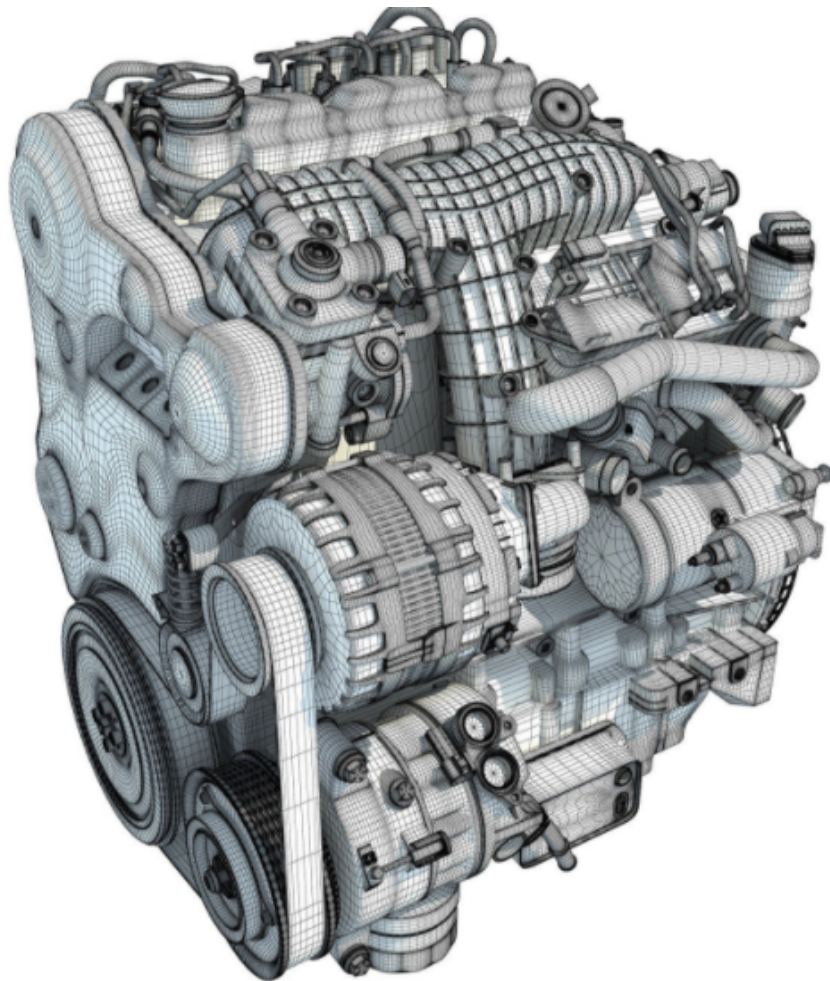




**CHALMERS**  
UNIVERSITY OF TECHNOLOGY

---



# **Online Closed Loop Combustion Analysis of Compressed Ignition Engines**

Master's Thesis in Automotive Engineering

KARTHIK HITAVALLI PRAKASH

RUSHI KIRAN VANGALA



MASTER'S THESIS 2017:92

MASTER'S THESIS IN AUTOMOTIVE ENGINEERING

# Online Closed Loop Combustion Analysis of Compressed Ignition Engines

KARTHIK HITAVALLI PRAKASH

RUSHI KIRAN VANGALA



Department of Mechanics and Maritime Sciences

*Division of Combustion*

CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2017

# Online Closed Loop Combustion Analysis of Compressed Ignition Engines

KARTHIK HITAVALLI PRAKASH  
RUSHI KIRAN VANGALA

© KARTHIK HITAVALLI PRAKASH, 2017  
© RUSHI KIRAN VANGALA, 2017

Supervisors: Björn Jonsson and Jian Zhu, Volvo Car Corporation  
Examiner: Sven B Andersson (Professor), Chalmers University of Technology

Master's Thesis 2017:92  
ISSN: 1652-8557  
Department of Mechanics and Maritime Sciences  
Division of Combustion  
Chalmers University of Technology  
SE-412 96 Gothenburg  
Telephone +46 31 772 1000

Cover: 3D model of a Volvo Diesel - [www.3dhorse.com](http://www.3dhorse.com)

Typeset in L<sup>A</sup>T<sub>E</sub>X  
Printed at Department of Mechanics and Maritime Sciences, Chalmers University  
of Technology  
Gothenburg, Sweden 2017

Online Closed Loop Combustion Analysis of Compressed Ignition Engines  
Master Thesis in Automotive Engineering  
KARTHIK HITAVALLI PRAKASH  
RUSHI KIRAN VANGALA  
Department of Mechanics and Maritime Sciences  
*Division of Combustion*  
Chalmers University of Technology

## Abstract

In recent fast growing automotive industry, modelling and simulations, particularly 1D gas exchange simulations have played a critical role in reducing of the lead time for the development of advanced engines concepts. These simulations are more of a predictive and theoretical approach and have to be backed by measurement and test results. The most optimum method to obtain these test results is by using test rigs. Test rigs these days are advanced and can be used to perform any kind of test to easily verify the simulated data. Single cylinder test rigs are mostly used to understand the combustion and the various parameters affecting the combustion in a cylinder. Single cylinder engines, due to their low cost, flexibility, and easy access for instrumentation are used to compliment simulations. This process of validating the simulation results using test rigs is time consuming and there is often a difference in understanding the process between simulation and test engineers.

The aim of this thesis was to develop an application to create a closed loop data exchange between a single cylinder test rig and 1D gas exchange simulation models. The application has been developed in PYTHON's QT designer plugin and Spyder, a scientific PYTHON development environment to communicate with various systems to create an automated data exchange between a single cylinder diesel engine test rig (AVL PUMA and AVL INNDICOM) and simulation model (GT-Power). In this thesis, the application was developed with built in functions to collect measurement data from the test rig, perform data quality check and use it as an input to the gas exchange models. The measurement data was used in combustion rate analysis and multi-cylinder 1D gas exchange simulations to generate boundary condition settings for the single cylinder engine rig. On completion of this master thesis, this process of completing these functions automatically with the use of a simple GUI would be achieved and improve the efficiency of development process at Volvo Cars Corporation. The main findings in this thesis were, the simulation models run longer than the rig can stay idle. The data quality check had to be performed on each of the 100 cycles of the measurement data. The data integration was achieved with the the application being the control for the data flow.

**KEYWORDS:** Diesel combustion, Three Pressure Analysis, Cylinder Only Pressure Analysis, Single Cylinder Test Rig, AVL PUMA, GT-Power, PYTHON.



# Acknowledgement

We would first like to thank our thesis examiner Professor Sven B Andersson from the Department of Mechanics and Maritime Sciences at Chalmers University of Technology. The door to Professor Sven B Andersson's office was always open whenever we ran into a trouble spot or had a question about our research or writing. He consistently allowed this paper to be our own work, but steered us in the right direction whenever he thought we needed it. The master thesis work was carried out at Volvo Car Corporation, Göteborg. We would like to thank Mr. Mattias Ljungqvist, Group Manager, Engine CAE Fluids at department of Propulsion Power Systems for providing us an opportunity to carry out the thesis and supporting us in every possible way. We would like to thank our supervisors Mr. Björn Jonsson and Mr. Jian Zhu at VCC for their guidance, recommendation, immense support and encouragement in the completion of the thesis work. We would also like to thank Fredrik Holst who was involved providing the necessary measurement data and helped us understand the operation of the single cylinder test rig and David Andersson and Meisam Farzaneh from CAE IT for their help in developing the GUI and control logic in PYTHON. Without their passionate participation and input, the master thesis could not have been successfully completed. This thesis would not have been successful without the help of Danniell Schimel at Gamma Technologies who supported us with every question we had regarding. Finally, we would like to thank Mr. Fredrik Olsson from AVL who helped us regarding the AVL PUMA Integration with the GUI developed during the thesis work in the test rig.

Finally, we must express our very profound gratitude to our parents and friends for providing us with unfailing support and continuous encouragement throughout the process of working on and writing this thesis. This accomplishment would not have been possible without them.

Thank you.

Authors

KARTHIK HITAVALLI PRAKASH,  
RUSHI KIRAN VANGALA.  
Goteborg. June 2017





# Contents

<b>List of Figures</b>	<b>xi</b>
<b>List of Tables</b>	<b>xiii</b>
<b>List of Abbreviations</b>	<b>xv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	1
1.1.1 Introduction to Single Cylinder Rig . . . . .	3
1.2 Aim and Description . . . . .	4
1.3 Objective . . . . .	5
<b>2 Literature Review</b>	<b>7</b>
2.1 Combustion Analysis . . . . .	7
2.1.1 Need for Combustion Analysis . . . . .	7
2.1.2 Three Pressure Analysis (TPA) . . . . .	8
2.1.3 Cylinder Only Pressure Analysis (CPOA) . . . . .	9
2.1.4 Burn Rate Input Data Inconsistency . . . . .	12
2.2 Measurement Data verification . . . . .	13
2.2.1 Encoder Error . . . . .	13
2.2.2 Pegging Error . . . . .	13
2.2.3 Thermal shock error . . . . .	14
2.3 Compression Ratio Adjustments . . . . .	15
2.4 Multi Cylinder Engine Model . . . . .	15
2.5 AVL Integration . . . . .	16
2.5.1 AVL PUMA . . . . .	16
2.5.2 INDICOM . . . . .	17
2.6 Application Development Tool . . . . .	18
<b>3 Methods</b>	<b>21</b>
3.1 Single Cylinder Engine Rig Measurement . . . . .	23
3.2 Measurement Data validation . . . . .	24
3.3 Combustion Analysis . . . . .	25
3.4 Boundary Condition Generation . . . . .	26
3.5 Graphical User Interface . . . . .	27
<b>4 Results</b>	<b>29</b>

<b>5</b>	<b>Discussion and Conclusion</b>	<b>33</b>
<b>6</b>	<b>Recommendations</b>	<b>37</b>
6.1	Faster Engine Models . . . . .	37
6.2	Using MATLAB instead of PYTHON . . . . .	37
6.3	AVL PUMA Integration . . . . .	37
6.4	Data quality checks . . . . .	38
	<b>Bibliography</b>	<b>39</b>
<b>A</b>	<b>Appendix 1</b>	<b>I</b>

# List of Figures

1.1	Percentage of fuel consumption in the automotive industry in the last decade . . . . .	1
1.2	Volvo cars two stage sequential turbocharger . . . . .	2
1.3	Schematic Representation of AVL Single Cylinder Test Rig . . . . .	3
2.1	Layout of TPA Model . . . . .	8
2.2	CPOA model layout . . . . .	10
2.3	Performance model and external subassembly . . . . .	16
3.1	Step by Step Closed loop Process Flow . . . . .	22
3.2	Process Flow of Single Cylinder Rig Measurement . . . . .	23
3.3	Process flow of measurement data validation . . . . .	24
3.4	Process flow of Burn Rate profile Generation . . . . .	25
4.1	Developed Graphic User Interface for the control of the Closed Loop .	30
4.2	Developed Graphic User Interface for the control of the Closed Loop .	31
4.3	Safety check list to have all the models in the right location . . . . .	31
4.4	Setup and Input parameters tabs . . . . .	32
4.5	Boundary conditions and application controls . . . . .	32

## LIST OF FIGURES

---

# List of Tables

2.1	Advantages and Dis-advantages of TPA and CPOA . . . . .	11
2.2	Comparision of matlab and Python . . . . .	19

## LIST OF TABLES

---

# List of Abbreviations

OEM - Original Equipment Manufacturer

EGR - Exhaust Gas Re-circulation

TPA - Three Pressure Analysis

CPOA - Cylinder Only Pressure Analysis

GT - Gamma Technologies

FRM - Fast Running Models

GUI - Graphic User Interface

IVO - Inlet Valve Open

IVC - Inlet Valve Close

EVO - Exhaust Valve Open

EVC - Exhaust Valve Close

IMEP - Indicated Mean Effective Pressure

FMEP - Friction Mean Effective Pressure

RMS - Root Mean Square

LHV - Lower Heating Value

TDC - Top Dead Center

BDC - Bottom Dead Center

PTC - Polytropic Coefficient

AEAP - Average Exhaust Absolute Pressure

CFD - Computational Fluid Dynamics





# 1

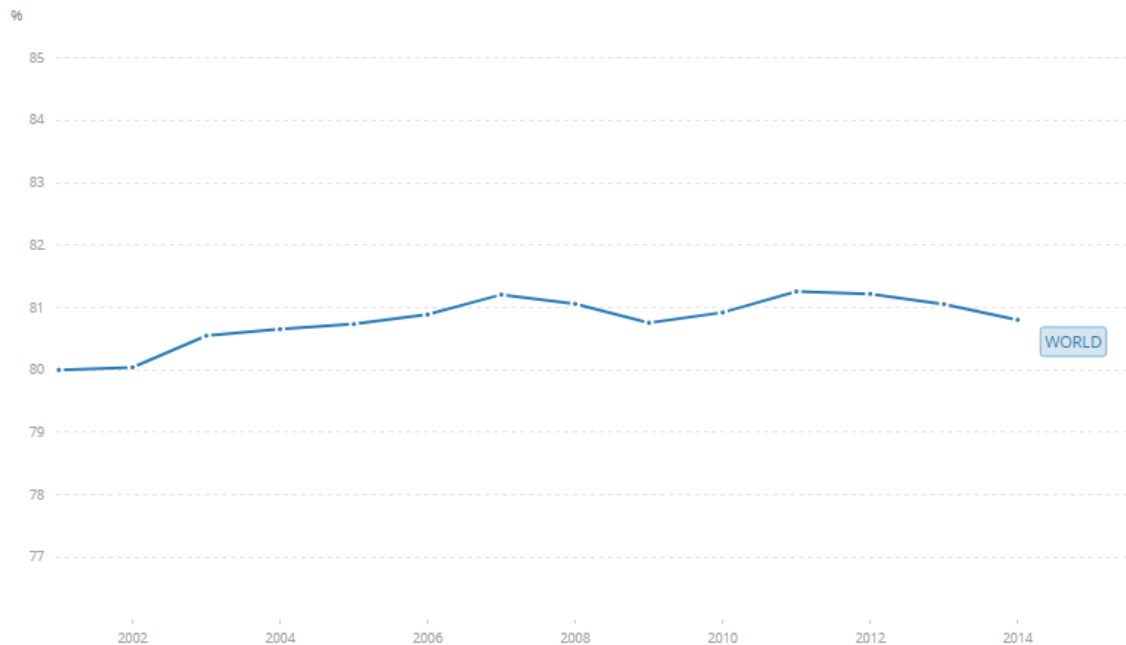
## Introduction

This Chapter gives a brief introduction about the background, aim and description of the thesis.

### 1.1 Background

In the last decade, the automotive industry was accounted for 80% of energy consumption in the petroleum sector as shown in *Figure 1.1*[1]. Vehicles running on conventional fuels are tremendously important sources of energy demand and greenhouse gas emissions, and they likely will remain so for years to come [1].

Modern day car manufacturers are trying hard to minimize fuel consumption and improve the performance.



**Figure 1.1:** Percentage of fuel consumption in the automotive industry in the last decade

Compression ignition engines are in widespread use as prime movers in the automotive industry especially in the personal transportation sector since they are superior to other kinds of internal combustion engines in terms of fuel economy and durability [2] for example, Diesel engines. There have been various technological advancements which improve fuel economy and performance in the recent times, one of them being the development of high-boost turbocharging, such as variable geometry turbocharging, axial-radial turbocharging, sequential turbocharging, two-stage turbocharging, etc [2]. Many OEMs have introduced these technologies in their latest models. For example, Volvo's Drive E technology with a serial sequential two stage turbocharger as shown in *Figure 1.2*[3] which allows both low and high speed responses.

The Drive E technology's advanced boosting enables the delivery of increased power but with lower fuel consumption [3]. Volvo Cars has developed an innovative way of delivering instant turbo response in diesel engines providing a distinct performance called Power Pulse. BMW and Mercedes Benz have also introduced technologies like Piezo common rail system, variable twin turbo system, Aluminum crankcase and SCR catalyst [4] [1].



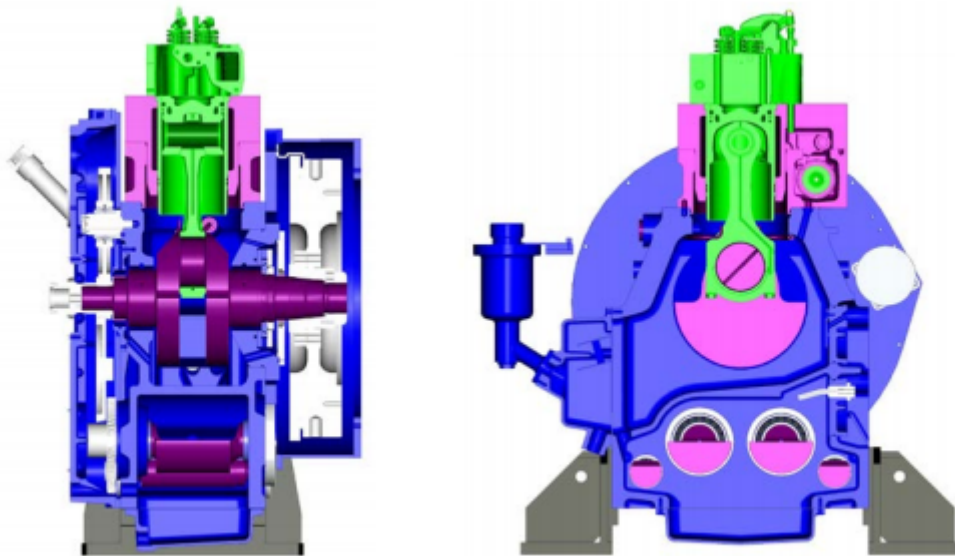
**Figure 1.2:** Volvo cars two stage sequential turbocharger

### 1.1.1 Introduction to Single Cylinder Rig

Single cylinder engines have many such attractive attributes used in research and development than the Multi cylinder engines due to their low cost, flexibility, and easy access for instrumentation. However, engine manufacturers continue to decrease the use of these engines in the engine development process because their dynamic and transient behaviours differ significantly from that of the multi-cylinder engine. The most significant differences are in rotational and gas exchange dynamics.

At Volvo Car Corporation, the single cylinder compression ignition engine test rig plays an important role in development of engines and engine components. This research engine is used to study the behavior of combustion with various engine prototypes. There are several manufacturers of single cylinder engine for research purpose, mainly AVL and FEV. The test rig used at the VOLVO Cars facility is developed by AVL.

In general, a single cylinder engine test rig is a fundamental tool for undertaking research and development in the field of internal combustion engines because it allows segregation of the performance within an individual while also eliminating the often complex inter-cylinder interactions. More importantly, unlike a conventional engine where trade-offs between the simultaneous availability of intake boost and EGR (exhaust turbocharger limitations) severely restrict the exploration of borderline engine conditions, a critical advantage of a single-cylinder engine is to enable the test engineer to independently investigate the effects of intake boost pressure, intake temperature and gas composition, exhaust back pressure and EGR on the engine operation and performance[12]. A schematic of the rig as provided by AVL is shown in *Figure1.3*



**Figure 1.3:** Schematic Representation of AVL Single Cylinder Test Rig

The dynamics in the air intake system are very different than a multi-cylinder engine. As only one cylinder draws air from the intake plenum, there are high pressure fluctuations. To partially compensate for the pressure fluctuation, intake pressure is controlled by the AVL PUMA system. This reduces the amplitude of the fluctuations but it still does not produce the same gas dynamics as a multi-cylinder engine. [14]

Following criteria are used in the gas exchange systems of single cylinder engine

1. The level of pressure fluctuations in the intake and exhaust systems and patterns of the pressure waves
2. The intake and exhaust flows should be reasonably close to those of the multi cylinder engine
3. The cylinder pressures during the combustion and gas exchange should be reasonably close to those of the multi cylinder engine under the same conditions for engine operation

A single cylinder compression ignition engine rig will be used as part of this thesis. As the output data from the rig would be used in a TPA/CPOA model, it would mainly consist of crank angle resolved pressures. The main interdependency of the engine rig with the engine model would be the effect of boost pressure as the combustion would change due to change in the thermodynamic conditions and increase in turbulence which would eventually lead to change in the cylinder temperatures and pressures.

## 1.2 Aim and Description

Today's engine development relies mainly on numerical simulations as well as accurate measurement of the engine prototype. To optimize the use of these systems (simulation tools and engine prototypes), high degree of integration is necessary during the initial engine development phase. In this thesis, the combustion is discussed for a single cylinder diesel engine with its intake and exhaust systems simulating a turbo-charged four-cylinder diesel engine.

Previously, this integration process was not completely automated. It was a lengthy and a time consuming procedure.

1. An engine is made to run in the test rig with the required selected values and it generates an output I-file consisting of standard parametric values.
2. A test bed engineer informs a simulation engineer regarding the availability of new measurements.
3. A simulation engineer extracts data from the measurements and begins the simulation.
4. The simulation engineer informs the test bed engineer that the new set point data is available.

The main work of the thesis is to focus on development of a tool using PYTHON to automatize the data exchange between a multi cylinder GT- POWER model and a single cylinder diesel engine test rig. The main objective is to ensure realistic boundary condition settings are obtained from the measurement data, combustion analysis and engine model simulations. Further, the platform/tool would be used to evaluate the performance of different gas exchange models such as Fast Running Model (FRM) and detailed model.

### 1.3 Objective

It is simple to understand the working behind each system of the entire loop independently but the integration of all these systems with a third-party tool would be of greater challenge.

By the end of the thesis, the following questions need to be answered,

1. Which of burn rate analysis method to be used (TPA or CPOA)?
2. Can the test bed engineer work more independently?
3. Which programming language is optimum to build the control logic?
4. Can GUI enable users to run GT-Suite in the background?
5. Can the measurement data be automatically analyzed, validated, and transferred without errors?
6. Can the integration of multiple workstation and servers be achieved?
7. Should the models be fast running models or detailed models?



# 2

## Literature Review

This Chapter gives a background of all the systems involved in the closed loop data flow based on available literature.

### 2.1 Combustion Analysis

Combustion Analysis or Burn Rate Analysis is a process of obtaining the Mass Burnt Fraction which is a release in chemical energy with respect to crank angle for each individual cycle. This burn rate is usually a normalized value from 0 to 1. In this thesis, the Burn rate analysis is performed once the measurements are made from the single cylinder test rig as the test rig cannot measure the normalized burn rate. As the measured data is mainly pressure data of cylinder, intake and exhaust, there are two ways to determine the Normalized Burn Rate.

1. Three Pressure Analysis (TPA)
2. Cylinder Pressure Only Analysis (CPOA)

#### 2.1.1 Need for Combustion Analysis

Three Pressure Analysis (TPA) and Cylinder Pressure Only Analysis (CPOA) analysis are two ways to generate a burn rate profile as discussed earlier.

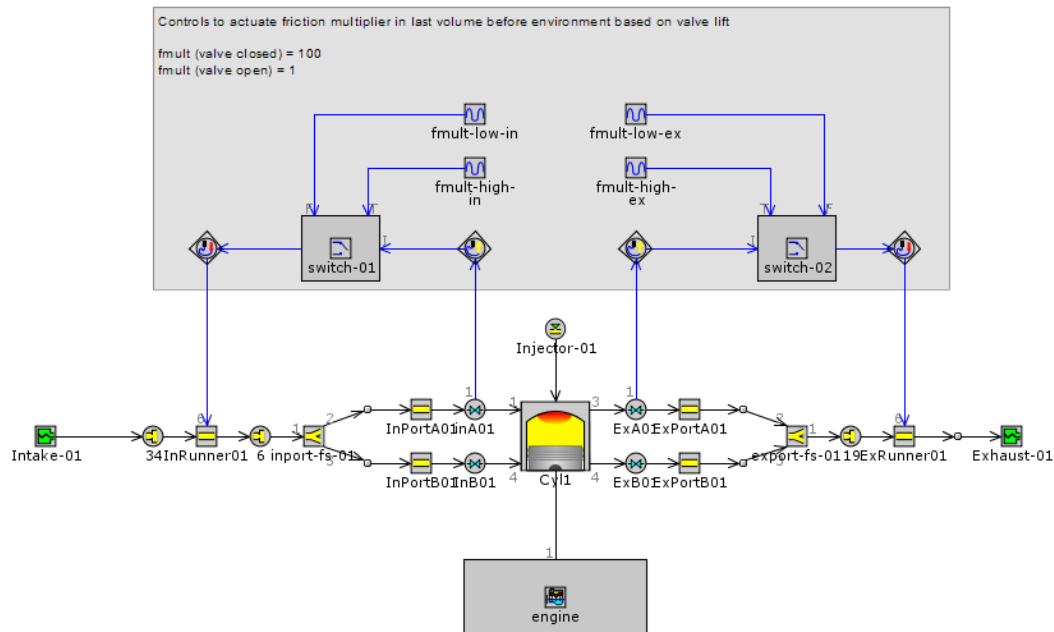
There are two other main reasons for which TPA is carried out. Firstly, it helps in the estimation of trapped quantities at the Inlet valve closing which is used as an input during calibration. This is done as it is difficult to estimate trapped quantities inside a test cell. Secondly, it helps in the quality analysis of the traced pressure curves before it is used for calibration purposes.

The primary inputs for the TPA are the three pressures - intake, exhaust and in-cylinder pressure trace. Other inputs include injection profile, emissions, measured air mass and fuel injection masses etc. For analysis purposes, GT-Power performs several pliability checks on the input data to assess its overall quality.

The CPOA analysis was performed to check the level of accuracy of measured data such as trapped quantity from TPA analysis was reasonable or not. The TPA model is a completely built engine model, whereas the CPOA model only consists of an Injector, cylinder and an engine crank train in the model built in GT SUITE. Therefore, the simulated pressure near IVC in CPOA is calculated based on the trapped quantities obtained from TPA. If the reckoning is correct, the simulated and the measured pressure traces will be in good agreement with each other.

### 2.1.2 Three Pressure Analysis (TPA)

The approach requires three measured pressures; intake, cylinder and exhaust, hence the name, Three Pressure Analysis (TPA). For this analysis, no estimation of the residual fraction and trapping ratio are needed as inputs. This approach requires an engine model including valves and ports at a minimum. The simulation is run for multiple cycles until the model has converged (if applicable). Thus, the trapping ratio and residual fraction (and other trapped quantities) will be calculated, which is why they are not needed as inputs. *Figure 2.1* shows a detailed layout of all the components used in a TPA model.



**Figure 2.1:** Layout of TPA Model



## Characteristics of TPA

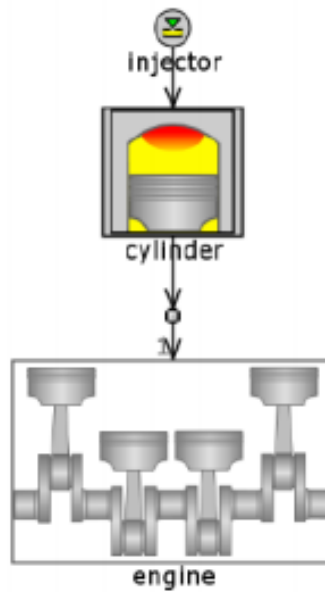
In general, the characteristics of the TPA model is as below, [16]

1. Multicycle analysis (multiple cycles are calculated until steady state is reached)
2. Trapped IVC conditions are calculated from flow through valves
3. Burn rates are calculated from cylinder pressure between IVC (or start of injection) and EVO
4. Required input data:
  - (a) Cylinder Pressure Profile
  - (b) Intake and Exhaust Instantaneous (Crank-angle Resolved) Pressure Profiles
  - (c) Intake and Exhaust Time-Averaged Temperature and Pressure
  - (d) EGR Rate
  - (e) Injection Profile
  - (f) Swirl/Tumble coefficients
  - (g) Start of Combustion

### 2.1.3 Cylinder Only Pressure Analysis (CPOA)

As the name suggests, the cylinder pressure only analysis data uses only the cylinder pressure unlike the TPA which uses three pressures namely Inlet, Outlet and Cylinder ones as shown in *Figure2.2*. This method is also used to estimate the burn rate during the combustion phenomenon. The procedures adopted for the calculations of the burn rate in this method are quite similar to that of the TPA. [17]

Usually the CPOA analysis is performed to check the accuracy of the trapped quantities estimated by TPA analysis. The main difference between TPA and CPOA is that, unlike TPA the CPOA is not a complete engine model. Hence the simulated cylinder pressure trace at IVC in CPOA is calculated based upon the trapped quantities obtained from TPA. Therefore if the estimation of trapped quantities in TPA is correct then the simulated pressure trace out of CPOA and TPA would match. But in this case, the choice is given to the user to choose between TPA and CPOA analysis based on the obtained data from the test rig.



**Figure 2.2:** CPOA model layout

### Characteristics of CPOA

In general, the CPOA model [16]

1. Carries out a single analysis of measured cylinder pressure starting from IVC
2. IVC conditions are based on the following user-defined inputs:
  - (a) Cylinder Pressure Profile
  - (b) Volumetric efficiency
  - (c) Trapping ratio
  - (d) Residual Fraction
3. Burn rates are calculated from cylinder pressure between IVC (or start of injection) and EVO
4. Required input data:
  - (a) Cylinder Pressure Profile
  - (b) Injection Profile
  - (c) Volumetric Efficiency
  - (d) Trapping Ratio
  - (e) Residuals Fraction
  - (f) Start of Combustion (spark or injection)

The following *Table 2.1* gives a brief comparison between the three pressure analysis and the cylinder only pressure analysis. It mainly emphasizes on which method could be used for the prediction of combustion analysis.

**Table 2.1:** Advantages and Dis-advantages of TPA and CPOA

	<b>TPA</b>	<b>CPOA</b>
<b>Advantages</b>	The primary benefit of this approach is that all of the cylinder trapped quantities are predicted by the simulation, including the trapping ratio and the residual fraction. However for these quantities to be accurate, the flow characteristics of the model must be accurate. This is accomplished by isolating within the model one cylinder and its associated valves and ports, while the measured instantaneous port pressures are imposed as boundary conditions in the simulation (the third pressure is the cylinder pressure)	The benefit of this approach is that it is fast and only requires one measured instantaneous pressure trace (cylinder pressure).
<b>Disdvantages</b>	The downsides of this approach are that additional measured data is required and that the calculations are slower due to the need to run simulation cycles until convergence. This approach is recommended for any operating point where the residual fraction or trapping ratio is not known or easily estimated (part load)	The main downside of this approach is that it requires the estimation of certain input parameters such as cylinder trapping ratio and residual fraction that are difficult to obtain from the test rig

### 2.1.4 Burn Rate Input Data Inconsistency

The burn rate data is generally subjected to discrepancies. Some of the factors that must be considered for data consistency checks are discussed below.

1. **Pressure Smoothing:** The measured cylinder profile must be reasonably smooth or must be smoothed using filters. A Root mean square error value is indicated in the analysis during the comparison of actual raw curve and the smoothed curve. If the value of RMS pressure is greater than 0.02, an error is flagged resulting in data loss.
2. **Cylinder Pressure at IVC:** During “TPA Steady Analysis”, cylinder pressure that’s measured is shifted automatically by 10 degrees so that it fit the simulated value perfectly or is pegged to predicted cylinder pressure value at the start of the compression angle. The shift of pressure angle is reported and if it is greater than 0.5 bar, an error is flagged. If the pressure is user implicated, then the error would not be flagged.
3. **Cumulative burn rate during Compression:** In a diesel engine, fuel is injected at the end of compression stroke. Hence, combustion occurs only after fuel is injected into the cylinder. Apparently, no fuel must be burnt before the Start of Injection (SOI). Any indication of fuel burnt, an error is indicated in input data.
4. **Compression Slope:** Slope of the Log P vs Log V measured during compression stroke from IVC and start of injection must be roughly constant. The value must be close enough to the polytrophic co-efficient. As the piston moves away from TDC, the temperature reduces and the slope decreases gradually. The value of PTC varies for different engines and differs at varied temperatures.
5. **Air and Fuel Mass:** For data accuracy, the measured and the simulated air flow during the process must be in the range of  $\pm 5\%$  of actual value. Deviation from the same, indicates an error in air and fuel mass delivery to the gas exchange models.
6. **Fuel Air Ratio:** The fuel air ratio obtained from the simulated values is compared with the actual test. If the error range is in the range of  $\pm 5\%$ , an error is flagged.

All the above errors that are considered must be satisfied, else there will be an error flagged each time in GT SUITE. These causes inaccuracies in the model input parameters and causes a large deviation in the resulting outputs. The analysis was performed for all the operating points considered. If any errors that had to occur during the analysis, they were to be rectified.

## 2.2 Measurement Data verification

The pressure data obtained must be verified for some of the common errors like encoder error, pegging error and thermal shock errors before they can be used further for the burn rate analysis and calibration. The test cell data must be analysed similar to AVL concerto.

### 2.2.1 Encoder Error

The error that occurs during the relative phasing between the signals from the pressure transducer and the crank angle encoder. The cylinder pressure trace must be highly accurate when measured during the phasing [18]. If the phase is altered to increase by a reasonable value, it will end up generating an error of the heat release curve in terms of both shape and size and hence there would be no accurate information about the engine performance characteristics.

There are 2 ways to determine the encoded error,

1. **TDC Sensor:** In this process, A sensor mounted with respect to highest priority on those injector or those flash fitting produces an voltage sign as an work of the piston development and aides in the correct determination of the TDC. It may be a standout amongst those recommended strategies since weight qualities doesn't influence sensor position brought about because of inaccurate pegging.[18]
2. **Motored engine pressure trace:**

If we consider an engine as a closed thermodynamic system, the rate of energy exchange during the compression stroke will be equal to that of expansion stroke. However, in case of a real engine, we have heat transfer losses, thermal losses etc. As of this effect, the point of maximum pressure would shift by a degree before compression stroke at TDC. [18]

### 2.2.2 Pegging Error

Pegging refers to ceiling the output values of the sensor. If pegging is not done, the input value tends to exceed the certain nominal value due to which the output is deviated. Hence, pegging is important. Here, piezoelectric pressure sensors need aid element sensors in view of those piezoelectric impact. In piezoelectric pressure sensors, charge created towards mechanical deformity quickly decays through self-discharge. Therefore, piezoelectric sensors can't be utilized for unfaltering state alternately gradually evolving weights. Nonetheless, they need aid exceptionally of service device for quickly evolving pressures, for example, encountered in internal combustion engines. These are commonly used for measuring pressure trace inside the cylinder. Here, a charge may be produced for an evolving weight which is changed over will. A voltage utilizing an advanced out. Hence, it may be paramount should peg the weight following each cycle. This helps in creating instant transfer function which is used for the later part of the cycle .

The general representation of the transfer function is shown below:

$$p(\theta) = P_{peg} + Gain(V(\theta) - V(\theta_{peg}))$$

Where,

$P_{peg}$  is the pegged pressure,

$Gain$  is the sensor gain value in bar/volt,

$V(\theta)$  is the voltage in Volts at a given crank angle  $\theta$  and

$V(\theta_{peg})$  is the voltage at the crank angle where the pressure is being pegged [19].

Incorrect pegging might lead to affecting the parameters such as instantaneous heat release, crank angle of peak pressure etc [19].

There are two ways to check for pegging error.

### 1. Polytrophic Coefficient (PTC)

The polytrophic value and its quality may be straightforwardly related the particular high temperature quality of the gasses and rate of heat exchange across the cylinder walls. For diesel engines, those PTC is found will be in the range for 1.35 during compression. Thus the pegged pressure must have value around this range [20].

### 2. Pressure Shift

If the intake system does not have a considerable characteristic changes, the pressure in the intake manifold is same as the cylinder pressure inlet at BDC. The error variation must be around 200 millibar between the intake pressure and the cylinder pressure [17]

## 2.2.3 Thermal shock error

During the combustion stroke, the quantity of heat released would be very high. This high heat generated can temporarily change the offset value from the sensors. This phenomenon is known as thermal shock. Sensors have very low time constants and recover before the start of next pegging cycle. However, if this doesn't happen, there would be an error which may lead to the inaccurate pressure readings [18].

Analysing the Average Exhaust Absolute Pressure (AEAP) between 240 to 320 crank angle degrees after TDC, the thermal shock error can be analyzed. For quality and better measurements, the range of AEAP must be within 5kPa [18].

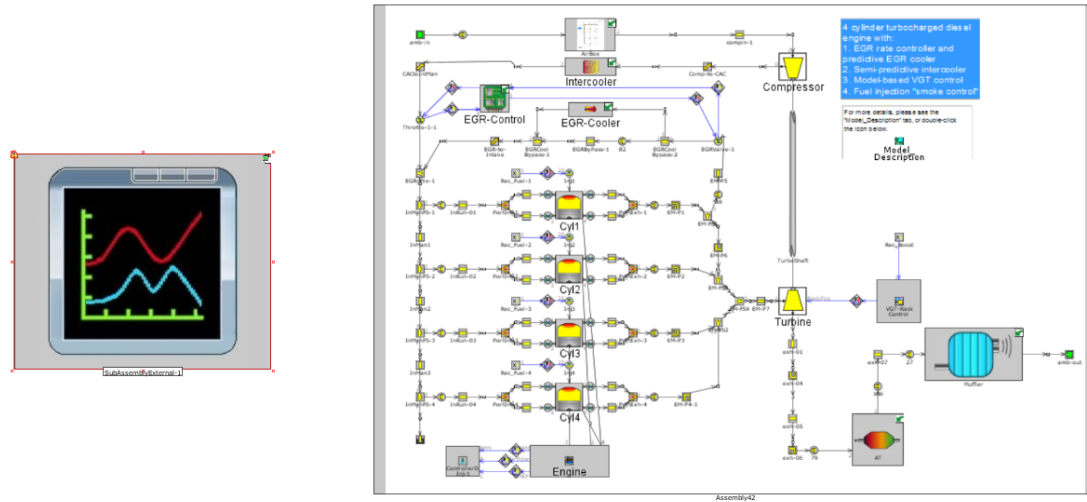
## 2.3 Compression Ratio Adjustments

Compression ratio is one of the parameter that determines the engine performance and fuel consumption. Compression ratio is the ratio between the cylinder swept volume to the combustion chamber volume. There are different ways to measure the compression ratio. Most commonly, Static Compression Ratio is used as it is obtained from the swept volume of the cylinder (BDC to TDC). On the other hand, Dynamic Compression Ratio uses the position of the piston at IVC. Therefore, if the IVC is known then the Dynamic compression ratio will be known. Compression ratio correction is performed in the simulations as the effects of thermodynamic compression ratio and effects of blow by are not considered. Thermodynamic compression occurs due to variable expansion of combustion chamber which could be due to varying temperature and pressures from cycle to cycle. Hence, TPA analysis was used to estimate the same. This was done by varying the compression ratio in a repeated phase until the simulated pressure trace was almost identical to the measured pressure trace

## 2.4 Multi Cylinder Engine Model

The engine used for this study was a turbocharged multi-cylinder engine. In this thesis, the engine model requires an input of burn rate and the outputs are of temperatures, pressures and other boundary conditions required for the single cylinder test rig. As the model is of a multi cylinder engine and the rig is single cylinder, the boundary conditions settings are taken for cylinder 2 of the engine model. Engine simulation models used for model-based development tasks are mean-value, empirical models, developed by testing the engine at various operating conditions in an engine test rig. Each component data such as injector timing, turbo maps, etc. are obtained from test rigs. The engine simulation model used for this study was a crank-angle resolved, physics based model, developed using GT Suite engine simulation software. The advantage of using this type of model is that components are physically represented, so hardware changes can be quickly and easily updated in the model. [21] [16]

As the burn rate model and the engine model are both developed in GT suite, integration of these models is not a big challenge. As per suggestions from Daniel Schimel from GT support, the burn rate analysis model could be integrated with engine model using sub-assemblies block as shown in *Figure 2.3*. This would automatically include all profiles from the external sub assembly (in this case TPA/CPOA models) in the main model (multi cylinder engine model). In the engine model, a dependence object for combustion would be imported from the burn rate analysis provided the referencing is done accurately. Depending on the level of accuracy, the model can be a detailed model or a fast running model.



**Figure 2.3:** Performance model and external subassembly

## 2.5 AVL Integration

The test rigs are controlled by AVL systems, some of the systems used at Volvo Cars Corporation and this thesis are AVL PUMA and AVL INDICOM. Integration with the AVL systems was one of the most complicated step in this thesis. The AVL systems work on a different network and the communication with the AVL network would not be possible with the existing security protocols.

### 2.5.1 AVL PUMA

AVLs PUMA system is an open test bed system which is largely used for power train testing and development. The advanced features and methods supports modern day testing on a large scale as well.[15].

1. Vehicle testbeds to fuel economy interpretation, driveability streamlining Also emanation certifications. [15].
2. E-motor testbeds: covering full four-quadrant operating
3. Powertrain testbeds for transmission solidness trying and the finish powertrain streamlining.
4. Motor testbeds with focus persistence, emanation levels to secondary end racing provisions.
5. Hardware-In-Loop testbeds will accept What's more on get ready complex test systems for finish dissection.



### 2.5.2 INDICOM

1. Indicom is a programming bundle generally utilized for combustion analysis that combines the control for information securing with professional information assessment for clear graphical presentation. [15].
2. Capable information securing device which may be suitable to an extensive variety about provisions in the field of powertrain advancement.
3. Highly accurate, reliable measurements, efficient sensor data management.
4. Easy and proven integration into any test cell automation environment with tailored and generic interfaces.[15]

## 2.6 Application Development Tool

Once the systems involved in the process flow were understood, the next step would be to choose an appropriate tool to develop a GUI and control logic. There are wide number of tools available in the market(Matlab, Python, C++, etc.). After careful consideration, MATLAB and PYTHON (an open source software) were chosen as they were readily available at Volvo Car corporation.

The main purpose of this tool/application would be to control the functioning of the closed loop as per user requirements.

Reasons to choose an open-source software:

1. Initial costs of an open-source software is usually negligible to none.
2. Support for using open source software is usually obtained for free from other users or developers and several forums.
3. Open source software can always be very flexible and can adapt to any new requirements that may come up.[22]
4. Lastly, the companies using open source software do not have to think about complex licensing models and do not need anti piracy measures like product activation or serial number. [23]

Apart from these advantages, there are few disadvantages.

1. No one in the open source community is obligated to help you unlike a licensed software.
2. Needs to be adapted to the specific requirements (specific packages need to be installed separately).
3. The available documentation of the software is usually less. So the initial learning curve can be steep. [23]

On evaluating the two available software as shown in *Table 2.2*, Python was chosen as the cheapest and the optimum software/tool for this thesis.

**Table 2.2:** Comparision of matlab and Python

<b>Python</b>	<b>Matlab</b>
Free (open Source)	Expensive (Licensed)
It has specific modules designed for the purpose of data preparation like NumPy, SciPy, Pandas, etc	It has a solid amount of functions
Powerful and Portable	No Good alternative for Simulink available in the market
Extra packages and a GUI development tool needs to be installed separately	It is easier for beginners, as all the add-ins are included in the package
Large public community and free of cost support	It has a large scientific community but to get support means paying more money



# 3

## Methods

This section mainly highlights the procedures and the methods regarding the development of the control logic of the closed loop, burn rate analysis and generation of boundary condition settings.

The first step of the closed loop would be to generate measurement and collect the data from the test rig (AVL PUMA and AVL INDICOM). Measurement data collection included crank angle resolved intake, exhaust and in cylinder pressure and parameters like air flow, fuel flow, average intake and exhaust pressure, compression ratio, injected mass.

The next step involves quality check of the measurement data. Objective of this step was to verify the input data for encoder, pegging and thermal shock errors.

Once the data validation was performed, the next step was to perform a burn rate analysis to obtain normalized burn rate profile. Burn rate analysis was performed in two ways based on the user input namely, Three Pressure Analysis (TPA) which as the name suggests uses intake, exhaust and cylinder pressure as input and Cylinder Pressure Only Analysis (CPOA) which uses only cylinder pressure.

Once the Burn Rate Profile was generated, the required performance model (Multi Cylinder Engine Model) must be modified to fit the requirement. As the performance model is modelled for multiple cases, a single case with necessary parameters was used. The generated burn rate profile had to be integrated to the performance model to be able to use the normalized burn rate profile in automated closed loop process.

The results from the performance model simulation were saved in an external file. These results are the required boundary condition settings for the single cylinder diesel engine test rig. The required boundary condition settings are average intake pressure, average exhaust pressure, average intake temperature.

Once each of the above steps were completer and each process was functioning as desired, the next step was to create and automate a loop with all processes. As the requirement of the thesis was to develop an application in PYTHON/Matlab, the control logic to automate the closed loop was developed using the same tool.

In this step, a GUI was developed which allows the user to input measurement data and then display the newly generated boundary condition settings. The primary objective is to ensure all the processes run in the background for which the network at Volvo Cars Corporation had to be understood so that the necessary files are accessible from the test rig location.

*Figure 3.1* shows the steps involved in the automated closed loop and the GUI which is the bridge between the user and the background process.



**Figure 3.1:** Step by Step Closed loop Process Flow

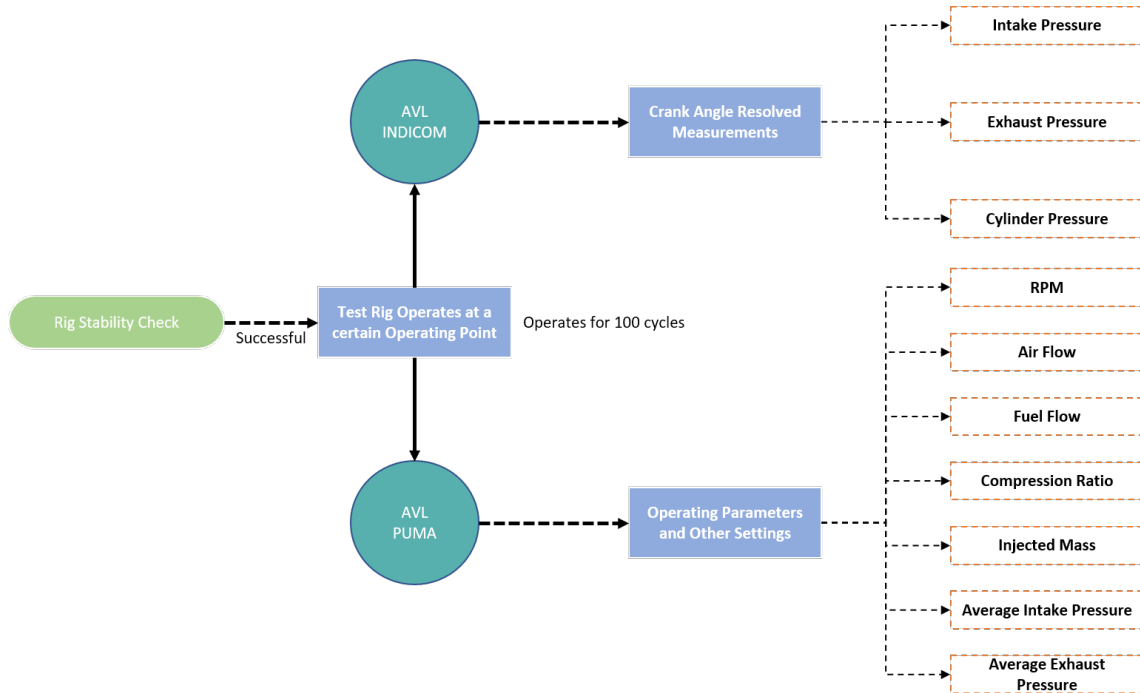
The step by step description of each stage in the cycle are explained in detail in the further sections and would give a clear understanding as to how the GUI developed would help in generating the final boundary conditions when integrated with the single cylinder diesel engine test rig.

### 3.1 Single Cylinder Engine Rig Measurement

On a daily basis, before performing any test or measurements in the test rig, a rig stability check is performed. The stability check requires the engine to be run at a constant speed of 2000 rpm. When the engine stabilizes, a series of automated checks were performed to identify errors in the measuring equipment by checking the deviation in cycle to cycle measurement. If the deviation of the measurement data is within the desired limits, the check is completed. All the crank angle resolved measurements are displayed on the AVL INDICOM system and all the set parameters are displayed and adjusted using the AVL PUMA system. On Completion of the Rig Stability Check, the necessary test can be performed.

As this thesis does not involve with any specific test or measurement data as long as the measurement data is clean and satisfactory. As the AVL Indicom and AVL PUMA systems were not linked to the Volvo Cars network, the only way to obtain the measurement data was to generate an iFile, which is a binary file generated by the AVL INDICOM system and contains crank angle resolved data of measurements. All the other operating parameters the engine was running at was exported in excel format by the AVL PUMA system.

Figure 3.2 shows the process flow of Single cylinder rig measurement and the required measured parameters from the respective systems.

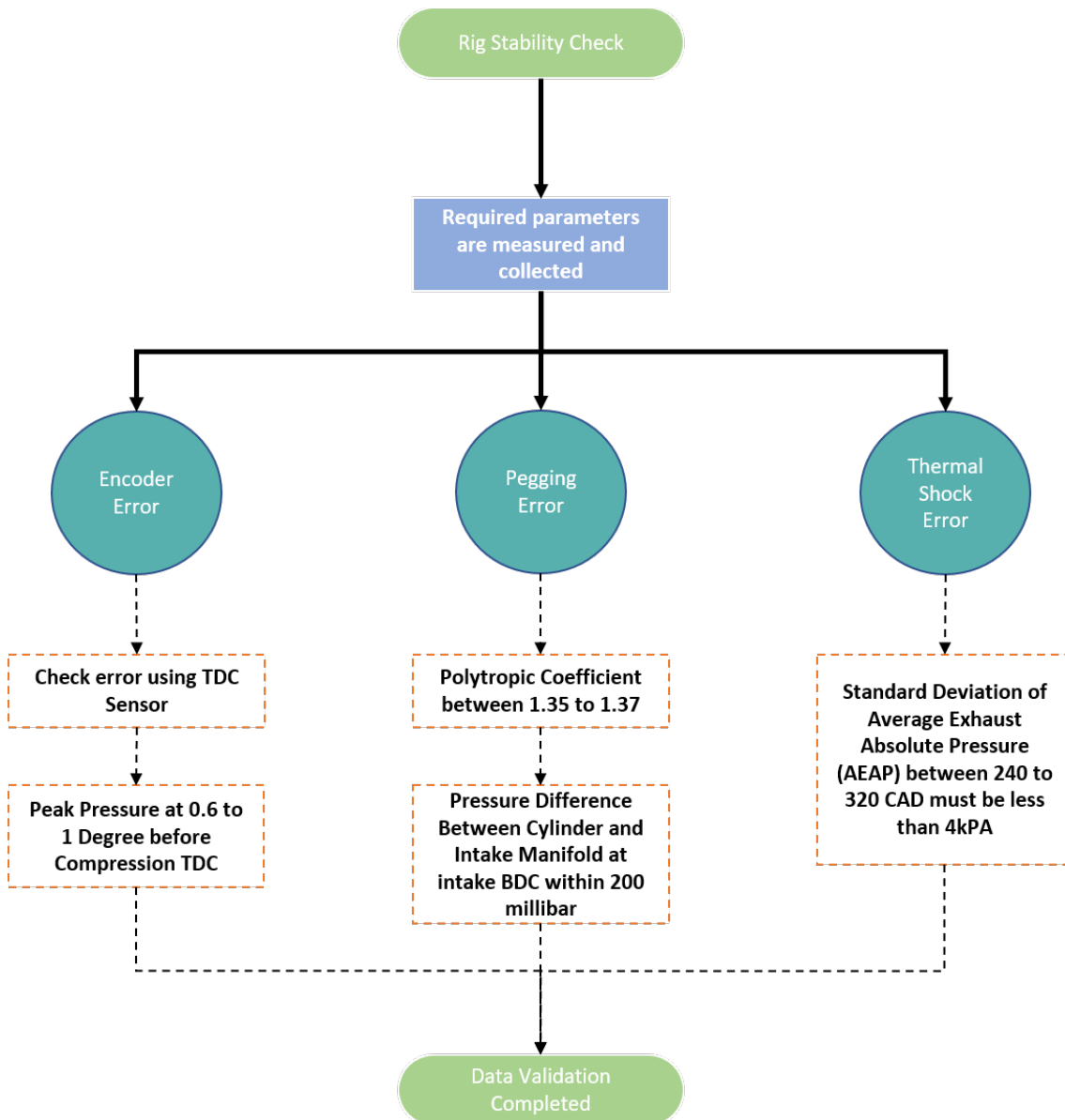


**Figure 3.2:** Process Flow of Single Cylinder Rig Measurement

## 3.2 Measurement Data validation

Once the measurement data is obtained, the next step would be to check if the data is of use or not. The data recorded from the rig must be validated due to the irregular calibrations of the measurement equipment and sensors used. Periodical calibration of sensors and other measurement equipment is very important consistent and accurate measurement. Inconsistency or irregularities in any data can be checked using three different types of errors. They are encoded error, pegging error and thermal shock error.

Measurement data validation is desired as and when new set of measurement data is generated. *Figure 3.3* shows the process flow of measurement data validation with the required change in error.



**Figure 3.3:** Process flow of measurement data validation

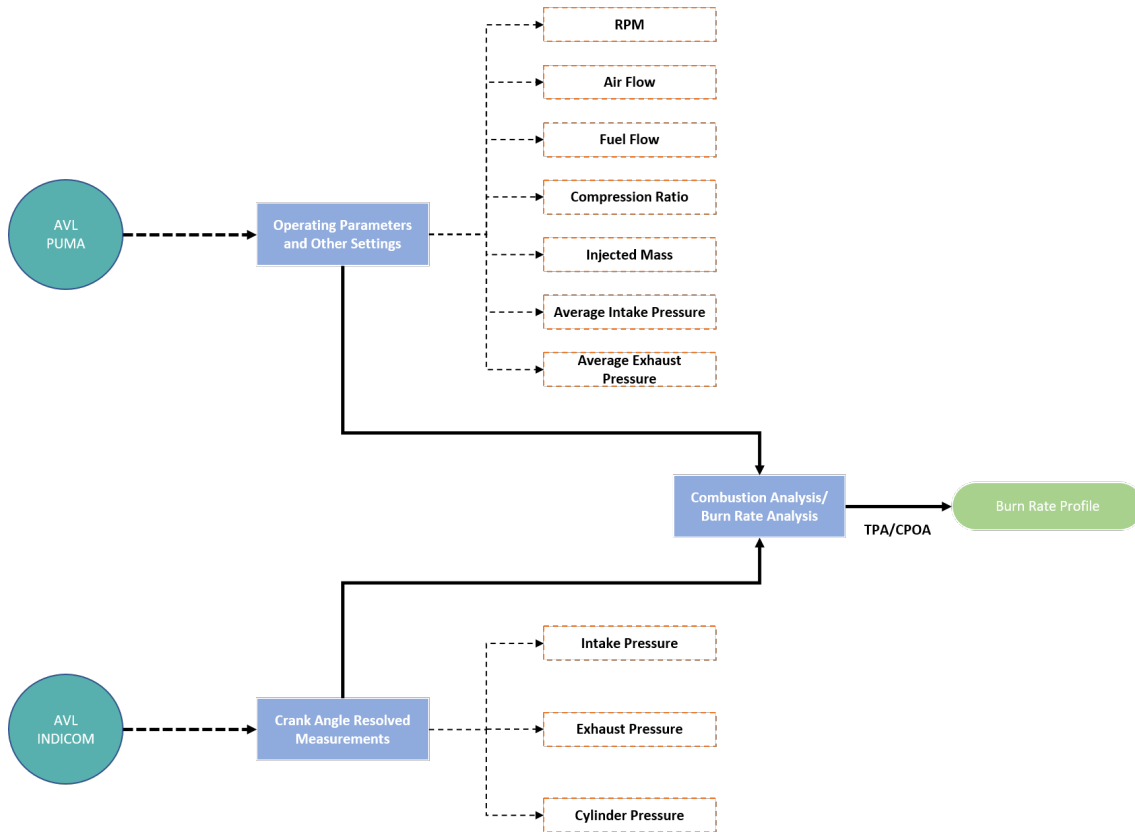


The measurement data obtained from the single cylinder test rig contains crank angle resolved pressure data (Intake, Exhaust and Cylinder pressure) for 100 consecutive cycles. The most optimum way to check the quality of the measurement data is to check for the possible errors cycle by cycle. This method eliminates all the cycles that do not satisfy the conditions for errors. The remaining cycles can be averaged and used in the simulation models. In this thesis, GT suite was used to read the ifile. GT suite averages the 100 cycle data.

### 3.3 Combustion Analysis

On obtaining the measurement data, the next step is to generate a burn rate profile using the measurement data.

The burn rate profile can be generated by using either TPA or CPOA as shown in *Figure 3.4*.



**Figure 3.4:** Process flow of Burn Rate profile Generation

### 3.4 Boundary Condition Generation

A Multi Cylinder Engine Model was developed in GT SUITE and was given to us by the VCC. It was a high-performance model that was developed and given solely for data integration. Parameters were preloaded for various parts such as port lengths, exhaust runner lengths, air fuel ratios etc. The model was a one dimensional scaled model, having few parametric values from 3D models of CFD.

The burn rate profile generated by TPA or CPOA can be integrated using two ways, In the main performance model an external subassembly is added which points to the TPA or CPOA model burn rate that is in a name\_prof.gtm. During run time the compiler would automatically include all profiles from the external subassembly in the main performance model. It is very important to make sure that the main model you use the same object names for the burn rate as in the subassembly (burn rate profile generated), without actually having objects in the main performance model. The parameter for the combustion object in the cylinder can be used and pointed from the Case Setup.

Another method would be automatically export the data from GT-POST > Tools > Export Data from the GT post file of TPA and CPOA. Create a exp file and reuse it every time as this can be called from the command line.

The first method was used at the integration is simple and can reduce the need of interference from python or other loop controlling tool.

The objective of this thesis was to enable boundary condition generation settings using any performance model. Therefore any performance model must be quickly modified and made suitable for the closed loop process. To enable this, a five step procedure was made to ensure usage any performance model.

1. Open any performance model and delete all the cases except one and star out the parameters that are expected to be taken from the test rig measurement.
2. Create an external sub assembly block and enter the location of the name\_prof.gtm file of TPA. Repeat the same process with another window of the same performance model but with the location of name\_prof.gtm file of CPOA.
3. In the Advance setup option, provide the location of Parameter.txt which contains the necessary stored parameters obtained from measurements.
4. Go to the cylinder object in the performance model and rename the combustion object to "burnrate". This is the reference name of the burn rate profile generated using TPA or CPOA.
5. Save the TPA and CPOA linked performance models in their respective locations. No the performance models should be ready for the automated closed loop process.

## 3.5 Graphical User Interface

This section describes how the GUI was developed using Python and how the GUI was used to run the Closed loop.

QT Designer, a plugin for Python to design GUI was used to develop the GUI. Qt Designer is the Qt tool for designing and building graphical user interfaces (GUIs) with Qt Widgets. You can compose and customize your windows or dialogs in a what-you-see-is-what-you-get (WYSIWYG) manner, and test them using different styles and resolutions.

Widgets and forms created with Qt Designer integrate seamlessly with programmed code, using Qt's signals and slots mechanism, so that you can easily assign behavior to graphical elements. All properties set in Qt Designer can be changed dynamically within the code. Furthermore, features like widget promotion and custom plugins allow you to use your own components with Qt Designer.



# 4

## Results

In this chapter the results and findings of the thesis. The main focus of the thesis was to develop the GUI and integration of all models and also achieving communication with AVL systems.

The main objective of designing a GUI was to enable the user to control what simulations to run and import/export necessary parameters without running the simulation software in the foreground.

The GUI give the user the following advantages.

1. Choose between Spark ignition or compression ignition rig which points to the location of spark ignition or compression ignition performance models.
2. Choose between TPA or CPOA based on the required level of accuracy or number of input parameters.
3. Import the parameters from AVL PUMA and INDICOM system, enables the user to make required modifications to the parameters and then export the parameters to the simulation models.
4. Validates the measurement data and displays selected errors.
5. Generates the boundary conditions and displays them on the GUI
6. Runs all GT Suite simulations in the background.

*Figure 4.1* shows the developed GUI and several options available for the user.

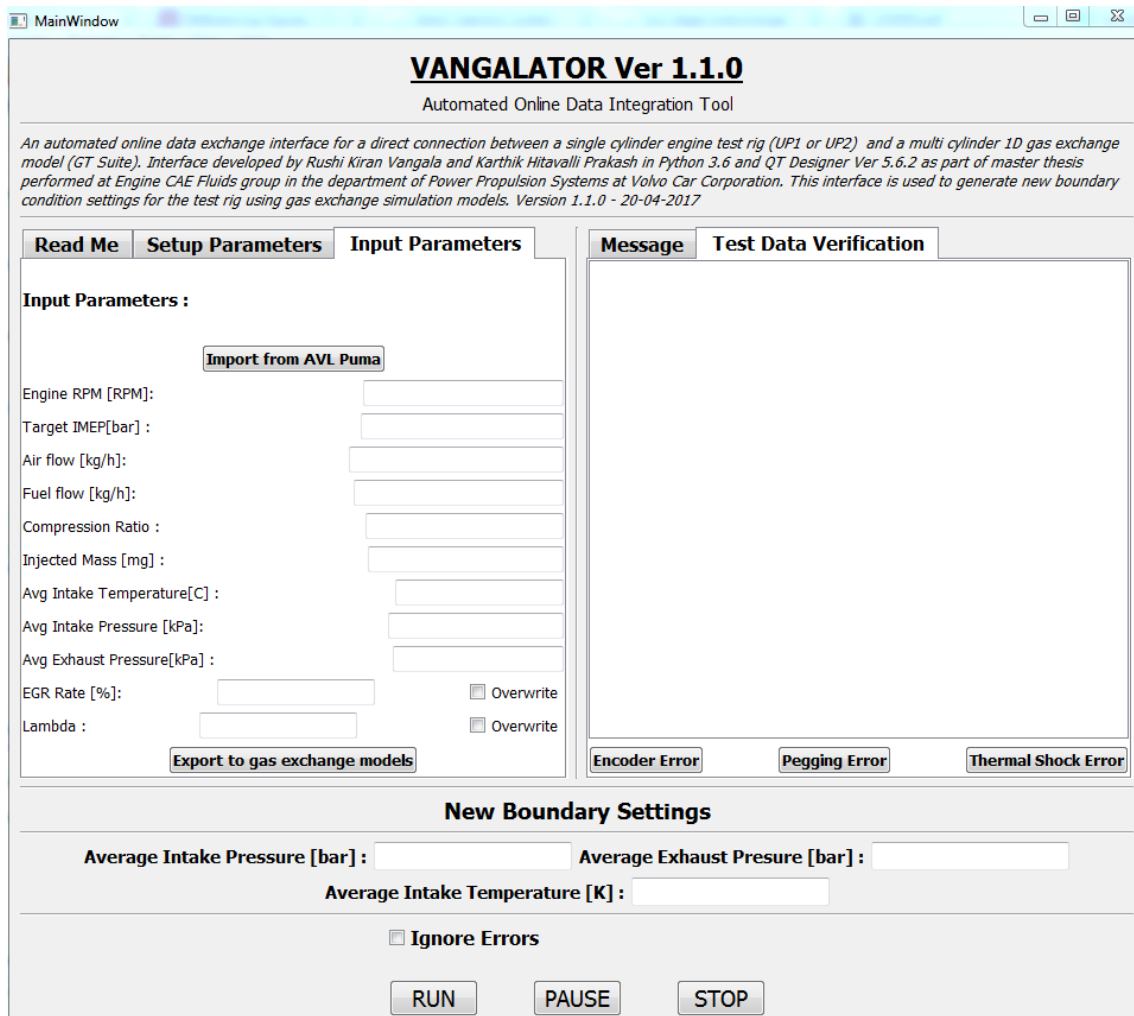
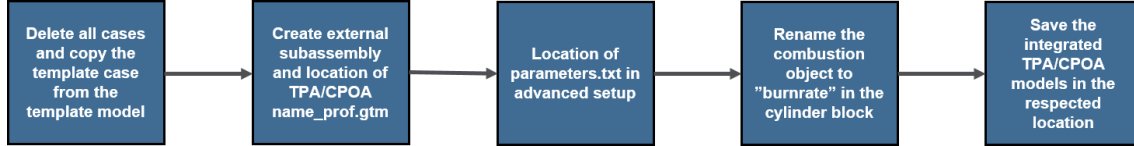
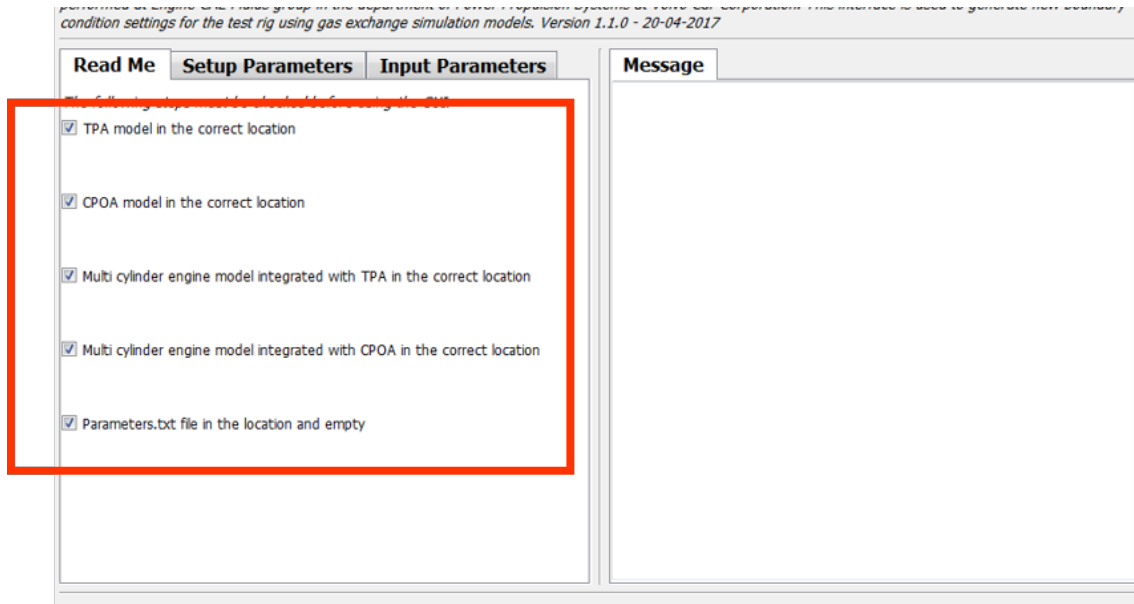


Figure 4.1: Developed Graphic User Interface for the control of the Closed Loop

The GUI was developed to make any simulation model compatible with the closed loop process. To make this compatibility easier, a five step procedure was drafted to use any engine model in the closed loop process. *Figure 4.2* shows the five step process. *Figure 4.3* shows the five step check to make sure all the models are in the right location.



**Figure 4.2:** Developed Graphic User Interface for the control of the Closed Loop



**Figure 4.3:** Safety check list to have all the models in the right location

The GUI gives a choice to the user between TPA and CPOA simulation to generate the burn rate profile. As shown in *Figure 4.4* A tab on the window "Input Parameters" this tab enables the user to import all the necessary parameters from AVL systems and export these parameters to the GT suite models.

**Figure 4.4:** Setup and Input parameters tabs

Figure 4.5 shows the necessary parameters which are the new boundary condition settings which are to be sent to the test rig. The boundary condition parameters are sent to a text file from which they are exported to AVL system.

**Figure 4.5:** Boundary conditions and application controls

The detailed process flow of the Application is shown in APPENDIX 1.



# 5

## Discussion and Conclusion

The aim of the thesis began with development of a GUI in either MATLAB or PYTHON to control and integrate the data between the single cylinder test rig and the multi cylinder GT SUITE engine model provided by VOLVO CAR CORPORATION. The process started with acquiring data from the test rig at selectively chosen operating points which represent Real Driving Emissions at different RPM's. Once the data required was achieved, they were stored in an IFILE and a PUMA file. In general, an IFILE consists of crank angle resolved data and the PUMA file consists of multiple parameters which include different temperature, air and fuel flow values etc. The crank angle resolved data had to be validated for errors due to irregular sensor calibrations and cycle to cycle variations. The data validated then were used as a source of input to TPA and CPOA models which would generate the burn rate data required for Integration.

The TPA and CPOA analysis were two prime methods which are used to obtain burn rate data required to integrate with the multi cylinder GT SUITE model. The TPA model uses intake pressure, intake temperature and exhaust pressure as inputs. For this method, no estimation of the trapping ratio and residual quantities are required as inputs. On running the simulation model, a \*\_prof.gtm file is obtained which consists of the burn rate data. The CPOA analysis uses only cylinder pressure and validates the trapped quantities as well quantities obtained from TPA. The CPOA model too generates the burn rate data used for integration with the multi cylinder engine model as a prof.gtm file. Each method has its own advantages under different circumstances. The quality of the burn rate data remains unaffected. However, depending on the suitable method for selection, TPA model is more of an actual engine model when compared to CPOA model which is only a cylinder model. Therefore, TPA analysis is more accurate to predict the combustion phenomenon when compared to the CPOA analysis.

The Analysis methods used to estimate the combustion phenomenon had its own advantages and dis-advantages. The data obtained from the Ifile had to be initially validated and quality checked before continuing with the same. The data thus obtained was not authentic enough to use directly in the gas exchange models. The data had to be checked for error range due to inaccurate sensor calibrations. Later, it had to be analyzed for pegging error, encoder error and thermal shock error to validate the pressure data obtained after the suitable burn rate analysis. A series of checks had to be done before coming to a conclusion regarding the data obtained after each step. Hence, the data obtained could not be automatically analyzed and a series of inspections were required after each step.

Once the burn rate data was obtained from the analysis techniques, they were integrated with Multi cylinder engine model to obtain the set of boundary conditions required as an input back to the test rig and match the performance characteristics of the 2nd Cylinder in the multi cylinder engine model. The traditional methods for obtaining the new boundary conditions had its own disadvantages and errors during the process. On completion of this thesis, the possibilities of errors would reduce considerably and minimize the effort of the person operating at the test rig. An individual test engineer can operate more independently than before to obtain the final boundary conditions.

The GUI developed in PYTHON was the main strength of the thesis work carried. Though the initial plan was to use MATLAB, PYTHON being a user free Open Source software application was given more preference. Finally, PYTHON was chosen for the coding purposes. Also PYTHON, a powerful tool used in recent times. The other main reason to choose PYTHON was the restrictions faced in implementing MATLAB in test rig computers. It was a complex procedure to ping the Ifile from test rig computer to the neighbouring systems because of the limited hardware options available for the test rig computers.

The piece of codes developed in PYTHON to run GT SUITE in the background would directly open the GUI. A user had to select the required quantities and then import the selective parameters from the Ifile which was written into a text file and then export these into the GT SUITE model. Once this was done and the RUN button was pushed, GT SUITE application would open in the background and perform the analysis and display the final boundary conditions in GUI required for the single cylinder engine test rig.

Another major issue faced during integration was handling data transfer on multiple server. This was important as the simulation models and the measurements were run of different servers. To tackle this issue, the programs were installed in the test rig systems and these systems could easily connect and talk to the single cylinder test rigs. On the other hand GT SUITE and PYTHON would use a single license.

The model used in the thesis was a performance model. Irrespective of the model, it finally depends on the simulation time through which the final boundary conditions are obtained. When the model was run locally on a system installation, it would take a big time of 45 mins to an hour for a complete simulation. The same on the server would require around 10 to 15 mins. The main reason being, the hardware configuration used for the test rig computers. They need an hardware update and therefore a proper planning is required for the up gradation. Without the hardware update, it would be impossible to run any model on a rig computer. Finally, after the update, we feel any model could be used for the computation.

The final part of the work was integration with the AVL PUMA systems. Once that was established, the GUI would directly import the set of parameters required to perform the TPA and CPOA checks, check whether the rig is a Petrol engine rig or a Diesel one, confirm for which range of performance (LP, MP, HP) engine the analysis is required and thus generate the boundary conditions.

To conclude, the GUI worked as expected showing the new boundary conditions, the errors were within the prescribed limits and communicational errors were reduced. The work of the rig engineer was reduced considerably compared to the traditional methods followed. The aim of the thesis was achieved in the planned and a scheduled manner. Data automatization was successfully established between single cylinder test rig and multi cylinder engine model. The GUI was successful for all level of performance models.



# 6

## Recommendations

The section mainly describes future recommendations, improvements and approaches to this work for a better outcome to the Volvo Car Corporation.

### 6.1 Faster Engine Models

The closed loop process has two simulations, burn rate analysis simulation and engine performance simulation. As these simulation models are detailed models and take some time to produce the results. This time has to be reduced as the engine rig cannot wait longer than sixty seconds to receive the new set boundary conditions. Therefor fast running models need to be used in order to get a convergence of the boundary condition settings.

### 6.2 Using MATLAB instead of PYTHON

PYTHON being an open source high level programming language was readily available. PYTHON also has a large community developed standard library. MATLAB on the other hand is not an open source software and is expensive to obtain a license. As GT Suite supports coupling Simulink models, MATLAB can be used to develop application and control the data transfer operation. On interaction with AVL support and Volvo test rig operators it was found that the code to extract data from AVL PUMA was developed in MATLAB. Measurement data quality check can also be performed as a similar operation was used by another team.

### 6.3 AVL PUMA Integration

The integration with AVL PUMA can be made more efficient. With the help of AVL, a simpler method of data transfer from AVL system to Volvo network can be performed without any intermediate system as this delays the data transfer process.

## 6.4 Data quality checks

The data quality check could not be achieved in the right way. In GT Suite, a certain cycle cannot be selected and checked for errors. The most important part of data quality check is to read the "ifile" which is a binary file type.

# Bibliography

- [1] Rissman, B.J. & March, H.K., 2013. Advanced Diesel Internal Combustion Engines. (Available at <http://energyinnovation.org/wp-content/uploads/2014/06/diesel-engines-case-study.pdf>)
- [2] Sugihara, H. et al., 2015. SAE TECHNICAL Effects of High-Boost Turbocharging on Combustion Characteristics and Improving Its Low Engine Speed Torque. (Available at <https://saemobilus-sae-org.proxy.lib.chalmers.se/content/920046>)
- [3] Volvo Cars corporation, 2008. Boosting - PowerPulse. (Available at <https://saemobilus-sae-org.proxy.lib.chalmers.se/content/16AUTP08,10>)
- [4] Hiemesch, D., 2008. BMW Diesel - Engine Concepts for Efficient Dynamics. Directions in Engine-Efficiency and Emissions Research, (August), pp.1–39. (Available at <https://www.energy.gov/sites/prod/files/2014/03/f8/deer08/hiemesch.pdf>)
- [5] Stone, R., 1989. Introduction to Internal Combustion Engines. Journal of Chemical Information and Modeling, 53, p.160. (Available at [http://160592857366.free.fr/joe/ebooks/Automotive/20engineering/20books/Introduction to Internal Combustion Engines.pdf](http://160592857366.free.fr/joe/ebooks/Automotive/20engineering/20books/Introduction%20to%20Internal%20Combustion%20Engines.pdf))
- [6] Heywood, J.B., 1988. Internal Combustion Engine Fundamentals. (Available at <https://2k9meduettaxila.files.wordpress.com/2012/09/internal-combustion-engines-fundamentals-heywood.pdf>)
- [7] Nicolas, Romain, 2013. Introduction to engine fuelling systems. (Available at <http://www.car-engineer.com/introduction-to-engine-fuelling-system>)
- [8] Buchwald, R. et al., 2006. Boost and EGR System for the Highly Premixed Diesel Combustion. (Available at <https://saemobilus-sae-org.proxy.lib.chalmers.se/content/2006-01-0204>)
- [9] D.Rakopoulos, C. & G.Giakoumis, E., 2013. Diesel Engine Transient Operation. (Available at <http://www.springer.com/gp/book/9781848823747>)
- [10] Schematic of R2S, BorgWarner two stage Turbocharger. (Available at <http://www.turbos.bwauto.com/products/r2s.aspx>)

- [11] Dr.-Ing. J. Boyde, 2015. GT-Power to enhance Single Cylinder Measurements. MTU. (Available at <https://www.gtisoft.com/wp-content/uploads/2015/11/EnhanceSingleCylinderMeasurements.pdf>)
- [12] Usman Asad, Raj Kumar, Xiaoye Han, Ming Zheng, 2011. Science Direct Precise instrumentation of a diesel single-cylinder research engine. (Available at <https://www.sciencedirect.com/science/article/pii/S0263224111001163>)
- [13] Snyder, M.W., Lahti, J.L. Moskwa, J.J., 2012. Simulating Transient Multi-Cylinder Engine Gas Exchange Dynamics on a Single-Cylinder Research Engine. (Available at [https://www.researchgate.net/publication/296673373SimulatingTransientMulti-CylinderEngineGasExchangeDynamicsonaSingle-CylinderResearchEngine2006\(724\)\)](https://www.researchgate.net/publication/296673373SimulatingTransientMulti-CylinderEngineGasExchangeDynamicsonaSingle-CylinderResearchEngine2006(724)))).
- [14] Lahti, J.L. & Moskwa, J.J., 2002. A Transient Hydrostatic Dynamometer for Testing Single-Cylinder Prototypes of Multi-Cylinder Engines. . (Available at [https://saemobilus-sae-org.proxy.lib.chalmers.se/content/2002-01-0616\(724\)\)](https://saemobilus-sae-org.proxy.lib.chalmers.se/content/2002-01-0616(724)))).
- [15] AVL, (2017). AVL Concerto combustion measurement. (Available at: <https://www.avl.com/-/avl-concerto-data-post-processing>)
- [16] GT- SUITE(2015), Engine Performance Application Manual, v 2016. (Available at [GT SUITE/Tutorials/EnginePerformance/EnginePerformanceTutorials.pdf](#))
- [17] Kumar, V.V.M., 2015. Predictive Diesel Combustion Using DI-Pulse in GT-Power. (Available at <http://publications.lib.chalmers.se/records/fulltext/225450/225450.pdf>)
- [18] Richard S. Davis and Gary J. Patterson, 2006. SAE Technical Cylinder Pressure Data Quality Checks and Procedures to Maximize Data Accuracy. (Available at <https://saemobilus-sae-org.proxy.lib.chalmers.se/content/2006-01-1346>)
- [19] Maurya, Datt Pal, Agarwal (2013). Digital signal processing of cylinder pressure data for combustion diagnostics of HCCI engine. Elsevier Journal. (Available at <https://www.sciencedirect.com/science/article/pii/S0888327011003037>)
- [20] Günter, Merker, Schwarz, Christian, Teichmann, Rüdiger (2012). Combustion Engines Development. (Available at <http://www.springer.com/gp/book/9783642029516>)
- [21] Damji, N., Dresser, D. & Bellavoine, J., 2016. Automated Model-Based Calibration for Drivability Using a Virtual Engine Test Cell. (Available at <https://saemobilus.sae.org/content/2015-01-1628>)
- [22] Martinez, I. & Hendricks, E., 2014. Open-source Software for Engine Model Development and Testing. , 2004(724). (Available at <https://saemobilus-sae-org.proxy.lib.chalmers.se/content/2004-01-0905>)



## BIBLIOGRAPHY

---

- [23] Chatterjee, S. et al., 2015. Evaluation of Open Source Tools and Development Platforms for Data Analysis in Engine Development. (Available at <https://saemobilus.sae.org/content/2015-26-0076>)

## BIBLIOGRAPHY

---

# A

## Appendix 1

### Process flow

