion Engine Fundamentals. New York: 1988.

[26] Studies U of P and E. Internal Combustion Engines-II n.d.:1–88.

[27] Heywood JB. Engine Design and Operating Procedures. Intern. Combust. Engine Fundam., 1988, p. 592–7.

[28] Sabbarao PM V. IC Engine Emissions n.d.:1–33.

[29] U.S. Environmental Protection Agency (EPA). Conversion Factors for Hydrocarbon Emission Components Conversion Factors for Hydrocarbon Emission Components NR - 002d n.d.

[30] Khan S, Clark NN, Gautum M, Wayne WS, Thompson GJ, Lyons DW. Idle Emissions from Medium Heavy-Duty Diesel and Gasoline Trucks. J Air Waste Manage Assoc 2009;59:354–9. doi:10.3155/1047-3289.59.3.354.

[31] Lindström M. Injector Nozzle Hole Parameters and their Influence on Real DI Diesel Performance 2009:1–45.

[32] Queen's University. IC Engine Exhaust Emissions Section 7 n.d.

[33] J K, S M, G B. An Investigation of Unburned Hydrocarbon Emissions in Wall Guided, Low Temperature Diesel Combustion. Oil Gas Sci Technol 2008;63:433–59. doi:10.2516/ogst.

[34] M K, H J. Emissions Formation in Diesel Engines. Dieselnet n.d. https://www.dieselnet.com/tech/diesel_emiform.php.

[35] U.S. Environmental Protection Agency (EPA). Particulate Matter (PM) Basics 2016. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics (accessed July 18, 2016).

[36] United States Environmental Protection Agency. The Plain English Guide to the Clean Air Act 2007:28.

[37] U.S. Environmental Protection Agency (EPA). NAAQS Table 2016. https://www.epa.gov/criteria-air-pollutants/naaqs-table (accessed July 19, 2016).

[38] Burtscher H, Majewski WA. Particulate Matter Measurements. Dieselnet 2012. https://www.dieselnet.com/tech/measure_dpm.php.

[39] Amaral S, de Carvalho J, Costa M, Pinheiro C. An Overview of Particulate Matter Measurement Instruments. Atmosphere (Basel) 2015;6:1327–45. doi:10.3390/atmos6091327.

[40] Srivastava DK, Agarwal AK. Particulate Matter Emissions from Single Cylinder Diesel Engine: Effect of Engine Load on Size and Number Distribution. SAE Int 2008. doi:10.1017/CBO9781107415324.004.

[41] Kittelson DB. Engines and nanoparticles: A review. J Aerosol Sci 1998;29:575–88. doi:10.1016/S0021-8502(97)10037-4.

[42] Burtscher H. Physical characterization of particulate emissions from diesel engines: A review. J Aerosol Sci 2005;36:896–932. doi:10.1016/j.jaerosci.2004.12.001.

[43] Environmental Protection Agency (EPA). Nitrogen Oxides (NOx), Why and How They Are Controlled. Epa-456/F-99-006R 1999:48. doi:EPA 456/F-99-006R.

[44] United States Environmental Protection Agency. Nitrogen Dioxide: Basic Information 2016. https://www3.epa.gov/airquality/nitrogenoxides/basic.html (accessed August 1, 2016).

[45] U.S. Environmental Protection Agency (EPA). Overview of Greenhouse Gases: Nitrous Oxide Emissions 2016. https://www3.epa.gov/climatechange/ghgemissions/gases/n2o.html (accessed August 1, 2016).

[46] Karavalakis G, Johnson KC, Hajbabaei M, Durbin TD. Application of low-level biodiesel blends on heavy-duty (diesel) engines: Feedstock implications on NOx and particulate emissions. Fuel 2016;181:259–68. doi:10.1016/j.fuel.2016.05.001.

[47] Özener O, Yüksek L, Ergenç AT, Özkan M. Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. Fuel 2014;115:875–83. doi:10.1016/j.fuel.2012.10.081.

[48] Xue J. Combustion characteristics, engine performances and emissions of waste edible oil biodiesel in diesel engine. Renew Sustain Energy Rev 2013;23:350–65. doi:10.1016/j.rser.2013.02.039.

[49] Cardenas MD, Armas O, Mata C, Soto F. Performance and pollutant emissions from transient operation of a common rail diesel engine fueled with different biodiesel fuels. Fuel 2016;185:743–62. doi:10.1016/j.fuel.2016.08.002.

[50] Rajasekar E, Murugesan A, Subramanian R, Nedunchezhian N. Review of NOx reduction technologies in CI engines fuelled with oxygenated biomass fuels. Renew Sustain Energy Rev 2010;14:2113–21. doi:10.1016/j.rser.2010.03.005.

[51] Wang X, Huang Z, Kuti OA, Zhang W, Nishida K. Experimental and analytical study on biodiesel and diesel spray characteristics under ultra-high injection pressure. Int J Heat Fluid Flow 2010;31:659–66. doi:10.1016/j.ijheatfluidflow.2010.03.006.

[52] Park SH, Yoon SH, Lee CS. Effects of multiple-injection strategies on overall spray behavior, combustion, and emissions reduction characteristics of biodiesel fuel. Appl Energy 2011;88:88–98. doi:10.1016/j.apenergy.2010.07.024.

[53] Nanthagopal K, Ashok B, Karuppa Raj RT. Influence of fuel injection pressures on Calophyllum inophyllum methyl ester fuelled direct injection diesel engine. Energy Convers Manag 2016;116:165–73. doi:10.1016/j.enconman.2016.03.002.

[54] Koc AB, Abdullah M. Performance and NOx emissions of a diesel engine fueled with biodiesel-diesel-water nanoemulsions. Fuel Process Technol 2013;109:70–7. doi:10.1016/j.fuproc.2012.09.039.

[55] Anbarasu A, Karthikeyan A. Diesel engine performance and emission evaluation using Canola biodiesel emulsion fuel. Aust J Mech Eng 2016;14:174–81. doi:10.1080/14484846.2015.1093222.

[56] Palash SM, Masjuki HH, Kalam MA, Masum BM, Sanjid A, Abedin MJ. State of the art of NOx mitigation technologies and their effect on the performance and emission characteristics of biodiesel-fueled Compression Ignition engines. Energy Convers Manag 2013;76:400–20. doi:10.1016/j.enconman.2013.07.059.

[57] Can Ö, Öztürk E, Solmaz H, Aksoy F, Çinar C, Yücesu HS. Combined effects of soybean

biodiesel fuel addition and EGR application on the combustion and exhaust emissions in a diesel engine. Appl Therm Eng 2016;95:115–24. doi:10.1016/j.applthermaleng.2015.11.056.

[58] Canada NR. Welcome to the Idle Free Zone 2014. http://www.nrcan.gc.ca/energy/effciency/communities-infrastructure/transportation/idling/4397 (accessed March 7, 2016).

[59] Natural Resources Canada. Drive Lean, Drive Clean. Ottawa: 2015.

[60] City of Kingston. Idling By-Law 2008.

[61] City of Thunder Bay. Corporate By-Law #120-2007 2007.

[62] Lewis P, Leming M, Rasdorf W. Impact of Engine Idling on Fuel Use and Emissions of Nonroad Diesel Construction Equipment. J Manag Eng 2012;28:31–8. doi:10.1061/(ASCE)ME.1943-5479.0000068.

[63] Khan AS, Clark NN, Thompson GJ, Wayne WS, Gautam M, Lyons DW. Idle Emissions from Heavy-Duty Diesel Vehicles: Review and Recent Data. J Air Waste Manage Assoc 2005:1404–19.

[64] Frey HC, Kuo P-Y. Real-World Energy Use and Emission Rates for Idling Long-Haul Trucks and Selected Idle Reduction Technologies. J Air Waste Manage Assoc 2009;59:857–64. doi:10.3155/1047-3289.59.7.857.

[65] Rahman SMA, Masjuki HH, Kalam MA, Abedin MJ, Sanjid A, Imtenan S. Effect of idling on fuel consumption and emissions of a diesel engine fueled by Jatropha biodiesel blends. J Clean Prod 2014;69:208–15. doi:10.1016/j.jclepro.2014.01.048.

[66] Lahane S, Subramanian KA. Effect of different percentages of biodiesel-diesel blends on injection, spray, combustion, performance, and emission characteristics of a diesel engine. Fuel 2015;139:537–45. doi:10.1016/j.fuel.2014.09.036.

[67] Öztürk E. Performance, emissions, combustion and injection characteristics of a diesel engine fuelled with canola oil-hazelnut soapstock biodiesel mixture. Fuel Process Technol 2015;129:183–91. doi:10.1016/j.fuproc.2014.09.016.

[68] Palash SM, Kalam MA, Masjuki HH, Arbab MI, Masum BM, Sanjid A. Impacts of NOx reducing antioxidant additive on performance and emissions of a multi-cylinder diesel engine fueled with Jatropha biodiesel blends. Energy Convers Manag 2014;77:577–85. doi:10.1016/j.enconman.2013.10.016.

[69] Roy MM, Wang W, Alawi M. Performance and emissions of a diesel engine fueled by biodiesel-diesel, biodiesel-diesel-additive and kerosene-biodiesel blends. Energy Convers Manag 2014;84:164–73. doi:10.1016/j.enconman.2014.04.033.

[70] Habibullah M, Masjuki HH, Kalam MA, Rizwanul Fattah IM, Ashraful AM, Mobarak HM. Biodiesel production and performance evaluation of coconut, palm and their combined blend with diesel in a single-cylinder diesel engine. Energy Convers Manag 2014;87:250–7. doi:10.1016/j.enconman.2014.07.006.

[71] Wood BM, Kirwan K, Maggs S, Meredith J, Coles SR. Study of combustion performance of biodiesel for potential application in motorsport. J Clean Prod 2015;93:167–73. doi:10.1016/j.jclepro.2014.12.091.

[72] Dyer JA, Verge XPC, Desjardins RL, Worth DE, McConkey BG. The impact of increased biodiesel production on the greenhouse gas emissions from field crops in Canada. Energy Sustain Dev 2010;14:73–82. doi:10.1016/j.esd.2010.03.001.

[73] Cheikh K, Sary A, Khaled L, Abdelkrim L, Mohand T. Experimental assessment of performance and emissions maps for biodiesel fueled compression ignition engine. Appl Energy 2016;161:320–9. doi:10.1016/j.apenergy.2015.10.042.

[74] Tomić MD, Savin LD, Mićić RD, Simikić MD, Furman TF. Effects of fossil diesel and biodiesel blends on the performances and emissions of agricultural tractor engines. Therm Sci 2013;17:263–78. doi:10.2298/TSCI111122106T.

[75] Aybek A, Başer E, Arslan S, Üçgül M. Determination of the effect of biodiesel use on power take-off performance characteristics of an agricultural tractor in a test laboratory. Turk J Agric 2011;35:103–13. doi:10.3906/tar-0907-242.

[76] Labeckas G, Slavinskas S. The effect of rapeseed oil methyl ester on direct injection Diesel engine performance and exhaust emissions. Energy Convers Manag 2006;47:1954–67. doi:10.1016/j.enconman.2005.09.003.

[77] Ozsezen AN, Canakci M, Turkcan A, Sayin C. Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. Fuel 2009;88:629–36. doi:10.1016/j.fuel.2008.09.023.

[78] Roy MM, Wang W, Bujold J. Biodiesel production and comparison of emissions of a DI diesel engine fueled by biodiesel-diesel and canola oil-diesel blends at high idling operations. Appl Energy 2013;106:198–208. doi:10.1016/j.apenergy.2013.01.057.

[79] Roy MM, Alawi M, Wang W. Effects of Canola Biodiesel on A DI Diesel Engine Performance and Emissions. Int J Mech Mechatronics Eng 2013;13:46–53. doi:10.1016/j.fuel.2012.10.081.

[80] Zhang ZH, Balasubramanian R. Investigation of particulate emission characteristics of a diesel engine fueled with higher alcohols/biodiesel blends. Appl Energy 2016;163:71–80. doi:10.1016/j.apenergy.2015.10.173.

[81] Verma P, Sharma MP, Dwivedi G. Evaluation and enhancement of cold flow properties of palm oil and its biodiesel. Energy Reports 2016;2:8–13. doi:10.1016/j.egyr.2015.12.001.

[82] Gomez A, Mata C, Armas O. Effect of Ethanol – Diesel Fuel Blend on Diesel Engine Emissions Produced by Different Bus Fleets 2016;142:1–9. doi:10.1061/(ASCE)EY.1943-7897.0000315.

[83] Yilmaz N, Vigil FM, Donaldson AB, Darabseh T. Investigation of CI engine emissions in biodiesel-ethanol-diesel blends as a function of ethanol concentration. Fuel 2014;115:790–3. doi:10.1016/j.fuel.2013.08.012.

[84] Panneer Selvam DJ, Vadivel K. The effects of ethanol addition with waste pork lard methyl

ester on performance, emission, and combustion characteristics of a diesel engine. Therm Sci 2014;18:217–28. doi:10.2298/tsci121010058j.

[85] Jagadish D, Ravi Kumar P, Murthy KM. The effect of supercharging on performance and emission characteristics of compresion ignition engine with diesel-ethanol-ester blends. Therm Sci 2011;15:1165–74. doi:10.2298/TSCI100513042J.

[86] Pidol L, Lecointe B, Starck L, Jeuland N. Ethanol-biodiesel-Diesel fuel blends: Performances and emissions in conventional Diesel and advanced Low Temperature Combustions. Fuel 2012;93:329–38. doi:10.1016/j.fuel.2011.09.008.

[87] Rakopoulos DC. Comparison of Combustion , Performance , and Emissions of HSDI Diesel Engine Operating on Blends of Diesel Fuel with Ethanol , n -Butanol , or Butanol Isomer Ether DEE. J Energy Eng 2015;141:1–12. doi:10.1061/(ASCE)EY.1943-7897.0000210.

[88] Rakopoulos DC, Rakopoulos CD, Giakoumis EG, Kosmadakis GM, Papagiannakis RG. Comparative Evaluation of Ethanol , n -Butanol , and Diethyl Ether Effects as Biofuel Supplements on Combustion Characteristics , Cyclic Variations , and Emissions Balance in Light-Duty Diesel Engine 2012:1–8. doi:10.1061/(ASCE)EY.1943-7897.0000399.

[89] Kannan TK, Marappan R. Comparative study of Performance and Emission Characteristics of a Diesel Engine Fueled by Emulsified Biodiesel/Diethyl Ether Blended Biodiesel. J Appl Sci 2011;11:2961–7.

[90] Satya VPU, Murthy KM, Rao GAP. Effective utilization of B20 blend with oxygenated additives. Therm Sci 2011;15:1175–84. doi:10.2298/TSCI110513093U.

[91] Achilias DS, Roupakias C, Megalokonomos P, Lappas AA, Antonakou V. Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP). J Hazard Mater 2007;149:536–42. doi:10.1016/j.jhazmat.2007.06.076.

[92] Kuzhiyil N, Kong S. Energy Recovery from Waste Plastics by Using Blends of Biodiesel and Polystyrene in Diesel Engines Energy Recovery from Waste Plastics by Using Blends of Biodiesel 2009:3246–53. doi:10.1021/ef801110j.

[93] Zhang Y, Mallapragada SK, Narasimhan B. Dissolution of Waste Plastics in Biodiesel. Polym Eng Sci 2010;50. doi:10.1002/pen.

[94] Mohammadi P, Nikbakht AM, Tabatabaei M, Farhadi K, Mohebbi A, Khatami far M. Experimental investigation of performance and emission characteristics of DI diesel engine fueled with polymer waste dissolved in biodiesel-blended diesel fuel. Energy 2012;46:596–605. doi:10.1016/j.energy.2012.07.049.

[95] Aghbashlo M, Tabatabaei M, Mohammadi P, Pourvosoughi N, Nikbakht AM, Goli SAH. Improving exergetic and sustainability parameters of a Di diesel engine using polymer waste dissolved in biodiesel as a novel diesel additive. Energy Convers Manag 2015;105:328–37. doi:10.1016/j.enconman.2015.07.075.

[96] Mohammadi P, Tabatabaei M, Nikbakht AM, Esmaeili Z. Improvement of the cold flow characteristics of biodiesel containing dissolved polymer wastes using acetone. Biofuel Res J 2014;1:26–9.

[97] Suresh R, Antony JV, Vengalil R, Kochimoolayil GE, Joseph R. Esterification of free fatty acids in non- edible oils using partially sulfonated polystyrene for biodiesel feedstock. Ind Crops Prod 2017;95:66–74. doi:10.1016/j.indcrop.2016.09.060.

[98] Dang Y, Luo X, Wang F, Li Y. Value-added conversion of waste cooking oil and post-consumer PET bottles into biodiesel and polyurethane foams. Waste Manag 2016;52:360–6. doi:10.1016/j.wasman.2016.03.054.

[99] Addison K. Make Your Own Biodiesel. Journey to Forever n.d. http://journeytoforever.org/biodiesel_make.html (accessed September 1, 2015).

[100] Bailey B, Eberhardt J, Goguen S, Erwin J. Diethyl ether (DEE) as a renewable diesel fuel. SAE Trans 1997:972978. doi:10.4271/972978.

[101] Gorski K, Przedlacki M. Evaluation of the influence of diethyl ether (DEE) addition on selected physicochemical properties of diesel oil and ignition delay period. Energy and Fuels 2014;28:2608–16. doi:10.1021/ef4025036.

[102] U.S. Environmental Protection Agency (EPA). Municipal Solid Waste Generation, Recylcing, and Disposal in the United States: Tables and Figures for 2012 2014.

[103] Durlak SK, Biswas P, Procter T. Characterization of Polycyclic Aromatic Hydrocarbon Particulate and Gaseous Emissions from Polystyrene Combustion 1998:2301–7.

[104] Mohammadi P, Tabatabaei M, Nikbakht AM, Farhadi K, Khatami Far M, Castaldi MJ. Simultaneous energy recovery from waste polymers in biodiesel and improving fuel properties. Waste and Biomass Valorization 2013;4:105–16. doi:10.1007/s12649-013-9214-2.

[105] Toolbox E. Fluids-Latent Heat of Evaporation n.d. http://www.engineeringtoolbox.com/fluids-evaporation-latent-heat-d_147.html (accessed January 18, 2017).

[106] Methanol Institute. Methanol Safe Handling Technical Bulletin 2011.

[107] Ashok MPP. Identification of best additive using the selected ratio of ethanol–diesel-based emulsified fuel. Int J Sustain Energy 2012;31:203–12. doi:10.1080/1478646X.2011.556736.

[108] Jawre SS, Lawanker SM. Experimental Analysis of Performance of Diesel Engine Using Kusum Methyl Ester With Diethyl Ether as Additive. Int J Eng Res Appl 2014;4:106–11.

[109] Szybist JP, Song J, Alam M, Boehman AL. Biodiesel combustion, emissions and emission control. Fuel Process Technol 2007;88:679–91. doi:10.1016/j.fuproc.2006.12.008.

[110] Lapuerta M, Rodríguez-Fernández J, Agudelo JR. Diesel particulate emissions from used cooking oil biodiesel. Bioresour Technol 2008;99:731–40. doi:10.1016/j.biortech.2007.01.033.

7. Appendices

7.1 Sample Calculations

7.1.1 Brake Thermal Efficiency (BTE) Equation (4-1)

$$BTE = \frac{3600 \times P(kW)}{FC\left({}^{kg}/_{h}\right) \times HHV\left({}^{kJ}/_{kg}\right)}$$

Where BTE is brake thermal efficiency, P is Power in kilowatts, FC is fuel consumption in kilograms per hour, and HHV is higher heating value in kilojoules per kilograms. For diesel at engine speed of 1000 rpm and light load setting we get P=1.17 kW, FC=0.334 kg/h, and HHV=45570 kJ/kg.

$$BTE = \frac{3600\left({}^{s}/_{\cancel{h}}\right) \times 1.17(kW)}{0.334\left({}^{\cancel{kg}}/_{\cancel{h}}\right) \times 45570\left({}^{kJ}/_{\cancel{kg}}\right)} = \frac{4212\ (\cancel{kJ})}{15220.38\ (\cancel{kJ})} = 0.277$$

Therefore, when fueled with neat diesel at 1000 rpm and low load condition, the light duty diesel engine has a BTE of 0.277. To get percentage BTE, multiply by 100.

$$BTE\% = 0.277 \times 100 = 27.7\%$$

7.1.2 Brake Specific Fuel Consumption (BSFC) Equation (4-2)

$$BSFC = \frac{FC\ (\frac{g}{h}\, or\, \frac{kg}{h})}{P\ (kW)}$$

Where BSFC is brake specific fuel consumption in grams per kilowatt-hour or kilograms per kilowatt-hour, FC is fuel consumption in grams per hour or kilograms per hour, and P is power in kilowatts. For this study FC of grams per hour was used. For B5 at 1000 rpm and low load condition, FC=336 g/h, and P=1.15 kW.

$$BSFC = \frac{336\ (\frac{g}{h})}{1.15(kW)} = 292.17\left({}^{g}/_{kW \cdot h}\right)$$

Therefore, when fueled the B5 at 1000 rpm and low load condition the engine has a BSFC of 292.17 grams per kilowatt-hour.

7.2Photographs of Equipment Used

Figure 7-1 Dynomite Data Acquisition System

Figure 7-2 CO Meter

Figure 7-3 Novagas Analyzer

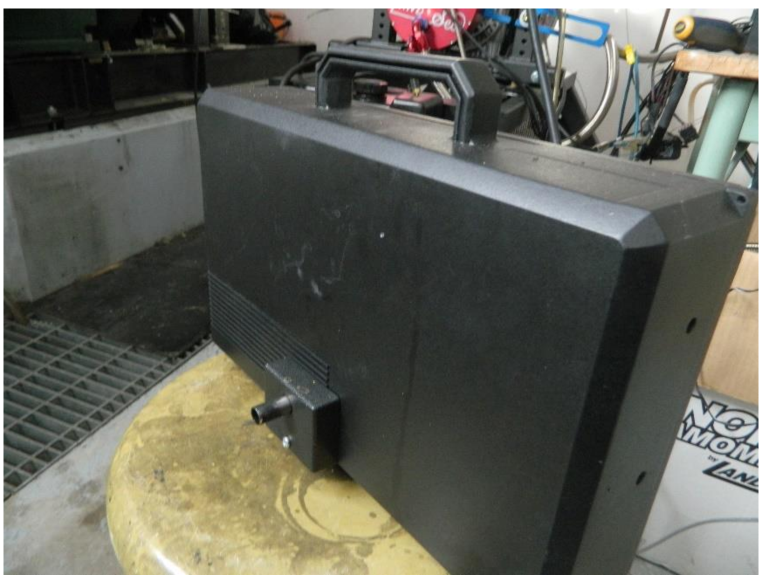

Figure 7-4 Smart2000 Smoke Opacity Meter

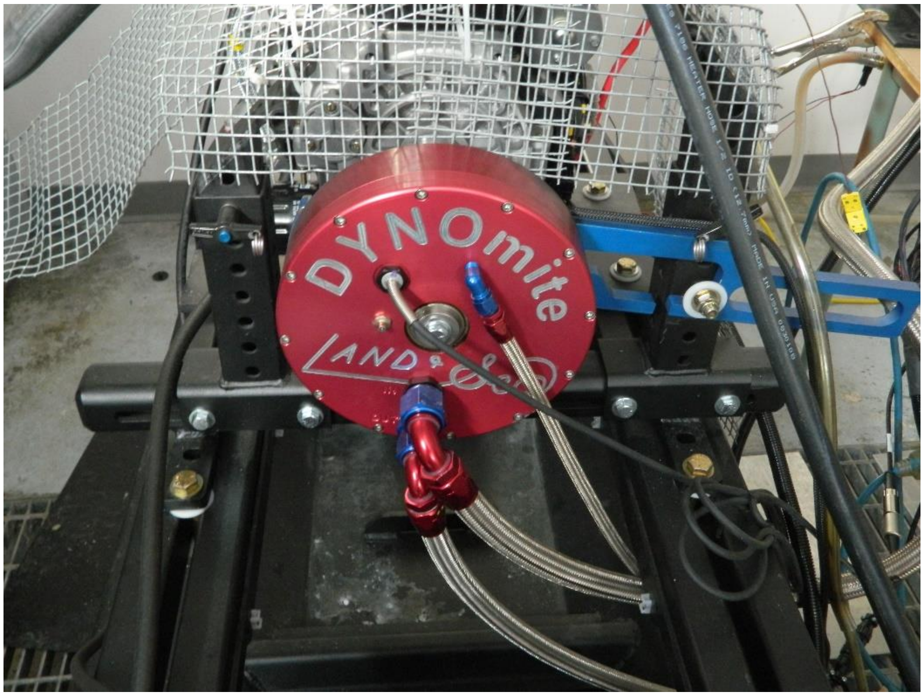

Figure 7-5 Land & Sea snowmobile dynometer

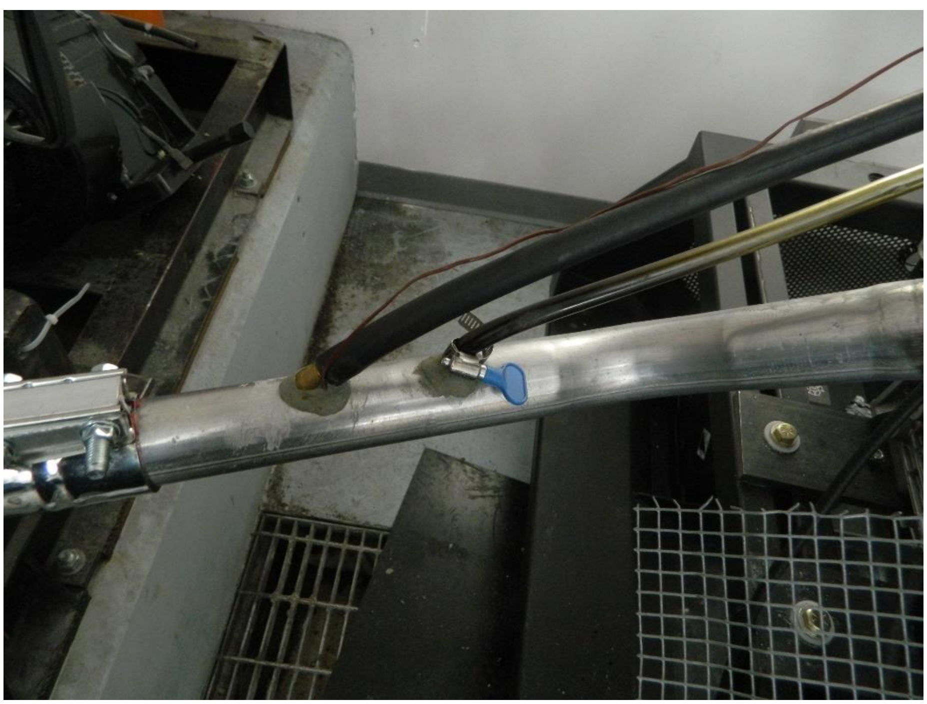

Figure 7-7 Exhaust System

7.3 Data Points for Graphs

Table 7-1 BTE Data Points for Figures 4-1, 4-2, 4-3

Brake Thermal Efficiency (BTE) EPS Series Light-duty Engine												
Fuel Types	Speed											
	1000 rpm				2100 rpm				3000 rpm			
	% Load											
	0%	20%	50%	80%	0%	20%	50%	80%	0%	20%	50%	80%
Diesel	0	27.6271	32.91639	33	0	22.80252	32.91639	32.91639	0	23.4676	32.91639	32.91639
B5	0	27.21712	27.22144	30.46744	0	24.18801	30.71658	32.85149	0	30.48499	36.28241	30.20753
B20	0	21.0084	35.15737	34.5	0	22.31994	32.45143	33.46539	0	29.0931	34.63261	33.53406
B50	0	25.16515	28.60079	32.21798	0	26.9692	36.9296	34.37689	0	22.86175	33.37684	27.4467
B100	0	32.85007	34.95548	35.8	0	25.13381	36.60569	33.0309	0	32.2997	37.24119	36.32129
BPS5	0	34	37	38	0	23.39259	35.78462	34.76704	0	28.27794	40.12147	32.23637
BPS20	0	29.19482	35.85524	34.5	0	22.92103	31.71833	33.79145	0	21.41684	39.34021	30.97998
BPS50	0	24.93054	37.10122	38	0	26.33196	33.58936	33.41651	0	24.47462	37.31949	35.91743
BPS100	0	21.78044	29	32	0	22.25396	25	26.52949	0	25.52189	37.60657	34.16885
BPS5A100	0	38	38.5782	40.11147	0	22.96163	24.35103	30.33708	0	29.32837	38	33.01009
BPS20A100	0	30.24793	40.40724	34.5	0	24.73732	36.64519	37.19851	0	25.96801	34.236	27.67589
BPS50A100	0	34.55252	31.41479	36.36377	0	25.87746	34.91536	33.36253	0	23.91128	35.71149	33.61827
BPS100A100	0	25.81308	33.11023	35.8	0	23.68083	32.07489	33.80146	0	23.46012	39.76122	38.90565
BPS5A250	0	37.25316	41	40.81472	0	26.25809	37.08443	37.69242	0	27.72647	43.5005	36.71313
BPS20A250	0	17.40128	25.96725	34.5	0	21.97456	38.79894	33.74595	0	26.78149	40.55141	33.57526
BPS50A250	0	26.60707	34.33096	38.74999	0	26.92672	37.72329	34.35612	0	31.27933	45	39
BPS100A250	0	17.7426	25	35.8	0	21.30727	31.16249	33.63874	0	29.1808	39.64899	38.23282

Table 7-2 BSFC Data Points for Figure 4-4

BSFC Data Points (g/kW-h)									
Fuel Type	Speed								
	1000 rpm			2100 rpm			3000 rpm		
	Load								
	LL (8 N.m)	ML (20 N.m)	HL (35 N.m)	LL (10 N.m)	ML (25 N.m)	HL (40 N.m)	LL (10 N.m)	ML (25 N.m)	HL (40 N.m)
Diesel	300.00	176.00	110.00	330.00	144.21	89.00	240.00	135.00	110.86
B5	291.99	175.22	128.39	328.55	155.46	91.27	233.43	130.74	122.16
BPS5	219.73	116.78	112.48	339.65	133.41	86.22	280.97	133.72	113.84
BPS5A100	193.39	125.86	99.27	352.32	199.62	100.61	275.84	130.96	113.20
BPS5A250	234.38	110.06	78.98	332.53	141.47	87.40	314.92	135.54	109.85
B20	385.08	138.11	97.17	362.45	149.79	91.21	278.07	157.74	111.43
BPS20	276.98	135.36	87.34	352.79	153.18	90.28	377.57	138.80	120.56
BPS20A100	276.98	124.44	87.51	338.68	137.37	84.97	322.63	165.24	139.83
BPS20A250	509.06	204.74	146.14	403.11	137.18	85.03	330.76	147.51	121.87
B50	333.46	176.10	128.20	311.16	136.54	92.10	367.06	169.77	141.22
BPS50	336.21	135.59	99.77	318.31	149.94	94.63	342.47	151.66	107.79
BPS50A100	250.76	165.53	117.28	334.82	149.10	97.98	362.35	163.83	119.04
BPS50A250	342.88	159.50	115.89	338.81	145.32	89.77	291.67	127.73	96.43
B100	436.00	135.49	80.47	267.16	129.41	107.96	317.86	186.54	114.43
BPS100	409.83	186.89	112.47	401.11	245.79	126.95	349.75	160.28	120.67
BPS100A100	242.02	117.80	92.09	387.81	172.04	102.51	391.46	155.97	109.03
BPS100A250	541.07	316.07	148.94	450.55	185.10	107.67	328.98	163.50	115.98

Table 7-3 CO Emissions Data Points for Figure 4-6, 4-7

Ethanol Series CO (PPM)				DEE Series CO (PPM)			
	Speed				Speed		
Fuel Blends	800 rpm	1000 rpm	1200 rpm	Fuel Blends	800 rpm	1000 rpm	1200 rpm
Diesel	164	188	286	Diesel	164.00	188.00	286.00
B20	156.60	170.00	210.00	B20	156.60	170.00	210.00
B20E5	139.40	166.20	198.80	B20DE5	125.00	129.90	123.80
B20E15	205.40	200.00	315.20	B20DE15	169.80	139.60	143.80
B50	147.00	160.20	198.60	B50	147.00	160.20	198.60
B50E5	131.60	133.20	112.00	B50DE5	98.80	134.40	99.60
B50E15	139.20	142.40	195.00	B50DE15	93.40	141.40	128.20
B100	105.07	103.00	122.20	B100	105.07	103.00	122.20
B100E5	117.60	116.60	123.00	B100DE5	137.60	123.00	129.00
B100E15	120.00	124.80	130.00	B100DE15	138.00	124.00	135.40

Table 7-4 CO Emissions Data Points for Figure 4-8

CO (PPM) Emissions for EPS Series												
Fuel Type	Speed											
	1000 rpm				2100 rpm				3000 rpm			
	Load											
	0%	20%	50%	80%	0%	20%	50%	80%	0%	20%	50%	80%
Diesel	507.33	384.00	315.25	273.75	363.17	319.25	286.50	261.75	363.00	319.25	287.25	268.50
B5	265.00	241.00	205.50	176.50	192.00	188.50	175.25	152.50	326.00	350.75	327.25	282.75
BPS5	327.67	313.00	280.25	240.00	209.67	293.33	323.33	210.00	349.00	367.50	367.50	320.67
BPS5A100	262.50	250.33	231.33	204.33	237.00	304.67	373.00	326.00	382.50	393.00	380.33	341.33
BPS5A250	306.33	285.00	258.33	227.67	272.50	257.00	238.00	199.00	368.00	389.50	389.33	342.00
B20	320.00	267.67	234.00	199.25	218.50	218.25	199.25	181.25	312.25	329.00	307.00	274.50
BPS20	270.33	246.00	228.67	211.67	194.00	183.67	172.00	169.33	255.67	273.50	237.33	201.33
BPS20A100	138.67	138.00	129.33	118.33	153.00	148.67	140.00	138.67	212.50	217.50	224.67	211.00
BPS20A250	160.67	160.00	149.00	137.33	160.33	162.50	153.67	142.33	244.00	252.50	252.33	225.67
B50	397.00	351.00	315.25	277.75	226.50	205.75	193.50	184.75	278.67	265.00	230.75	202.25
BPS50	157.33	147.67	136.33	126.00	138.33	131.00	120.50	109.50	174.50	177.00	173.00	159.67
BPS50A100	171.67	154.33	143.33	133.33	140.67	135.67	124.33	117.00	199.67	211.00	211.67	196.67
BPS50A250	253.00	225.33	198.75	178.33	188.00	180.33	168.33	155.67	254.67	265.33	256.67	241.67
B100	433.00	313.00	278.50	235.75	218.75	207.33	186.50	176.25	281.80	286.50	264.00	223.75
BPS100	343.83	268.75	245.00	173.25	157.75	139.00	134.25	127.75	200.00	215.25	207.50	230.50
BPS100A100	227.00	185.00	157.67	138.75	141.00	128.00	114.67	108.33	225.25	234.33	224.00	210.00
BPS100A250	245.25	225.33	196.33	161.25	201.50	194.67	177.50	168.33	197.00	184.00	143.00	225.00

Table 7-5 NO_x Data Points for Figures 4-9, 4-10

Ethanol NOx Emissions							DEE NOx Emissions						
Fuel Blends	Speed						Fuel Blends	Speed					
	800 rpm		1000 rpm		1200 rpm			800 rpm		1000 rpm		1200 rpm	
	NO	NO2	NO	NO2	NO	NO2		NO	NO2	NO	NO2	NO	NO2
Diesel	258.00	42.07	215.00	35.60	190.33	50.53	Diesel	258.00	42.00	215.00	35.60	190.33	50.53
B20	261.80	43.20	223.40	52.40	203.00	55.60	B20	261.80	43.20	223.40	52.40	203.00	55.60
B20E5	245.40	46.60	221.00	51.00	192.40	57.40	B20E5	258.60	41.40	233.00	42.60	205.00	42.00
B20E15	236.60	52.60	207.80	53.00	176.00	59.20	B20E15	260.00	46.80	218.40	42.60	200.20	40.00
B50	265.00	46.60	228.00	53.40	209.00	55.80	B50	265.00	46.60	228.00	53.40	209.00	55.80
B50E5	245.40	44.20	208.60	44.00	199.40	53.40	B50DE5	264.60	41.00	226.60	43.80	208.60	41.80
B50E15	240.60	45.40	204.20	44.20	197.60	47.20	B50DE15	263.60	36.40	223.60	38.20	199.60	40.20
B100	281.93	35.93	248.80	38.20	216.80	49.00	B100	281.93	35.93	248.80	38.20	216.00	47.00
B100E5	242.40	41.40	223.50	37.00	190.40	43.00	B100DE5	270.80	38.00	239.75	40.80	214.20	44.60
B100E15	210.40	31.60	200.00	38.60	169.60	37.40	B100DE15	262.60	42.20	238.00	42.20	210.60	44.00

Table 7-6 NOx Data Point for Figure 4-11

NOx Emissions (PPM) Data Point for EPS Series												
Fuel Blends	Speed											
	1000 rpm				2100 rpm				3000 rpm			
	Load											
	0%	20%	50%	80%	0%	20%	50%	80%	0%	20%	50%	80%
Diesel	102.33	159.00	188.00	247.00	90.33	122.25	147.75	176.75	64.17	78.50	105.50	139.50
B5	103.00	124.00	171.50	236.25	121.50	112.50	134.25	171.50	76.50	73.00	90.25	116.50
BPS5	105.67	121.33	167.75	240.75	131.67	113.67	123.33	176.67	89.50	88.00	102.50	132.33
BPS5A100	96.50	107.67	163.67	245.67	126.33	100.67	107.50	134.33	82.50	83.00	102.33	99.67
BPS5A250	95.33	115.00	163.33	242.33	95.50	111.00	142.50	181.33	94.00	91.00	105.67	135.50
B20	117.25	169.33	219.33	291.00	124.25	120.75	145.50	179.00	89.25	88.25	106.25	133.50
BPS20	124.00	135.67	169.67	224.67	124.33	130.00	154.50	183.67	86.67	83.50	100.67	130.33
BPS20A100	122.67	139.33	185.00	256.33	127.50	133.33	159.33	177.33	97.50	91.00	99.00	124.00
BPS20A250	129.00	138.67	179.33	244.33	132.33	128.00	151.00	179.33	97.00	91.50	109.00	170.00
B50	114.50	165.00	208.25	265.25	110.33	134.25	158.00	187.00	80.50	118.75	146.50	179.75
BPS50	97.33	111.33	143.00	195.00	105.00	108.50	129.75	157.25	85.00	83.00	94.00	116.67
BPS50A100	98.33	111.33	147.00	197.00	114.00	118.00	143.67	168.33	89.33	84.00	96.33	115.00
BPS50A250	109.67	119.67	159.75	216.67	110.67	110.00	132.67	162.33	85.00	80.00	95.00	114.67
B100	83.50	155.75	204.50	289.00	117.00	133.67	160.50	197.25	90.40	98.75	120.50	150.00
BPS100	68.83	92.25	116.50	158.25	98.00	94.75	104.50	131.00	75.00	78.75	96.25	149.00
BPS100A100	92.95	104.75	129.00	177.75	103.75	114.00	131.67	167.00	81.25	76.33	85.33	111.67
BPS100A250	85.75	92.33	119.00	159.00	99.25	106.67	125.00	151.33	70.67	68.67	74.00	81.50

Table 7-7 HC Emissions Data Points for Figures 4-12, 4-13

Ethanol HC Emissions (PPM)				DEE HC Emissions (PPM)			
Fuel Blends	Speed			Fuel Blends	Speed		
	1000 rpm	2100 rpm	3000 rpm		1000 rpm	2100 rpm	3000 rpm
Diesel	40.00	35.00	32.60	Diesel	40.00	35.00	32.60
B20	38.00	33.00	26.00	B20	38.00	33.00	32.50
B20E5	36.00	32.00	30.00	B20DE5	36.00	32.00	32.50
B20E15	28.00	26.00	30.00	B20DE15	38.00	34.00	32.00
B50	36.00	32.00	18.00	B50	34.00	32.00	29.00
B50E5	28.00	28.00	18.00	B50DE5	38.00	34.00	20.00
B50E15	26.00	24.00	18.00	B50DE15	40.00	38.00	24.00
B100	32.67	26.00	20.67	B100	32.67	26.00	26.33
B100E5	10.00	8.00	10.00	B100DE5	34.00	28.00	24.00
B100E15	16.00	10.00	10.00	B100DE15	36.00	30.00	26.00

Table 7-8 Smoke Opacity Data Points for Figure 4-14

Smoke Opacity (%) for EPS Series												
Fuel Blends	Speed											
	800 rpm				1000 rpm				1200 rpm			
	Load											
	0%	20%	50%	80%	0%	20%	50%	80%	0%	20%	50%	80%
Diesel	14.58	3.80	3.47	5.28	1.16	1.14	2.10	3.10	1.35	1.42	1.61	1.98
B5	6.52	2.34	2.99	4.11	1.09	1.48	2.50	3.72	0.71	1.05	1.57	2.43
BPS5	6.61	4.21	4.68	6.18	1.43	1.09	1.47	2.93	0.66	0.91	1.21	1.91
BPS5A100	1.87	1.81	2.45	3.50	0.73	0.78	0.93	1.56	0.92	0.98	1.72	2.70
BPS5A250	2.87	2.53	3.12	4.19	0.58	0.97	2.00	3.07	0.70	0.89	1.16	1.69
B20	8.14	7.75	7.39	6.82	1.68	1.70	3.11	4.35	0.87	0.88	1.10	1.71
BPS20	7.90	4.13	4.46	5.89	1.09	1.46	2.48	3.73	0.89	0.93	1.37	2.08
BPS20A100	1.83	2.45	3.44	4.99	0.84	1.18	2.15	3.21	0.61	0.68	0.88	1.41
BPS20A250	4.45	3.44	3.71	5.29	0.77	0.78	1.54	2.80	0.67	0.70	0.98	1.51
B50	5.47	3.85	4.97	6.31	1.52	1.46	2.71	4.13	0.91	0.85	1.22	1.81
BPS50	10.82	8.58	8.23	9.43	1.34	1.71	3.16	4.66	0.91	0.98	1.55	2.25
BPS50A100	13.88	9.79	8.66	10.09	1.42	1.49	2.99	4.42	0.97	0.99	1.53	2.07
BPS50A250	20.89	14.34	8.49	10.42	1.25	1.41	2.81	5.25	0.94	0.97	1.40	1.70
B100	17.86	17.13	15.10	14.11	3.44	2.80	3.45	4.72	1.68	1.62	1.93	2.50
BPS100	30.90	32.10	23.80	21.60	3.94	4.32	6.26	7.28	2.25	2.61	3.28	4.07
BPS100A100	19.93	16.29	14.88	14.71	1.75	1.77	3.15	4.61	1.13	0.99	1.30	1.71
BPS100A250	20.26	18.11	16.52	16.93	2.25	2.09	3.42	4.09	1.30	1.34	1.38	1.86