DEVELOPMENT OF ELECTRONICALLY CONTROLLED COMMON RAIL FUEL INJECTION SYSTEM AND OPTIMIZATION OF INJECTOR PARAMETERS IN SINGLE CYLINDER DIESEL ENGINE

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF NOTATIONS AND ABBREVIATION

°CA	Degree Crank Angle
BTDC	Before Top Dead Center
CAD	Computer Aided Design
CI	Compression Ignition
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COV	Coefficient of Variation
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECM	Engine Control Module
ECU	Engine Controller Unit
EGR	Exhaust Gas Recirculation
EOI	End of Injection
EU	European Union
GHG	Greenhouse Gas
Gt	Giga tonnes
HC	Unburned Hydrocarbon
HRR	Heat Release Rate
IC	Integrated Circuit
IEA	International Energy Agency
IMEP	Indicated Mean Effective Pressure
Mtoe	Million Tons of Oil Equivalent
NO_x	Nitrogen Oxide
O_2	Oxygen
Pa	Pascal
PID	Proportional-Integral-Derivative
PM	Particulate Matter

PRR	Pressure Rise Rate
PWM	Pulse-Width-Modulation
rpm	Revolution per Minute
RSM	Response Surface Methodology
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SOI	Start of Injection
TDC	Top Dead Center
VOC	Volatile Organic Compound

ABSTRAK

Kebelakangan ini, permintaan tenaga seluruh dunia telah berkembang pesat disebabkan oleh pertumbuhan populasi, pembangunan teknologi dan perindustrian. Sektor pengangkutan adalah pengguna utama bahan minyak dan menghasilkan banyak bahan pencemar udara. Penggunaan enjin diesel berdasarkan pencucuhan mampatan semakin popular kebelakangan ini. Walau bagaimanapun, ia mengeluarkan nitrogen oksida (NOx) dan jirim zarahan (PM) yang tinggi dan akan menyebabkan isu kesihatan. Kawalan parameter pancitan bahan api yang tepat boleh meningkatkan prestasi enjin diesel dan mengurangkan pelepasan yang merbahayakan. Projek ini bertujuan untuk menukar sistem suntikan pam-saluran-nozzle sebuah enjin silinder tunggal dengan kepada sistem pancitan rel sepunya dan mengoptimumkan parameter-parameter pancitan. Pada mulanya, sistem penyampaian bahan api telah dipasang dan unit pengawal enjin (ECU) telah dibentukkan. ECU yang dibentuk adalah berdasarkan mikropengwawal Arduino, Arduino Mega dan Arduino Uno telah digunakan. Pengoptimuman parameter-parameter penyuntik dilakukan dengan perisian reka bentuk eksperiment dan penilaian pada keadaan optimum telah dilakukan. Peratusan ralat untuk pengoptimuman adalah kurang daripada 5%. Eksperimen telah dijalankan untuk menilai sistem pancitan rel sepunya yang telah dibinakan. Keputusan menunjukkan bahawa ECU yang dibentuk mampu mengawal masa pancitan, tekanan pancitan dan jumlah pantican dalam satu kitaran.

ABSTRACT

Recent year, global energy demand grew rapidly due to growth in population, technology development and industrialization. The transportation sector is the major consumer of oil and produces a lot of air pollutants. Compression ignition diesel engine is gaining popularity over the year. However, it emits high nitrogen oxide (NO_x) and particulate matter (PM) that cause health hazards. Precise control of fuel injection parameters can improve the diesel engine performance and reduce harmful emissions. This project aims to convert a single cylinder engine with pump-line-nozzle injection system to common rail injection system and optimize the injector parameters. At first, fuel delivery system has been installed and Engine controller unit (ECU) has developed. The ECU is based on Arduino microcontrollers, Arduino Mega and Arduino Uno were used in the development. Optimization of injector parameter is carried out by design of experiment software, and evaluation of optimum condition is performed. The percentage of error for optimization is less than 5%. Experiments have been carried out to evaluate the developed common rail fuel injection system. The results indicated that the developed ECU is capable to control injection timing, injection pressure and number of injections per cycle.

CHAPTER 1: INTRODUCTION

1.1 Global energy demand and prediction

Energy is now an essential to our life nowadays. The demand of energy worldwide has increased rapidly due to the growth in population, technology development and industrialization. The world population has reached 7.4 billion in 2015 with 1.1% of annual growth and estimated to reach 9.2 billion in 2040 which will further increase to 11.2 billion in 2100 as shown in Figure 1.1 (United Nation, 2017). The additional number of people will require energy. The global energy demand is estimated to increase by about 25% from 2016 to 2040 (ExxonMobile, 2018). The demand growth will come from non-OECD country and lead by China and India, where the energy demand is expected to increase by roughly 40% as shown in Figure 1.2. For Association of Southeast Asian Nations (ASEAN), the total primary energy demand in 2016 is 643 Million tons of oil equivalent (Mtoe) and is predicted will rise to 1133 Mtoe in 2040 with average annual growth rate of 2.1% (International Energy Agency (IEA), 2017). In addition, Indonesia is predicted to be the fifth largest energy consumer in the world as it will exceed Japan’s energy consumption in 2035. Figure 1.3 shows the primary energy consumption in ASEAN from 2011 to 2040 (Mofijur et al., 2015).

In general, crude oil, coal and natural gas are the primary source of energy. ASEAN countries are heavily dependent on fossil fuel. It is forecasted that, in ASEAN, the contribution of fossil fuel to the total energy demand will increase from 77% to 79% from 2016 to 2040. Coal and oil demand will increase by 40% while natural gas demand will increase by 60% over the same period as illustrated in Figure 1.4 (International Energy Agency (IEA), 2017). By referring to Figure 1.5, energy demand by sector in ASEAN for 2011 and 2035. The transportation sector is the major consumer of oil with energy demand growth of nearly doubles and the industrial sector is the highest energy consumer (International Energy Agency (IEA), 2013).

As we all know, fossil fuels are limited resources that will eventually exhaust. Based on current fossil fuel reserves, coal will be depleted in 115 years, oil and natural gas will be depleted in around 50 years (BP, 2016). Combustion of fossil fuels produces carbon dioxide (CO_2), nitrogen oxide (NO_x), unburned hydrocarbon (HC) and volatile organic compounds (VOC) that cause air pollution. CO_2 is the primary greenhouse gas (GHG) contributor and the emission is rapidly increasing in developing and transition countries especially China, India and ASEAN. The total CO_2 emission from these countries is responsible for more than 50% of global emission (Behera and Dash, 2017). Figure 1.6 indicates global CO_2 emission by source (Virginie Marchal, 2011). Based on the figure, transport CO_2 emissions are projected to double between 2010 and 2050 because of a strong increase in demand for cars in developing countries and growth in air transport. According to the IEA (International Energy Agency (IEA), 2013), the energy related CO_2 emission of ASEAN will increase from 1.2 Gt (Giga ton) in 2011 to 2.3 Gt in 2035, which is equivalent to 6.1% of global emission, as can be seen in Figure 1.7. If the effect of CO_2 emission on global warming is overlooked, with 2 ℃ rise in global temperature can cause up to hundreds of millions of lives (Liaquat et al., 2010). Global warming and climate change are taken seriously by European Union (EU) countries. As response to the environmental effects due to transport section, two pathways have introduced by EU independently. The first way is to promote the use of biofuels and other renewable fuels for transport to reduce the GHG emissions and the second way is through emissions regulation of diesel-powered vehicles (Gilpin et al., 2014). It is obvious that the world is facing fossil fuel depletion and climate change crises. A diesel engine incorporates with advance control system is required to increase the engine efficiency and meet the emissions standards.

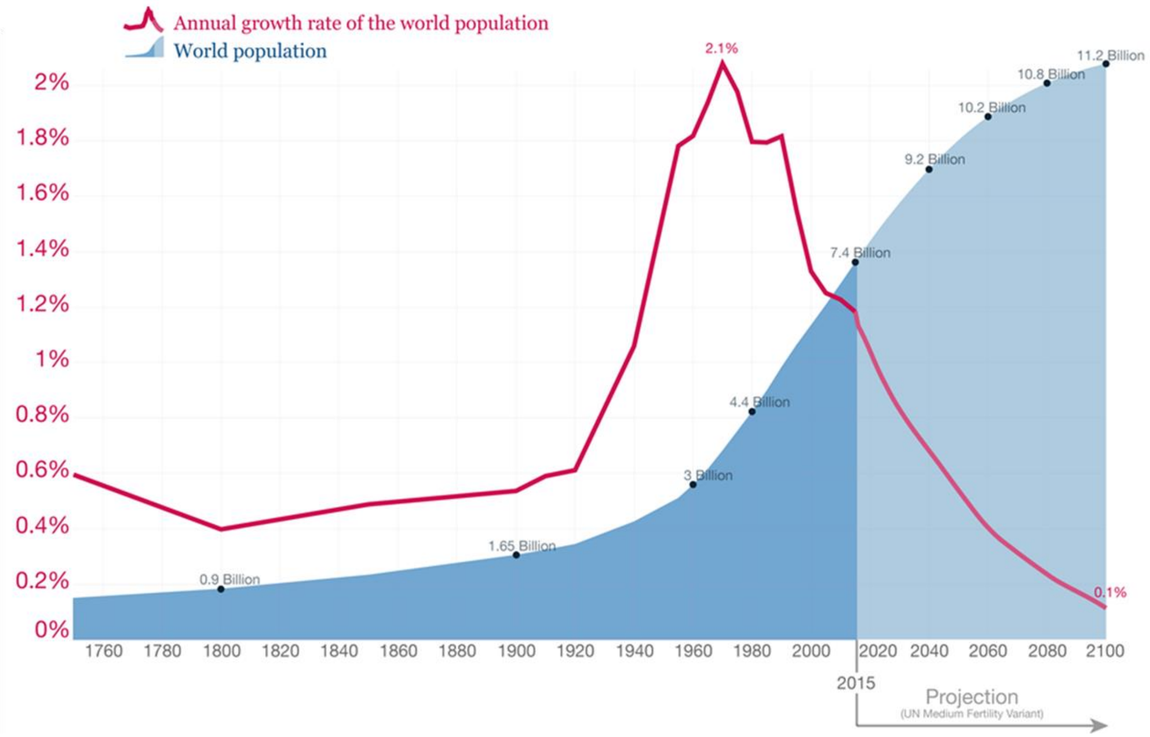


Figure 1.1: World population, 1750 to 2015 and projections until 2100.

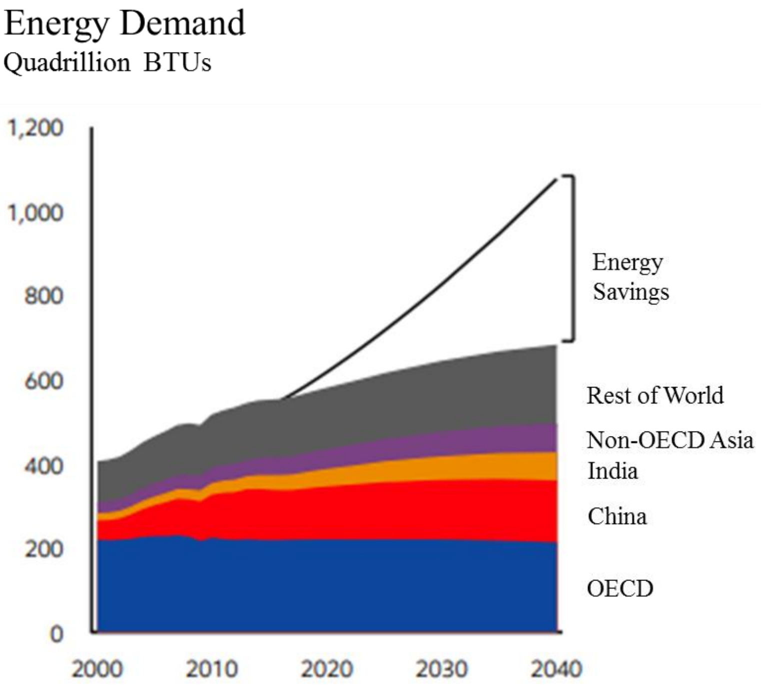


Figure 1.2: Global energy demand and estimation (ExxonMobile, 2018).

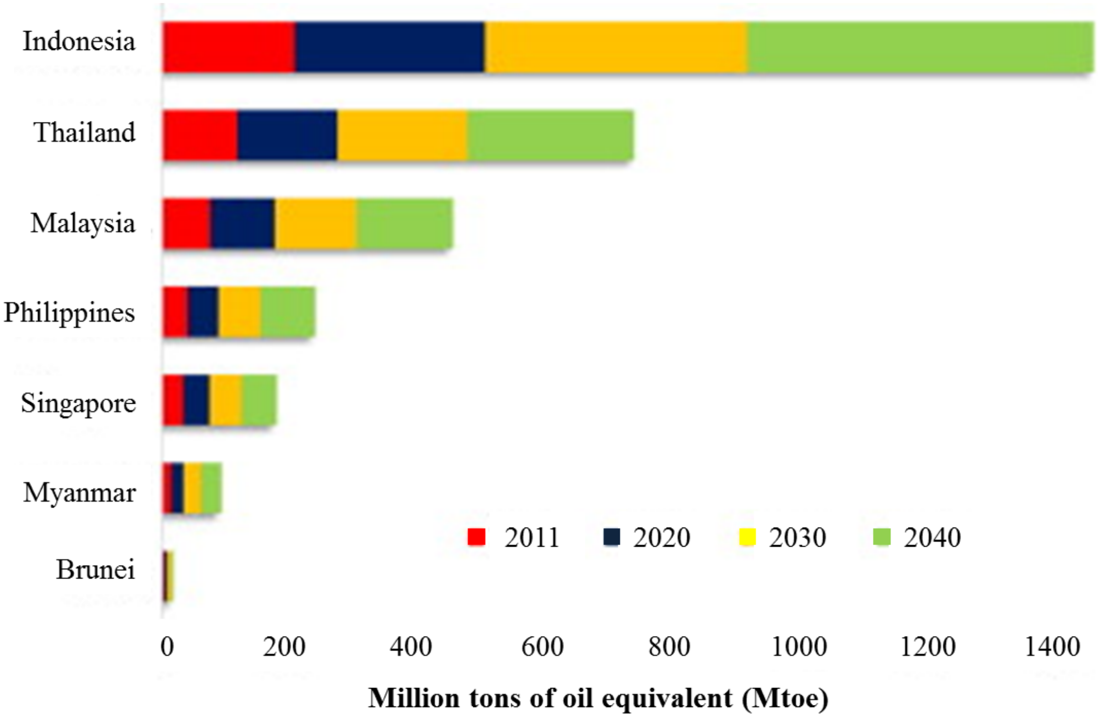


Figure 1.3: Primary energy consumption from 2011-2040 in ASEAN.

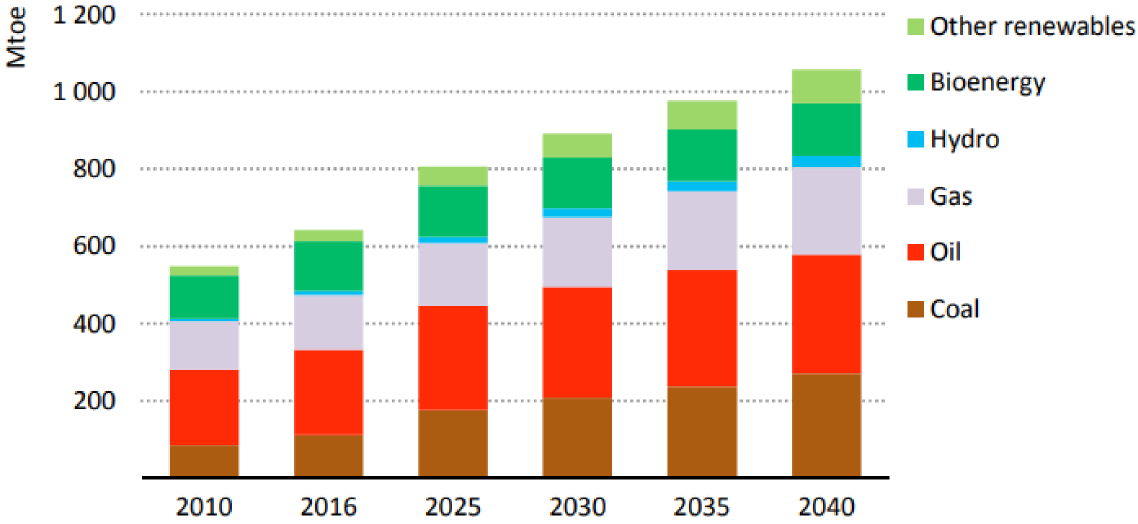


Figure 1.4: Primary energy demand in ASEAN by fuels type.

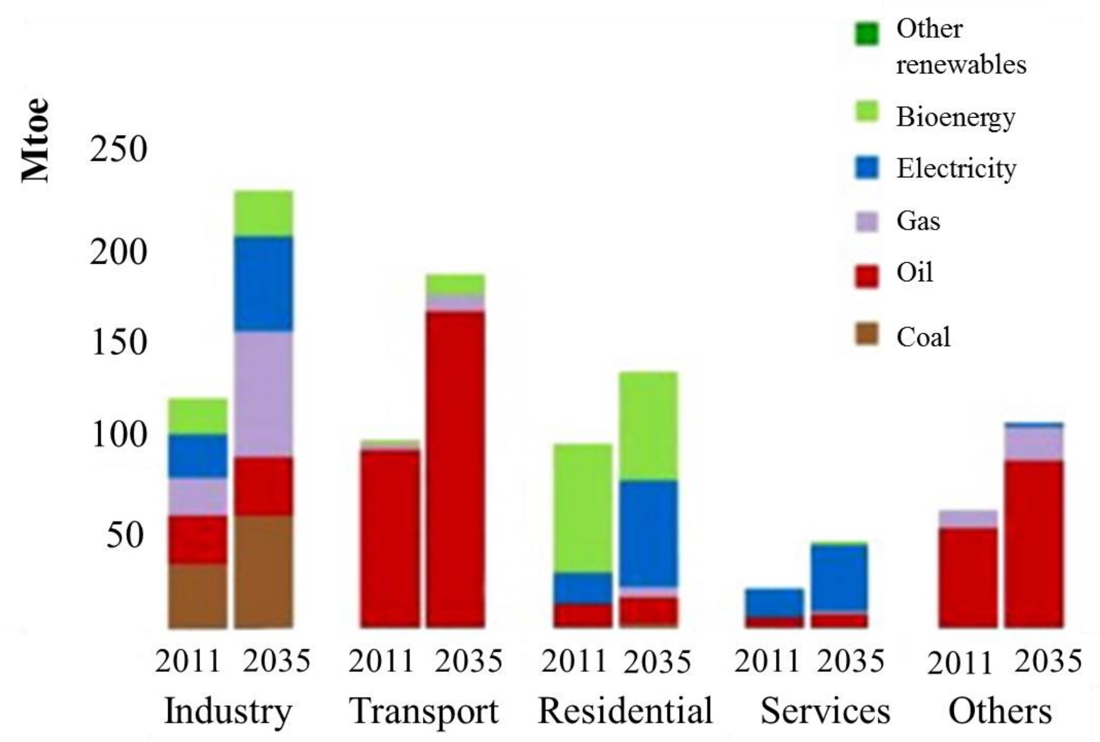
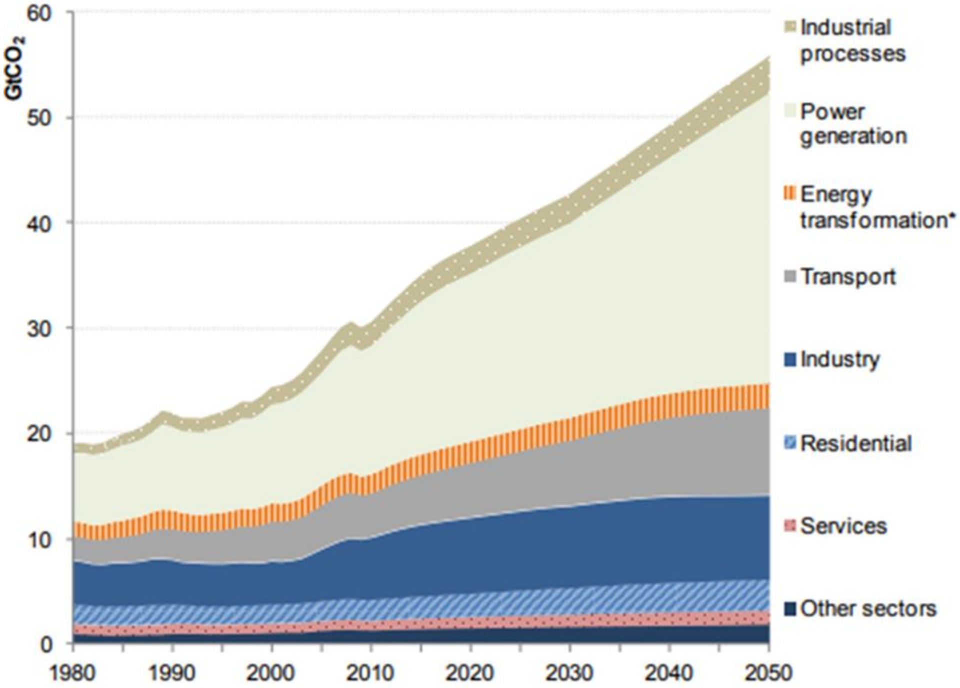


Figure 1.5: Energy demand by sector in ASEAN.



*Included emissions from oil refineries, coal and gas liquefaction

Figure 1.6: Global CO_2 emissions by source from 1980 to 2050.

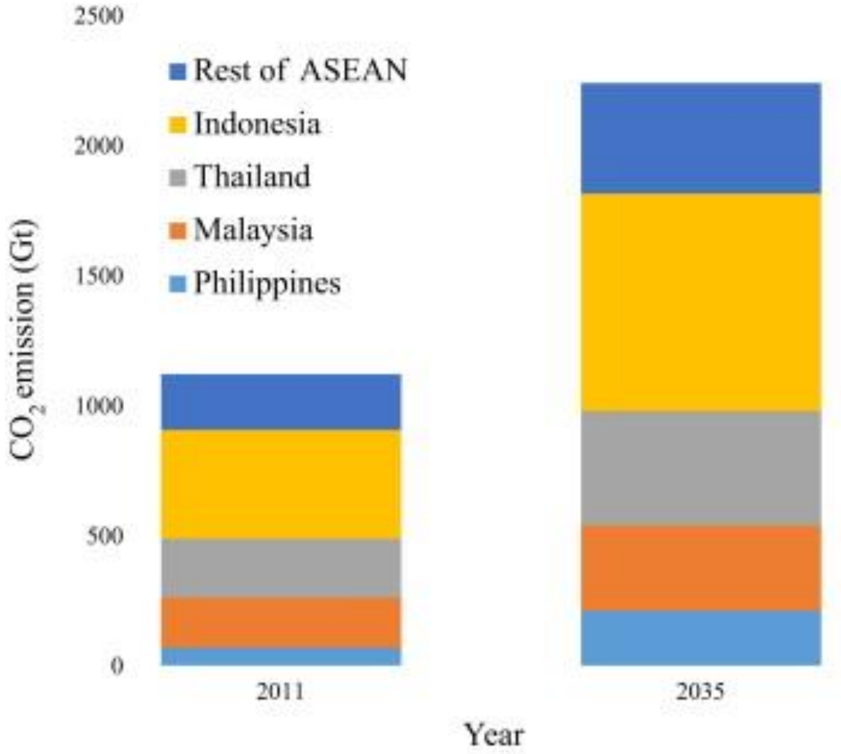


Figure 1.7: Energy related CO_2 emission in ASEAN.

1.2 Background

Internal combustion engine is an energy conversion device that was invented more than a century ago and ever since then, it plays a huge role in the transportation sector. Generally, two types of internal combustion engine are used in transportation, namely: Spark ignition (SI) and Compression ignition (CI) engine. CI direct injection diesel engine is favourable prime movers due to its high thermal efficiency. The superior in thermal efficiency of CI engine is because of its higher compression ratio. Diesel engines have been used widely not only in heavy-duty vehicle and marine transportation, but also in light-duty vehicles, especially in Europe and Japan. As indicated in Figure 1.8, 55% of all new cars registered in Western Europe in 2012 are powered by diesel engine as compared to only 14% in 1990. However, the CI diesel engine emits high NO_x and particular matter (PM) emissions (Tamilselvan et al., 2017). These emissions cause undesired human health problems (Wierzbicka et al., 2014) and environmental degradation, hence they are subjected to federal government regulations (Mohan et al., 2013). Over the decades, regulations on emissions from diesel powered vehicles have drastically stringent in the United States, Europe and Japan as shown in Table 1.1.

Performance of diesel engines is heavily affected by their fuel injection system design. Fuel must be injected in the correct timing and amount into the cylinders. Due to progressively tightened emissions standard, automakers have to come out with new technology to reduce the emissions. Conventional pump-line-nozzle injection system has lower injection pressure and poor flexibility control over fuel injection timing. This is because both fuel pressure and injection timing is dependent on engine speed as they are timed by the camshaft. Common rail fuel injection system has eliminated cam driven fuel injection systems and dominated as the primary fuel system. It offers high degrees of freedom for combustion optimization and has significant advantages. The key advantage of a common rail system is its independence. The fuel pressure and injection event are controlled electronically and independently of the engine speed. Besides, the common rail injection system also able to increase the injection pressure to a very high extends (up to 2700 bar for Robert Bosch CRS 3-27 common rail injection system) and helps to improve the engine performance and reduce the harmful emissions (Tan et al., 2012).

Other than that, utilization of clean alternative fuel (Sajjad et al., 2014), new combustion mechanism (Saxena and Bedoya, 2013) and exhaust emissions after-treatment (Schmitt and Parmentier, 2013) in diesel engine reduced the harmful emissions. Although these strategies can effectively reduce the emission of diesel engine, but there is also some trade-off in term of performance. Take exhaust gas recirculation (EGR) as an example, it can effectively reduce NOx emission, but over use it will cause higher fuel consumption and soot emission (Abaas, 2016). Besides, exhaust gas after-treatment system has proven their effectiveness in controlling diesel engine emissions such as diesel oxidation catalyst (DOC) to control CO, and HC emissions, selective catalytic reduction (SCR) to control NOx emissions and diesel particulate filter (DPF) to control PM emissions (Reşitoğlu et al., 2015). However, implementation of these systems increases the complexity of the engine and hence increases the cost (Posada et al., 2016).

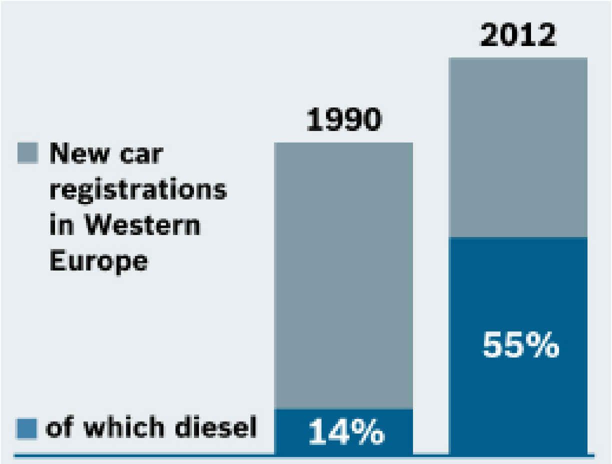


Figure 1.8: New car registered in Western Europe in the year 1990 and 2012 (Robert Bosch, 2013).

Table 1.1: Emission standard for NO_x and PM for heavy duty diesel powered vehicles in United States, European Union and Japan (TransportPolicy.net, 2014, Johnson Matthey, 2016)

Region	**Implementation year**	**Emission Standard (g/kWh)**	
		NO_x	**PM**
United States	1998	5.4	0.13
	2004	2.7	0.13
	2007	0.27	0.013
European Union	2005	3.5	0.02
	2008	2.0	0.02
	2013	0.4	0.01
Japan	2005	2.0	0.027
	2009	0.7	0.01
	2016	0.4	0.01

1.3 Problem statement

Common rail injection system is widely used in passenger cars and trucks. However, due to the cost issue, it is rarely found a single cylinder engine quipped with electronically controlled fuel injection system. The available single cylinder diesel engine is equipped with mechanical fuel injection system. This conventional single injection mechanical fuel injection system is cam driven by predetermined injection parameters. Conversion of fuel injection system and development of engine controller unit (ECU) has to be done to provide flexibility in controlling engine's injection parameters such as injection timing, injection pressure and number of injections per cycle of operation to enable a more advanced combustion study.

1.4 Objective

The objectives of the project are as follows:

1. To convert and develop common rail fuel injection system for a single cylinder diesel engine equipped with conventional mechanical fuel injection system.
2. To optimize the injector parameters based on response surface methodology (RSM).

1.5 Scope of work

The scope of this project is as follows:

1. Convert a conventional mechanical fuel injection system to high pressure common rail fuel injection system.
2. Develop an engine controller unit (ECU) based on the Arduino microcontrollers to control the injection timing, injection pressure and number of injections per cycle.
3. Optimize the injector parameters (Open Time, Low Time and duty cycle) based on RSM.
4. Evaluate the developed ECU capability in control injection timing, injection pressure and number of injections per cycle based on combustion curve.

1.6 Chapter outline

This thesis consists of five chapters with the outline as follows:

- Chapter 1 begins with an overview of current and future prediction for global energy demand. Through background study, the technologies implemented in diesel engine in order to achieve higher efficiency and meet the tightening emission standards have been defined. This chapter also included the problem statement, objectives and scope of work for this project.
- Chapter 2 provides the literature review for previous studies in related areas. The regulation and emission standards for diesel engine all over the world, strategies to reduce diesel engine emission have been reviewed. Working principle of the common rail injection system and conservations that have been carried out as well as optimization process are also included.
- Chapter 3 indicates the methodology of this project. In this chapter, conversion of fuel injection system, development of ECU and optimization process is detailed.
- Chapter 4 presents all the results of this project and the results has been evaluated and discussed with reference of previous studies.
- Chapter 5 draws the conclusion for this project and recommendation for future work that can be continued with the converted engine.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This literature review consists of five sections, starts with fundamental of internal combustion engine and diesel engine emissions regulation and standards. This is followed by review of emissions improvement strategies of diesel and working principle of the common rail injection system. After that, the review continues with the conversions of common rail injection system that have been done and lastly the optimization methodology used in this project.

2.2 Fundamental of internal combustion engine

Internal combustion engine is an energy conversion device that was invented more than a century ago. It extracts mechanical power from combustion/oxidation of fuels. The working principle of an internal combustion engine is simple, but required complex controls in a lot of aspects to achieve high engine efficiency as well as low emissions. The cycle of internal combustion engine begins by drawing air into the engine combustion chamber. Then the air inlet valve of combustion chamber will be closed and formed an enclosed volume that will be compressed. After that, fuel is combusted and increases the temperature and pressure of the compressed air inside the enclosed combustion chamber. With the increased in pressure, the air expanded and exert force on the piston of the engine to produce power. Finally, the exhaust gases (combusted products) are discharged from the combustion chamber through the exhaust valve and ready for next cycle. Of course, the processes are far more complicated in real application, but the working principle remains unchanged for every internal combustion engine. Internal combustion engine is categorized into SI and CI engine based on the method of fuel ignition. In 1876, the SI gasoline engine was developed by Nikolaus Otto and later in 1892, CI diesel engine was developed by Rudolf Diesel. The engines can be further categorized into two-stroke and four-stroke cycle engine based on their operating cycle.

2.3 Diesel engine emissions regulation and standards

In general, the combustion process and heat release curve of a CI diesel engine is divided into four phases as shown in Figure 2.1. The four phases are known as ignition delay, premixed burning, mixing controlled combustion and late burning phase (Heywood, 1988). The duration from the start of fuel injection to the start of fuel combustion is the known as ignition delay. After that, a rapid heat release from the combustion of fuel that premixed with air and accumulated during the ignition delay phase happens in the premixed combustion phase. After the initial rapid premixed burning, a comparatively slower and controlled mixing combustion takes place. This phase is majority controlled by the fuel atomization, air fuel mixing and chemical reactions. In late combustion phase, the heat release slowed down and extended itself into the expansion stroke. Ideally, the complete combustion of diesel fuel in diesel engine will only produce CO_2 and H_2O. However, due to various reasons such as cycle-to-cycle air-fuel ratio variation, ignition timing, combustion temperature and so on, harmful products are produced during fuel combustion. The most significant harmful emissions are CO, HC, NO_x, and PM that cause environmental and health hazard (Hoeft et al., 2012, Weijers et al., 2001, Kampa and Castanas, 2008).

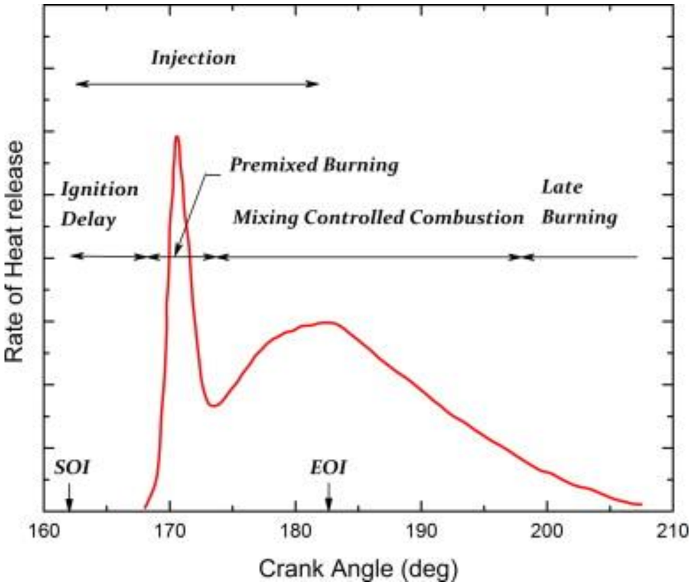


Figure 2.1: Typical heat release curve of CI diesel engine (Mohan et al., 2013).

The emission standards are different for different country. The European Union's emission regulations for light-duty vehicle are known as Euro 1 to Euro 6 while for heavy-duty engines is known as Euro I to Euro VI. Summary of the European Union's emission standards and their implementation dates are shown in Table 2.1. From the table, we can notice that the emission has been progressively tightened, especially for PM and NO_x. Other than European Union, United State, Japan and China also introduced their own emission standards. Figure 2.2 shows the timeline for worldwide emission standards and testing procedures. It is expected that the emission standard will continue to stringent over the years. The first heavy-duty engines emission standard (Euro I) was introduced in 1992 (DieselNet, 2012). Malaysia begins to adopt European Union's emission standard from year 1997 and aim to actualize Euro 5 by the year 2025 (Malaysia Online, 2016, Clean Air Asia, 2016).

Table 2.1: EU emission standards for heavy-duty diesel engines: steady-state testing (DieselNet, 2012).

Stage	**Implementation Date**	**Test**	**CO**	**HC**	**NOx**	**PM**
			g/kWh			
Euro I	1992, ≤ 85 kW	ECE R-49	4.5	1.1	8	0.612
	1992, > 85 kW		4.5	1.1	8	0.36
Euro II	1996.1		4	1.1	7	0.25
	1998.1		4	1.1	7	0.15
Euro III	1999.10 EEV only	ESC & ELR	1.5	0.25	2	0.02
	2000.1		2.1	0.66	5	0.10[a]
Euro IV	2005.1		1.5	0.46	3.5	0.02
Euro V	2008.1		1.5	0.46	2	0.02
Euro VI	2013	WHSC	1.5	0.13	0.4	0.01
a - PM = 0.13 g/kWh for engines < 0.75 dm^3 swept volume per cylinder and a rated power speed > 3000 rpm						

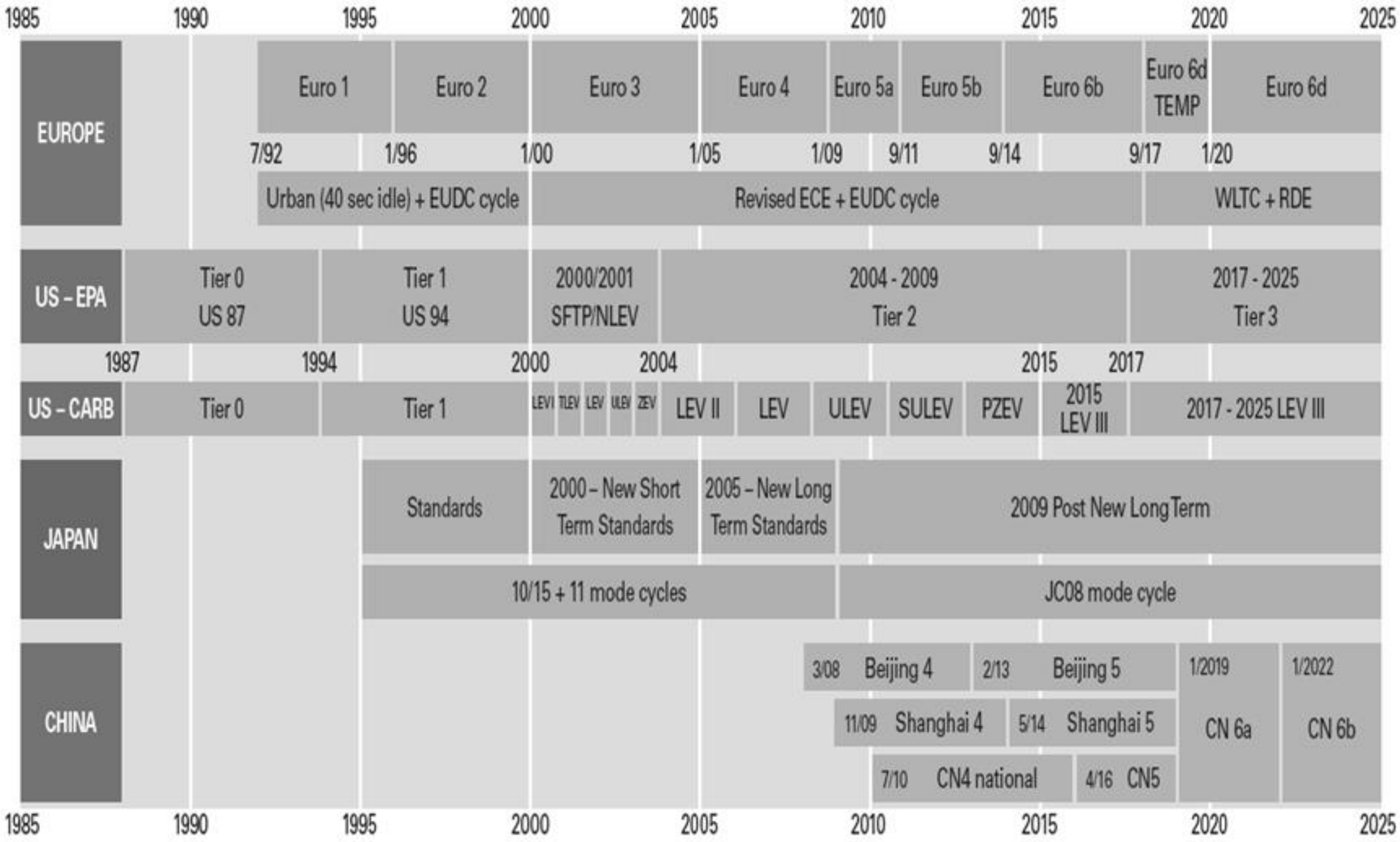


Figure 2.2: Timeline for worldwide emission standard and testing procedure (Delphi, 2017).

2.4 CI engine's emission improvement strategies

Majority studies in CI engines are comparing between diesel and biodiesel. Biodiesel fuel has higher cetane number (CN), does not contain sulphur and aromatic contents, renewable and biodegradable (Semwal et al., 2011). Biodiesel can be produced from vegetable oil, animal fats and waste cooking oil (Buyukkaya, 2010). In general, the use of biodiesel in CI engine significantly reduces emission of HC, CO and soot compared with fossil fuel diesel but with a trade-off of increases the emission of NO_x and BSFC (Rashedul et al., 2014, Sivalakshmi and Balusamy, 2013). The increase in formation of NO_x is due to the oxygen content in biodiesel. The increased in oxygen level causes excess hydrocarbon oxidation lead to high local temperature and increase the maximum temperature of combustion. The increase of BSFC of biodiesel is due to its higher density and lower calorific value (Buyukkaya, 2010, Dhar et al., 2012). Through fuel modification only, the target of reducing NO_x emission seems difficult to be achieved. Therefore, adjustments in engine operating parameters such as injection strategies and exhaust gas recirculation (EGR) are implemented to compensate the difference between biodiesel and diesel in combustion characteristics.

Injection parameters such as injection timing, injection pressure and injection duration play a very important role in the performance and emissions of diesel engine. Various studies have indicated that injection timing retardation reduces NO_x emissions (Natarajan et al., 2017, Ashok et al., 2017, Lim et al., 2014, How et al., 2018). This is because retarding the injection timing reduces the maximum combustion temperature and pressure in the cylinder and hence decreases the formation of NO_x. On the other hand, the emission of HC and CO decrease in advanced injection timing. A study performed by Agarwal et al. (Agarwal et al., 2013) on the effect of fuel injection timing on a single cylinder diesel engine using diesel. The results showed that both HC and CO emission decreases, but NO_x emission increase significantly with advanced injection timing. Park et al (Park et al., 2013) also reported with advancement in injection timing, both HC and CO emissions reduced significantly. Another important injection parameter is the injection pressure. In general, increasing the injection pressure will improve fuel atomization results in better air fuel mixing, shorten the ignition delay and more complete combustion (Khalid and Manshoor, 2012, Chen et al., 2013, Srinath Pai et al., 2013). With the increase in injection pressure, the fuel droplet diameter and the variation became smaller (Chen et al., 2013). This improves the air fuel mixing and rapid evaporation of fuel that lead to complete combustion and reduces the HC, CO and soot emissions (Hwang et al., 2014, Aalam et al., 2016). However, the NO_x emission increases with the increase of injection pressure (Nanthagopal et al., 2016, Gumus et al., 2012, Tan et al., 2012). This is due to reduce in ignition delay, lead to higher heat released in premixed phase and increase the in-cylinder temperature (Labecki and Ganippa, 2012, Srinath Pai et al., 2013).

Multiple fuel injection strategies have been proven to reduce the CI engine emission (Sperl, 2011, Wang et al., 2015). Figure 2.3 shows the typical multiple injections used in CI engine. As shown in the figure, pilot injection can help to reduce the engine noise and NO_x emissions (Busch et al., 2015). Main injection with fully open needle (rectangular shape) or boost type shape will also reduce NO_x emissions and post injection reduce the soot emissions (Badami et al., 2002, S. d'Ambrosio and A. Ferrari, 2015). Zhuang et al (Zhuang et al., 2014) studied the effect of multiple injection strategies in four-cylinder diesel engine. The effects of main injection timing, pilot injection quantity and timing as well as post injection quantity and timing have been investigated. They reported early pilot injection with retarded main injection reduces NO_x emissions and combustion noise while retarded main injection with post injection reduce NO_x and soot emissions. However, injection quality and timing have to be controlled precisely.

Another effective method to reduce NO_x emissions in diesel engine is by using EGR technique. Part of the engine exhaust gases is rerouted back to the combustion chamber via the inlet system with a control valve. EGR displaces portion of the fresh air inlet (O_2) with diluents (CO_2 and H_2O) and acts as a heat sink which can delay the auto-ignition timing, reduce the heat release rate, and thus lower peak cylinder pressure to suppress the NO_X formation (Yao et al., 2009, Thangaraja and Kannan, 2016). There are two types of EGR: internal and external EGR. The internal EGR rate is obtained by trapping the exhaust gas through changing period of valve overlap whereas external EGR rate is controlled by the combination of exhaust back-pressure valve and EGR valve (Nishi et al., 2016). A summary of the EGR effect on diesel engine is provided in Figure 2.4. However, using only EGR has some significant disadvantages such as reduce energy efficiency and higher HC, CO and soot emissions (Thangaraja and Kannan, 2016). Hence, researchers focus on investigating the effects of combination of biodiesel and EGR. The results of combining biodiesel and EGR show it is an effective strategy to reduce NO_x (Yasin et al., 2015). Rajan and Sethilkumar (Rajan and Senthilkumar, 2009) investigated the effect of sunflower methyl ester (SFME) biodiesel on four stroke diesel engine with employing EGR technique. They found that there is a 25% NOx emission reduction on at the same level soot emissions with 15% EGR rate. Investigation of Saleh (Saleh, 2009) on operating an diesel engine with Jojoba methyl ester (JME) with implementation of EGR has found that the BSFC decreased with EGR rate of 5% at 25% load and 1600rpm. The results also show that for all operating conditions, a better trade-off between HC, CO and NOx emissions can be attained with low EGR rate (5–15%) with very little economy penalty.

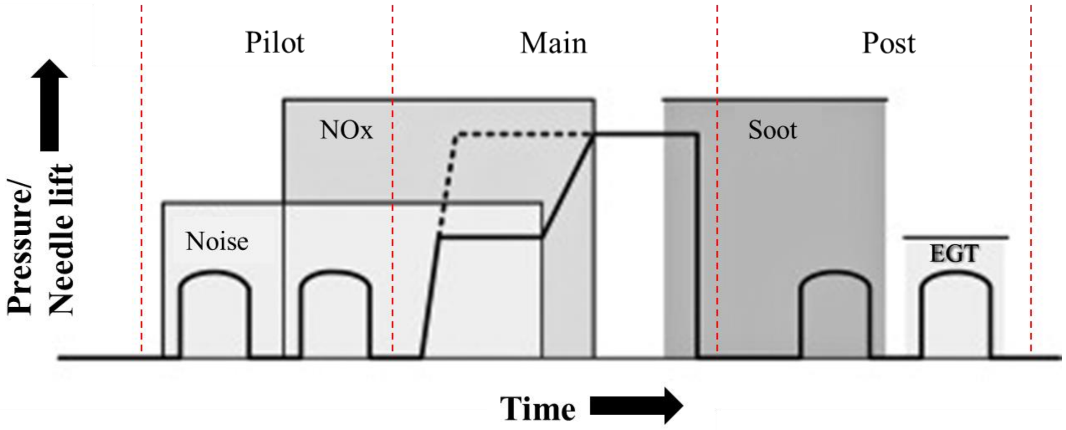


Figure 2.3: Typical multiple injections used in CI engine (Mohan et al., 2013).

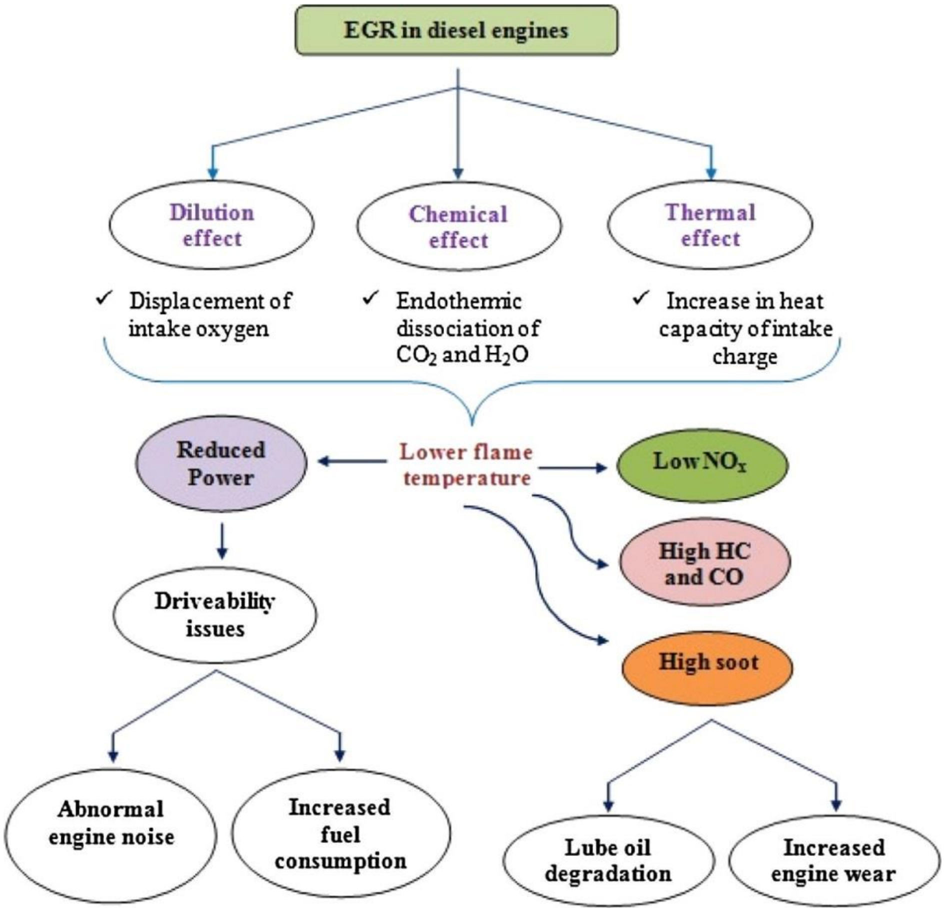


Figure 2.4: Summary of effects of EGR in diesel engine. (Thangaraja and Kannan, 2016).

2.5 Common rail injection system

Conventional mechanical type pump-line-nozzle injection system is cam driven, therefore it has some limitations, including injection pressure is dependent on engine speed, low maximum fuel pressure and difficult to achieve multiple injection. These limitations lead to low combustion efficiency and high exhaust emission. With the introduction of common rail injection system, the problems stated were resolved. The history of common rail can be tracked back to early-1950s and the first successful usage in a production vehicle began in Japan in the mid-1990s (Messeni Petruzzelli, 2015). Figure 2.5 shows the schematic of a typical common rail fuel injection system. The term “common rail” is used because high pressure fuel is supplied to multiple fuel injectors by a single rail. In this system, fuel is pressurize by high pressure pump and fed into the rail. The pressure in the rail is controlled by suction control valve and the injection event is controlled electronically by engine control unit (ECU). Precise control over injection parameters is achieved with ECU to make sure the engine is always operated under optimum conditions.

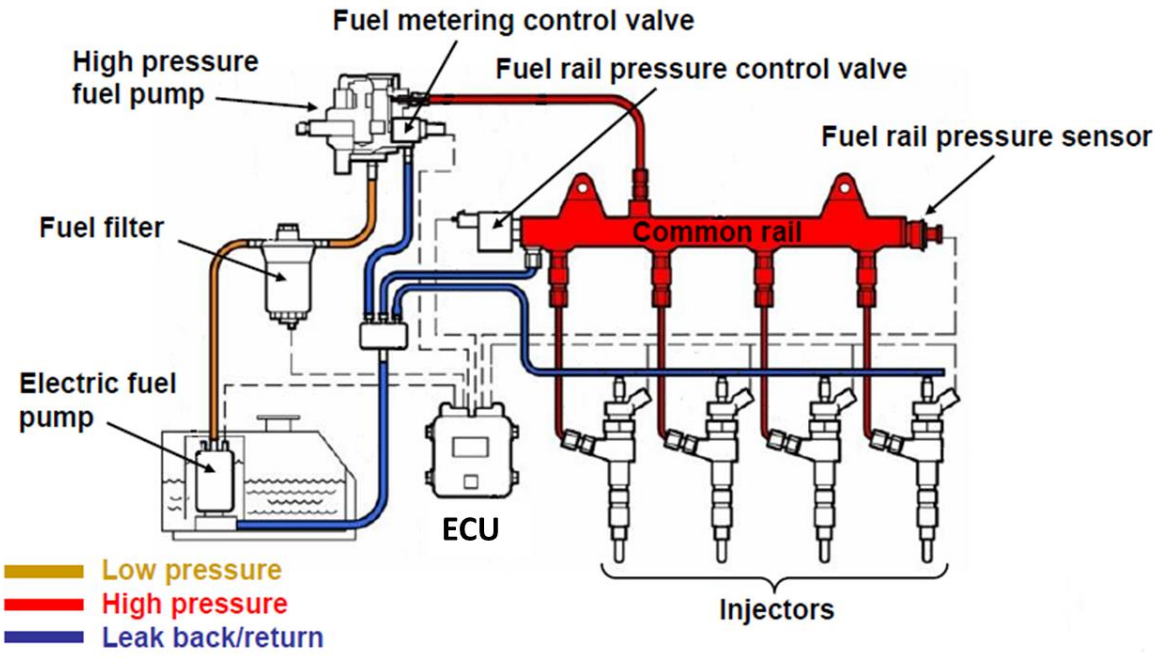


Figure 2.5: Common rail fuel injection system (Kitchen, 2016).

The injector used in common rail system can be divided into solenoid actuated and piezoelectric actuated (Satkoski et al., 2009, Woo et al., 2016, Kim et al., 2016, Chen et al., 2017). Piezoelectric type injector is claimed to have several advantages over solenoid type injector (Ferrari et al., 2013, Payri et al., 2011). First of all, the dynamic response of a piezoelectric injector is better. Nozzle opening delay and nozzle closure delay for piezoelectric injector is shorter than solenoid injector. This means that piezoelectric injector can perform higher number of multiple injections. Piezoelectric injector also reduced volume fluctuation amplitude of the injected fuel with respect to dwell time in multiple injections and 30% reduction in fuel leakage through the pilot valve at 1800 bar.

A solenoid is a coil of wire, when current pass through it, an electromagnetic field is formed. The magnetic field created by solenoid has positive (North) and negative (South) poles and the pole position is depending on the direction of current flow. The position of positive (North) and negative (South) poles can be easily determined by using the right hand grip rule as shown in Figure 2.6. The diagram of solenoid injector with its natural position is shown in Figure 2.7. Figure 2.8 (a) and (b) illustrates the opening and closing of solenoid injector. During opening, a peak current is flow through the solenoid coil to actuate electromagnetic force and elevate the armature quickly. After a short amount of time, the peak current has reduced to hold current (refer Figure 2.9) to remain the actuated electromagnetic field and hold the armature position. As the armature is lifted, fuel is allowed to flow from the valve control chamber to the return. The inlet throttle prevents the pressure between valve control chamber and rail from fully equalizing. Hence, the pressure in the valve control chamber dropped due to Venturi effect and became lower than the pressure in the nozzle's chamber volume, which is always the same with the pressure level of the rail. The pressure dropped in the valve control chamber decreases the downward force exerted on the top face of valve piston and causes the nozzle needle to open and injection begins. During closing, the solenoid coil is de-energized. The solenoid valve spring pushes the armature downward and builds up rail pressure in the control chamber again. The increased in pressure exerts more force on the valve piston. When the total downward force from the valve control chamber and nozzle spring exceeds the upward force acting on the nozzle needle, the nozzle needle moves down and closes the spray holes.

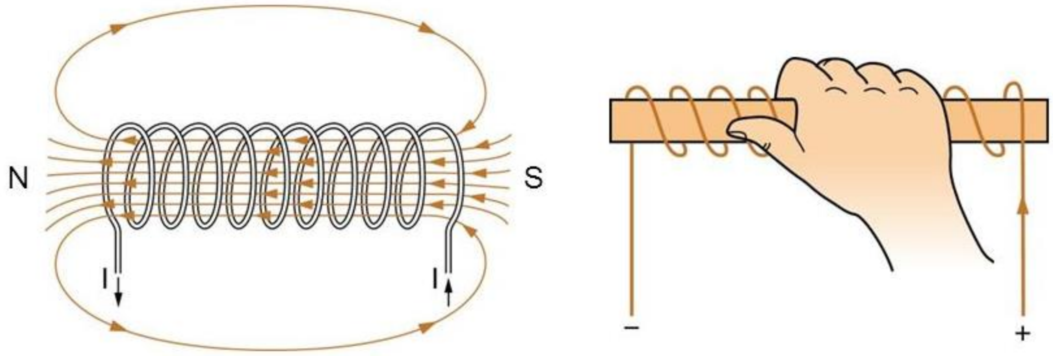


Figure 2.6: Solenoid magnetic field and right hand grip rule.

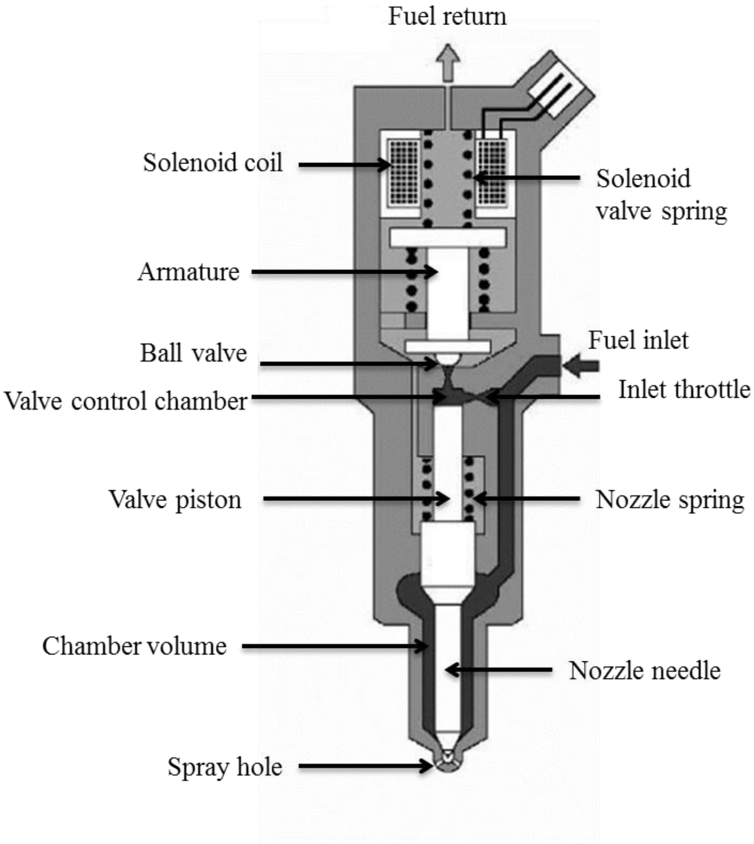


Figure 2.7: Solenoid injector with its natural position (Egler et al., 2010).

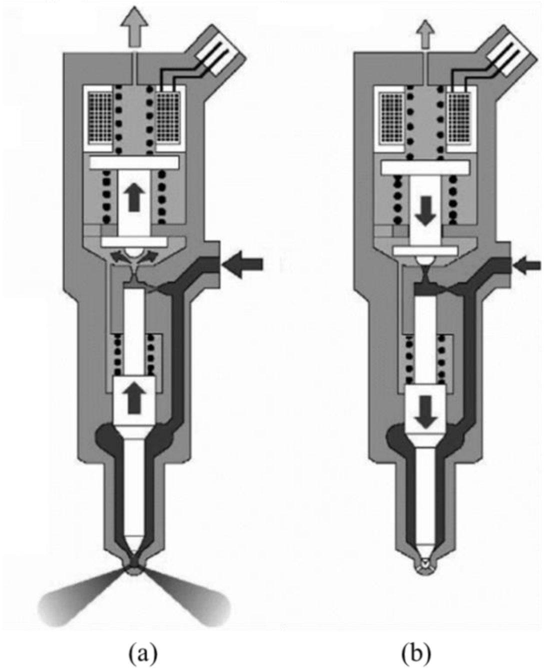


Figure 2.8: (a) injector opening and (b) injector closing.

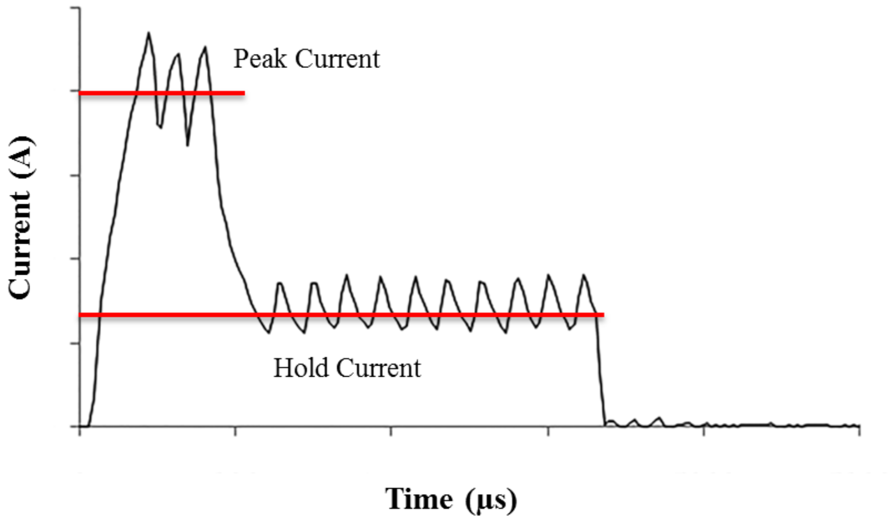


Figure 2.9: Current profile of solenoid injector (Carpenter et al., 2016).

The working principle of piezoelectric injector is quick similar to solenoid injector. Figure 2.10 shows the diagram of a piezoelectric injector. Piezoelectric injector utilizes the property of a piezo element to control the injection. A piezoelectric element will generate electrical charge when mechanical stress is applied and it will expand or contract depends on the polarity of current supplied to it. During opening, a high voltage is supplied to the injector, energize the piezo actuator. The stroke of piezo actuator is proportional to the voltage rise. The stroke of piezo actuator is amplified by hydraulic amplifier and pushes down the control valve allowing fuel flow to return. This causes the pressure in the control chamber drops and reduces the downward force acting on nozzle needle. As the total upward force exerted by the fuel on the lower part of the needle is higher than downward force on the upper part of it, the nozzle needle moves up and injection begins. Figure 2.11 shows the current and voltage profile of a piezoelectric injector. From the figure, we can see that a positive current is first supplied to the injector, the voltage rise and the piezo actuator stroke increased, indicating the start of injection. After that, a negative current is supplied to the injector, the voltage dropped and piezo actuator stroke return to its original length, indicating the end of injection.

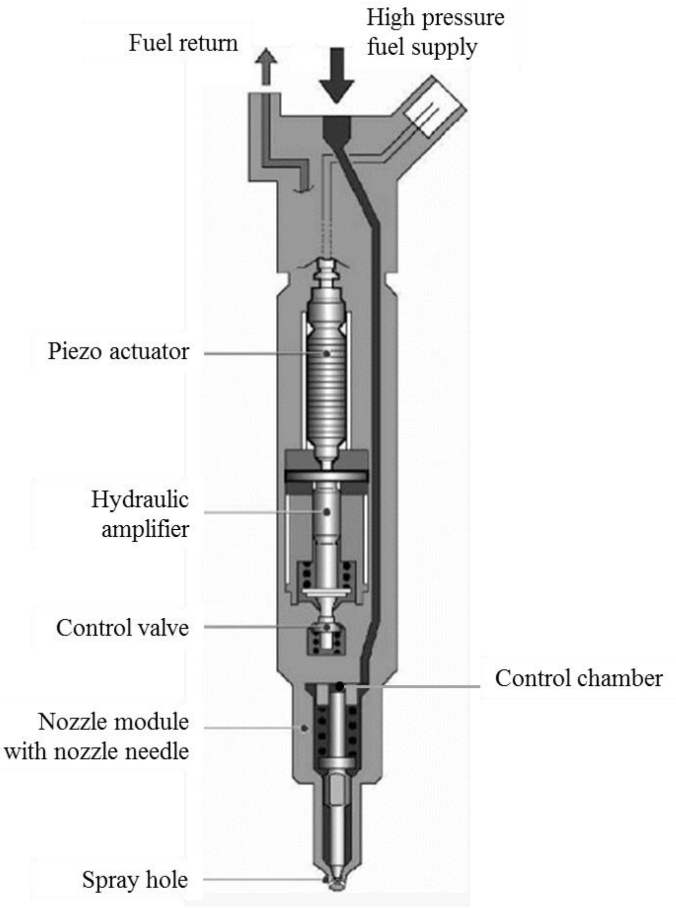


Figure 2.10: Piezoelectric injector in its natural position.

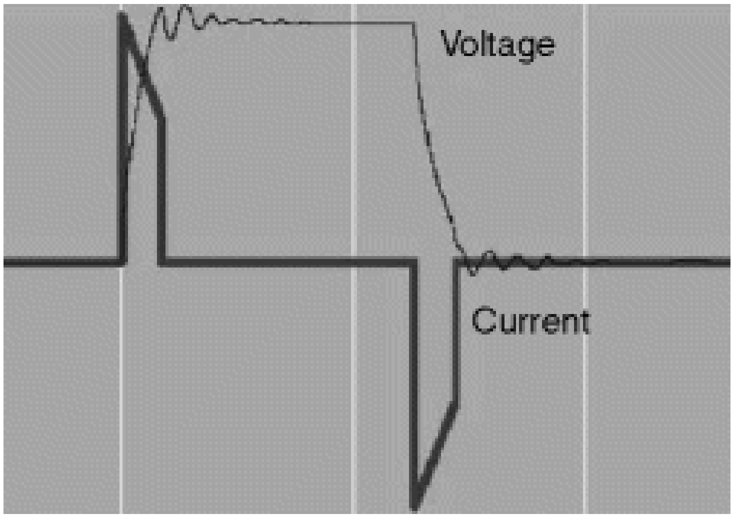


Figure 2.11: Current and voltage profile of a piezoelectric injector.

Other than common rail injection system, another system known as Hydraulic Electric Unit Injection (HEUI) system is also able to achieve high injection pressure. This system utilized engine oil as the pressurize agent to pressurize the fuel and the fuel is injected when the fuel pressure is exceeded the injector nozzle valve pressure (Diesel Hub, 2009). Higher pressure is required to achieve better fuel atomization (Shameer and Ramesh, 2018). This will improve the combustion in the cylinder and reduce the amount of soot contained in exhaust gases. Figure 2.12 shows series of high pressure pump produce by Denso Corporation. The maximum injection pressure increased from 60 MPa (A type and VE type) to 185 MPa (HP 3, 4). Common rail injection system provides continuous precise control of injection timing and injection quality as the injector is electronically controlled. The comparisons of common rail system with conventional mechanical type pump-line-nozzle injection system are listed in Table 2.3.

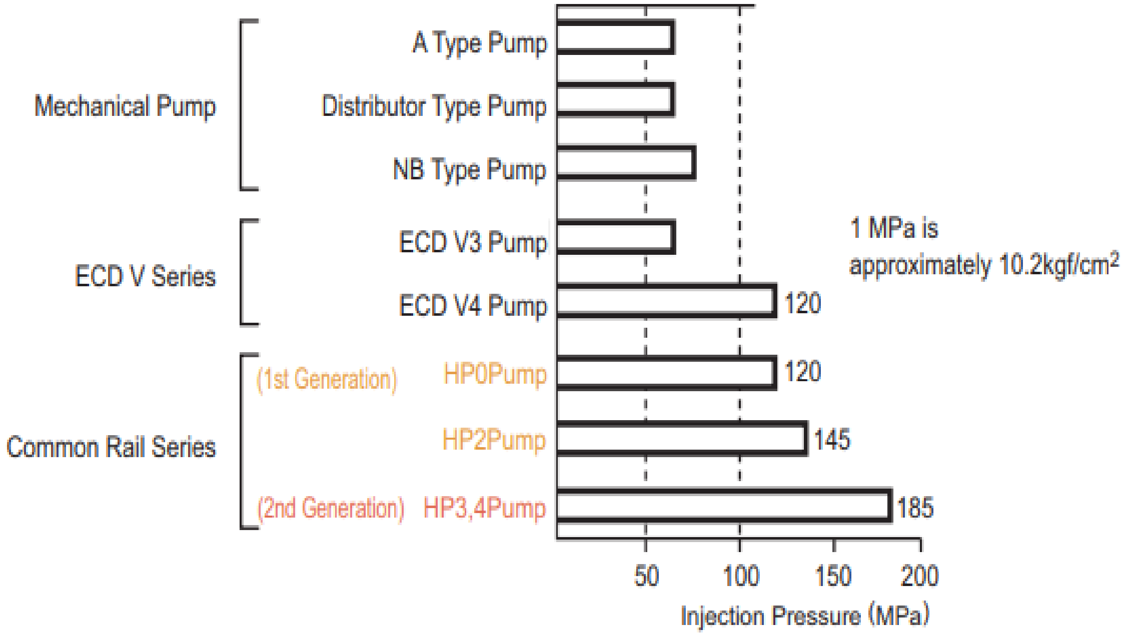


Figure 2.12: Comparison of high pressure pump and injection pressure (Denso Corporation, 2007).