BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE, PILANI

Comprehensive Project report

Title-Downsize the engine and optimize the forced induction system and calibration parameters to achieve the best emission performance

Name of Students		ID numbers
Arpan Kumar Sharma	-	2018A4PS0580P
Prithvi Ramesh	-	2018A4PS0502G
Shantanu Ketan Gaikwad	-	2018A4PS0345H
Tanmay Ojha	-	2018A4PS0017H

- **Sirius Motorsports, Chennai**
- **A Practice school Station of**
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Prepared in the fulfilment
of the PS -1 Course Numbers
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AT

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BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE PILANI
(RAJASTHAN)
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Abstract-

As the auto industry leapfrogs to stricter emissions norms, it sounds good to consumers, but it isn't all hunky-dory for the automobile- manufacturers. Internal Combustion Engines (ICEs) are notoriously known for the production of harmful emissions like Carbon monoxide(CO), hydrocarbons(HC), oxides of nitrogen (NO_X) and particulate matter. With global emissions norms getting stricter, it led automakers to trod down the alleys of 'downsized turbocharged engines' that pack a punch and are efficient. A downsized engine has a smaller engine displacement value hence it has less frictional losses and emits fewer emissions due to a lower BSFC value. But to maintain the gradability of the vehicle, forced induction techniques like turbochargers are used to get more specific power and torque.

The baseline data like brake power, brake thermal efficiency & emission plots etcetera against discrete engine speeds (in rpm) are obtained from RICARDO WAVE, a state-of-the-art 1D gas dynamic simulation tool which enables analysis of any virtual intake, combustion and exhaust system process. The main motive of this report is to document the various advantages and means of Downsizing engines, the methodology followed to select the forced induction system and model the engines, and the tuning operation on a Virtual Dyno application- ReynICE.

To validate the aim of the project; the results, conclusions & corresponding inferences drawn from comparing our downsized '3 cylinders SI Forced Inductions (FI) engine' with a '4 cylinders SI Naturally aspirated (NA) engine' has been documented with various plots, graphs, and data as proof.

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I. INTRODUCTION

The current scenario of emission control around the world, calls for us to upgrade the engines of automotive vehicles from BS-IV to BS-VI. The Bharat Stage(BS) are standards instituted by the government to regulate the emissions of air pollutants from motor vehicles. With appropriate fuel and technology, they limit the release of air pollutants such as nitrogen oxides, carbon monoxide, hydrocarbons, Particulate Matter (PM), and sulfur oxides from vehicles using internal combustion engines. As the stage goes up, the emission norms become stricter. The standards are based on European regulations that were first introduced in 2000.

New technology and innovative measures will be needed by the automotive industries in the field of combustion, ignition, carburettors, and exhaust system. Taking a leap from BS-IV to BS-VI comes with immense technical challenges. It took Europe nearly 9 years to completely implement the Euro VI standards. Car-makers will have to spend heavily to develop BS-VI compliant engines for their existing product line.

A study by ‘System of air quality and weather forecasting’ under ‘The Ministry of Earth services’ showed that the Transport sector contributes around 41% to the pollution in Delhi. Cleaner fuel is one of the ways to combat air pollution. BS-VI fuel will bring down the concentration of sulfur by 80%, i.e. from the 50 parts per million to 10 parts per million. BS-VI fuel is expected to reduce the NO_x(nitrogen oxides) emissions from diesel cars by 70% and from petrol cars by 25%. RDE (Real Driving Emission) will be introduced that will measure the emission in real-world conditions and not just under test conditions. BS-VI norms will also change the way particulate matter is measured. It will now be measured by number standard instead of mass standard thereby, regulating the fine particulate matter as well.

Another set of norms called the Corporate Average Fuel Economy (CAFE) norms, first introduced in the United States, have been put into place in India and many other developing countries to improve the engine efficiency of cars and light trucks. These standards regulate how far a car must travel on a gallon of fuel and aims to lower fuel consumption by lowering CO_2 levels. The norms are applicable for petrol, diesel, LPG, and CNG passenger vehicles. Under this, average corporate CO_2 emission must be less than 130 gm per km till 2022 and below 113 gm per km thereafter. Upgrading to stricter pollution norms is one of the ways to tackle air pollution. These norms have been brought in place to reduce the carbon footprint of the automobile industry

However, in certain countries such as Japan, the automobiles are taxed based on the displacement volume of the engine. Hence it becomes very necessary for the engineer to optimize both the emissions as well as the displacement of the engine. Our goal in this project was to optimize both the engine size as well as the emissions released by the automobiles.

Emission Standards for Light Duty Vehicles[iii]

		BS-IV Norms			BS-VI Norms		
Petrol Vehicles	Unit	M & N1 Class I	N1 Class II	N1 Class III	M & N1 Class I	N1 Class II	N1 Class III
CO	g/ km	0.50	0.63	0.74	0.50	0.63	0.74
HC	g/ km	-	-	-	-	-	-
HC+NOx	g/ km	0.30	0.39	0.46	0.17	0.195	0.215
NOx	g/ km	0.25	0.33	0.39	0.08	0.105	0.125
PM	g/ km	0.025	0.04	0.06	0.0045	0.0045	0.0045
Diesel Vehicles	Unit	M & N1 Class I	N1 Class II	N1 Class III	M & N1 Class I	N1 Class II	N1 Class III
CO	g/ km	1.00	1.81	2.27	1.00	1.81	2.27
HC	g/ km	0.10	0.13	0.16	0.10	0.13	0.16
HC+NOx	g/ km	-	-	-	-	-	-
NOx	g/ km	0.08	0.10	0.11	0.060	0.075	0.082
PM	g/ km	-	-	-	0.0045	0.0045	0.0045

M category include motor vehicles having at least four wheels and for the carriage of passengers
N1 Class I include Power-driven vehicles having at least four wheels and for the carriage of goods (< 3.5 tonnes)
N1 Class II include Power-driven vehicles having at least four wheels and for the carriage of goods (>3.5 tonnes and < 12 tonnes)
N1 Class III include Power-driven vehicles having at least four wheels and for the carriage of goods (> 12 tonnes)
Source: http://transportpolicy.net/index.php?title=India:_Light-duty:_Emissions

Figure1: A comparison between BS-IV andBS-VI norms

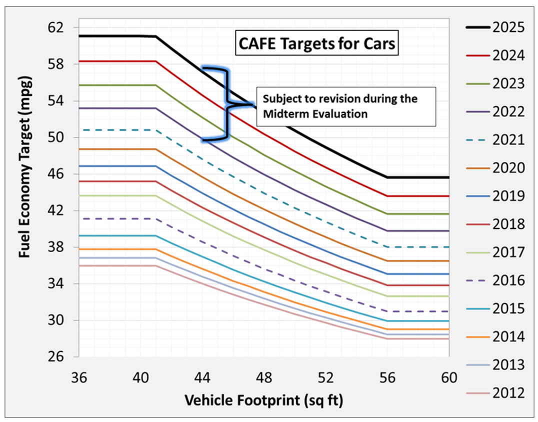


Figure 2: A plot showing the CAFE norms ie. Fuel Economy targets against the Vehicle footprints. The section for motor-cars has been highlighted at the top

II. OVERVIEW

A. DOWNSIZING OF THE ENGINE

Engine Downsizing refers to the use of smaller engines over larger ones having the same capacity. Engine downsizing can be achieved by reducing the total displacement volume of the engine and by reducing the number of cylinders. The downsized engine has many advantages namely:
a) Reduced emissions due to an efficient engine.
b) Reduced sprung mass of the car leading to better vehicle handling characteristics and reduced load on the engine.
c) Compact engine bays. Smaller engines save space and reduce the complexity of larger engine blocks.
d) Improved driveability of the engine. Higher fuel efficiency.

Engine downsizing offers significant fuel economy benefits for passenger car applications. A smaller engine has reduced friction losses, pumping losses, lower heat losses, and higher efficiency. For a given power requirement at a constant speed, a downsized engine operating at higher BMEP (Brake Mean Effective Pressure) produces higher efficiency (or low BSFC). Due to low BSFC and improved combustion, emissions are reduced significantly. Many automotive manufacturers are turning towards engine downsizing to reduce carbon-dioxide emissions and helping them comply with new emission norms. With the optimization of the intake and exhaust valve timing by the means of free-valve, variable valve duration or VVT, with intake and exhaust manifolds having runners of different lengths for different engine speed and with the use of other such technologies, we can make sure the downsized engines perform if not better then at par to the bigger engines.

B. TURBOCHARGERS & SUPERCHARGERS

I. *Brief Introduction*

The main drawback of using a smaller engine is the reduced brake power and brake torque delivered particularly at high speeds. Despite its lower displacement, the performance of a downsized engine can be improved by increasing the MAP (Manifold Intake Pressure) and injecting more air into the combustion chamber to burn additional fuel.

Turbocharging provides the engine with the mass of air needed to ensure highly efficient and clean combustion. In both petrol and diesel vehicles, the turbocharger comprises two assemblies: a centrifugal compressor and a turbine. Hot exhaust gases rotate the turbine which rotates the compressor as both are connected via the same shaft. The compressor comprises an impeller and a diffuser, housed in the compressor casing. The impeller accelerates the air drawn from the atmosphere and forces it towards the diffuser. The diffuser slows the fast-moving air which raises its pressure and temperature in the compressor housing. The cold & compressed air is then directed to the engine. This way, more air is injected into the combustion chamber to burn the additional fuel injected.

Forced induction allows for sufficient air to enter the combustion chamber to ensure complete combustion. As a result of which the formation of carbon monoxide and other pollutants created due to lack of oxygen is reduced to the bare minimum. The volumetric Efficiency or the breathing capacity of the engine is also improved. However, the trade-off is the formation of nitrogen oxides. These pollutants are formed due to excess oxygen and high temperature in the combustion chamber. It is due to this factor in combination with others like 'turbo-lag' which has made the use of single turbocharger obsolete. Modern forced induction systems use several variations viz.. Bi-turbo, twin-turbo, and superchargers.

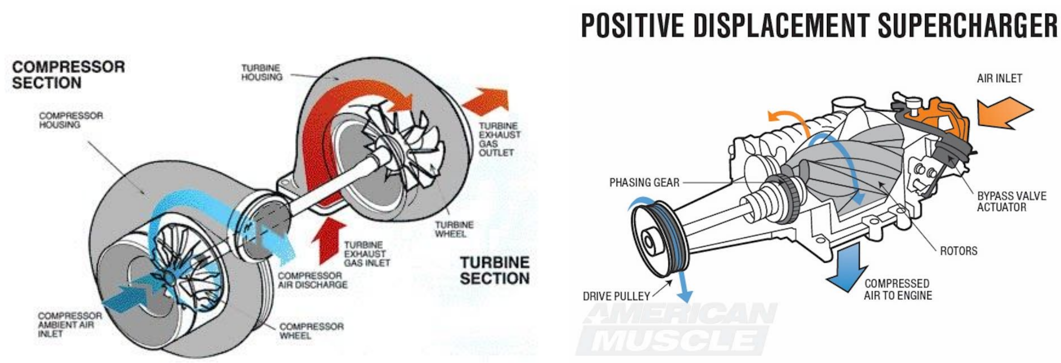


Figure3: A turbocharger and a supercharger, forced induction methods

II. Selecting a Turbocharger

To achieve the best engine performance in terms of horsepower, torque, volumetric efficiency, etcetera it is important to select the perfectly sized forced induction system.

The first step is to choose between a turbocharger and a supercharger. And for this, it is essential to understand the difference between these two. While a supercharger draws power from the engine, a turbocharger recovers waste heat from the exhaust gases. According to the Sankey heat balance diagram of engines roughly about 60% of the fuel energy gets converted to and wasted as heat, the turbocharger uses this heat to produce useful work in the form of compression of intake heat. Also while the supercharger is a constant pressure pump which means that the pressure does not vary, the turbocharger is a variable pressure pump. This means that by varying the pressure produced(using a wastegate) we can vary the volumetric efficiency and torque produced at various RPMs and throttle positions. Due to these advantages, a majority of the automotive industries prefer a turbocharger.

The sizing of the Compressor (cold) and the turbine (hot) should be decided based on these characteristics given below-

Type	**Size**	**Inertia**	**Airflow**	**Lag**	**Power**
Compressor	Large	Large	More	More	More
Compressor	Small	Small	Less	Less	Less
Turbine	Large	More	More	More	More
Turbine	Small	Small	Less	Less	Less

Table 1: A table to decide the sizing of the Compressor and Turbine of the Turbocharger

We were taught to select turbochargers from the various options that ‘Garett-Motion’ a Turbocharger manufacturer has to offer, specifically models like the ‘ GT15’, ‘GT20’ which are most often fitted to smaller engines. If we look at the turbocharger compressor's map in Figure 4, the islands represent the efficiency values and RPMs of the compressor. The method to be followed is as follows-

a) The target boost pressure and pressure ratio are decided
b) The value of airflow can be calculated with the help of the formula

   *AF = (HP*AFR*BSFC)/60 lb/min*

   Where ;
   i) HP = Total brake horsepower of the engine.
   ii) AFR = Air fuel ratio at particular engine speed.
   iii) BSFC = Brake specific fuel consumption.
c) The target airflow can be deduced through an online calculator - *Boosttown.com*. The engine RPM, engine size, Volumetric efficiency & boost pressure targeted for the engine are input into the online calculator to find the air-flow value.
d) The previous step is repeated for increasing engine speeds until we reach the redline RPM of the engine.
e) The island plots of the turbocharger having pressure ratio and corrected airflow on the 'Y' & 'X' axis and the contours representing the turbocharger efficiency of the graphs are procured and studied.
f) The values of airflow rates obtained from the calculator are plotted approximately on the island plot.
g) Depending on the location of the point on the plot, we can determine which efficiency contour intersects with our point. 60% efficiency on the contour would mean that 40% of the energy input from the exhaust gases is lost as heat.
h) If the points fall out of the contour zone at low RPMs, it is indicative of the fact that the airflow is too less to spool the turbocharger while at high RPMs choking of airflow is taking place,

Point	Air-flow value	Inference
A	3.89	68% efficiency
B	7.78	72% efficiency
C	15.52	Choking

Table 2: Airflow values for a 2000cc 150 Hp engine at 85% Volumetric efficiency and 0.7bar Boost pressure. The pressure ratio is 1.5

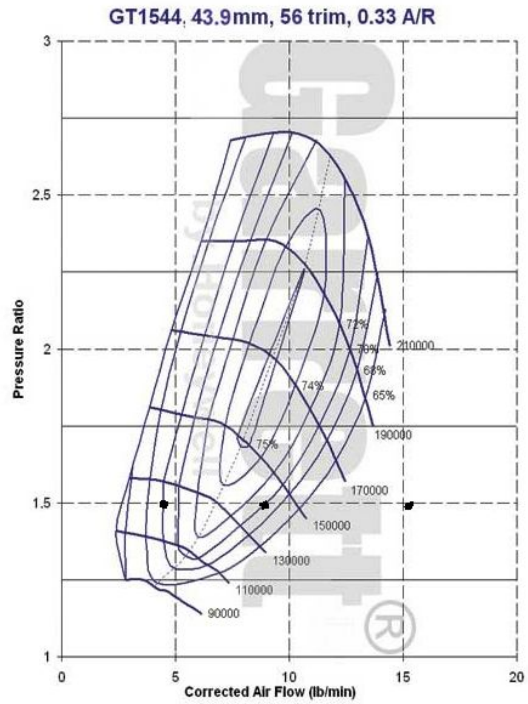


Figure 4: Garrett turbocharger GT1544 plot.

C. AIR-FUEL RATIO, VALVE TIMING, SPARK ADVANCE & VARIABLE RUNNERS

The *Air-fuel ratio* has an important influence on the emissions produced. A very rich air-fuel ratio would create an excess of fuel which would lead to inadequate oxygen molecules present to completely react with it. This leads to incomplete combustion and therefore the formation of carbon monoxide. This odourless and colourless gas is very harmful.

A slightly lean mixture, on the other hand, would result in the formation of oxides of nitrogen. In a lean mixture, there is excess oxygen and therefore complete combustion takes place raising the temperature in the combustion chamber. This high temperature and oxygen percentage catalyze the formation of nitrogen oxides. These oxides of Nitrogen are harmful to the ozone layer. Therefore the necessary air-fuel ratio needs to be maintained to ensure that the least amount of emissions are produced.

The *Valve Timing* dictates the duration in which charge; Gasoline and air in the case of the SI engine and air in case of CI engine, is inducted into the cylinder and also the time for the exhaust stroke. The time available for combustion depends on valve timings. This results not only in power loss but also in the formation of products of incomplete combustion like Carbon Monoxide. Modern downsized engines are equipped with a Variable valve timing & Valve lift control mechanism to regulate the valves at different engine speeds.

Spark advance is the time in terms of crank angle from the TDC in which the spark-plug fires. This has a direct effect on combustion characteristics namely - a time of combustion, peak pressure, maximum temperature acquired. It also influences knocking characteristics.

Since the combustion characteristics influence the combustion products, optimum spark advance value has to be calibrated. A spark that happens too late can result in incomplete combustion due to the expansion motion. There are other parameters of the intake and exhaust manifold design like - length, bends, and curve, pipe diameter, scavenging effect, etc; which have a direct or indirect effect on combustion. Complete combustion at not a very high temperature is ideal from an emission point of view.

Variable-length Intake Manifold - An internal combustion engine equipped with a variable-length intake manifold (VLIM) or variable intake manifold (VIM) can use variable geometry intake system to achieve the best performance in terms of brake torque, brake horsepower and volumetric efficiency at a wide range of operating speed (RPM) range. Most engines achieve this system by having two intake ports each with a short and a long runner length which are controlled by a valve. The main goal of this system is to achieve maximum swirl or turbulence in the combustion chamber, this reduces engine knock, allows rapid fuel vaporization and mixing, aids in the combustion process.

At a very low RPM, the speed of the charge of air approaching the engine is slow, and therefore the longer and shorter runner is used, this is done to increase Reynold’s number of the airflow and also its speed. It also improves the low RPM torque.

At a higher RPM, when the engine is running at full load, the shorter and wider runner is used to reduce the restrictions to the airflow and allow for more air to enter the combustion chamber.

This type of intake system is very useful especially in vehicles that routinely operate at wide ranges of speed. It was first patented by Daimler Benz AG.

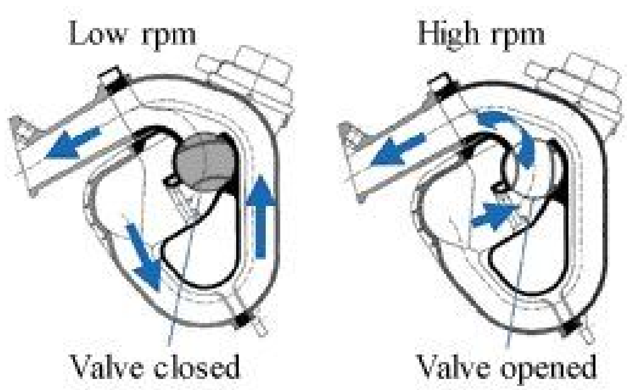
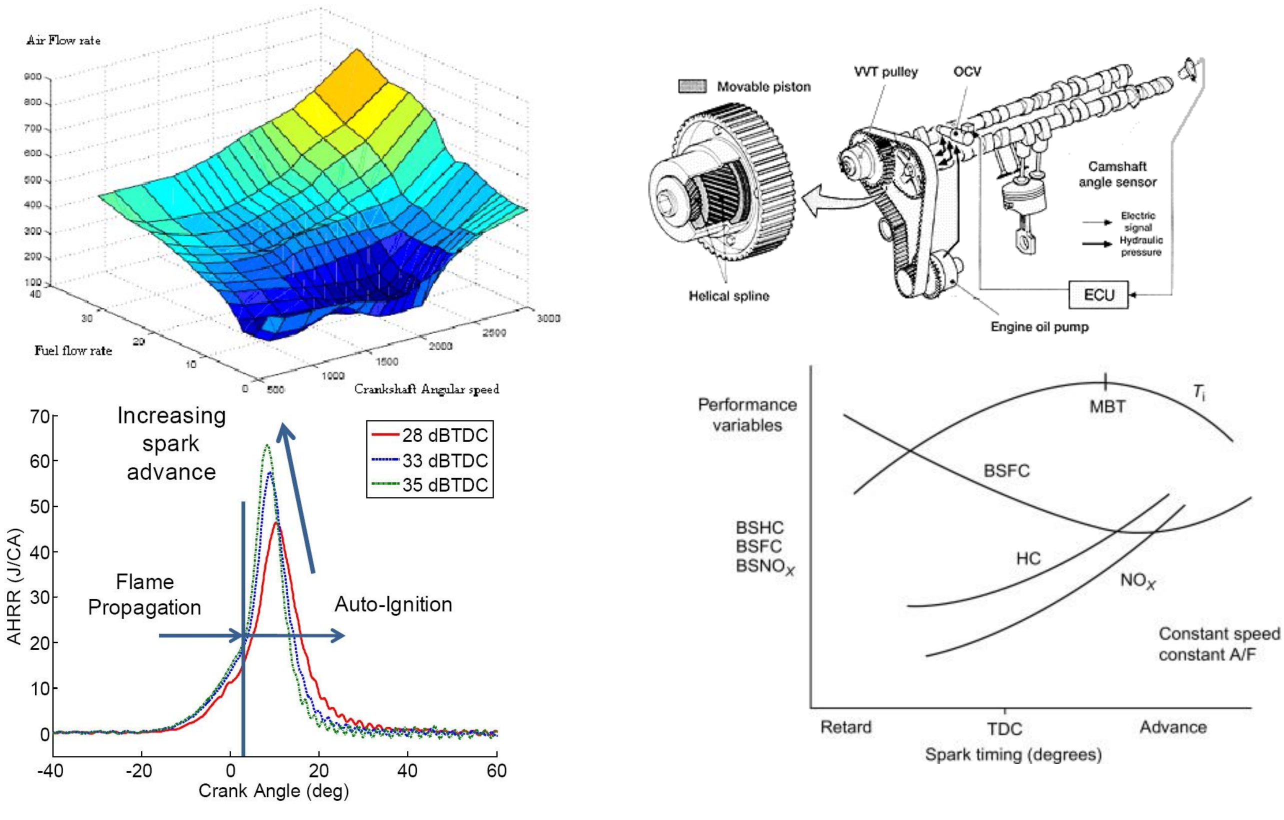


Figure 5: A Figure showing the intake runner length being changed by actuating the valve.



(c)

Figure 6: (a) SI engine model look-up table. (b) A VVT(Variable Valve timing train with its pulley. (c) Effect of spark timing on heat release. (d) Effect of spark timing on various engine parameters.

	CO, HC	**NO_X**	**Torque**
Min	AFR lean SA optimum	AFR rich SA less	AFR lean SA less
Max	AFR rich SA less	AFR lean SA optimum	AFR rich SA optimum

Table 3 - (SA optimum- 20 deg BTDC; SA optimum- 5-10 deg BTDC)

Table 2 illustrates that the best efficiency, emissions, and performance cannot be achieved with a particular SA and AF ratio. A rich AFR not only produces more torque but also more CO and HC, so they have to be regulated constantly by the engine's ECU (Electronic Control Unit) to get the best output from the engine.

D. DRIVING CYCLE AND CHASSIS DYNAMOMETER

I. Driving cycle

The Drive cycle is one of the techniques used by a vehicle's PCM (Powertrain Control Module) to make sure that an emission system test is performed successfully. It is a series of data points representing the speed of the vehicle in the vertical axis and time on the horizontal axis. Different drive cycles are set by different countries and authorities to determine the vehicle's performance in various ways, for example polluting emissions and fuel consumption.

There are two kinds of driving cycles,

1. The modal cycle is the European standard NEDC, Japanese 10-15 MODE.
2. The transient cycles are the FTP-75, IDC, or Artemis cycle.

A Modal cycle is a Velocity v/s Time plot having regions of both linear acceleration and uniform velocity. They involve protracted periods at constant speeds and are representative of real driver behaviour. The transient cycles involve speed variations, representing the constant speed changes typical of on-road driving.

In India, the ARAI (Automotive Research Association of India) provides technical expertise in testing and certification, homologation, and framing of vehicle regulations. The IDC (Indian Driving Cycle) was first developed by ARAI in 1985 under the Central Motor Vehicles Rules of India. The cycle was based on actual on-road measurements and is still followed for testing of emissions for two/ three-wheelers. IDC (for 1981,92 & 98 norms for 4W) was actually a very short cycle (although comprising six driving cycle modes) of just 108 seconds and did not cover all the different driving conditions observed on the road. The average speed of IDC is 21.9 km/h, covering 3.94km, which also seems to be high in view of rising congestion in Indian cities. Moreover, all two-and-three wheeler vehicles except diesel vehicles are run with 40 seconds idling as preconditioning before sampling on a chassis dynamometer. The modified IDC introduced a few years ago is 1180 sec long and covers a total distance of about 10.647 km. The organization carefully worked on the driving cycle and took urban streets, rural roads and highways or motorways running conditions and predicted how the vehicle would behave in these scenarios.

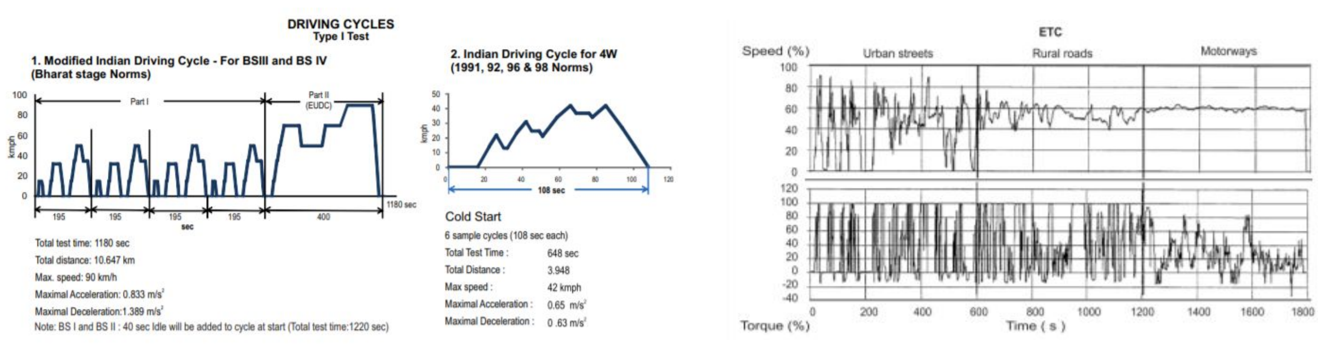


Figure 7: (a) Figure showing the modified Driving cycle which is 1180 seconds long for BS-III & BS-IV compliant engines. (b) Figure showing the older 4W Driving cycle. (c) Figure showing

II. *Chassis Dynamometer*

A chassis dynamometer (or rolling road) is a device used for vehicle development and testing. It uses a roller assembly and simulates a road in a controlled manner. They are of many types of dynamometer according to the target requirement, like emission measurement, noise vibration, performance measurement, miles accumulation, tuning chassis dynamometer, etc.
There are strain gauges that will measure the torque created by the dynamometer's rollers. Air and fuel are provided according to the engine's ECU calibration and torque meter will run accordingly. The diluted air is passed through the exhaust gas bags which test the air with different techniques for different emissions, ex. Chemiluminescent Analysis of Nitrogen Oxides, Heated flame ionization detector for hydrocarbon emissions, etc. The air is diluted because the exhaust contains volatile material, like water, sulfur, etc and cooling it may lead to the supersaturation of many of those species, resulting in condensation and nucleation. To avoid this, the exhaust gases are either diluted or the volatile material has to be removed.

The chassis dynamometer must be capable of simulating road load within some classification when vehicles are tested on various parameters, like fixed load curve, number of rollers, simulators of inertia and load, accuracy, etc.

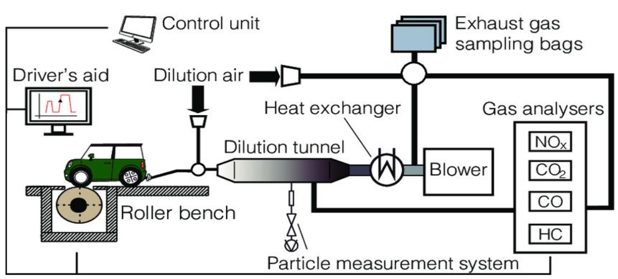


Figure 8: An emission measurement chassis dynamometer model showing the test vehicle on the rig, the dilution chamber, gas analyzers and the exhaust sampling bags.

III.METHODOLOGY

A. RICARDO WAVE

I. *About Ricardo wave*

Ricardo Wave is a 1-dimensional gas dynamics simulation software that is used for simulating various IC Engines and Gas Turbines. The software can be used throughout the engine design process, from early concept research to optimizing a complete engine. improving the volumetric efficiency, designing complex boost systems, improving transient response or extracting the maximum performance from a race engine, For the software to be able to solve given tasks, coefficients and advanced sub-models are implemented. With user-provided data, pre-programmed equations and governing laws of physics like momentum, energy- and mass conservation, different aspects of the particular engine can be solved. This engine simulation software was developed to reduce the cost and time spent on developing real working prototype engine models by shortening testing time and effort required to reach the desired results. Both Ricardo Wave and GT-Power are two of the leading engine simulation software which provides manufacturers with valuable results on several parameters for optimization of components.

II. *Work-flow on Ricardo Wave*

We will simulate the stock 4 cylinders provided on Ricardo Wave. Various plots e..g BSFC, Brake torque, Brake power and Volumetric efficiency will be studied. The displacement volume of the 3 cylinders downsized engine will be determined based on the dimensions of the combustion chamber. A drop in brake power and torque is expected due to the decrease in the engine capacity. To combat this, we turn to turbocharger and supercharger assemblies.

The 3 cylinder engine model will be now paired with different configurations of forced inductions like for example a) Simple turbocharged/supercharged b) Bi-turbo or Twin-turbo. The simulation results of all the cases will be studied to pick the case providing the best torque and power output. The data of the 'Downsized SI engine model look-up table' containing AFR v/s Engine speed in rpm and throttle positions, is then converted into an array to be fed into MATLAB for easing further calculations and for tuning purposes

The above-mentioned process would have been the ideal work-flow to observe. We were provided with an already modelled made 3 cylinders downsized SI engine fitted with a turbocharger. The input parameters like engine speed, throttle percentage, spark advances, compressor RPMs etcetera were provided to be fed into the system. 416 such test cases were run where a drive cycle for engine speed was followed. The results of the simulation were compiled in an excel document which was later fed into MATLAB to plot the result curves, comparing the data of the already available NA engine with that of the FI engine. Various parameters like Brake horsepower, Brake torque, Volumetric efficiency, BSFC values and emission value were plotted and studied.

B. MODEL-BASED APPROACH TO CALIBRATION ON MATLAB SIMULINK

Traditionally calibration requires many months. This is because the process had to be started from scratch. Thus it used to take a lot of time to tune the engine parameters in order to achieve the best fuel economy and emission performance. However, after the onset of the use of control systems and software technology it has reduced significantly. The primary goal of calibration is the tuning of the ECUs in the right manner. This task is accomplished in the following three steps

1. Model in the loop test: in this step we run the Simulink model with entering the constant data which we had entered in the Ricardo wave 1D analysis in the Simulink model which is being shown in Figure 9. The Simulink model was provided to us by the industry expert so that we can input the values and get the corresponding data. This is a very crucial approximate method as it helps in saving a lot of time. On giving satisfactory results in this step, the next step follows.

2. The software in the loop test: In this step, we have to run convert the Simulink file into C++ code and then use the knowledge of control systems to tune the engine accordingly using a high-level programming language.
3. Hardware in the loop test: once the engine has been tested through the above 2 steps we move on to this step. In this step, we examine the intricacies of the measurement equipment of the ECUs, i.e. the valve clock which is used for the timing of the opening and closing of the intake valve and exhaust valve. Such differences may arise due to the high speed of the engine and normally the timing of the opening or closing of the intake valve has to be done in a time as less as 20 ms. After passing this step the calibration is considered completed.

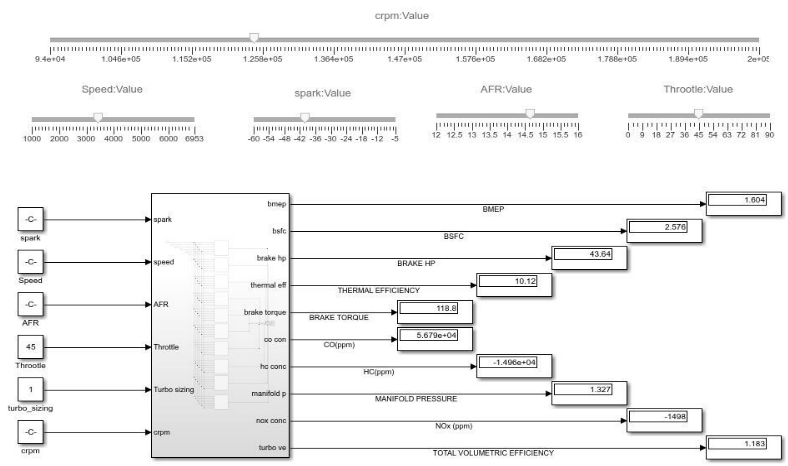


Figure 9: Calibration in MATLAB Simulink

C. AUTOMATIC GEARBOX SIMULATION USING STATE FLOW

A finite state machine is a mathematical model of an abstract machine that can be in exactly one of a finite number of states at any given time. A classic example of this is a traffic light signal which switches between colours Red-Yellow-Green (usually) and stays in one state at a given time. An important application of a finite element machine in the automobile is the transmission system or the gearbox. Here unlike the traffic signal, the variable that decides the shifts to different states is the vehicle RPM. Internal Combustion engines have high efficiency and torque delivery in a relatively narrow range of RPMs in which the vehicle operates. Therefore, a model on 'Simulink State Flow' is created as a virtual gearbox in which the conditions for shifting gears according to the RPM can be modelled into it. This model can be tested for different driving conditions and it can be used to observe how the gearbox would respond to rapid changes in RPM.

The vehicle's wheel speed is monitored through an installed wheel sensor and this is fed in as the value for the RPM. In the state flow model, four states are created each as the first, second, third, and fourth gear. A change to a higher gear is termed as a UP shift and a change to a lower gear state is called DOWN shift. The gear states are contained inside one super-state called 'gear_state' another superstate is created below for the shifting gear states this is called 'Shift_State'.

In a practical driving environment, a situation may arise wherein the driver is required to rapidly accelerate and conversely may also be required to rapidly decelerate. In these situations, it is not advisable to shift gears. Therefore modern Automatic Gearboxes are programmed to delay the gear shift for a waiting period. In our model, the gearbox is programmed to shift to the 'Shift_State' if the vehicle speed exceeds (in case of UP) or decreases below (in case of DOWN) the threshold. After this, it waits for a given period and if the condition pertaining to the threshold remains, it engages the UP shift in the 'gear_state', else it returns to the steady-state. 'UP' and 'DOWN' are defined as actions or events in the gear_state.

The final state flow model which accepts the vehicle speed from the sensor is placed in the Simulink model and its output which is the gear value is fed to the transmission state flow. In the Autumn IC gearbox, the values are controlled by solenoids that open and close to allow the fluid to operate the actuators. A particular set of actuators and its corresponding solenoid need to be open for a particular gear shift. Therefore in the transmission state flow signals are passed as 0 or 1. 1 which corresponds to actuation and 0 is steady-state.

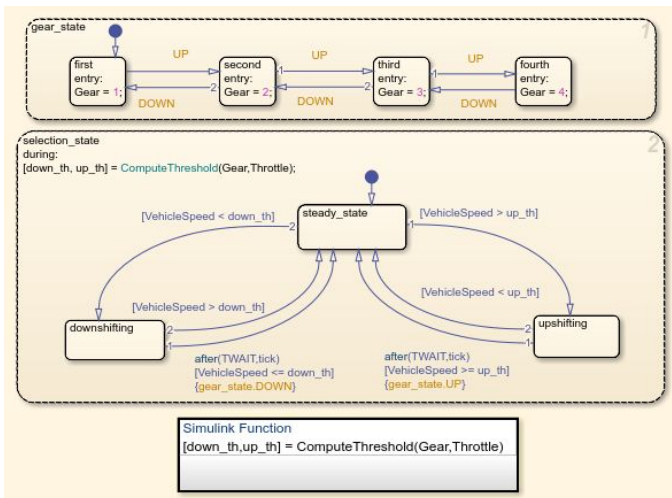


Figure 10: Stateflow model of an automatic gearbox

D. REYN-ICE

ReynICE was created as a virtual calibration tool for a better understanding of the engine tuning process and for cost reduction. The software package allows for setting ECU parameters like Air-Fuel ratio, Spark advance, throttle, RPM to different values depending on engine loads and driving conditions. The results obtainable include emissions of different pollutants and knocking effects. After the engine parameters are selected, the ECU controlled parameters are calibrated against the RPM and throttle values to get the least emissions and best performance.

A real dynamometer must be used to tune the ECU of the downsized FI engine in such a manner that the engine produces maximum torque, is fuel-efficient, and produces fewer emissions than the bigger engine.

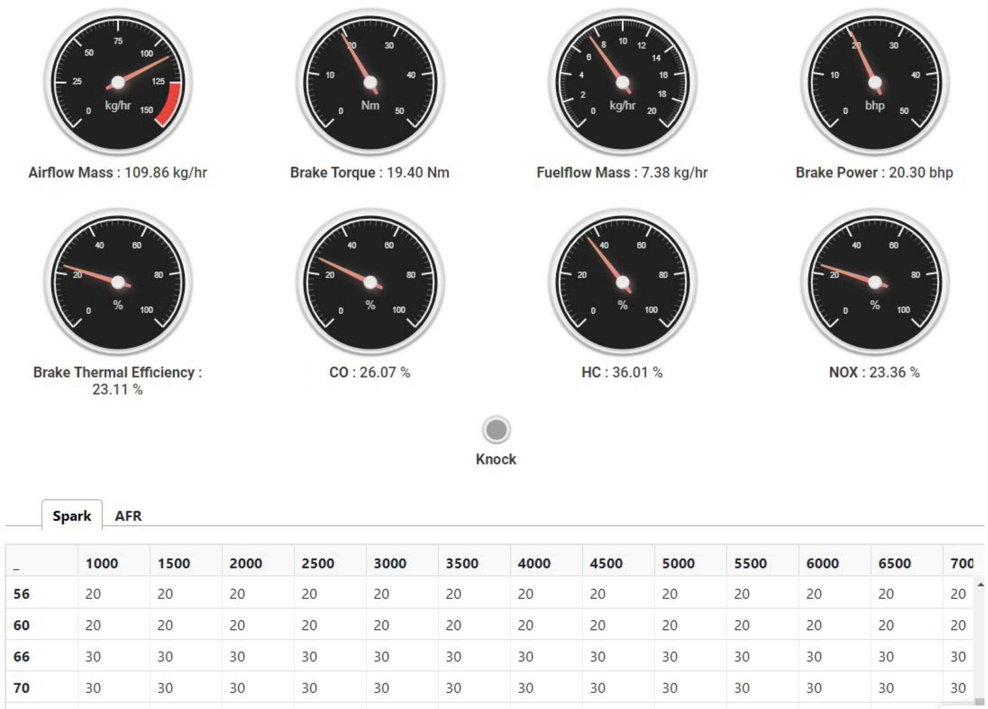


Figure 11: The Virtual Dyno-ReynICE showing engine parameters for 100% throttle at 10k RPM

IV. RESULTS

A. Results Table

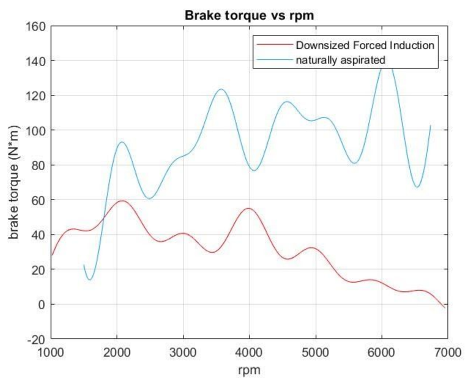
Parameters	The maximum value for a 3cyl FI SI (approx)	Value for a 4cyl NA SI (approx)
Brake Horsepower	45 BHP at 4000 RPM	32 BHP at 4020 RPM
Brake Torque	80 Nm at 4000 RPM	76.82 Nm at 4020 RPM
Mass air-flow rate	340 kg/hr over 4750-7000 RPM	324 kg/hr at 7100 RPM
Mass fuel-flow rate	27 kg/hr over 4750-7000 RPM	27 kg/hr at 7100 RPM
Volumetric Efficiency	1.61 over 2000-5000 RPM	1.07 at 4800 RPM
BSFC	0.6 kg/kW/hr over 2500-5000 RPM	0.4 kg/kW/hr over 2500-5000 RPM

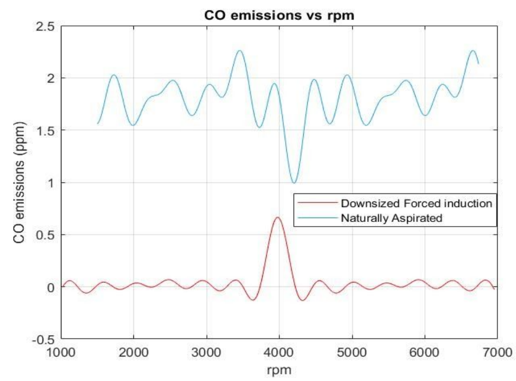
Table 4: A table which has various parameters mentioned against the values obtained from the simulation results. A 3 cylinder downsized SI FI engine has been compared with a 4 cylinder naturally aspirated SI engine both having a displacement volume of 1292cc

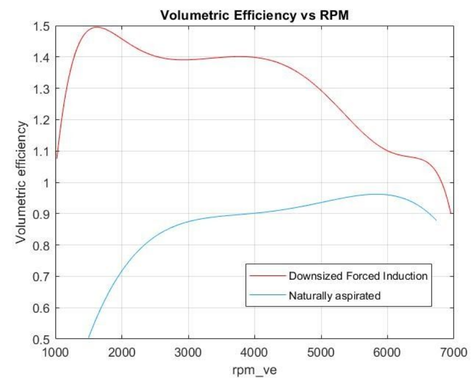
B. Result Plots

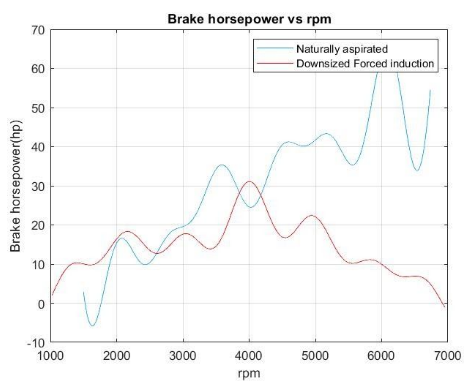
During the course of the project, tailored data was given to us by the industry experts consisting of the constants of speed, throttle, AFR, Turbo sizing, Wastegate temperatures, Spark, Coefficient of discharge, Coolant head temperature, Coolant temperature, Engine bay temperature, manifold absolute pressure and Compressor RPM namely. On entering the given parameters in the constant table in Ricardo wave software we got the other corresponding engine parameters such as BSFC, Indicated MEP (Mean effective pressure), MEP, Frictional MEP, Emissions values of CO, HC, NOx, and particulate matter in PPM.

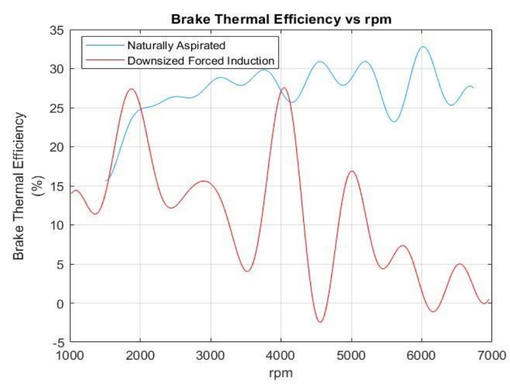
The corresponding data was tabulated and with the help of MATLAB and plots are given as follows.

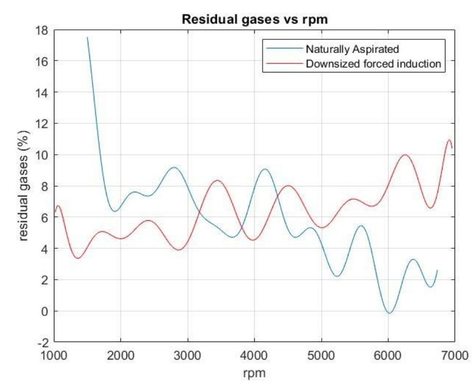


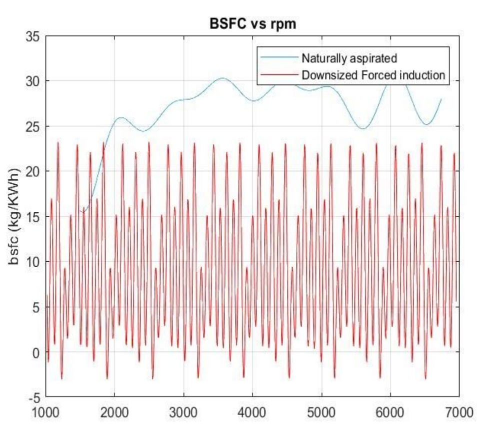












(NOTE: All the plots in the results are best-fit curves and express the best possible relationship between the points obtained from RICARDO WAVE simulations.

Fourier curve fitting Toolbox was used in MATLAB for the best fit results.

Fourier theory states that we can model any time series with a series of sine and cosine curves. It is represented in either the trigonometric form of the exponential form. The toolbox provides this trigonometric Fourier series form: $y=a_0+\sum a_i cos(iwx)+b_i sin(iwx)$.)

C. Inferences

I. *Brake horsepower*-

Inference - The engine redlines at 7000 RPM but the power output is very less. The maximum value of Brake horsepower is obtained when the turbo boost is maximum that is at 4000 RPM. The naturally aspirated engine has a lower power output at similar engine speeds.

II. *Brake torque* -

Inference - The engine gives a consistently high torque output from 1500-4000 RPM. The high value of brake torque over the mentioned range is justified because of the turbo boost kicking in due to the increased air mass and fuel flow rates.

The naturally aspirated engine has a lower or almost similar torque output at similar engine speeds.

III. *Mass airflow rate* -

Inference - The engine has a high airflow rate at high RPMs. The value increases with the increasing engine speed and reaches a maximum at around 4500 RPM. The increasing values are indicative of cold compressed air being pushed into the intake manifold by the compressor of the turbocharger which leads to a turbo boost at 4000 RPM. The naturally aspirated engine has lower airflow values at the same engine speed.

IV. *Fuel flow rate* -

Inference - The fuel flow rate increases with increase in the engine speed and as the mass air flow to the engine increases more fuel is injected by the injector into the combustion chamber to burn more fuel.

The naturally aspirated engine has lower fuel flow values at the same engine speed.

The volumetric efficiency of the downsized engine is higher than that of the NA engine which means turbochargers increase the pressure of air entering the cylinders, giving the engine a volumetric efficiency greater than 100%. Also, more oxygen will be available for the combustion process. Our NA engine also has a volumetric efficiency of over 100 per cent which is possible with proper engine tuning.

V. *BSFC* (Brake specific fuel consumption)

Inference - The BSFC values for the NA engine are lower than those for the FI engine over a range of engine speed. A lower BSFC is indicative of an efficient engine, yet it proves the point stating that turbochargers are not very fuel-efficient and need to be tuned properly to give the best performance and emission results. In the ideal case, the BSFC value of the downsized engine is lower than that of the larger engine, making the downsized engine efficient and favourable.

VI. Emissions

Inference - Because of the extra inducted air and the fuel mass injected into the combustion chamber, most of the fuel is completely burnt to leave behind very little or no toxic gases thus reducing hydrocarbon emission. But this leads to higher cylinder temperatures which lead to the increased NOx emission as is observed from the simulation results. There is a stark difference between the emissions of 1.3L naturally aspirated 4 cylinder SI Engine's NOx emissions as compared to the emissions we obtained from the turbocharged engine as the turbocharged uses direct injection in our engine. This increases the homogeneity of the air-fuel mixture which is being supplied to the cylinder thus ensuring the fuel mixes properly with the air. The forced induction system sucks in more air into the intake manifold and subsequently into the engine. As a result, the amount of oxygen available for combustion increases and complete combustion takes place. This results in the formation of carbon monoxide(CO) being lower than in the naturally aspirated engine.

V. CONCLUSION AND RECOMMENDATIONS

The downsized engine gives better performance than the original engine only in a narrow range of engine speed(RPM). For a specific power output, the downsized engine has greater mean effective pressure (MEP) as compared to later. It is outplayed by the naturally aspirated engine in the parameter of brake thermal efficiency. Emissions wise, the values of NOx are higher but the CO & HC values are lesser than that of the bigger engine. This is also a significant reason for the high value of BSFC of the engine which is more than the naturally aspirated engine. From the results and their corresponding inferences we can say that the engine's ECU needs to be calibrated for better Brake Horsepower, Brake Torque, and BSFC values. The downsized engine does not perform well at high engine speeds of more than 6000 RPM so if we limit the engine to redline at 4000 or 4500 RPM with the help of a Rev limiter or an engine governor which is the ECU, we could ensure we have the best performance in terms of power delivery, fuel efficiency and emissions. We can tune the ECU on a dynamometer by setting values of AFRs and spark timings to even further maximise power and torque while keeping the emissions at bay. Use of better valve timing technology, variable runner lengths and a tailored Turbocharger for the engine are some of the means to improve the driveability of the engine. Increasing the area under the Torque v/s RPM curve, can improve the characteristics of the engine and its overall performance. We can satisfactorily say that the payoff between a cylinder, reduction in the displacement volume and the addition of a forced induction system definitely pays off in terms of power, fuel efficiency and emissions. Yet , much work and research is needed to tackle some inherent limitations like cylinder balancing and their poor performance at high engine speeds, before such engines are mass produced.

VI.REFERENCES

1. https://www.mathworks.com/help/curvefit/fourier.html
2. Muhammad Usmain, *Use of Gasoline, LPG and LPG-HHO Blend in SI Engine: A Comparative Performance for Emission Control and Sustainable Environment,* processes, 2020
3. https://www.mathworks.com/help/curvefit/curve-fitting.html
4. Internal Combustion Engines by Ganesan
5. https://www.diva-portal.org/smash/get/diva2:1025473/FULLTEXT02.pdf
6. https://inpressco.com/wp-content/uploads/2017/06/Paper75319-324.pdf

VII.GLOSSARY

1. Abstract: existing only as an idea, not as a physical thing.
2. BSFC - Brake specific fuel consumption, the fuel consumption per unit time divided by the brake power.
3. BS-IV/VI - Generations of Bharat stage emission standards (BSES) issued by the Government of India
4. Catalyse- cause or accelerate a reaction by means of a catalyst .
5. Calibration : the act of marking units of measurement on an instrument so that it can be used measuring something accurately.
6. Carbon footprint - the amount of carbon dioxide released into the atmosphere as a result of the activities of a particular individual, organization or community.
7. Hunky Dory: fine; going well
8. Knocking - engine vibration and sound produced due to flame fronts colliding inside the combustion chamber.
9. Manifold: many; of many different types.
10. NOx - class of different oxides of nitrogen.
11. Naturally aspirated: supplied with air without the use of supercharging or turbocharging.

12. Optimize: make the best or most effective use of a situation of resource

13. Parameters: something that decides or limits the way in which something can be done
14. Solenoid - a cylindrical coil of wire acting as a magnet when carrying electric current.
15. Webinar - Seminar done on the internet