PARAMETRIC STUDY OF INTERNAL COMBUSTION ENGINE

By

Babar Shahzad

00000119028

Supervised By

Dr. Emad Ud Din

A thesis submitted in partial fulfillment of the requirements for the degree of Masters of Science in Mechanical Engineering

School of Mechanical and Manufacturing Engineering,

National University of Sciences and Technology (NUST),

Islamabad, Pakistan

(19 Feb, 2018)

National University of Sciences & Technology

MASTERS THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by: Babar Shahzad (00000119028) Titled: Parametric Study of Internal Combustion Engine be accepted in partial fulfillment of the requirements for the award of Masters of Science in Design and Manufacturing Engineering degree with (____ grade)

Examination Committee Members

1. Name: Dr. Sami Ur Rahman Signature:__________________

2. Name: Dr. Aamir Mubashar Signature:__________________

3. Name: Dr. Riaz Ahmad Mufti Signature:__________________

Supervisor's Name: Dr. Emad Ud Din Signature:__________________

Date:__________________

_______________________ Head of Department

_______________________ Date

COUNTERSIGNED

Date:________________

_______________________ Dean/Principal

Declaration

I certify that this research work titled "*Parametric Study of Internal Combustion Engine"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student

Babar Shahzad

00000119028

Copyright Statement

Dedicated to my teachers for their supervision,

to my parents and my beloved wife for their prayers

and support

Acknowledgments

I am thankful to ALLAH, whose REHMAT is always upon me. I am sincerely thankful to my supervisor Dr. Emad Ud Din and guidance and review committee Dr. Sami Ur Rehman Shah, Dr. Riaz Ahmad Mufti and Dr. Aamir Mubashar for their technical guidance and advice. I am grateful that their endless effort kept my thesis work on the right track.

My profound gratitude to my colleagues, without whom I would not be able to complete my thesis work in time.

Babar Shahzad

Table of Contents

Declaration 1

Copyright Statement 2

Acknowledgments 4

1 Introduction 11

1.1 Motivation 11

1.1.1 Effect of Engine Efficiency on Economy 11

1.1.2 Effect of Engine Efficiency on Environment 11

1.2 Thesis Layout 12

2 Literature Review 13

2.1 Background 13

2.1.1 Stroke 13

2.1.2 Four Stroke Engine 13

2.2 Evolution of IC Engine 14

2.3 Software simulation 15

2.4 Literature Survey 15

3 Methodology and Governing Equations 17

3.1 Methodology 17

3.1.1 WaveBuilt 17

3.1.2 WaveMesher 18

3.1.3 Wave 18

3.1.4 WavePost 20

3.2 Model setup 20

3.2.1 Basic Inputs 21

3.3 Engine Specifications 21

3.3.1 Y- Junctions 22
3.3.2 Types of Y-Junctions 22
3.4 Advanced Inputs 22
3.4.1 Flow Parameters 23
3.4.2 Valve Lift 23
3.4.3 Cylinder Pressure 23
3.4.4 Combustion Model 24
3.5 Simulation Setup 25
3.5.1 Transient and Steady State Simulations 25
3.5.2 Flow Field Reinitialization 26
3.5.3 Convergence 26
3.5.4 Simulation Duration 26
3.6 1-D CFD Flow Analysis 26
3.6.1 Discharge coefficients 27
3.6.2 Flow Simulation Losses 27
4 Modeling 28
4.1 Model Development 28
4.1.1 Modeling Constraints 28
4.1.2 Initial Validation 28
4.1.3 Model Accuracy 29
4.2 Parametric Study 29
4.2.1 Torque Output 29
4.2.2 Intake and Exhaust Length 30
4.3 Optimization 31
4.3.1 Optimal Performance Parameters 31
4.4 Experimental Setup 32
4.4.1 Dynamometer 32

4.4.2 Engine Cooling 33

4.4.3 Ambient conditions 33

4.4.4 Engine Test Stand 33

4.4.5 Electronic Control Unit 33

4.4.6 Testing Speed Range 34

4.4.7 Parameter Analysis 34

4.5 Software Model Setup 34

4.5.1 Initial Modeling strategy 34

4.5.2 Intake and Exhaust Ports 34

4.5.3 Port Flow Parameters 34

4.5.4 Intake and Exhaust Components 35

4.5.5 3D Mesh Modeling 35

4.6 Model Validation 35

4.6.1 Torque Validation 35

4.6.2 Predictions Validation 36

4.6.3 Sensitivity Study 36

5 Results and Discussion 37

5.1 Validation Results 37

5.1.1 First Test Point 37

5.1.2 Second Test Point 38

5.1.3 Third Test Point 39

5.2 Tuning 40

5.3 Conclusions 46

6 References 47

List of Figures

Figure 3-1: GUI of the Ricardo WAVE software 17
Figure 3-2 Example of WveMesher GUI 18
Figure 3-3 WVVE GUI Example 19
Figure 3-4 Example of WAVE Post GUI 20
Figure 3-5 Simulation Inputs 21
Figure 4-1 Compression Ratio Study Example 30
Figure 4-2 Optimal Performance Parameters Tuning 32
Figure 4-3 Engine Test Bed 33
Figure 5-1 Power Vs RPM at C.R 16 41
Figure 5-2 Power Vs RPM at C.R 18 41
Figure 5-3 Power Vs RPM at C.R 20 42
Figure 5-4 Torque Vs RPM at C.R 16 42
Figure 5-5 Torque Vs RPM at C.R 18 43
Figure 5-6 Torque Vs RPM at C.R 20 43
Figure 5-7 BMEP Vs RPM at C.R 16 44
Figure 5-8 BMEP Vs RPM at C.R 18 44
Figure 5-9 BMEP Vs RPM at C.R 20 45

List of Tables

Table 5-1 First Test Point Results 37
Table 5-2 First Test Point Validation Results 38
Table 5-3 Second Test Point Results 38
Table 5-4 Second Test Point Validation Results 39
Table 5-5 Third Test Point Results 39
Table 5-6 Third Test Point Validation Results 40
Table 5-7 Tuning Parameters 40

Abstract

The objective of this study is to validate simulation model with the experimental setup data and to analyze engine operating parameters at different RPM, Air/Fuel Ratio, intake pressure, compression ratio and valve lift for the optimization of engine for better performance. A test bench containing a diesel engine was used to collect experimental data on different operating parameters on different test points using sensors. On the other hand, a software model was designed using Ricardo WAVE for obtaining simulation results on the test points similar to experimental data. Aim of this study is to design a software model validating experimental data which leads towards obtaining optimum operating parameters and improvement in engine design. Another benefit of this study is that software tuning of engine becomes relatively easier as sometimes experimental tuning is difficult due to various design constraints which limits the changes required in parameters for tuning. This research will be helpful in designing engines with better performance and emissions.

1 Introduction

1.1 Motivation

With everyday automobile industry is focusing on producing efficient engines. Consumers are also demanding economical and efficient engines. There is a significant impact on the economy of a region having thermally efficient automobiles. With the increase in efficiency of an internal combustion engine there is a significant effect on the rate of fuel consumption which further effects in the reduction of transportation cost. This will also increase supply, demand and trade of efficient vehicles. Efficient engine reduces the discharge of harmful exhaust gases which has an adverse effect on the atmosphere.

1.1.1 Effect of Engine Efficiency on Economy

There is almost 25 million barrels per day consumption of gasoline around the globe[1]. If the efficiency of an engine is increased by 1% only the gasoline consumption can be reduced by 39 million liters per day. Also, the demand will drop globally due to reduction in overall fuel cost. Better fuel economy will cause reduction in transportation cost and it will also reduce. By reducing the fuel cost the inflation rate can also be reduced as the cost variation is associated with the supply of goods basic consumer needs to market. Furthermore, Delays in supply will be avoided and bulk orders would be effortlessly achieved.

1.1.2 Effect of Engine Efficiency on Environment

Engine exhaust gases contains many harmful greenhouse gases which contributes towards increase in environmental pollution. As from a survey the number of cars in year 2010 increased by a massive amount of 1 billion [2], most of the vehicles uses gasoline as fuel. Around 75% percent of the greenhouse gases are released by motor vehicles globally. Fuel consumption and release of greenhouse gases can be reduced easily by increasing engine efficiency and will also effect environment positively.

1.2 Thesis Layout

There will be a brief literature review in the start. After that, the governing equations of the engine with some physics will be presented along with the specific problem which will be discussed in detail. Case study of research such that geometry modeling, boundary conditions, experimental setup and software model will be explained. In the end, results will be presented in the forms of sweep plots and validation of software data with experimental data will be performed. After that tuning of engine will be performed for getting optimum operating parameters. Then conclusion will be presented from the obtained results.

2 Literature Review

2.1 Background

Basic terms of the diesel engine are prerequisite to any discussion on its evolution and history. There are some concepts regarding diesel engine and its working are listed below.

2.1.1 Stroke

The full movement of the piston from top dead centre to bottom dead centre is called a stroke.

2.1.2 Four Stroke Engine

To complete one thermodynamic cycle in a four-stroke engine piston performs four complete strokes. Stroke description is listed below.

1. **Intake Stroke**

   Intake stroke comprises of motion of the piston from TDC to BDC which creates vacuum in the cylinder and the air from the atmosphere along with the fuel enters the cylinder through the intake port due to the pressure difference between atmosphere and the cylinder.

2. **Compression Stroke**

   After the completion of the intake stroke the air fuel mixture is compressed in the cylinder when the piston moves from BDC to TDC. In this compression stroke both exhaust and the intake valves remain closed.

3. **Power**

   In power stroke, the air fuel mixture that was compressed in the compression stroke is ignited when the piston reaches close to the TDC. The ignition is performed using spark plug in gasoline based engines while in the diesel based engines the air fuel mixture ignites due to the heat produced during compression stroke[6]. This stroke is called power stroke because it provides the energy by the help of the blast produced at the TDC which pushes the piston to move towards the BDC. This energy is transferred to the flywheel via crankshaft.

4. **Exhaust**

When the power stroke is completed the exhaust gases and the unburnt air fuel mixture is expelled to the atmosphere from the cylinder via exhaust port when piston moves from BDC to TDC.

2.2 Evolution of IC Engine

During early days after the invention of gasoline engine the study of the properties of the fuel air mixture and physics of the flow was not complete. The design of the engine was completely based on the experimentation and the inspiration of the predecessors as they attained the recognition about their design and features. However, there were some notable exceptions that carried the evolution of the engine to the next phase.

H. R. Ricardo and his colleague professor Bertram Hopkinson from the Cambridge university worked from 1903 to 1907 on the flame propagation, engine knock, combustion of the air fuel mixture, turbulence and the effects on the heat transfer in the cylinder of the IC engine. Their study laid the foundation on the advancement in the engine technology as the turbulence in the air fuel mixture was the largely discussed topic on that time.

Their study provided great improvement in the engine design of the military tanks in the first world war.

Another research [3], [4] in that era, worth mentioning, was done upon swirl and tumble produced by different inlet configurations, and their effect on combustion inside the cylinder. The authors related swirl and tumble to increased turbulence.

Unfortunately, all these pre-war works were forgotten and not taken seriously until the end of 19th century.

When the infamous penta-head aircraft engine was designed to maximize the valve area which reduces Mach index, although Mach index was not understood at the time. The orientation of inlet valve and the position of spark plug produced increased values of tumble, resulting in uniform burning of air fuel mixture, allowing increase in compression ratios without inducing engine knock. This phenomenon was already explained by Ricardo [5], but was forgotten and rediscovered recently.

Modern engines are designed to introduce such characteristics in the engine which results in high efficiency and better performance. However, even today engine designs are based on predicted empirical fluid mechanics correlations and the true nature of turbulence and flow physics are not understood completely [7].

2.3 Software simulation

Engine simulation is very vital in the development process of an engine. The use of software for research and development is the new era in the technology as it is more convenient and less time-consuming practice as compare to hardware research as it takes more time and is also difficult to obtain all desired results at once. Parametric analysis is limited on experimental setup due to design and other operating parameters constraints. There is significant reduction of time in the experiments and prototyping through engine simulation as software can simulate most of the engine experiments. Model can be used with confidence to optimize engine performance as long as it is validated to higher level of accuracy (i.e. +/- %5). After the simulation, only final prototype needs to be validated.

For the study of the engine parameters we used WAVE module from the Ricardo software. This software is capable of many sophistications in other areas like emissions, combustion kinematics and CFD the co-simulation and other advanced features. This design only used a fraction of this software potential.

2.4 Literature Survey

H. R. Ricardo (1907) [5] studied the effect of turbulence on combustion, flame speed and heat transfer in IC engines. He also related engine knocking to non-uniform flame propagation and found the concept of octane number.

Heywood (1988) [6] reported that vortex flows inside IC engines leads to faster flame propagation due to increased turbulence.

Gurney, David. (2001) [10] 1D wave action simulation has been used to construct models of a number of turbocharged spark ignition engines. This paper describes how the models have been applied in the development of those engines. The simulation has been used to optimize many components including the inlet and exhaust manifolds, the valve timing and the turbo match. The models have been validated against test data. The method of modelling unsteady flow is described and the behavior of the turbocharger in unsteady flow investigated.

Cordon, Charles D. (2007) [14] Studied the use of one-dimensional CFD engine simulation tool for the engine development process. Engine design through simulation can drastically reduce time needed to perform engine experiments and prototyping, as most engine experiments can be simulated within the software.

Brahim Menacer and Mostefa Bouchetara (2014) [15] Analyzed the thermodynamic performance of a turbocharged compression ignition engine with heat transfer and friction term losses.

Anoop Selvaraj and Ramzy Gouda. (2012) investigated the Dual Fuel Two Stage Combustion Engine using 1D simulation software Ricardo WAVE.

J. Galindo, H. Climent. (2011) [17] did detailed methodology analysis for heat release determination in two-stroke engines under wide range of running conditions; obtained empirical data will serve for building ad-hoc Wiebe functions, whose four parameters will be finally correlated with engine related

parameters derived from 1D simulations.

Peter M Fussey, David J N Limebeer (2012) [18] described a model that is detailed enough to predict emissions trends, yet is suitable for implementation in a future real-time automotive control unit.

Dai CHOI, Paul C (2005) [19] studied diesel combustion in a low-temperature, late-injection combustion regime.

B.Jayashankara, V.Ganesan (2010) [20] presented the computational fluid dynamics (CFD) model to study the effect of fuel injection timing and intake pressure (naturally aspirated as well as supercharged condition) on the performance of a direct injection (DI) diesel engine.

3 Methodology and Governing Equations

3.1 Methodology

To develop simulation of engine using Ricardo WAVE requires several modules which have separate purpose like statistical analysis of the output model, model setup and 3D modeling. Four programs used for this research are: WavePost, WaveMesher and WaveBuilt[13].

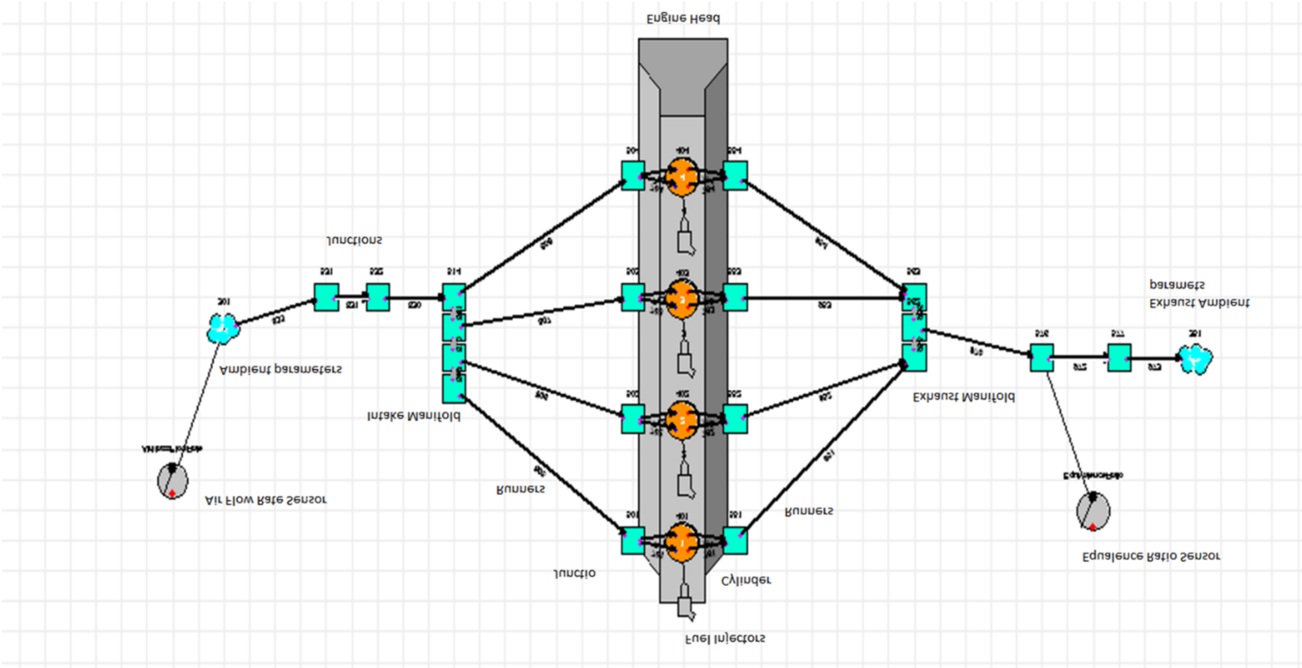

Figure 3-1: GUI of the Ricardo WAVE software

3.1.1 WaveBuilt

Wavebuilt is a pre-processor program and GUI which is used to input all simulation and engine parameters. All of the simulation and model parameters are defined in this program without using external CAD geometries. Figure 3.1 shows a GUI of a layout model of the engine designed in Wavebuilt using its built in available elements such as engine block, ducts, cylinders, injectors, orifices and inlet and exhaust manifolds. All the elements have different input parameters that can be defined and modified at any stage according to the requirement. Sometimes it is time consuming and difficult to construct geometries using the available elements.

3.1.2 WaveMesher

Moreover, complex model geometries like intake and exhaust manifold design can be directly imported from a 3D CAD file to WaveBuilt using the WaveMesher module. WaveMesher then processes the 3D CAD model by breaking down the model to understandable one-dimensional form for Wave software processing. A screenshot of GUI of the WaveMesher window is shown in figure 3.2 in which an intake manifold model is being meshed in to one dimensional form after importing from CAD software. After meshing the model can be used as an element in the WaveBuilt program.

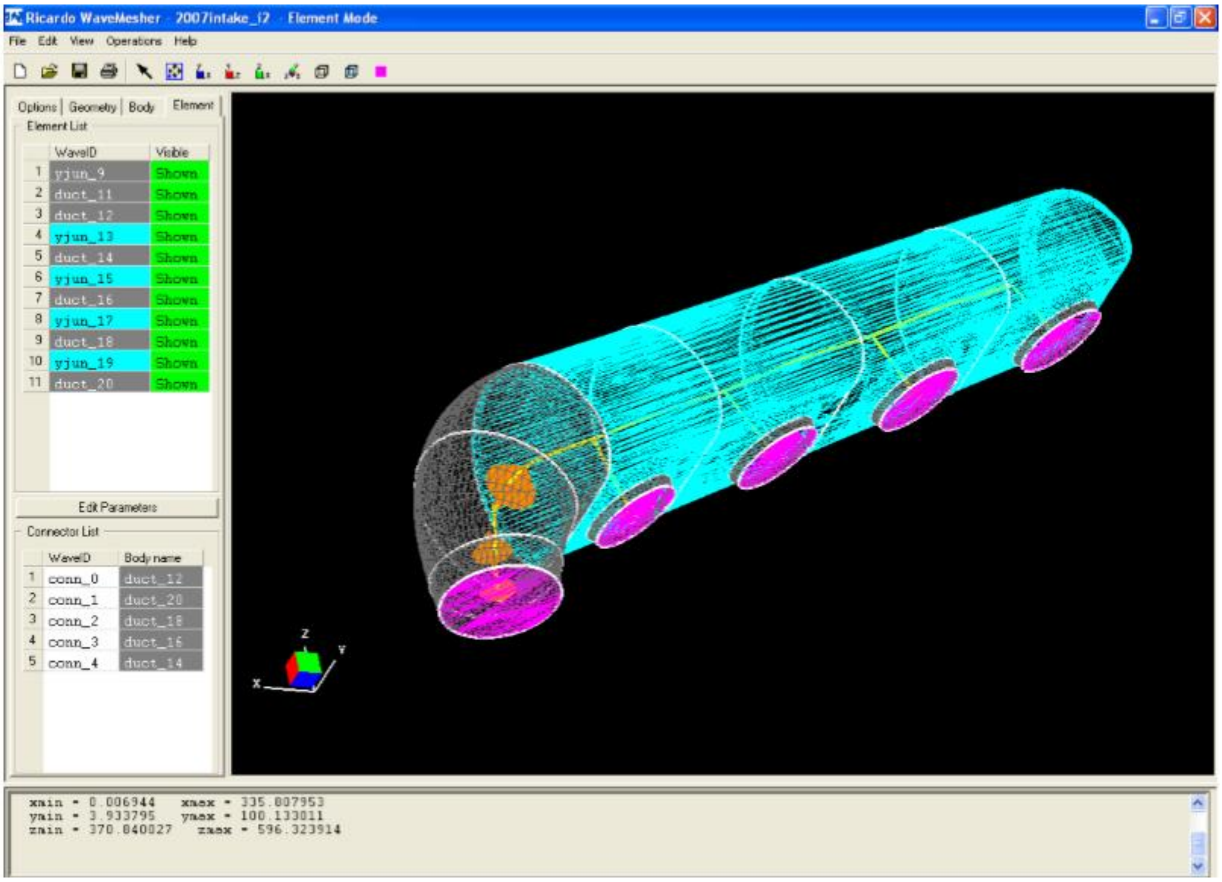

Figure 3-2 Example of Wave Mesher GUI

3.1.3 Wave

Simulation can be started by running the WAVE software code after the model is meshed and setup in the Wavebuilt as shown in figure 3-3. Wave program is the 3rd step in the simulation which is a solver that performs all the related calculations needed to complete the simulated engine operation. It runs in a DOS window which is a non-interactive session.

Simulation progress is shown streaming the output data in each cycle separately. The simulation output data is customizable to show only the parameters of interest. These output parameters act as indicators that shows whether the simulation is producing the acceptable output results or not. Simulation will be stopped if the model does not function properly and shows errors in the end.

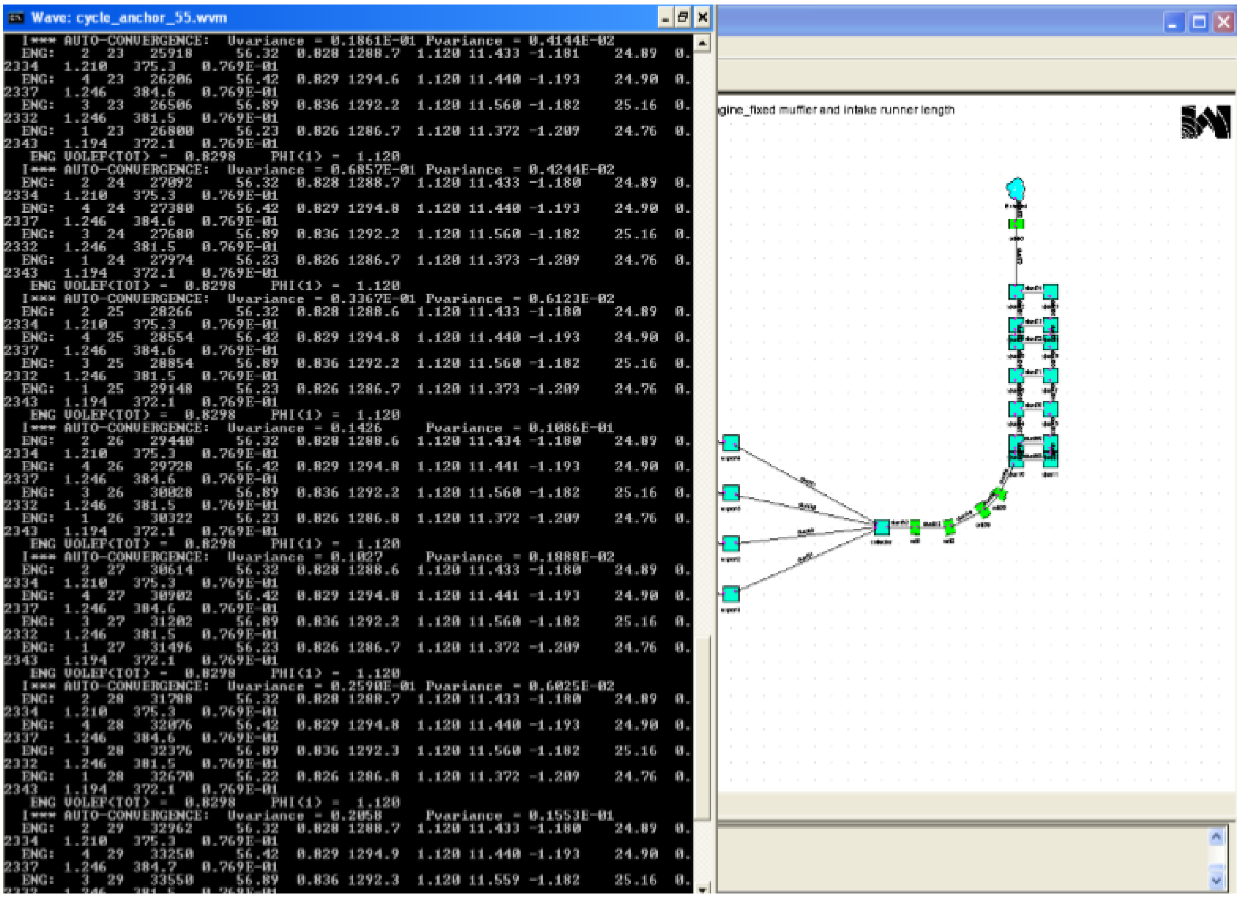

Figure 3-3 WAVE GUI Example

3.1.4 WavePost

A large file is created at the end of the simulation which can be analyzed for the simulated engine operation in the program WavePost. WAVE simulations post processor program is called WavePost. It contains all the output simulated data of the input operating parameters. WavePost simulated data can be analyzed in the form of sweep plots, time plots, TCMAP plots (for compressors and turbines) and spatial plots (animated). A screen shot of the WavePost is shown in Figure 3.4 with a sample sweep plots of compression ratio variations on different parameters.

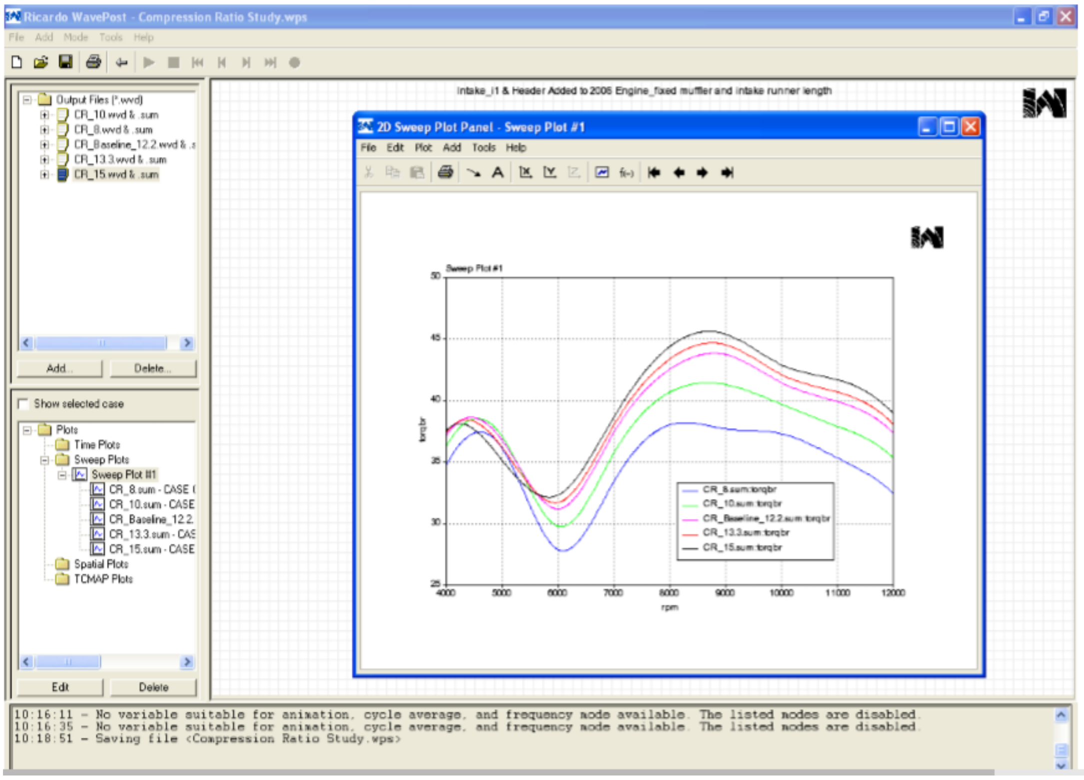

Figure 3-4 Example of WAVE Post GUI

3.2 Model setup

The model to be tested is setup by putting some relatively basic and advanced operating parameters which are to be tested via engine simulation.

3.2.1 Basic Inputs

Boundary conditions and engine geometry are the basic inputs as shown in figure 3-5. Therefore, basic inputs dimensions must be input from ducting of input to exhaust must be input and recorded.

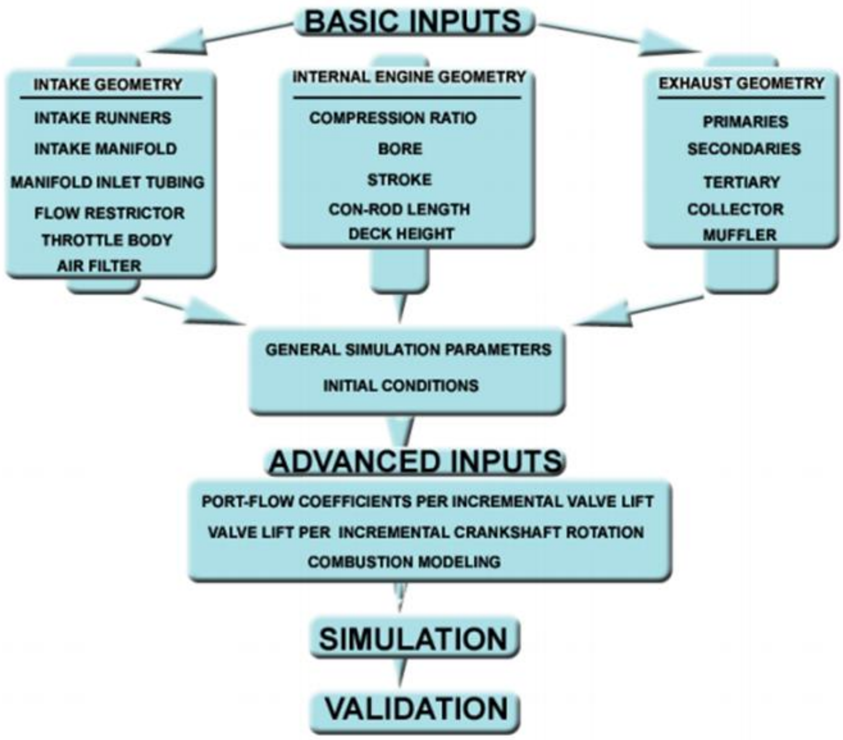

Figure 3-5 Simulation Inputs

3.3 Engine Specifications

Furthermore, specification of the engine geometry such as compression ratio, wrist-pin offset, connector rod length, bore and stroke. Other initial conditions need to be input like intake temperature, cylinder wall temperature and exhaust temperature. All these inputs can be modified any time when the actual engine values become available. Figure 3.4 shows a general flow diagram for the development process of an engine.

There are four basic junctions used to connect elements and duct in WaveBuilt GUI.

- Ambient: A condition in which duct is open to atmospheric pressure at one end. It is used mostly in muffler outlets and in air filter openings.
- Orifice: It is a zero-length and massless junction that is used give direct connection to two ducts. To match the connecting ducts its default diameter is the diameter of the

ducts to which it is connected. Also, its diameter can be modified independently when needed.

- Y-Junctions: To model complex geometries like intake manifolds and exhaust manifolds this junction is used which have more than 2 openings it is used to develop geometries that cannot be made using orifices and ducts. It is used to model complex model geometries like air filters, mufflers, exhaust collectors and intake manifolds.
- Engine Cylinder: An internal combustion engine cylinder element that represent engine cylinder of either 4-stroke or 2-stroke type. It can also be modified to be used as 6-stroke and 8-stroke engines.

3.3.1 Y- Junctions

To properly create a model by using these basic junctions one must well understood these basic conventions in modeling. When a desired complex geometry cannot be made using ducts and orifices it is then made using multiple opening Y- junctions. Branched flow (i.e collectors and manifolds) elements must be made through Y-junctions.

3.3.2 Types of Y-Junctions

There are two types of Y-junctions one is complex Y-junction and the other one is simple Y-junction. Spherical volume shape Y-junctions are called simple Y-junction that distribute flow to multiple ducts in the model. Simple Y-junctions are also referred to as over simplified complex Y-junction and they are rarely used in modeling. An arbitrary shaped volume junction is called complex Y-junction. With the help of three-dimensional view in WaveBuilt junctions are arranged relative to ducts to be modeled properly. Moreover, the parameters like area, discharge coefficient, duct opening, duct length properties and back wall of the volume can be modified easily when needed.

3.4 Advanced Inputs

After putting in basic inputs in the model, some advanced inputs of the engine cylinder head are defined which are most integral part of the simulation. These parameters are: valve lift per crankshaft rotation, combustion modeling and port flow coefficients.

3.4.1 Flow Parameters

To achieve higher accuracy than 1D CFD modeling the flow parameter of the engine cylinder head ports that are to be used as an input to simulation should be the measured directly from the engine head as the flow through the engine highly depends upon the flow through the engine cylinder head ports. Flow bench can be used to measure these port flows parameters. Mostly, a volumetric flow from the engine head ports can be measured at incremental valve lifts through the valves and a pressure drop of 28’’ of water is applied on one cylinder. Later these measured flow values to understandable port flow coefficients can be converted by the help of a table provided by Ricardo.

3.4.2 Valve Lift

Now comes the second advanced coefficient is the valve lift per crankshaft rotation within the cylinder head. With the help of a dial indicator which measures the valve lift per camshaft rotation when camshaft is rotated incrementally. Then the relative TDC points of opening of the intake and exhaust valves must be known so that the camshaft rotation data can be referenced to the crankshaft rotation points.

3.4.3 Cylinder Pressure

The most important third advanced input datasets that are required to validate simulation results and characterize the engine model is the cylinder inside pressure values. Friction correlations and combustion models can only be determined when the crank referenced pressure points are obtained at each operating point for complete engine cycle. Unfortunately, it is not a simple task to obtain in-cylinder pressure data unless a physical pressure sensor is inserted inside the engine cylinder, there is still needs to be some special equipment that can interpret cylinder pressure data from the pressure sensor at higher speeds. The National university of science and technology currently does not have this facility in their small Engine Research Facility; thus, for this modeling research in-cylinder pressure measurements were not available.

3.4.4 Combustion Model

The combustion model had to predicted based on the Wiebe function parameters because of the unavailability of the in-cylinder pressure data. There are three parameters that WAVE allows to be input in the Wiebe correlation as: Wiebe exponent, 50 percent burn point and the 10-90 percent burn duration. [WAVE, 2007]

The Wiebe combustion model is defined by:

$$W = 1 - e^{\left[-AWI\cdot\left(\frac{\Delta\theta}{BDUR}\right)^{WEXP+1}\right]} \qquad \text{(Equation 1)}$$

where,

W = Cumulative mass fraction burned
$\Delta\theta$ = Crank degrees past start of combustion
BDUR = User-entered 10-90 percent burn duration in crank angle degrees
WEXP = User-entered Wiebe exponent
AWI = Internally calculated parameter to allow BDUR to cover the 10-90 percent range
CA50 = User-entered 50 percent burn location in crank angle degrees after top-dead center

Table 3-1 Wiebe Function Parameters

Data Group	Engine Speed (RPM)	BDUR (Degrees)	WEXP	CA50 (ATDC)
Recommended NA* Values [Blair, 1999]	1200	14	1.72	20
	2400	15	1.93	25
	3600	17	1.82	25
	6000	21	1.64	32
NA* Input Values	3000	16	1.85	25
	4000	17	1.75	27
	5000	19	1.70	29
	6000	21	1.60	32
	7000	22	1.55	33
	8000	23	1.50	34
	9000	23	1.45	35
	10000	23.5	1.45	35
	11000	24	1.45	35

* NA = Naturally Aspirated

Blair determined Wiebe parameters for naturally aspirated engines operations are shown in Table 1. Similarly, the Blair's findings on based inputs are included in the table. The duration of the burn does increase slightly with engine speed but remains relatively constant. Wiebe exponent, WEXP, decreases with decrease in engine speed. Lastly, 50 percent burn point in the cylinder remains constant but the ignition timing advance increases with the increase in engine speed.

3.5 Simulation Setup

Simulation setup must be setup after the advanced and basic inputs are defined. Both transient and steady state simulations can be performed in WAVE. Steady state simulations are performed in the early stages of the development of the engine design.

3.5.1 Transient and Steady State Simulations

Transient state simulations are more detailed overview of the engine operational performance analysis. Steady state simulations have a significant advantage that any parameter can be modified independently on each engine speed that is to be simulated. There are some other important parameters in the simulation that comprises of: convergence tolerances, convergence detection and cycles to run for convergence. Above discussed parameters are some of general parameters that are used in simulation.

3.5.2 Flow Field Reinitialization

There is another important and useful customizable parameter that can be used in between simulation cases is to reinitialize flow field in each case according to the user defined parameters such as ambient conditions of the gas and wall temperature of the cylinder. This function is turned off by default, because often the initial conditions guessed by the user are closer to the previous final gas conditions of the prior case.

3.5.3 Convergence

Convergence detection is another important general simulation parameter. WAVE code moves to the next case when the convergence is detected once user specified convergence tolerance is attained as the solution completes on the case that is active at that time.

3.5.4 Simulation Duration

Another important general parameter is simulation duration. Number of cycles for the engine are defined in this parameter and it settles for a solution of the active case until number of cycles complete. WAVE will move automatically to the next case when auto convergence is active and convergence is reached regardless of the number of specified cycles. WAVE will give warning on the output when the code unable to reach convergence within the specified number of cycles and moves to the next case by letting the user know that within the desired tolerance convergence was not reached.

3.6 1-D CFD Flow Analysis

1D CFD flow analysis require special attention as it has some limitations associated with its operation. Ricardo has made highly customizable flow model with its comprehensive set of data inputs. When modeling geometries that include ducts that change over small length increments it has limitation. Bell mouth of an intake runner is such an example that is difficult to make with ducts. Such geometry cannot be modeled by 1D code which have the 3-D flow phenomenon.

3.6.1 Discharge coefficients

Discharge coefficients of bell mouth shape runner are used in this case that are published using experimental findings. So, for such bodies that cannot be accurately modeled in 1D code, flow loses can be imposed on the instances of geometry.

3.6.2 Flow Simulation Losses

Moreover, it has another limitation while modeling tapered ducts, angles smaller than 7 degrees are recommended in these types of ducts. This is due to the phenomenon of flow separation that is not modeled in 1D code that occurs on 7 degrees or more flow angles. There was another instance encountered in the simulation that was the modeling of flow restrictor that has converging angle of more than 20 degrees. WAVE simulator will show overpredicted power than expected in the output if the designed restrictor is according to its physical geometry. This is due to inability of the WAVE to measure losses associated with the flow separation.

4 Modeling

4.1 Model Development

Model's accuracy depends upon the data input. To validate a model this principle must always be kept in mind during simulation. Similarly, 100 percent accurate gas dynamics prediction is not possible in 1D simulation. Results can be within 5 percent tolerance of the actual, performance in good simulation. To perfectly match simulation prediction to empirical data the amount of time spent on troubleshooting should be limited.

4.1.1 Modeling Constraints

A full-blown 3D CFD simulation can take up to weeks to measure engine performance on a single engine speed, that the reason why 1D simulation is trending in engine simulation because it takes less time and allows rapid development of engine model. It is proved from study that results from two identical engines cannot match and on different conditions it shows slightly different performance. These conditions include valve seating, fuel consumption, bearing wear, carbon built-up and piston ring seal. Due to all these reasons, perfect matching predictions cannot be expected. One advantage of this software is that its simulation can predict graph curve of torque rather than the exact matching magnitude.

4.1.2 Initial Validation

Initial validation and calibration of the model should be done by the comparison between actual and measured value of volumetric efficiency to the predicted value. Validation can also be done by comparing air mass flow rate at the inlet and Exhaust. An accurate air mass flow rate sensor must be mounted on the engine and dynamometer to measure the volumetric efficiency calculations. Other parameters like torque output on the dynamometer can also be used to validate with the simulation model torque output data. Contradictions may occur because of several sources between measured and predicted values. The accuracy of the intake and exhaust valve opening inputs must be checked if the model is not predicting accurate pressure wave induced at intake and exhaust peak locations within the engine cylinder.

4.1.3 Model Accuracy

Friction correlations, combustion model and heat transfer should be checked for accuracy if the torque magnitude is offsetting slightly across engine speed range. Erroneous inputs are most often caused due to guessed inputs due to data lack. It is important keep it in mind while modelling. If this case occurs the data should be modified or required to match the empirical results of the simulation. Model can be further refined when it shows remarkable predicted results. During the actual engine testing pressure and temperature can be measured at different junctions. Later it can be matched with the input initial conditions and boundary conditions. Convergence computational time can be decreased and model accuracy can be improved by this technique.

4.2 Parametric Study

Simulated model can be used as a most effective and valuable design and development tool once it is validated with the actual engine results. The typical application of wave's feature in this research is to develop high performance engine model through the simulation results.

4.2.1 Torque Output

Engine's intake runner length and exhaust header primary length is a good starting point in the modelling. For desired torque output near optimum dimensions of one geometry at a time can be studied parametrically. For full system optimization design of experiment(DOE) method can be effective tool. A geometric parametric study of torque output is shown in figure 4-1 on various engine compression ratios.

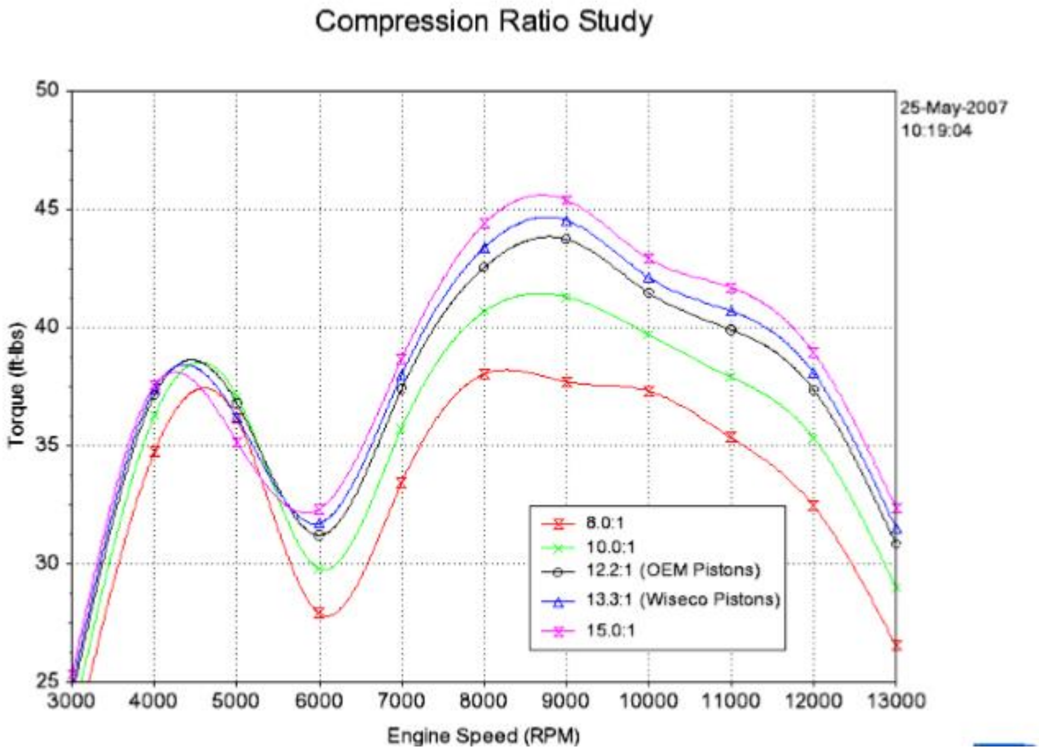

Figure 4-1 Compression Ratio Study Example

4.2.2 Intake and Exhaust Length

A valuable investigating trends are to examine one parameter at a time but this trend does not always tell the full story of the simulation parameter. The engine speed dependent parameters such as duct length of exhaust and intake can be examined as described previously. Example of this can be that the intake resonance effect will be severely hindered from a poorly timed exhaust pressure wave from the headers which occurs at the same engine speed having an intake resonance. On the other hand, the parameters that's effect is less dependent on the other parameters is tubing diameter.

4.3 Optimization

General trends, near optimal values and sensitivities must be investigated before optimizing an entire package. To produce usable results physical constraints must be applied to the optimization model as it is general a good practice in modelling. Header and primary constraints could be applied. If application demands light weight and short package, restrictions on length can be applied on boundary conditions of an experiment. Through experiment feature optimization can be done by wave software. Variations in minimum and maximum values of any parameter you want can be achieved through this experiment feature.

4.3.1 Optimal Performance Parameters

Any parameter can be maximized and minimized according to the need once the experiment has been completed. If the user requirement is to optimize parameters of the camshaft, the lobe anchors, duration multipliers and lift multipliers could be varied along simulation model. Figure 4-2 shows the sample of post processing screen of the experiment. Through slide bars of the parameters shown on the left side of the screen can be modified. The change in the graph on the right side will be reflected in real time, if we adjust the slide bars. Comprehensive numbers of graphs are available on the left side of the screen that can be analyzed through these parameter variations. For example, torque output can be maximized if the user clicks on the torque and adjust slide bars and get the optimal performance experiment parameters. Similarly, any output can be minimized such as trapped residuals and can get that parameters on which this minimum can be achieved.

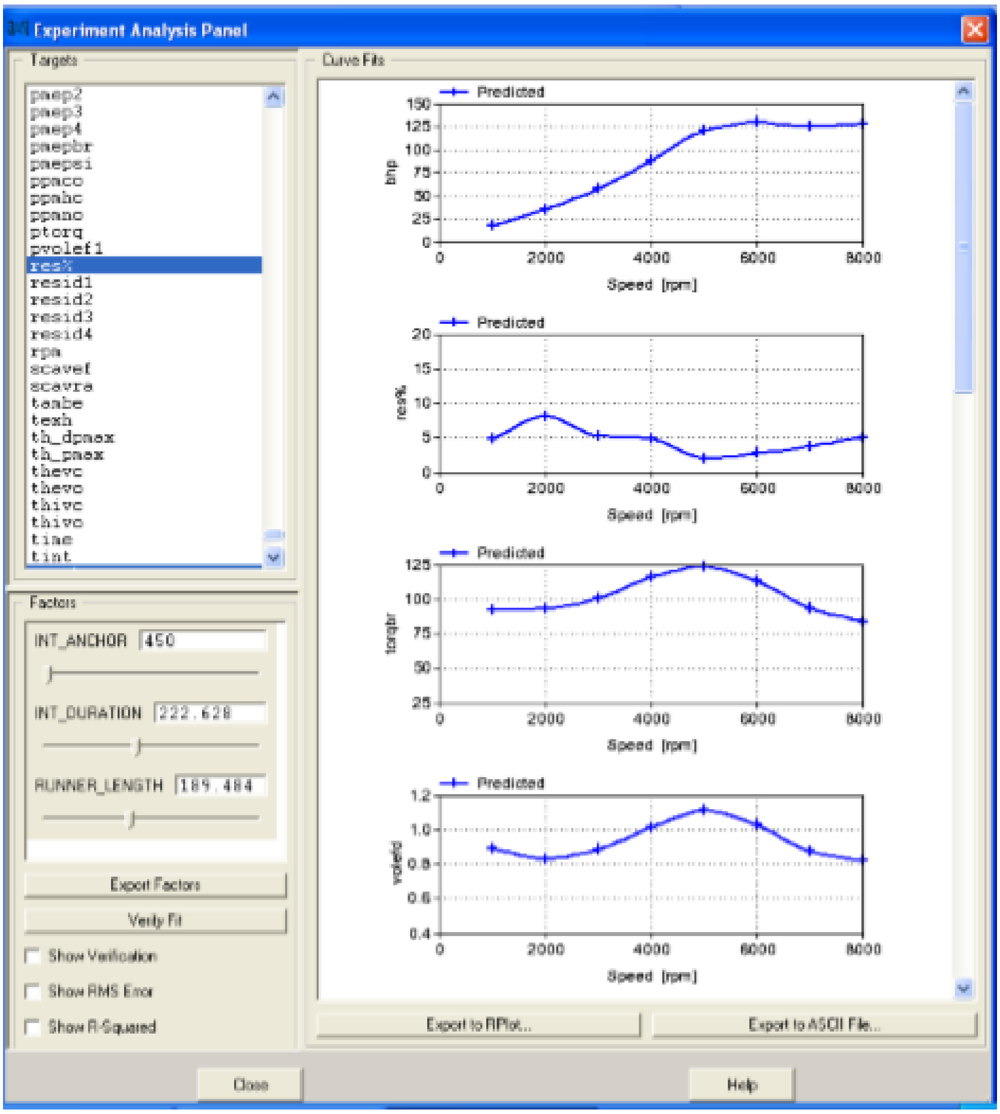

Figure 4-2 Optimal Performance Parameters Tuning

4.4 Experimental Setup

Wide array of sensors must be instrumented on engine to properly validate a simulation of engine model, whose data is logged through acquisition of data. Fueling should be modified and logged through engine control unit(ECU) to match the model for each cylinder, if the model assumes air fuel ratio to be same for each cylinder in the simulated model. For the engine to be operated as intended numerous sensor implementation on engine is must as it allows for simulation to be validated and act as an engine diagnostic tool for performance enhancement.

4.4.1 Dynamometer

Type of dynamometer used in this research was Shank engine dynamometer, which goes nicely with the simulation of engine model. Shank type dynamometer is generally used in many applications but another type that is land and sea dynamometer that has more precise control over its measurements.

4.4.2 Engine Cooling

Cooling cart was used for cooling of the engine. For prolonged steady state testing of engine can be performed if enough cooling is provided by the cooling cart.

4.4.3 Ambient conditions

Ambient conditions do fluctuate slightly throughout testing sessions because it is not regulated.

4.4.4 Engine Test Stand

In figure 4-3, an engine test stand is shown which is directly plugged to data acquisitions systems and dyno controls and frequent testing is being done on dynamometer. Dyno was coupled with engine through transmission shaft output by connecting directly constrained with two pillow type block bearing.

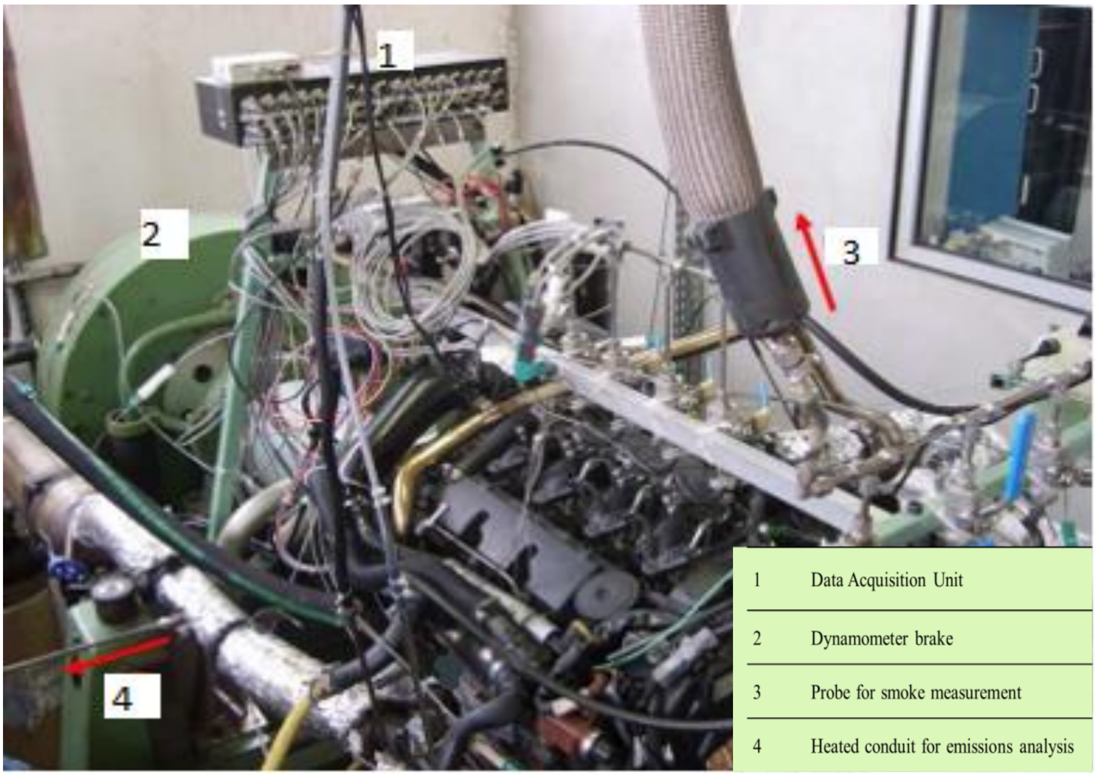

Figure 4-3 Engine Test Bed

4.4.5 Electronic Control Unit

A diesel engine of displacement 2.0 litre is used in this research for parametric analysis. Data was collected through, Open reprogrammable ECU. One of the feature of this ECU is that it can be adapted practically to any engine and is highly customizable ECU available in the market.

4.4.6 Testing Speed Range

Speed range for testing was in the range of 1000 RPM to 5000 RPM measurements were taken of the stabilization of exhaust and engine coolant temperature. At around hertz sensor output and torque measurements were recorded when speed of the engine was varied from high to low and then low to high.

4.4.7 Parameter Analysis

Parameters like torque, power, inlet pressure, intake and exhaust temperatures, exhaust back pressure, engine knock, air mass flow, air fuel ratio, throttle position, valve lilt and shaft rpm were measured and analyzed. Many sensors were used for data acquisition in engine testing. After measuring all these parameters were validated with the simulation results.

4.5 Software Model Setup

Engine itself contains the first basic inputs that are needed to be satisfied. Such quantities include compression ratio, cylinder head clearance, bore and stroke needs to be defined for modelling. Service manuals which are provided by the manufacturer contain all these inputs.

4.5.1 Initial Modeling strategy

Initial modelling setup strategy is to first start with the engine and then move towards outward parameters like from intake and exhaust geometries to port geometries to manifold or header.

4.5.2 Intake and Exhaust Ports

Intake and exhaust ports are the nearest connection to the bores of engine cylinder. One of the important parameter length to measure is the centerline distance from top of the port to valve for both intake and exhaust and inlet. Due to complex geometry and small port size it is difficult to measure these values. By using bent wire this distance was measured approximately.

4.5.3 Port Flow Parameters

Only the centerline and inlet/outlet diameter must be defined in the modelling as flow from the ports will be defined by coefficients of valve flow which were determined using testing on flow bench.

4.5.4 Intake and Exhaust Components

All exhaust components and external intake components needs to be measures precisely after the port lengths are defined because these values are going to be used as inputs in the simulation model. Pressure wave forming in ducts is affected by the exhaust and intake components that's why their length measurements are very critical. For exhaust header primaries and intake runner this is especially true. Original solid models developed in CAD that were used for manufacturing play a key role in providing all the dimensions needed for intake and exhaust components. For example, exhaust header is one of the parameter that is difficult to measure directly from the engine so solid CAD model is very valuable in providing these model measurements.

4.5.5 3D Mesh Modeling

Rather than modelling using one dimensional parameters some components like intake manifold can be modelled using 3D mesh which is reliable and easier method. Based on the imported CAD model junction parameters can be calculated automatically using WAVE mesher because complex Y-junction modelling can be difficult. Area ratios and certain volumes would have to be calculated at each manifold junction without the CAD model. Supporting documents provided by the WAVE software was used to model muffler and air filter. Zero length ducts connecting two Y-junctions were used to model air filter.

4.6 Model Validation

To validate engine model number of parameters can be used. Overall operation of an engine can be evaluated by parameters like air mass flow rate, torque, intake pressure and valve lift magnitude. These parameters validation with the experimental results can give a wide array of design modification areas within the engine.

4.6.1 Torque Validation

While validation through torque output, predicted torque curve trends can easily be validated. Certain valleys and torque peaks shown in engine testing results that represent either exhaust geometry or intake geometry. Simulation predicted valleys and peaks should be at the same engine speeds. It is important that trends like these should be validated as intake/exhaust valve lift profiles and intake/exhaust geometry strictly produce the pressure induced torque peaks. Valve lift and predicted peaks should be investigated and modified if the valley and peaks predicted in the simulation are not occurring at correct engine speeds.

4.6.2 Predictions Validation

Validation of predictions could not be done to reasonable accuracy while attempting to validate via torque output for this case study. Exhaust primary length and intake runner length experiments were investigated to know whether the effect in given peaks or valleys is caused by intake or exhaust. Intake and exhaust modelled geometry should be checked if there are problems in validation through torque.

4.6.3 Sensitivity Study

Sensitivity study can be done on intake valve opening location for further troubleshooting. Considering limited amount of data input the predicted results were satisfactory. Without the combustion analysis, we cannot expect a highly accurate simulation modelling. Likewise, other parameters like power output, intake pressure, air-fuel ratio, compression ratio and valve lift were used to validate the model.

5 Results and Discussion

5.1 Validation Results

Validation on three engine speed points were done with different experimental operating points on each engine RPM. The error in validation caused due to the incomplete combustion model and heat transfer model. These models were incorporated in the software as default for this simulation. The simulation results showed the model accuracy which was built in the Ricardo software. Advantage of this simulation include engine tuning through software rather than on the flow bench which is difficult due to many design and parameters constraints.

5.1.1 First Test Point

Flow bench operating points on engine RPM 1663 which were incorporated in the simulation software are shown in table 5.1.

Table 5-1 First Test Point Results

Parameters	Values
Fuel Air Ratio	0.04545
Exhaust Temperature	487 ℃
Air Inlet Temperature	24 ℃
Intake Valve Dia	27.62 mm
Exhaust Valve Dia	22.7 mm
Exhaust Pressure	1.282 bar
Air Intake Pressure	1.188 bar
Ambient Temperature	8.3 ℃
Injection Duration	6.28°
Injection Quantity	3.73 mg/deg

Validation of the simulation model with the experimental model is shown in the table 5.2.

Table 5-2 First Test Point Validation Results

	Power (kW)	Torque (Nm)	BMEP (bar)
Theoretical	21.52	123	7.77652
Experimental	20.61	118	6.9
Percentage error	5.00%	5.00%	12%

5.1.2 Second Test Point

Similarly, validation on the other engine speed point (1994 RPM) was done. Operating parameters on this RPM are shown in Table 5.3.

Table 5-3 Second Test Point Results

Parameters	Values
Fuel Air Ratio	0.0511
Exhaust Temperature	615 ℃
Air Inlet Temperature	26.24 ℃
Intake Valve Dia	27.62 mm
Exhaust Valve Dia	22.7 mm
Exhaust Pressure	1.753 bar
Air Intake Pressure	0.984 bar
Ambient Temperature	20 ℃
Injection Duration	11.19°
Injection Quantity	3.55 mg/deg

Validation on this engine speed point is relatively accurate and contain less error as the operating points and design parameters incorporated in the software matched the default heat transfer and combustion model. Results from validation are shown in Table 5.4.

Table 5-4 Second Test Point Validation Results

	Power (kW)	Torque (Nm)	BMEP (bar)
Theoretical	43.2046	206.876	13.0151
Experimental	42.15	201.85	12.5
Percentage error	2.50%	2.50%	4%

5.1.3 Third Test Point

Table 5-5 Third Test Point Results

Parameters	Values
Fuel Air Ratio	0.0214
Exhaust Temperature	255.37 ℃
Air Inlet Temperature	24 ℃
Exhaust Pressure	1.277 bar
Air Intake Pressure	1.11 bar
Intake Valve Dia	27.62 mm
Exhaust Valve Dia	22.7 mm
Ambient Temperature	14.42 ℃
Injection Duration	4.59°
Injection Quantity	2.409 mg/deg

Table 5-6 Third Test Point Validation Results

	Power (kW)	Torque (Nm)	BMEP (bar)
Theoretical	7.5745	47.8705	3.01166
Experimental	6.889	43.54	2.8
Percentage error	9.00%	9.00%	8%

5.2 Tuning

Tuning was done on three variable parameters after validating the simulation model with the experimental model. The default compression ratio of the engine is 18. For tuning purposes, these parameters were varied randomly and observed effect on the output power, torque, BMEP and ignition delay in the simulation model. Table 5.7 shows the tuning parameters and their values.

Table 5-7 Tuning Parameters

Intake Pressure	**20% increase**	**20% decrease**
1.188 bar	1.4256 bar	0.9504 bar
Max Valve Lift	**10% increase**	**10% decrease**
8.5 mm	9.35 mm	7.65 mm
Compression Ratio		
16	18	20

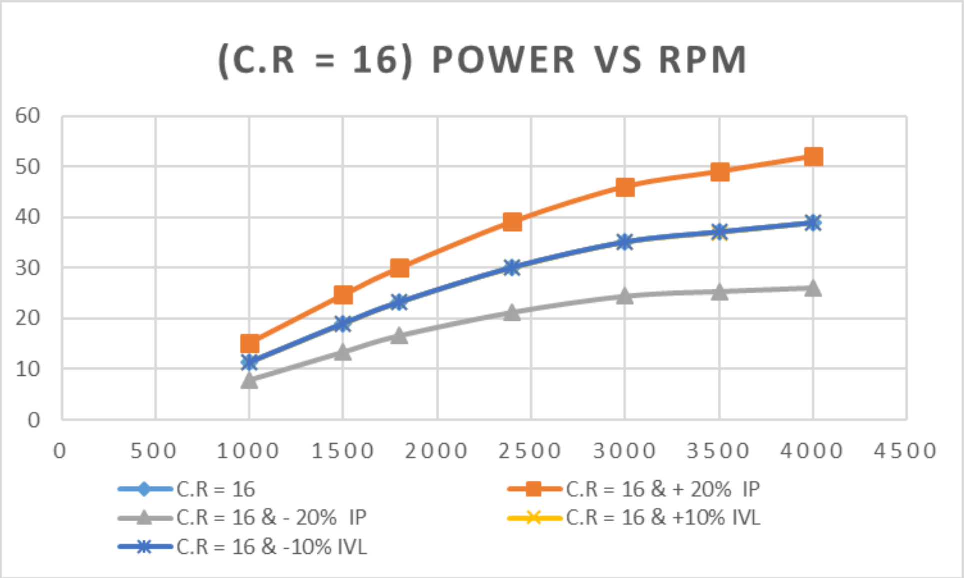

Figure 5-1 Power Vs RPM at C.R 16

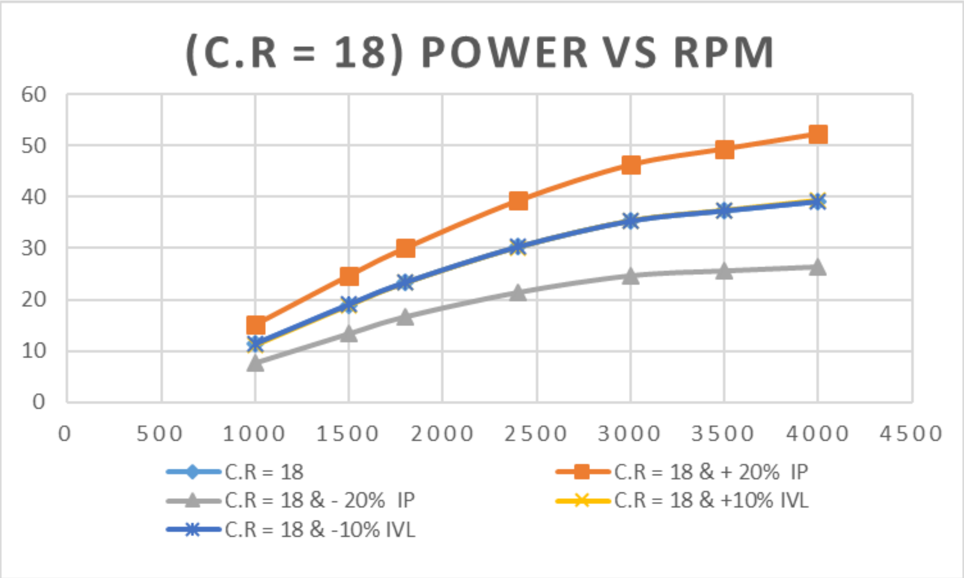

Figure 5-2 Power Vs RPM at C.R 18

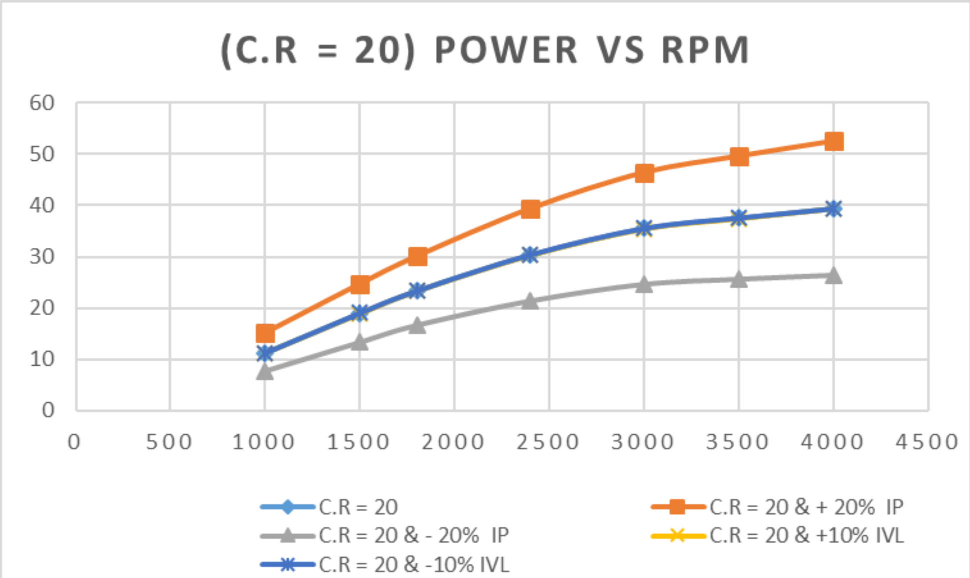

Figure 5-3 Power Vs RPM at C.R 20

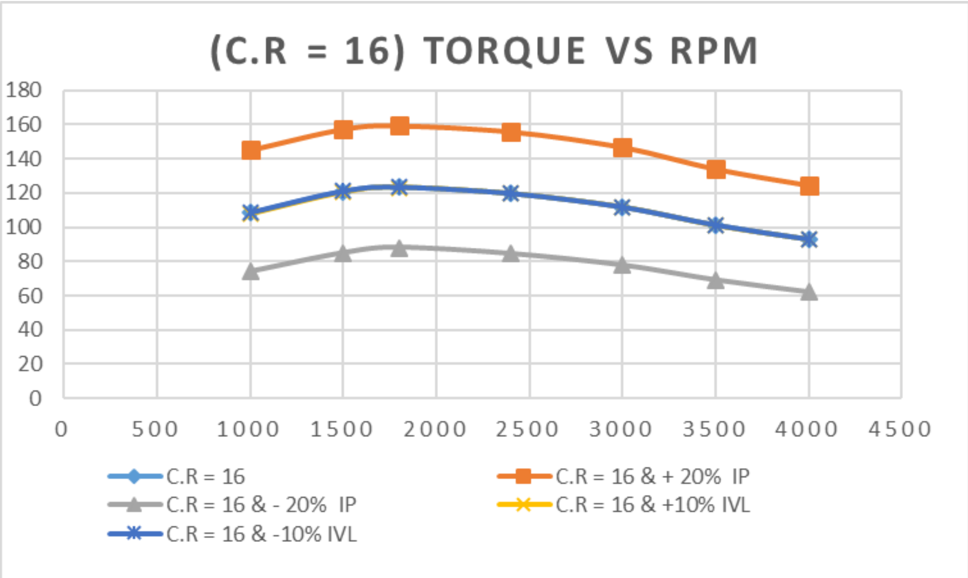

Figure 5-4 Torque Vs RPM at C.R 16

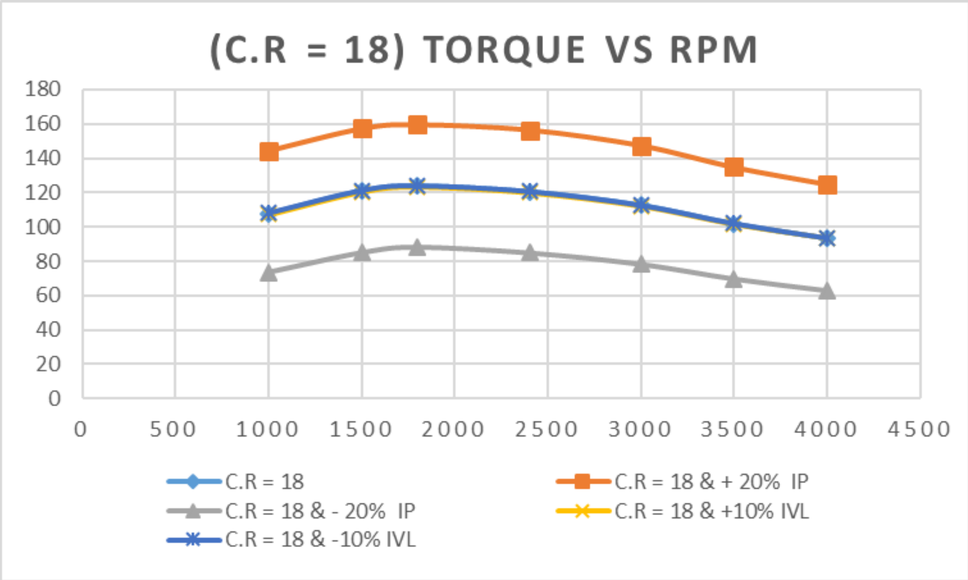

Figure 5-5 Torque Vs RPM at C.R 18

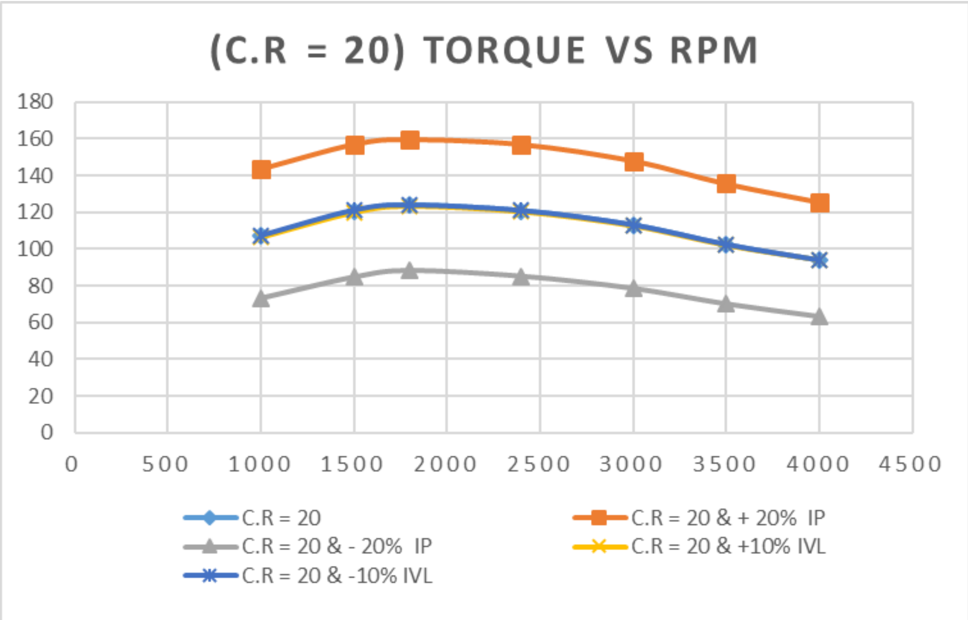

Figure 5-6 Torque Vs RPM at C.R 20

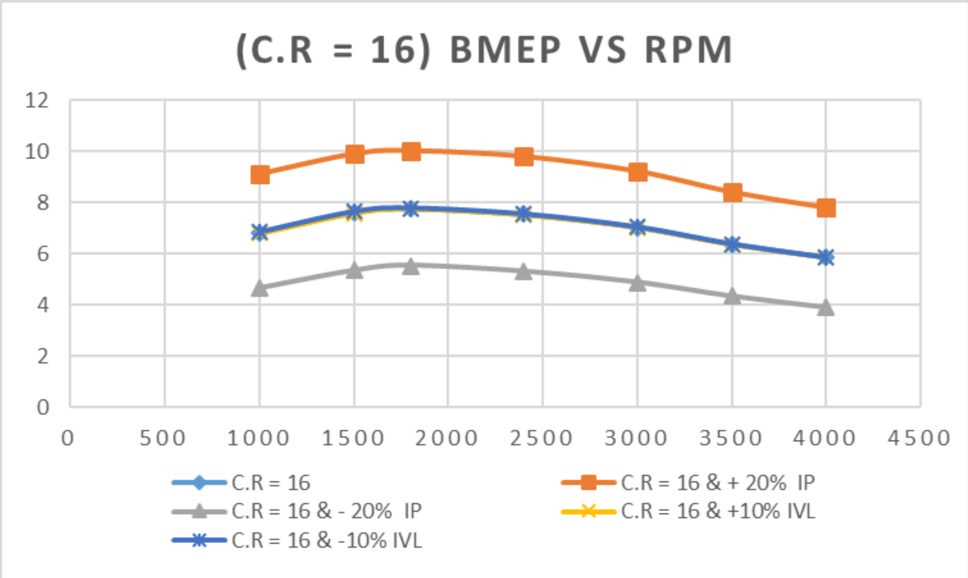

Figure 5-7 BMEP Vs RPM at C.R 16

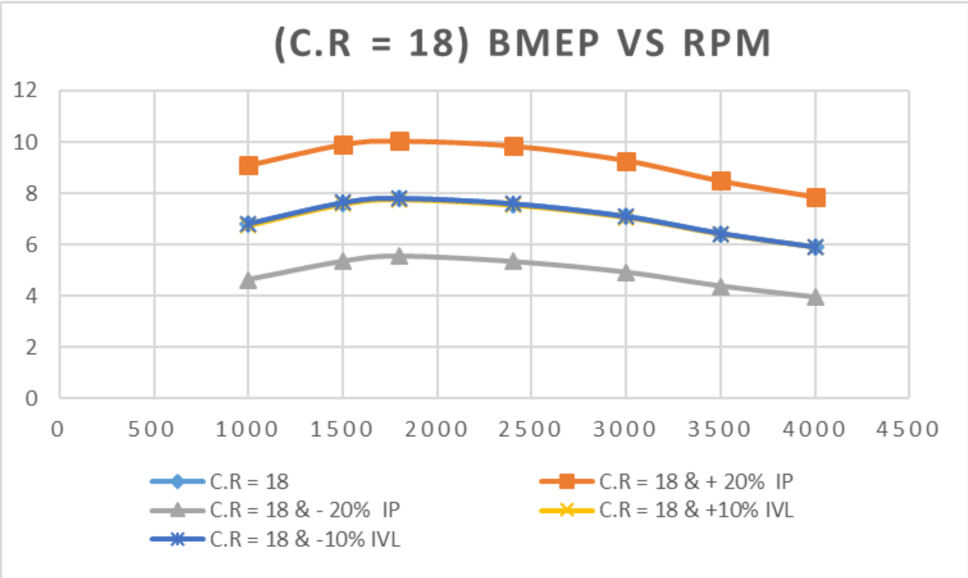

Figure 5-8 BMEP Vs RPM at C.R 18

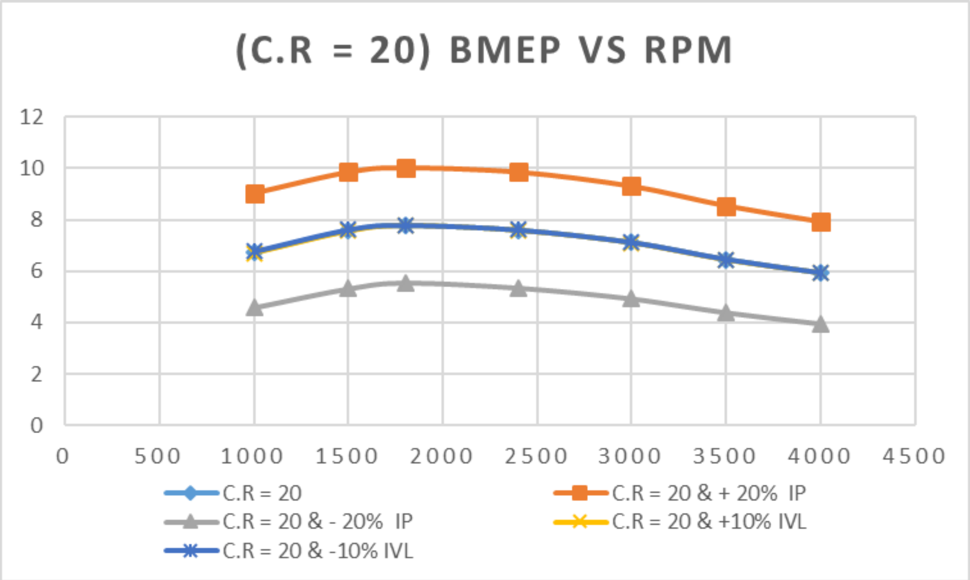

Figure 5-9 BMEP Vs RPM at C.R 20

5.3 Conclusions

1. Software simulation result showed close validation with the experimental setup.
2. Software showed notable change in performance of the engine when intake air intake pressure was varied by 20%.
3. There was almost no change in engine performance with the change in intake valve lift by 10%.
4. Parametric study and design parameters can be carried out theoretically on engine which is tuned on these test points.
5. Validation error occurred due to incomplete heat transfer mode (Wiebe Model). Default model was used.
6. Software output gives sweep plots, time plots and spatial plots which are viable for performance analysis.
7. This method of tuning can help designers to implement parameters which can significantly enhance engine performance and efficiency.

6 References

[1]. (September).IndexMundi.Available: http://www.indexmundi.com/energy/?product=gasoline&

[2]. (September).Wards Auto. Available:http://wardsauto.com/news-analysis/world-vehicle-population-tops-1-billion-units

[3]. D. W. Lee, "A study of air flow in an engine cylinder," 1939.

[4]. A. M. Rothrock and R. C. Spencer, "The Influence of Directed Air Flow on Combustion in Spark-Ignition Engine," 1939.

[5]. W. R. Hawthorne, "Biographical memoir of H. R. Ricardo," Biographical Memoirs of the Royal Society, vol. 22, pp. 359-380, 1976.

[6]. Heywood, J. B., “Internal Combustion Engine Fundamentals”, McGraw-Hill Book Company, 1988

[7]. Lilly, L. R. C., “Diesel Engine Reference Book”, Butterworth and Co Publichers Ltd., 1986

[8]. Bell, A. Graham. Four-Stroke Performance Tuning. Haynes Publishing. Sparkford, Nr Yeovil, Somerset. 1998.

[9]. Blair, Gordon P. Design and Simulation of Four-Stroke Engines. Society of Automotive Engineers, Inc. Warrendale, Pa. 1999

[10]. Gurney, David. The Design of Turbocharged Engines Using 1D Simulation. SAE 2001-01-0576, 2001.

[11]. Heywood, John B. Internal Combustion Engines Fundamentals. McGraw-Hill, New York, 1988.

[12]. Stone, Richard. Introduction to Internal Combustion Engines. Third Edition. Society of Automotive Engineers, Inc, Warrendale, Pa. 1999.

[13]. WAVE Knowledge Center v7.0p3. Ricardo Software. 2007

[14]. Cordon, Charles D. “One-dimensional engine modeling and validation using Ricardo WAVE” NIATT, 2007.

[15]. Brahim Menacer and Mostefa Bouchetara. Parametric study of the performance of a turbocharged compression ignition engine, SAGE, 2014.

[16]. Anoop Selvaraj and Ramzy Gouda. “Investigation into a dual fuel two stage combustion concept engine” EAAS, 2012.

[17]. J. Galindo, H. Climent, B. Plá, V.D. Jiménez. Correlations for wiebe function parameters for combustion simulation in two-stroke small engines. Applied Thermal Engineering, Elsevier, 2011.

[18]. Peter M Fussey, David J N Limebeer “A control orientated combustion model” IFAC, 2012.

[19]. Dai CHOI, Paul C. “A parametric study of Low-Temperature, Late injection combustion in HSDI Diesel engine” JSME, 2005.

[20]. B.Jayashankara, V.Ganesan “Effect of fuel injection timing and intake pressure on the performance of a DI diesel engine – A parametric study using CFD” Energy Conversion and Management, 2009.