A REPORT

ON

STUDY THE EMISSIONS PERFORMANCE OF A DIESEL ENGINE AND DEVELOP EFFICIENCY ISLAND PLOTS FOR HC, CO & NOX

BY

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MAMLESH BOHARI	2018B2A40622G
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MIHIR JESHURUN	2018B4A40972H
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AT

SIRIUS MOTORSPORTS, CHENNAI

A Practice School-1 Station of

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AT

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BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE PILANI
(RAJASTHAN)
Practice School Division

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Name and designation of the expert: Mr. Sajeeth Kumar, CEO
Name of PS Faculty: Dr. R Parameshwaran

Key Words: Emission Plots, Diesel CI Engine, Ricardo WAVE, SIMULINK, ReynICE

Project Areas: Emission Control, Engine Calibration, Engine Modelling

Abstract: Diesel engines have high efficiency, durability, and reliability together with their low-operating cost. They are considered as one of the largest contributors to environmental pollution caused by exhaust emissions, and they are responsible for several health problems as well. The four main pollutant emissions from diesel engines are carbon monoxide-CO, hydrocarbons-HC, particulate matter-PM and nitrogen oxides-NOx.

The following report discusses engine calibration and modelling as a method to reduce these emissions. Engine modelling is used to model the engine and vary various parameters to optimize efficiency and emission performance. It further focuses on engine modeling of a 4-cylinder turbocharged diesel engine and it`s resultant plots.

Signature of Student(s) Signature of PS Faculty
Date: Date:

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1. Introduction

Increasing emissions is one of the major concerns of the 21st century. With increasing global warning, governing bodies around the globe are pushing the automotive industry actively toward a greener future. While passenger cars may be fully electric in the near future, it is not a viable solution for commercial vehicles. Therefore heavy duty engines are still and will continue to be relevant for the foreseeable future. With the newest emission norms such as BS6 and Euro6, we can see a stricter approach being taken towards diesel vehicles, therefore it is essential that diesel emissions are reduced through proper engine design and calibration. This project aims to model a diesel engine at various operating conditions and in different configurations to generate its emission island plots and study methods to reduce emissions.

2. Sirius Motorsports: An Overview

Sirius Motorsports is an Automotive EdTech Start-Up which is at present the only training center in India to offer training on:

- Engine Modelling and Simulation using Ricardo Wave
- ECU Tuning and ECU Re-Mapping
- Automotive Mechatronics
- Automotive Diagnostics.

Sirius Motorsports are also largely involved in active research in developing low-cost testing solutions and laboratories that students and educational institutes can use to carry out experiments and understand various automotive engine design and calibration related topics.

2.1 History Of The Company

Sirius Motorsports started off as an engine calibration specialist catering to race cars in 2010. From there on they have been working as an exclusive Engine Calibration Company, since 2013 (One of India's first ever) offering calibration / tuning and training services for OEMs, OEM tier1 suppliers and colleges. The headquarters is based in Chennai, Tamil Nadu.

2.2 The Team And Key Employees.

The team at Sirius Motorsports consists of highly qualified engineers and technicians that ensure highest standard of work. A certified engine calibration expert takes care of ECU tuning and remaps. Some of the key employees at Sirius Motorsports:

- Sajeeth Kumar (Co-Founder, Head of Operations)
- Rishabh Gill (Chief Marketing Officer)
- Ashwin TN (Marketing Director)
- Sri Vignesh (Lead Engine Calibration Expert)

2.3 Vision Of The Company

Going forward, Sirius Motorsports aims to be the world’s best automotive training and industry service provider specialized in engine modelling and calibration technologies.

2.4 Key Achievements

Following are few notable achievements of Sirius Motorsports:

- The rally spec VW Polo 1.6 cars tuned by Sirius Motorsports ended up on podium every single time.
- Some of the best championship winning G13s were tuned by them.
- Sirius Motorsports have tuned numerous race cars for ITC and IJTC which have broken records repeatedly.

2.5 Infrastructure And Facilities Provided

Sirius Motorsports have a state-of-the-art dyno facility to test and tune ECU maps and remaps. They have state of the art data logging tools and OEM spec vehicle scanners as well. The only Ricardo certified training center in India and have also developed OEM standard ECU SIL/HIL test benches.

Sirius Motorsports specializes and provides services in the following areas:

- Engine simulation and development
- Engine Calibration and Dyno support
- Faculty Development Programs
- Ricardo Wave Training
- ECU Tuning and ECU Remap

3. Project Overview

3.1 Project Description

In the present-day scenario, we notice how every automobile company aims to design their engine in such a way that it develops high levels of torque and power while simultaneously making sure that its emission levels follow the current emission norms (BH6 norms in India, Euro6 norms in most other countries). In such a situation, it becomes crucial to examine various calibration parameters and striking a right balance between them to achieve an efficient model cutting down emission levels in the process.

•This project involves the study of the performance of a diesel engine initially to obtain data of various emissions like NOX, CO and HC corresponding to different values of RPM and Torque.
•We will be using Ricardo WAVE software to first get Base-Line values and then tabulate and re-use these values in Simulink to do a second and final simulation because simulating using Ricardo WAVE is very time consuming.
•The final step would be to prepare efficiency island plots using the tabulated data thereby finding the optimum points of the parameters considered. By doing so, we are able to understand how emissions vary with various calibration parameters and thereby calibrate the given engine to get the best performance while simultaneously following the emission norms.

3.2 Project Objectives/ Goals

•To obtain a fundamental understanding of how a Diesel (Compression Ignition) Engine works differently to that of a Gasoline (Spark Ignition)
•To study and gain knowledge on various emissions like CO, HC, NOX and how they depend on the AFR being rich or lean and get to know the current emission norms.
•Virtually model a diesel engine to prepare island efficiency plots by choosing the optimum engine operating points.
•Study the effect of changing engine parameters on engine performance and emissions.
•To optimize engine operation from an emissions perspective and thereby develop control strategies.

3.3 Project Methodology

3.3.1 Learning Process

The videos uploaded on canvas platform by the faculty were the source of knowledge for us to learn about the engine structure and working thoroughly. An in-depth presentation about the working of an engine, the difference between the operating mechanism of the petrol and diesel-based engines, various norms related to the emissions in India and abroad, etc. was delivered by Mr. Sajeeth Kumar.

3.3.2 Learning The Use Of MATLAB And Ricardo WAVE

- We got acquainted with the software like MATLAB, RICARDOWAVE and ReynICE which is an inhouse developed calibration software by the Sirius Motor Sports. In the subsequent lectures we quite developed an interest and gained an insight about the applications of these modelling softwares.
- We went through the modules provided and learned about the modelling of single and multi-cylinder engines using Ricardo WAVE. Then we practised single cylinder modelling of SI and CI engine on WAVE build in the BITS Pilani Virtual Lab.
- The experience with MATLAB was more alike the others. We learnt how to import the tabulated data to MATLAB Simulink and develop graphs by varying parameters like engine speed and throttle. In one of the lectures ,our instructor suggested us about a very efficient method of simulation .It was about getting the Base-Line values and then tabulating and reusing these values in Simulink to do second and final simulation .This method proved to be very efficient over the time consuming one using Ricardo WAVE.
- Later this week, we learned to use ReynICE software and performed various calibrations on Virtual Dyno and calibrated fuel look-up table, spark look-up table and emissions control.

3.3.3 Modelling Diesel Engines

We used Ricardo WAVE for modelling a single cylinder diesel engine. We practiced the modelling procedure as described in the module shared by our faculty. We then obtained the first iteration of the plots and analysed these plots closely in-order to identify areas where we could improve the emissions and performance.

3.4 Project Timeline

3.4.1 Week 1:

- 18th May: We started our journey on 18th May with Orientation with our Industry mentor Mr. Sajeeth and PS Faculties, who gave us a broad overview of the projects we will be doing.
- 19th May-23rd May: Went through the functionality of Canvas LMS, watched the introductory videos uploaded on Canvas. Kept in constant touch with Industry Mentors and PS Faculties.
- 24th May: We ended our week with our first assignment: PS Diary. The main objective of which was to throw lights on the major challenges we faced during that week, soft

skills or technical skills we gained, our learning milestones and our plans for the next week.

3.4.2 Week 2:

- 25th May: While our PS Faculties and our Industry Mentors were busy forming the groups for Projects, we were getting geared up for our first Quiz the following Tuesday.
- 26th May: Started our day with our Quiz-1, which was based on our basic understandings of IC - Engines and about our PS-Station. While the process of Group formation was still ON, we were introduced to the basic concepts of IC - Engines by Dr. Saket Verma, which would be helpful for our project work.
- 27th May: We started our day with Work Plan-1 followed by a Webinar on our projects with Mr. Sajeeth. We continued our day with another lecture by Dr. Saket on IC-Engines and finally we were introduced to MATLAB programming by Mr. Siddhartha on that day.
- 28th May: Another webinar with Mr. Sajeeth, wherein he gave us deeper insights into our Project domains. This day marked the last introductory lecture by Dr. Saket on IC-Engines and we downloaded the MATLAB software for future use as guided by Mr. Siddhartha.
- 29th May: Yet another day in our Project work, we had a lab session with Mr. Siddhartha on MATLAB programming which was the founding stones for our next task SIMULINK.
- 30th May: As the week was coming to end, we had got some idea on how to proceed with our project and what all were the requirements. Having nothing scheduled for today, we enhanced our own understanding of our Project.
- 31st May: End of our work week was dated along with the end of the month, and we submitted our next assignment: PS Diary-2. Fully laying down stones for future endeavors we were now ready for Project Work.

3.4.3 Week 3:

- 1st June: We entered our third week with login details for ReynICE software waiting for us. We performed various calibrations on Virtual Dyno, where we were supposed to calibrate fuel look-up table, spark look-up table and emissions control.
- 2nd June: On Tuesday, we had a morning session on 1-D modelling by Mr. Sajeeth, laying the building blocks for Ricardo-WAVE. We were asked to fill an interim Survey regarding our PS and finally we had a lab session with Mr. Siddhartha on MATLAB Programming.

- 3rd June: The following day constituted of just an evening lab session with Mr. Siddhartha. However, we were given instructions on booking slots and working on 1-D modelling using Ricardo WAVE, and run test simulations on ReynICE.
- 4th June: Wednesday was filled with webinars with industrial specialists. Morning we had a talk with Mr. Arun Sreyas (BITSian) who is the co-founder of RACEnergy and is dealing with Electric Mobility. Followed by an afternoon session with Mr. Nitin Pai (BITS alumni) who is the CTO for marketing and strategy at TATA-Elxsi. Finally, we had our routine session with Mr. Siddhartha, who started with the basics of SIMULINK.
- 5th June: As we approached the ending of the third week, we had a scheduled Seminar, wherein each member of the group was asked to present their fundamental understanding of the Project. Our session was organized by Dr. Parameshwaran who is also our PS Faculty.
- 6th June: We finally submitted the project report assigned to us by the faculty. This was the project which required team work and we collectively prepared it and every group member gave his/her inputs in this task.
- 7th June: We reached the end of the week. We didn't have any lectures as it was Sunday. But there was an assignment to be submitted i.e. the PS weekly diary 2. So, submitted it and also submitted it and also the Observation report 1.

3.4.4 Week 4

- 8th June: We didn't have any lectures on this day. We kept practicing the engine modelling and simulation on Ricardo WAVE.
- 9th June: We had a lab session in the evening by Mr. Siddharth Sir.
- 10th June: Today too we had a lab session in the evening.
- 11th June: We didn't have any lectures.
- 12th June: We had a lecture regarding the emissions, forced inductions and Engine performance by Mr. Siddhartha Sir. Also, we received an email from the faculty regarding the Group Discussion. The topic given to us was: Mechatronics-Emission norms for automotive vehicles in India-Present and future perspectives.
- 13th June: It was the D-day. We had our first group discussion which was conducted by Mr. R Parameshwaran. Guess what, we nailed our presentation and received appreciation from our instructor.
- 14th June: We had no lectures. We submitted the weekly diary 4.

3.4.5 Week 5

- 15th June: Our faculty had organised a webinar on the topic: Introduction to Global Wealth Management by Mr. Rahul Pate who is the Executive Director of UBS which is an Asset Management Company. We had a great time with the speaker as he traversed us through the world of finance and wealth management sharing his valuable experiences in this field.

- 16th June: We had another webinar conducted by Ms. Pooja Lakshmi who works for Ford Motors. She spoke about the latest trends in Automotive world and various domains which have the scope of innovation. The very evening, we had our lab focusing on Dyno- Testing of Automobiles.
- 17th June: Today was the continuation of the webinar held by Ms. Pooja Lakshmi. In this session, she talked about the electric vehicles, very popularly known through the buzzword EVs. She also discussed about the challenges faced by the Automotive industry in making transition from conventional automobiles to the EVs. But on the other hand, she was also optimistic about the future of EVs. In the evening there was a lab session on Vehicle's testing using Chassis Dynamometer.
- 18th June: This day too was a webinar day. This time we had Mr. Deepak Tomar, Executive Director of Nomura as our speaker. This session was focused mainly on Investment Banking. This was followed by a lab on emission testing.
- 19th June: Submitted the weekly diary 5.
- 20th June: We had a PS data Analysis session in the afternoon and a lab on control systems.
- 21st June: A webinar was arranged focusing on the wholesale strategy in the arena of Investment banking. Mr. Ankit Tawar, Executive director and Head of Wholesale Strategy, Nomura Capital.

3.4.6 Week 6

- 22nd June: Observation 2 was announced and we had to submit it on or before 25th June.
- 23rd June: No lectures on this day. We were running simulations on MATLAB for obtaining the graphs of emissions like CO, HC and NOx.
- 24th June: No lectures on this day too. Busy with our project 2 work.
- 25th June: Submitted the weekly diary 6 report and also the observation 2 report. Busy preparing the Project Report 2 and slides for tomorrow's Seminar 2. Also submitted the weekly diary 6.

4. Background Knowledge

Diesel engines are compression ignition engines which operate at high compression ratios. Unlike spark ignition engines, the combustion in CI engines is done by fuel injection. Hence, the air-fuel charge is not homogenous. This causes irregular pockets of combustion, knock and inefficient burning. The combustion characteristics can be controlled by changing the air fuel ratio and time of combustion initiation. Through this we can change the torque characteristics and amount of emissions produced.

In diesel engines, we have to control the amount of particulate matter and maintain a stoichiometric relation between amounts of HC, CO & NOx such that the reaction inside the catalytic converter eliminates maximum pollutants.

Through engine modelling, we can predict engine behaviour and generate performance and emission plots. By changing various engine parameters we can rapidly iterate to make the engine perform in a desirable manner such as minimizing emissions. This enables us to develop engines and their control systems in a quick and cost effective manner.

In this project, we will use 1D engine simulation on Ricardo WAVE and SIMULINK to extract emission efficiency island plots for a diesel engine. Then, we will optimize engine parameters to minimize emission levels while preserving drivability.

4.1 Emissions And Regulations

4.1.1 Overview

The Emission norms were first introduced in India in the year 1991 for petrol-based motor engines and in 1992 for the diesel-based vehicles. The use of catalytic converter was made mandatory in the year 1996 and unleaded petrol was introduced in the market to make a cut on the pollution.

The dawn of the 21st century saw the introduction of Bharat Stage I norms which were then named as ‘India 2000’. In the year 2001, Bharat Stage II norms were introduced for all the metros, CNG and LPG vehicles. Later the BS II norms were brought into effect in all over the country in 2003. From 1st of April 2005, the BS IV norms were introduced for 13 major cities of India. These norms were equivalent to the Euro norms IV introduced in the West. In 2017, the Bharat stage IV norms were rolled-out for all the vehicles in the whole nation, which was only restricted to 4- wheelers in 13 major cities back then in 2010.

Recently, on 1st April 2020, the BS VI norms were introduced in the nation which in turn are stricter and more restrictive when compared to their BS IV counterparts.

4.1.2 Need For BS VI Norms

India's Auto sector accounts for about 18% of the total CO_2 emissions produced in the country. Recently, CO_2 emissions from the transport industry has risen rapidly in the recent years, but unlike EU there were no standards for CO_2 emissions limits for pollution from the vehicles. As per BS VI, the emission of carbon monoxide is to be reduced by 30% and NO_x by 80%. The BS VI norms also sets limits for hydrocarbon and particulate emissions, which were not specified in earlier norms.

4.1.3 Difference Between BS IV And BS VI Norms

The following are the key differences between BS IV and BS VI norms:

- Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR) were introduced with the rollout of BS VI norms, which were not a part of BS IV norms.
- Real Driving Emission (RDE) will be introduced in India for the first time with implementation of the upgraded norms. It will allow to measure a vehicle's emissions in real time conditions against laboratory conditions.
- Another change that is being introduced with the implementation of BS VI emission norms is that Onboard Diagnostics (OD) has been made mandatory for all vehicles.
- The most crucial difference between BS VI and BS IV grade fuel will be in terms of Sulphur and Nitrogen Oxide content. The Sulphur traces in BS VI fuel (10 ppm) is five times lower as compared to the sulphur traces in BS IV fuel (50 ppm). Further, nitrogen oxide content in the BS VI graded diesel engines and petrol engines will be brought down by 70 % and 25 % respectively.

4.1.4 Will BS VI Vehicles Be Able To Run On BS IV Fuel And Vice-Versa?

Adding further, if a BS IV compliant fuel is used in BS VI engine, then it will lead to the clogging of the fuel filter and the catalytic converter fitted in an automobile due to large content of sulphur in it. On the other hand , if a BS VI graded fuel is used in a BS IV engine, then it will cause the wear and tear of the engine due to its low sulphur content as sulphur acts as a lubricant in the fuel injectors, which further will cause frictional issues and disrupt the fuel flow pattern of the fuel and increase emissions. In both the cases, the diesel engines will be more adversely affected as compared to the petrol ones.

4.1.5 Will BS IV Vehicles Be Banned After The Intro Of BS VI Vehicles?

As per the mandate ruled out by the Supreme Court of India in October 2018, the sale and purchase of Bharat Stage IV vehicles will be banned after April 2020. The court has asked all car manufacturers to clear their stock of BS4 vehicles before the deadline. The court has also made it clear that it will not provide any extension to car manufacturers for the stock clearance of BS4 vehicles.

However, the Finance Minister of India, Smt. Nirmala Sitharaman has stated that BS4 vehicles purchased till March 2020 will remain operational throughout the period of registration.

4.2 Turbocharged Diesel Engine

Turbo-diesel, refers to any diesel engine equipped with a turbocharger. And against a Naturally Aspirated engine, turbocharging a diesel engine can greatly increase its power output. A turbocharger, is a turbine driven, forced induction setup that increases an IC engine's efficiency and power output by forcing extra compressed air into the combustion chamber. Its advantage over a naturally aspirated engine is that its compressor can force more air into the combustion chamber than atmospheric pressure thereby increasing its power output.

There's another type of forced induction device called **Superchargers.** In fact, turbochargers were earlier called turbosuperchargers. The key difference between the two is that a supercharger is driven by the engine, mechanically, through a belt connected to the crankshaft, on the other hand a turbocharger is powered by a turbine driven by the engine's exhaust gas. This is also its advantage over superchargers as it does not drain power from the engine.

4.2.1 Design And Operation

A turbocharger consists of two chambers connected by a center housing. The two chambers contain a turbine wheel and a compressor wheel connected by a shaft which passes through the center housing.

The turbocharger is usually placed near the exhaust manifold, this allows the hot exhaust to pass directly into the unit with minimum heat loss. The exhaust gas entering the unit rotates the turbine blades. The turbine wheel and compressor wheel are on the same shaft so that they turn at the same speed. Rotation of compressor wheel draws air through a central inlet and centrifugal force pumps it through an outlet at the edge of the housing. A pair of bearings in the center housing support the turbine and compressor wheel shaft, and are lubricated by engine oil.

When the engine is started and runs at low speed, both exhaust heat and pressure are low and turbine runs at a low speed (approx. 1000 RPM). Because the compressor does not turn fast enough to develop boost pressure, air simply passes through it and the engine works like any naturally aspirated engine. As the engine runs faster or load increases, both exhaust heat and flow increase causing the turbine and compressor wheel to rotate faster. Since there is no brake and very little rotating resistance on the turbocharger shaft, the turbine and compressor wheels accelerate as the exhaust heat energy increases.

Engine deceleration from full power to idle requires only a second to two because of internal friction, pumping resistance and drivetrain load. The turbocharger, however has no such load on its shaft and is already running much faster than the engine. As a result, it can take longer to than the engine to return to idle after the engine. If properly maintained turbocharger is a trouble-free device and to prevent problems, following conditions must be met:

- The turbocharger bearings must be constantly lubricated with clean engine oil. They should have regular oil changes at half the time or mileage intervals specified for non-turbocharged engines.
- Dirt particles and other contamination must be kept out of the intake and exhaust housing.
- Whenever a basic engine bearing is replaced the turbocharger must be flushed with clean engine oil.
- If the turbocharger is damaged, the engine oil must be drained and flushed and the oil filter replaced as part of the repair procedure.

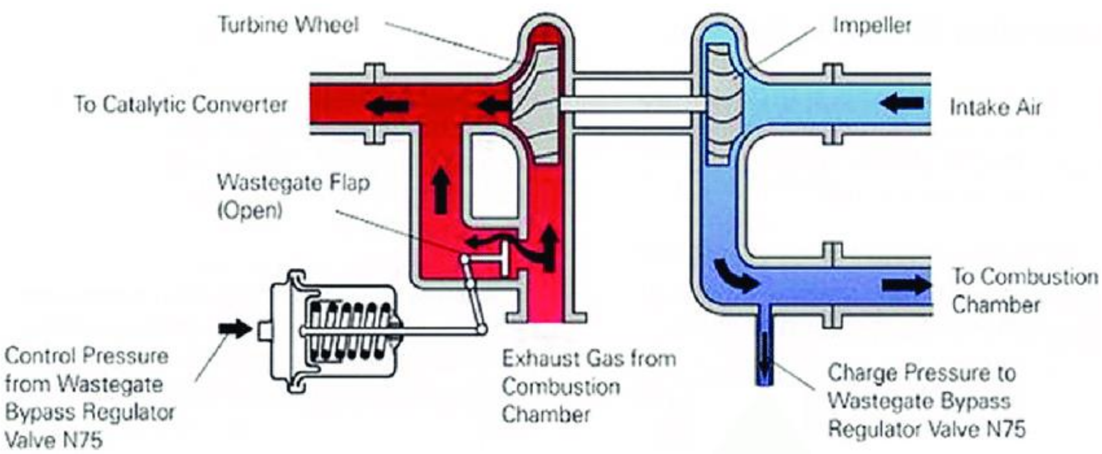

Figure 1: Turbocharger

4.2.2 Boost Control

The turbocharged system is designed to provide a pressure greater than atmospheric pressure in the intake manifold. This increased pressure forces more air into the combustion chamber than the naturally aspirated engine. This increased charge increases engine power. The amount of boost is measured in pounds per square inches (PSI), in bars or in atmospheres. 1 atmosphere=14.7 PSI. The higher the level of boost (pressure), the greater the horsepower potential. However, some factors must be considered when increasing boost pressure:

- As boost pressure increases temperature of air also increases. As temperature increases, combustion temperature also increases, which increase the chances of detonation.
- Power can also be increased by cooling the compressed air after it leaves the turbocharger. A typical cooling device is called an intercooler, it is similar to a radiator, wherein outside air can pass through cooling the pressurized heated air.
- As boost pressure increases, combustion pressure and pressure also increase which if not controlled can cause severe engine damage. The maximum exhaust gas temperature must be 1550 F.

4.2.3 Wastegate

Turbocharger uses exhaust gases to increase boost, to prevent over boost and engine damage, most turbochargers use a wastegate. A wastegate is a bypass valve at exhaust inlet to the turbine, and allows all of exhaust gas into turbine. If the valve is closed then all the exhaust gas travels to the turbocharger. When a predetermined amount of boost pressure develops, the wastegate valve is opened. As the valve opens, most of the exhaust gas flows directly out the exhaust system, bypassing the turbocharger. With less exhaust flowing across the vanes of the turbocharger, the turbocharger decreases in speed and boost pressure is reduced. When the boost pressure drops, the wastegate valve closes to direct the exhaust gas to the turbine and again allows the boost pressure to rise. Wastegate operation is a continuous process to control boost pressure.

The wastegate is usually controlled by the onboard computer through a boost control solenoid.

4.3 Overview Of Engine Modelling

The use of one-dimensional computation fluid dynamic (1D CFD) engine simulation software is widespread throughout the engine development industry. This simulation method allows for characterizing engine operation without the need for high-end processing and time-intensive computations.

One of the primary engine simulation software packages used in the industry today is Ricardo WAVE.

4.3.1 Fluid Dynamic Simulation Of The Engine

The basic operation of the WAVE code analyses flow networks composed of ducts, junctions, and orifices. Within this network of plumbing, engine cylinders, turbochargers, superchargers, compressors, and pumps can be inserted. WAVE can simulate internal combustion engines as well as the other compressible-fluid flow systems.

The simulation process can be divided into several steps. First step is pre-processing, next is solver and post-processor. Pre-processor of wave software is a part, which is called Wave Build, is used for building of engine model and allows defining network of plumbing, its geometry and all features of the simulated engine. After the build a model and define parameters of engine, can be solving algorithm running. When the simulation ends, it's creating a large output file containing all data necessary to evaluate the simulation process.

For the interpretation of simulation results is used post-processor Wave Post. It allows the creation of time-dependent graphs, torque and power speed characteristics, animated diagrams and pressure maps for turbocharger and compressors.

4.3.2 Thermodynamic Model Of Combustion

The model of combustion is concerned with heat release process in engine cylinder. This process is influenced by the method of mixture preparation, fuel type and conditions in the cylinder during combustion. In an ideal combustion cycle is all heat released in an infinitely short time at the top dead center of piston. In the real combustion cycle of engine, this heat is releasing gradually and unevenly. Inserting the model of combustion to the complex mathematical simulation model of the combustion engine leads to precise results and saves time in the engine development.

Currently, there are not generally valid mathematical-physics equation that would allow a matching precision to determine combustion process on the basis of the design and operating parameters of the engine (2).

Still effective is use of simplified models of combustion, or analogies. The default formula for calculating the combustion in the cylinder of internal combustion engine is the equation, which was deduced by Wiebe.

The Wiebe function is widely used to describe the rate of fuel mass burned in
thermodynamic calculations. This relationship allows the independent input of shape function parameters and of burn duration. It is known to represent quite well the experimentally observed trends of premixed spark ignition combustion.

4.3.3 Design And Setup Of Model

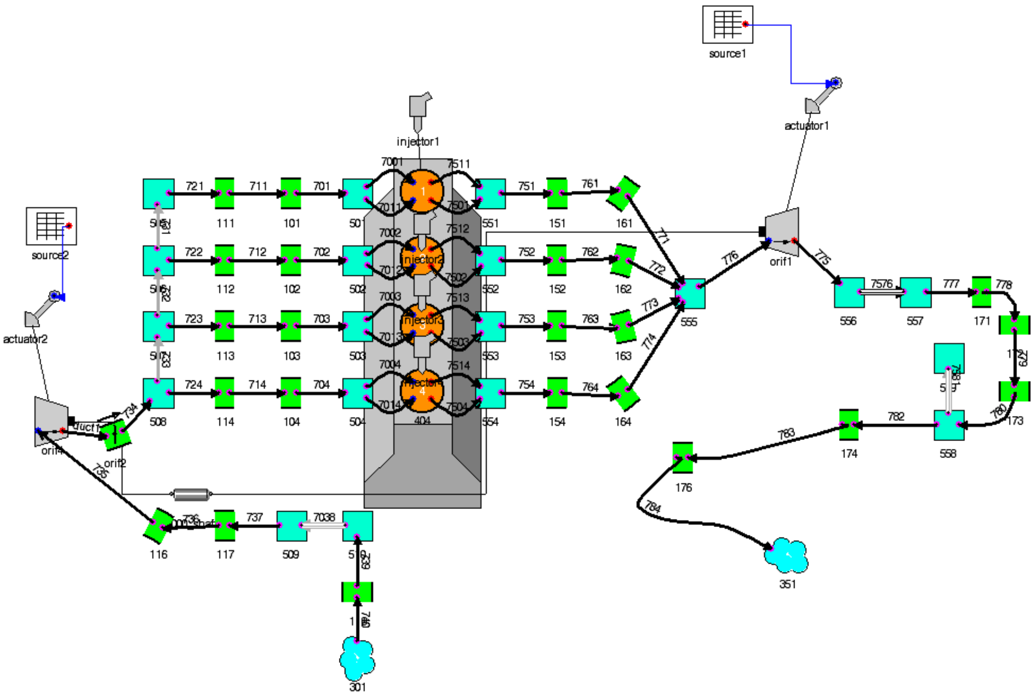

Figure 2: Engine Model On Ricardo WAVE

Visualization of engine in Ricardo Wave software is composed of the creation and definition geometry of cylindrical unit (engine cylinder and engine head). Then the cylindrical unit in the direction from intake to exhaust is connected and defined the geometry of the intake and exhaust pipe with accessories (throttle, mufflers, etc.)

After the setup of basic input parameters, other parameters, which define the gas exchange process and the combustion must be set. They are especially the port flow coefficients, valve lift per crankshaft rotation, and combustion modelling.

The aim of calculation cycles of real internal combustion engines is to determine changes in state variables during the engine working cycle.

From the state variables are calculated following values, as mean indicated pressure, indicated efficiency, mechanical and thermal loads. The program uses calculations based on the law of conservation of energy and mass.

4.3.4 Simulation Results

Ricardo Wave displays the calculation results for the individual steps in real time. In the post-processor Wave Post we can see all the simulation results. We can display flow velocity in any section of pipe, the pressure in the pipeline, but also in the cylinder and all performance parameters. The result of this simulation in the development of engine is torque and power characteristics depending on engine speed.

This simulation model was used to estimate various parameters like

- Brake Horsepower
- Brake specific fuel consumption
- Indicated horsepower
- Knock
- Total volumetric efficiency
- Brake Torque
- FMEP
- Fuel Flow
- IMEP
- Indicated Torque
- Manifold Pressure (Intake Port static pressure)
- Residual Gas %
- Exhaust Gas Temperature
- BMEP
- Air flow
- Brake Thermal Efficiency
- CO concentration PPM
- HC concentration PPM
- NOx concentration PPM

5. Results / Outcomes Obtained

This project involves the study of the performance of a diesel engine initially to obtain data of various emissions like NOX, CO and HC corresponding to different values of RPM and Throttle.

One of the first results we obtained in our project was the output data for our model CI engine which we simulated on WAVE Build and exported the data from WAVE Post into separate excel files which were later compiled into a single result sheet as shown below.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	NAME	Engine Speed	Throttle	Injected Mass	Turbo Sizing	Wastegate	CRPM	Lambda	BHP	BSFC	Ind HP	Knock	Tot VE
2	UNITS	RPM	%	mg		mm^2	RPM		kW	kg/kW/hr	HP		%
3	CASE 1	4867	7	60	1	758	168000	0.05785	-21.6976	-1.61488	-13.4932		0.108377
4	CASE 2	3367	32	10	1	1258	162936	4.19909	16.3972	0.246408	34.0564		1.33201
5	CASE 3	3367	32	25	1	1258	162936	1.66733	46.7272	0.21617	74.8306		1.31409
6	CASE 4	3367	32	35	1	1258	162936	1.19098	58.1925	0.24301	90.1515		1.31439
7	CASE 5	3367	32	45	1	1258	162936	0.92696	67.5491	0.269164	102.712		1.3163
8	CASE 6	3367	32	60	1	1258	162936	0.69433	63.047	0.384513	96.5725		1.31316
9	CASE 7	6367	82	10	1	258	168000	3.88348	10.755	0.710406	46.5793		1.21354
10	CASE 8	6367	82	25	1	258	168000	1.5448	60.5581	0.315416	113.473		1.20865
11	CASE 9	6367	82	35	1	258	168000	1.10655	74.7521	0.357735	132.413		1.21219
12	CASE 10	6367	82	45	1	258	168000	0.86073	82.8732	0.414872	143.247		1.2123
13	CASE 11	6367	82	60	1	258	168000	0.64479	74.1242	0.618454	131.382		1.21084
14	CASE 12	1492	76	10	1	882	94120	3.26166	7.87261	0.227422	14.2138		1.03007
15	CASE 13	1492	76	25	1	882	94120	1.29906	20.0013	0.223785	30.5069		1.02256
16	CASE 14	1492	76	35	1	882	94120	0.90117	23.5204	0.266424	35.214		0.987763
17	CASE 15	1492	76	45	1	882	94120	0.70239	22.4202	0.359354	33.6898		0.989991
18	CASE 16	1492	76	60	1	882	94120	0.53087	20.6179	0.521023	31.2176		0.998547
19	CASE 17	4492	26	10	1	1882	168000	3.16353	17.4924	0.308158	40.7725		0.99772
20	CASE 18	4492	26	25	1	1882	168000	1.266	48.906	0.275549	82.9061		0.998107
21	CASE 19	4492	26	35	1	1882	168000	0.9057	59.2534	0.318402	96.787		0.99635
22	CASE 20	4492	26	45	1	1882	168000	0.70409	55.2702	0.438876	91.353		0.997114
23	CASE 21	4492	26	60	1	1882	168000	0.52752	48.4243	0.667896	82.0542		0.997808
24	CASE 22	2992	1	10	1	382	159920	0.05468	-9.08942	-0.341246	-5.45722		0.00686057
25	CASE 23	2992	1	25	1	382	159920	0.0124	-9.57254	-0.943254	-6.14807		0.00626192
26	CASE 24	2992	1	35	1	382	159920	0.0058	-9.76664	-1.24405	-6.40973		0.00382278
27	CASE 25	2992	1	45	1	382	159920	0.0036	-9.76833	-1.60686	-6.40852		0.00375956
28	CASE 26	2992	1	60	1	382	159920	0.00219	-9.83862	-2.11846	-6.49728		0.00368062
29	CASE 27	5992	51	10	1	1382	168000	3.98754	17.0464	0.421813	51.9522		1.24993
30	CASE 28	5992	51	25	1	1382	168000	1.59695	66.2522	0.271327	118.039		1.25104
31	CASE 29	5992	51	35	1	1382	168000	1.1409	80.9564	0.310864	137.691		1.25227
32	CASE 30	5992	51	45	1	1382	168000	0.88739	92.3989	0.350186	153.004		1.25254

	A	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
1	NAME	Brake Torque	FMEP	Fuel Flow	IMEP	Ind Torque	MAP	Residual Gas	xhaust Gas Ter	BMEP	Air Flow	: Thermal Effic	CO conc.	HC conc	NOx conc.
2	UNITS	Nm	Bar	kg/hr	Bar	Nm	Bar	%	K	Bar	kg/hr	%	ppm	ppm	ppm
3	CASE 1	-42.5719	1.82577	35.039	-1.57882	-19.742	0.196224	0.036441	610.52	-3.40459	28.7597	-5.20857	0.193858	2.19E+06	1.63E-06
4	CASE 2	46.5049	2.04103	4.0404	5.76016	72.0264	1.64731	0.626732	599.823	3.71913	244.533	34.1353	0.199909	17.891	918.245
5	CASE 3	132.526	2.05811	10.101	12.6566	158.261	1.65494	0.994422	987.89	10.5984	241.243	38.9103	217.471	42.1354	1864.79
6	CASE 4	165.043	2.04892	14.1414	15.2479	190.663	1.65489	0.861529	1316.47	13.199	241.297	34.6126	2467.28	58.2331	2350.94
7	CASE 5	191.58	2.05109	18.1818	17.3723	217.227	1.6541	0.791227	1423.77	15.3212	241.647	31.2494	24182.5	72.6779	2125.39
8	CASE 6	178.811	2.03389	24.2424	16.3339	204.243	1.6554	0.901354	1224.61	14.3	241.072	21.875	104788	89.0278	217.323
9	CASE 7	16.1305	2.87618	7.6404	4.16618	52.0949	1.4002	2.93544	713.7	1.29	421.284	11.84	0.906668	18.3111	865.656
10	CASE 8	90.826	2.88567	19.101	10.1493	126.909	1.41514	2.94884	1179.86	7.26361	419.588	26.667	654.851	44.8082	1771.85
11	CASE 9	112.114	2.87728	26.7414	11.8434	148.093	1.40433	2.02809	1558.94	8.9661	420.815	23.5124	8352.64	62.1894	2429.41
12	CASE 10	124.295	2.87216	34.3818	12.8124	160.209	1.40389	2.01175	1533.31	9.94019	420.853	20.2742	48030.1	76.3844	1183.09
13	CASE 11	111.173	2.86032	45.8424	11.7511	146.939	1.40834	2.35056	1320.8	8.89079	420.346	13.6004	126882	92.8129	164.888
14	CASE 12	50.3875	1.39564	1.7904	5.42526	67.8389	1.2869	1.51405	609.836	4.02962	83.7958	36.9851	0.296416	21.7571	1294.38
15	CASE 13	128.016	1.40641	4.476	11.6442	145.602	1.2872	1.28659	1061.46	10.2378	83.1844	37.5861	533.708	53.4605	2321.24
16	CASE 14	150.539	1.4018	6.26641	13.4408	168.068	1.28719	2.75033	1213.71	12.039	80.354	31.5708	30655.9	73.3356	1349.83
17	CASE 15	143.497	1.38315	8.0568	12.859	160.793	1.28723	2.67431	1074.56	11.4759	80.5352	23.4065	95653.4	87.368	165.943
18	CASE 16	131.962	1.36205	10.7424	11.9154	148.993	1.28725	2.27215	902.798	10.5534	81.2312	16.1437	159162	104.887	7.48616
19	CASE 17	37.1862	2.19512	5.3904	5.169	64.6345	1.22117	1.03711	713.906	2.97388	244.362	27.2952	2.83593	22.5572	1106.57
20	CASE 18	103.967	2.19603	13.476	10.5106	131.427	1.21821	0.597324	1292.92	8.31453	244.457	30.5253	2433.2	55.0719	2364.08
21	CASE 19	125.964	2.19665	18.8664	12.2703	153.432	1.22589	0.743986	1472.96	10.0737	244.027	26.417	31790.8	74.2198	1979.31
22	CASE 20	117.497	2.18492	24.2568	11.5815	144.817	1.22296	0.704472	1294.25	9.39653	244.213	19.1654	102951	88.475	357.081
23	CASE 21	102.943	2.16992	32.3424	10.4026	130.076	1.21954	0.670022	1075.5	8.23264	244.383	12.5936	169564	106.359	12.5448
24	CASE 22	-29.01	1.28131	3.10173	-1.0387	-12.9881	0.0830838	17.3164	1632.99	-2.32001	1.1192	-24.6485	52908.5	3.45E+06	28.0015
25	CASE 23	-30.552	1.27313	9.02934	-1.17019	-14.6324	0.0441718	8.42912	823.028	-2.44333	1.02154	-8.91723	7516.6	7.36E+06	9.75858
26	CASE 24	-31.1714	1.27287	12.1502	-1.21999	-15.2551	0.0397299	4.3191	662.059	-2.49286	0.62363	-6.76115	3429.24	1.04E+07	2.05093
27	CASE 25	-31.1768	1.27353	15.6963	-1.21976	-15.2522	0.0443119	2.67112	572.061	-2.4933	0.613316	-5.23457	1924.62	1.12E+07	1.59242
28	CASE 26	-31.4011	1.27458	20.8428	-1.23666	-15.4635	0.0526281	1.89809	501.792	-2.51124	0.600439	-3.97043	143626	1.17E+07	0.969663
29	CASE 27	27.1665	2.76497	7.1904	4.93755	61.7404	1.43198	1.51675	664.687	2.17258	408.36	19.9406	0.70831	18.1443	838.64
30	CASE 28	105.585	2.77456	17.976	11.2185	140.279	1.43628	1.33845	1104.14	8.44391	408.722	31.0003	524.867	44.0323	1713.4
31	CASE 29	129.019	2.76825	25.1664	13.0862	163.633	1.43295	0.997276	1472.56	10.318	409.123	27.0576	6173.2	60.8963	2339.11
32	CASE 30	147.254	2.76519	32.3568	14.5415	181.831	1.43217	0.947322	1515.57	11.7763	409.212	24.0193	38468.2	75.3251	1535.71

Figure 3: Compiled Results

After running the simulations for the first time on Ricardo WAVE we were able to get data for various parameters and compile them into a result excel sheet. We later started simulations on MATLAB Simulink by working on subsystems of various parameters by importing data from the compiled excel. Emission plots we generated on MATLAB working on the subsystems provided for various emissions like CO, HC and NOx.

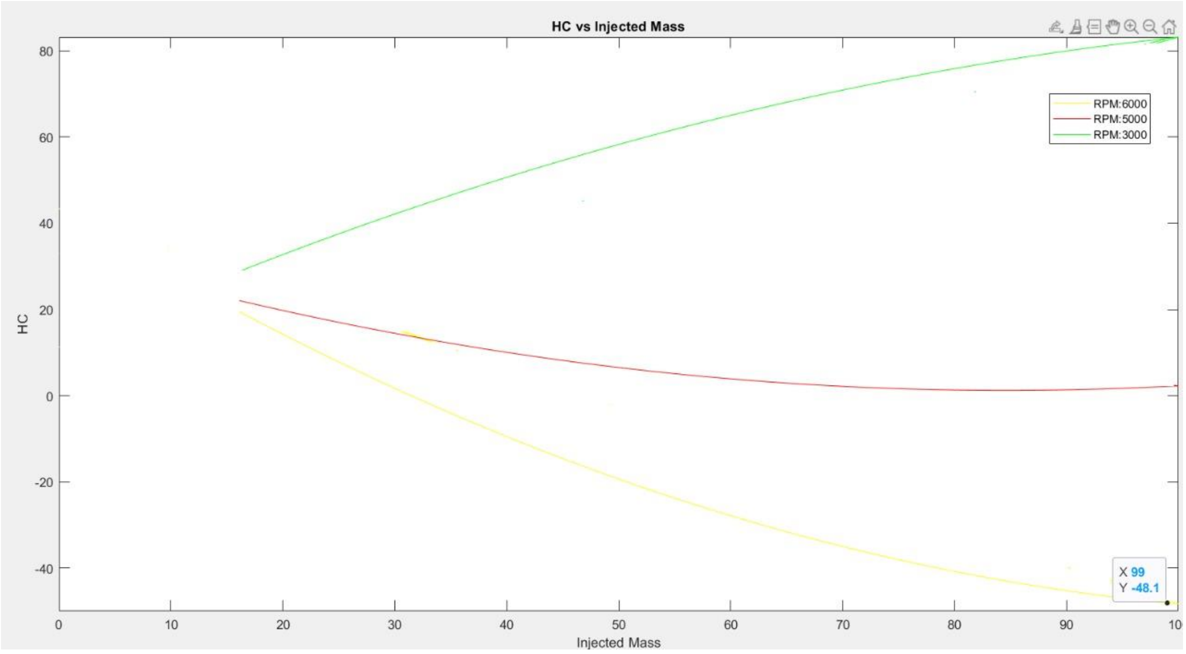

Figure 4: Plot Showing HC Vs Injected Mass (At Different RPMs)

This graph shows how the concentration of HC changes with injected mass. We have obtained three curves for the RPM values of 3000, 5000 and 6000. We observe that initially at an injected mass of 15-20 all the curves have the concentration values with minimal difference. As we increase the injected mass value from 20 onwards till 100 the difference starts increasing. This is because at a higher RPM like 6000 when the injected mass in increased, the air/fuel mixture is generally rich resulting in the lack of oxygen for proper combustion. This eventually leads to high amounts of HC concentration (ppm) released into the atmosphere.

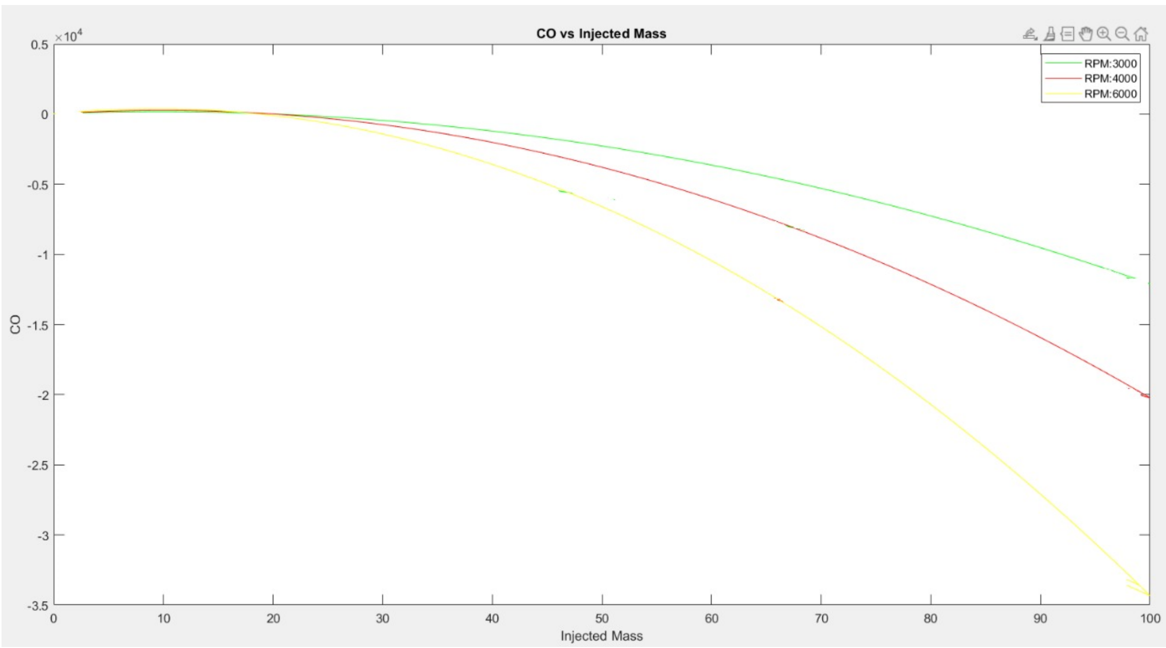

Figure 5: Plot Showing CO Vs Injected Mass (At Different RPMs)

This graph shows how the concentration of CO changes with injected mass. We have obtained three curves for the RPM values of 3000, 4000 and 6000. We observe that initially at an injected mass of 0-25 all the curves have almost the same concentration values. As we increase the injected mass value from 25 onwards till 100 the difference starts increasing. We observe that the concentration of CO falls more rapidly for a 6000 RPM engine compared to a 3000 rpm one.

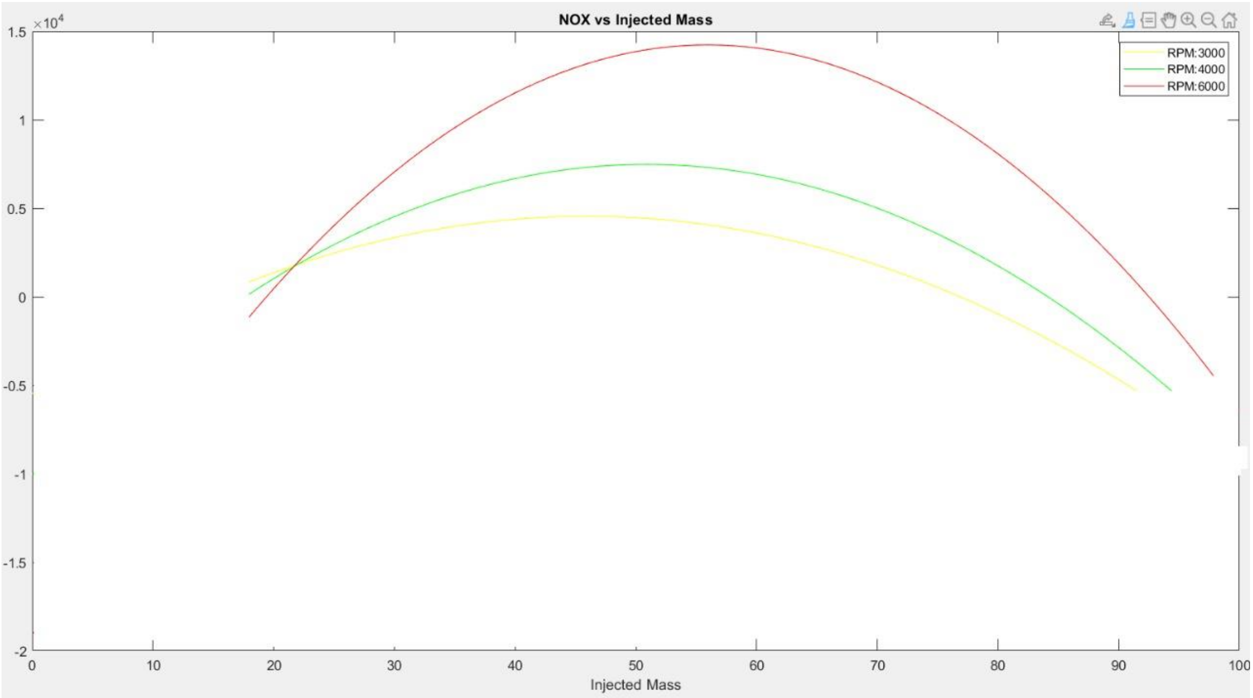

Figure 6: Plot Showing NOx Vs Injected Mass (At Different RPMs)

This graph shows how the concentration of NOx changes with injected mass. We have obtained three curves for the RPM values of 3000, 4000 and 6000. We observe that initially at an injected mass of around 20 all the curves have almost the same concentration values as the curves coincide. As we increase the injected mass value from 20 onwards till 60, the concentration keeps increasing for all the three curves with the RPM 6000 being the highest. 60 onwards the curves eventually start declining indicating a fall in NOx concentration and they move towards each other. High NOx values can be explained with an increase in temperature inside the cylinders and once the injected mass is increased to a certain extent, the AFR starts becoming richer leading to the fall in NOx concentrations.

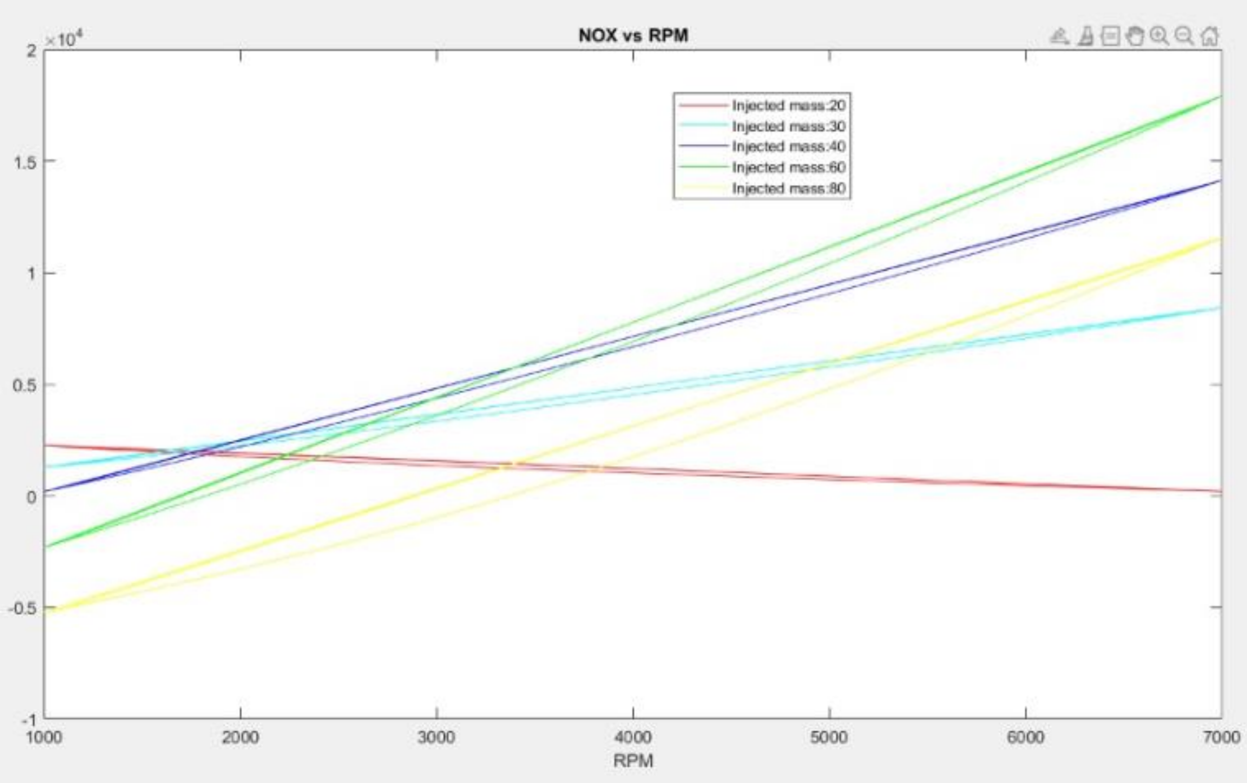

Figure 7: Plot Showing NOx Vs RPM (At Different Injected Masses)

This graph shows how the concentration of NOx changes with engine speed (RPM). We have obtained five curves for the injected mass values of 20,30,40,60 and 80. At steady state the injected mass of 80 shows the least concentration of NOx emitted. But as we keep moving towards higher RPM, we observe the injected mass of 20 has the least NOx emission. High NOx values can be explained with an increase in temperature inside the cylinders and once the injected mass is increased to a certain extent, the AFR starts becoming richer leading to the fall in NOx concentrations.

Solely in terms of minimizing the NOx emissions,

- At 1000 RPM, the ideal injected mass value would be 80
- At 2000 RPM, the ideal injected mass value would be 80
- At 3000 RPM, the ideal injected mass value would be 80
- At 4000 RPM, the ideal injected mass value would be 20
- At 5000 RPM, the ideal injected mass value would be 20
- At 6000 RPM, the ideal injected mass value would be 20
- At 7000 RPM, the ideal injected mass value would be 20

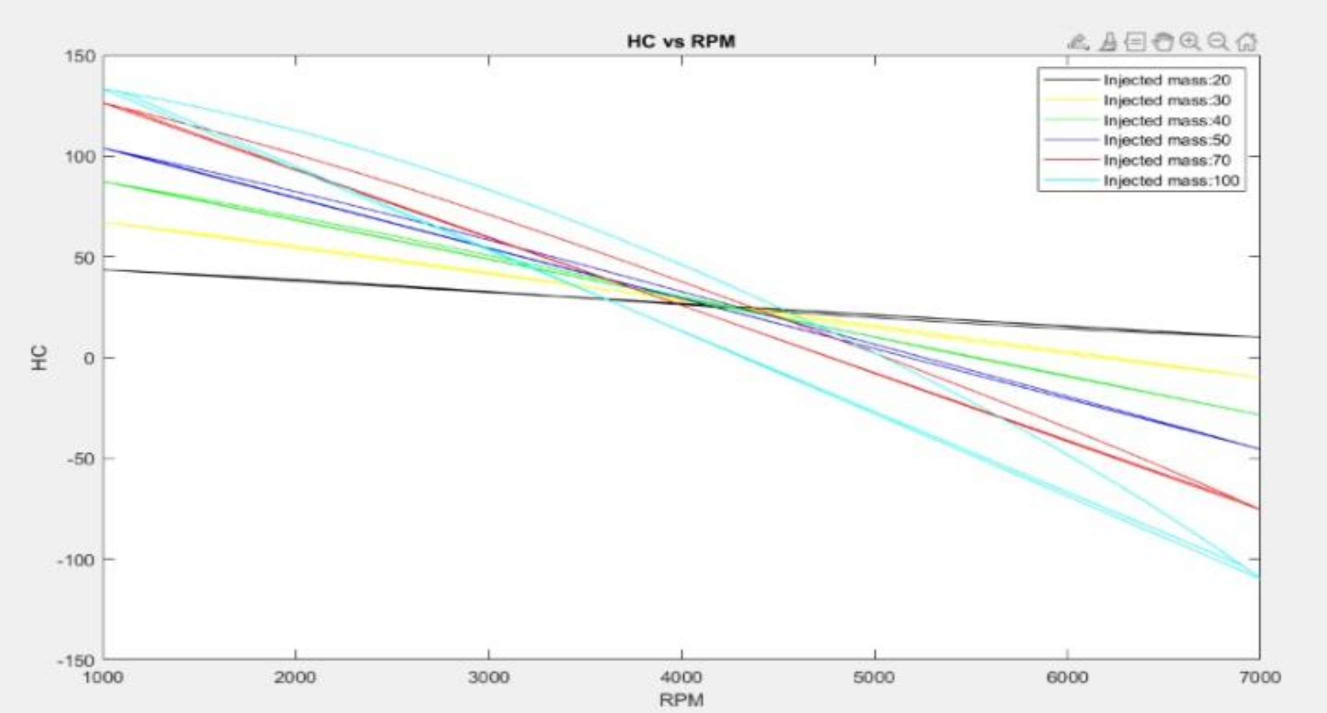

Figure 8: Plot Showing HC Vs RPM (At Different Injected Masses)

This graph shows how the concentration of HC changes with engine speed (RPM). We have obtained six curves for the injected mass values of 20,30,40,50,70 and 100. At steady state the injected mass of 20 shows the least concentration of HC emitted. But as we keep moving towards higher RPM, we observe the injected mass of 100 has the least HC emission.

Solely in terms of minimizing the HC emissions,

- At 1000 RPM, the ideal injected mass value would be 20
- At 2000 RPM, the ideal injected mass value would be 20
- At 3000 RPM, the ideal injected mass value would be 20
- At 4000 RPM, the ideal injected mass value would be 100
- At 5000 RPM, the ideal injected mass value would be 100
- At 6000 RPM, the ideal injected mass value would be 100
- At 7000 RPM, the ideal injected mass value would be 100

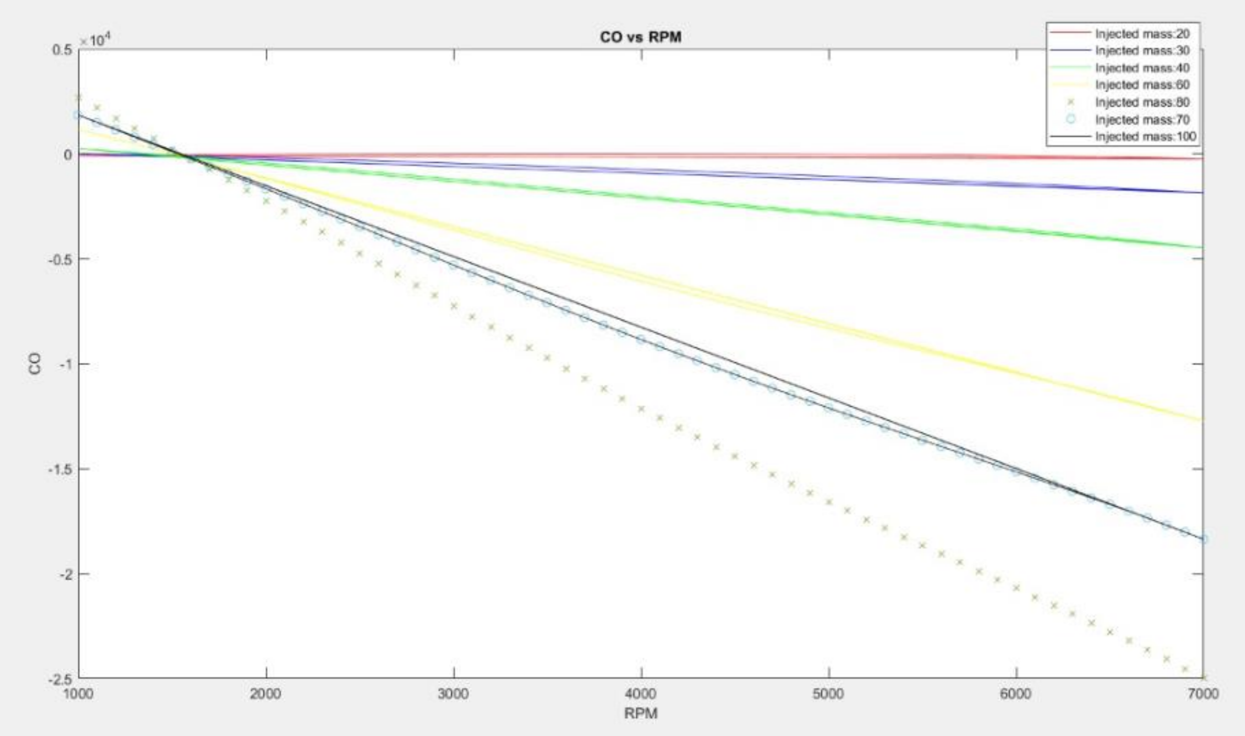

Figure 9: Plot Showing CO Vs RPM (At Different Injected Masses)

This graph shows how the concentration of CO changes with engine speed (RPM). We have obtained seven curves for the injected mass values of 20,30,40,60,70,80 and 100. At steady state the injected mass of 20 shows the least concentration of CO emitted. But as we keep moving towards higher RPM, we observe the injected mass of 80 has the least CO emission.

Solely in terms of minimizing the HC emissions,

- At 1000 RPM, the ideal injected mass value would be 20
- At 2000 RPM, the ideal injected mass value would be 20
- At 3000 RPM, the ideal injected mass value would be 20
- At 4000 RPM, the ideal injected mass value would be 80
- At 5000 RPM, the ideal injected mass value would be 80
- At 6000 RPM, the ideal injected mass value would be 80
- At 7000 RPM, the ideal injected mass value would be 80

5.1 Plots Showing Concentration Vs Injected Mass (For CO, HC And NOx) For Different Rpms (1000-7000)

Here we consider an example of a case where the RPM is pre-defined at 6000. We clearly observe a point where all the curves meet. This point where the curves for CO, HC and NOx intersect is considered to be the optimal point.

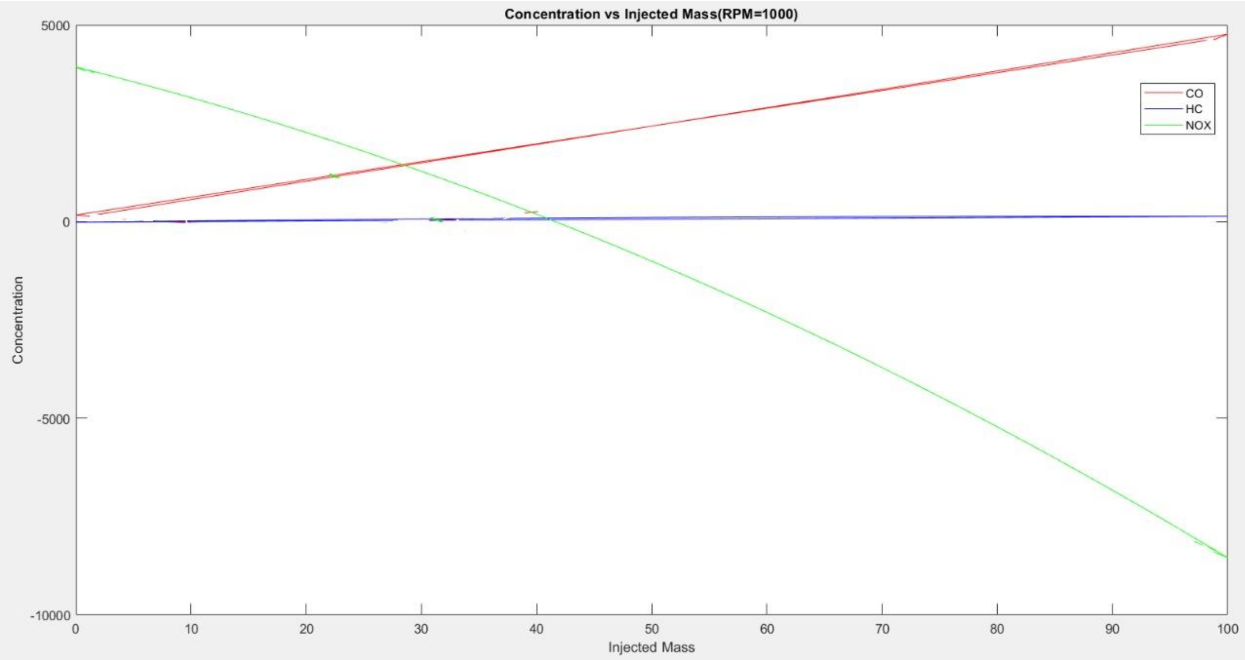

Figure 10: Plot Showing Concentration Vs Injected Mass (For CO, HC And NOx) For 1000 RPM

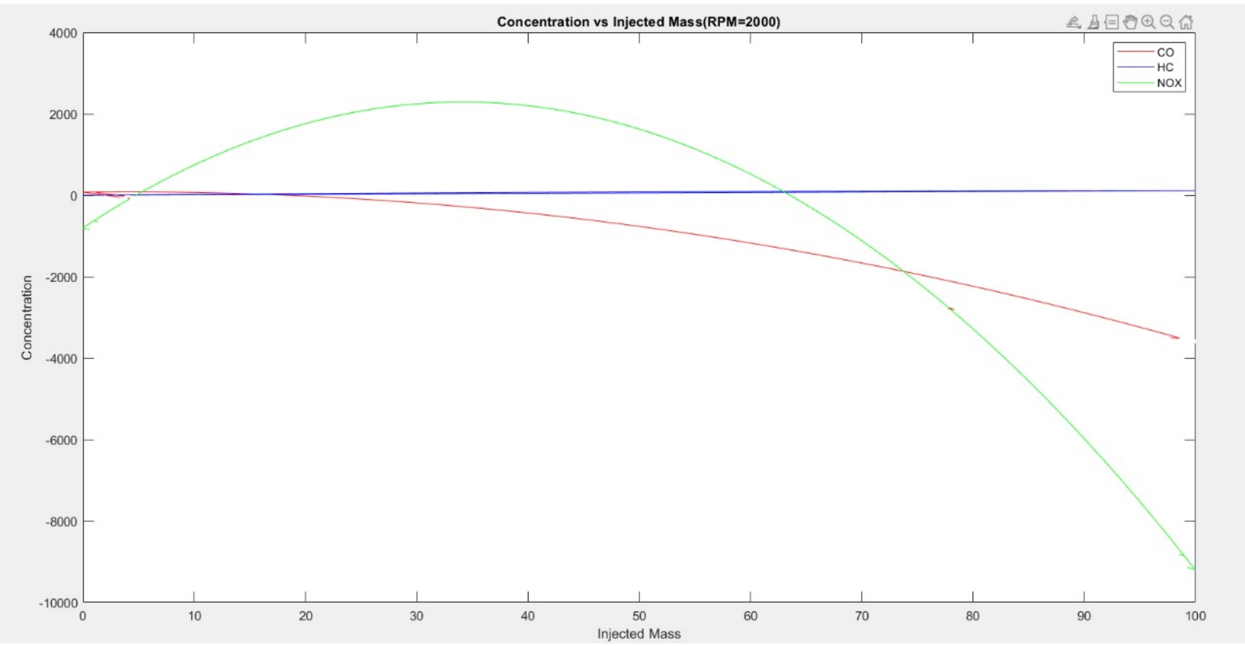

Figure 11: Plot Showing Concentration Vs Injected Mass (For CO, HC And NOx) For 2000 RPM

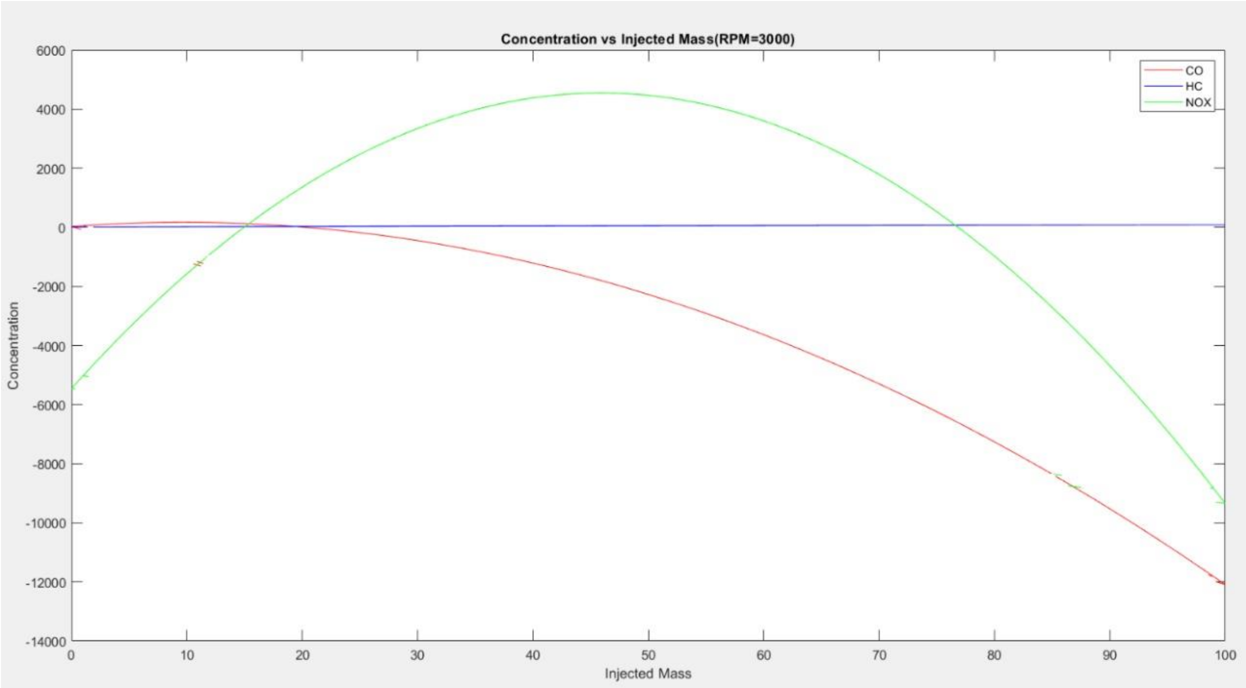

Figure 12: Plot Showing Concentration Vs Injected Mass (For CO, HC And NOx) For 3000 RPM

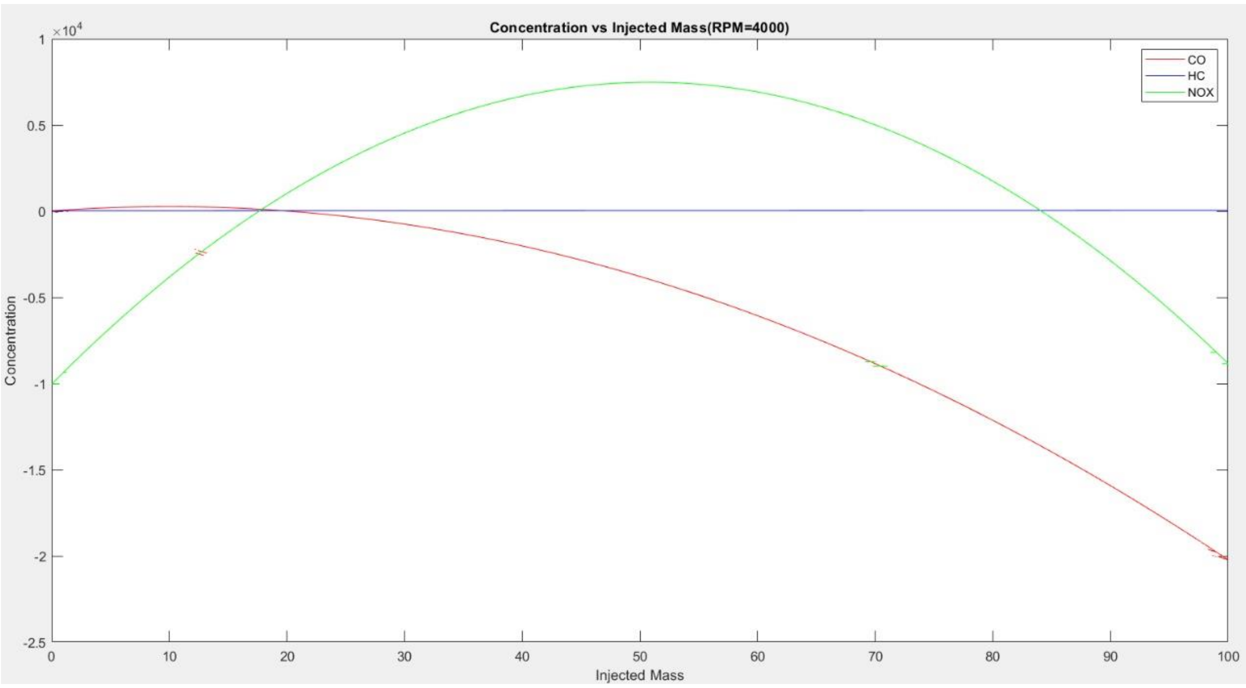

Figure 13: Plot Showing Concentration Vs Injected Mass (For CO, HC And NOx) For 4000 RPM

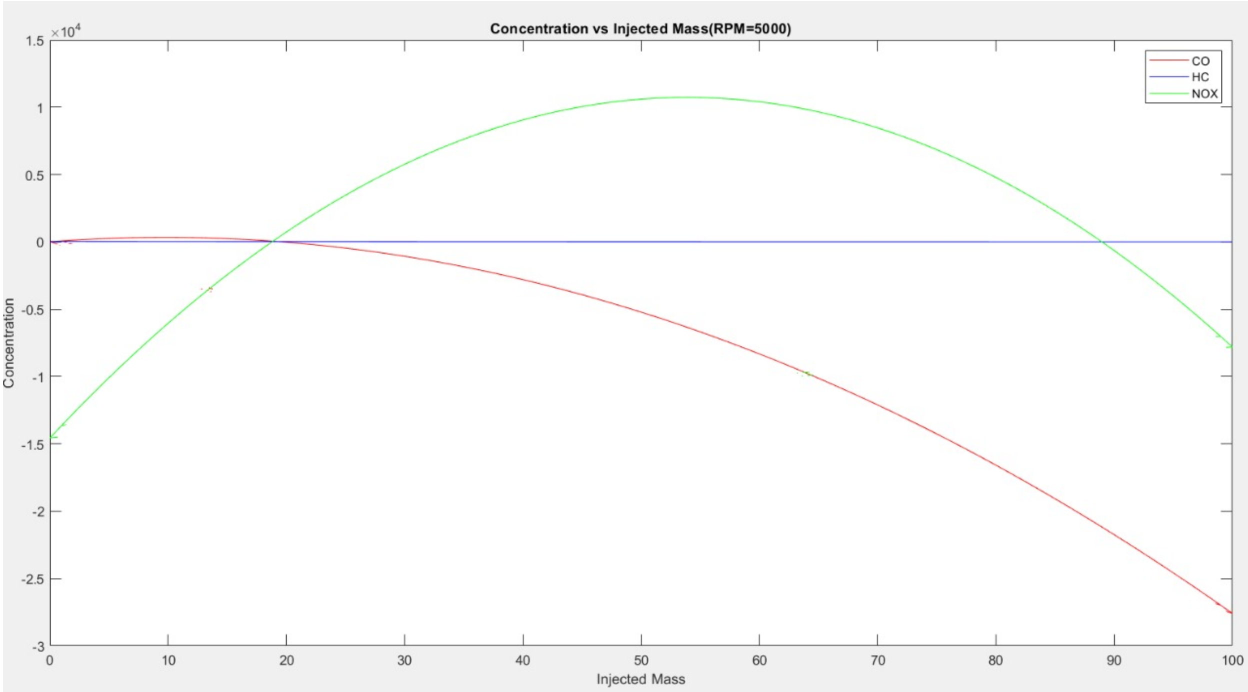

Figure 14: Plot Showing Concentration Vs Injected Mass (For CO, HC And NOx) For 5000 RPM

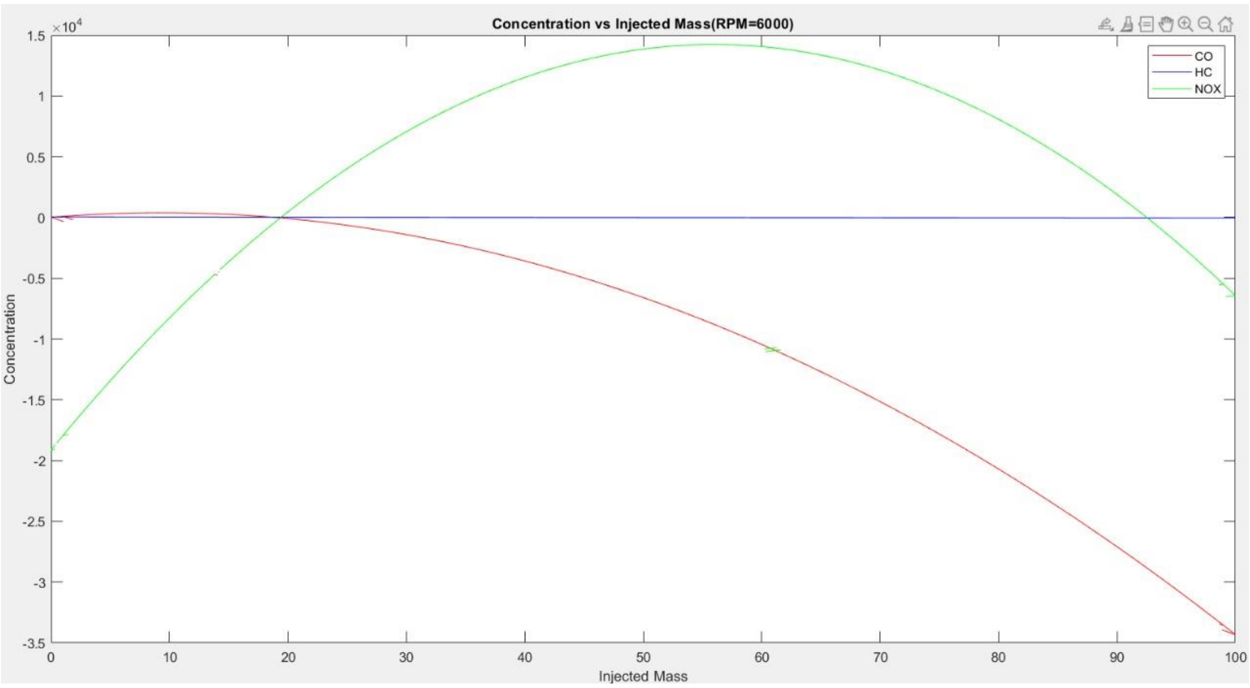

Figure 15: Plot Showing Concentration Vs Injected Mass (For CO, HC And NOx) For 6000 RPM

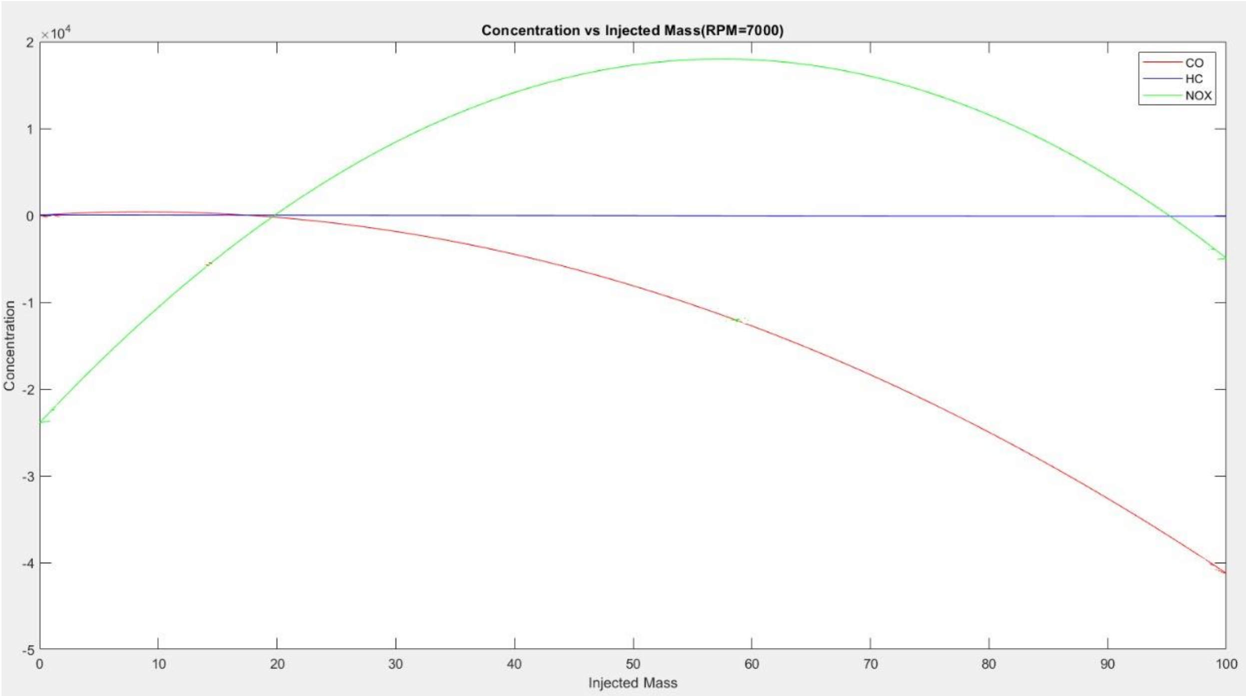

Figure 16: Plot Showing Concentration Vs Injected Mass (For CO, HC And NOx) For 7000 RPM

Based on the above plots we were able to compile and make a table for the optimal points of injected mass and RPM that show the least emissions

	EMISSIONS		
	CO	HC	NOx
Injected Mass (mg)	25mg	34mg	46mg
Engine Speed (rpm)	3812	2992	5570

Figure 17: Table Of Optimal Points

Based on our graphs generated, we have also devised a table for throttle percentage vs RPM for optimal points of injected mass where the emissions of CO, HC and NOx where minimal.

	ENGINE SPEED (RPM)					
THROTTLE	1000	2000	3000	4000	5000	6000
10	20	25	31	31	40	41
20	26	30	36	37.5	39	42
30	32.5	38	41	41.3	44	42.5
40	36	47	54.5	48	49	46
50	37.5	51	58	58.5	58	45.5
60	43	52.5	61.5	57.5	52	49
70	45	53	60.5	55	62	50
80	47	50	58.5	55.5	64	64
90	39	48	57.5	54	63	62
100	40.5	47	56.5	54	63.5	64

Figure 18: Table Of Injected Masses For Minimum Emissions

8. Conclusions

The project we have been working on has helped us gain significant knowledge in the field of automobiles and has provided a valuable experience beyond the classroom setting by academically being engaged in a project identified from the industry. Under the expert supervision of our BITS faculty and the valuable guidance of our industry mentor Mr. Sajeeth we have done tremendous progress in terms of learning project specific concepts and have been exposed to some extensive software like MATLAB, Simulink and Ricardo WAVE which have a wide range of scientific and engineering applications and would be quite essential for us in the near future.

We have achieved the following milestones while working on this project

- Worked on simulating a 1-D model diesel engine on Ricardo WAVE and obtained data for various parameters like brake power, BMEP, BSFC etc.
- Compiled the data in an excel sheet from a total of 421 cases dividing 85 each amongst the five of us.
- Worked on subsystems in Simulink where we could generate the emission plots for CO, HC and NOx.
- Analyzed plots to extract useful emissions and performance data.
- Devised a table for throttle percentage vs RPM for optimal points of injected mass where the emissions of CO, HC and NOx where minimal.

NOTE: We were successful in completing the major part of the project but due to lack of time as believed by Mr. Sajeeth Sir as well, we still have to improve the efficiency island plots in terms of performance and work on more accurate outputs for the entire project to be completed as a whole. As Mr. Sajeeth suggested we would be working a little more on this project after our PS is completed to give a more satisfactory result to our Industry mentor.

Nevertheless, we could identify optimal points for injected mass and RPM using the resources and time we had and we have presented the findings in the result section.

The project allowed us to get a deeper understanding of how various design and operating parameters affect the performance and emission characteristics of a CI engine. These results have been summarized in this document. The project allowed us to look at the practical application of our theoretical knowledge and the learning outcomes are unparallel. Our overall experience of working on this project has been really great throughout.

9. References

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10. Table Of Figures