TECHNICAL FEASIBILITY ASSESSMENT FOR USAGE OF BIO-DIESEL AND HVO IN CUMMINS HIGH HORSEPOWER ENGINES

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

THERMAL ENGINEERING

Submitted by:

SAUMYA SHREY

(2K21/THE/15)

Under the Supervision of

Dr. NAVEEN KUMAR
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M.TECH **(MECHANICAL ENGINEERING DEPARTMENT)** **[SAUMYA SHREY]** **2023**

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Bawana Road Delhi – 110042

CANDIDATE'S DECLARATION

I, **SAUMYA SHREY**, Roll No.:- **2K21/THE/15** students of M.Tech Thermal Engineering, hereby declare that the project Dissertation titled "**TECHNICAL FEASIBILITY ASSESSMENT FOR USAGE OF BIO-DIESEL AND HVO IN CUMMINS HIGH HORSEPOWER ENGINES"** which is submitted by me to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Date: 10.06.2023
Place: Delhi

SAUMYA SHREY
(2K21/THE/15)

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CERTIFICATE

I hereby certify that the project Dissertation titled "**TECHNICAL FEASIBILITY ASSESSMENT FOR USAGE OF BIO-DIESEL AND HVO IN CUMMINS HIGH HORSEPOWER ENGINES**" which is submitted by **SAUMYA SHREY**, Roll No.- **2K21/THE/15** to the Department of Mechanical (Thermal) Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Date: 10.06.2023 **(Dr. NAVEEN KUMAR)**
Place: Delhi (Professor)

Mechanical Engineering Department
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(SUPERVISOR)

ABSTRACT

The world is facing the pressing issues of rising global temperatures and an escalating need for renewable energy sources. As natural energy resources continue to deplete considering the significant demand for petroleum fuels in the power generation, transportation, and agricultural sectors, there is a growing emphasis on developing feasible solutions for usage of alternative energy sources to replace fossil fuels. This trend is gaining momentum as an array of solutions are being introduced to the market. Paraffinic fuels: Hydrotreated Vegetable Oil (HVO) and Biodiesel (FAME) are being increasingly seen as a viable substitute for traditional diesel fuel. Based on government mandates, there is an increasing demand of the application of non-diesel fuels applications for High Horsepower Engines from the customers' end. CMI & Cummins India are working together to identify, benchmark and evaluate non-diesel fuel options like Biodiesel blends and HVO in various Cummins HHP applications. The present project aims to add to the efforts of understanding usage of Biodiesel Blends and HVO (Hydrotreated Vegetable Oil) in various Cummins applications by Combustion Simulation, Field & Test cell Performance and Production Validation methodologies.

The objective is to compare the in-cylinder performance and emissions characteristics of Cummins HHP engines using different fuels: Diesel, HVO, and biodiesel blends (ranging from 20% to 100% volume of biodiesel with diesel). The project intends to conduct these comparisons without making any modifications to the engine or fuel. Additionally, the project aims to study the compatibility of Cummins engine components, such as fuel filters, with biodiesel blends (B20, B40, B50, B75 & B100) and HVO. It also includes the simulation of in-cylinder performance using GT-Power software and the development of a predictive combustion model for various biodiesel blends. When running the test engine with different fuels and same combustion inputs, the drop of 1.03% in peak torque at 1500 rpm was observed for HVO and a significant reduction of 10.9% in peak torque for Biodiesel (B100). The in-cylinder performance parameters indicates an increase of 5% fuel consumption for Biodiesel whereas 3% reduction for HVO compared to Diesel. Brake Thermal Efficiency of HVO is higher by 3% and lower by 12% for Biodiesel throughout the torque curve. The lower efficiency of Biodiesel is attributed to the low calorific value of the fuel. Exhaust Gas Temperature (EGT) is higher for both the fuels than baseline fuel.

Comparative analysis of emission parameters indicate that HVO is much cleaner fuel than Diesel. All the major pollutants like NOx, Hydrocarbons, CO and PM show a reduction in the emission levels by 10.4%, 31.37% and 25% respectively. However, Biodiesel shows slight increase in the NOx emissions by 8.8% but reduction in other pollutants like CO and PM. The simulation model results of the predictive combustion model for Biodiesel blends show that the in-cylinder performance parameters are within the +/-3% error band and the model and can be used to observe combustion behaviour and provide reliable predictions for future cases.

ACKNOWLEDGEMENTS

The present research work was carried out under the esteemed supervision of my guide Dr. Naveen Kumar from Delhi Technological University and my supervisor M/s Manali J Talathi from Cummins India Limited. It is my honour and privilege to express a deep sense of gratitude to them for their panegyric efforts, ever-helping attitude, critical and valuable comments and constant inspiration.

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Last but not least; I thank my friends and family for giving me the strength and patience to complete this work in all respects and for leading me to the path of success.

New Delhi
June, 2023

(SAUMYA SHREY)

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NOMENCLATURE

@	At the rate
A/F	Air to Fuel
AN	Acid Number
ASTM	American Society for Testing and Materials
ATDC	After Top Dead Center
AVL-437	AVL-437 Smoke Meter
BIS	Bureau of Indian Standard
BMEP	Break Mean Effective Pressure
SBSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
BTDC	Before Top Dead Center
^{o}C	Degree Celsius
cc	Cubic centimeter
CI	Compression Ignition
cm-1	Per Centimeter
CN	Cetane Number
CO	Carbon Monoxide
CO$_2$	Carbon Dioxide
cSt	Centi Stoke
Cu	Copper
CV	Calorific Value
D100	Neat Diesel
DI	Direct Injection
DF	Diesel fuel
EJ	Exo-Joules
^{o}F	Degree Fahrenheit
F/A	Fuel to Air
FFA	Free Fatty Acid
FIT	Fuel Inlet temperature
g	Gram
g/cc	Gram per cubic centimeter
HC	Hydrocarbon
H2O	Water
HP	Horse Power
HVO	Hydrotreated Vegetable Oil
IC	Internal Combustion
IDI	Indirect Injection
IR	Infra Red
IS	Indian standard
KVA	Kilo Volt Ampere
kW	Kilo Watt
kW-h	Kilo Watt Hour
LSD	Low Sulphur Diesel
LPM	Liter per Minute

1M	1 Mole
Min.	Minute
ml	Milliliter
mm	Millimeter
Mt	Million Tonnes
Mtoe	Million Tonne of Oil Equivalent
NO	Nitric Oxide
Nos.	Numbers
NO2	Nitrogen Di-oxide
NOx	Oxides of Nitrogen
nPAH	Nitro Poly Aromatic Hydrocarbon
O2	Oxygen
PAH	Poly aromatic Hydrocarbon
PM	Particulate Matter
ppm	Parts per million
rpm	Revolutions Per Minute
SAE	Society of Automobile Engineering
sfc	Specific Fuel Consumption
TDC	Top Dead Center
THC	Total Hydrocarbon
ULSD	Ultra Low Sulphur Diesel
UBHC	Unburnt Hydrocarbon
Vs	Versus
v/v	Volume/ Volume
ρ	Density
%	Percent

CHAPTER 1

INTRODUCTION

The world is grappling with the pressing issues of rising global temperatures and an escalating need for renewable energy sources. To achieve sustainable development in the energy industry, a steady supply of renewable and sustainable energy is crucial. With economic and population growth, the demand for energy is expected to rise substantially. At present, the world is heavily reliant on fossil fuels such as crude oil, natural gas, and coal, which account for 80% of global energy consumption [1]. These resources are derived from organic matter that formed millions of years ago and cannot be replenished quickly - regeneration can take hundreds of years. Furthermore, as fossil fuel combustion and industrial processes have contributed to 78% of greenhouse gas emissions in recent decades, urgent action is needed to transition to a low-carbon economic system that can replace our reliance on fossil fuels [1]. Biofuels are one of several renewable technologies that have played and will continue to play a significant role in meeting targets for the use of renewable energy resources and reducing greenhouse gas emissions.

In addition to addressing these demanding environmental concerns, developing and applying biofuels offers other benefits such as improving national energy security, utilizing existing transportation and fuel distribution systems, and facilitating rural development. Biofuels Report (2021) [4] quoted that in 2021, biofuels accounted for 3.6% of the global demand for energy in the transport sector, primarily used in road transportation. According to the Net Zero Scenario, the contribution of biofuels to the transport sector is expected to quadruple to 15% by 2030, making up nearly one-fifth of the fuel demand specifically for road vehicles. While the overall demand for biofuels has increased, the growth has been uneven across different types of biofuels. Ethanol demand increased by 6% from 2020 to 2021 but remains 7% lower than the demand in 2019. Biodiesel, specifically referring to FAME (Fatty Acid Methyl Esters), marginally exceeded the demand in 2020 by 0.3% and reached 1.4 EJ (exajoules). On the other hand, renewable diesel, known as HVO (Hydrotreated Vegetable Oil), continued its exponential growth, with consumption in 2021 being 65% higher than in 2019 [4].

1.1 GLOBAL ENERGY SCENARIO

According to BP Statistical Review of World Energy 2022 [25], primary energy experienced a significant surge in 2021, marking the largest increase in history and completely reversing the sharp decline observed in 2020. Compared to 2019, primary energy in 2021 surpassed the levels by 8 EJ. This substantial growth in primary energy during 2021 was propelled by emerging economies, particularly China, which witnessed an expansion of 10 EJ. Since 2019, primary energy consumption in emerging economies has grown by 15 EJ, largely driven by China's remarkable increase of 13 EJ. On the other hand, developed economies witnessed a decrease in energy demand in 2021, which was 8 EJ lower than the levels seen in 2019. Notably, the rise in primary energy from 2019 to 2021 can be solely attributed to renewable energy sources, as there was no change in the consumption of fossil fuels during this period. While there was a decrease in oil demand (-8 EJ), it was offset by higher consumption of natural gas (5 EJ) and coal (3 EJ). Figure 1.1 shows the Energy consumption (EJ) by different fuels from 2007 to 2021. Primary energy use in 2021was 1.3% above 2019 levels.

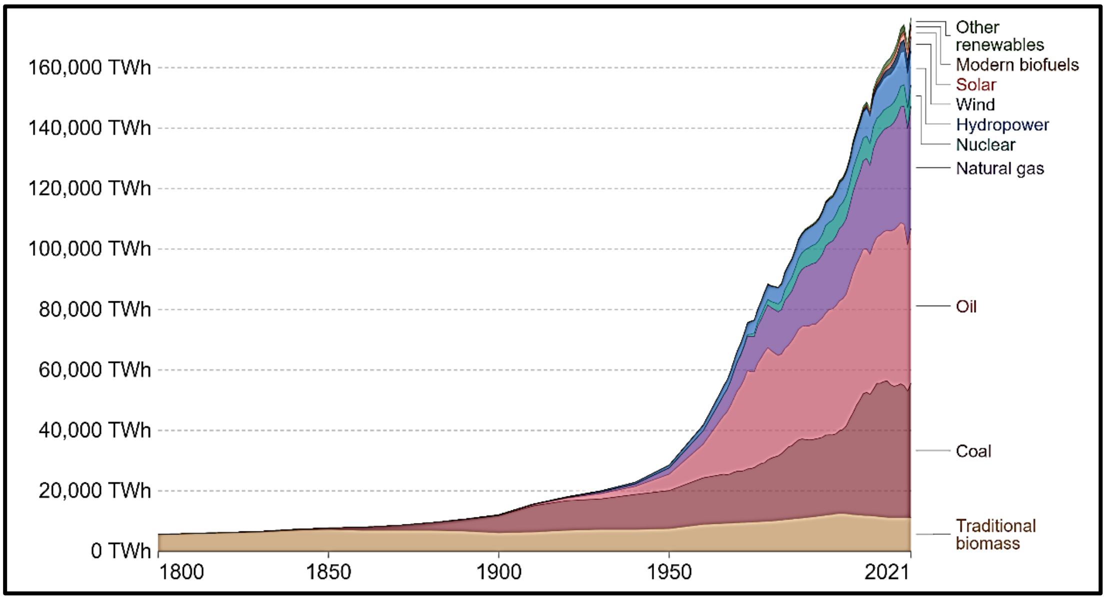


Figure 1.1: Energy consumption (EJ) by different fuels

(*Source: BP Statistical Review of World Energy 2022; 71st Edition)*

Bioenergy holds the position of being the largest renewable energy source worldwide, contributing to 55% of renewable energy generation and accounting for over 6% of the global energy supply. The Net Zero Emissions by 2050 Scenario foresees a significant upsurge in the utilization of bioenergy as a substitute for fossil fuels by 2030. The adoption of bioenergy has witnessed an average annual growth rate of approximately 7% from 2010 to 2021 and continues to exhibit an upward trajectory. This scenario calls for a yearly increase in deployment by 10% between 2021 and 2030, while simultaneously ensuring that the production of bioenergy does not give rise to adverse social and environmental consequences. Praveen Bains et.al [4] in their report 'Biofuels' forecasts the trend of Global biofuel demand in transport sector in 2030. The key findings are summarized below:

1. In 2021, biofuels were responsible for meeting 3.6% of the global transport energy demand. The contribution is expected to quadruple to 15% by 2030.
2. In 2030, biofuels produced from wastes, residues, and dedicated crops that do not compete with food crops are expected to make up around 50% of the biofuels consumed, up from an estimated 8% in 2021.
3. Biodiesel, experienced a demand increase of 0.3% in 2021, reaching 1.4 EJ. Renewable diesel, witnessed 65% increase in consumption in 2021 as compared to 2019, reaching over 0.3 EJ.
4. Average production cost of advanced biofuels is 2-3 times that of fossil fuel equivalents, however, it is expected to decrease by up to 27% over the next decade.

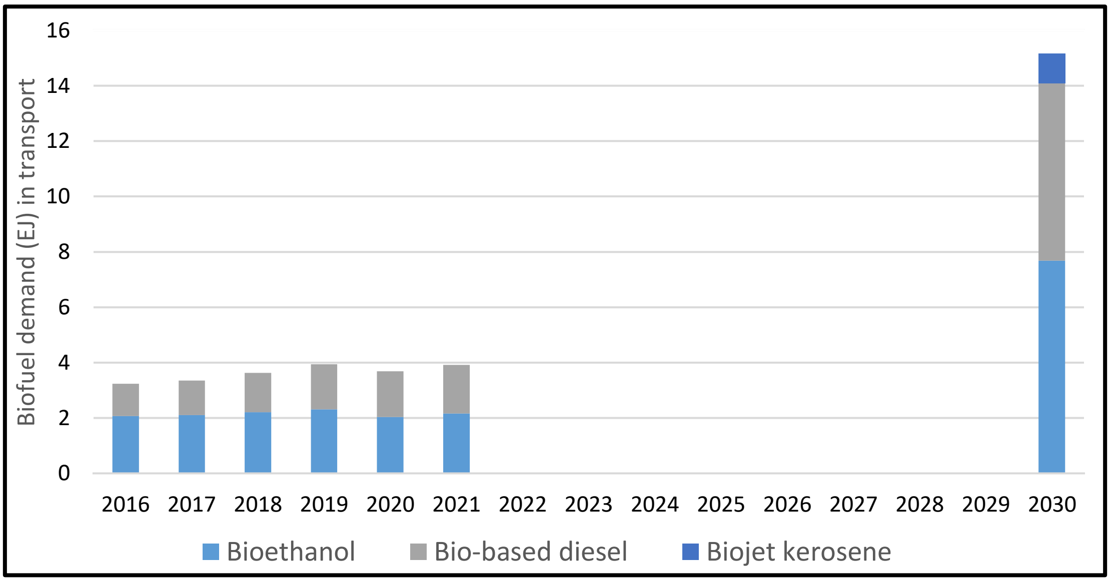


Figure 1.2: Global biofuel demand (EJ) in transport, 2016-2030

1.2 INDIAN ENERGY SCENARIO

Due to increasing incomes and improving living standards, India has become the world's third-largest consumer of energy. Energy consumption in the country has doubled since 2000, with coal, oil, and solid biomass accounting for 80% of the demand. On a per capita basis, India's energy usage and emissions are less than half of the global average. Similarly, key indicators such as vehicle ownership, steel production, and cement output are also below the world average. As India emerges from the economic downturn caused by the Covid-19 pandemic in 2020, it is entering a highly dynamic phase in its energy development.

BP Statistical Review of World Energy 2022 quoted that the consumption of primary energy saw a 10% annual increase, rising from 32 EJ in 2020 to 35 EJ in 2021. The combined proportion of oil, gas, and coal in energy consumption remained steady at 90%. Among these fuels, coal experienced the highest growth rate, with a 16% increase and surpassing its 2019 level by 8% [25].

1. Coal accounted for 57% of primary energy, significantly higher than the global average of 24%. Notably, India accounted for 12.5% of global coal consumption and ranked as the second-largest producer of coal, just behind China.
2. Natural gas consumption reached 62 billion cubic meters (bcm), representing a 3.1% increase. However, the share of natural gas in primary energy declined slightly from 6.8% to 6.3%.
3. Renewable energy sources experienced a growth rate of 13.2%; however, their proportion in primary energy only increased by 0.1 percentage points, reaching 5%. In India, the production of biofuels saw a significant increase from 23 to 37 kilo barrel of oil equivalent per day (kboe/d), marking a 60% rise.
4. Biofuel consumption rose from 36 to 43 kboe/d, resulting in a decrease in India's reliance on biofuel imports. On the other hand, CO2 emissions stemming from energy use surged by 12%, surpassing the pre-pandemic level and reaching over 2.5 Gt.

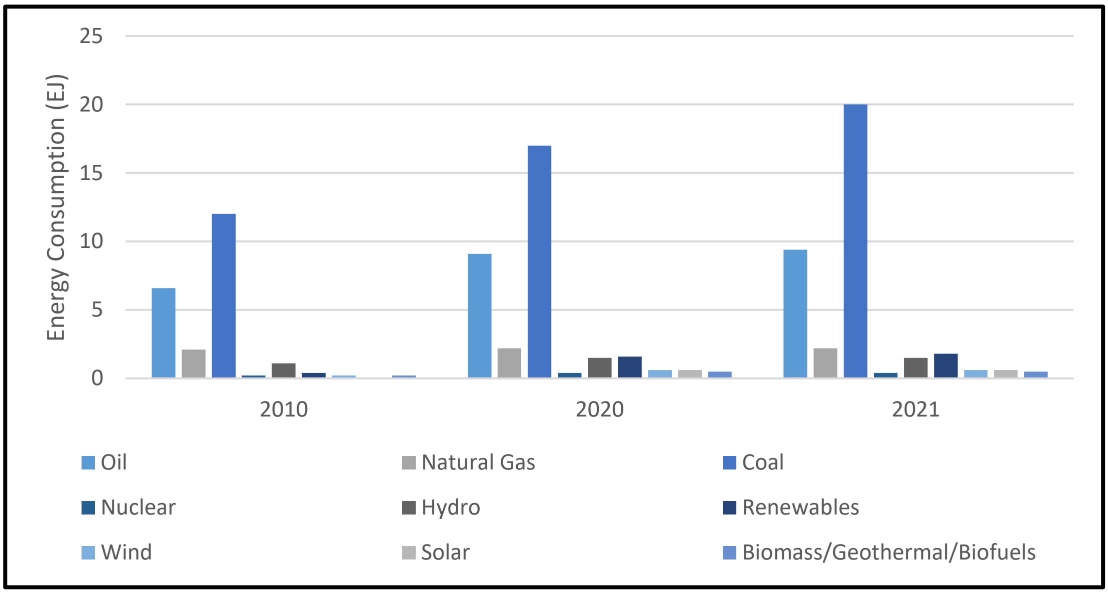


Figure 1.3: Energy Consumption (EJ) by different fuels in India

1.3 BIOFUELS SCENARIO IN INDIA

1.3.1 Policy and Programs

1. **National Biofuel Policy (NBP) 2018**

India's biofuels policy [2] aims to achieve several objectives:

- Decreased reliance on oil imports and enhanced self-sufficiency: The Ministry of Petroleum and Natural Gas (MoPNG) believes that a successful E20 program could lead to potential savings of $4 billion per year. Currently, India imports approximately 86% of its petroleum requirements, with fossil fuels meeting around 98% of the transportation sector's fuel needs.
- Protection of farmers' economic interests: Indian oil marketing companies (OMCs) have paid sugar mills around $5.4 billion for ethanol through the Ethanol Blended Programme (EBP). Additionally, the inclusion of damaged and surplus food grains as a feedstock provides additional income opportunities for producers.
- Reduction in emissions: According to MoPNG, the EBP is projected to result in a decrease of 19.2 million metric tons (MMT) of greenhouse gas (GHG) emissions from 2014 to 2021.
- Improved ease of doing business through technology: State governments in India facilitate business activities such as e-approvals, permits, and electronic and GPS tracking of the ethanol logistics fleet through the implementation of

the Industries Development and Regulation Act. This enhances the ease of doing business in the sector.

2. Net Zero Emissions (COP 26)

In November 2021, the Prime Minister announced India's net-zero emissions commitment by 2070 at the Conference of Paris (COP 26) *(Source: Ministry of External Affairs)*. India's other commitments intended to be achieved by 2030 include:

- Increasing non-fossil energy capacity to 500 GW
- Fulfilling 50 percent of energy requirements from renewable sources
- Reducing carbon intensity of the economy by 45 percent
- Reducing total projected carbon emissions by one billion tons

1.3.2 Biodiesel Market Assessment: India

Biodiesel production has gained international and national momentum. It has been promoted for production and consumption by the Indian government since the early 2000s, with various state governments also joining in on the efforts. NBP 2018 [2] has put forward an indicative target of 5% blending of biodiesel in diesel by 2030. Biofuels Annual (India 2022) [3] depicted the production and consumption quantity of Biodiesel in India in the last decade. The report states that India's annual biodiesel consumption increased by 3% between 2013-2020. Biodiesel market penetration for on-road diesel remains marginal and is estimated at 0.07 percent. The National Biofuel Policy 2018 (NBP) supported the increase of the production of biodiesel in the country but, India's production and consumption trends showed a decline in the year 2020-2021 attributable to plant closures and reduced global energy demand during the COVID-19 pandemic. The report concluded that the biodiesel market in India remains decentralized, with very limited domestic production, most of which is consumed locally to generate stationary power. Other factors which add to the limited market of Biodiesel include high global feedstock prices and inconsistent supply chain for feedstocks.

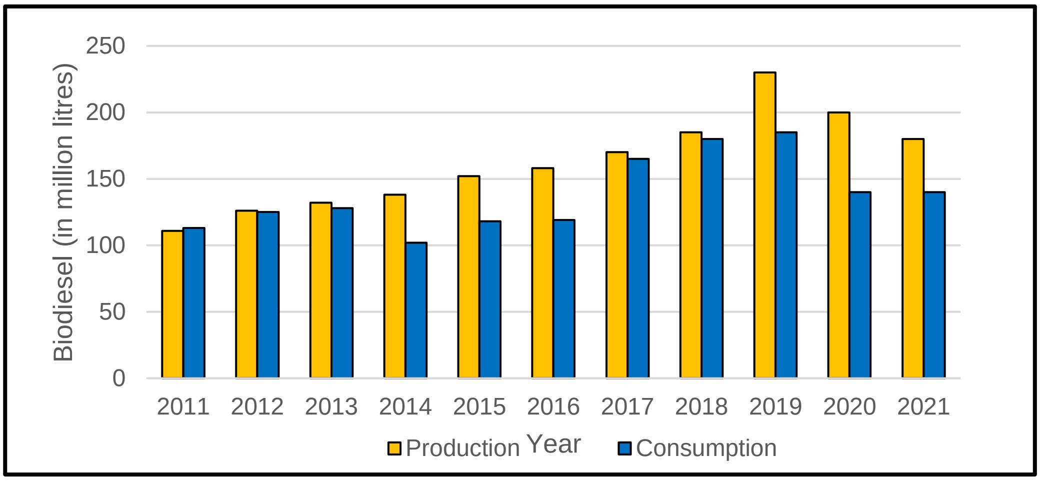


Figure 1.4: Production and Consumption of Biodiesel in India

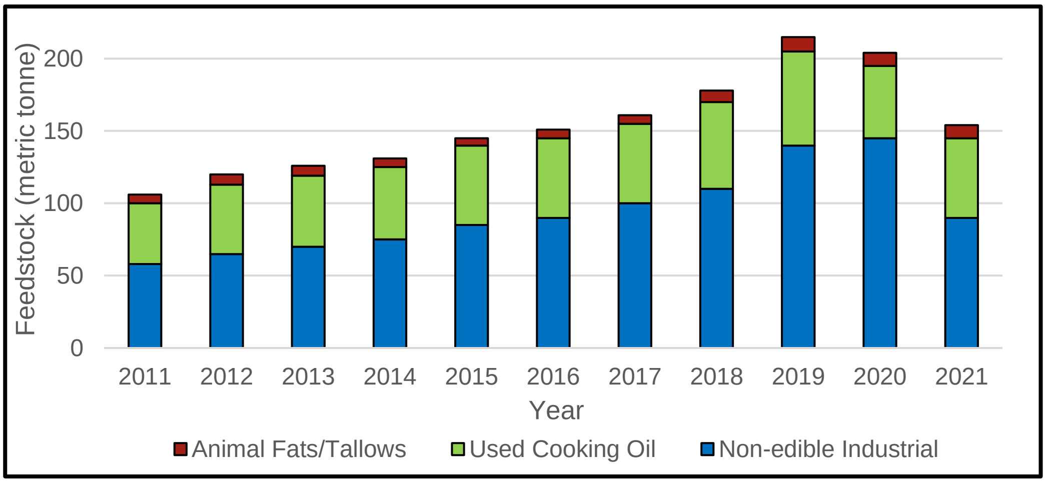


Figure 1.5: Trend of usage of different feedstocks in Biodiesel Production in India

The report ‘Biodiesel in India’ [5] concluded in their study that a viable market for biodiesel has yet to emerge due to its high-cost relative to conventional diesel. Additionally, biodiesel production is not yet efficient, and most oil-bearing trees remain wild plants with limited yields, particularly on marginal or dry lands. Consequently, niche markets such as seedling reproduction, oil extraction for the chemical industry, and Clean Development Mechanism (CDM)-funded projects are currently the only economically feasible options. However, the study considers that the production of biodiesel is the favorable prospect to generate extra income sources for India's rural population, as well as to increase land use intensity and promote ecological sustainability.

1.4 MOTIVATION

- To address the pressing issues of rising global temperatures and energy security, there is an escalating need for renewable energy sources.

- India ranks 4th globally on installed Renewable energy capacity; with a target of achieving 175 gigawatts (GW) of installed capacity with renewable energy by 2022. This target includes 100 GW in solar, 60 GW in wind energy, 10 GW from biomass and 5 GW from hydropower. Moreover, Conference of Paris (COP26) committed net-zero emissions by 2070
- National Biofuel Policy 2018 (update 2022) has an indicative target of 5% blending of biodiesel in diesel /direct sale of biodiesel is proposed by 2030
- Based on government mandates, there is an increasing demand of the application of non-diesel fuels applications for High Horsepower Engines from the customers' end
- CMI & Cummins India are working together to identify, benchmark and evaluate non-diesel fuel options like Biodiesel blends and HVO in various Cummins HHP applications
- Power Solution Business Unit (PSBU) India CPE (Combustion Performance Emissions) team is planning to execute various assessment tests for Biodiesel blends up to B50 for High Horsepower applications (19L to 60L Engines) to understand performance and endurance on Biodiesel at CTCI (Cummins Technical Center India)
- The present project aims to add to the efforts of understanding usage of Biodiesel Blends and HVO (Hydrotreated Vegetable Oil) in various Cummins applications by Combustion Simulation, Field & Test cell Performance and Production Validation methodologies

1.5 ORGANIZATION OF THESIS

The thesis entitled, "**Technical Feasibility Assessment for Usage of Bio-Diesel and HVO In Cummins High Horsepower Engines**" gives an outline of the usage of Biodiesel Blends and HVO in various Cummins applications by Combustion Simulation, Field & Test cell Performance and Production Validation methodologies. This thesis is made up of five chapters.

The organization of the chapters is as follows:

CHAPTER 1: INTRODUCTION: This chapter gives the background of the research. It starts with an introduction into the energy scenario of the world and

India. It also highlights the Policy and Programs and the Biofuel market penetration in India, that helped to define the motivation of the research.

CHAPTER 2: LITERATURE REVIEW: The focus of this chapter is to provide an overview of new and emerging sources of biofuels. Additionally, the chapter examined the biodiesel and HVO feedstocks available in India, the technologies used for their production, the standards and characterization of Biodiesel and HVO, as well as their properties and test procedures of the Physico-chemical properties. Moreover, the chapter highlights the literature done on the property variation and impact on in-cylinder performance, emission, and combustion potentials of Biodiesel and HVO fuels. This chapter also benchmarks other companies' study on the impact of usage of Renewable fuels (HVO), to be used as drop-in replacements for diesel fuel. Finally, the research gap, problem statement and objectives of the research are outlined.

CHAPTER 3: METHODOLOGY AND SYSTEM DEVELOPMENT: It explains the procedure for biodiesel production of Biodiesel and HVO. It discusses the Cummins stand on the usage of Biodiesel and HVO in Diesel engines and analyses the compatibility of the Cummins engines parts like fuel filters, fuel lines and gaskets with the biodiesel fuel. Also, the system development for the engine and its specifications are listed. The chapter also described the procedures for the simulation of predictive combustion model in GT-Power.

CHAPTER 4: RESULTS AND DISCUSSION: This chapter discussed all the results obtained from the experimental work, simulation work and statistical calculations, and presented the findings of the study followed by detailed argument and analysis of these findings and comparing them with the existing results included in the literature. Results herein are presented in tables and graphs.

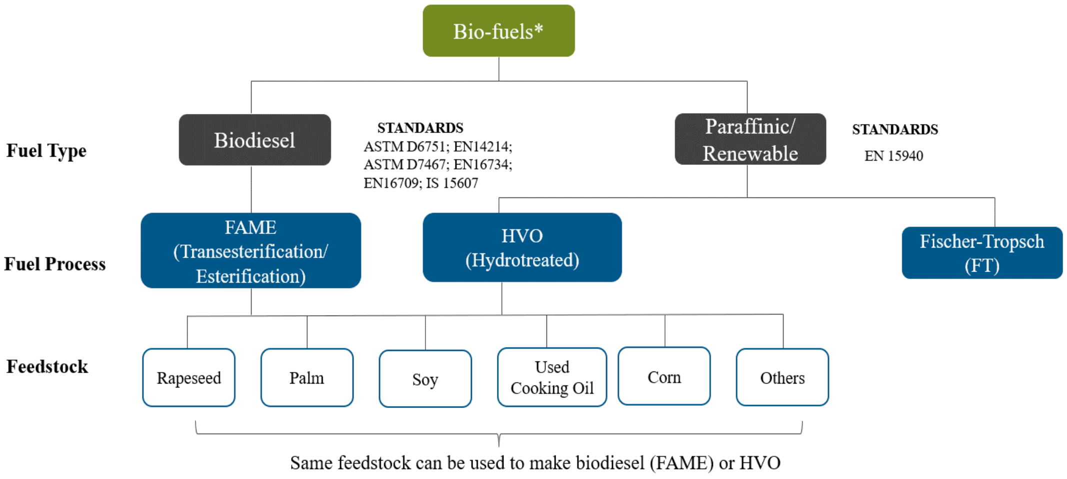
CHAPTER 5: CONCLUSION: It provides a summary of the key findings in the light of the research and put logical conclusions supported by facts and figures obtained in this research. Finally, some recommendations for the future studies have been included in this chapter.

CHAPTER 2

LITERATURE REVIEW

1.1 BIOFUELS: INTRODUCTION

Biofuels, which are renewable liquid fuels derived from biological sources, have emerged as viable alternatives to oil in the transportation and agriculture sectors. They are gaining global recognition as solutions for addressing environmental degradation, energy security, import restrictions, rural employment, and agricultural economy challenges. Among biofuels, ethanol, methanol, vegetable oils, paraffinic fuels- Hydrotreated Vegetable Oil (HVO) and Biodiesel (FAME) are the most promising options. Greenhouse gas emissions, particularly CO2 emissions, are inherent in most types of fuels. However, when biofuel energy is utilized instead of fossil fuels, there is typically a net reduction in CO2 emissions. Additionally, the emissions of SO2 tend to be significantly lower. There is also a decline in traditional motor pollutants such as carbon monoxide, unburned hydrocarbons, and particulate matter, however, that there is an increase in the release of nitrogen oxides and aldehydes when biomass energy is used.



*Biofuels Compatible with Compression Ignition Engines

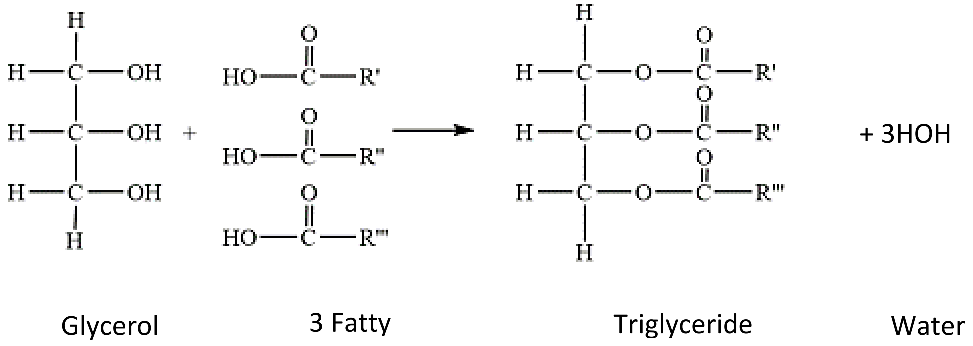
Figure 2.1: Classification of biofuels, fuel process and the feedstock

Though, ethanol and methanol being widely used as fuel, they are compatible with spark ignition engines because of lower cetane number than that of conventional diesel. Biodiesel and HVO are derived from vegetable oils, as well as animal fats through transesterification and hydrogenation processes. Biodiesel and HVO can be blended in any proportion with petroleum diesel, therefore are compatible with Compression Ignition engines.

2.2 BIODIESEL

2.2.1 Vegetable Oil:

The composition of vegetable oils is primarily composed of triglycerides, accounting for approximately 97% of their content. The remaining 3% is comprised of di- and monoglycerides, as well as three fatty acids and accompanying fat, which are largely eliminated through the refining process. In terms of structure, a triglyceride is formed through a chemical reaction involving one molecule of glycerol and three molecules of fatty acids, resulting in the release of three molecules of water and the formation of one molecule of triglyceride.



where R, R’ and R’’ are the alkyl groups of different carbon chain lengths (varying between 12-18), and -COO- is a carboxyl group.

The term "biodiesel" encompasses a range of products that are created by combining vegetable oils or animal fats (triglycerides) with alcohol (such as methanol or ethanol) to form alkyl esters of fatty acids. Biodiesel is formed using different manufacturing processes like: Alkali esterification, Acid esterification, Glycerolysis and Enzymatic process. Furthermore, these products adhere to rigorous quality standards (ASTM, EN, BIS etc.) to be considered suitable for use as transportation fuels. Biodiesel can be produced from different feedstocks with varying levels of free fatty acids (FFAs), and the FFA content is a significant factor in determining the appropriate manufacturing process for biodiesel production. The most used feedstocks for producing Biodiesel and their free fatty acid content (FFA) are listed in Table 2.1

Feedstocks	**Free Fatty Acid (FFA) content (%)**
Used Cooking Oil (UCO)	Less than 5%
Palm Oil Methyl Ester (POME)	Less than 5%, Greater than 5%
Stearin	Less than 5%
Tallow	Less than 5%, Greater than 5%
Rendered oil	Less than 5%, Greater than 5%
Acid oils (edible)	Greater than 5%

Table 2.1: Feedstocks and their Free Fatty Acid (FFA) content

2.2.2 Transesterification:

Transesterification is considered the preferred method for its cost-effectiveness, high yields, and simplicity. This chemical process involves the reaction of alcohol with vegetable oils. By combining one mole of fat or oil with three moles of a short-chain alcohol in the presence of a catalyst, one mole of glycerin and three moles of alkyl esters are produced. Through a stepwise conversion, triglycerides are transformed into diglycerides, monoglycerides, and eventually glycerol, which can be easily separated into biodiesel and glycerol layers using gravity. Glycerol is a valuable by-product commonly used in the cosmetic industry. Methanol and ethanol are the primary alcohols used in transesterification due to their relatively low cost.

Transesterification processes generally fall into two main categories: catalytic and non-catalytic methods. The use of a catalyst enhances alcohol solubility, leading to increased reaction rates. Alkaline catalysts, such as NaOH, KOH, $NaOCH_3$, and $KOCH_3$, have been extensively reported in research. Acid catalysts include sulphuric acid, hydrochloric acid, ferric sulphate acid, phosphoric acid, para toluene sulfonic acid (PTSA) and Lewis acids ($AlCl_3$ or $ZnCl_2$). Researchers have shown that acid catalysts are more tolerant than alkaline catalysts for vegetable oils having high FFA and water.

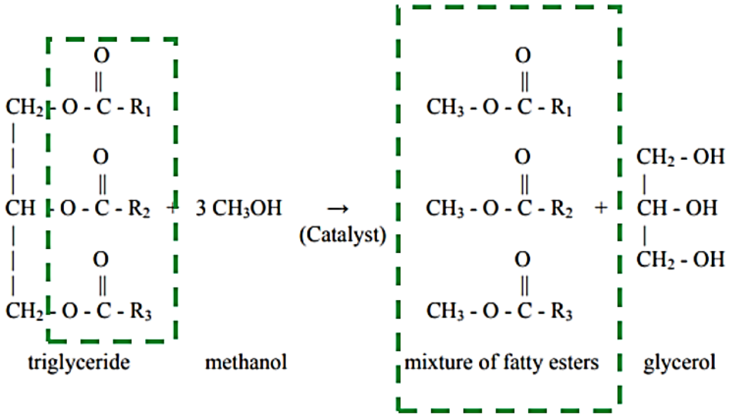
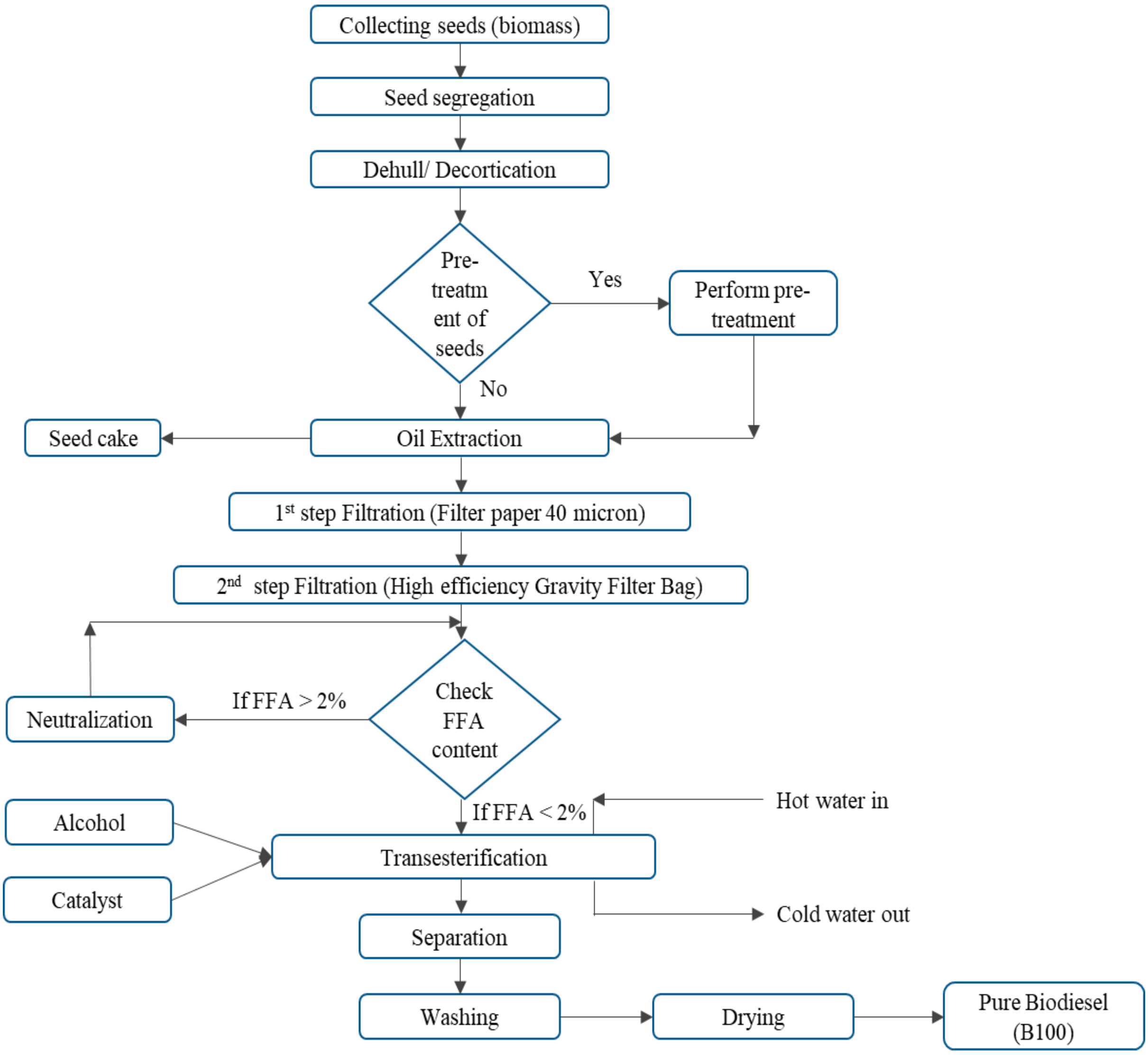


Figure 2.2: Transesterification method to synthesis Biodiesel (FAME)

2.2.3 Biodiesel Production Flowchart:



(Source: Quality biodiesel production and engine performance emission evaluation using blends of castor biodiesel; SAE Technical Papers)

2.3 HYDROTREATED VEGETABLE OIL (HVO)

Hydrogenated vegetable oil (HVO), also known as Renewable Diesel, is a type of renewable diesel fuel that can be produced from various vegetable oils and fats containing triglycerides and fatty acids. The term HVO specifically refers to renewable diesel fuels obtained through the processes of hydrogenation and hydrocracking, using feedstocks such as tall oil, rapeseed oil, waste cooking oil, and animal fats. HVO shares many chemical properties with fossil diesel, except some differences. It has a lower density and energy content compared to fossil diesel. One notable advantage of HVO is that it is free from sulphur, oxygen, and aromatic hydrocarbons. Additionally, HVO exhibits a high cetane number, which indicates good ignition quality and combustion efficiency.

2.3.1 Hydrogenation/ Hydrocracking:

HVO is manufactured through the process of hydrogenation and hydrocracking, involving vegetable oils and animal fats, hydrogen, and catalysts under high temperatures and pressures. This hydrotreating process eliminates oxygen from the triglycerides and/or fatty acids present in the feedstocks. The resulting products are comprised of straight-chained hydrocarbons, specifically paraffins, with varying properties and molecular sizes depending on the characteristics of the feedstocks and process conditions. The conversion of the feedstocks typically occurs in two stages: hydrotreatment followed by hydrocracking/isomerization. Hydrotreatment is usually conducted at temperatures ranging from 300 to 390°C. During the treatment of triglycerides, propane is commonly generated as a by-product. The production process of HVO involves several steps. Initially, hydrogen is introduced to the double bonds present in the renewable feedstock, resulting in saturation. Subsequently, additional hydrogen is added to facilitate the removal of propane through the cleavage of triglycerides into fatty acids. In the final stages, the fatty acids undergo hydrodeoxygenation, where oxygen is eliminated as water, and/or decarboxylation, where oxygen is removed as carbon dioxide. Following these steps, the resulting hydrocarbons are further processed to meet specific quality standards required by end-users. This may involve treatments such as isomerization and cracking to optimize the characteristics of the HVO, aligning it with conventional petroleum fuel criteria.

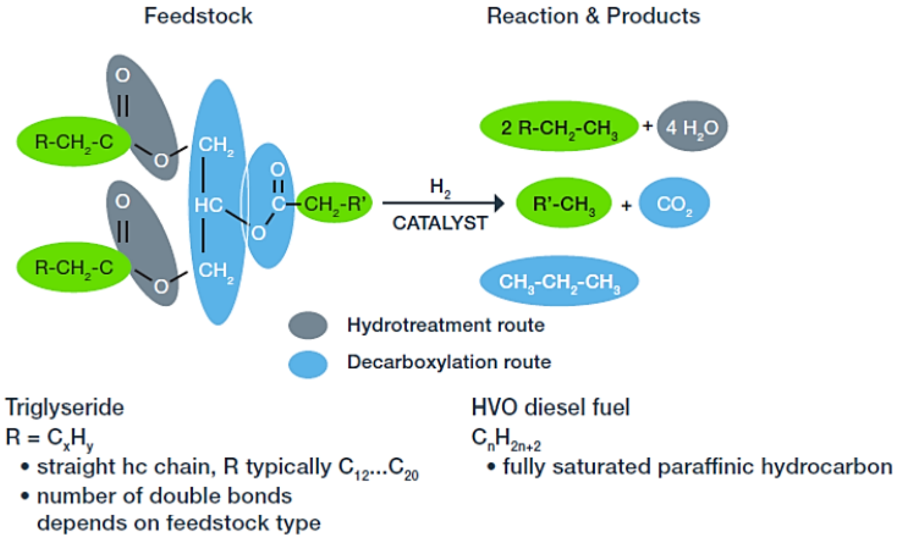


Figure 2.3: Hydrogenation method to synthesis Hydro-treated Vegetable Oil

2.4 PHYSICO-CHEMICAL PROPERTIES AND TEST PROCEDURES

Sr.no	Parameters	Description	Test Standard	Test Apparatus/Methods
1.	Calorific Value	Quantity of heat produced by the combustion of biofuel under standard conditions and at constant pressure and	IS 1448 (P:6)	**Bomb calorimeter:** M.easure the heat of combustion of a sample by burning it in oxygen under controlled conditions. The mass of the sample and the increase in temperature are taken into account to calculate the heat of combustion, considering factors such as heat transfer and the formation of nitric and sulfuric acid in the bomb. This value represents the gross heat of combustion at a constant volume. The calibration of the bomb is performed using the combustion of benzoic acid
2.	Flash point	Lowest temperature of the test portion, at which the application of an ignition source causes the vapor of the test portion to	IS:1448 (P-21)	**Pensky-Marten's closed cup test apparatus:** The sample to be tested is placed in a test cup. The temperature of the test cup is gradually increased and the contents are

		ignite and the flame to propagate across the surface of the liquid under the specified conditions of test		continuously stirred. At regular temperature intervals, an ignition source is introduced through an opening in the lid of the test cup. The flash point of the sample is determined as the lowest temperature at which the application of the ignition source causes the vapor of the sample to ignite and spread over the liquid's surface.
3.	Density at 15^{o}C	**Density**: mass of liquid per unit volume at 15^{o}C **Relative density:** ratio of mass of given volume of liquid at 15^{o}C to the mass of equal volume of water at same temperature	IS:1448 (P-16)	**Glass hydrometer:** The sample is heated to a specified temperature and then transferred to a cylinder that is also at a similar temperature. A suitable hydrometer is immersed into the sample and given time to settle. Once the temperature equilibrium is achieved, the hydrometer's scale reading is recorded, along with the temperature of the sample.
4.	Distillation	The boiling range gives information on the composition, the properties, and the behavior of the fuel during storage and use.	IS:1448 (P-18)	Distillation unit: Distillation flask, the condenser and associated cooling bath, a metal shield or enclosure for distillation flask, the heat source, the flask support, the temperature measuring device and the receiving cylinder to collect the distillate.
5.	Cleanliness	Excessive contamination of diesel fuel can cause: Premature clogging of diesel fuel filters and/or premature wear of critical fuel injection system parts Reduced component life Component	ISO 4406	18/16/13: Cleanliness codes are expressed as a series of three numbers (x/x/x), which correspond respectively to the number of particles greater than 4, 6, and 14 microns. 21- Up to 20,000 particles larger than 4µm (per mL of fuel) 18 - Up to 2,500 particles larger than 4µm (per mL of fuel) 16 - Up to 640 particles larger than 6µm (per mL of fuel)

		malfunction Fuel system and/or engine failure		13 - Up to 80 particles larger than 14µm (per mL of fuel)
6.	Ash	The inorganic residue left after ignition of the sample under prescribed conditions, calculated as the percentage by mass of the original sample	IS:1448 (P-4)	Methods A1 and A2: Determination of ash from greases. Method B : Determination of the sulphated ash from unused lubricating oils containing additives and from additive concentrates used in compounding.
7.	Sulphur	Means of monitoring the sulphur level of various petroleum products and additives	IS:1448 (P-33)	The sample undergoes combustion in a high-pressure decomposition device where it is oxidized in the presence of pressurized oxygen. The resulting washings from the high-pressure decomposition device, which contain sulphur in the form of sulphate, are subjected to a gravimetric analysis to determine the amount of sulphur present.
8.	Corrosion - Copper strip	Determination of the corrosiveness to copper of liquid petroleum products and certain solvents.	IS:1448 (P-15)	Polished copper strip is placed into a predetermined volume of the sample being tested. The strip is then subjected to specific temperature and time conditions that are tailored to the particular class of material under evaluation. After the designated heating period, the strip is taken out, cleaned, and its color is compared against corrosion standards.
9.	Cetane Number	Cetane number is a measurement of the combustion quality of diesel fuel during	IS:1448 (P-9)	

		compression ignition.		
10.	Kinematic viscosity	Resistance to flow of the liquid; it is commonly called the viscosity of the liquid. Kinematic Viscosity is a measure of the resistance to gravity flow of a fluid.	IS:1448 (P-25)	Apparatus: Glass capillary viscometer Method: The time is measured in seconds for a fixed volume of liquid to flow under gravity through the capillary of a calibrated viscometer under a reproducible driving head and at a closely controlled temperature. The kinematic viscosity is the product of the measured flow time and the calibration constant of the viscometer.
11.	Cloud Point	The temperature at which a cloud of wax crystals first appears in a liquid when it is cooled under specified conditions.	IS:1448 (P-10)	A sample is cooled at a specified rate and examined periodically. The temperature at which a cloud is first observed at the bottom of the test jar is recorded as the cloud point.
12.	Lubricity	Fuel with lower sulfur and viscosity tends to have lower lubricity.		1. Scuffing Load Ball On Cylinder Evaluator (SLBOCLE) 2.High Frequency Reciprocating Rig (HFRR)
13.	Carbon Residue	Carbonaceous residue formed during evaporation and pyrolysis of a petroleum product. The residue is not entirely composed of carbon but is a coke which can be further changed by pyrolysis.	IS:1448 (P-8)	Ramsbottom Method: Glass coking bulb with a capillary opening is used. The test portion, which has been weighed, is placed in this bulb, which is then placed inside a metal furnace maintained at a temperature of around 550 degrees Celsius. The test portion in the bulb is rapidly heated to the point where all volatile substances evaporate from the bulb, either with or without decomposition. Meanwhile, the heavier residue in the bulb

				undergoes cracking and coking reactions. Towards the end of the heating period, the coke or carbon residue may undergo slow decomposition or slight oxidation if air enters the bulb. After a specified heating period, the bulb is taken out of the furnace, allowed to cool in a desiccator, and then weighed again. The remaining residue is calculated as a percentage of the original test portion's mass.
14.	Oxidation Stability	Time which passes between the moment when the measurement is started and the moment when the formation of oxidation products rapidly begins to increase	EN 14112	The sample, heated to a specific temperature, is exposed to a continuous flow of purified air. The vapors released during the oxidation process, along with the air, are directed into a flask containing demineralized or distilled water. Within the flask, an electrode is present to measure conductivity, and it is connected to a measuring and recording device. As the oxidation process proceeds, volatile carboxylic acids are formed and absorbed in the water. The induction period ends when the conductivity begins to rapidly increase, indicating the dissociation of these volatile acids in the water.
15.	Cold Filter Plugging Point (CFPP)	Highest temperature at which the fuel when cooled under the prescribed conditions; either will not flow through the filter or requires more than 60 seconds for 20ml to pass through	IS:1448 (P-110)	The fuel sample is cooled under the prescribed condition and at intervals of 1°C, a vacuum of 200 mm water gauge is applied to draw the fuel through a fine wire mesh filter. As the fuel cools below its cloud point, increasing number of wax crystals will be formed. This will cause the flow rate to decrease eventually complete plugging of the filter will occur.

Table 2.2: Physico-chemical properties and their Test procedures

2.5 REGULATIONS FOR BIODIESEL AND HVO

2.5.1 BQ 9000

The National Biodiesel Accreditation Program (BQ-9000) is a cooperative and voluntary program for the accreditation of producers and marketers of biodiesel fuel. The program is a unique combination of the ASTM standard for biodiesel (ASTM D6751) and a quality systems program that includes storage, sampling, testing, blending, shipping, distribution, and fuel management practices. BQ 9000 Seal of Approval assures "cradle-to-grave" fuel quality.

Figure 2.4: Cradle to Grave illustration of a Biodiesel

Goals:

1. To promote the commercial success and public acceptance of Biodiesel
2. To help assure that biodiesel fuel is produced to and maintained at the industry standard, ASTM D6751

Categories:

1. Producer: This classification refers to companies engaged in the production of biodiesel fuel. To be legally considered biodiesel, the fuel must adhere to the ASTM D6751 standard.
2. Marketer: This category pertains to distribution companies that specialize in selling biodiesel and biodiesel blends.
3. Lab: This classification encompasses commercial laboratories that are involved in the analysis of biodiesel and biodiesel blends.

2.5.2 Biodiesel

Several factors can impact the quality of biodiesel fuel, including the quality of the feedstock, the fatty acid composition of the feedstock, the production and refining processes used, and post-production parameters. Since biodiesel is produced from various sources with different qualities and origins, it is crucial to establish standards for fuel quality to ensure smooth engine performance. The establishment of biodiesel standards depends on the regulations and specifications set by each country. These standards serve to protect consumers and producers while supporting the growth of the biodiesel industry. Biodiesel specifications include the American Standards for Testing Materials (ASTM 6751), the European Union (EN 14214) Standards, and India's own standard (IS 15607). These standards outline the physical and chemical characteristics of biodiesel, including caloric value (MJ/kg), cetane number, density (kg/m3), viscosity (mm2/s), cloud and pour points (°C), flash point (°C), acid value (mg KOH per g-oil), ash content (%), copper corrosion, carbon residue, water content and sediment, sulfur content, phosphorus (mg/kg), and oxidation stability.

Parameter	**Biodiesel (B100)**		
	ASTM D6751	**EN 14214**	**IS 15607**
Density at 15 °C, kg/m3	-	860-900	860-900
Kinematic viscosity at 40 °C, cSt	1.9-6.0	3.5-5.0	3.5-5.0
Flash point (PMCC)1) °C, Min	130	101	101
Total Sulphur, mg/kg, Max	15	10	10
Carbon residue, (%m/m), Max	0.05	-	0.05
Sulfated ash, (%m/m), Max	0.02	0.02	0.02
Water content mg/kg, Max	500	500	500
Total contamination, mg/kg, Max	-	24	24
Copper strip corrosion, 3 h at 50 °C, Max	3	1	1
Cetane No., Min	47	51	51
Acid value, mg KOH/g, Max	0.5	0.5	0.5
Methanol, (%m/m), Max	0.2	0.2	0.2
Ester content, (%m/m), Min		Min: 96.5	96.5
Phosphorous mg/kg, Max	10	4	4
Na +K mg/kg, Max	5	5	5
Ca + Mg mg/kg, Max	5	5	5
Iodine (I) value, gm, Max		120	120
Oxidation stability, at 110 °C, Min hrs.	3	8	8
Cold filter plugging point (CFPP), °C Max	-	-	-
a) summer	18	-	18
b) winter	3	-	6
Triglyceride content, (%m/m), Max	-	0.2	0.2

Table 2.3: ASTM D6751, EN 14214 & BIS 15607 Standards of Biodiesel (B100)

Parameter	EN 16709		ASTM D 7467
	Minimum	Maximum	
Density at 15 °C, kg/m3	820	860	
Viscosity at 40 °C, mm2/s	2	4.62	1.9-4.1
Flash point (PMCC)1) °C, Min	Above 55		52
Sulphur content, mg/kg		10	15
Manganese content, mg/l		2	
Polycyclic aromatic hydrocarbons, %(m/m)		8	
Water content, mg/kg		260	0.05*
Total contamination, mg/kg		24	
Ash content, %(m/m)		0.01	0.01
Cetane Number		51	40
Ester content, %(V/V)	14	20	6 - 20
Oxidation stability, hrs.	20		6
Distillation %(V/V) recovered at 250 °C %(V/V) recovered at 350 °C 95%(V/V) recovered at, °C	- 85 -	<65 - 360	343
Acid value, mg KOH/g, Max			0.3
Carbon residue, percent by mass, Max			0.35
Lubricity, HFRR at 60 °C, micron			520
Copper strip corrosion, 3 h at 50 °C, Max			3

* Water & Sediment, % vol, Max

Table 2.4: ASTM D7467 & EN 16709 Standards of Biodiesel (B6-B20)

2.5.3 Hydrotreated Vegetable Oil

HVO specifications include the European Union (EN 15940) Standards. This standard outlines the physical and chemical characteristics of biodiesel, including caloric value (MJ/kg), cetane number, density (kg/m3), viscosity (mm2/s), cloud and pour points (°C), flash point (°C), acid value (mg KOH per g-oil), ash content (%), copper corrosion, carbon residue, water content and sediment, sulfur content, phosphorus (mg/kg), and oxidation stability.

Parameter	EN15940	
	Minimum	Maximum
Cetane No.	51	-
Density at 15°C, kg/m3	780	810

Flash point ,°C	Above 55.0	-
Viscosity at 40 °C, mm2/s	2	4.5
Distillation %(V/V) recovered at 250 °C %(V/V) recovered at 350 °C 95%(V/V) recovered at, °C	- 85 -	<65 NA 360
Lubricity, wear scar diameter (wsd) at 60 °C, micron	-	460
FAME content, %V/V	-	7
Manganese content, mg/l	-	2
Total aromatics content, %(m/m)	-	1.1
Sulphur content, mg/kg	-	5
Carbon residue, (on 10% distillation residue) %(m/m)	-	0.3
Ash content, %(m/m)	-	0.01
Water content, mg/kg	-	200
Total contamination, mg/kg	-	24
Copper strip corrosion (3h at 50 °C)	Class 1	
Oxidation stability, h	20	-

Table 2.5: EN 15940 Standard of HVO

2.6 PROPERTY VARIATION OVER STORAGE

Biodiesel blend stocks often contain fatty acid chains with one, two, or three unsaturated bonds, resulting in significant levels of unsaturation. Over time, these unsaturated sites are prone to oxidation, leading to the formation of peroxides, acids, and polymer gums. This oxidation process can negatively impact the stability of biodiesel, resulting in higher acid numbers, increased viscosity, and sediment formation. Compared to conventional diesel, biodiesel generally exhibits lower long-term storage stability due to its susceptibility to oxidation. Various factors influence the oxidative stability of biodiesel, including the degree of saturation in the feedstock, the natural antioxidant content, carbon chain length, and the presence of glycerides.

While stability is important for both conventional diesel and biodiesel, it is particularly critical for biodiesel due to its higher vulnerability to oxidation and subsequent degradation. Proper storage and handling conditions are essential to minimize the negative effects of oxidation and maintain the quality of biodiesel over time. Many literatures studied the property variation of Biodiesel over storage.

Surface Vehicle Information Report, “Biodiesel in Automotive Application; Lessons Learned”, highlighted the impact of long storage duration on oxidation stability, microbial growth and material of construction. The Table 2.6 summarizes the observations of the long storage duration on Biodiesel properties.

Sr.No.	Property	Observations
1.	Oxidation stability	Biodiesel has lower oxidative (long-term storage) stability than conventional diesel Factors affecting biodiesel’s oxidative stability include the degree of saturation of the feedstock, the level of natural antioxidant content, carbon chain length and the presence of glycerides
2.	Duration	B100, B20 and B5 to be used within six months
3.	Antioxidants	Should be added if the fuel is kept longer after production, and periodic tests should be performed to ensure the fuel continues to meet the ASTM D6751 specification
4.	Heating	Heating can greatly accelerate the aging process. A cushion of 10 °C above the cloud point should be sufficient
5.	Material of Construction	Metals such as copper, brass, bronze, lead, tin and zinc should be kept out of contact with the biodiesel Suitable storage tank materials are steel, aluminum, fluorinated polyethylene, fluorinated polypropylene and Teflon. Nitrogen blanketed storage vessels are also used to reduce the tendency of stored biodiesel to oxidize and to help keep moisture and condensation out of the tank
6.	Microbial growth	The higher susceptibility to oxidation can lead to the formation of corrosive acids. These acids will accumulate in the water phase and must be removed on a frequent basis to prevent tank corrosion The proactive use of biocides is not recommended unless it is to remedy a situation with clear biological growth. Keeping water out of tanks will aid in the prevention of corrosion.

Table 2.6: Property variation over storage summary based on Surface Vehicle Information Report

Tsesmeli et.al (2020) studied a set of biodiesel fuel microcosms, contaminated with particulate matter, subjected to stable storage conditions for a duration of six months. Throughout the storage period, the number of particulate contaminants was monitored using a multiple filtration technique. The literature highlighted that effect during a 6-month long-term storage period on the solid particulate matter present in both untreated and biocide-treated (250 ppm) contaminated FAME microcosms. Furthermore, the oxidation stability and acid number of the fuel phases in all examined microcosms were determined at the conclusion of the storage period. The observations of the study are summarized in Table 2.7

Sr.No.	Property	Observations
1.	Fuel samples	RM (Reference Microcosms) DWM (Distilled Water Microcosms); water to fuel ratio = 1:5 CWMs (Contaminated Water Microcosms) BTMs (Biocide Treated Microcosms); MBO at 250 ppm
2.	PM Contamination	Highest concentration of insoluble solids reported in the case of CWMs after 90 days of storage Slight increase observed in BTMs after 90 days of storage At the end of storage period (6 months), the formation of biomass was almost the same in both microcosms
3.	ATP Concentration	Highest ATP value was reported in the case of the CWM untreated contaminated microcosms Lower levels of microbial growth were detected in the MBO treated microcosms (BTM)
4.	Oxidation Stability	The microcosms treated with biocide (BTM) appeared to be more susceptible to oxidative deterioration and the respective specification could not be fulfilled after a 6-month storage period
5.	Acid Number	The highest values of acid number were recorded in the case of BTMs, which was almost nine times higher than the initial ones

Table 2.7: Summary of property variation over storage summary based on Tsesmeli et.al (2020) study

The National Biodiesel Accreditation Program (BQ-9000) is a cooperative and voluntary program for the accreditation of producers and marketers of biodiesel fuel. The program is a unique combination of the ASTM standard for biodiesel (ASTM D6751) and a quality systems program that includes storage, sampling, testing, blending, shipping, distribution, and fuel management practices. The report gives some guidelines about Biodiesel Storage Tank Sampling and Testing.

Sr.No.	Property	Observations
1.	Biodiesel Storage and Distribution Tanks	All Biodiesel storage and distribution tanks shall be dedicated to Biodiesel service If a tank is changed from some other service to Biodiesel storage, the tank should be drained dry, cleaned, and then inspected
2.	Biodiesel Storage Tank Sampling and Testing	Inspection and testing functions, associated with the verification that specified product requirements are being met, shall be defined in documented procedures. The procedures for final inspection and testing shall require that all specified inspections and tests have been carried out and that the results meet specified requirements
3.	Stored Biodiesel Product Verification	If a Biodiesel storage tank has not had any incoming product for 45 days, product shall not be shipped from the storage tank until an outlet sample A representative sample of the product according to ASTM D4057, is taken and tested for Haze per ASTM D4176 (Procedure 2, Maximum value of 2), Water and Sediment, and Oxidation Stability per current ASTM D6751 If any testing fails to meet specification, the Biodiesel shall be isolated and procedures for the control of nonconforming product shall apply.

Table 2.8: Property variation over storage summary based on BQ 9000 Report

2.7 IMPACT ON ENGINE OUT PARAMETERS

2.7.1 Effect of Feedstock on Engine Out Parameters:

The use of B100 and B20 results in a reduction of 78.45% and 15.66%, respectively, in CO2 emissions during the entire life cycle compared to petroleum diesel. This decrease is attributed to the carbon recycling that occurs in plants (Majewski et.al [15]). I.L.García [14] estimated the Greenhouse gas emissions savings for different raw materials and processing methods based on Life Cycle Assessment (LCA) in their paper. It was observed that the Waste Vegetable Oil Biodiesel contributed approximately 83% in Greenhouse Gas emissions savings. The Table2 below summarizes the Feedstocks and their respective Greenhouse Gas Emissions savings.

Feedstock	Greenhouse Gas Emissions Savings
Rapeseed Biodiesel	38%
Soybean Biodiesel	31%
Sunflower biodiesel	51%
Palm oil biodiesel	19%
Palm oil biodiesel with methane capture at oil mill	56%
Waste vegetable oil biodiesel	83%

Table 2.9: Greenhouse Gas Emissions savings for different feedstocks

Pawar et.al [10] also studied the impact of different feedstocks on the engine out emissions (PM, NOx and CO emissions), In Figure 2.4 the study observed that the PM emissions are almost similar to that of Diesel except it decreases for Soybean and Palm oil derived Biodiesel. CO emissions are reduced for Palm oil and Mahua to 500 ppm and 557 ppm respectively compared to 821 ppm of Diesel. However, NOx emissions increase when compared with 820 ppm of Diesel. The Palm oil derived Biodiesel showed the maximum NOx emission of 1300 ppm.

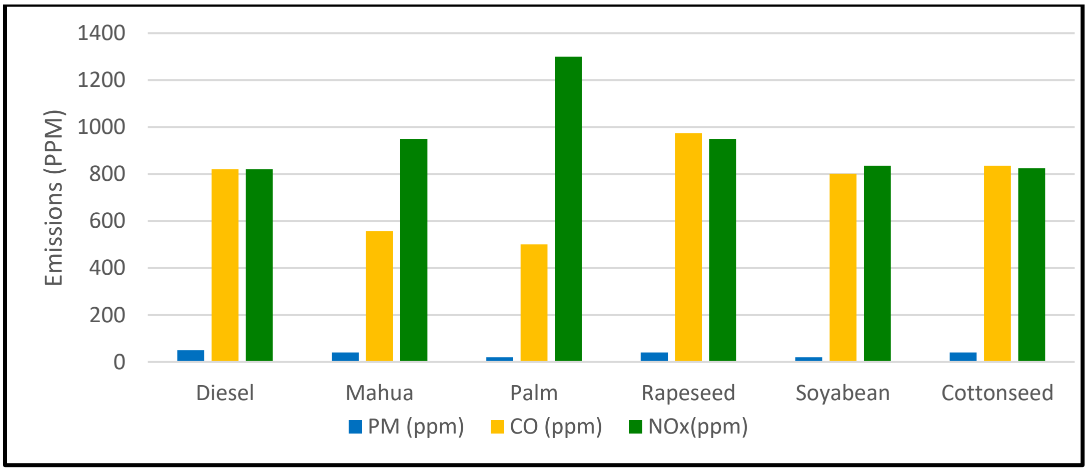


Figure 2.4: NOx, PM and CO emissions for Biodiesel derived from different feedstock

2.7.2 Summary of Impact of Biodiesel on Engine Out Parameters:

Rakopoulos et al. [16] carried out a study aimed at evaluating and comparing the effectiveness of different vegetable oils, sourced from various origins, as additives to traditional Diesel fuel. These vegetable oils were blended at ratios of 10% and 20% with Diesel fuel and tested in a direct injection (DI) Diesel engine.

The study revealed that the incorporation of vegetable oil in the Diesel engine led to a reduction in nitrogen oxides (NOx) emissions.

Pryor et al. [24] conducted experiments using neat crude soybean oil and crude degummed soybean oil in a three-cylinder, 2600 series Ford Tractor engine. They observed that the engines running on soybean oil produced a similar power output compared to when using diesel fuel. However, it was noted that the brake specific fuel consumption (BSFC) for soybean oil was 11-13% higher than that of diesel fuel across all loads.

Forsen et al. [20] investigated the effects of different fuel blends on a single-cylinder direct-injection engine. They tested three blends: 97.4% diesel and 2.6% Jatropha oil, 80% diesel and 20% Jatropha oil, and 50% diesel and 50% Jatropha oil, all measured by volume. The researchers found that carbon dioxide (CO2) emissions were similar for all fuel blends. However, the 97.4% diesel and 2.6% Jatropha blend was identified as having the lowest net contribution to atmospheric CO2 levels. The study also revealed that the use of Jatropha oil and its blends with diesel resulted in improvements in brake thermal efficiency, brake power, and a reduction in specific fuel consumption. Remarkably, the 97.4% diesel and 2.6% Jatropha blend exhibited the highest brake power and brake thermal efficiency values while also having the lowest specific fuel consumption. Additionally, Forsen et al. suggested the utilization of Jatropha oil as an ignition-accelerator additive for diesel fuel, highlighting its potential to enhance the overall performance of the engine

Pramanik [19] conducted an analysis of engine performance using blends of diesel and jatropha oil in a single-cylinder compression ignition (C.I.) engine, comparing it with pure diesel fuel. The study revealed a significant improvement in engine performance when using the diesel-jatropha oil blends compared to using vegetable oil alone. The incorporation of jatropha oil in the blends resulted in a decrease in viscosity of the vegetable oil, leading to reductions in specific fuel consumption and exhaust gas temperature. Additionally, the engine achieved acceptable thermal efficiencies when utilizing blends containing up to 50% volume of jatropha oil. Based on the properties of the fuel blends and the engine test results, it was established that 40-50% of jatropha oil could be substituted for diesel without requiring any modifications to the engine. This suggests the potential for using jatropha oil as a renewable and sustainable substitute for a portion of diesel fuel, offering improved engine performance while reducing the dependence on pure diesel.

Xue et.al [13] published the comprehensive review on the effects of Biodiesel on Engine performance and emissions. The study concluded that most of the literature work observed the decrease in Brake Power when an engine is run on Biodiesel attributed to the lower heating value of Biodiesel (approx. 38MJ). However, the degree of power loss depends on several factors, such as the engine type, fuel blend, and operating conditions. In some cases, the power loss may be negligible, while in others, it may be more significant. Most of the literature agreed that the CO, HC and PM emissions would decrease as Biodiesel has a higher oxygen content and lower carbon-to-hydrogen (C/H) ratio compared to conventional diesel. Moreover, higher oxygen content resulted in the increased NOx emissions for Biodiesel run engines. Inconsistent conclusions were drawn for CO2 emissions. Lower CO2 emissions were the result of low C/H ratio whereas, higher CO2 emissions were attributed to the more complete combustion due to availability of oxygen in the fuel.

Engine out Parameter	**Number of references reviewed**	**Number of References on the effect of Biodiesel compared with baseline Diesel (in percentage)**		
		Increase %	**Similar %**	**Decrease %**
Brake Power	27	7.4	22.2	70.4
Carbon Dioxide	13	46.2	15.4	38.5
Nitrogen Oxides	69	65.2	5.8	29.0
Carbon Monoxide	66	10.6	3.0	84.4
Hydrocarbons	57	5.3	5.3	89.5
Particulate Matter	73	9.6	2.7	87.7

Table 2.10: Effect of Biodiesel on Performance and Emission parameters based on Xue et.al study

Summary of some other literature review on the study of Biodiesel for various blends running on Diesel engines are listed below. The increment and reduction percentages are with respect to the baseline Diesel. The common trend observed the increase in NOx whereas reduction in other emissions like CO, HC and PM.

Study	NOx	CO	HC	PM
Jedynska et.al [7] (2015)	26% Increment	42% Reduction	Similar	80% Reduction
Cheikh et.al [6] (2016)	6% Increment	28.9% Reduction	40% Reduction	43.2% Reduction
Nystrom et.al [8] (2016)	21% Increment	11% Reduction	NA	46% Reduction
Tomic M et.al [12] (2021)	2.4% Increment	Reduction	NA	NA
O’Malley & Searle [9] (2021)	2% Increment	Similar	4% Reduction	6% Reduction

Table 2.11: Summary of Performance and Emission parameters

2.8 BENCHMARKING

2.8.1 MTU: HVO vs Diesel for Generator Sets

Ponstein et.al in their report “HVO Fuel Proven to Be Effective for Diesel Generator Sets” [22], conducted system tests (field tests) and engine-only tests (testbeds) to check the effectiveness of HVO as a drop-in fuel for MTU diesel generator sets: 20V 4000 G94S engine and 20V 4000 DS3000 generator set. The observations are summarized below:

Sr.No.	Parameter	Observation
1.	Fuel consumption	Specific fuel consumption improves using HVO, due to higher combustion efficiency (higher cetane number) Slightly higher volumetric fuel consumption, which can be attributed to the HVO’s lower density
2.	NO_x emissions	The NOx reduction of approximately 8% was observed, with a higher reduction at lower loads
3.	CO2 emissions	The reduction of CO2 was observed to be 3% in the D2 Cycle emissions testing
4.	Particulate matter	The reduction of PM emissions ranges from 50-80% with a 42% reduction in D2 cycle emissions

Table 2.12: Summary of MTU study on HVO vs Diesel for Generator Sets

2.8.2 Caterpillar: Renewable Fuels in Diesel Engines

Caterpillar’s report “Renewable and Alternative Fuels for Use in Diesel Engines” [21] checks the effectiveness and impact of Renewable fuels (HVO), whether at 100% or blended, to be used as drop-in replacements for diesel fuel for CAT engines. The key insights are listed below:

- No specific engine conversion process is needed when these fuels are used for the first time or thereafter
- These fuels may reduce the power output of engines due to their low density (up to a 5% reduction may be noted at 100%.)
- They are compatible with aftertreatment technologies such as DPF, DOC and SCR, and they can be used on engines that meet Tier 4, Stage V, and similar advanced emission standards
- They are compatible with filters and engine oils used with typical diesel fuels
- No impact on maintenance intervals is expected
- They are compatible with elastomeric materials and hoses used on most modern engines. Certain elastomers used in older engines, such as those manufactured prior to the early 1990s, may not be compatible with the new alternative fuels
- They can be stored in the same tanks used for diesel fuel, and they have a similar aging life as diesel fuel
- As with all fuels, renewable and alternative fuels must be managed to reduce contamination and water ingress
- Standard warranty is not impacted with the use of renewable and alternative fuels that meet recommended specifications
- EPA emissions certifications are not impacted with the use of renewable and alternative fuels that meet recommended specifications

2.11 PROBLEM STATEMENT

The literature review indicates that vegetable oil can be utilized in diesel engines either as an extender or as a complete replacement for diesel fuel. However, researchers have encountered difficulties when using vegetable oil in diesel engines, which can be attributed to its low heating value, high viscosity, low stability, and the presence of oxygen in the fuel. These issues can cause challenges when the fuel is used in diesel engines without any modifications to the engine architecture. To address these challenges, different strategies have been proposed in the literature. One approach is to modify the engine itself to accommodate the properties of the vegetable oil-based fuel. Another approach involves processing the fuel by incorporating additives, emulsifiers, or antioxidants to improve its compatibility with the engine.

Most of the existing literature on the comparative study of usage of biodiesel and HVO (Hydro-processed Vegetable Oil) focuses on low horsepower, single-cylinder engines operating at a constant speed. This project aims to investigate the technical feasibility of using biodiesel and HVO in Cummins High-Horsepower (HHP) engines, which are multi-cylinder and variable speed engines. The objective is to compare the in-cylinder performance and emissions characteristics of Cummins HHP engines using different fuels: Diesel, HVO, and biodiesel blends (ranging from 20% to 100% volume of biodiesel with diesel). The project intends to conduct these comparisons without making any modifications to the engine or fuel. Additionally, the project aims to study the compatibility of Cummins engine components, such as fuel filters, with biodiesel blends and HVO. It also includes the simulation of in-cylinder performance using GT-Power software and the development of a predictive combustion model for various biodiesel blends.

Overall, the project seeks to assess the feasibility of using biodiesel and HVO in Cummins HHP engines, compare their performance and emissions characteristics, and understand the impact on engine components. It also aims to develop predictive models to aid in the optimization of engine performance with different biodiesel blends. Therefore, the following objectives were envisaged for the present research work.

2.12 OBJECTIVES

1. Comprehensive Literature Review
2. Selection of Cummins HHP, Multi-cylinder, Variable speed engine for study
3. Understand the Cummins’s stand on usage of Biodiesel and HVO in HHP Engines and compatibility of engine components like fuel filters with Bio-diesel blends & HVO

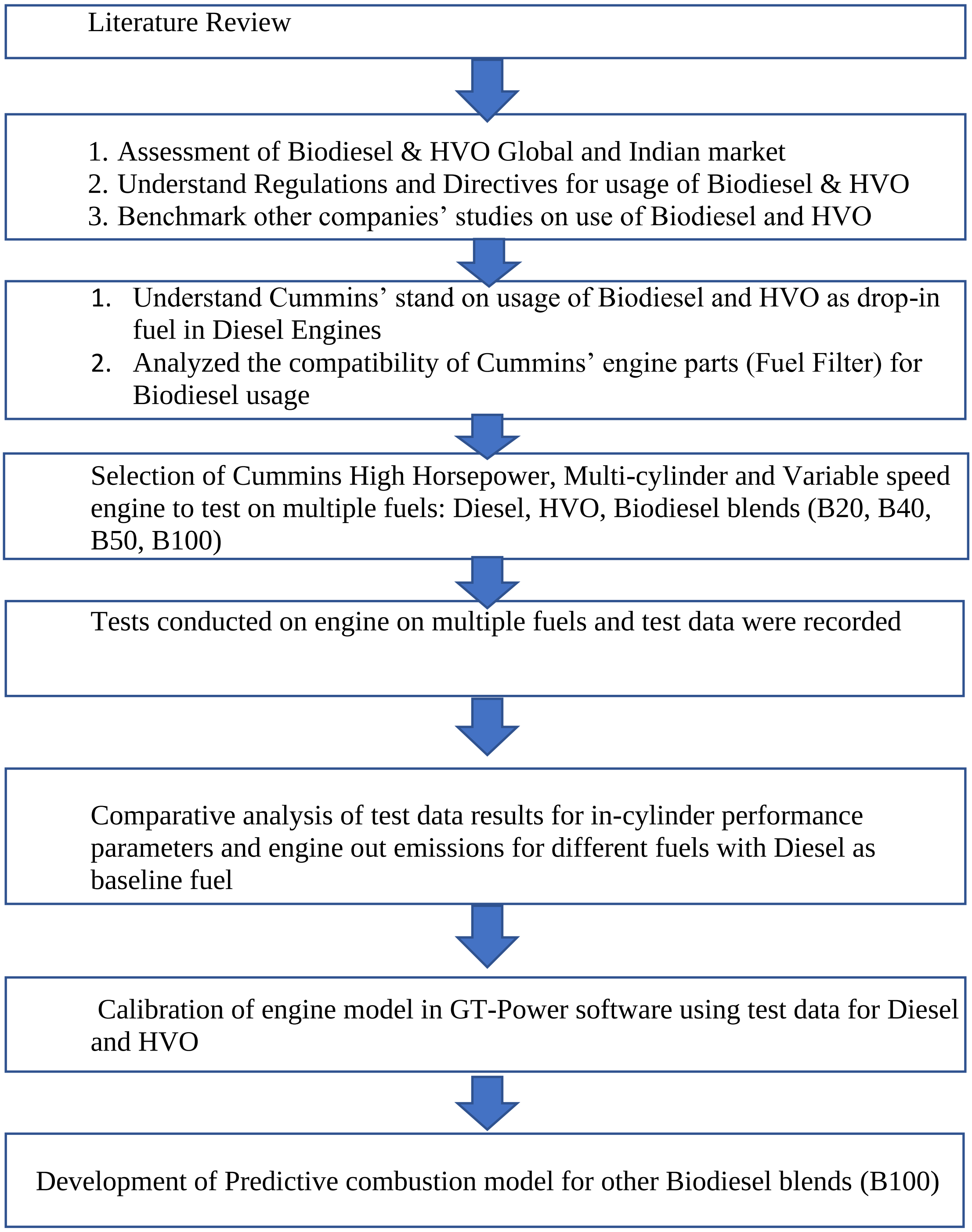
4. To check the feasibility of test methods to determine the quality of biodiesel blends used for Cummins approved engines on the fields
5. Analysis of test results of selected engine for different fuels
6. Calibration and simulation of the selected engine for Diesel and HVO
7. Comparison of the model results with the test data for Biodiesel blends to validate the predictive model

CHAPTER 3

METHODOLOGY AND SYSTEM DEVELOPMENT

3.1 INTRODUCTION

The following methodology was adopted for conducting the study on "Technical Feasibility Assessment for Usage of Bio-Diesel and HVO In Cummins High Horsepower Engines" with the systematic execution of the steps mentioned. Figure 3.1 gives a brief summary of the flowchart of the research.



Literature Review

1. Assessment of Biodiesel & HVO Global and Indian market
2. Understand Regulations and Directives for usage of Biodiesel & HVO
3. Benchmark other companies' studies on use of Biodiesel and HVO

1. Understand Cummins' stand on usage of Biodiesel and HVO as drop-in fuel in Diesel Engines
2. Analyzed the compatibility of Cummins' engine parts (Fuel Filter) for Biodiesel usage

Selection of Cummins High Horsepower, Multi-cylinder and Variable speed engine to test on multiple fuels: Diesel, HVO, Biodiesel blends (B20, B40, B50, B100)

Tests conducted on engine on multiple fuels and test data were recorded

Comparative analysis of test data results for in-cylinder performance parameters and engine out emissions for different fuels with Diesel as baseline fuel

Calibration of engine model in GT-Power software using test data for Diesel and HVO

Development of Predictive combustion model for other Biodiesel blends (B100)

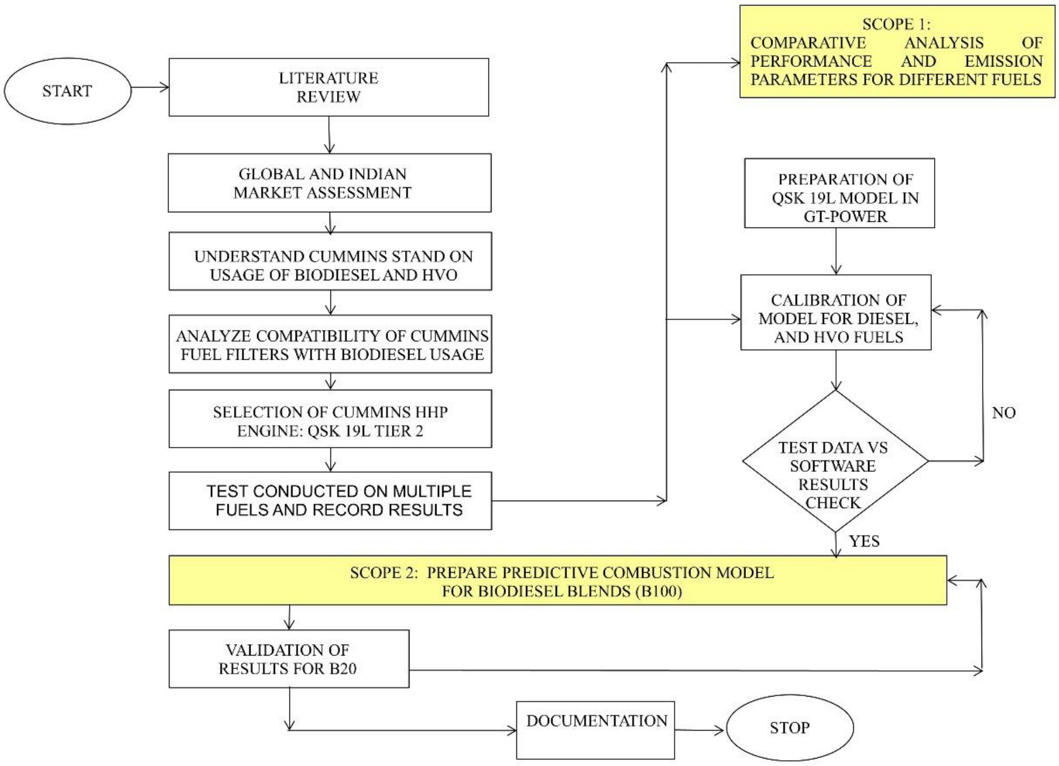


Figure 3.1: Flowchart of implemented steps in research work

3.2 BIODIESEL AND HVO

Biodiesel is a type of fuel made from vegetable oils, animal fats, and cooking oils, which undergo a process called transesterification to produce long chain fatty acid-based oxygenates in the form of methyl/ethyl esters. These fuels are commonly referred to as Fatty Acid Methyl Esters (FAME). Biodiesel shares properties like diesel fuel, as opposed to gasoline or gaseous fuels, and can therefore be utilized in compression ignition engines.

HVO, also known as Hydrotreated Vegetable Oil, is a type of renewable fuel derived from vegetable oil and animal fats. It is classified as a bio-based paraffinic diesel fuel. Unlike biodiesel, which is produced through an esterification process, HVO fuel is created through a hydrotreatment process. This distinction in production processes sets biodiesel and HVO fuel apart from each other.

Summary of Biodiesel and HVO is listed in Table 3.1.

Parameters	**Biodiesel (FAME)**	**Hydrotreated Vegetable Oil (HVO)**
Common Nomenclature	1. BD 2. Fatty Acid Methyl Esters (FAME) 3. Blends identified by Bxx (B20 is 20% biodiesel with 80% diesel)	1. HVO (hydrotreated vegetable oil) 2. Renewable Diesel (RD)
Fuel Standards	ASTM 6751 / EN14214 (B100) ASTM D7467 (B6-B20) IS 15607	EN 15940
Production Process	Esterification/ Transesterification	Hydrotreating/ Hydrogenation
Feedstocks	Soybean, palm, canola, rapeseed, biomass and others	Used cooking oil & tallow (animals fats), Soybean, palm, canola, rapeseed, biomass
Fuel Technical Properties (Performance & Emissions)	1. Generally, blend limited up to 10% less power output for B100 2. Lower smoke than diesel 3. Less than 1% aromatics 4. Good natural lubricity 5. Biodegradable & renewable	1. Chemically very similar to diesel 2. Approx. 1-2% less power output 3. Very low smoke & sulfur 4. Less than 1% aromatics 5. Reduced emissions: NOx, particulate matter and hydrocarbon 6. Requires lubricity additive to meet EN15940 7. Biodegradable & renewable
Handling & Storage	1. Unique storage & handling requirements due to stability & shelf-life limitations 2. Additional requirements in cold weather operation / higher cloud point than diesel	1. No infrastructure changes required 2. Cold weather capability to -40C

Table 3.1 Summary of Biodiesel and HVO

3.3 CUMMINS STAND ON USAGE OF BIODIESEL AND HVO

3.3.1 Biodiesel

1. Cummins only approves Biodiesel Blends up to B20 (B20 is 20% biodiesel with 80% diesel) as approved on March 21, 2007 (approvals limited to targeted engines) [26].
2. Cummins recommend strongly that to successfully use Biodiesel, the fuel should be of good quality and must adhere to the specifications and standards. All biodiesel fuel blends are to be comprised of petrol-diesel meeting ASTM D975, and B100 meeting either ASTM D6751 or EN14214.

3. For North American markets, Cummins Inc. recommends that the Biodiesel blend should be purchased and sourced from BQ 9000 certified Marketer and BQ 9000 accredited Producer respectively.

3.3.2 Technical challenges in usage of Biodiesel blends (higher than B5) in Cummins Engines

Sr.No.	Parameter	Observations	Cummins recommended actions [26]
1.	Material Compatibility	Metals: • Non - compatible with biodiesel B20 blend: Brass, Bronze, Copper, Lead, Tin, Zinc Non-Metals: • Non - compatible with biodiesel B20 blend: Natural rubber, butyl rubber, some types of nitrile rubber	Compatible with B20: Teflon (PTFE), Viton 401-C, Viton GFLT

2.	Fuel Storage	The poor oxidation stability qualities of biodiesel can accelerate fuel oxidation in the fuel system, especially at increased ambient temperatures	• Use biodiesel fuel within six months of its manufacture • Cummins Inc. does not recommend using biodiesel for low use applications, such as standby power or seasonal applications • Avoid storing equipment with biodiesel blends in the fuel system for more than three months, or fuel system damage can occur
3.	Fuel Filtration	• Emulsified water separation • Filter plugging	• Cummins filters with **Strata pore** media required for water separation • Filter inserts needs to be replaced twice at half of regular intervals
4.	Microbial Growth	Microbe and sludge formation in biodiesel results in premature filter choking	• Maximum storage period should be not more than 3 months • Storage tanks must be equipped with a fuel water separator • Vehicle and storage tanks are kept full to reduce the potential for condensation accumulating in the fuel tank
5.	Low Temperature Performance	Biodiesel fuel properties change at low ambient temperatures, which can pose problems for both storage and operation	• Store the fuel in a heated building or a heated storage tank or use cold temperature additives • The fuel system can require heated fuel lines, filters, and tanks

Table 3.2: Summary of usage of Biodiesel Blends (up to B20) in Cummins engines

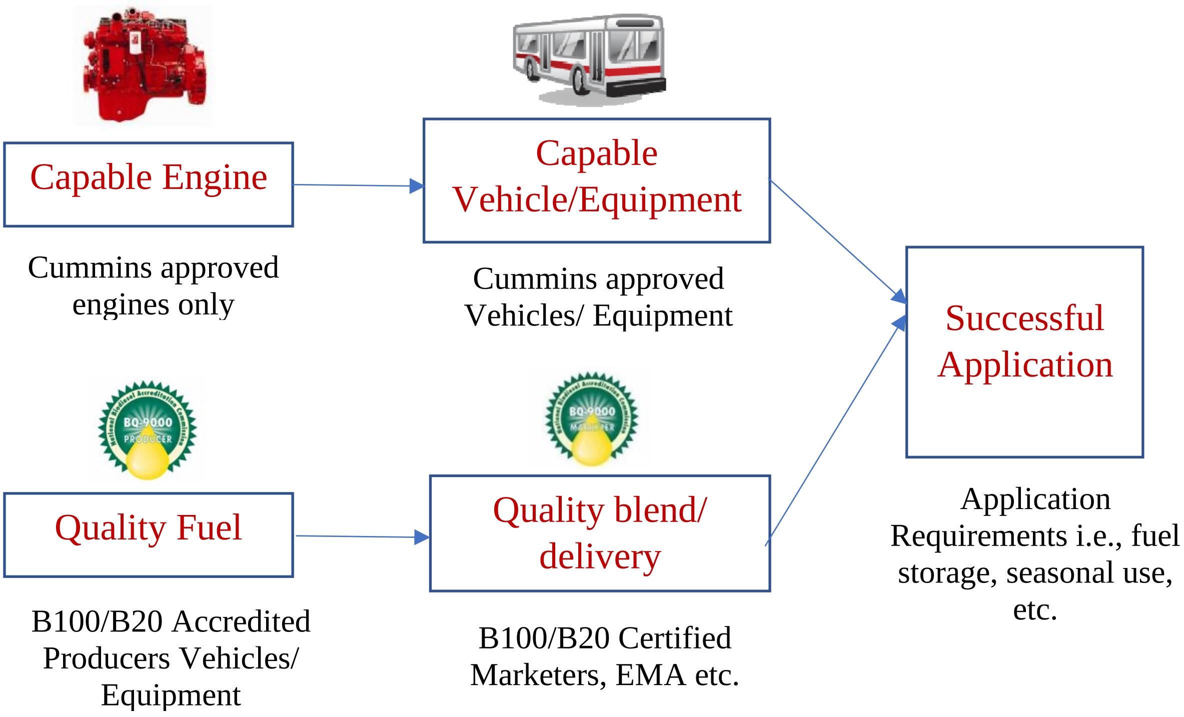


Figure 3.2: Key requirements for usage of Biodiesel blends in Cummins approved engines

3.3.3. Hydrotreated Vegetable Oil (HVO)

Cummins approves usage of Hydrotreated Vegetable Oil (HVO) in Cummins engines (approvals limited to targeted engines) [27] that meets EN15940 for all blends up to 100%. Summary of the observations by Hawes are tabulated in Table 3.3.

Sr.No.	Parameter	Observations
1.	Specifications	Cummins requires that HVO fuel complies with the requirements of EN15940
2.	Performance	1. 1-2% lower power with HVO fuel 2. 3-5% higher fuel consumption by volume with HVO fuel 3. No anticipated failures attributed to running the generator sets with HVO fuel
3.	Emissions	1. Lower smoke and particulate matter emissions with HVO fuel 2. Comparable NOx emissions

4.	Operation and Maintenance	1. Maintenance and storage recommendations are the same for diesel and HVO 2. HVO is a more stable fuel than biodiesel and is not susceptible to bacterial growth and oxidation stability concerns 3. Cummins neither approves nor disapproves of additives, however many diesel additives can be used with HVO

Table 3.3: Summary of usage of HVO in Cummins engines

3.4 COMPATIBILITY OF CUMMINS ENGINE PARTS WITH BIODIESEL BLENDS

3.4.1 Fuel Filters

Technical challenges of usage of Biodiesel on Fuel Filters:

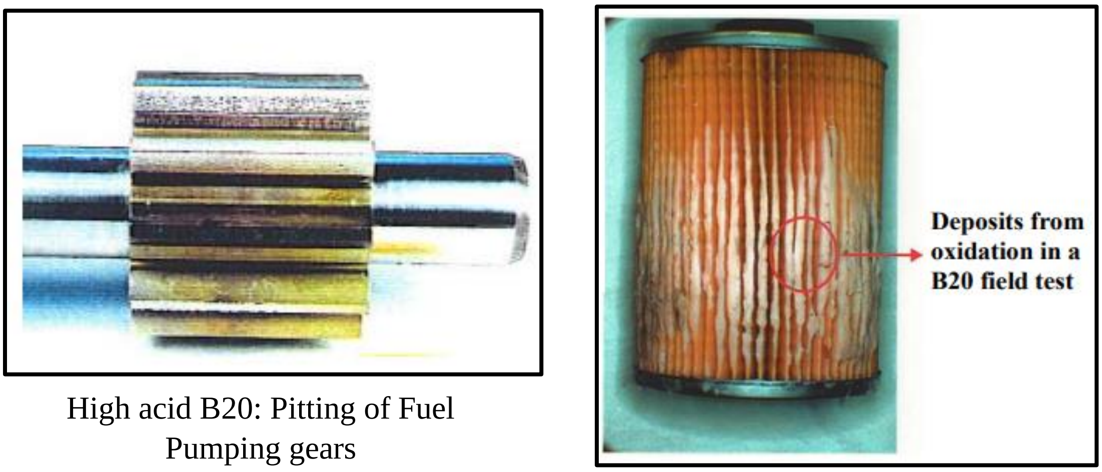
Biodiesel and bio-oil fuels have gained significant momentum, but they present some challenges that limit the successful application of Biodiesel blends. Fleetguard report on Fuel Filtration (2020) [28] lists some of the technical challenges:

1. Biodiesel exhibit a higher affinity for water, which poses challenges in water separation.

2. Biodiesel can promote the growth of microbes more aggressively, necessitating the use of secondary filtration systems to effectively safeguard modern HPCR (high-pressure common rail) systems

3. Biodiesel may encounter cold temperature-related issues earlier or at relatively higher temperatures compared to conventional diesel fuels

Filter Manufacturers Community report on “The effect of Biodiesel on Fuel Filters” [29] states that Biodiesel possesses solvent properties and can function as a solvent within the fuel. Blends containing more than 20% biodiesel (B20) may exhibit a solvent effect that can dissolve varnish deposits present on the surfaces of fuel storage tanks or fuel systems. As a result, these dissolved varnish deposits can contaminate the fuel with particulate matter, leading to a rapid clogging of fuel filters.



High acid B20: Pitting of Fuel Pumping gears

Figure 3.3: Fuel Filter defects on usage of Biodiesel blends
(Source: Purdue University Road Show, Biodiesel Update [28])

Cummins Recommended Fuel Filters:

Cummins recommend the usage of StrataPore media in Fuel Filters in place of cellulose filters for engines running on Biodiesel blends. The StrataPore synthetic media offers superior performance and extended lifespan compared to traditional cellulose or micro glass media. It achieves this by precisely targeting the desired level of particle removal. StrataPore’ s unique ability to optimize each layer of the media according to the specific particle size requirements makes it highly effective, especially in environments where prolonged service is required. Figure 3.4 and Figure 3.5 show that StrataPore media fuel filters have better fuel/water separation efficiency and three times longer life *(Source: https://www.cumminsfiltration.com/sites/default/files/LT32555_1.pdf).* Benefits of using StrataPore media fuel filters for engines running on Biodiesel blends are:

1. Sustains optimal fuel/water separation efficiency
2. Facilitates extended service intervals
3. Enhanced efficiency and extended lifespan
4. Unparalleled fuel/water separation capability
5. Exceptional strength and durability

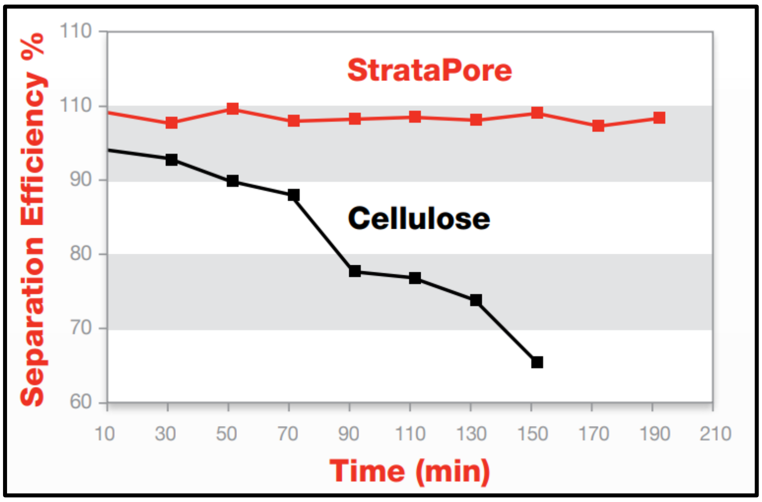


Figure 3.4: Fuel/water separation efficiency of StrataPore vs Cellulose media

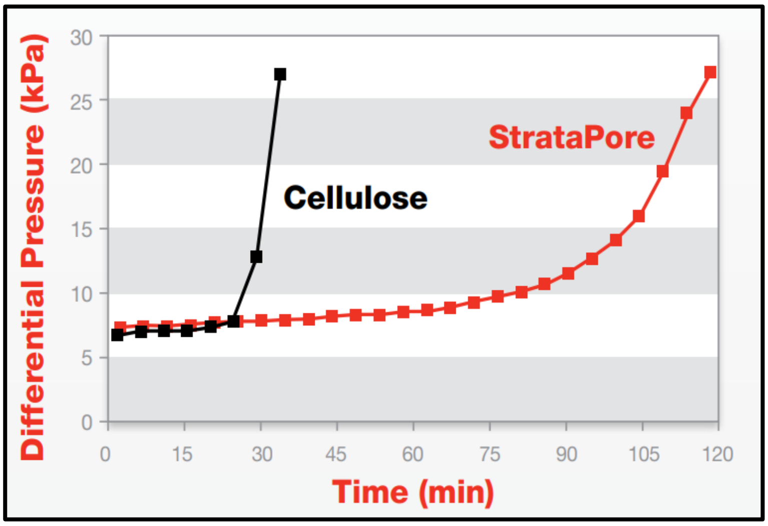


Figure 3.5: Contamination holding capacity of StrataPore vs Cellulose media

3.4.2 Fuel lines and Gaskets:

Zack Ellison report [28] recommended not to use metals like brass, bronze, zinc, lead or tin for storage tanks material or fuel lines as they accelerate the oxidation of Biodiesel.

Furthermore, avoid using natural, nitrile or butyl rubber fuel lines and gaskets as these materials are not compatible with Biodiesel and degrades over time causing leakage.

Filter Manufacturers Community report on “The effect of Biodiesel on Fuel Filters” [29] suggests that filters utilized in specific applications involving high blends of biodiesel, particularly those approaching B100 or unblended B100, should incorporate sealing materials or gaskets that are resistant to solvents. Continued usage of standard sealing materials commonly found in most used fuel filters may lead to the deterioration or swelling of the material, potentially resulting in leaks.

3.5 FEASIBILITY STUDY OF BIODIESEL FIELD TESTS

Objective:

To check the feasibility of test methods to determine the quality of biodiesel blends used for Cummins approved engines on the fields

Purpose:

To determine the quality of biodiesel and its usage in the fields to do potential ok/not-ok check. Following parameters are crutial for checking the quality of biodiesel:

Sr.no	Parameter	Unit	Test Method	Remarks
1.	Water content	%	ASTM D 6304	Test detects water content above 100 ppm
2.	Acid value	mg KOH/g	ASTM D 664	
3.	FAME content	%V/V	EN 14103	
4.	Oxidation Stability	Hours	EN 15751	Time required is 16 hours and the apparatus used is complex

Table 3.4: List of Critical parameters for checking the quality of Biodiesel in fields

Observation:

1. Acid number, oxidation stability and water content are usually affected upon storage for long durations
2. First test the biodiesel sample with a quick inexpensive methanol (27/3) test. If it fails, there is no need to further pursue the other tests since it is most likely poor quality
3. The test for water content, FAME content and acid number can be carried on fields using simple apparatus and chemicals or kits

4. Water content kit: 100-200 ppm water will give you pink spots in the white powder. More than 200 ppm water will turn all the powder hot pink. Acceptable limit of water content (ASTM D6751) is 500 ppm for B100 and 260 ppm for B6-B20 blend (EN16709)
5. Oxidation stability test on field is not feasible as it needs 16 hours for performing the test and requires complex apparatus

3.5.1 Biodiesel Field Test apparatus for critical parameters

Parameters	**Apparatus**	**Time required (min)**
Water content	Fuel test W-5 (Dieselcraft Fluid engineering)	5
Acid value	Stirrer, 250 ml beaker, mass scale, titration bulb	20
Methane Testing	Beaker, syringe.	35-40
FAME content	FAME check kit (Dexsil)	30
Oxidation stability	Heating source, conductivity meter, test tube, air tubes, air pump and small flask	16 hrs

Table 3.5: Biodiesel fiels test appartatus

The feasibility study of the above mentioned Biodiesel quality check apparatus was conducted based on three criteria: Feasibility to test on fields, ease of operation and cost feasibility. The observations are summarized below.

Parameter	**Field Test Method**	**Feasibility to test on fields**	**Ease of operation**	**Cost feasibility**
Water content (%)	Fuel test W-5 (Dieselcraft Fluid engineering)	Yes	Yes	Rs. 3676 (5 tests per kit)
Acid value (mg KOH/g)	Acid value test	Yes	No	
FAME content	FAME check kit	Yes	Yes	Rs. 1200 (1 test per

(%v/v)	(Dexsil)			kit)
Oxidation Stability (hours)	Rancimat test	No	No	

Table 3.6: Feasibility to check the quality of Biodiesel in fields

Observation:

Acid value & Oxidation stability: It is cheaper to do a professional analysis (lab tests) for less frequency of testing. However, for a regular testing with investment in equipment & apparatus, it is cheaper to conduct field experiments than to do a professional analysis

3.6 ENGINE SELECTION

Cummins diesel engine model which is a 6-cylinder inline engine with a 19-liter displacement was selected for the present research work, which is primarily used for industrial applications as shown in Figure 3.6.

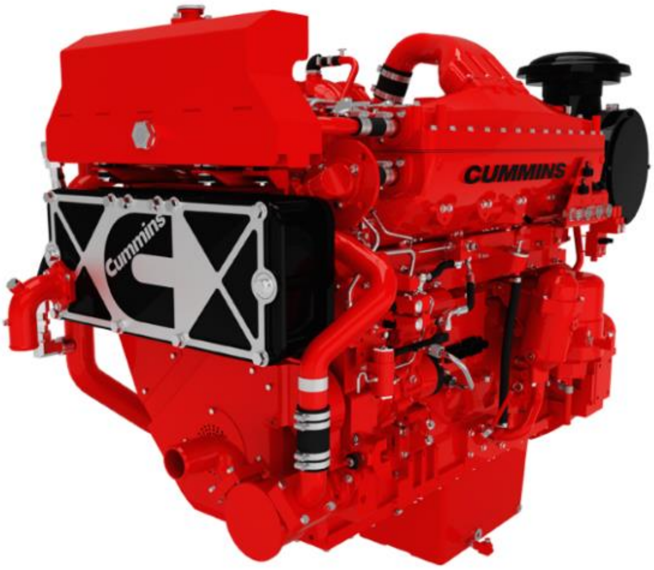


Figure 3.6: Cummins Engine model

It is a six- cylinder, turbocharged charged- air cooled, four stroke with a displacement of 19-liter and U.S EPA Tier 2 compliant engine. This engine utilizes modern electronics and premium engineering to provide superior performance levels, reliability and versatility for Standby, Prime and Continuous Power applications. Outstanding performance, efficiency, and diagnostics are provided by the high-pressure fuel pump, Modular Common Rail Fuel System (MCRS), and integrated electronic control system. The electronic fuel pumps eliminate the need for mechanical linkage modifications and provide up to 1600 bar injection pressure. Selected engine requires the use of Charge-Air-Cooler (CAC) to reduce the IMT (Intake Manifold Temperature) and to comply with the lower emissions requirements. The cylinder block is made up cast iron with ferrous cast ductile iron (FCD) pistons to ensure superior durability and reliability. Fuel filters used in the engine are spin-on with water separator. The rated power of this engine is 567 kW at 2100 rpm and peak torque obtained is 2275 lb-ft at 1500 rpm.

The detailed technical specifications of the engine are given in Table 3.4.

Make	Cummins
Application	Industrial
Emission certification	U.S E.P.A. Tier 2
Rated speed (rpm)	2100
Peak Torque (lb-ft)	2275 at 1500 rpm
Number of Cylinders	6 (inline)
Bore x Stroke (mm x mm)	158.75 x 158.75
Compression ratio	15.0:1
Cooling system	Turbo-charged charged air cooled (CAC)
Displacement (capacity, in liter)	19
Fuel System	Cummins MCRS
Fuel filters	Spin-on fuel filters with water separator

Table 3.7: Specifications of selected engine model

For conducting the desired set of experiments for the comparative analysis of in-cylinder performance and emissions parameters for different fuels: Diesel, HVO, Biodiesel blends (B20, B40, B50 & B100), the same diesel engine was used without any engine architecture modifications. The engine was tested at Cummins Seymour Engine Plant (SEP) test cell. The schematic representation of the test cell is illustrated in Figure 3.7

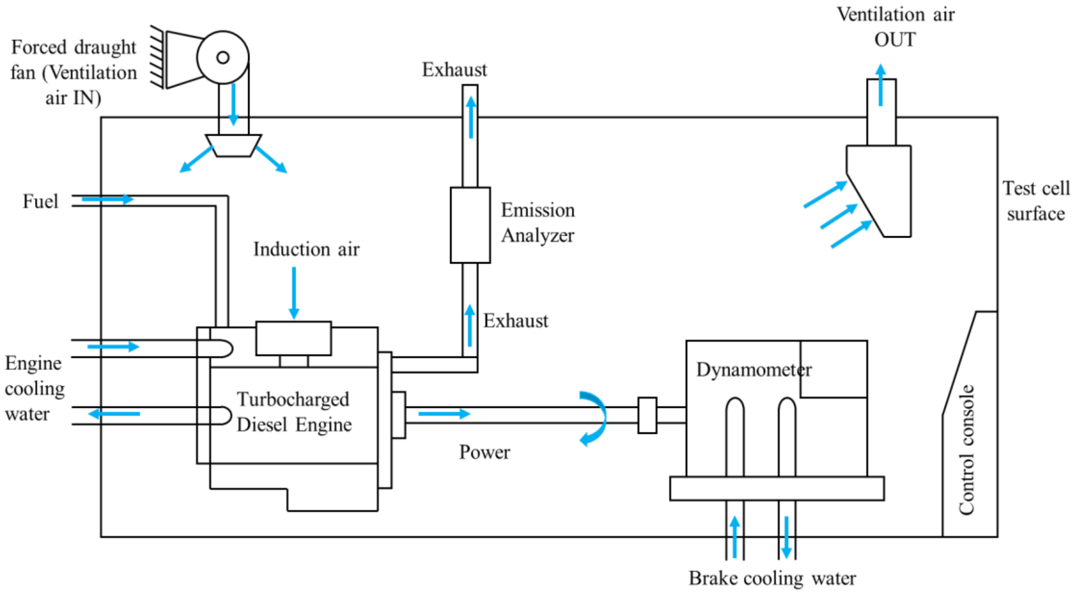


Figure 3.7: Schematic Diagram of Test cell

3.7 FUELS USED IN THE EXPERIMENT

To conduct the comparative analysis of the engine out parameters, different fuels were experimented on the engine model without any engine modifications. Diesel was taken as the baseline fuel and the engine was run on six different fuels.

1. Diesel (Baseline Fuel) (B0)
2. Hydrotreated Vegetable Oil (HVO)
3. Biodiesel blends

- B20 (B20 is 20% biodiesel with 80% diesel)
- B40 (B40 is 40% biodiesel with 60% diesel)
- B50 (B50is 50% biodiesel with 50% diesel)
- B100 (B100 is pure Biodiesel)

3.7.1 Physico-chemical properties of the fuels tested

Property	Diesel	HVO	B20	B40	B50	B100
Density (kg/m^3)	841.30	781.10	848.80	857.10	861.80	881.10
Water content (ppm)	20	37	66	87	118	201

Cetane Index	47.64	96.162	47.84	49.21	49.98	60.94
Low Heat Value (LCV) (MJ/kg)	45.00	44.59	42.75	41.17	39.6	36.82
Net Energy Content (MJ/kg)	42.81	43.79	41.63	40.58	40.20	37.37
Heating Value (MJ/liter)	36.01	34.42	35.33	34.78	34.64	32.926
Carbon Fraction (%)	83.86	-	82.91	81.07	79.54	75.87
Hydrogen Fraction (%)	14.14	-	12.57	12.29	12.18	11.87
Oxygen Fraction (%)	0	-	4.52	6.64	8.28	12.26
Boiling Point (°C)	332-667	396-600	356-652	368-656	375-658	521-664
Viscosity (cSt @40°C)	2.38	2.99	2.49	2.80	3.02	3.90
Sulphur content (mg/kg)	12	0.7	12	8.7	7.4	2

Table 3.8: Physico-chemical properties of the fuels tested

3.7.2 Tests Performed

The following steady-state tests were performed on the engine with multiple fuels:

1. Torque Curve
2. 8 mode analysis: 8 mode analysis was done according to 1SO 8178 Test cycles (Type C1)

Mode	1	2	3	4	5	6	7	8
Torque (%)	100	75	50	10	100	75	50	0
Speed (rpm)	Rated Speed				Intermediate Speed			Low Idle
Weightage	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

Table 3.9: ISO 8178 Test cycle (Type C1) weightage factor

3.8 PARAMETERS SELECTION

The main performance parameters desired from the selected engine are listed below:

1. Power produced
2. Brake specific fuel consumption
3. Brake thermal efficiency
4. Fuel consumption
5. Peak Cylinder Pressure

The main emission parameters desired from the selected engine are listed below:

Emissions	Limit (Tier 2 CFR 40)
Brake specific Nitrogen Oxide+ Brake specific Hydrocarbons	4.7 g/(hp-hr)
Brake specific Carbon Monoxide	2.6 g/(hp-hr)
Brake specific Particulate Matter	0.15 g/(hp-hr)

3.9 GT-POWER SIMULATION

GT-Power is a widely used engine performance simulation software developed by Gamma Technologies. It allows to model and simulate various aspects of internal combustion engines and their associated systems. Here's an overview of how simulation is conducted in GT-Power:

1. Component Modeling: GT-Power provides a comprehensive library of pre-defined components such as intake and exhaust systems, combustion chambers, pistons, valves, turbochargers, and fuel injection systems.

2. System Assembly: Once the components are selected, they can be assembled to create a complete engine or powertrain system. The software allows to define the system layout, including the arrangement of cylinders, intake and exhaust manifolds, and other connecting components.

3. Boundary Conditions: To accurately simulate the engine behavior, boundary conditions need to be defined. This includes specifying the operating conditions such as engine speed, load, ambient temperature, pressure, and other relevant parameters.

4. Solver Setup: GT-Power utilizes a solver algorithm to calculate the engine performance based on the defined model and boundary conditions. Users can configure the solver settings, such as the simulation time step, convergence criteria, and other numerical parameters.

5. Simulation Execution: Once the model, boundary conditions, and solver settings are established, the simulation can be executed. GT-Power performs a series of calculations based on the model equations and iteratively solves them to predict the engine's behavior.

6. Results Analysis: After the simulation is completed, GT-Power provides various tools and graphical outputs to analyze the results. It can examine performance parameters like engine power, torque, emissions, temperatures, pressures, and other relevant variables. These results help in evaluating the engine's performance and identifying areas for improvement.

7. Model Calibration and Validation: To improve the accuracy of the simulation, GT-Power allows to calibrate and validate the model against experimental data. This involves adjusting certain model parameters to match the simulation results with the measured data.

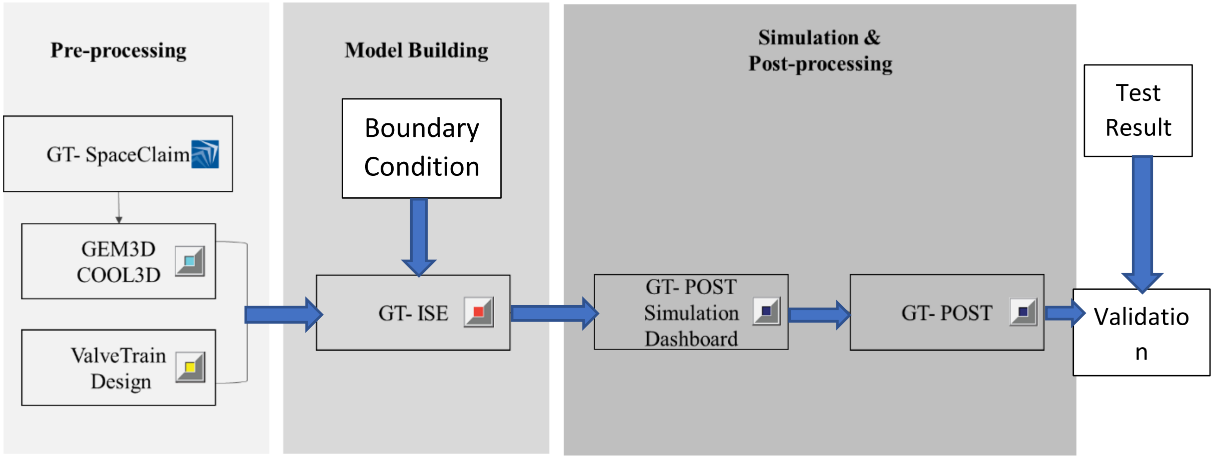


Figure 3.8: Flowchart of GT-Power simulation work

3.10 OBJECTIVE

The aim of this section is to calibrate a combustion model for a Diesel engine in GT-Power software with an objective to develop a predictive combustion model for different Biodiesel blends which should be able to predict the in-cylinder performance parameters within the suggested error band.

3.11 GT-POWER COMBUSTION MODELS

GT-Power has different types of combustion models [30]:

1. Non-Predictive combustion model: The Non-predictive combustion model imposes a predetermined burn rate that is not influenced by the conditions inside the combustion chamber. This model is employed to describe combustion and emission-related parameters without considering the in-cylinder conditions. One significant advantage of this model is its ability to provide rapid simulation results, making it suitable for evaluating concepts that do not affect the burn rate characteristics.

2. **Predictive combustion model**: In a predictive combustion model, the burn rate is dynamically computed for each cycle, considering the specific conditions inside the combustion chamber. Unlike the non-predictive model, this approach requires more time for simulation. To ensure accurate predictions, it is essential to calibrate the model initially using experimental test data. By calibrating the model, it can be fine-

tuned to match the observed behavior and provide reliable predictions for future cases.

3. DI-Pulse Combustion model: It is a multi-zone combustion model to accurately forecast the in-cylinder combustion and associated emission parameters for direct injection Diesel engines with single or multi-pulse injections. The model operates by predicting the combustion rate using factors such as pressure and temperature profiles, mixture composition at intake valve closure (IVC), and injection rate profile. Additionally, four calibration parameters/multipliers are used to calibrate the model: Entrainment, Ignition delay, premixed combustion rate and diffusion combustion rate multipliers.

3.12 ANALYSIS OF ENGINE BURN RATE

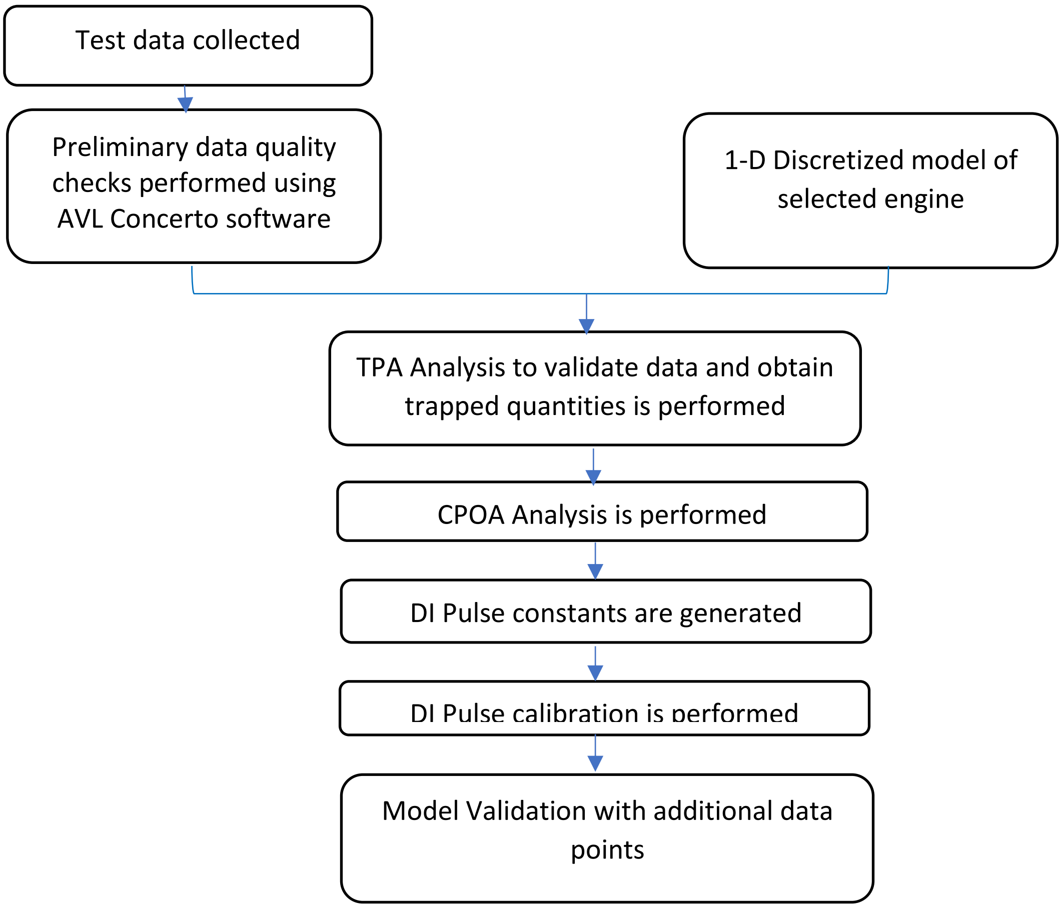
In GT-Power, the burn rate is determined by the quantity of mixture transferred from the unburnt zone to the burnt zone within the combustion chamber. This transfer can be calculated based on the cylinder pressure. In GT-Power by knowing the cylinder pressure, the burn rate can be calculated and vice versa. It uses a ‘reverse run’ simulation to estimate the burn rate from the cylinder pressure and a ‘forward run’ simulation where the cylinder pressure is estimated based on the burn rate. (GT-Suite, 2021).

There are two types of Burn Rate Analysis:

Three Pressure Analysis (TPA)	**Cylinder Pressure Only Analysis (CPOA)**
Burn Rate is derived based on three measured pressures namely intake, exhaust and cylinder pressure for an operating condition	Burn rate for an operating condition is estimated based on the measured cylinder pressure only
Initial values of volumetric efficiency, trapping ratio and residuals quantities are predicted based on the measured port pressure and average temperature imposed in the end environment	Initial values of volumetric efficiency, trapping ratio and residuals quantities must be provided as an input

3.13 METHODOLOGY

The following process is followed for the calibration of DI Pulse model [30]:



3.14 GT-POWER MODEL

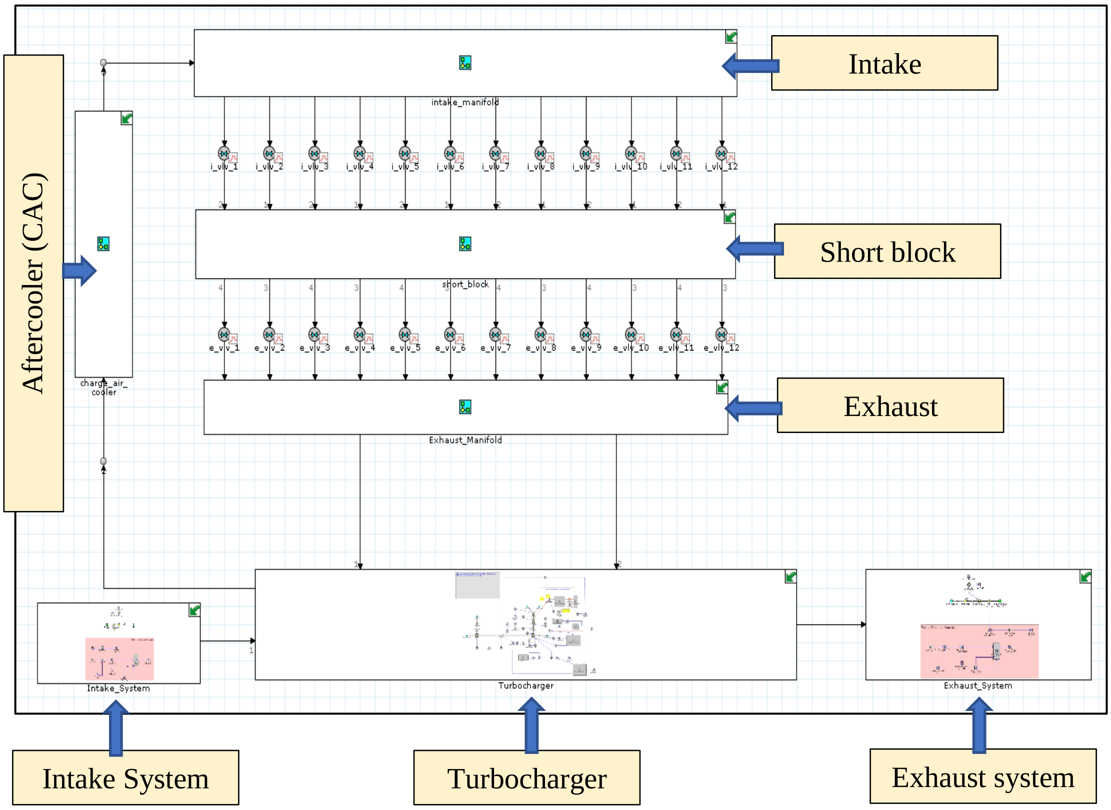


Figure 3.9: 1D-Discretized model of selected engine in GT-Power

CHAPTER 4

RESULTS AND DISCUSSION

The present study was conducted on Diesel engine which was run on multiple fuels without any engine modifications. The scopes of this research work were defined as:

1. To analyze the test data for comparative analysis of multiple fuels for in-cylinder performance parameters and engine out emissions with baseline test data of Diesel

2. To calibrate the Diesel engine model in GT-Power software with the test data with an objective to develop a predictive combustion model for different biodiesel blends

4.1 COMPARISON OF PHYSICO-CHEMICAL PROPERTIES

The different fuels (Diesel, HVO & Biodiesel blends) were collected from the supplier and the Physico-chemical properties were tested in Cummins Chemistry Labs and external facility the test reports were recorded and analyzed. Summary of the Physico-chemical properties of fuels are listed in Table 4.1.

Property	**Diesel**	**HVO**	**B20**	**B40**	**B50**	**B100**
Density (kg/m^3)	841.30	781.10	848.80	857.10	861.80	881.10
Water content (ppm)	20	37	66	87	118	201
Cetane Index	47.64	96.162	47.84	49.21	49.98	60.94
Low Heat Value (LCV) (MJ/kg) (Estimated)*	45.00	44.59	42.75	41.17	39.6	36.82
Net Energy Content (MJ/kg) (Measured)**	42.81	43.79	41.63	40.58	40.20	37.37
Heating Value (MJ/liter)	36.01	34.42	35.33	34.78	34.64	32.926
Carbon Fraction (%)	83.86	-	82.91	81.07	79.54	75.87

Hydrogen Fraction (%)	14.14	-	12.57	12.29	12.18	11.87
Oxygen Fraction (%)	0	-	4.52	6.64	8.28	12.26
Boiling Point (^{o}C)	332-667	396-600	356-652	368-656	375-658	521-664
Viscosity (cSt @40^{o}C)	2.38	2.99	2.49	2.80	3.02	3.90
Sulphur content (mg/kg)	12	0.7	12	8.7	7.4	2

Table 4.1: Test report of Physico-chemical properties of the fuels tested on engine

* Lower Heating Value (Estimated) is taken from the literature

** Net Energy Content (Measured) is the actual value obtained from test lab and has been used for the calculations of the test results in this research

4.1.1 Key Insights for Biodiesel and HVO

The comparison of the major Physico-chemical properties Biodiesel (B100) and HVO with those of Diesel are summarized in the Table 4.2

Parameter	Biodiesel (B100)	HVO
Density (kg/m^3)	4.73% Increase	7.15% Decrease
Energy content per unit mass (MJ/kg)	12.70% Decrease	2.28% Increase
Energy content per unit volume (MJ/l)	8.56% Decrease	4.41% Decrease
Viscosity (cSt @40^{o}C)	63.86% Increase	25.63% Increase
Sulphur content (mg/kg)	Less than diesel	Less than diesel

Table 4.2: Comparison of Physico-chemical properties Biodiesel (B100) and HVO

1. Biodiesel is 4.73% dense whereas the density of HVO is 7% lesser than Diesel
2. HVO has 2.28% higher energy content per unit mass and 4.73% lower energy content by volume
3. Biodiesel has 12.7% lower net energy content than Diesel
3. Cetane number and cetane index are higher for both Biodiesel and HVO
4. Sulphur content is significantly lower in HVO and Biodiesel blends
5. HVO and Biodiesel blends are more viscous than Diesel

4.2 COMPARATIVE ANALYSIS OF PERFORMANCE PARAMETERS

1. TORQUE:

Figure 4.1 shows the torque curves of the test engine run on different fuels when operating under the same combustion conditions and 100% throttles. The torque decreases with increase in the blend percentage of Biodiesel attributed to the lower heating value of blends when compared to diesel. The torque values of HVO are similar to that of Diesel. The peak torque for different fuels is obtained at 1500 rpm.

When running the test engine with different fuels and same combustion inputs, the drop of 1.03% in peak torque at 1500 rpm was observed for HVO and a significant reduction of 10.9% in peak torque for Biodiesel (B100). The peak torque measured decreases with blend concentration by 4%, 5.2% and 5.5% for B20, B40 and B50 respectively. The difference in the torque values is more at intermediate speeds as compared to higher speeds due to better fuel mixing at higher swirl of air produced by the engine at high speed [32].

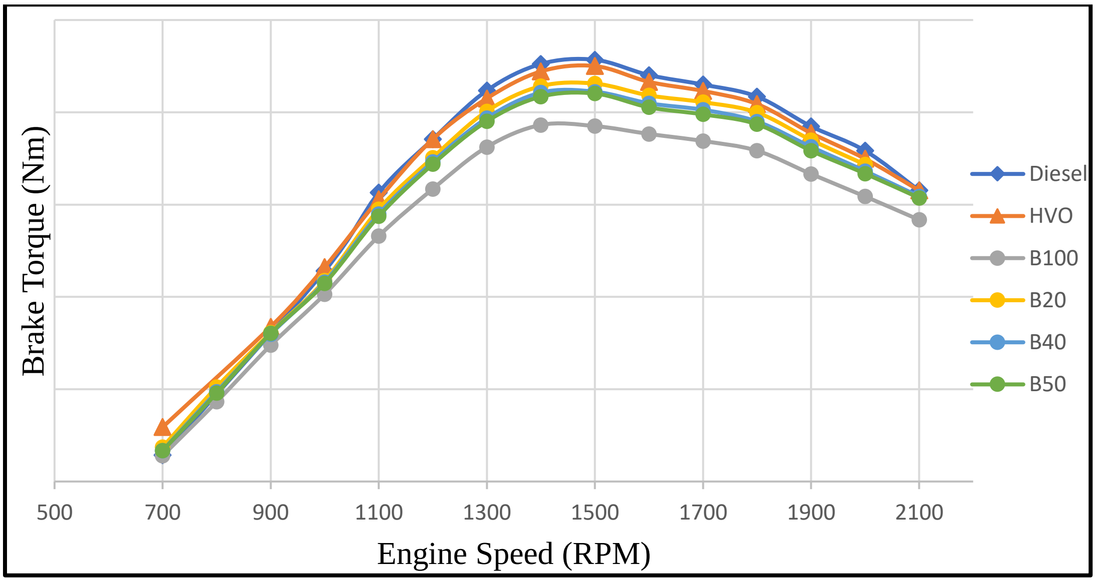


Figure 4.1: Torque curves of different fuels run on test engine

2. POWER:

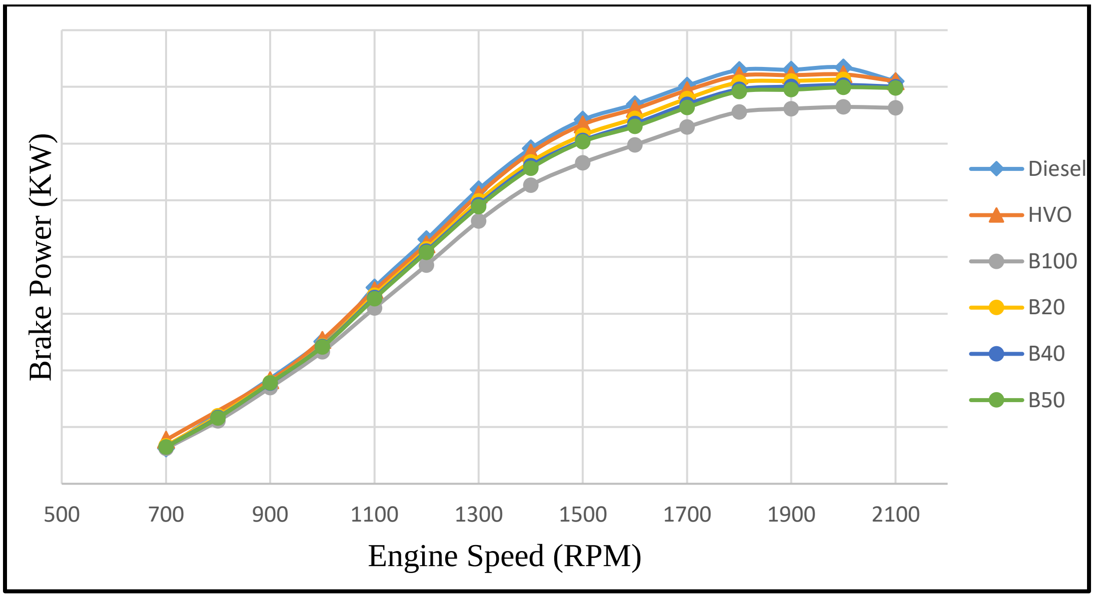


Figure 4.2: Power curves of different fuels run on test engine

Figure 4.2 shows the variation of brake power for different fuels with engine speed when operating under the same combustion conditions and 100% throttles. The brake power and brake torque follow the similar trend of decreases as the blend percentage of Biodiesel increases due to reduced heating value of blends when compared to diesel. The maximum power is attained at the rated speed of 2100 rpm for all fuels. With Biodiesel (B100), maximum power drop of 9% was observed when compared with Diesel. However, HVO shows a slight decrease of 1.1% with similar combustion inputs.

The various engine performance parameters could be compared for multiple fuels with baseline fuel for the same engine speed and brake torque provided. But, for various fuels, different torque values at same combustion conditions and 100% throttle value were obtained due to variation in heating value of the fuels. Therefore, method of normalization of brake power and BMEP (Brake Mean Effective Pressure) were considered for the comparative analysis of various fuels. The varying torque values of Diesel, HVO and Biodiesel (B100) were normalized with respect to the minimum brake power/BMEP amongst the three fuels.

1. Brake Mean Effective Pressure: It is a measurement used to evaluate the average pressure exerted on the piston during the power stroke of an internal combustion engine.
The formula for BMEP is as follows:

BMEP = (2 * π * Torque) / (Displacement * Number of Cylinders)

2. Brake power: It is the amount of power that an engine produces and delivers to its output shaft. It represents the actual power available for doing useful work, such as propelling a vehicle or operating machinery. Brake power is typically measured in units of horsepower (hp) or kilowatts (kW). Brake power can be calculated using the following formula:

Brake Power = (2 * π * Torque * Engine Speed (in rpm))/60

4.2.1 Fuel Consumption

Figure 4. shows that the mass fuel consumption tends to increase with the increase in brake power for the fuels tested on the engine. The mass fuel consumption (kg/hr) of Biodiesel (B100) is higher than Diesel and HVO attributed to the high density and low calorific value of Biodiesel. Biodiesel (B100) is 5% more dense than Diesel fuel and this reduction was clearly seen with 6% increase in fuel consumption at rated speed. Similarly, HVO is 7% less dense than Diesel which accounts for 3% less fuel consumption when compared to Diesel at 2100 rpm.
It is also evident from the graph that the Biodiesel with same commanded fueling cannot produce same power as that of Diesel due to its lower calorific value.

BSFC quantifies the amount of fuel consumed by an engine to produce a unit of power. BSFC is typically expressed in units of fuel consumption per unit of power, such as grams per kilowatt-hour (g/kWh) or pounds per horsepower-hour (lb/hp-hr).
BSFC can be calculated using the following formula:

BSFC = Fuel Flow Rate / Brake Power

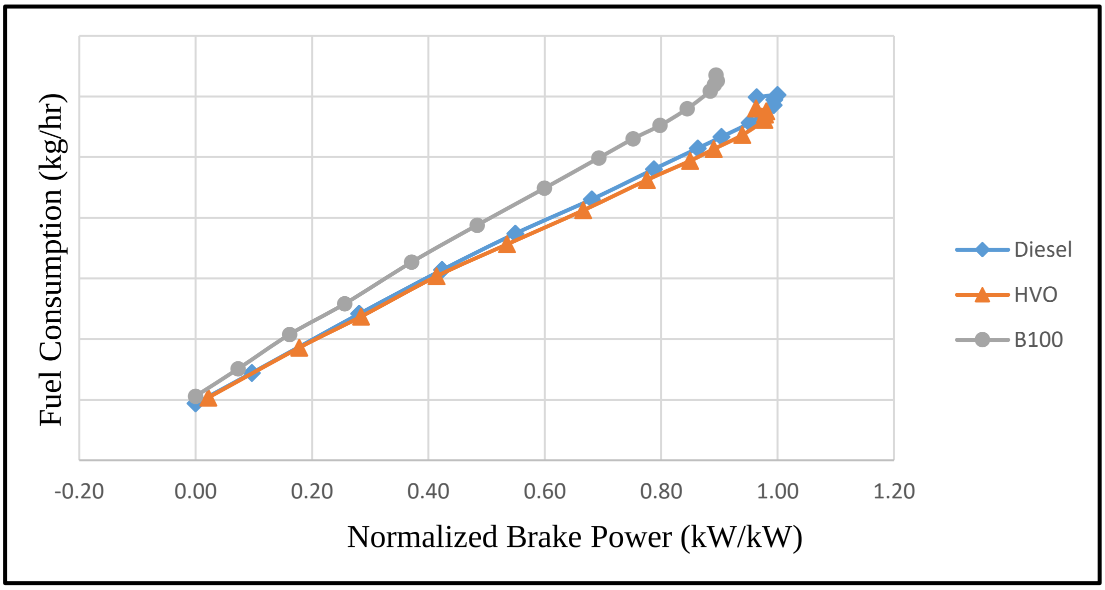


Figure 4.3: Fuel Consumption vs Normalized Brake Power

4.2.2. Brake Thermal Efficiency

The variation of brake thermal efficiency of the engine with multiple fuels is shown in Figure 4. From the test results obtained it was observed that with increase in brake power, the BTE of all the fuels increased initially and then it tends to reduce with further increase in brake power. The BTE of Biodiesel were found to be lower by 12% than that of Diesel due to the possible reasons of higher density and lower calorific value of the fuel.

HVO shows higher BTE by 3% throughout the power curve due to higher measured net energy content of HVO.

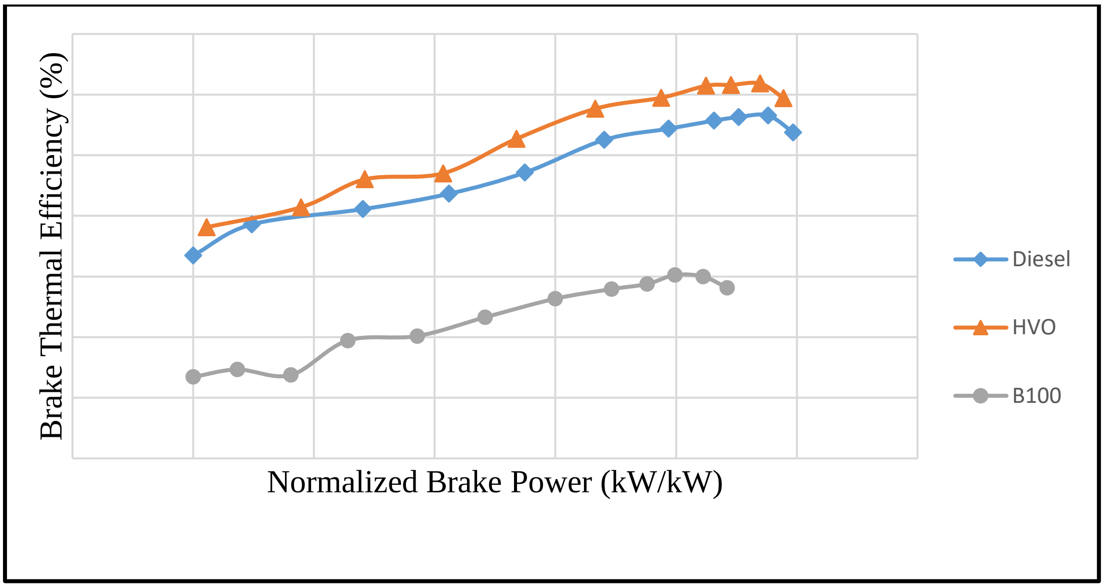


Figure 4.4: Brake Thermal Efficiency vs Normalized Brake Power

4.2.3 Exhaust Gas Temperature

The variation of Exhaust Gas Temperature (EGT) of multiple fuels is shown in Figure 4. From the test results obtained it was observed that with increase in BMEP, the EGT of all the fuels increased. The EGT of Biodiesel were found to be higher by an average of 15% whereas HVO shows higher EGT than baseline fuel by 2%.

The elevated exhaust temperature observed suggests that the engine has a lower thermal efficiency. A decrease in thermal efficiency means that a smaller portion of the energy provided by the fuel is transformed into useful work, consequently leading to higher exhaust temperatures.

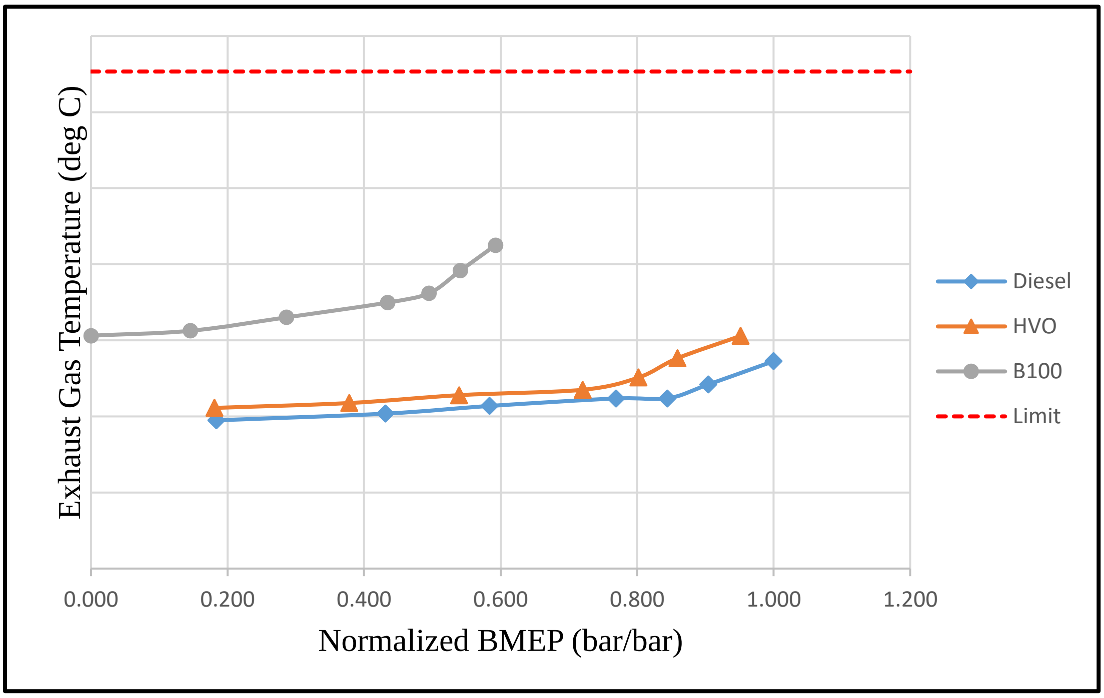


Figure 4.5: Exhaust Gas Temperature vs Normalized BMEP

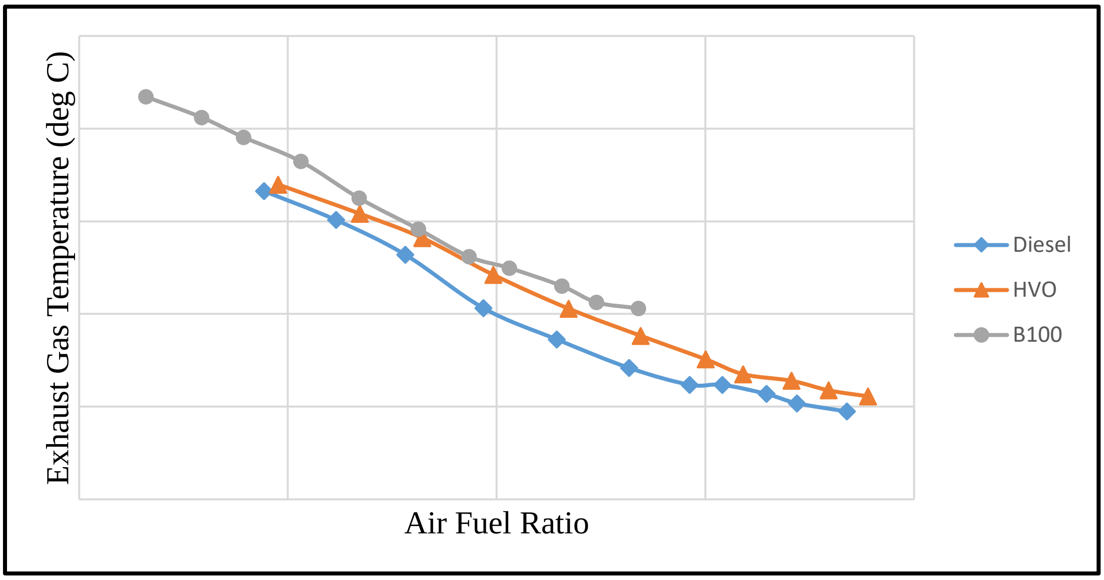


Figure 4.6: Exhaust Gas Temperature vs Air Fuel Ratio

4.2.4 Other Performance Parameters

1. Peak Cylinder Pressure

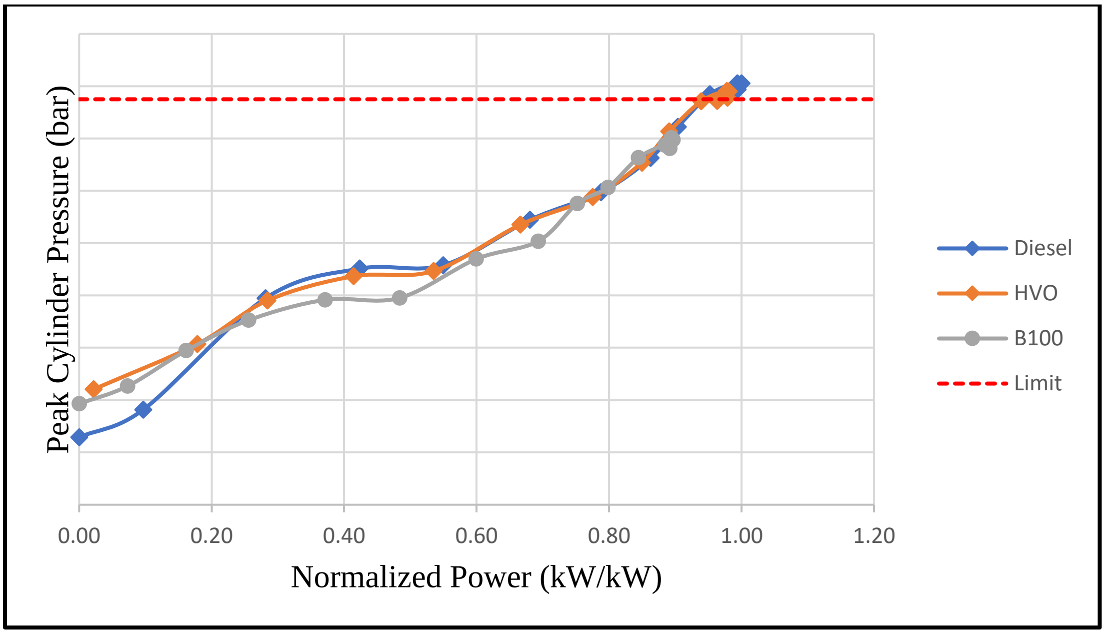


Figure 4.7: Peak Cylinder Pressure vs Normalized Power

2. Compressor Out Temperature

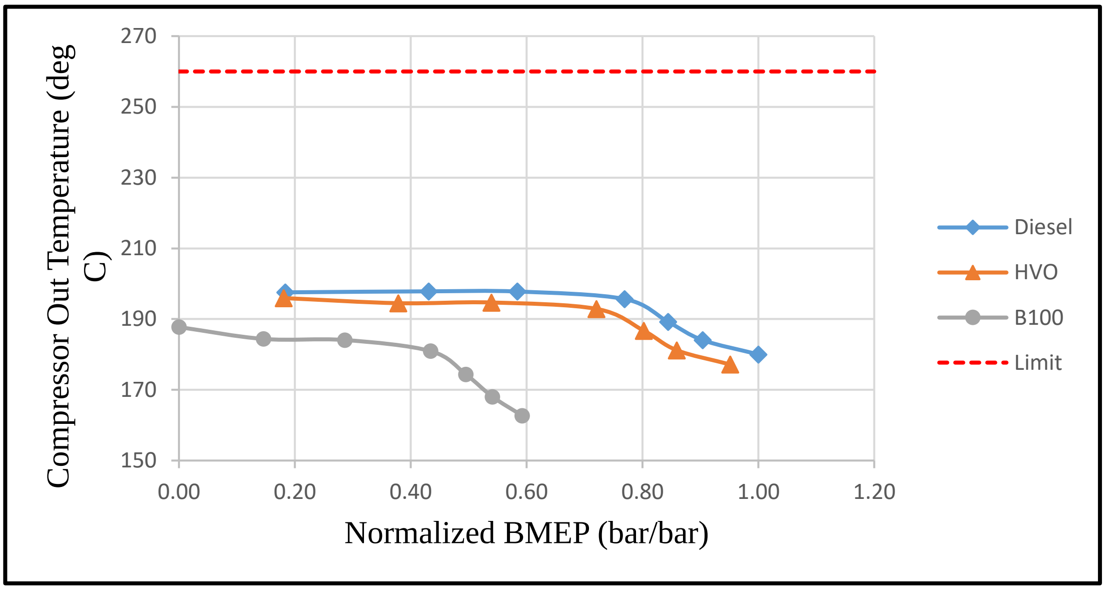


Figure 4.8: Compressor Out Temperature vs Normalized BMEP

3. Turbine In Temperature

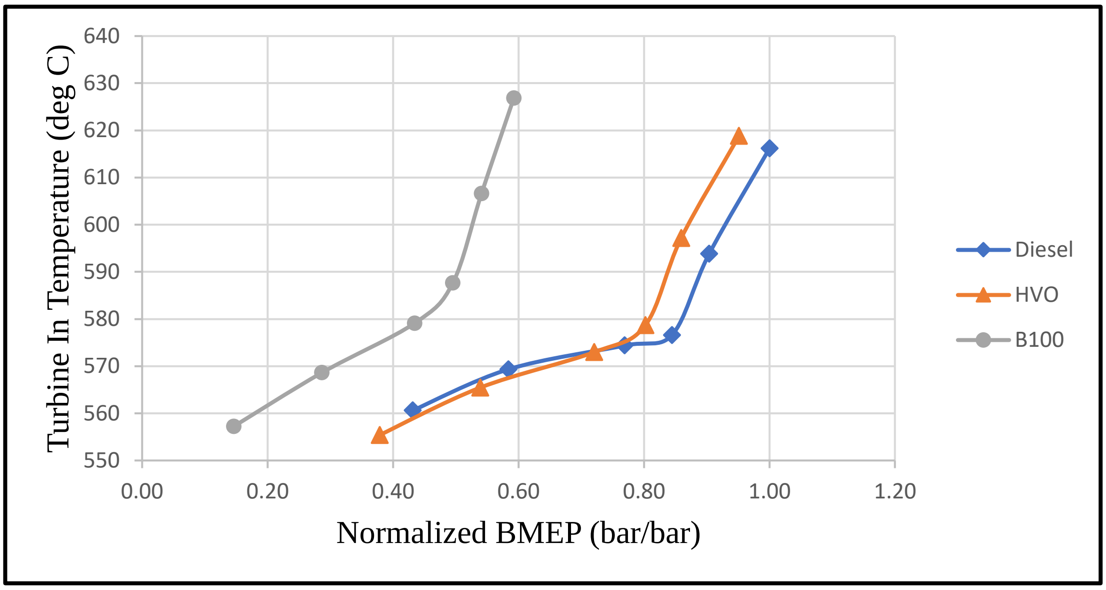


Figure 4.9: Turbine In Temperature vs Normalized BMEP

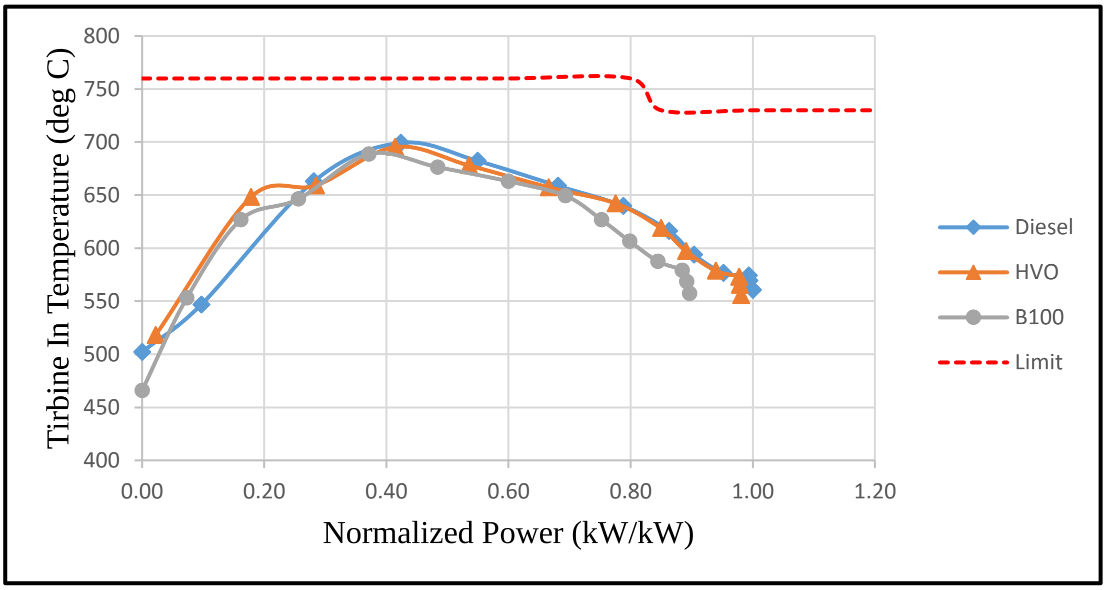


Figure 4.10: Turbine In Temperature vs Normalized Power

4.3 COMPARATIVE ANALYSIS OF EMISSION PARAMETERS

4.3.1 ISO 8178 (Type C1): 8 Mode Analysis

ISO 8178 is an internationally recognized standard that establishes guidelines and criteria for testing the emissions of internal combustion engines. This standard offers a consistent approach to measuring pollutants like carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) emitted by these engines.

Within ISO 8178, Cycle C1 is specifically designated as one of the prescribed test cycles for conducting steady-state evaluations of engines with power outputs ranging from 19 kW to 560 kW.

Mode	1	2	3	4	5	6	7	8
Torque (%)	100	75	50	10	100	75	50	0
Speed (rpm)	2100	2100	2100	2100	1500	1500	1500	700
Weightage	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

For 8 mode analysis, the commanded torque was matched with the required torque of this rating. The following emission parameters were compared for multiple fuels to meet the 8-mode targets of Tier 2 requirements of CFR 40:

1. Brake Specific NOx (BSNOx) + Hydrocarbons (HC)
2. Brake Specific Carbon monoxide (BSCO)
3. Brake Specific Particulate Matter (BSPM)

4.3.2 Brake Specific NOx (BSNOx) + Hydrocarbons (HC)

NOx, commonly known as nitrogen oxides, is a significant concern when it comes to emissions from diesel engines. These emissions primarily consist of nitric oxide (NO) and nitrogen dioxide (NO2) and are generated through a process known as the "Zeldovich Mechanism."

Figure 4.6 and Figure 4.7 show the brake specific NOx and Hydrocarbon emissions in different modes for three fuels. Mode 8 (idle speed) is not depicted due to the low load condition (approx. 0.5hp) which exploded break specific values.

The brake specific NOx emissions are observed to be higher in Biodiesel (B100) whereas, HVO showed less amount of BSNOx when compared with baseline fuel. These trends are complementing the prior art on Biodiesel and HVO. The NOx emissions are increased in Biodiesel (B100) attributed to the higher availability of oxygen content which results in improved combustion and higher in-cylinder temperature.

NOx emissions reduced in HVO due to its higher cetane number which leads to lower premixed combustion and ignition delay as compared to Diesel resulting in lower combustion temperature.

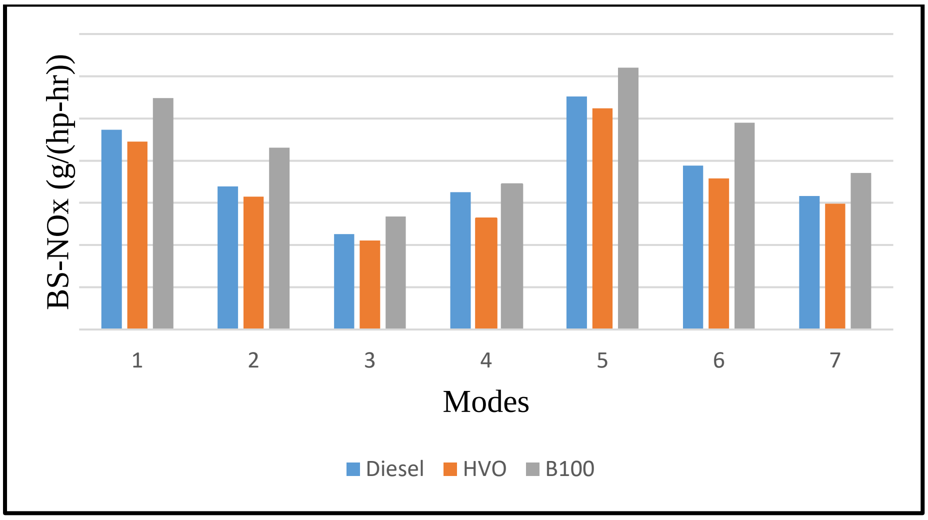


Figure 4.11: BS-NOx emissions for various modes

At Mode 4, that is low load at rated speed, the hydrocarbon emissions are the highest compared to other modes. During low-load conditions in an engine, the combustion process may not be fully efficient due to lower cylinder temperature. Therefore, the combustion process may not completely consume the hydrocarbon fuel, leading to the release of higher amounts of unburned hydrocarbon emissions.

This trend is in agreement with the previous research which states that the lower amount of unburnt hydrocarbons are due to increased oxygen content in biodiesel and high paraffinic content and very low aromatic content in HVO.

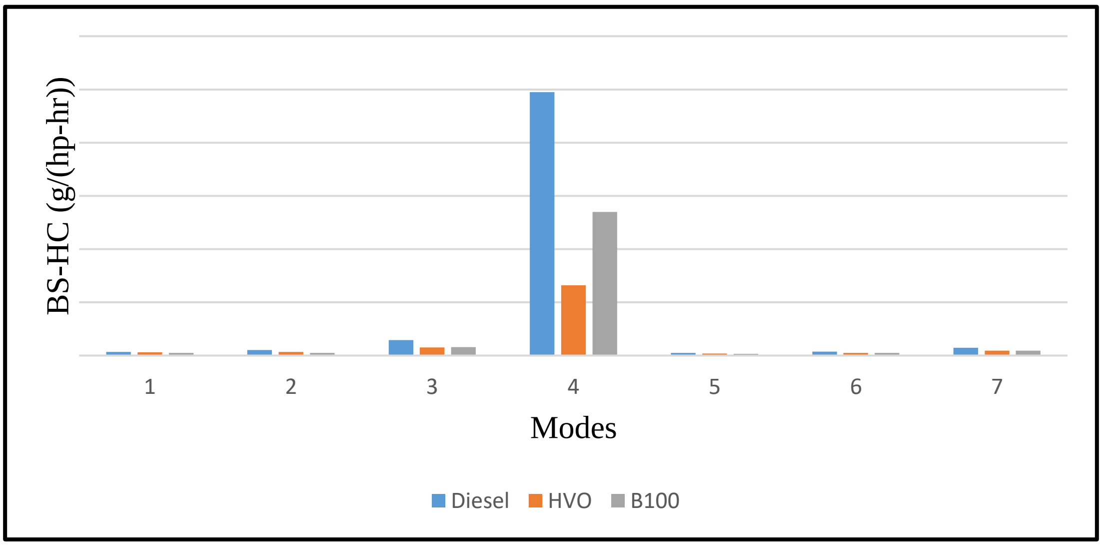


Figure 4.12: BS-HC emissions for various modes

Figure 4.8 depicts the average of cumulative BS-NOx + BS-HC emissions for the three test fuels and the target line indicates the Tier 2 requirement of CFR 40) for (BS-NOx +BS-HC) emissions. It is evident from the test results that HVO is a better fuel as compared to Diesel as it shows a decrease of (BS-NOx +BS-HC) emissions by 10.4% whereas, Biodiesel (B100) shows an increase of 8.8% in the emissions. Also, HVO emissions are much lower than the target requirement of 7.7 g/(hp-hr) according to CFR 40 but the biodiesel emissions are slightly above the target value of 4.7 g/(hp-hr).

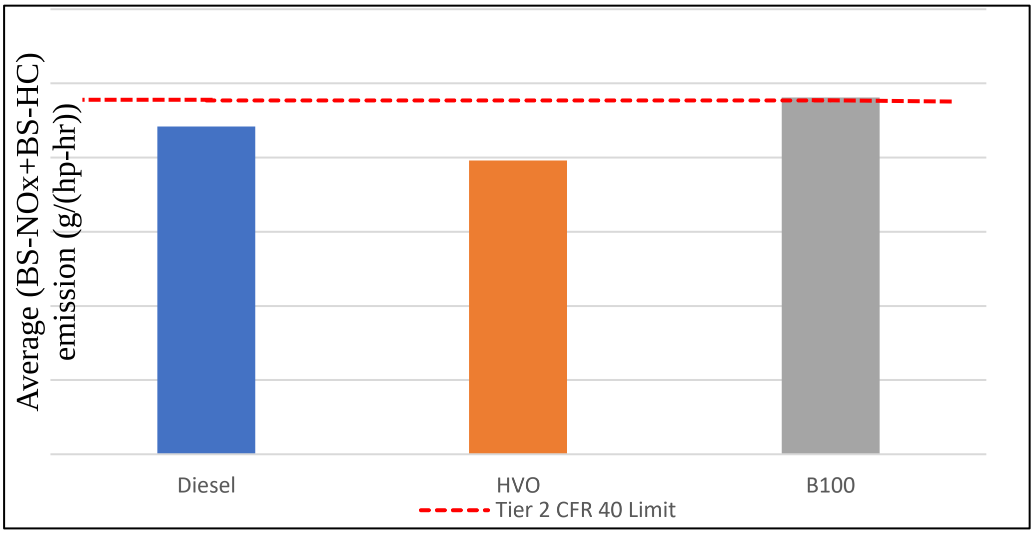


Figure 4.13: Average (BS-NOx+ BS-HC) emissions

4.3.3 Brake Specific Carbon monoxide (BSCO)

The formation of CO during combustion in diesel engines is primarily attributed to lower fuel-air equivalence ratios of combustible mixtures. Figure 4.9 depicts the average of brake specific CO (BS-CO) emissions for the three test fuels and the target line indicates the Tier 2 requirement of CFR 40) for (BS-CO) emissions.

It is observed that CO emissions are less for both the test fuels by 31.3% and 17.6% compared to baseline fuel. Also, the emission values of the test fuels are within the target of 2.6 g/(hp-hr) to meet the emission standards of CFR 40. The lower CO emissions in Biodiesel are due to the oxygenated nature of the fuel and its lesser C/H ratio than Diesel resulting in enhanced combustion. Better combustion of the hydrotreated vegetable oil due to high paraffinic content and very low aromatic content resulted in the reduced carbon monoxide emissions in HVO.

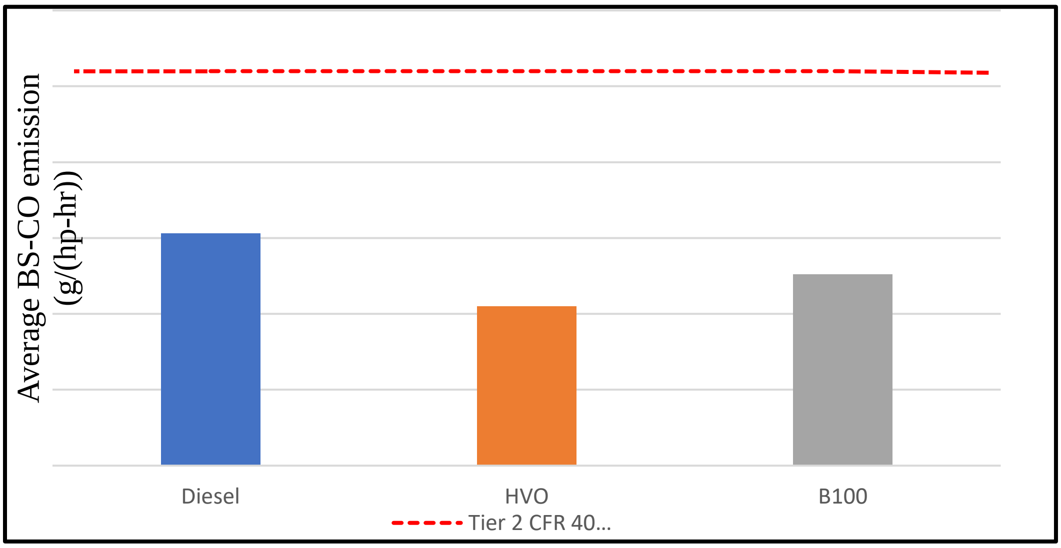


Figure 4.14: Average BS-CO emissions

4.3.4 Brake Specific Particulate Matter (BSPM)

Figure 4.10 shows the average of brake specific particulate matter (BS-PM) emissions for the three test fuels and the target line indicates the Tier 2 requirement of CFR 40) for (BS-PM) emissions. It is observed that particulate matter emissions are less for both the test fuels by 25% and 77.5% compared to baseline fuel. Also, the emission values of the test fuels are within the target of 0.15 g/(hp-hr) to meet the emission standards of CFR 40. The lower PM emissions in test fuels are attributed to lesser C/H ratio and higher cetane number of the two test fuels than Diesel resulting in enhanced combustion.

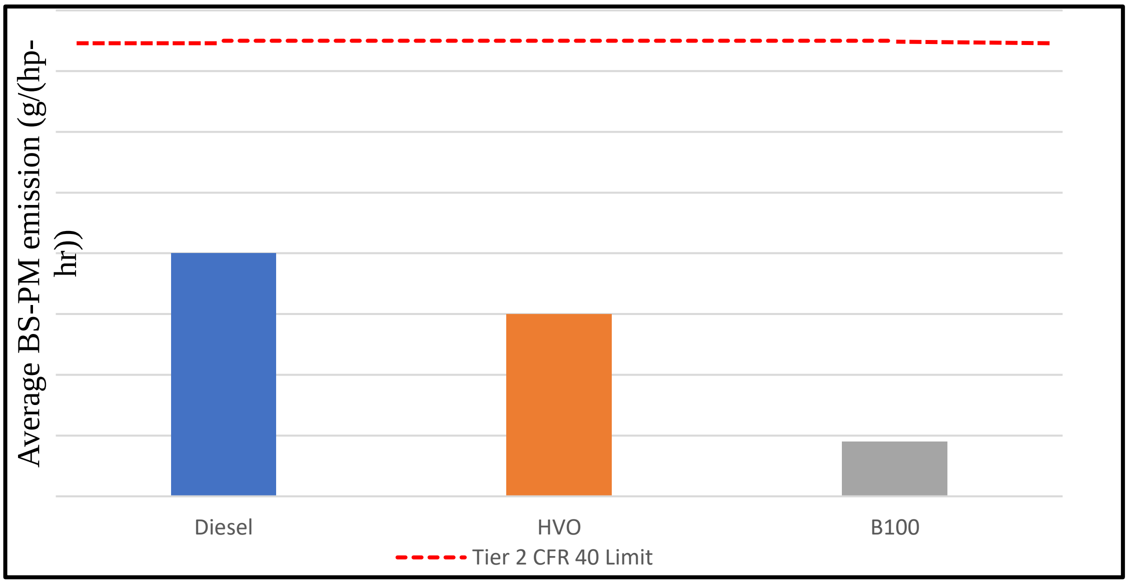


Figure 4.15: Average BS-PM emissions

4.4 SIMULATION RESULTS OF PREDICTIVE COMBUSTION MODEL IN GT-POWER

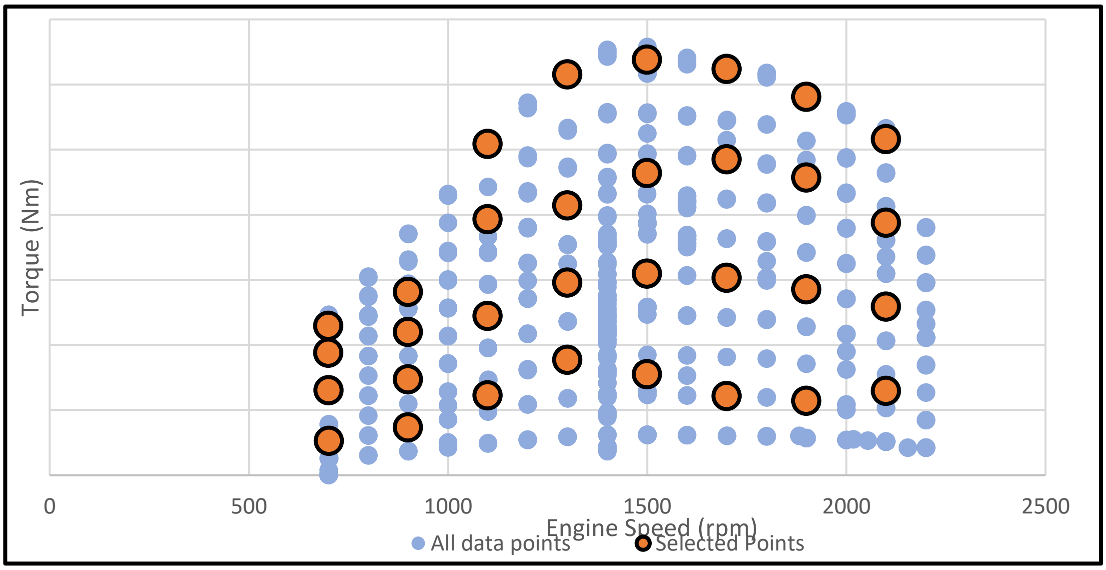


Figure 4.15: Selected points for Diesel calibration of model in GT-Power

Figure 4.11 shows the 32 points were selected across the complete data set of Diesel points to have a complete span of different speeds and different loads for the calibration of the engine model in GT-Power software. Similarly, for the calibration of the same engine model for the HVO, another set of 30 points were selected across the HVO torque curve as shown in Figure 4.12.

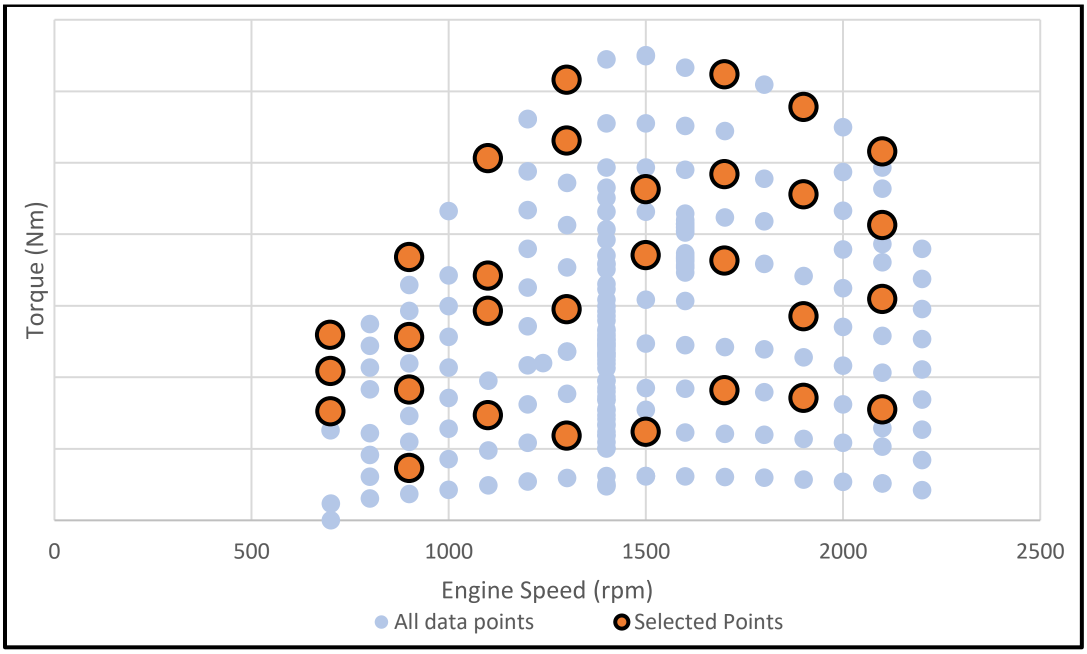


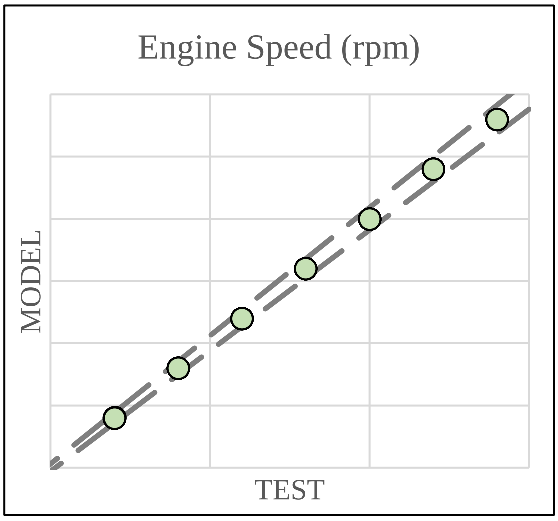
Figure 4.17: Selected points for HVO calibration of model in GT-Power

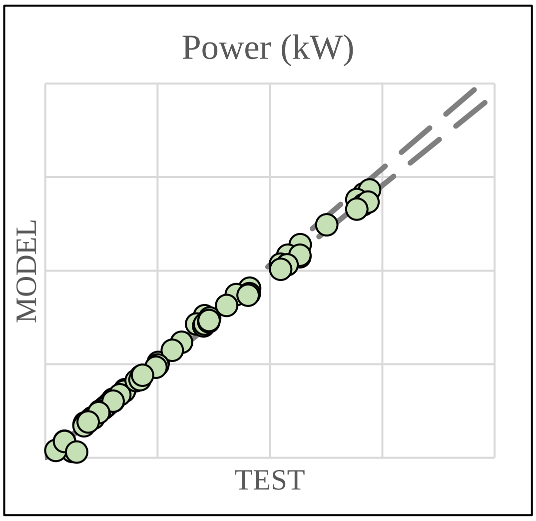
4.4.1 Acceptance criteria considered for calibration model

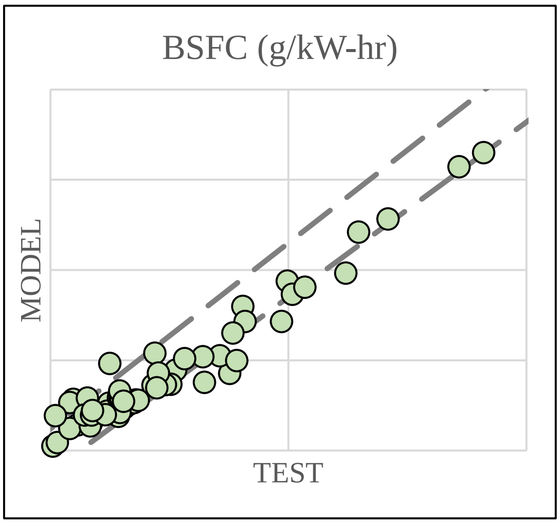
		Acceptance Criteria	
Parameters	**Units**	**Average Error (%)**	**Stdev of Error**
Engine Speed	Rpm	Imposed	Imposed
Torque (corrected)	Mn	3	3
Brake Power	Hp	3	3
BSFC	g/KW-hr	3	3
Fuel rate	Kg/hr	Imposed	Imposed
Charge flow Volmetric Efficiency	NA	3	3
Air Flow	g/sec	3	3
Air fuel ratio	NA	3	3

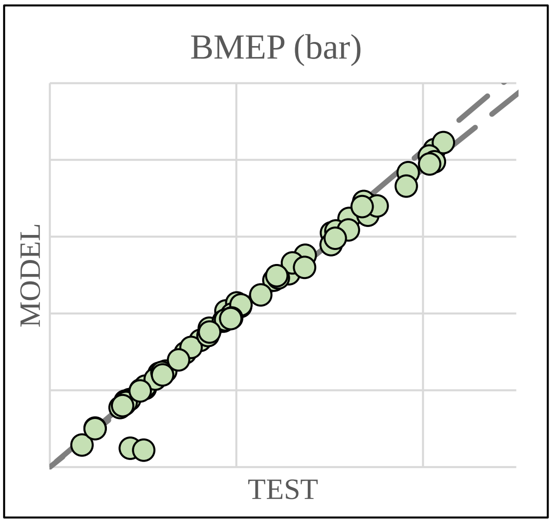
GIMEP	Bar	3	3
PMEP	Bar	30	60
NIMEP	Bar	3	3
BMEP	Bar	3	3
PCP	Bar	5	3
Inlet Manifold Pressure	Bar	3	3
Turbine In Pressure	bar	10	10

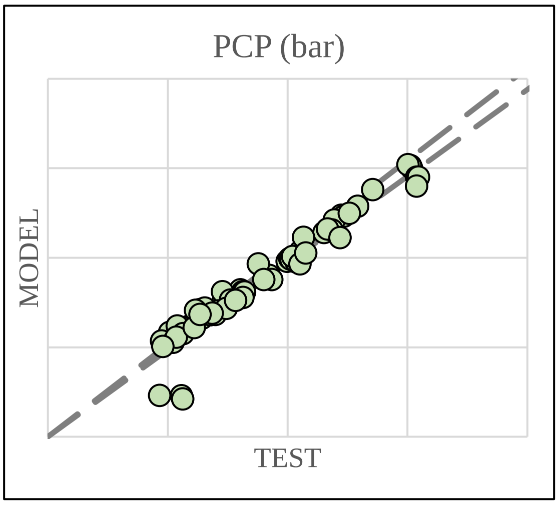
4.4.2 Results of Calibration for Diesel and HVO model

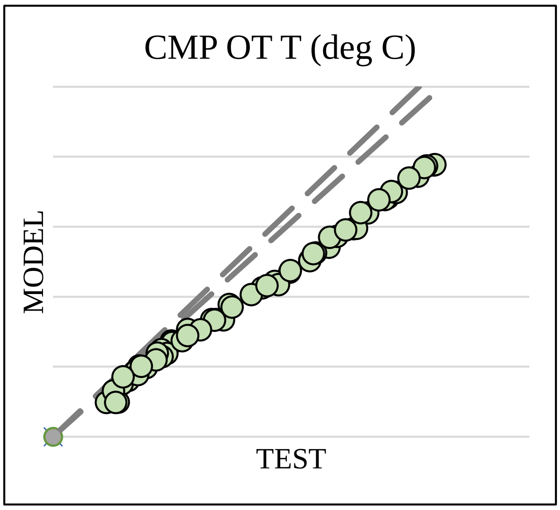


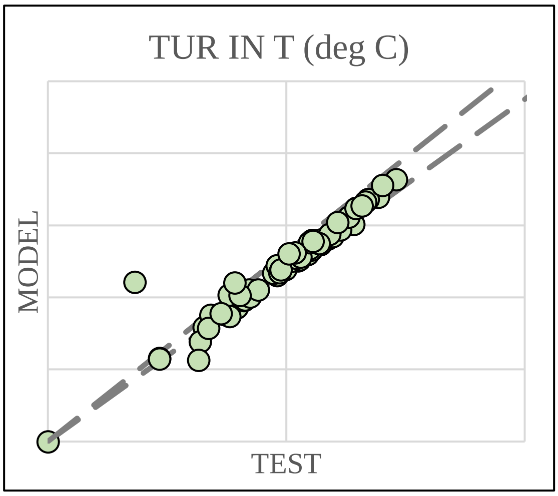


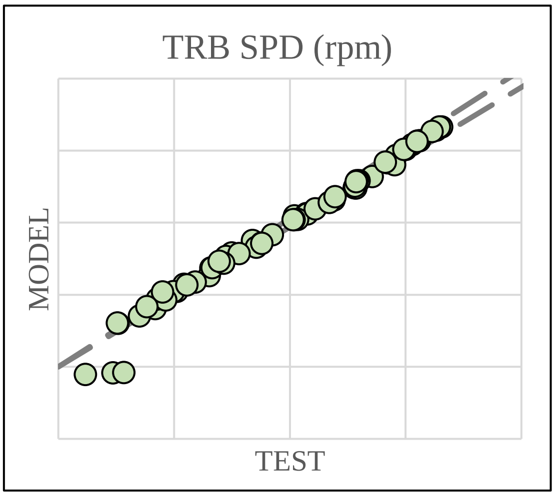












The calibration results for model run on Diesel and HVO selected points are summarized above for the important performance parameters. The graphs are plotted between the model results predicted by the GT-Power by imposing the boundary conditions and the test results obtained from the actual experiment conducted on Diesel and HVO in the test cell. From the graphs it can be concluded that the performance parameters of the calibrated model are within the acceptance criteria except the low load data points described in Section 4.4.1. Therefore, the model was accurately calibrated for most of the torque curve points with the two fuels for the validation of the predictive combustion model for Biodiesel fuel.

4.4.3 Validation of Predictive Combustion Model for Biodiesel fuel

Figure 4.13 shows the 32 points selected across the torque curve of Biodiesel (B100) blend for the validation of the GT-Power model predicted results.

Eight random points are selected from the 32 selected points of Biodiesel and numbered to compare the pressure traces of these points between the pressure trace generated by the GT-power depicted in blue colour in the figure and the pressure trace imposed through burn rate depicted in red colour in the figure.

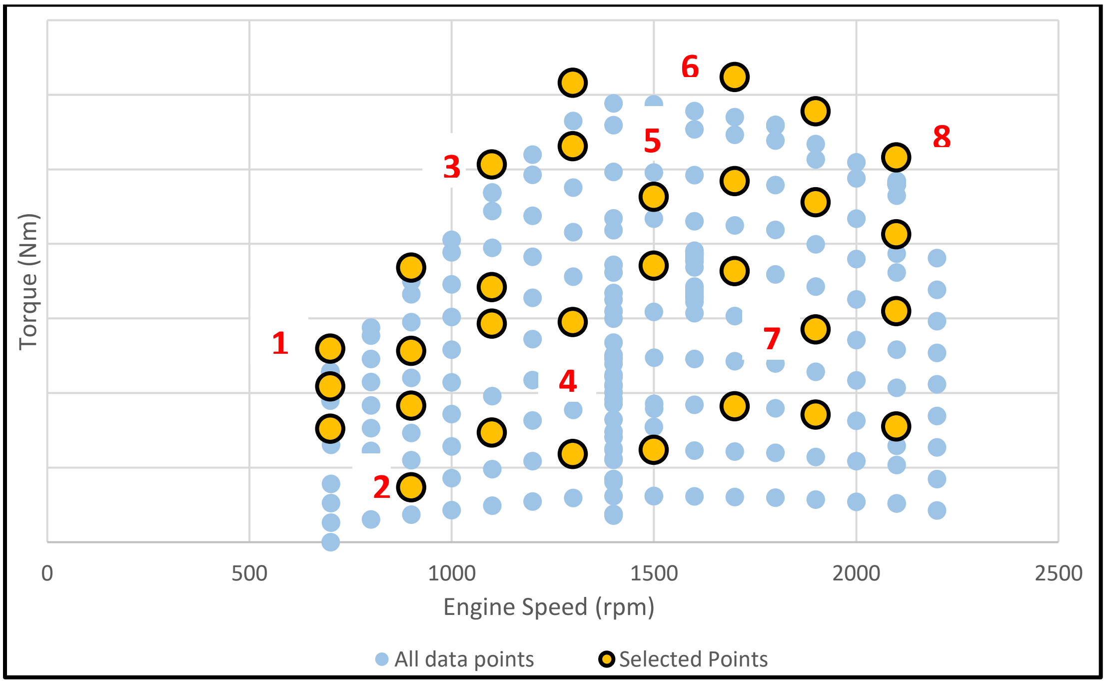
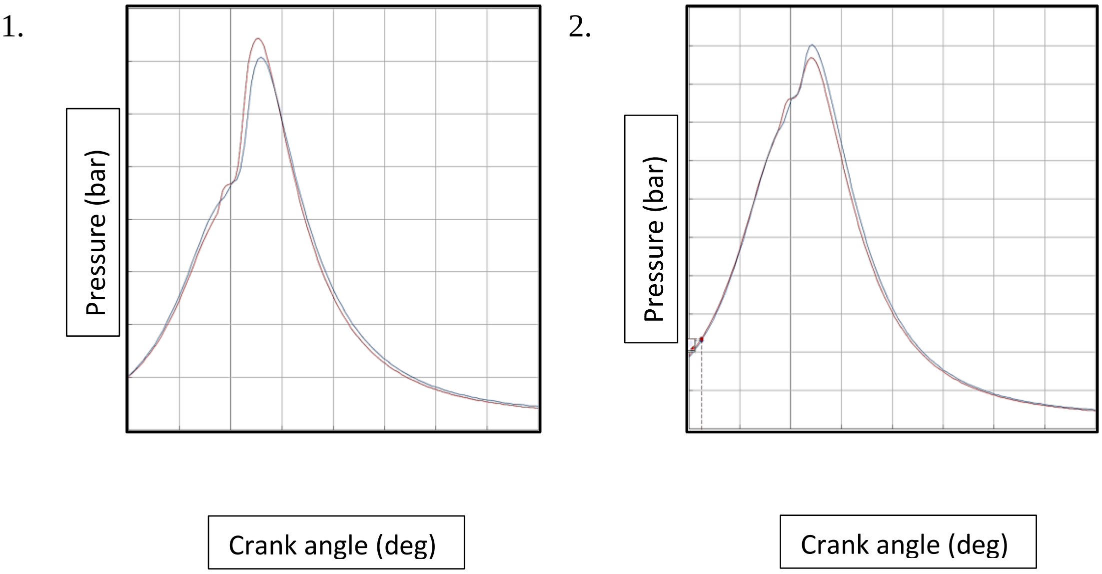


Figure 4.18: Selected points for Biodiesel for validation of model in GT-Power



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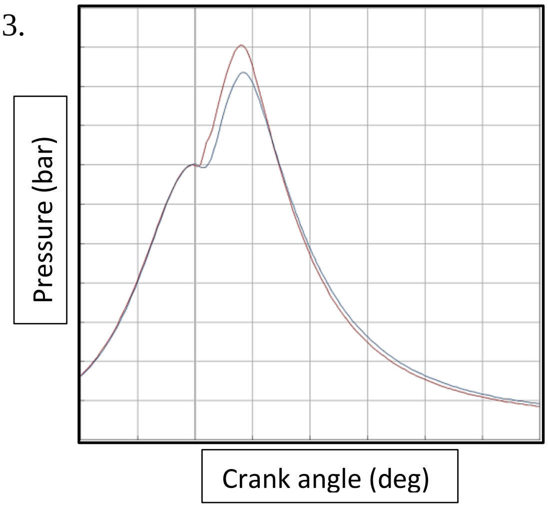

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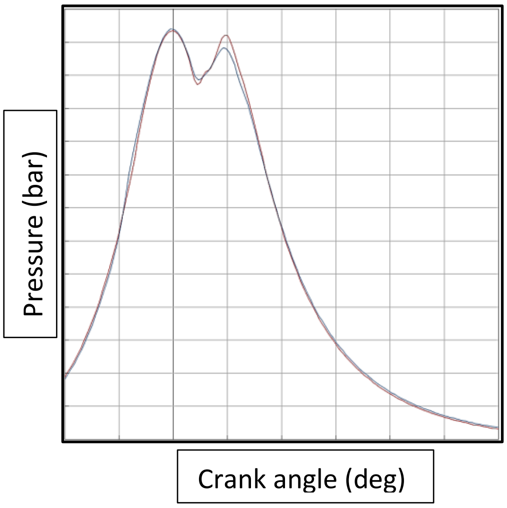

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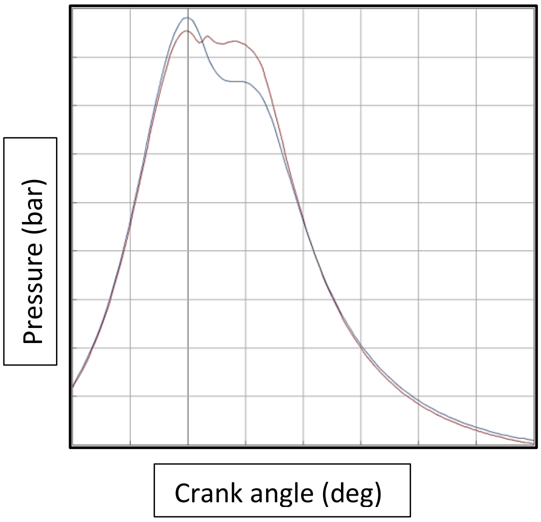

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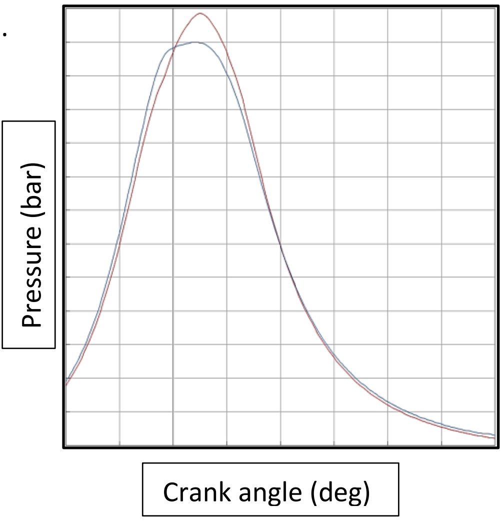

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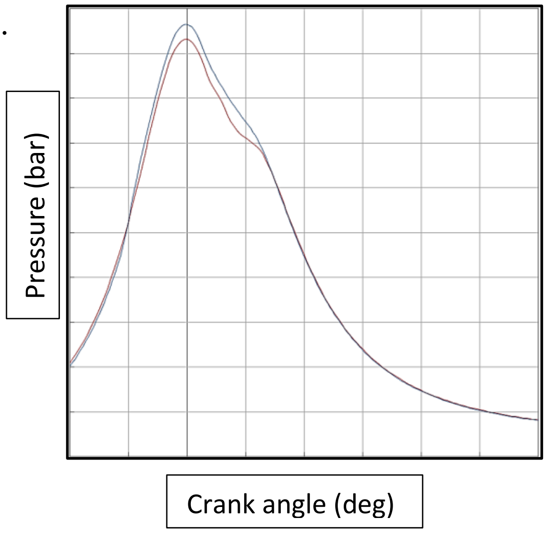

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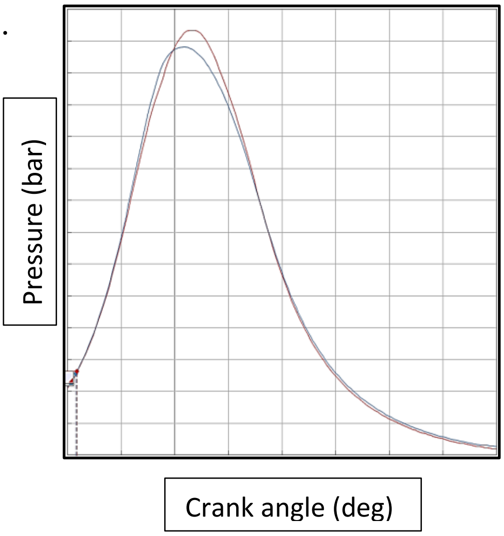
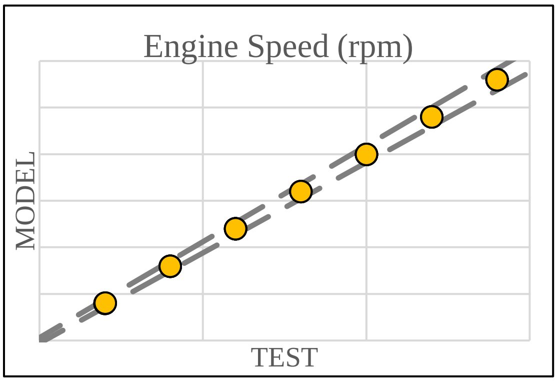
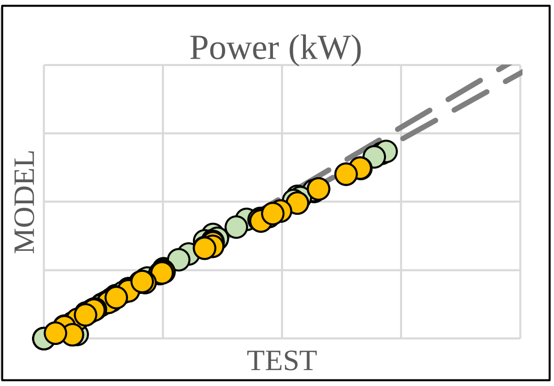
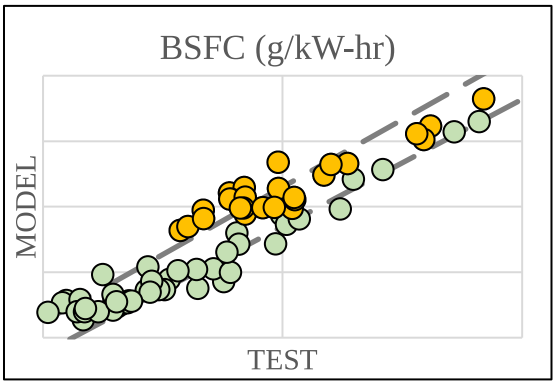


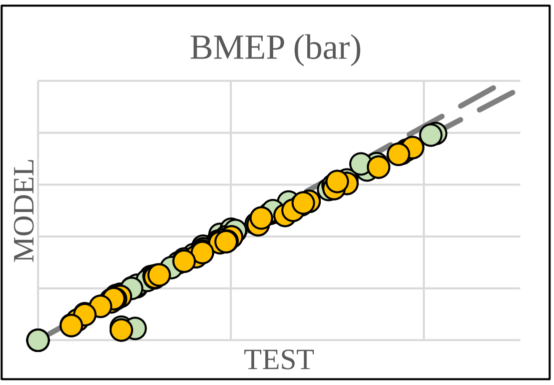
The graphs show the a good match of the predicted pressure trace and the measured pressure trace.

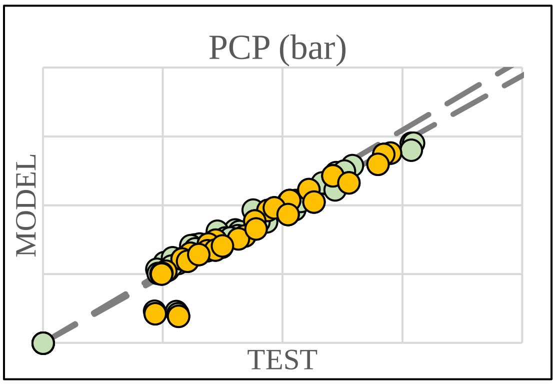
4.4.4 Combustion Performance Parameters Plots

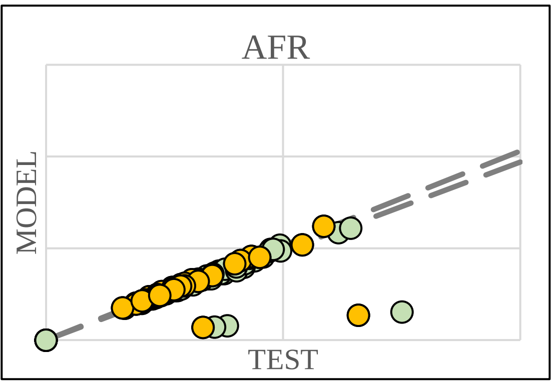


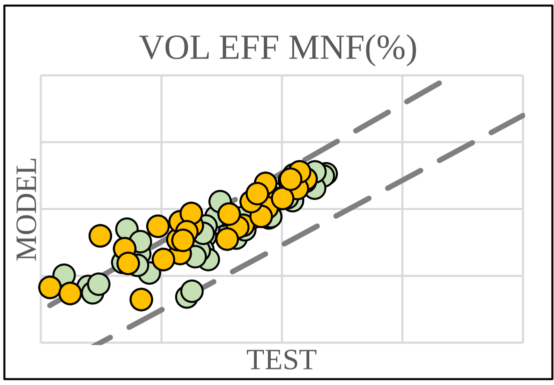


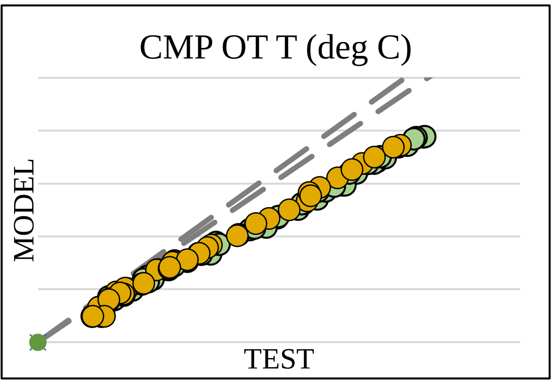


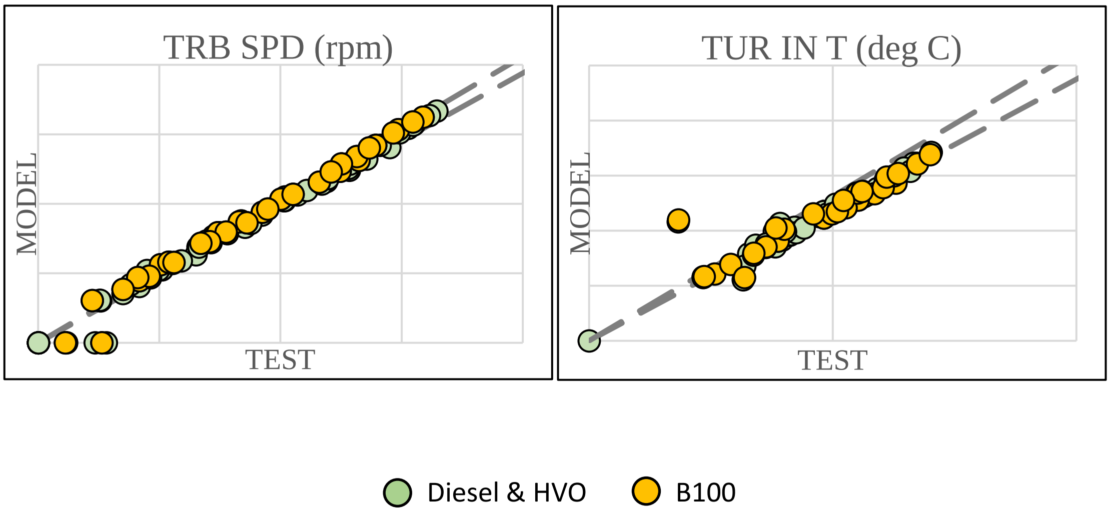












The Biodiesel full order results for 32 selected points of Biodiesel are summarized above for the important combustion and turbocharger performance parameters. The graphs are plotted between the model results predicted by the GT-Power by imposing the boundary conditions and the test results obtained from the actual experiment conducted on Biodiesel Blend (B100) in the test cell.

Biodiesel fuel properties like heat of vapourization, number of carbon and hydrogen atoms, density and other properties were either taken from literature (external) or calculated from the historic data trends. Since, the Biodiesel test points were validated on the Diesel fuel model, some of parameters show error percentage outside the acceptance limit. However, for most of the value points, it could be concluded that the performance parameters and turbocharger parameters show a good match between the actual test data and the GT-Power model predicted values except for low load points. The error percentage of most of these critical parameters lie within the acceptance criteria described in Section 4.4.1.

The model can be further tuned for Biodiesel properties and could be used for predicting the in-cylinder performance and behaviour for different biodiesel blends in future.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

The present study was carried on an unmodified diesel engine which was made to run on multiple fuels. The objective is to compare the in-cylinder performance and emissions characteristics of Cummins HHP engines using different fuels: Diesel, HVO, and Biodiesel blends (ranging from 20% to 100% volume of biodiesel with diesel). Additionally, this research also studied the compatibility of Cummins engine components, such as fuel filters, with biodiesel blends (B20, B40, B50, B75 & B100) and HVO. It also included the simulation results of in-cylinder performance using GT-Power software and the development of a predictive combustion model for various Biodiesel blends

1. The experimental results showed that the engine performance with HVO is superior than Diesel and could be used as a drop-in fuel in the Diesel engines due to its high cetane number, less density and higher net energy content.

2. The Cummins engines parts were also found to be compatible with the usage of HVO. Therefore, Cummins approves the usage of Hydrotreated Vegetable Oil (HVO) in Cummins engines (approvals limited to targeted engines) that meets EN15940 for all blends up to 100%.

3. The comparative analysis of emission parameters indicated that HVO is much cleaner fuel than Diesel. All the major pollutants like NOx, Hydrocarbons, CO and PM showed a significant reduction in the emission levels and were within the target value of the Tier 2 emission standards of CFR 40 report.

4. Biodiesel (B100), however was found to be slightly inferior to the performance with diesel fuel. The thermal efficiency of the engine was lower and the brake specific energy consumption of the engine was higher when the engine was fueled with Biodiesel blends.

5. The oxides of nitrogen (NOx) from B100 fuel were higher than the Diesel and slightly above the target value of the Tier 2 emission standards of CFR 40 report. These NOx emissions can be reduced by several methods such as EGR and After-treatment Systems in the modified engines. The Carbon monoxide (CO),

Hydrocarbon (HC), Particulate Matter (PM) were found lower than diesel fuel during the complete 8 mode analysis.

6. Cummins only approves Biodiesel Blends up to B20 (B20 is 20% biodiesel with 80% diesel) strongly recommends that the fuel should be of good quality and must adhere to the specifications and standards.

7. GT- Simulation results showed that the predictive combustion model calibrated to run on Biodiesel (B100) had the major in-cylinder performance parameters within the +/- 3% range and could be used to predict the combustion behaviour and provide reliable predictions for future cases.

FUTURE SCOPE

This research covered the functioning of the unmodified Diesel engine on Biodiesel and HVO and their effect on performance and emission parameters. Further research topics that are suggested related to the usage of biofuels in compression ignition engines are:

1. Effect of Biodiesel blends and Hydrotreated Vegetable Oil (HVO) on After-treatment systems, spray penetration and injection timings.

2. Effects and opportunities of using biodiesel blended with paraffinic fuels. Both the biofuels are observed to significantly reduce emissions. However, they have some of the parameters that are complementary to each other like density, distillation temperatures and viscosity of the fuels.

3. Based on external literature review [32, 33], it was observed that use of Biodiesel blends has impact on the unregulated emissions like formaldehyde, acetaldehyde, ethanol, n-butane, methane and polycyclic aromatic hydrocarbons (PAHs). Future scope of this project includes the measurement and comparative analysis of these unregulated emissions.

4. Validating the GT-Power model for other Biodiesel blends (B20, B40 etc.) and fine tuning the turbocharger conditions for more robust and accurate predictive combustion model.

5. Development of predictive GT-Power model for the prediction of emission parameters for different fuels.

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