DESIGN AND DEVELOPMENT OF ENGINE CONTROL SYSTEM FOR ADVANCED DIESEL ENGINE RESEARCH

By:

EDMUND UNG ENG SOON

(Matrix No.: 137806)

Supervisor:

Dr. Teoh Yew Heng

July 2021

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfilment of the requirement to graduate with honors degree in

BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

DECLARATION

I hereby declare that this work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed: ………………………………………....…… (EDMUND UNG ENG SOON)

Date: ……………………………………………………………….…… (9/7/2021)

STATEMENT 1

The work reported in my thesis is the result of my own investigation, except where otherwise stated. Other sources are acknowledged by giving explicit references.

Bibliography/references are appended.

Signed: ………………………………………....…… (EDMUND UNG ENG SOON)

Date: ……………………………………………………………….…… (9/7/2021)

STATEMENT 2

I hereby give consent for my thesis, if accepted, to be available for photocopy and for interlibrary loan, and for the title and summary to be made available outside organizations.

Signed: ………………………………………....…… (EDMUND UNG ENG SOON)

Date: ……………………………………………………………….…… (9/7/2021)

ACKNOWLEDGEMENT

The completion of this project and thesis would not be possible without the help of many people. First of all, I would like to express my utmost gratitude to Dr Teoh Yew Heng for his guidance throughout this project and also providing me with sufficient knowledge in electronics and engine testing that are used in the completion of this project. His constant support and input have helped me carry out this project to the best of my abilities especially during these hard times due to the Covid-19 pandemic.

Next, I would also like to thank Mr. Leong Hau Kian for his guidance in the engine troubleshooting and also data collection during the experiment. I would also like to thank him for his patience in explaining and sharing various knowledge in detailed on the various parts on the engine research apparatus.

My sincere thanks to all the assistant engineers in the School of Mechanical Engineering especially Mr. Mohd Zalmi Yop who has always been a helping hand in operating and handling the engine research apparatus. Special thanks to Mr. Abdul Halim Che Aat and Mr. Baharom Awang who have guided me in the fabrication process. Other notable names include Mr. Fakruzi Fadzli for lending and guiding me in using the Dewesoft apparatus and Mr. Abd Latif Amzah for providing me the anemometer for the air flow tests.

I would also like to thank my parents and family members for their endless support and financial help throughout my undergraduate degree and my circle of friends who have helped me and supported me throughout this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
ATDC	After Top Dead Center
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTDC	Before Top Dead Center
BTE	Brake Thermal Efficiency
CA	Crank Angle
CI	Compression Ignition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPU	Central Processing Unit
DAQ	Data Acquisition System
DC	Direct Current
EGR	Exhaust Gas Recirculation
EN	European Standards
GUI	Guided User Interface
H_2	Hydrogen Gas
HRR	Heat Release Rate
HC	Hydrocarbons
IC	Integrated Circuit
MAF	Mass Air Flow
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NOx	Nitrous Oxides
OBD	On-board Diagnostics
Op-Amp	Operational Amplifier
PC	Personal Computer
PID	Proportional-Integral-Derivative
PM	Particulate Matter
PWM	Pulse Width Modulation
RC	Resistor - Capacitor
RE	Renewable Energy

RES	Renewable Energy Sources
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SOI	Start of Injection
UART	Universal Asynchronous Receiver-Transmitter
USB	Universal Serial Bus
VI	Virtual Instrument
WOT	Wide Open Throttle

LIST OF APPENDICES

REKA BENTUK DAN PEMBANGUNAN SISTEM KAWALAN ENGIN UNTUK PENYELIDIKAN ENGIN DIESEL MAJU

ABSTRAK

Enjin diesel adalah salah satu enjin yang paling cekap tenaga dan paling banyak digunakan dalam industri sekarang. Dengan keprihatinan global terhadap krisis tenaga dan peningkatan tahap pencemaran, enjin diesel baharu harus dikaji dan direka bentuk agar lebih mesra alam serta mempunyai peningkatan prestasi enjin. Di Pusat Pengajian Mekanikal Universiti Sains Malaysia, peralatan enjin penyelidikan yang sedia ada harus dinaik taraf untuk memudahkan penyelidikan enjin diesel maju seperti bahan bakar biodiesel yang berbeza, kawalan bekalan udara masuk dan strategi suntikan berpecah. Oleh itu, pelbagai sistem telah diperkenalkan ke dalam mesin penyelidikan yang sedia ada, termasuk kawalan pendikit isyarat elektrik, kawalan injap pendikit, kawalan injap EGR dan sistem pemerolehan data OBD. Di samping itu, panel kawalan bersepadu sepenuhnya dirancang untuk mengawal dan memaparkan data-data semua sistem yang baharu dipasang serta sistem yang sedia ada dalam bangku uji. Hasil kajian telah menunjukkan bahawa sistem yang baru dipasang berfungsi dengan lancar tanpa kesilapan. Projek ini adalah langkah pertama untuk mengembangkan mesin penyelidikan yang berkebolehan sepenuhnya untuk menguji pelbagai parameter lain mengenai kesinambungan pada mesin diesel.

DESIGN AND DEVELOPMENT OF ENGINE CONTROL SYSTEM FOR ADVANCED DIESEL ENGINE RESEARCH

ABSTRACT

Diesel engines are one of the most energy efficient and most used engines in the industry today. With the global concern on energy crisis and rising pollution levels, new diesel engines should be researched and designed to be more environmentally friendly as well as having increased engine performance. In the Mechanical School of Universiti Sains Malaysia, the existing research engine equipment were upgraded to be able to facilitate advanced diesel engine tests such as different biodiesel fuels, intake air supply control and split injection strategies. Therefore, various systems have been implemented into the existing research engine including the electrical signal throttle control, throttle valve control, EGR valve control and OBD data acquisition system. On top of that, a fully integrated control panel is designed to control and display data of all newly installed systems as well as the existing systems on the testbench. Results shows that the newly installed systems were working smoothly with very little to no errors. This project is a first step in developing a fully capable research engine to test out various other parameters regarding sustainability on the diesel engine.

CHAPTER 1

INTRODUCTION

1.1 Introduction to Diesel Engine Improvements Towards Sustainability

Diesel engines produce more power and utilize less fuel than other engines comparatively sized engines such as gasoline, compressed natural gas or liquified natural gas engines and is known as the world's most efficient internal combustion engine. With such a widespread of uses for diesel engines worldwide in transportation, shipping, construction, mining, agriculture etc., the diesel industry has made great progress in improving the emission levels and eliminate key pollutants associated with the use of diesel engines (Dulles, 2001). Some of the more obvious technologies that can be found today can be shown in Table 1.1 together with their advantages. In the light of this project, we will be focusing two technologies which are the EGR and split injection strategies.

Table 1.1: Technologies in Diesel Engines to Improve Emission Performance

Technologies	Advantages
Electronic Fuel Injection	Reduce PM and NOx emissions
High Pressure Fuel Injection	Reduce PM emissions
Variable Injection Timing	Reduce NOx emissions
Improved Combustion Chamber Configuration	More complete combustions and reduce PM emissions
Turbocharging	Reduce PM emissions and improve fuel economy
Air-to-air Charge Cooling	Reduce NOx emissions
Exhaust Gas Recirculation	Reduce NOx emissions
Hydraulic Electric Unit Injection	Lower emissions and improve fuel economy
Oxidation Catalysts	Reduce PM emissions
Selective Catalytic Reduction	Reduce PM, NOx and HC emissions
Particulate Filters	Reduce PM emissions
NOx Catalysts	Reduce NOx emissions
Diesel-electric Hybrids	Reduce NOx and PM emissions and improve fuel economy

1.1.1 Biodiesels as Diesel Substitutes

There are many improvements that can be implemented in diesel engines to improve their performance as well as their environmental impact. Narrowing down to our topic of engine performance and emissions, we will focus primarily on the RES of bioenergy, typically biodiesels. Biodiesels are quite similar to fossil diesel but are made from the process of transesterification of animal fats, vegetable oils or cooking oils with the help of alcohol (Mumtaz et al., 2017). Biodiesels are have benign properties, are eco-friendly and biodegradable which is in line with the sustainability goal of this project such as to ensure affordable, reliable and sustainable energy to combat climate change and its impacts for humanity (Cîrstea et al., 2018). Up to date, many researches had been done using biodiesel or biodiesel blends as substitutes for diesel in diesel engines and the majority of them concluded that using biodiesels can improve the performance of the engine and produce cleaner emissions. However, one major problem in using biodiesels as diesel substitutes are the high NOx emissions. (Rajkumar & Thangaraja, 2019) Due to the increasing stringent emission regulations around the world, many more researches and tests have to be done before biodiesels can be fully used in a large scale.

1.1.2 Exhaust Gas Recirculation (EGR)

With the rise in NOx emissions levels in diesel engines, one of the mechanisms to reduce NOx emissions is by using EGR system. Generally, EGR works by recirculating some of the engine's exhaust gas back into the engine cylinders for combustion. This strategy works by reducing the oxygen content in the incoming intake air supply causing lesser NOx formation after combustion in the engine cylinders (Balamurugan & Gowthaman, 2021). The down side of using EGR in both CI and SI engines are the formation of excessive soot when the combustion of mixture using EGR is not happened properly (Dubey et al., 2019). Soot or also known as PM forms when there is occurrence of incomplete combustion in the engine cylinder. They can range in size from a few nanometers up to hundreds of nanometers and mainly consist of unburned carbonaceous particles in the fuel mixture (Neha et al., 2020). Therefore, using the EGR system is not as straight forward as it seems as there are certain environmental drawbacks in the system. EGR systems are also not much effective due to its overall implementation cost and also its low efficiency respectively.

1.1.3 Split Injection Strategies

Recent researchers have also moved their attention to the implementation of split injection strategies and techniques in diesel engines. Split injection or also known as SOI strategy is a concept where parts of the fuels are injected into the intake manifold instead of one full injection of fuel. With this strategy, the ignition is delayed from the pilot ignition indicating less premixed combustion, lowering the peak HRR in the engine cylinder (Mohammad Reza Herfatmanesh et al., 2013). Split injection techniques also injects the fuel along with air forming a more homogenous mixture of fuel and air thus, reducing the formation of NOx emissions (Balamurugan & Gowthaman, 2021). Therefore, varying the pilot injection strategies such as the proportions, injection timing and pressure along with EGR systems could prove to have improvements over the engine performance and emissions.

1.2 Problem Statement

Currently, the existing diesel setup in USM, there are limited apparatus and parts to execute advanced tests which includes different biodiesel fuels, different intake air supply capabilities, different injection strategies etc. There are also limited sensors to measure the performance, emissions and combustion characteristics to produce results needed for an advanced diesel engine research. Therefore, the objective of this project is to design and develop a comprehensive engine control system to detect and measure most of the important engine parameters to enable advanced diesel engine research.

1.3 Project Objectives

- To develop an electronic throttle simulator replacing a mechanical throttle actuation by an acceleration pedal.
- To design and develop a throttle valve system, EGR valve system, OBD data acquisition system and an MAF sensor for advanced diesel engine research capabilities.
- To develop a datalogging program using NI LabView to control all sensors connected to the engine and simultaneously read and log the data of real-time engine performance and emissions.

1.4 Scope of Work

This project will be focusing on the design and development of various control systems and data acquisition system that are lacking for the execution of advanced diesel engine research in the USM Mechanical Engineering Engine Laboratory facilities. In this project, an electronic signal throttle actuation system, a throttle valve control system and an EGR valve control system will be developed and tuned for a smooth and reliable control. Furthermore, a comprehensive datalogging system will be developed using NI LabView software that is able to control all the sensors and actuators connected to the diesel engine and be able to read real-time data on the performance and emissions of the diesel engine during an experiment. Finally, an OBD system will be developed to read the engine performance from its internal sensors to be able to compare with results from the external DAQ from external sensors installed on the engine.

CHAPTER 2

LITERATURE REVIEW

2.1 World Energy Overview

Over the past century, fossil fuels have been used to provide humans with energy to carry out their daily activities. According to the BP Statistical Review of World Energy in 2019, fossil fuels, typically oil are the primary energy source used around the world for power generation (BP, 2020). Using Data Envelopment Analysis (DEA) Toshiyuki Sueyoshi and Miko Goto conducted studies to assess the performance of worldwide energy industries to study and analyze the current energy trends of the world and predict the energy trends in the future. According to this study, the authors predicted that the fossil fuels demand will be increasing rapidly with the rapid increase in industrialization and economic boom which is happening around the world (Sueyoshi & Goto, 2017). The statement can also be supported by general trend of the world primary energy consumption that continues to increase from 482.82 to 583.90 exajoules of energy from year 2008 to 2018 indicating an average annual increase of 1.6% over the period of a decade (BP, 2020). The world primary energy consumption graph can be depicted in Figure 2.1.

Unfortunately, these non-RES are in the facing depletion if there are no supply of alternative fuels as a substitute. With the current advancements in technology and the increase in researches on the implementation of RES over non-RES (Qazi et al., 2019), the global energy demand will gradually be covered by RES (Jurasz et al., 2020). RE comes in various forms such as oil, natural gas, coal, nuclear, hydroelectric, geothermal, solar, wind and tide energy. Therefore, to maintain a foreseeable future for the planet, renewable and sustainable energy sources are needed as substitutes for non-RES.

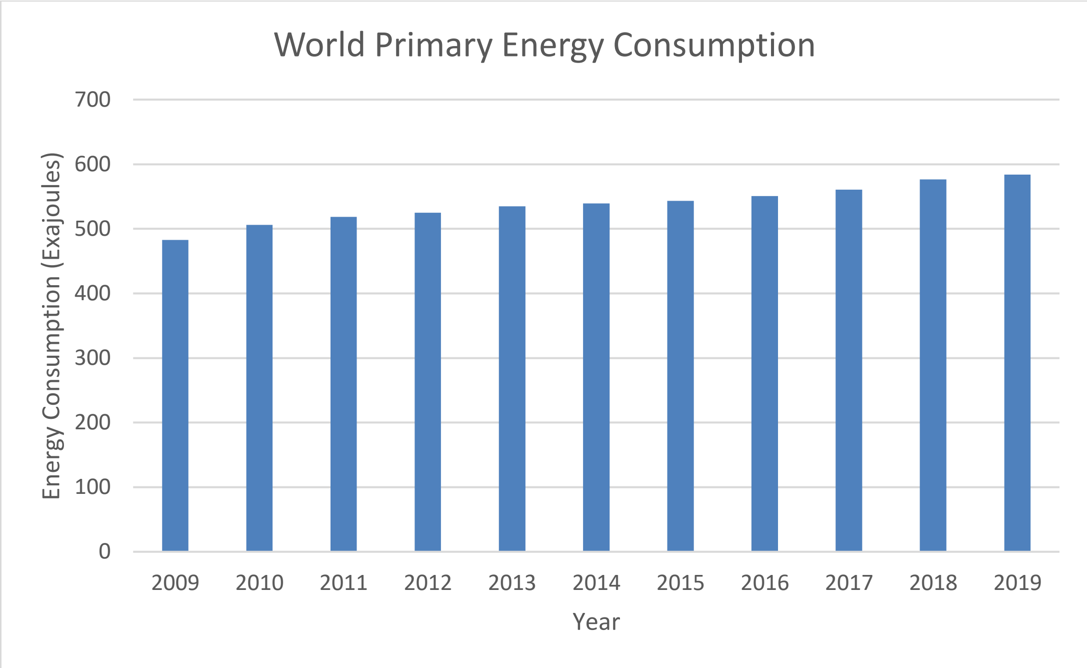

Figure 2.1: World Primary Energy Consumption (Source: BP Statistical Review of World Energy 2019)

2.1.1 Malaysian Energy Scenario

For a very long time, Malaysia has been dependent on fossil fuels, typically coals and natural gas sources for electricity generation. In Malaysia, there is an average energy growth of 2.3% from year 2008-2018 and a 1.3% increase of energy consumption from year 2018 to 2019. However, through the decades of excessive exploitation of these resources, these natural resources have contributed to climate change and global warming as well (Oh et al., 2018). The total primary energy supply in Malaysia can be depicted in Figure 2.2.

From Figure 2.2, Malaysia's main source of energy is from crude oil since 1980. With the occurrence of two international oil crisis in 1973 and 1979, the Malaysian government called for the diversification of energy sources through the Malaysian National Energy Policy. Crude oils and natural gas sources are still dominated energy supply in Malaysia and are expected to continue to play a major role in energy generation in the country. However, continuous and long-term usage of these energy sources might be a major global environmental concern because of its climate change issue. Therefore, in year 2001, the Malaysian Government implemented the Small Renewable Energy Power Programme (SERP) to encourage the use of RES in power generation (Ong et al., 2011). It is only after the year 2011 that RES such as biodiesels have been introduced to the power generation in Malaysia, followed by biomass, biogas and solar power in the year 2012 (Statistics, 2019). From there, the usage of RES in the country has been increasing until the present day.

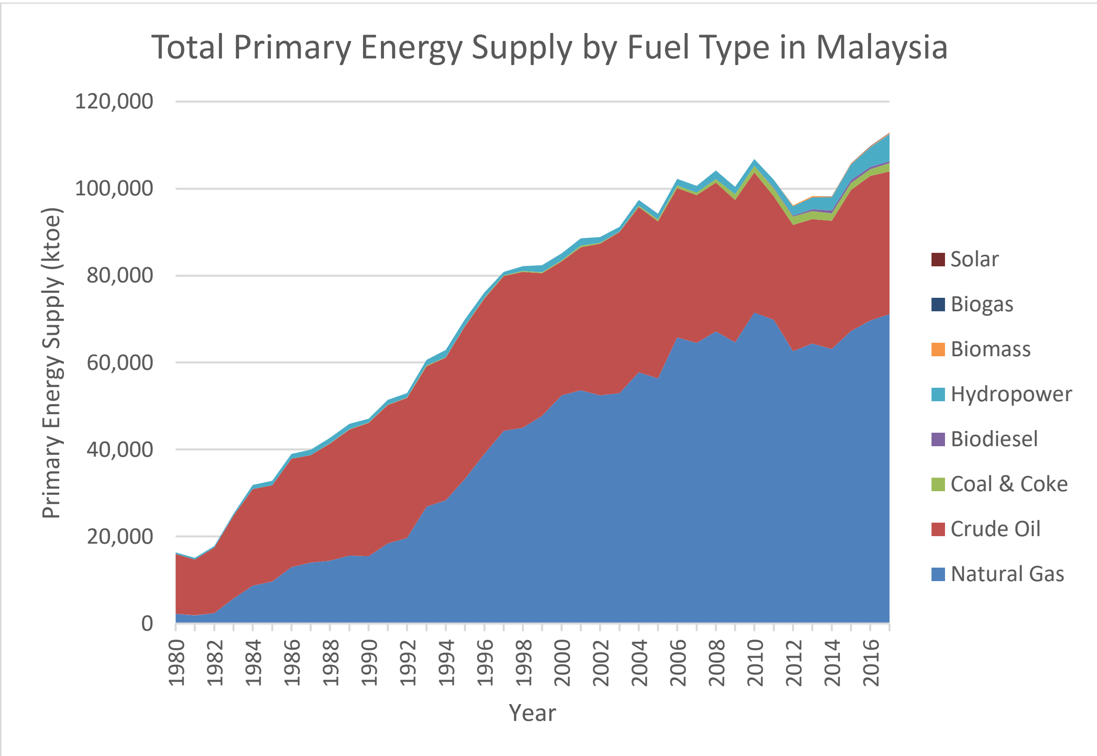

Figure 2.2: Total Primary Energy Supply by Fuel Type in Malaysia (Source: Malaysia Energy Statistics Handbook 2019)

2.2 Biodiesel

Biodiesels are mainly made up of mono-alkyl esters of long-chain fatty acids produced by the process of transesterification using alcohol, usually methanol and a catalyst (Mumtaz et al., 2017). Biodiesels are mainly classified into four different groups or generations based on its source (Lau et al., 2020) (Silitonga et al., 2020) (Silitonga et al., 2019) (Goh et al., 2019). The first generation of biodiesels are edible oils, the second generation biodiesel are non-edible oils, the third generation biodiesels come from waste oils and lastly the fourth generation biodiesels are advanced solar biodiesels (D. Singh et al., 2019). A summary of the classifications of the common biodiesels can be shown in Figure 2.3. Biodiesels or biodiesel-diesel fuel blends possesses very desirable characteristics as a diesel substitute namely because of its biodegradable and non-toxic properties in addition to being a RES (Hoang, 2018). It could also directly replace fossil diesels without undergoing any major modifications (Hoang, 2017).

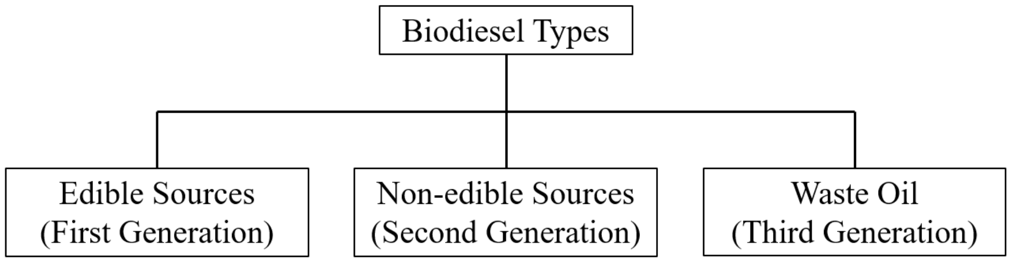

Figure 2.3: Classifications of Biodiesels

It is necessary for biodiesels to have standards around the world to control its quality and properties. Biodiesels can be characterized by several properties including viscosity, density, cetane number, flash point and cloud point. Viscosity plays an important role in fuel injection in the engine where it affects the fuel fluidity.

Biodiesels have viscosities of up to 10-15 times greater than traditional fossil diesel due to the large molecular mass and chemical structure (Mishra & Goswami, 2018). On the other hand, the fuel density is a key property as it is related to the cetane number and heating values which therefore directly affects the engine performance (Sundus et al., 2017). Biodiesel density is higher than that of fossil diesels. The high viscosity and density in biodiesels might lead to poor atomization and long breakup time for the fuel which leads to an increase in carbon deposition and lower performance of engine (Hoang, 2018). Biodiesels also have higher cetane number than fossil diesels which results in their superior fuel flammability (Yew Heng Teoh, How, Balakrishnan, et al., 2020).

Biodiesels have been widely researched on its usage as a suitable diesel substitute. According to many researchers, biodiesels have properties that sometimes has more benefits in terms of generating greater engine performance (Mekhilef et al., 2011) (Atadashi et al., 2011).

2.2.1 Edible Biodiesel (First Generation Biodiesels)

First generation biodiesels or also known as feedstock biodiesel. They are usually made from food and edible oils. Some examples of first-generation biodiesels include rapeseed, soybean, peanut, sunflower, palm oil and coconut oil (Samani et al., 2021). Since these sources of biodiesels are edible, some people might argue that the use of these sources will reduce the food supply for us humans. In the long term, this problem might cause the food prices to increase due to the high demand in feedstock biodiesels (Bhuiya et al., 2020). The use of these sources of biodiesel are a double-edge sword as they provide us with fuel to power up engines or other locomotives but at the same time depletes the human source of nourishment. Therefore, this problem has causes researches to shift their focus on other biodiesel sources that does not deplete the human food supply (Mofijur et al., 2021).

2.2.2 Non-edible Biodiesel (Second Generation Biodiesels)

Second-generation biodiesels, unlike first-generation biodiesels, are acquired from non-edible sources which are then processed to form biodiesels (Rahman et al., 2016). Compared to first-generation biodiesels, these sources are not edible by humans and does not interrupt the food supply for humans. Feedstocks used for the production of second-generation biodiesels include Jathropa, Karanja, sea mango, algae, halophytes, jojoba oils and tobacco seed (X. J. Lee et al., 2020). Second-generation biodiesels produced from feedstocks have much more benefits and are more ecological compared to first-generation biodiesels (Pinzi et al., 2009). However, the growth of second-generation feedstocks isn't problem-free as it still consumes a large amount of land for growth and cultivation. This causes a competition in land space between the cultivation of edible food crops and the cultivation of second-generation biodiesel feedstocks (Mofijur et al., 2021) (Mofijur et al., 2019). In other occasions, waste oils and recycled oils can be reused and repurposed into biodiesels. These are advanced second-generation biodiesels since they are also produced from non-crop feedstock (Foteinis et al., 2020). These biodiesel sources are also promising in terms quality and production costs (César et al., 2017).

2.2.3 Waste Oil Biodiesels (Third Generation Biodiesels)

Third-generation biodiesels reduces both the problems faced by first-generation and second-generation biodiesels regarding food and land problems. In third-generation biodiesels, microalgae are used in the production of biodiesels (Chia et al., 2018). Microalgae biodiesel usage are considered more feasible when compared to the sources of biodiesels (Leong et al., 2018) (Hossain et al., 2020) as its yield per unit area can reach up to 15-300 times more compared to traditional crops (Hossain, Zaini, & Indra Mahlia, 2019) (Hossain, Zaini, Mahlia, et al., 2019).

2.2.4 Biodiesel Standards

With the increasing use of biodiesels in our daily lives, the assurance of quality of fuel has become a public concern typically for the commercialization and market acceptance of biodiesel fuel. Therefore, biodiesel standards have been developed in various counties and regions to control its quality (Knothe, 2006). The most commonly used standards used as references or as a baseline worldwide for biodiesel analysis are the American standard, ASTM D 6751 and European Standard, EN 14214 (Knothe & Razon, 2017). This standards are made to ensure satisfactory use of biodiesels around the world (Sajjadi et al., 2016).

2.2.5 Biodiesel Performance Vs Fossil Diesel

Biodiesels have been widely researched on its usage as a diesel substitute. The majority of researchers stated that biodiesel or biodiesel-diesel fuel blends can produce better engine performance with lesser harmful emissions compared to using fossil diesel. A research done by Teoh et al. and How et al. suggests that when using *Cocos nucifera* biodiesel blends in a common rail injection system diesel engine, BTE and BSFC of the engine tends to be higher (Teoh et al., 2020) (How et al., 2014). However, Kanth et al. reported that the BTE of a diesel engine is reported to be lower especially in higher loads when using biodiesel blends (Kanth et al., 2020). They also researched that by enriching the biodiesel with hydrogen, H_2, the BTE can increase up to 2.2% at higher load conditions. Similarly, they also reported higher percentages of BSFC when hydrogen is added to the biodiesel fuel mix. They found out that the hydrogen enriched biodiesel blends increase the heat releasing rate causing reduction in combustion time when compared to diesel fuels. Moreover, the performance of the engine is lower compared to using diesel fuels and the emissions of NOx is higher when using biodiesel-diesel blends. Similar results and findings are also recorded from Teoh et al. (Teoh et al., 2020) using palm cooking oil methyl esters in a single-stroke water-cooled 4-stroke DI engine, using Moringa oleifera biodiesel-diesel blends in a common-rail diesel engine (Teoh et al., 2019) and also researches from Mahmudul et al. (Mahmudul et al., 2017). The authors explained that the higher NOx emissions typically from the use of biodiesel fuels compared to diesel fuels are due to the higher oxygen content which leads to an increase of formation of NOx. However, some researchers report a higher BTE when using diesel compared to biodiesel-diesel blends (Bhowmick et al., 2019). Vijay Kumar et al. studied the performance of the engine can be increased by using biodiesels compared to diesels together with their emissions in general (Kumar et al., 2018). However, this researcher uses additives in the fuel blends thus, giving out better results in terms of performance and emissions compared to when using pure biodiesel or biodiesel-diesel blends.

2.2.6 Summary

As an overview for the effect of performance of diesel engines using different biodiesel fuels, the majority of researchers have found positive results in terms of BTE and BSFC. In terms of emissions, the majority of researchers report that CO levels and soot emission significantly reduce when using biodiesels compared to fossil diesels.

On the contrary, the NOx emissions are higher when using biodiesels as fuel compared to fossil diesels.

2.3 Intake Air Supply Control

The rise in NOx emissions in diesel engines from using biodiesels as fuel has contributed to the researches in controlling the emission levels of a diesel engine. At present, there are many ways that can be implemented to reduce NOx emissions. (Dulles, 2001) Some of the technologies mentioned are presented in Table 1.1. However, in the scope of this project, we will be focusing on the method of EGR system implementation on the diesel engine. On top of that, we will also be discussing on the effect of intake air pressure towards the emissions of the diesel engine.

2.3.1 Exhaust Gas Recirculation (EGR)

Exhaust Gas Recirculation system or better known as EGR is a system that helps reduce the amount of NOx emissions (Zhao et al., 2020). The EGR system works by recirculating the exhaust gas which is rich in carbon dioxide and water vapour content into the combustion chamber together with a percentage of fresh air intake. As a consequence of this air displacement, there are lower amounts of oxygen in the intake air mixture available for combustion thus, reducing the formation of NOx during combustion (P Naresh, V Madhva, 2015). However, based on past researches, researchers have reported that the use of EGR has raised the concerns of HC and CO emissions despite the ability to reduce NOx emissions from the engine’s exhaust (Venu et al., 2019). The EGR system are also reported to have significant performance boost to a diesel engine especially at low engine loads (Verma et al., 2019).

One such research was done by Mahalingam et al.. The authors found out that with 20% EGR rate, the smoke, NOx and BTE dropped by 7.1, 5.1 and 4.4% respectively and the CO, HC emissions and BSFC increased by 2.1, 2.8 and 3.8% respectively (Mahalingam et al., 2018). Similar results can also be found by researchers done by Damodharan et al., Gong et al., Yu et al., Santhosh et al., and Y. Li et al. (Damodharan et al., 2018), (Gong et al., 2021), (Yu et al., 2019), (Santhosh et al., 2020) (Y. Li et al., 2019). He et. al. also studied that the ITE decreases with increased EGR rates (He et al., 2018). A research done by Veerabadran et al. was concluded that the use of 5% EGR produced the best engine performance when fueled with carbon nanotubes doped sunflower acid oil (Veerabadran et al., 2020). Venu et al. however, found that the BSFC levels of the engine had a slight increase for 10% and 20% EGR rates compared to no EGR rate using a 30% palm oil biodiesel fuel blend (Venu et al., 2019). Prakash et al. found that the most optimum HC and CO emissions was at 20% EGR rate compared to 10% and 30% EGR rates when using 20% pongamia methyl ester fuel blend (Prakash et al., 2020). Damodharan et al. found that the BTE under 10% EGR rates is the highest compared to higher EGR rates at different injection timings using neat waste plastic oil (Damodharan et al., 2018).

2.3.2 Intake Air Pressure

In an unmodified diesel engine, the intake air pressure that enters the engine's combustion chamber is at atmospheric pressure. This can be explained by the downward suction of the piston cylinder causing a vacuum pressure area in the cylinder. Supercharging is a method that increases the pressure of the intake air by compressing atmospheric air into higher boost pressure. This leads to more mass of air entering the combustion chamber thus, leading to more oxygen content and therefore producing a leaner, oxygen-rich fuel for combustion (Muqeem et al., 2015). Theoretically, with a higher oxygen content for combustion, it will be more likely for the formation of NOx molecules thus, leading to higher NOx emissions. Many researches had been done in this field.

One of the researches is done by Patel et al.. Patel et al. studied the effects of different air pressure as the intake in a dual-fuel engine. They used a fuel blend of biogas and diesel in their experiments (Patel et al., 2020). Their results shows that with higher intake air pressure, the BTE can reach up to an increment of 5% with higher brake specific energy consumption, BSEC. In terms of emissions, it is reported that the emissions of NOx, CO and HC decreased with higher intake air pressure levels.. However, when the intake air pressure is too high, the harmful gaseous emissions tend to increase due to formation of ultra-lean mixtures that decreases combustion efficiency in the engine. Similar findings can be found from researches done by (Di Battista et al. and Meng et al. (Di Battista et al., 2018) (Meng et al., 2019). Rocha et al. however, used a different approach. They studied the effects hydrogen enriched air to the intake air of a compresseion ignition engine (Rocha et al., 2017). They found out that the addition of hydrogen in the intake air results to a higher engine performance and reduction of CO_2 emissions. However, with higher percentages of hydrogen in the intake air, NOx emission levels tends to be higher as well. They explained that the hydrogen promotes rapid combustions with higher heat release rate and can be associated with higher tempreature levels inside the combustion chamber. Similar results were also acquired by Talibi et al. (Talibi et al., 2017) (Talibi et al., 2018). In both the researches, they used hydrogen in the intake air which is similar to the research done by Rocha et al. and Talibi et al. reported that with the addition of hydrogen in the intake air siupply, NOx emissions were seen to be directly proportional to the hydrogen supply while the percentages of CO and PM emission levels decreased.

2.3.3 Summary

Overall, there were various approaches in optimizing the performance and emissions of an engine through intake air supply control.

Majority of the researchers concluded that using higher EGR rates caused recirculation of exhaust gas into the combustion chamber that reduces the amount of oxygen for combustion. This causes a significant reduction in NOx emissions from the engine but on the other hand, increased the HC and CO emissions. On top of that, the researchers also found that BTE increases with increasing EGR rates while BSFC decreases with increasing EGR rates. Most of the researchers also found out that the most optimum point for NOx reduction with comparison to the HC and CO emission is at 10%-20% EGR rates.

Majority of the researchers also concluded that using higher pressures of intake air will result in better combustion of fuel and reduce harmful gaseous emissions such as NOx and CO which are mainly caused by incomplete combustions of fuel. However, extensive pressure levels will backfire and cause poor mixing of fuel and air in the combustion chamber thus, promoting more incomplete combustion.

2.4 Split Injection Strategies

Fuel injection plays an important role in achieving optimization in the performance of a diesel engine. Alongside with EGR systems, split injection strategies also contribute to the reduction in NOx emissions of the diesel engine but in a much more efficient way (Balamurugan & Gowthaman, 2021). In the split injection technique, parts of the fuel are injected into the engine compared to one single injection (R. Singh et al., 2019). studied that by using split injection strategies, the PM emissions can be reduced by 90% along with 50% and 35% reduction in HC and CO emissions respectively. Generally, there are a few varying parameters that could be adjusted in the split injection strategy.

2.4.1 Varying Injection Proportion

Researchers have found that in split injection strategy, the first injection or also known as the pilot injection plays an important role in the reduction of NOx emissions of the diesel engine. Higher proportions of the fuel in the pilot injection may lead to incomplete combustion due to insufficient air and lower proportions of fuel in the pilot injection might increase the NOx emissions due to heterogeneous mixture.

G. Li et al. studied that 25% of the total fuel should be supplied to the pilot injection for better engine performance (G. Li et al., 2019). However, Sindhu et al. and Zheng et al. both suggested that 25% of the total fuel should be supplied to the pilot injection for a better overall engine performance (Sindhu et al., 2018) (Zheng et al., 2015). How et al. discovered that the NOx emissions can be reduced up to 25% when using 25% pilot injection proportions (How et al., 2018). Similar results are also found by Kim et al. and Woo et al. that indicate a boost in performance up to 50% when using split proportions of fuel injection strategy compared to single injection (Kim et. al., 2012) (Woo et al., 2016).

2.4.2 Varying Injection Timing

Another parameter that can be considered in split injection strategy is time variation between each injection. Injection timing is a major parameter affecting the engine performance as well as its emissions (Gnanasekaran et al., 2016). The injection timing is usually measured with reference to the position of piston in ATDC or BTDC. How et al. concluded that the engine efficiency can be improved using 54° BTDC and 12° BTDC for the first and second injection respectively (How et al., 2018). G. Li et al. also discovered that 60° BTDC timing for the first injection resulted in maximum BTE (G. Li et al., 2019). Jain et al. concluded that the injection timing should not be too advanced as it might cause higher HC emissions from the diesel engine (Jain et al., 2017). The injection timing should not have high intervals as it may reduce the BTE and combustion performance due to low combustion temperatures (Park et al., 2018). Similar results can also be found from a research by Yang & Zeng where they found increase in NOx emissions with reduced HC and CO emissions using -240° CA ATDC compared to -500° CA ATDC (Yang & Zeng, 2018).

2.4.3 Varying Injection Pressure

Split injection can also be controlled by varying the injection pressure. Variation in the fuel injection pressure affects the heterogeneity of the air-fuel mixture thus affecting the NOx emissions of the diesel engine. Excessive pressure in the fuel injection causes a heterogenous mixture of fuel thus promoting the formation of NOx formation during combustion and vice versa (Edara et al., 2018). Fayad also explained that the heterogenous mixture from high injection pressures of fuel enhances the combustion in the combustion chamber (Fayad, 2020).

Edara et al. studied the engine performance by comparing split injection pressures from 200-350 bar in regular intervals and concluded that the engine produced better performance at 350 bar injection pressure (Edara et al., 2018). Yousefi et al. also reported that the BTE could be increased by 36.6% at 800 bar injection pressure

(Yousefi et al., 2018). However, M. R. Herfatmanesh et al. found that the NOx emissions could be increased at the pressure of 800 bar due to peak combustion temperatures (M. R. Herfatmanesh et al., 2011). Similar results were also studied by Emiroğlu and Rajak et al. using butanol-diesel blends and microalgae-diesel emulsion respectively (Emiroğlu, 2019) and (Rajak et al., 2019).

2.4.4 Summary

Overall, there are many researches done on the effects of different injection strategies on the engine performance and emissions. From the literature review, majority of the researchers agree that multiple fuel injections produced better engine performance and have cleaner emissions compared to single fuel injection. During the splitting of fuel injection, the proportions of the pilot injection also play an important role in engine performance. High pilot injection proportions increase the CO emissions due to incomplete combustion and low pilot injection proportions increase the NOx emissions due to heterogenous fuel mixture. Therefore, the optimization point has to be studied between the CO and NOx emissions. In the injection timing variation, the researchers explained that the high dwell time causes decrease in engine performance. Similarly with pressure, higher injection pressure promotes NOx formation whereas lower fuel injection pressure affects the engine performance.

Therefore, a balance between the discussed parameters must be studied to achieve the most optimal engine performance and optimal balance between NOx, CO and HC emissions form the engine.

CHAPTER 3

METHODOLOGY

3.1 Engine Dynamometer Bed Preparation

The engine used for this researched is a diesel engine taken from a Renault Kangoo. It is also known as the K9K engine by the manufacturer and is debuted in the year 2001 in the Renault Clio II. The engine specifications are shown in Table 3.1. Before the start of the experiment, a few subsequent steps are set up onto the engine. In this project, new apparatus such as the throttle valve, EGR valve and OBD data acquisition systems has been imposed onto the existing research engine testbed. Alongside with those improvements, the throttle pedal has been improved from using mechanical pedal control to electronic signal control for better precision and accuracy. A summary of the new research engine testbed is represented in Figure 3.1

Table 3.1: Engine Specification

Type of Engine	Diesel, 4-stroke, turbocharged direct injection engine
Fuel Injection System	Diesel common rail
Cylinder	4
Valve per Cylinder	2
Bore x Stroke	76.0 mm x 80.5 mm
Connecting Rod Length	135 mm
Displacement	1461 cm^3
Compression Ratio	18.25: 1
Maximum Power & Torque	48kW @ 4000 rpm & 160 Nm at 2000 rpm

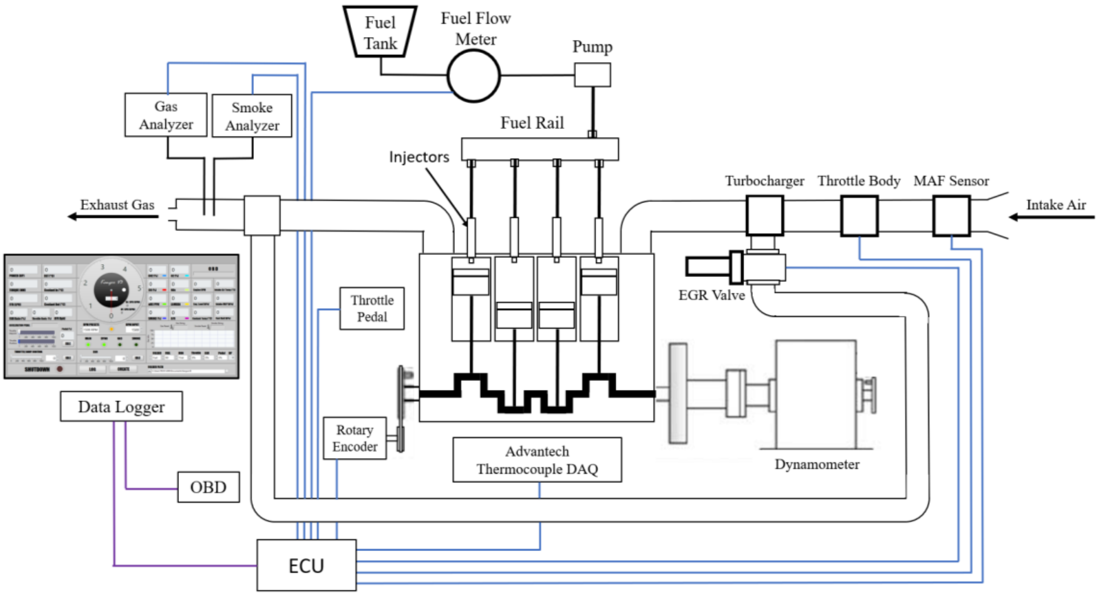

Figure 3.1: Schematic Representation of New Research Engine

3.1.1 Conversion of Mechanical Throttle Actuation to Simulated Electrical Signal.

The existing setup for the acceleration pedal is shown in Figures 3.2 and 3.3. Currently, the accelerator pedal is pulled by a throttle cable controlled by a 12V servo motor. Originally this setup simulates the action of a driver giving a throttle input via the pulling action of the servo motor on the mechanical pedal. However, excessive use from previous researchers have caused the throttle cable which is connected between the pedal and servo motor to have wear and show signs of snapping. Therefore, a simulated electrical signal is implemented to control the throttle pedal without mechanical means to reduce the risk of mechanical failure.

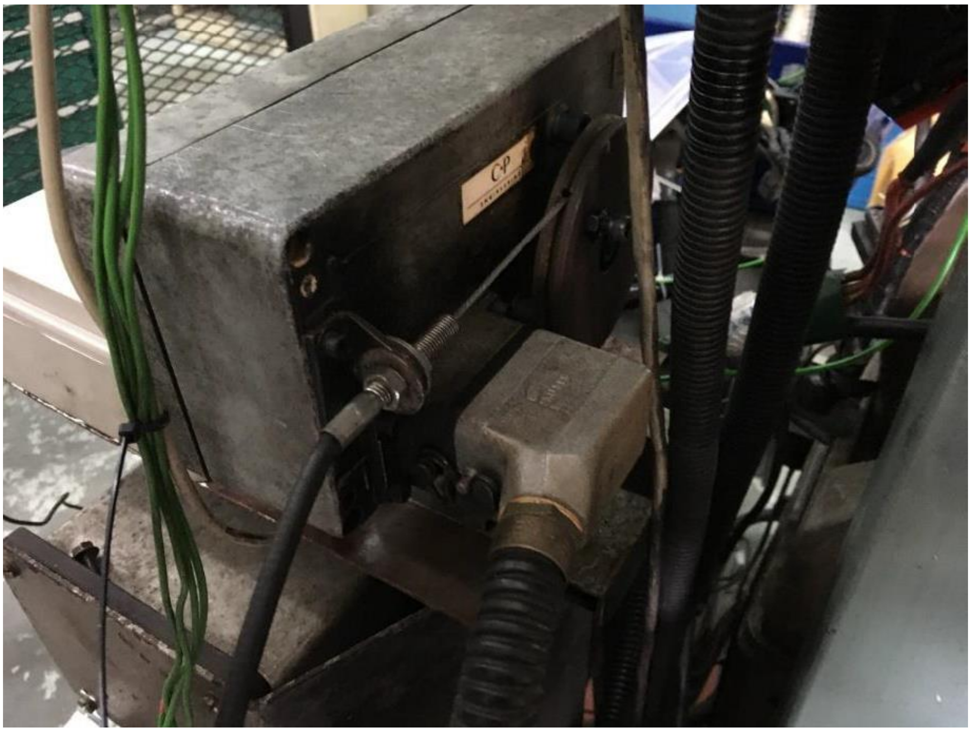

Figure 3.2: Throttle Cable Connected to a 12V Servo Motor

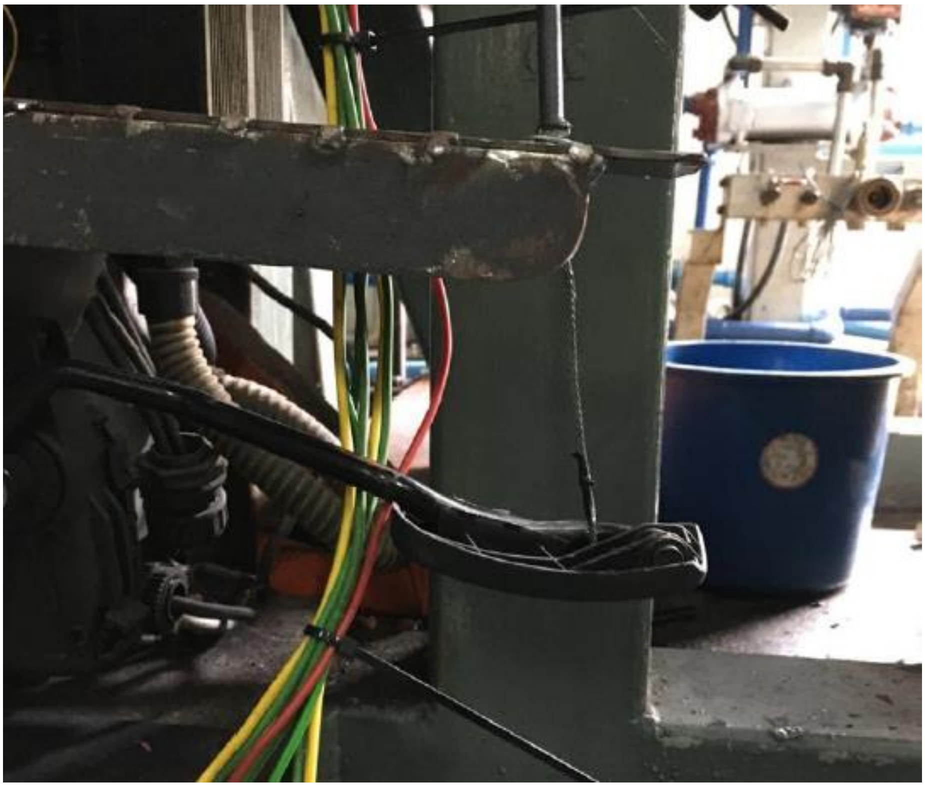

Figure 3.3: Accelerator Pedal Pulled with Throttle Cable

The pinouts for the acceleration pedal are determined for the measurement of potential difference and is recorded in Table 3.2 together with the functions of the pins which is shown in Figure 3.4. The potential difference across the pedal were recorded beforehand to determine the voltage values for wide open throttle (WOT) and fully closed throttle. Theis is done by measuring the voltage values between the signal pins and their respective ground pins using a multi-meter. The throttle pedal is also left constant around the middle position between the WOT and fully closed throttle and the potential difference values at that particular point was also recorded and tabulated in Table 3.3. This step is done to verify that the increase and decrease in potential difference values are linear throughout the movement of mechanical throttle. A graph is plotted to indicate the linearity of the potential difference values between the two internal potentiometers and can be shown in Figure 3.5.

Table 3.3: Pinouts for Acceleration Pedal

Pin Number	Function
1	Signal 1
2	5V_1
3	5V_2
4	Signal 2
5	GND_2
6	GND_1

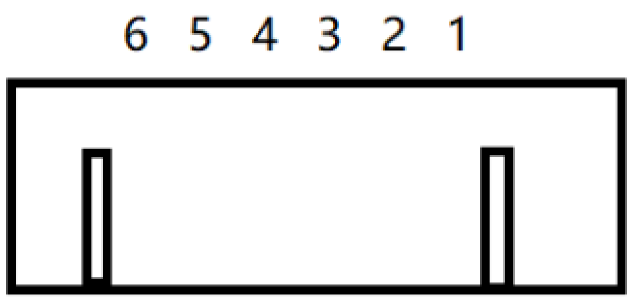

Figure 3.4: Pinouts for Acceleration Pedal