ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

MODEL PREDICTIVE CONTROL OF A TURBOCHARGED DIESEL ENGINE WITH EXHAUST GAS RECIRCULATION

M.Sc. THESIS

Muharrem Ugur YAVAS

Department of Control and Automation

Control and Automation Engineering Master Programme

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

AŞIRI DOLDURMALI VE EGZOZ GAZ ÇEVRİMLİ DİZEL MOTORDA MODEL ÖNGÜRÜLÜ KONTROL

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Muharrem Ugur Yavas, a **M.Sc** student of ITU **Graduate School of Science and Engineering** student ID **504111143**, successfully defended the **thesis/dissertation** entitled "MODEL PREDICTIVE CONTROL of a TURBOCHARGED DIESEL ENGINE with EXHAUST GAS RECIRCULATION", which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family and good friends,

FOREWORD

I would like declare my biggest appreciation to my parents and my sister for their lifelong support, to my advisor Metin Gokasan for his great vision and tutoring, to my best friends but specially Sertac Karapinar who is a great computer engineer. I would like also to thank TUBITAK for the bursary during my master education.

December 2014

Muharrem Ugur YAVAS
Senior Calibration and Controls Engineer

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ABBREVIATIONS

BSFC	: Brake Specific Fuel Consumption
ECU	: Electronic Control Unit
EGR	: Exhaust Gas Recirculation
MAF	: Mass Air Flow
MAP	: Manifold Absolute Pressure
MIMO	: Multi Input Multi Output
MPC	: Model Predictive Control
MVM	: Mean Value Modeling
NOx	: Nitrogen Oxids (NO, NO_2)
PCM	: Powertrain Control Module
PI	: Proportional Integral
PID	: Proportional Integral Derivative
PM	: Particulate Matter
PRBS	: Pseudorandom Binary Sequence
SISO	: Single Input Single Output
VGT	: Variable Geometry Turbocharger
ZN	: Ziegler Nichols Method

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MODEL PREDICTIVE CONTROL OF A TURBOCHARGED DIESEL ENGINE WITH EXHAUST GAS RECIRCULATION

SUMMARY

In the 21th century, despite the research in electric and hybrid cars, internal combustion engines still have the domination. However, todays's combustion engines differ a lot from their old ancestors due to stringent emission regulations which forces automotive industry to design green engines. Tighter emission regulations caused the downsizing trend which made the turbocharger is a must in the new engine familes. On the other hand, diesel engines with turbochargers has been drawn a lot attention due to its great fuel economy, strong low end torque and better compression ratio. In order to deal with famous emission phenomena, NOx – PM trade off, of the diesel engines, exhaust gas recirculation systems has been designed reduce NOx emissions. Therefore, the diesel engine to be focussed on this study, have the two fundamental technology: turbocharger and exhaust gas recirculation, which projects the almost all diesel engines currently in the automotive industry.

Turbocharger system works with a compressor in the intake and a turbine in the exhaust port which are coupled to each other via shaft. When the energy due the exhaust flow throught the turbine is transferred to the compressor via shaft and this provides the power for the compression of intake air by just using waste exhaust gases. Moreover, compression of intake air incresases the air density for the same volume so incresas the volumetric efficiency of the combustion chamber. This is the key element which initites downsizing era in the internal combustion engines. On the other hand, reason of the exhuast gas recirculation system is completely to reduce NOx emissions. Exhaust gas recirculation system returns the some part of exhaust flow before turbine, then cools it down and blows it to the intake manifold. Mixture of fresh air with the burned air results less oxygen in the air to be combusted. Thus, peak combustion temperature, which is strictly depends on oxygen concentration and the main reason of NOx production, is reduced. In summary, modern diesel engine has a complex air path structure due to turbocharger and exhaust gas recurculation. As a result, control of the flow and pressure of intake air mass which will be sucked into combustion chamber, becomes complicated. This study investigates different approaches to the control of air path as model predictive control and compares it with the control algorithm currently being used.

Developing control oriented diesel engine models is not a new topic and under investigation for the last twenty years. Mean value engine modeling is one of the most popular and accepted method to do so. However, creation of diesel engine model is a longlasting and diffuclt process due to its complex, non-linear equations and the differential equations. This study offers an easier method for the modeling which is the use of AVL Boost RT. The software works as component based

modeling logic and each possible transfer is handled differently as mechnanical, heat or flow. To reach a accurate diesel engine model, it is only necessary to parametrize each component to be modeled. Then Boost RT handles all the solution of differantial equations and the physical phenomenas. The use of modeling software gives the great advantage of work with complex systems rather easier to the control society. Another big advantage is that once the diesel engine model is ready, it can be imported to Matlab Simulink to design and simulation of the controllers. The diesel engine models desingned in Boost RT, is quite flexible and model is easy to convert or adapt to the different engines or different designs.

Diesel engine air path as a system itself should have two inputs, which are turbocharger vane position and exhaus gas recirculation valve position, and two outputs, which are manifold absolute pressure (MAP) and mass air flow (MAF). So, this is a multi input multi output system which is strongly coupled. For example, openin further of the exhaust gas recirculation will cause reduction in fresh air so mass air flow plus it will also reduce the manifold absolute pressure by diverting some of the exhaust gases which drives the turbine. However, in the automotive industry, the general control approach the diesel engine air path is using two seperate single input single output systems despite the explained coupled behaviour. In order to get good set point tracking and disturbance rejection, there are too many parameters to be calibrated for each PID controller of the air path. For example, P, I and D term have all different 2D interpolation maps which depends on the error and engine operating point in terms of engine speed and load. Additionaly, open loop feedforward structure has 2D interpolation look up tables to be filled. On top of that in order to cope with system non-linearites, there are some special functions to be calibrated as rata limitation, dynamic response, output hysteresiz. Finally, despite all the calibration efforts, overall controller response of diesel engine air path has a lot of overhsoots, undershoots and short term instabilities.

Calibration of the PID controllers for the air path system, Ziegler Nichols osscilation method is being used. Controllers without feedforward control would give a poor performance. This has been proved by the addition of feedforward term to the main controllers. In addition to that, new calibration method for the air path controllers are suggested as the use of genetic algorithm. Tuning controllers may take too much time with genetic algorithm but the output is much more succesfull than the ones tuned by Ziegler Nichols. On the other hand, feedforward approach does not give much to the controller tuned by genetic algorithm. Hence, this raise a new approach by removing feedforward terms which would reduce system complexity and reduced time.

At last, model predictive controller was designed to control diesel engine air path. Model predictive control has a natural advantage to cope with multi input multi output system due to its quadratic problem solving method. Besides, it handles with system constraints very well and once the plant model is designed, rest of the calibration action is just adjusting scaling factors to prioriteze outputs. On the other hand, plant model may be created with various methods but it needs to be linear. In this work. Matlab system identification toolbox was used. Direct two input two output state spce model of the system was used. The plant model is imported to the model predictive control block in Simulink. Then the controller is tuned in terms of prediction horizon, constraints and scaling factors. Prediction horizon is the number of samples that the plant model simulated to get future plant responses. System constraints are the maximum and mimum position of the actuators, actuators controller step rates and physical limits of mass air flow and manifold absolute pressure. In short, model predictive controller gave a better performance than the any other controllers which is a promising result.

During this work, for the engine model Boost Rt and the rest of the calculations Matlab Simulink and its system identification, model predictive control and parameter estimation toolbox were being used. The algorithms work behind this elements were shared to provide theoretical background. In the last chapter possible further steps were disscussed.

AŞIRI DOLDURMALI VE EGZOZ GAZ ÇEVRİMLİ DİZEL MOTORDA MODEL ÖNGÖRÜLÜ KONTROL

ÖZET

Günümüzde içten yanmalı motorların tekonolojisi son derece ilerlemiş ve elektronik kontrol uygulamalarının bir çok örneği içten yanmalı motorlarda uygulanır hale gelmiştir. 21. Yüzyıl ile birlikte otomotiv endüstrisi aşırı doldurma teknolojisini kullanarak motorların hacminde küçülmeye gitmiştir. Böylelikle birim hacimden üretilen motor gücü yükselmiştir. Öte yandan emisyon regülasyonları giderek sıkılaşmakta ve içten yanmalı motorlarda farklı ekipmanların emisyonları düşürmesi için kullanılması gerekmektedir. Egzoz gaz çevrimi sistemi Nox emisyonlarını azaltması için yanmış egzoz gazının bir bölümünü tekrardan emme manifoldu vasıtası ile silindirlere yöneltir. Bunun sonucu ise hava yakıt karışımında daha az oksijen bulunması ve NOx oluşmunun en büyük sebebi olan silindir için yanma sıcaklığının düşürülmesidir.Sonuçta aşırı doldurma ve egzoz gaz çevrimi bugun her dizel motorda bulunan birer teknoloji haline gelmiştir. Modern bir dizel motorda otomatik kontrol sistemleri fazlasıyla kullanılmaktadır. Mekanik motordan elektronik motora geçilmesi ile kontrol algoritmaları karmaşıklaşmış ve kalibrason süreci uzamıştır. Günümüzde otomotiv üreticilerinin en çok araştırma yaptığı konulardan bir tanesi içten yanmalı motorlarda bulunan bu kontrol sistemlerinin en isabetli şekilde kontrol edilmesi ve bunun da en kısa sürede yapılmasıdır. Bu durum şüphesiz ki dinamometrelerden sanal test merkezlerine geçilmesinde ve içten yanmalı motorların bilgisayar ortamında modellenmesine ve benzetiminin yapılmasına sebep olmuştur.

Aşırı doldurma sistemi, egzoz gazına bağlanan bir türbine ile emme hattına bağlanan bir kompressor ve bunları birbirine bağlayan bir şafttan oluşur. Egzoz gazı türbini çevirerek mekanik bir enerji yaratır ve bu enerji şaft ile kompressöre aktarılarak, kompressörün emme manifolduna sıkıştırılmış hava göndermesini sağlar. Havanın yoğunluğu ne kadar artarsa volumetrik verim o kadar artacak ve böylelikle daha küçük hacimdeki motorlardan daha çok güç elde edilebilecektir. Öte yandan, egzoz gaz sistemi egzoz akışının bir kısmını tekrardan bir soğutucudan geçirdikten sonra emme manilfolduna aktarır. İki sistemin de hem egzoz ve emme manifoldu ile olan ilişkisi, çok girişli çok çıkışlı bir sistemin oluşmasına sebep olur. Öte yandan endüstride dizel motor hava yolu problemi iki ayrı tek giriş tek çıkış sistem olarak ele alınır. Bu durum beraberinde bir çok sorunu ve ek çalışmayı getirir. Zira, egzoz gaz çevrimi doğrudan egzoz ile emme manifoldu arasındaki basınç farkı ile sürülmektedir ve bu hat doğrudan aşırı doldurma sistemine bağlıdır. Çalışmada standart kontrolör yapılarının sisteme tek giriş tek çıkış iki ayrı sistem gibi yaklaşıldığında nasıl kötü sonuçlar verdiği irdelenmiştir. Bu durumdan kurtulmak için açık çevrim ileri besleme sisteme eklenmiş ve daha isabetli sonuçlar alınmıştır.

Son yıllarda, motor modellenmesine verilen önem giderek artkmaktadır. Bunun en önemli sebebi şüphesiz giderlerin azaltılması ve zamandan elde edilen kazançtır. Bu çalışmada yüksek modelleme kapasitesine sahip AVL Boost RT programı ile aşırı doldurmalı ve egzoz gaz çevrimli dizel motor modeli elde edilmiştir. Boost RT çalışma prensibi ve denklemleri ayrıca açıklanmıştır. Programın kullanılmasının şüphesiz en büyük avantajı, modelleme fazının daha kolaylıkla geçilerek kontrol uygulamaları kısmına daha çok zaman ayırabilmesi ve diğer araştırma alanlarından insanların da içten yanmalı motorlar üzerinde benzetim yapabilmesidir.

Bu çalışmada elde edilen dizel motor modelinin hava yolu üzerinde standart PID kontrolörün performansı Ziegler Nichols ve genetik algoritma metodları ile kalibre edilerek incelenmiştir. Ardından, otomotıv sektöründeki popüler kontrol uygulaması, açık çevrim ileri besleme sisteme eklenmiş ve sonuçlar karşılaştırılmıştır. Hava yolu sisteminin iki ayrı çevrimi türbin kanat pozisyonu girişi ve emme manifoldu basıncı bir sistem, egzoz gaz çevrim valfi pozisyonu girişi ve emme manifoldu hava akışı çıkışı olacak şekilde iki ayrı tek giriş çıkış sistem halinde incelenmiştir.

AVL Boost RT yazılımı ile gerçek zamanlı çalışan ve dolayısı ile çevrim dışı test sistemlerinde kullanılması mümkün karmaşık modeller elde edilebilir. Boost RT ile yapılan model rahatlıkla Simulink ortamına veya test merkezine aktarılarak benzetim imkanı sağlanır. Boost RT ile modelleme yapılırken dikkat edilmesi gereken önemli hususlar motorun silindir çapı, hacmi, kran mili uzunluğu ve daha niceleri gibi önemli parametrelerin bilinmesi gerekliliğidir. Çünkü, blok tabanlı bir modelleme programı olan yazılım, benzetimi yapılacak her element için gereken karakteristik bilgiyi soracaktır. Aşırı doldurma sistemi modellenirken örneğin, eğer tedarikçiden elde edilen kompresör ve türbin haritaları mevcutsa bu haritalar ilgili blokların içerisine yerleştirilmelidir. Aksi takdirde aşırdı doldurma sisteminde daha basit bir modelleme yaklaşımı olarak sabit verim kullanılabilir. Egzoz gazı çevrim modellemesi ise biraz daha karmaşıktır. Doğru akışın yakalanması için kompressör çıkış basıncı ve egzoz basıncının isabetli şekilde modellenmesi gerekir. Çalışmada emisyonlar açısından bir bakış doğrudan bulunmadığı için egzoz manifoldundan sonra türbine yer verilmiş sistemin geri kalanı modellenmemiştir. Fakat bu noktada isabetli egzoz basıncı modellenmesi için egzoz hattında bulunan emisyon düşürücü sistemleri temsil edecek bir ters basınç yaratılmıştır.

Çalışmanın önerdiği diğer bir kontrol uygulaması ise, standart PID kontrolör yerine, sistem üzerinde çok giriş çok çıkış yapısının uygulanabileceği model öngörülü kontroldür. Model öngörülü kontrol, sistemin modelini kullanarak gelecekteki çıkışlarını öngörererk belirlenen optimizasyon problemini çözer. Bu çalışmada kullanılan sistem modeli giriş – çıkış verilerine dayanarak 4. dereceden bir durum uzay denklemidir. Model öngörülü kontrolör de doğrusaldır ve kısıtlar eyleyici pozisyonlarına göre belirlenmiştir.

Model öngörülü kontrol yapısı gereği çok giriş çok çıkış sistemlerle başa çıkabilir. Yapılan işlemler temel olarak belirli bir ufuk boyunca ki ufuk sistemin geleceği anlamına gelir, sistemin gelecekteki davranışları hesaplanarak bir sonraki kontrolör çıkışı için quadratik bir optimizasyon problemi çözülür. Bu noktada sistemin çok giriş ve çok çıkışlı olması sadece işlem karmaşasını artırıken sistemin kısıtları da hesaplamalara eklendiğinde, kontrolörün bir sonraki yanıtı ortaya çıkan kısıtlı optimizasyon probleminin çözümüdür. Model öngörülü kontrol günümüzde, proses endüstirisinde sıklıkla kullanılmaktadır. Buradaki sistemlerin çok giriş ve çok çıkışlı lineer olmayan sistemler olduğu düşünülürse, PID kontrolör bu gibi sistemler karşısında yeterli performansı gösterememektedir. Öte yandan proses endüstirsindeki sistemlerin dinamiği oldukça yavaştır ve model öngörülü kontrolör için gerekli hesaplamaların yapılması için gereken zaman vardır. Son on sene içerisinde, motorlu taşıtlardaki motor kontrol modüllerinin tamamen elektronik hale gelmesi ve hesap kapasitelerinin yükselmesi ile model öngrörülü kontrolün otomotiv sektöründe de uygulamaları başlamıştır.

Çalışmada kullanılan diğer önemli bir metod, şüphesiz ki genetik algoritma ile yapılan PID kalibrasyon işlemidir. Genetik algoritma ile PID kontrolörün kalibrasyonun yapılması yeni bir şey olmamakla beraber, otomotiv alanında hava yolu hattı için daha önce kullanılmamıştır. Bu noktaya gelinmesini sağlayan en önemli gelişme bilgisayar ortamında yapılan gerçekci içten yanmalı motor modelleri ile yapılan benzetimlerdir. Bir kez becerikli bir model ve benzetim ortamı kurulduğunda, gerçek hayatta saatler sürecek ve ekonomik açıdan handikap yaratacak testler otomatik olarak bilgisayar ortamında sürdürülebilir. Böylece günümüzde otomotiv sektöründeki en büyük mücadelelerden biri haline gelen en kısa zaman içerisinde en uygun fiyata en başarılı ürün fikri gerçeklenebilir.

Bu araştırmanın sonucunda model öngörülü kontrolörün standart PID kontrolörlere göre daha başarılı bir kontrolör performansı sergilediği görülmüştür. PID yapısının kalibrasyonu için ise Ziegler Nichols yerine genetik algoritmanın kullanılması yine kontrolör performansını arttıracaktır. Model öngörülü kontrolör tasarlanırken henüz genel geçer bir metoda ulaşılamamıştır. Bu bir nevi dezavantaj olmakla beraber kontolör tasarımını doğrudan etkliyen kısıtlar ve kısıt kazançlarının sistem yanıtını nasıl değiştireceğine dair çalışmalar yapılmıştır. Neticede, iki farklı model öngörülü kontrolör yapısı önerilmiştir ki bunlardan bir tanesi agresif ve hızlı bir cevba sahipken diğeri daha yumuşak ve aşımsız bir performans sergiler. Bu kontrolörlerden hangisinin kullanılacağı sistemden sisteme farklılılk gösterecektir. Öte yandan, otomotiv sektöründe sıklıkla kullanılan açık çevrim ileri besleme kontrol yapısının standard kontrolör yapılarına olan katkısı doğrulanmıştır. Model öngörülü kontrolörün normal kontrölör yapılarına karşı olan en büyük avantajı sistemin kalibrasyonunun basitliği ve çok daha az değişkene sahip olmasıdır. Kısaca model öngörülü kontrol yapısı kullanıldığında eforların büyük çoğunluğu model tanılamada harcanıcak ve arkasından kontrolör tasarımı kolaylıkla gerçekleştirilecektir.

1. INTRODUCTION

Due to global warming and environmental pollution effects, exhaust gas composition of internal combustion engines have gained a lot of attention since its massive use in a daily life from passenger cars to heavy-duty trucks and non-road industrial applications. In order to meet with lower emission demands regulated by the official authorities, many new technologies have been introduced. Apart from emission constraints, each automotive company has to deliver sufficient torque and power to the customer by having least fuel economy. In addition to fuel economy and emission considerations, many improvements have been seen with the drivability, comfort and safety on the vehicles thanks to high technology sensors and actuators together with electronic control of entire engine and vehicle functions via ECU (Electronic Control Unit).

Turbochargers and EGRs (Exhaust Gas Recirculation) have become coupled solution for clean downsized diesel engine development, which meets with stringent emission limits and fuel economy targets. Since then, EGR and turbocharger system have been analyzed and examined by the automotive and control society due to its non-linear, multivariable nature.

1.1 Motivation

Diesel engines and gasoline engines have different exhaust emission mixtures due to their different combustion characteristics and air/fuel mixture. In the last few decades, diesel engines have become quite popular within few critical technological developments: Multiple injections, turbochargers and EGR. Pilot injection reduced the combustion noise, turbocharger increased volumetric efficiency, which helps downsizing, and exhaust gas recirculation reduced NOx emission that was a challenge to meet with regulations because of NOx – Pm (Particulate matter) trade off.

Figure 1.1 shows the NOx – Pm trade off with historical change in the regulations and finally the aid of turbocharger and electronic control. The more emission regulations get tighter, the better control of EGR is crucial. Since EGR is strongly coupled with turbocharger, it also requires good controller response. Exhaust gas recirculation helps to reduce NOx emissions but it increases fuel consumption and particulate matter. On the other hand, turbochargers are mostly variable geometry turbochargers (VGT) which controls intake manifold pressure by changing vane or blade angles in the turbine. Intake manifold pressure control is critical in terms of fuel economy and engine performance since it is directly linked with torque generation. Hence, there exists a multi input and multi output system in the diesel engine air path having multiple objectives to be optimized.

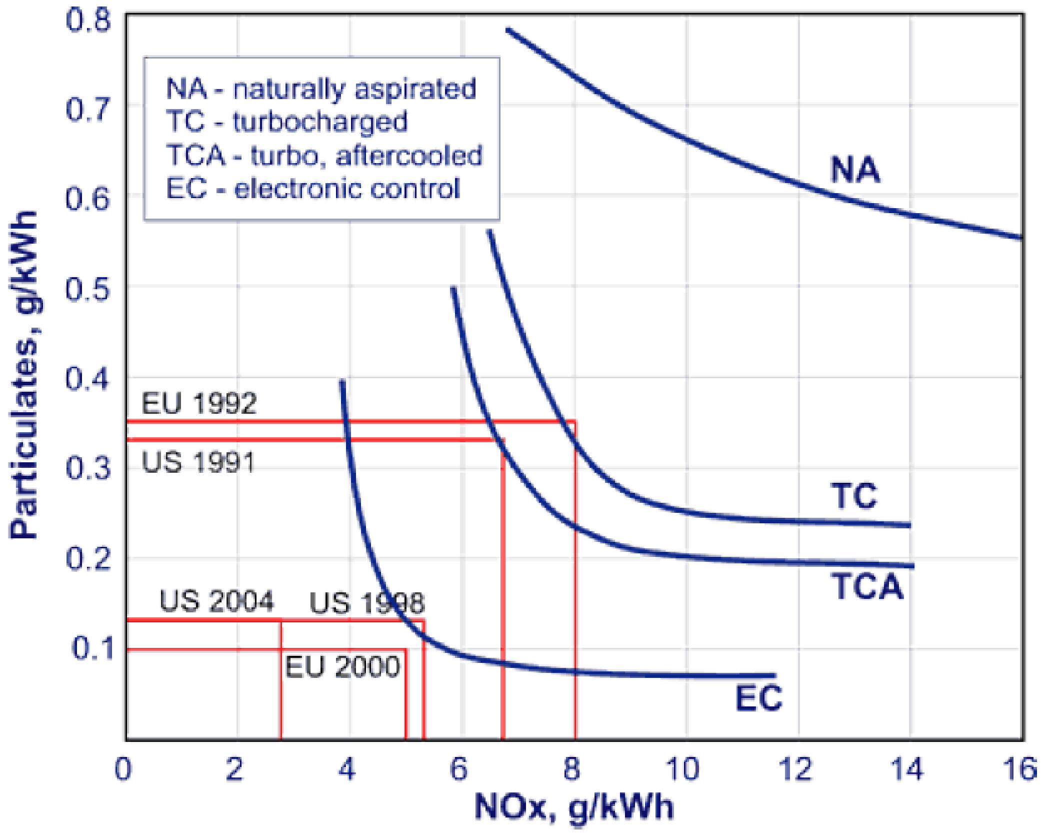

Figure 1.1 : NOx – Pm Trade Off [1].

There are many critical control loops in the modern diesel engines such as idle speed control, cruise control, rail pressure control apart from EGR and VGT control. All of these control schemes are handled inside ECU by using mostly PI controllers. Simple PI controller can give sufficient response under limited operating window and conditions. Hence, different operating windows are defined according to torque and engine speed for different controller gains and additionally correction factors are introduced for different ambient temperature, altitude etc. This leads to longer period of calibration of the engine functions and more complexity in the ECU architecture. Figure 1.2 shows the increasing trend of number of variables in the ECU software to be calibrated.

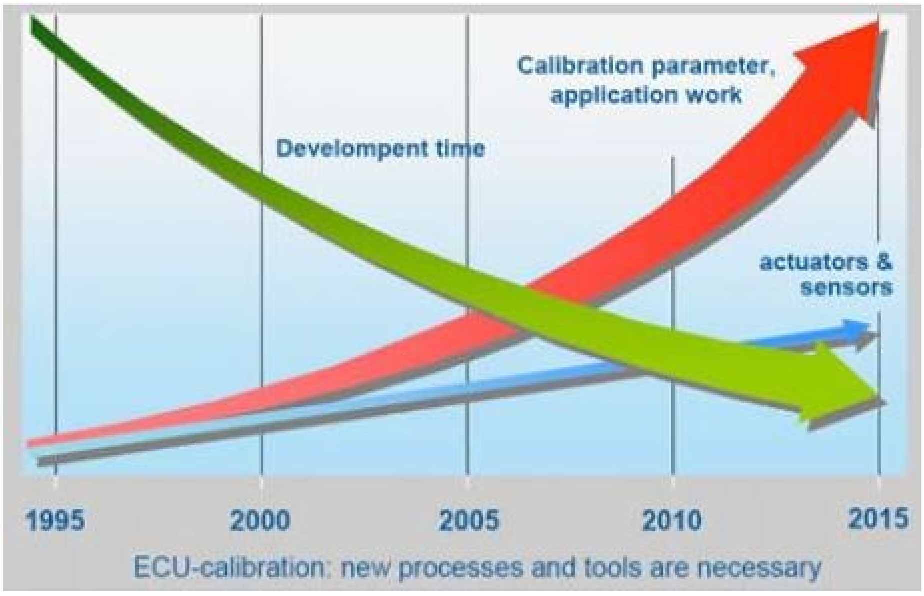

Figure 1.2 : Calibration parameter increase in recent years[2].

1.2 Objective

There are few major objectives of this work. First one is to develop model of turbocharged diesel engine with EGR by using AVL Boost RT. Using a standalone modeling software like Boost RT is quite important considering complex modeling process as in the various studies [3-5], requires too much effort and it is quite difficult for the researchers with only controls background due to complex thermodynamic equations and fluid mechanics. Nevertheless, AVL Boost RT makes modeling process faster, easier and more robust.

Secondly, non-linear air path control problem is analyzed with different control structures, starting from standard proportional integral derivative (PID) controller to PID controller with open loop feedforward control which is the current approach in the industry. Then, multi input multi output model predictive control (MPC) is applied to system. MPC has a great potential in the use of air path control and it has been already subject to many researches.[6-8]

Finally, as a combination of first and two paragraphs, main scope of this work is to fast simulation and modeling environment for different diesel engine concepts with different control architectures by the take advantage of offline calculations which would reduce the efforts in the engine calibration phase and provide better control.

2. FUNDAMENTALS OF TURBOCHARGED DIESEL ENGINES WITH EGR

The use of diesel engines have increased in recent years due to the fact that they have better fuel economy, better low end torque and greener exhaust gases. In figure 2.1, main components and system layout of a turbocharged diesel engine with EGR are shown. Apart from connection of components, general signals read by the sensonrs on the engine and commanding signals by ECU such as EGR position, can be seen.

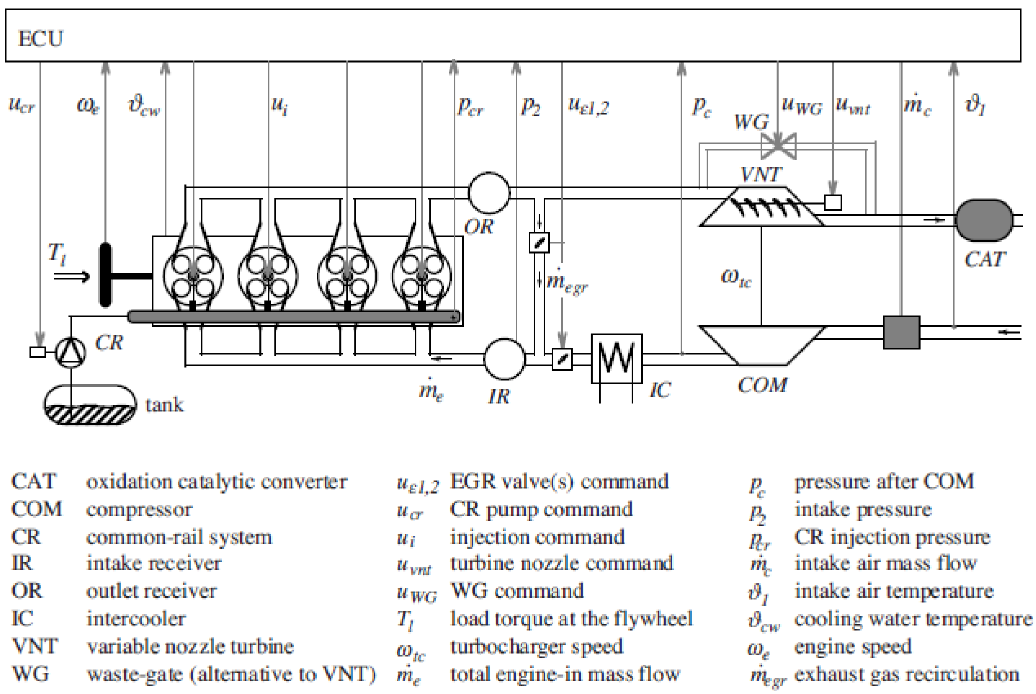

Figure 2.1 : System layout of modern diesel engine[9].

Starting from the right side of the figure, there is the fresh air entrance throught the air filter. Compressor of turbocharger compresses filtered air. Because of compression, temperature of the air rises. Because of that heat exchanger cools the air. Cooled fresh air mixed with cooled exhaust gas, which is recirculated by EGR valve. Air mixture is then suckey by the cylinders to further mix with fuel to start combustion. On the other hand, fuel is pumped from tank and it reaches to fuel filter first. Afterwards, it is pumped by common rail high-pressure pump and arrives to rail. Rail distributes pressurized fuel to injectors.

Three important control loops exist considering control engineering principles in the modern diesel engine: fuel, air and EGR [9]. Fuel path refers to fuel injection in cylinder within specifications to meet with torque demand and emission constraints. One can think fuel path as optimization problem, which have inputs as start of injection, number of injections, rail pressure setpoint and amount of injection. By manipulating these inputs, engine should generate suffiecnt torque demanded by the driver but it should remain in the green emission boundary. Air path should refer to travel of fresh air to the cylinders by the effect of turbocharger. EGR path is simply the gas recirculation from the exhaust manifold to intake manifold. In this study, EGR path and air path were combined together as air path. Nevertheless, air path have the inputs as vane position of turbine and EGR valve position. By the actuation of those, desired amount of air with the desired pressure should be sucked by cylinders. Next, detailed description of air path actuators, control problem of air path and literature survey will be given.

2.1 The Variable Geometry Turbocharger (VGT)

In diesel engines, unlike gasoline engines, there is no air-fuel ratio control. Hence, in order to produce more torque more air suction is necessary. Thanks to turbocharger systems, amount of air in the combustion chamber, might be increased without needing bigger cylinders. Turbocharger has one compressor and turbine that are connected to each other with a shaft. The waste exhaust gasses are used to rotate the turbine wheel which is housed in the turbine casing. The turbine wheel is connected to a common shaft which in turn rotates a compressor wheel. As the turbine wheel increases in speed, so does the compressor wheel. This creates a sucking process and pulls air into the compressor cover from the atmosphere. Figure 2.2 shows the described working principle.

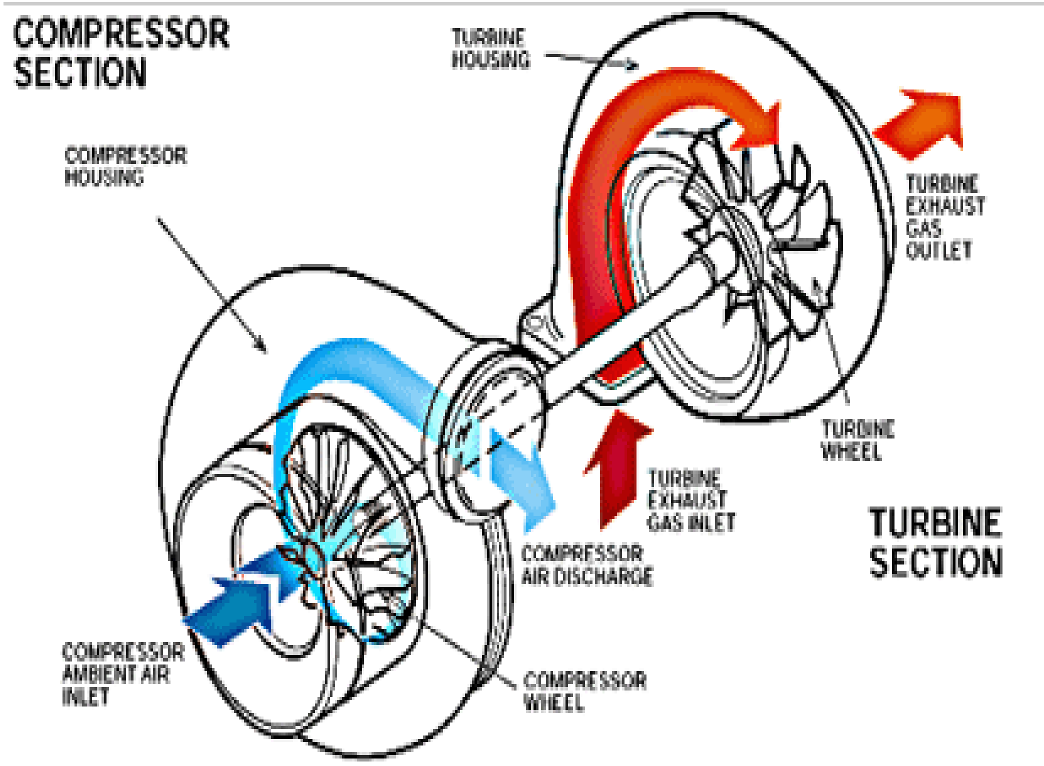

Figure 2.2 : Turbocharger layout[10].

Turbochargers operate in different efficieny levels according to changing turbine speed. Flow, compression ratio, turbine speed and compression efficiency are the key factors that would determine the condition of air. However, the relation in between is quite complex. In the industry, turbocharger suppliers share the performance maps for the turbine and compressor. According to these maps, working range of turbocharger is limited considering maximum speed, efficency and possbile compressor stall or turbine choke. Figure 2.3 shows an example of performance map. There are isolines for turbine speed and contour for the efficiency. X axis is mass flow through the compressor and Y axis is the pressure ratio between input and output of compressor.

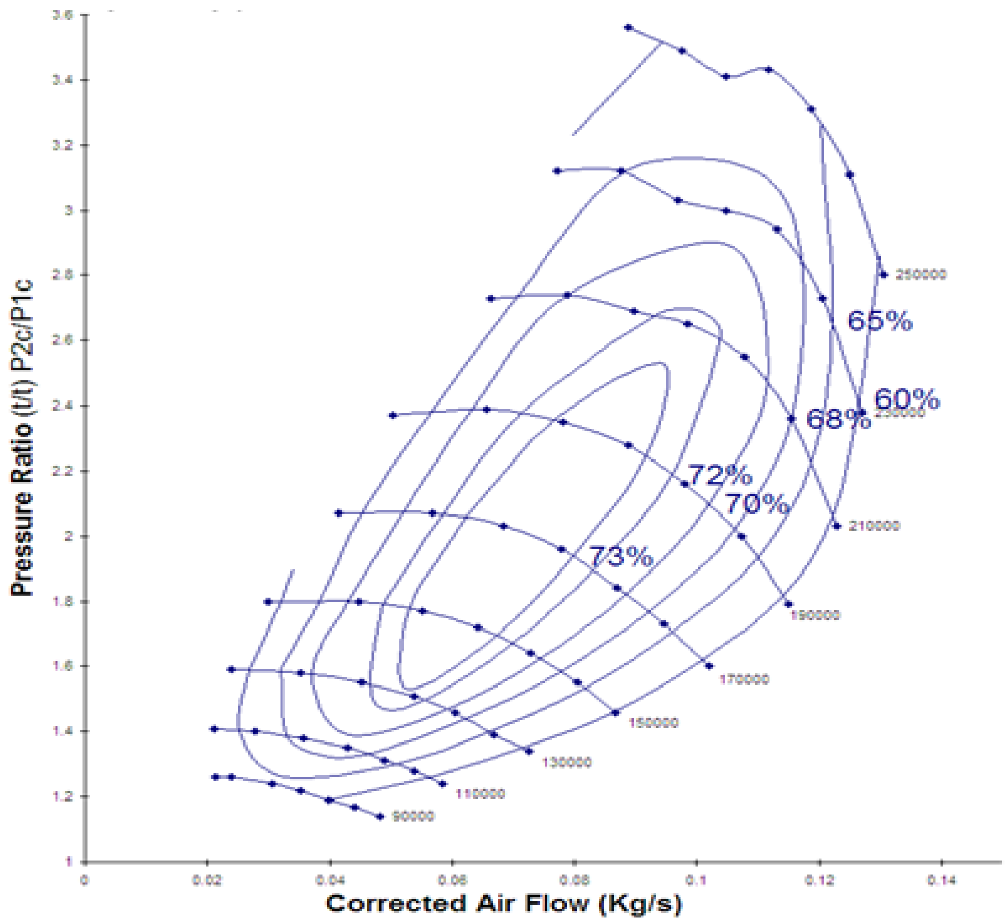

Figure 2.3 : Typical compressor map.

Variable geometry of the turbocharger gives an advantage of using exhaust energy in more efficient manner. Change in the vane position determines directly the exhaust flow and pressure through the engine. Close of vanes will create high exhaust pressure which helps effective EGR flow. On the other hand, opening of the vanes will create better boost in low exhaust energy. VGT system is usually taken as single input single output system, vane position is the controller output and manifold absolute pressure is system output. Effect of vane position is not linear and changes according to exhaust pressure and position itself.[11]

2.2 Exhaust Gas Recirculation (EGR) System

Main reason of the exhaust gas circulation is to reduce NOx emission, which is a historical challenge due to high air to fuel ratio. Formulation of NOx emission highly depends on high combustion temperatures. Recirculating exhaust gas, which has poor portion of oxygen due to combustion, would reduce the peak temperature during the combustion. Reduction in the peak cylinder temperature would cause less NOx output due to chemical reaction. Figure 2.4 shows the high-pressure exhaust gas recirculation system in which exhaust gas is recirculated righ after turbine.

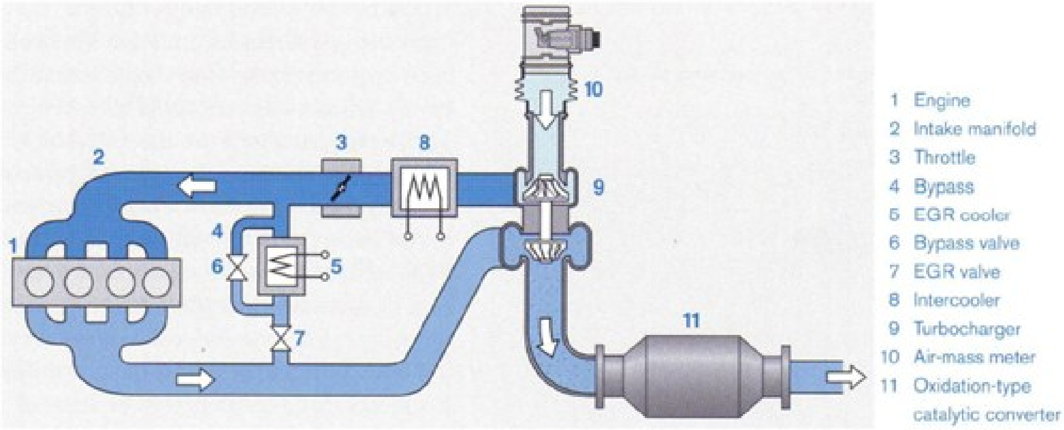

Figure 2.4 : High Pressure EGR [12].

Heat exchanger is necessary to cool down hot exhaust gas so that more EGR flows to the intake manifold. EGR valve has a limited operation considering that it make fuel consumption worse despite emission benefit. Figure 2.5 shows the effect of EGR ratio to the emissions and fuel consumption. EGR valve is not linear as VGT. Especially, opening and closing of the valve may cause whirls in the flow that changes the flow characteristic. EGR system is usually considered as single input single output system, where controller output is the EGR ratio and system output is intake air mass flow.

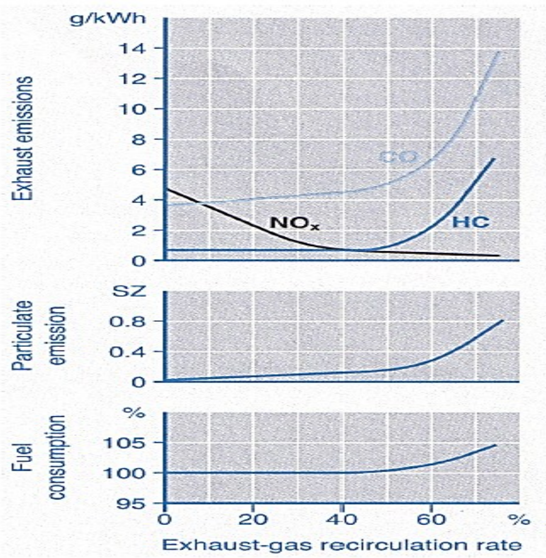

Figure 2.5 : Effect of EGR ratio to the emissions.[12].

2.3 Control Problem of Air Path with EGR and Turbocharger

As stated in the earlier sections, EGR and VGT both operate by exhaust flow of the engine. Hence, this leads to multivariable system approach. However, in the industry, cross coupling of EGR and VGT are ignored and systems are being approached as two separate single input single output systems. Figure 2.6 shows the generic air path so that mass airflow (MAF) and manifold absolute pressure (MAP) control strategy, which are currently being used in the automotive industry.

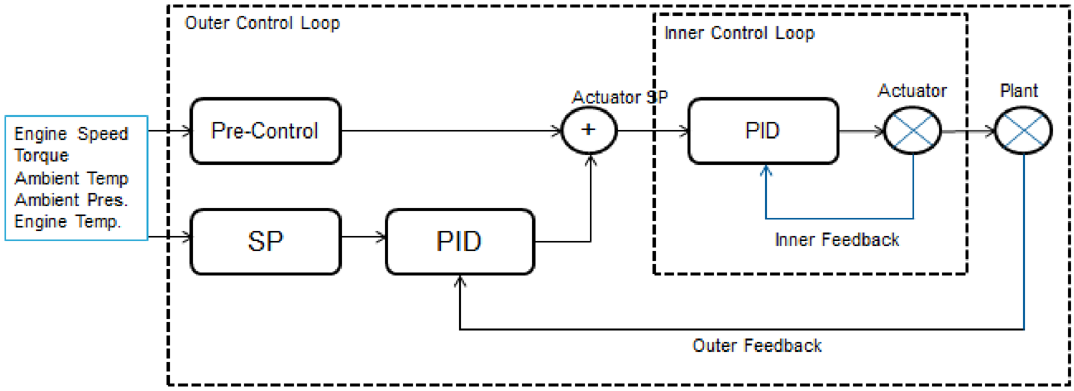

Figure 2.6 : Generic control approach.

In order to compensate the neglected cross coupling of the system, there needs to be big amount of steady state static mapping work, which is not cost, and time efficient during the development phase. Instead of the current approach, model predictive control (MPC) structure might be applied to system with the advantage of handling multivariable system. In this study, linear MPC will be designed for the diesel engine air path and compared with the single input single output approach used in industry.

2.4 Literature Review

With the age of electronic Engine Control Unit (ECU), internal combustion engines have started to get attention from the controls society to chase best controller performance while dealing with constraints. Thus, many researchers developed mathematical modeling of internal combustion engines. Comprehensive work by Guzella [9] explains the mean value modeling approach for both diesel and spark ignition engines. By using the physical equations of the gas exchange, two different air path models derived, first one is seventh order and second one is third order systems [13,14]. These models were accepted and used widely in the academic society. However, due to differential equations and computational complexity, some researchers used modeling softwares like GT Power and Dymola to reduce the efforts on modeling [15,16]. In this study, AVL Boost RT modeling environment is chosen to derive diesel engine model.

There are different control algorithms applied to air path problem such as robust control [5], fuzzy control [17] and model predictive control [8]. Use of model predictive control in air path control is a newer trend because of the recent advancements in ECUs made model predictive control possible in automotive applications. Use of different approaches as Model Predictive Control (MPC), in terms of linearity, different modeling, might be found in [7,18,19].

3. Diesel Engine Modeling with AVL Boost RT

Mean value modeling (MVM) approach is one of the most popular ways to create engine models, which are suitable for accurate simulations. There are several different physical phenomena happen in internal combustion engine in order to burn the fuel with required amount of air to torque build up while optimizing emissions. However, combustion dynamics are quite fast to catch its dynamics and in mean value modeling, they are taken as static effects. Furthermore, so called control oriented models are focused more into air exchange system that is strongly coupled and nonlinear in the recent engines. MVM approach has already widely used in many researches and one can find detailed information in [9].

Since MVM modeling is the easiest way to get accurate engine models, there are several commercial tools in the industry such as Ricardo Wave, GT Power and AVL Boost Rt that would ease modeling efforts by standardized components, which have the physical equations, are already imported. This gives a great advantage to the researchers who would like to focus more on controls side rather than modeling. In next pages, modeling steps of Boost Rt will be shown; the model created for air path control applications will be analyzed and compared with test bench data.

3.1 Overview of Boost RT Model

AVL Boost RT is real time simulation capable, modeling environment which is flexible and easy to adapt to different engines. Each components of the diesel engine shall be parameterized in order to have precise simulations. In automotive terminology, the transfer of air and fuel into cylinders are described as air path and fuel path, similar approach might be used in Boost RT to determine engine layout to be modeled. Besides, there are three different connections are available between components such as air and fuel flow, heat transfer and mechanical coupling. Accordingly, following layout has been designed which shows mainly the key factors to produce torque and power. Figure 3.1 shows the diesel engine layout in Boost RT.

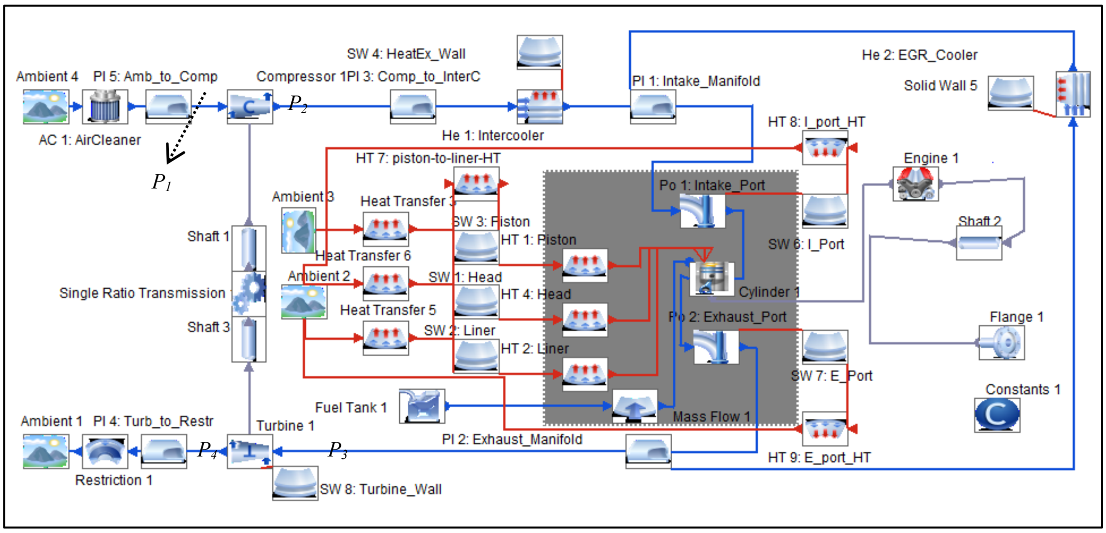

Figure 3.1 : Diesel engine layout in Boost RT.

Starting from the top left, fresh air in the ambient condition is sucked into engine, is filtered by the air cleaner. Then the compressor of turbocharger compresses it. The intercooler cools down hot compressed air and it reaches to the cylinder after passing by intake port. Cylinder is where combustion happens. Hence, the air contains combustion residuals, is being swept through exhaust port then it rotates turbine of turbocharger which creates the power to drive compressor. Finally, the air is sent back to the atmosphere. In addition to previously described travel of air, some portion of the air in the exhaust manifold is returned back to intake manifold after cooled down with another intercooler.

Apart from travel of air to cylinders, also fuel shall be delivered to start combustion. Fuel path model is less complex than air considering the focus of the work. Fuel is pumped from fuel tank to cylinder via mass flow element which allows defining fuel rates to the cylinder so the combustion chamber. Furthermore, there are mechanical linkages due to turbocharger; the compressor and the turbine are connected to each other by a shaft. The torque produced by engine is transferred to the shaft which is supposed to rotate the wheels in a vehicle application, but in this case it transferred to flange element which might be thought as brakes.

Finally, heat transfer and heat losses are added to layout to represent heat release after combustion and intercooler mechanisms. Once the engine layout is designed, next step is to supply necessary information to the each component, which aligns with the target engine to be simulated. The most critical elements for the control-oriented simulation are turbocharger as compressor and turbine, EGR system and cylinder. Thus, modeling focus will be on those instead of the other elements. All the equations about the compressor and turbine can be found in [20].

3.1.1 Model of turbocharger - compressor

In order to model turbocharger, compressor and turbine should be modeled by the separate blocks then they should be connected via shaft unit. In terms of compressor model, Boost RT gives two different model structures: Simplified model and full model. Simplified model requires less data to parameterize compressor but suggested to use only in steady state applications. On the other hand, compressor maps that should be supplied by supplier, is necessary to parameterize full model. Compressor maps give the characteristic of flow and compression ratio as explained in the previous chapter. Boost RT uses the well-known isentropic efficiency equations:

$$P = \dot{m} \cdot (h_{02} - h_{01}) \quad \textbf{3.1}$$

$$h_{02} - h_{01} = \frac{1}{\pi_{s,C}} \cdot c_p \cdot T_1 \cdot \left[\left(\frac{p_{02}}{p_{01}} \right)^{\frac{k-1}{k}} - 1 \right] \quad \textbf{3.2}$$

$$\Pi = \frac{p_{02}}{p_{01}} \quad \textbf{3.3}$$

$$n_{cor} = \frac{n}{\sqrt{T_{01}}} \quad \textbf{3.4}$$

$$\dot{m}_{cor} = \frac{\dot{m} \cdot \sqrt{T_{01}}}{p_{01}} \quad \textbf{3.5}$$

Power consumption of the compressor might be calculated by the mas flow through compressor and enthalpy difference. Enthalpy difference is the function of upstream and downstream pressure of compressor and compressor inlet temperature. Equations 3.3 -3.5 calculate pressure ratio of compressor, corrected speed and corrected flow.

3.1.2 Model of turbocharger - turbine

In order to work with turbocharger model, as it was with compressor model, performance map of the turbine is necessary. Accordingly, by using the relation of isentropic efficiency and enthalpy difference, same set of equations are being used.

$$P = \dot{m} \cdot (h_{03} - h_{04}) \qquad \textbf{3.6}$$

$$h_{03} - h_{04} = \eta_{s,T} \cdot c_p \cdot T_{03} \cdot \left[1 - \left(\frac{p_{04}}{p_{03}} \right)^{\frac{k-1}{k}} \right] \qquad \textbf{3.7}$$

$$\Pi = \frac{p_{03}}{p_{04}} \qquad \textbf{3.8}$$

$$n_{cor} = \frac{n}{\sqrt{T_{03}}} \qquad \textbf{3.9}$$

$$\dot{m}_{cor} = \frac{\dot{m} \cdot \sqrt{T_{03}}}{p_{03}} \qquad \textbf{3.10}$$

Turbocharger control method is determined in the Turbine block as well. There are different methods to regulate the power of turbine according to exhaust flow such as waste gate and variable geometry turbine. In this study, VGT type turbocharger is selected.

3.1.3 Combustion modeling with Boost RT

In order to model combustion, cylinder and engine elements are used. The cylinder element calculates thermodynamic processes in the cylinders considering conservation of mass, energy, and species masses. The cylinder is calculated on a crank angle basis, where integration time step is given in the Engine element and is equal for all cylinders attached to the particular Engine element. The Cylinder element comprises two combustion models: Vibe and Table Input. Main inputs of cylinder element are given below in figure 3.2.:

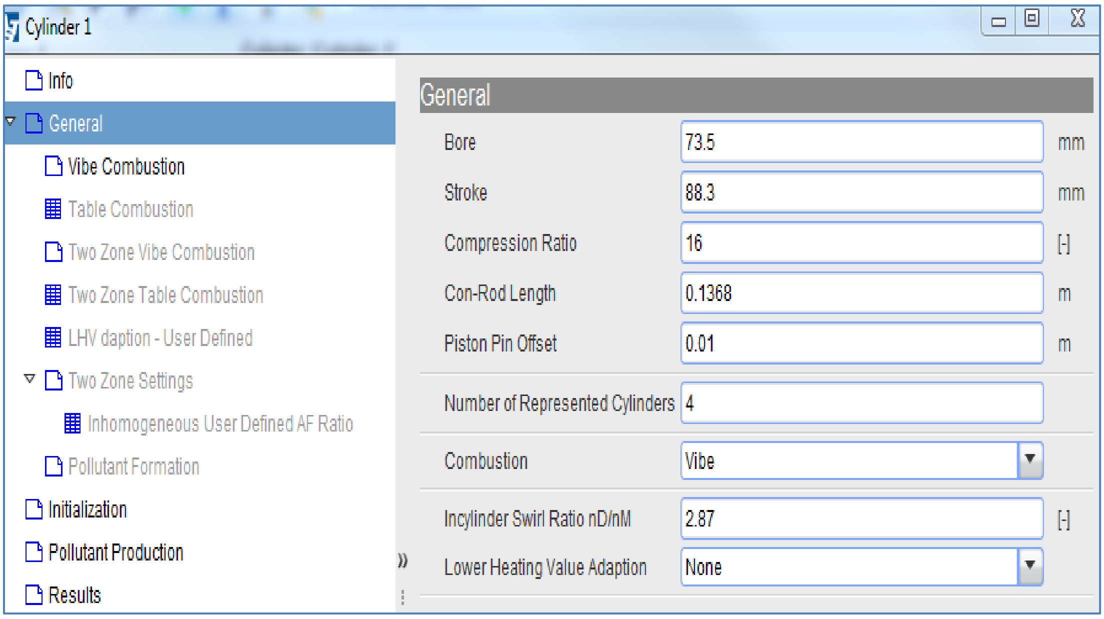

Figure 3.2 : Boos RT Cylinder Block.

In addition to figure 3.2., there is also the section for vibe combustion characteristics which is the case in this work. Figure below shows those parameters necessary to model combustion via vibe function which is shown in figure 3.3.

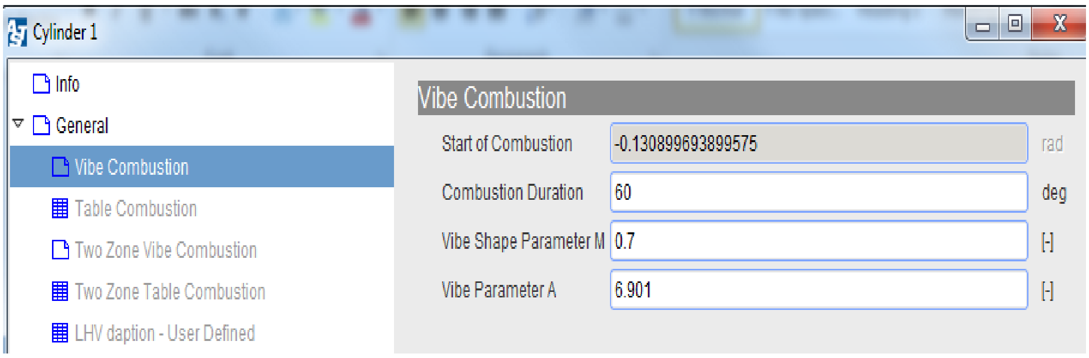

Figure 3.3 : Vibe combustion parameters in Boost RT.

Another important element to model combustion and torque build up is engine block which is presented in figure 3.4. With this section, one can choose between mean value engine modeling or filling emptying model. In this study, mean value modelling method has been selected.

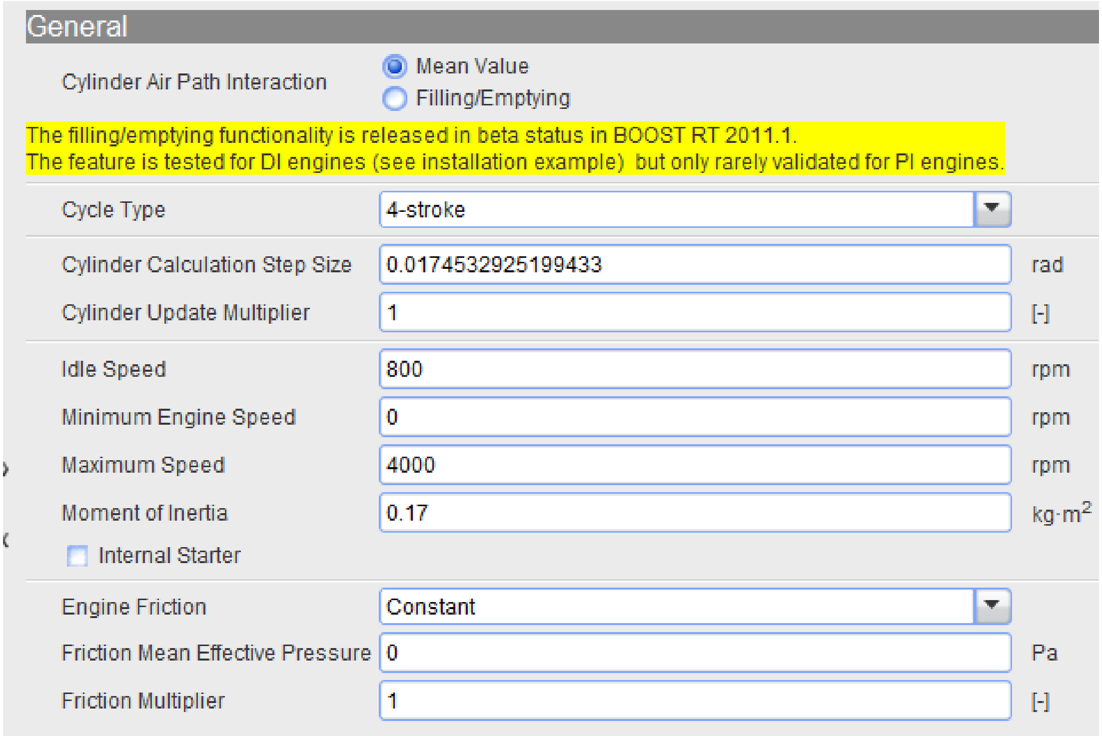

Figure 3.4 : Engine block in Boost RT.

3.1.4 Exhuast gas recirculation (EGR) model

Since flow equation of EGR is quite complex and strongly coupled with exhaust system, modeling the EGR system is not a straightforward task. There might be two different approaches to model EGR system via Boost Rt: 1. Using restriction element and intercooling 2.Using only intercooler. First option makes the calculation more complex and cause slower simulation response. Hence, as it is suggested in the user guide, EGR can be modeled by just using heat exchange unit itself. In order to achieve this, flow coefficient of intercooler shall be used to simulate actuation of EGR valve. Furthermore, it should cooled the air circulated from exhaust to intake.

Considering EGR is not being used during entire engine operating range, it might be good to begin simulations where there is no egr. Once, the air and fuel system without egr gives good response compared to test bench data, egr points might be focused to get better results.

3.2 Evaluation of the Boost RT Model of Diesel Engine

Boost RT makes possible to simulate different engine tests for the evaluation of the engine model. Hence, previously designed diesel engine model was simulated in the Boost RT platform to validate its accuracy and calculation efficiency. Figure 3.5 and figure 3.6 show the combustion characthrestic of the model at 1000 rpm in terms of pressure and temperature profile according to crank angle. Four-cylinder engine model represents the right temperature and pressure rise profile.

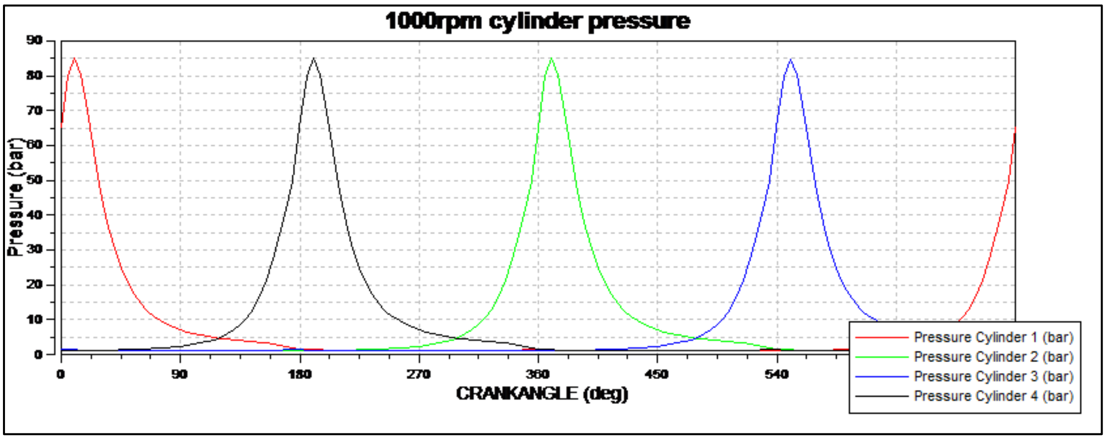

Figure 3.5 : Peak firing pressure versus crank angle.

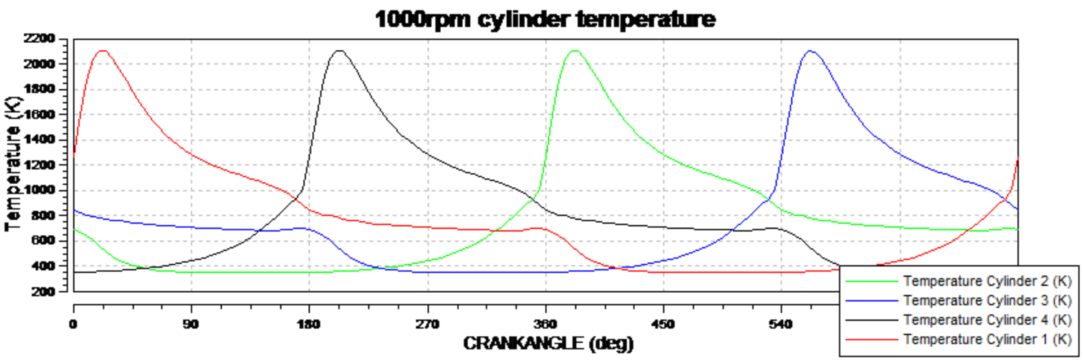

Figure 3.6 : Temperature profile during the combustion.

Figure 3.7, 3.8 and 3.9 show engine performance during the full load cycle test. When Boost RT model output compared with the test bench results, torque and maximum cylinder pressure modeling accuracy is very high. Brake specific fuel consumption, another important engine performance metric, also have good modeling accuracy especially catching the dynamics.

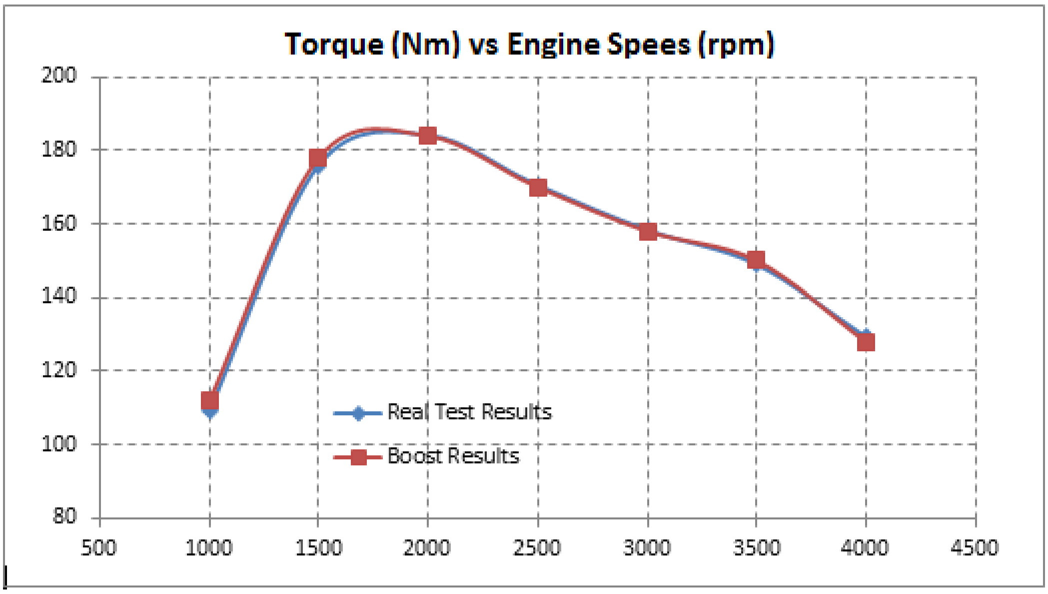

Figure 3.7 : Full load torque curve comparison of the model.

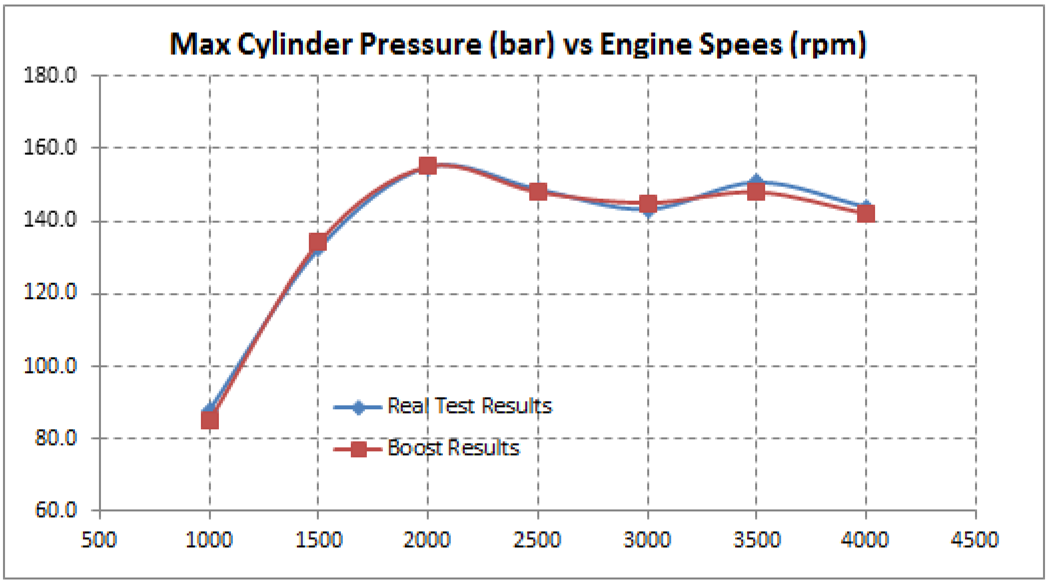

Figure 3.8 : Maximum cylinder pressure comparison during full load cycle.

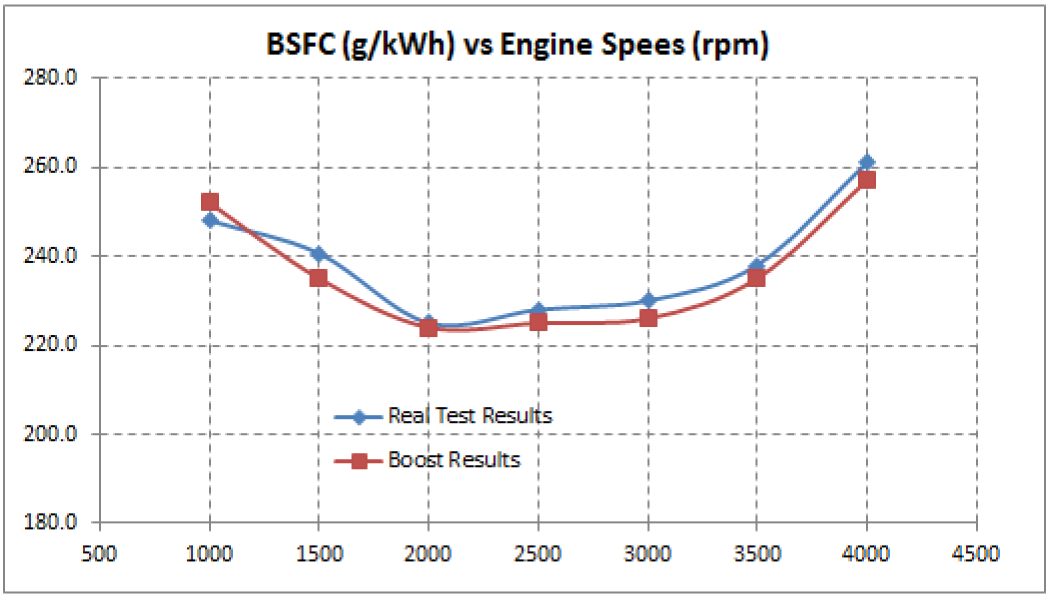

Figure 3.9 : Break specific fuel consumption (BSFC) during full load cycle.

3.3 Simulation Environment in Simulink

Once the full load curve of the engine model gave accurate results during simulations in Boost RT, as a next step, simulation platform was changed to Matlab Simulink. Figure 3.10 shows the simulation structure with the main blocks: powertrain control module (PCM), Boost - EGR controller, Boost RT.

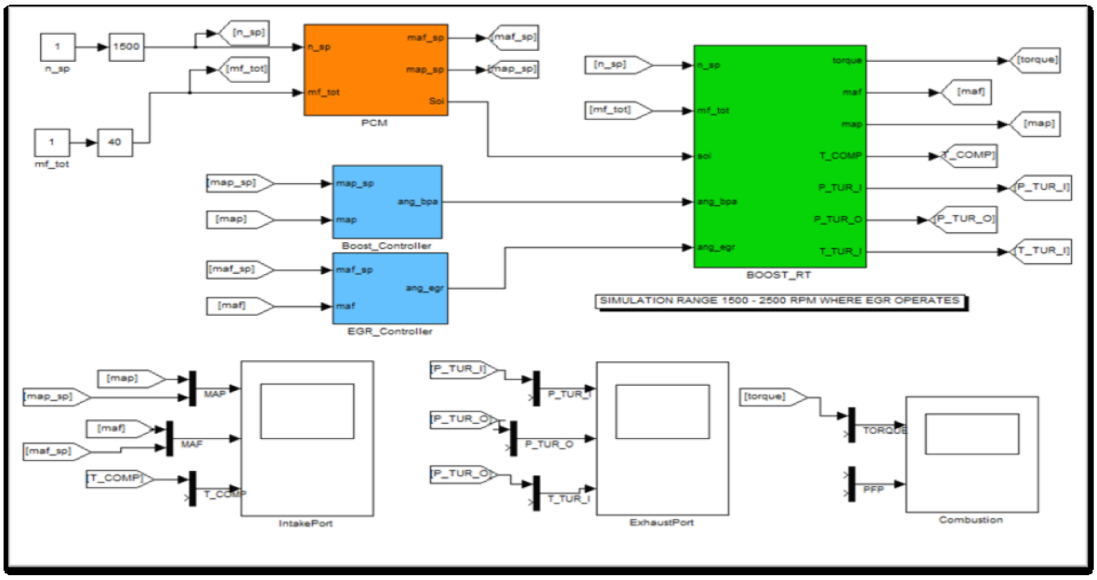

Figure 3.10 : Overview of the simulation in Simulink.

PCM block contains the look up tables of the engine for the determination of mass airflow, manifold absolute pressure and start of injection setpoints. Look up table method is the way widely used in automotive industry, calculating setpoints of air system according to engine operation as fuel and engine speed by using 2D interpolation method. Figure 3.11 shows inside of the powertrain control module (PCM) block and example of surface creation by data fit in order to build look up tables. In order to meet with emission stringent emission legislations, for each operating points in terms of engine speed and load, mass air flow and manifold absolute pressure set points are needed to determined. Thus, before control system design, critical study is conducted to find out set points, which would homologate the engine according to emission regulations.

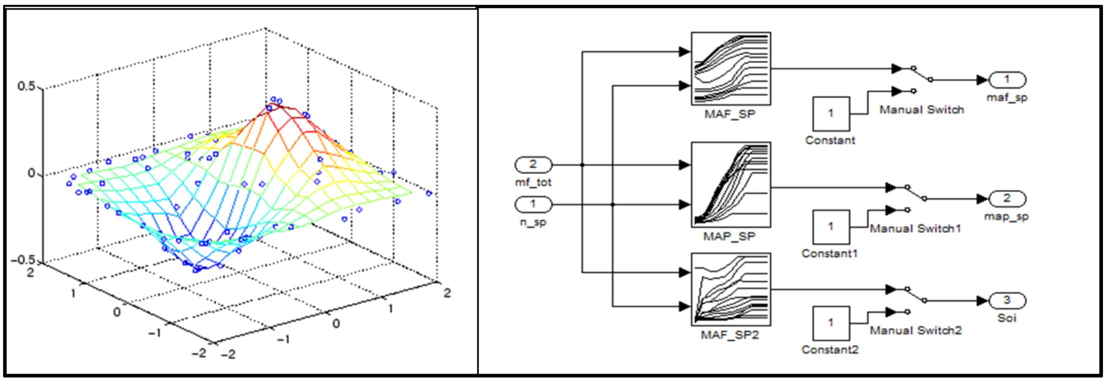

Figure 3.11 : Surface fitting to data and PCM block.

Boost RT block contains the diesel engine model designed in Boost RT. There is an interface available in Boost RT to compile engine model to be applicable with Simulink and organize the model inputs, which will be supplied by Simulink and model outputs, which will be fed to simulin to the controllers. Figure 3.12 displays the inputs and outputs of the engine model. There are five inputs of engine model: Fuel, engine speed, start of injection setpoint, position of EGR valve and position of turbine blades of turbocharger. According to those inputs, engine model generates following outputs: Torque, turbine speed, mass airflow, manifold absolute pressure, compressor outlet temperature, and turbine inlet and outlet pressures.

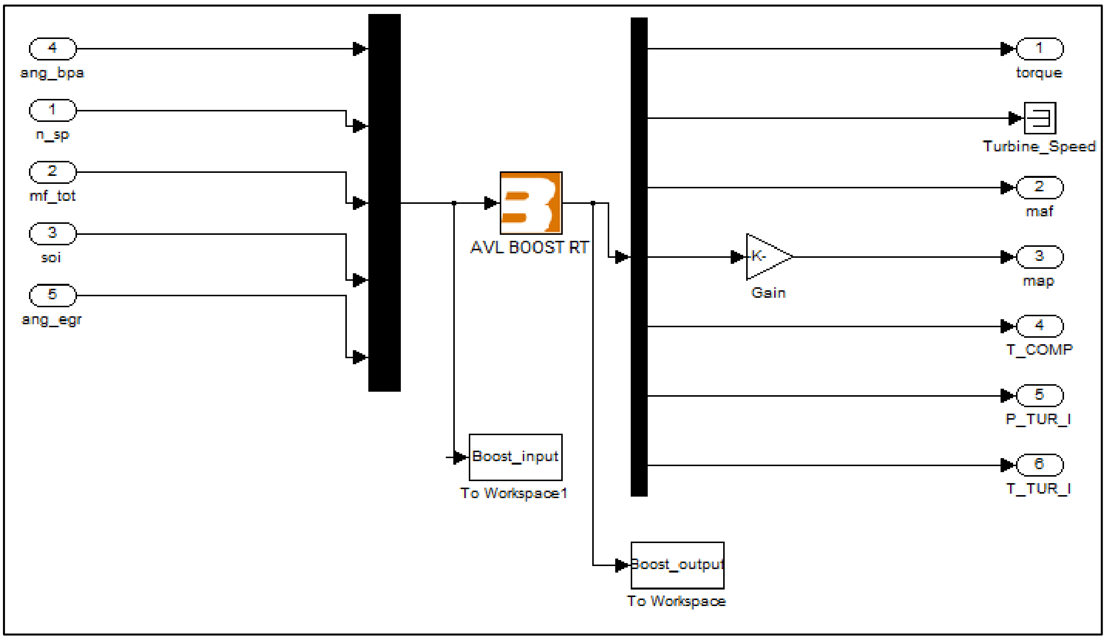

Figure 3.12 : Boost RT model in Simulink.

Further validation of the diesel engine model was simulated by the inputs from test bench data to check model capabilities. Next figures, figures 3.13, 3.14, 3.15, 3.16, display the inputs and system response successively. The overall result of model is positive with accuracy and trend tracking.

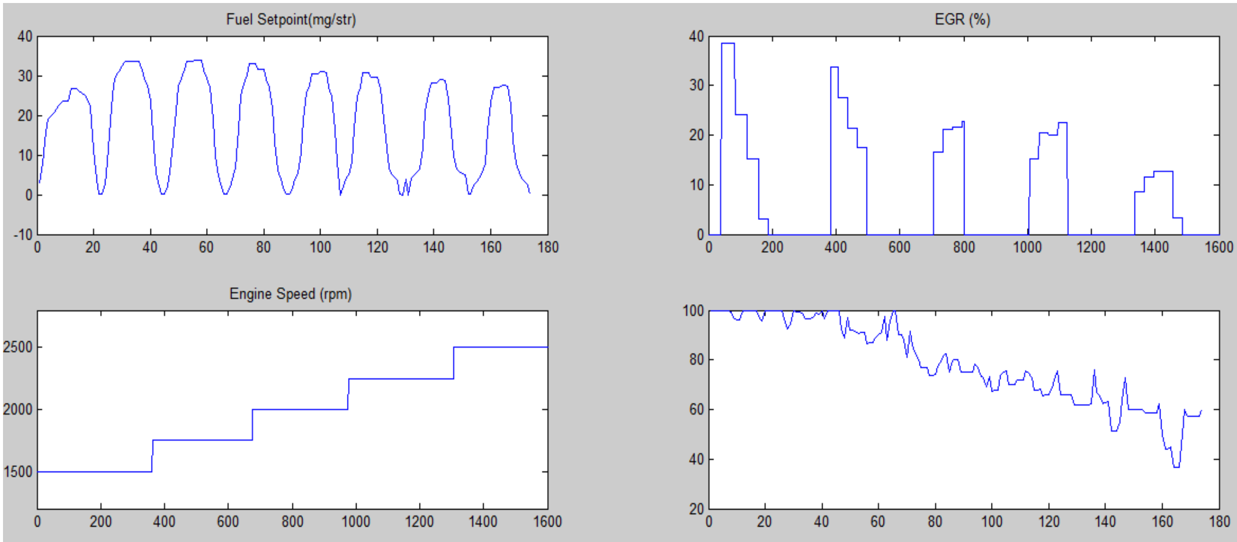

Figure 3.13 : System Inputs.

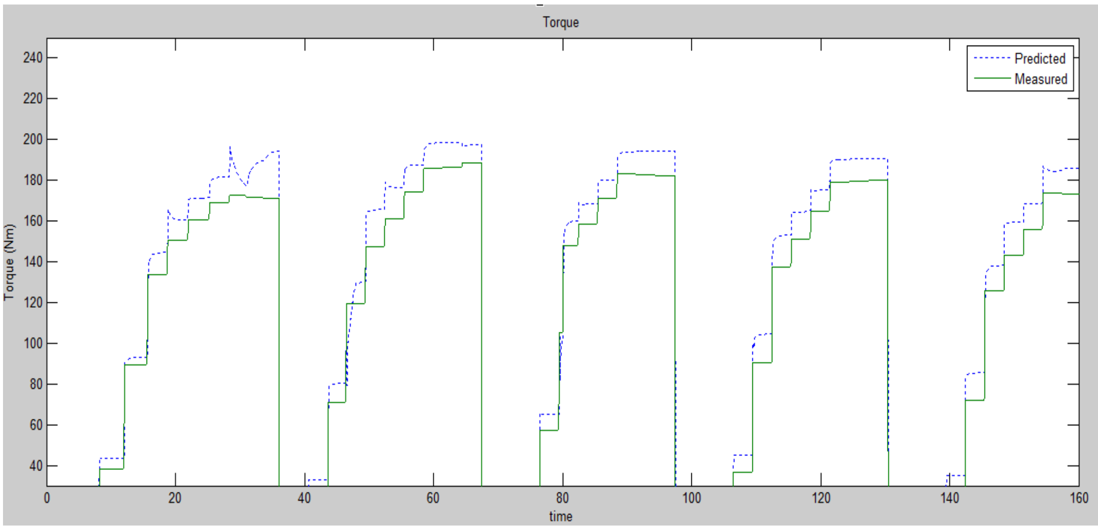

Figure 3.14 : Measured torque vs model output.

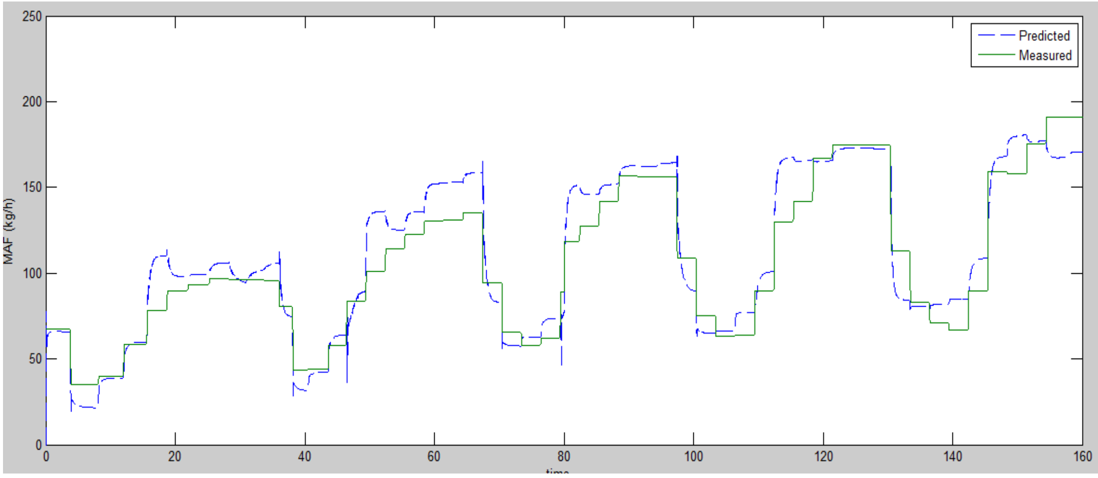

Figure 3.15 : Measured mass airflow vs model output.

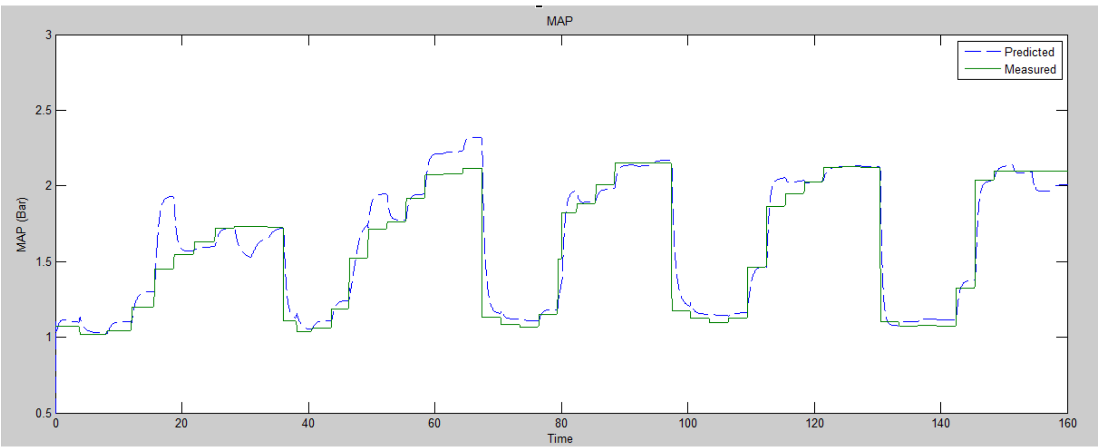

Figure 3.16 : Measured manifold absolute pressure vs model output.

4. STANDARD PID BASED CONTROL OF AIR PATH

In this chapter, classic PID controllers will be designed to control engine air system. Mass airflow and manifold absolute pressure control would be approached as two single input and single output systems. Two different tuning methods were used: Ziegler Nichols oscillation method and genetic algoritm.

4.1 Single Input Single Output (SISO) Approach

Figure 4.1 shows two separate control loops, which have two sets of PID controllers.

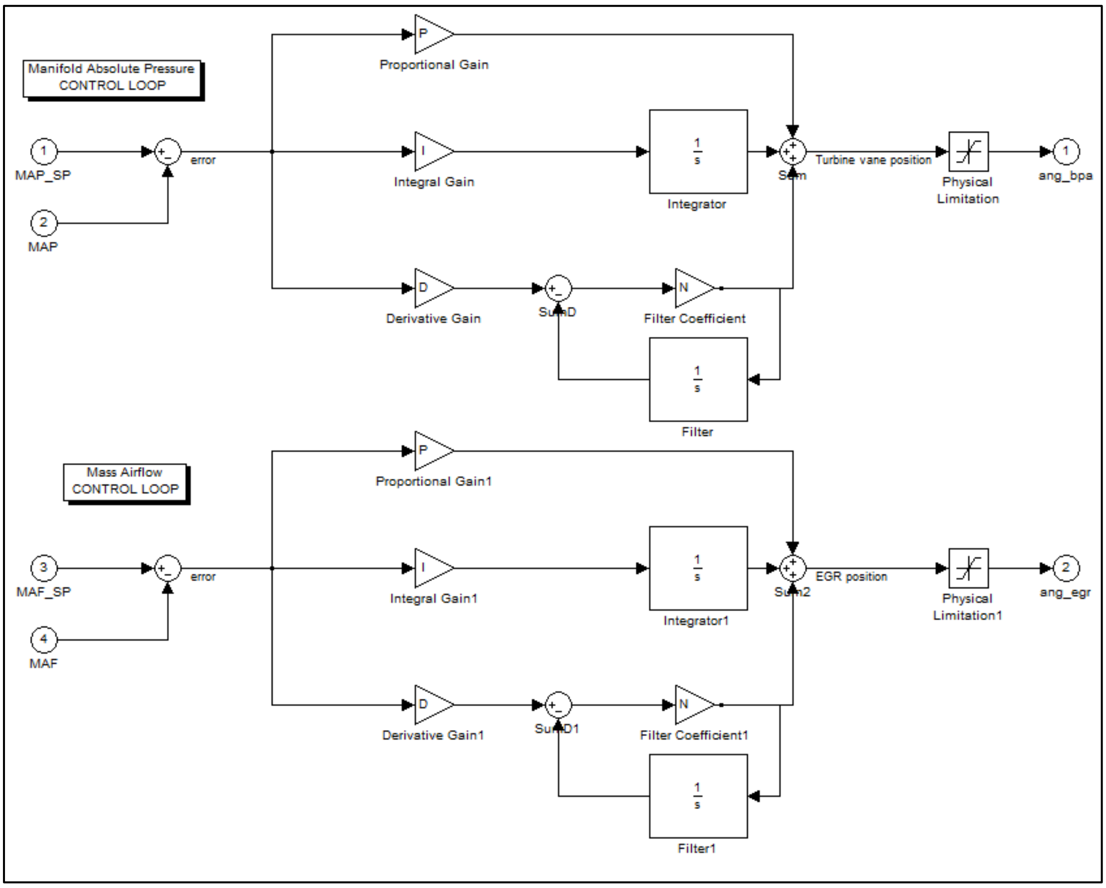

Figure 4.1 : Overview of SISO control loops of air-path.

4.2 PID Controller Tuned by Ziegler Nichols

Starting with the calibration of manifold absolute pressure (MAP) control loop, integral term and derivative term of the MAP controller were set to zero and then proportional gain was adjusted until critical oscillation begins. One can see the critical oscillation on MAP in Figure 4.2 and the values of controller parameters by Ziegler Nichols method in table 4.1

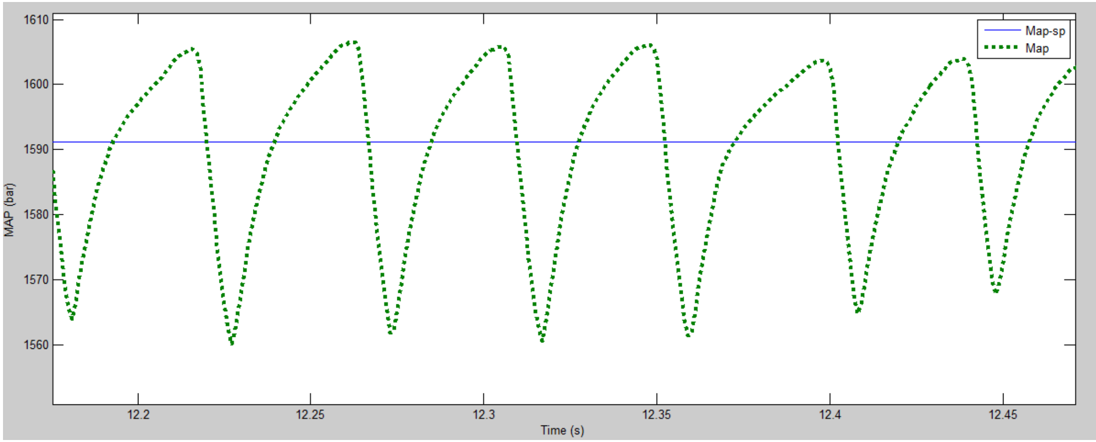

Figure 4.2 : Critical oscillation on the manifold absolute pressure.

Table 4.1. Values of PID terms according to Ziegler Nichols method.

Ziegler Nichols Method			
Control Type	Kp	Ki	Kd
PID	0.6 * Ku	2Kp / Tu	KpTu / 8
values	1.2	0.12	0.03

2250 rpm was chosen as the operating engine speed for the all controller simulations. Step in the fuel input of 10 mg/str change was being used as a test signal. Since, engine operating window changes, automatically new setpoint for mass airflow and manifold absolute pressure is being asked. In figure 4.3, one can see the response of PID controller in terms of MAP change, its effect on mass air flow (MAF) due to coupled system and VGT position as controller output.

After control loop of manifold absolute pressure calibration, EGR controller is calibrated in a same manner by actuating the system, so MAF, until critical oscillations begin. Figure 4.4 displays system response while both controllers are operating. With the activation of EGR, it may seem that MAP control has benefits, better controller performance because of the coupling. However, performance of the mass airflow controller is far from ideal, despite Ziegler Nichols (ZN) method, controller gets unstable before reaching steady state.

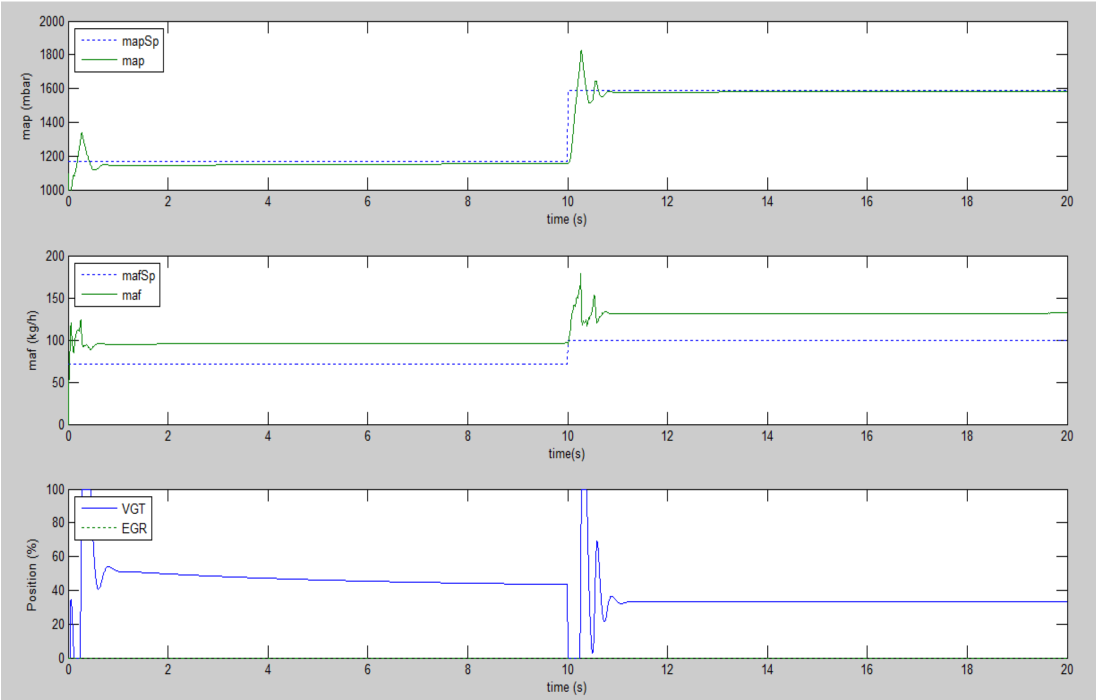

Figure 4.3 : Performance of the PID controller by ZN method.

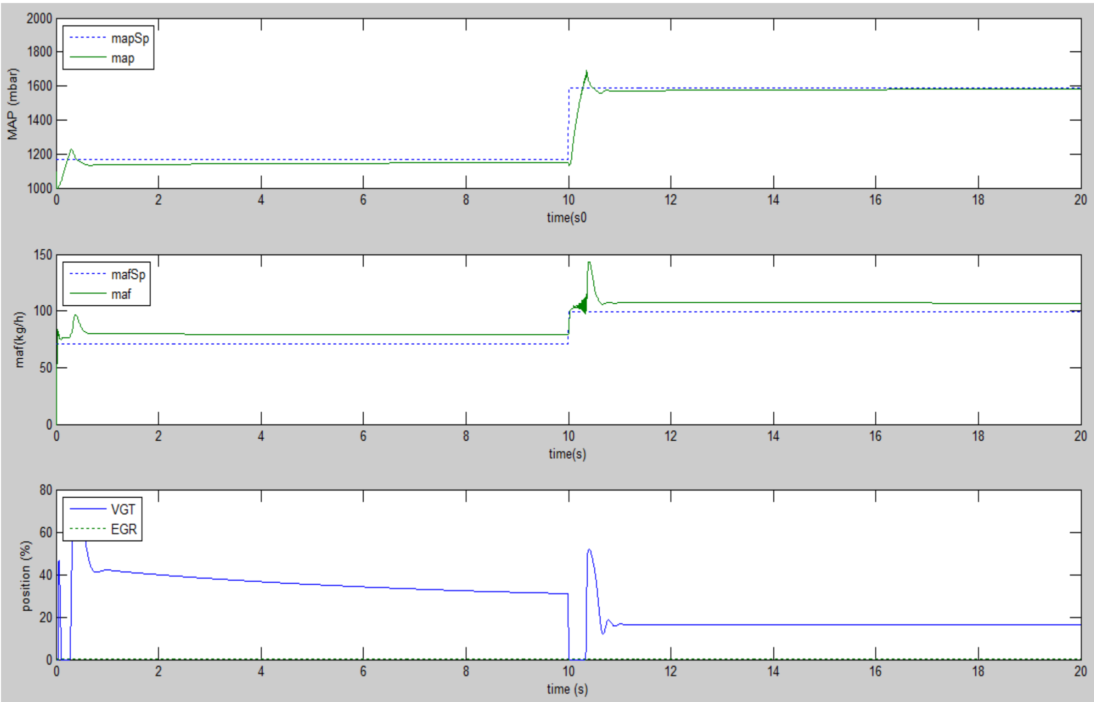

Figure 4.4 : Airpath control with PIDs by ZN method

4.3 PID Controller Tuned by Genetic Algorithm

Using genetic algortim method to tune PID controllers in order to get optimum performance is well known method in the control society. Hence, instead of trial and error method, which is not systemeatic and never guarantees optimum performance, genetic algorithm was used to tune PID terms. Flow chart of genetic algoritm is displayed in figure 4.5. It is a recursive method depending on the mutations and survival of the fittest.

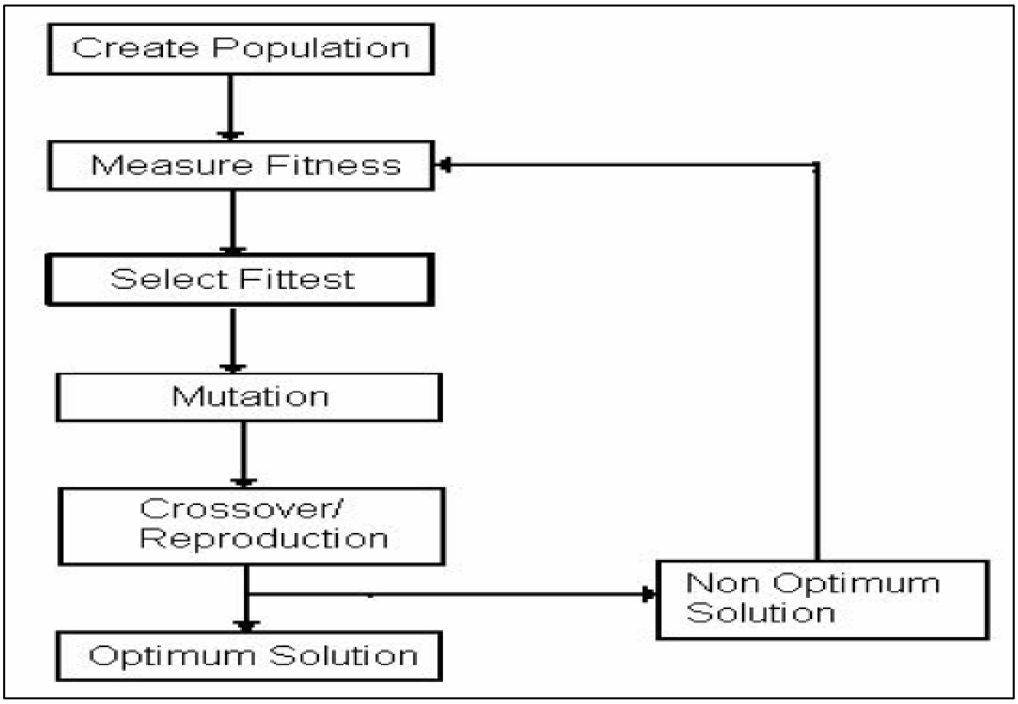

Figure 4.5 : Flow chart of the genetic algorithm [21].

Initially, PID controller of manifold absolute pressure was tuned by genetic algorithm. To manage that egr valve is deactivated and cost function is defined to be minimized which is the integral absolute error criteria of manifold absolute pressure. Figure 4.6 and figure 4.7 show the performance of the system as MAP controller tuned by genetic algorithm and EGR loop by Ziegler Nichols. Next, another set of simulations are run for the EGR controller to seek fittest PID terms.

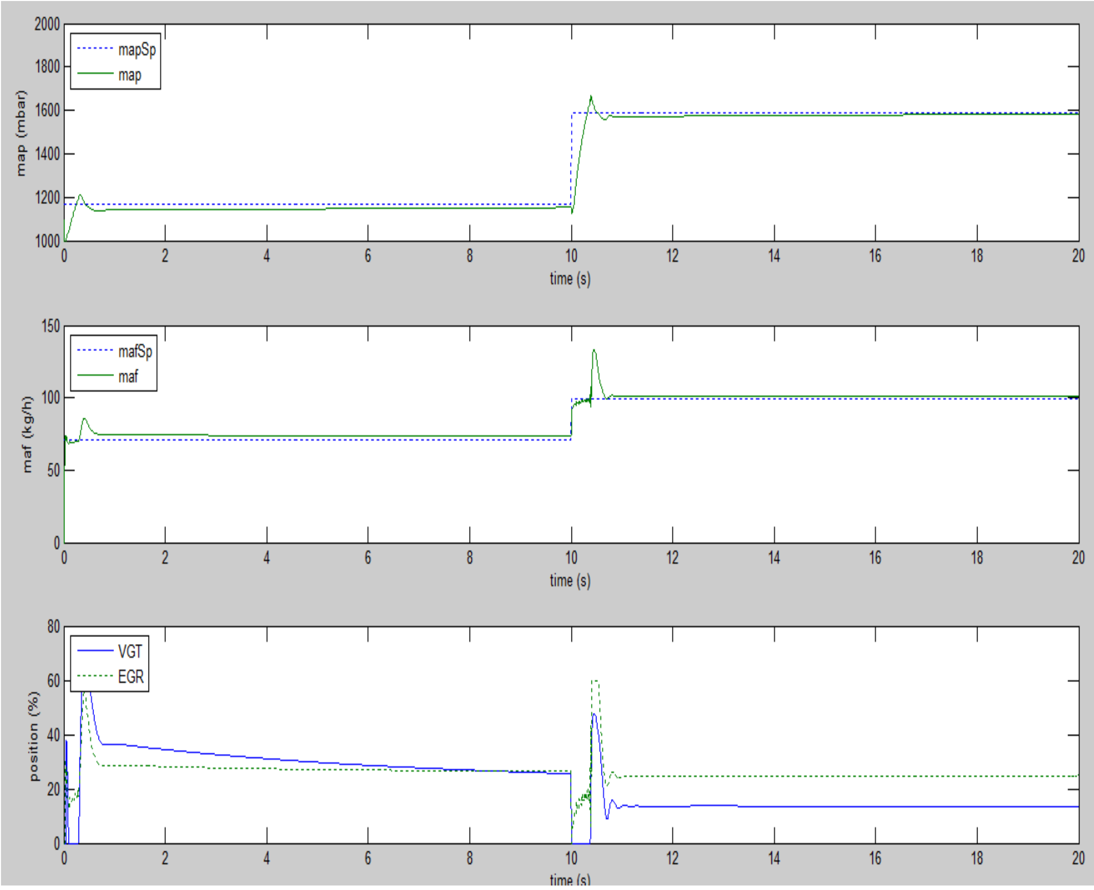

Figure 4.6 : MAP controller tuned by genetic algorithm and EGR by ZN.

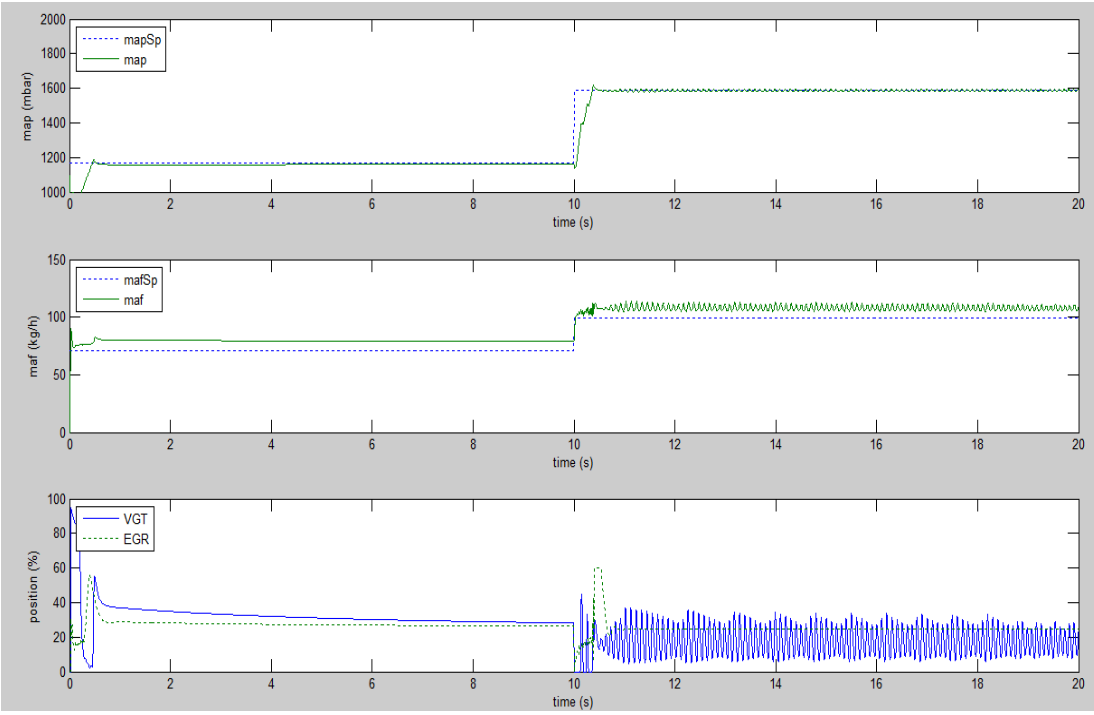

Figure 4.7 : Both Contollers tuned by genetic algorithm.

4.4 Effect of Open Loop Feedforward Controller

Open loop feedforward, so called precontroller, is a popular method in automotive industry to get faster system response and cope with system non-linearites. PID controllers tuned by Ziegler Nichols method and genetic algorithm, struggle to give sufficient airparth performance in previous sections. Additon of open loop feedforward term to the ouput of controller may create the advantage of directing PID to the setpoint band quickly in other words handle with transient performance then leave the rest to the PID controller for the steady state operation. Because of that, openloop approach is employed instead of closed loop. All engine-operating points should be visited to find out which position of EGR valve and VGT nozzle give the requested setpoints. Then, this steady state equilibrium points create the 2D interpolation map or look table, which have inputs of engine speed and load to determine desired control action. Summation of this term and PID output gives final control action. Figure 4.8 shows the structure in Simulink and effect of feedforward to the controller performance is shown after in figure 4.9 and figure 4.10. When the performance of the controllers with feedforwad strategy is evaluated, controller reacts faster and reaches its setpoint quicker than the standard control scheme.

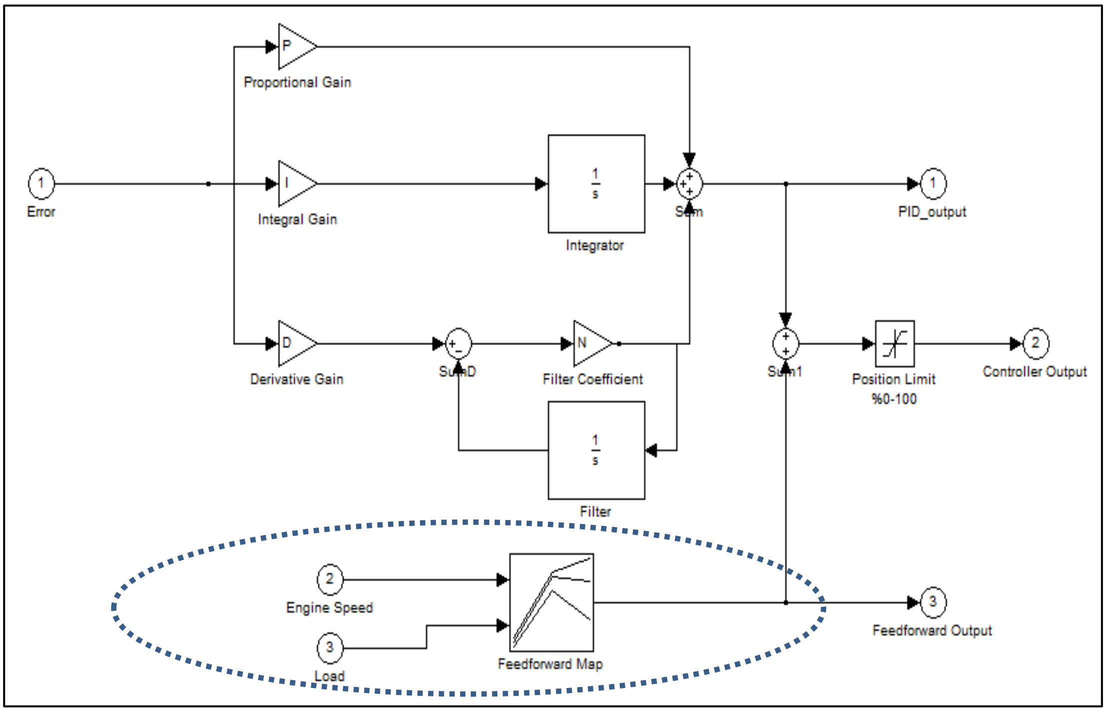

Figure 4.8 : Open loop feedforward control strutcture

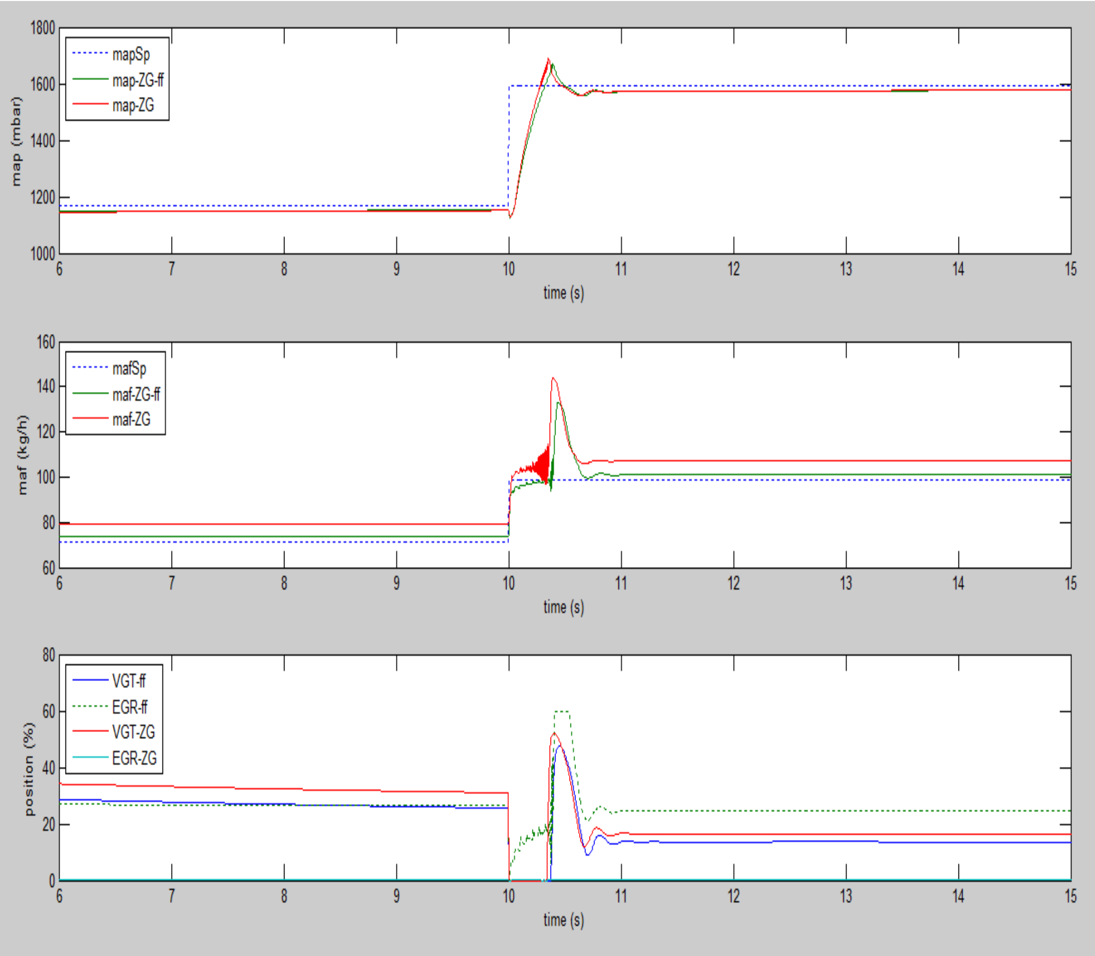

Figure 4.9 : Controllers tuned by Ziegler Nichols with feedforward.

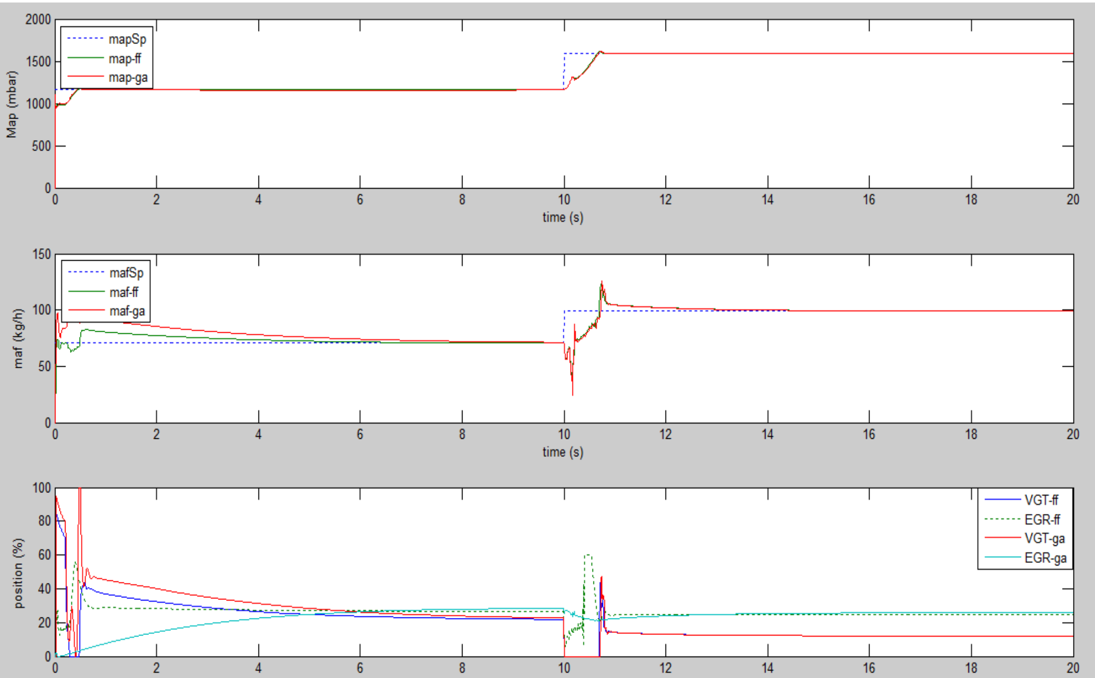

Figure 4.10 : Controllers tuned by genetic algorithm with feedforward.

5. MODEL PREDICTIVE CONTROL (MPC) OF AIR PATH

Model predictive control is not a new control technique. The first paper about MPC was published back to 1976 [8]. Until the last decade, MPC was being used mostly in process control such as chemical plants due to slower system response of those systems and the high computational requirement of MPC. However, within the advancement in the electornic control units of automotive industry, use of MPC against non-linear coupled systems becomes possible [6]. The biggest advantage of MPC algoritm is its capability to handle multi input multi output systems by optimizing constraints..

5.1 Overview of Model Predictive Control

The main idea of the MPC control scheme is to use a model of the plant to predict the future evolution of the system by optimizing the controller signal. For the calculation of each controller output, system response is predicted for a finite time horizon. Thus, there is an iterative open loop optimasation method which turns to closed loop by the update of the feedback from system output. Figure 5.1 shows the typical calculation steps for the prediction horizon.

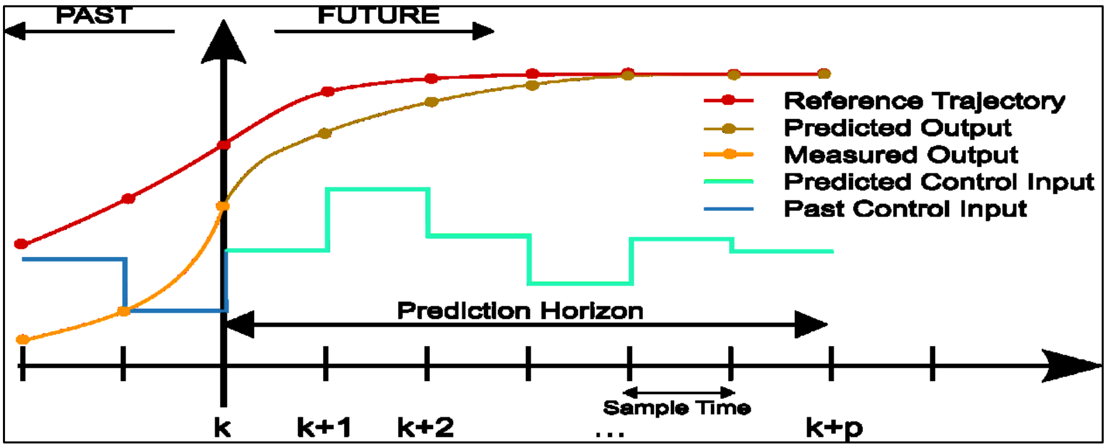

Figure 5.1 : MPC calculation steps[22].

There are three important elements of the MPC algorithm: Plant model, Constraints and Weight Tuning. Modeling requires most of the efforts due to its directly critical with the controller performance. However, having a perfect system model is impossible. Thus, the plant model should catch the main system dynamics to avoid calculation complexity. Next section shows the modeling of the air path for the MPC controller. Moreover, system constraints in terms of output and input limits further shape the optimization problem, which will be solved in each control step. MPC control scheme has the weighting factors for the constraints which defines the performance trade offs versus constraints and controller aggressiveness.

In this work, in order to design MPC controller, Matlab MPC toolbox is being used. All equations in the following sections can be found in [23].

5.2 System Identification of the Plant

Air path of diesel engine has a non-linear coupled complex structure. However, by approaching the system with the certain operating ranges, there might be linear models derived. In this case, 2200 rpm is chosen as the engine operating speed. By using Matlab System Identification Toolbox, input-output model of 2200 rpm is created. During the first modeling trials, accuracy of the linear models were very low. As a solution, pseudo random binary sequence (PRBS) perturbation method was applied on the actuataros, which are egr and vgt. The basic idea of the PRBS signal is to apply perturbations to the system at rest to catch important system dynamics. Figure 5.2 shows the system inputs with PRBS signal and the accuracy of resultatnt identified plant model.

The result of system identification of input-output relation is fourt order linear system in the state space format. Thus, following representation show the plant model for the MPC controller.

$$\begin{aligned} \dot{x}(t) &= A \cdot x \cdot (t) + Bu(t) + K \cdot e(t) \\ y(t) &= C \cdot x(t) + D \cdot u(t) + e(t) \end{aligned} \qquad \textbf{5.1}$$

In formula 5.1, one can see the general state space representation of the linear system as x(t) state vector, y(t) output vector, u(t) input vector and K disturbance matrix.

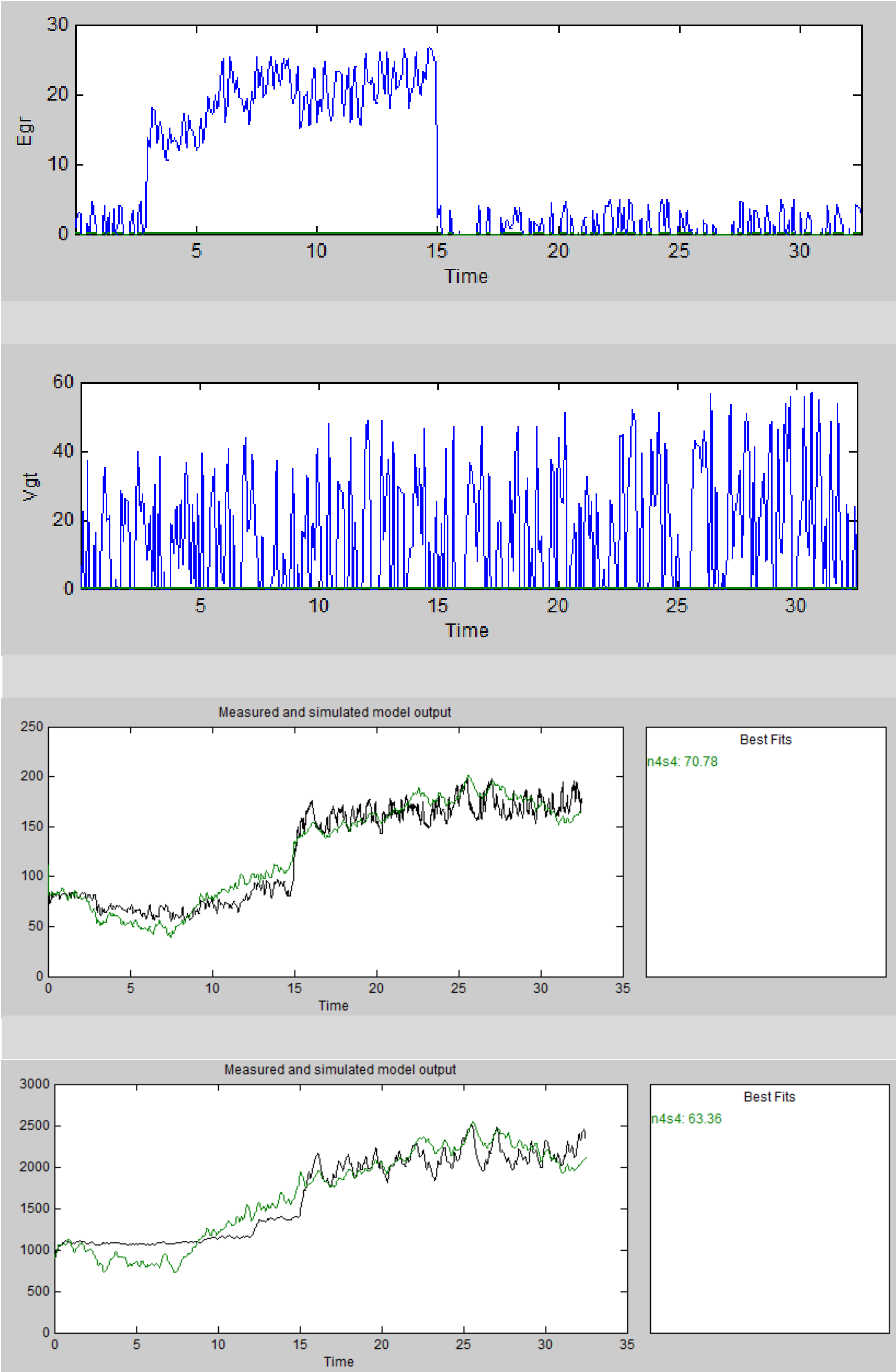

Figure 5.2 : Inputs with PRBS and output comparison for the model and plant.

5.3 Design of Model Predictive Controller

Model predictive control actually deals with a quadratic optimization problem. The general elements of the cost function include output tracking (J_y), manipulated variable tracking (J_u), manipulated variable move suppression ($J_{\Delta u}$) and constraint violation (J_c) [matlab]. Each element has a specific weighting factor to determination of prioritization.

$$J_{mpc}(z) = J_y(z) + J_u(z) + J_{\Delta u}(z) + J_c(z) \tag{5.2}$$

According to MPC design and system requirements, there might be the only output tracking curve by setting the weights of other elements to the zero, which is actually unconstrained mpc problem with flexible inputs.

$$J_y(z_k) = \sum_{j=1}^{n_y}\sum_{i=1}^{p}\left(w_{i,j}^{y}\left[r_j(k+i\backslash k) - y_j(k+i\backslash k)\right]\right)^2 \tag{5.3}$$

Equation 5.3 shows the cost function of the output tracking criteria. In the equation, current control interval is k, prediction horizon is p, number of system outputs is n_y, w term is the weighting factor, r term is the reference value and y predicted output. Sometimes, the controller outputs have the nominal values; hence, manipulated variable tracking cost function is calculated if it is the case.

$$J_u(z_k) = \sum_{j=1}^{n_u}\sum_{i=0}^{p-1}\left(w_{i,j}^{u}\left[u_j(k+i\backslash k) - u_{j,t\arg et}(k+i\backslash k)\right]\right)^2 \tag{5.4}$$

In equation 5.4 differs from equation 5.3 by n_u as number of manipulated variables and the term to be minimized is the difference of the controller output and its target. Next cost function contributor is the manipulated variable move suppression which is actually a rate limiting in the controller input.

$$J_{\Delta u}(z_k) = \sum_{j=1}^{n_u}\sum_{i=0}^{p-1}\left(w_{i,j}^{\Delta u}\left[u_j(k+i\backslash k) - u_j(k+i-1\backslash k)\right]\right)^2 \tag{5.5}$$

Finally, the constraints on the input, input rate and outputs define the constraint violation part of the optimization problem in next equation.

$$u_{\min}(i) \leq u(i) \leq u_{\max}(i)$$
$$\Delta u_{\min}(i) \leq \Delta u(i) \leq \Delta u_{\max}(i) \qquad \textbf{5.6}$$
$$y_{\min}(i) \leq y(i) \leq y_{\max}(i)$$

Previously shown equations are calculated the inside of MPC controller block in Matlab Simulink. Once the block is introduced to the system, as a first step, necessary input output connections are made. Controller needs the measured outputs, which are map and maf, reference signals, which are the setpoints, manipulated variables are the controller outputs to the Boost Rt model as EGR ratio, and VGT position. Figure 5.3, shows the described structure.

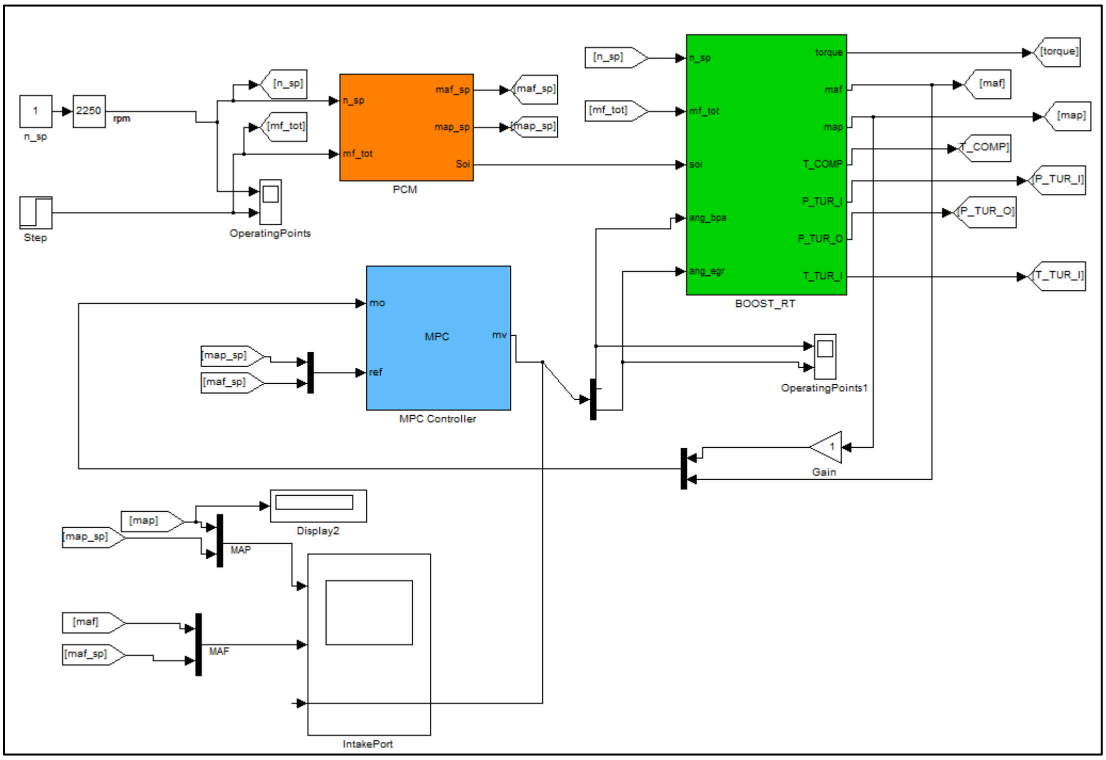

Figure 5.3 : Simulink layout with MPC block.

Simulink MPC controller block requires a linear plant model. As a first step of the design, plant model identified in the previous section, is imported to the MPC controller in figure 5.4. This also defines the number of inputs and outputs of the system.

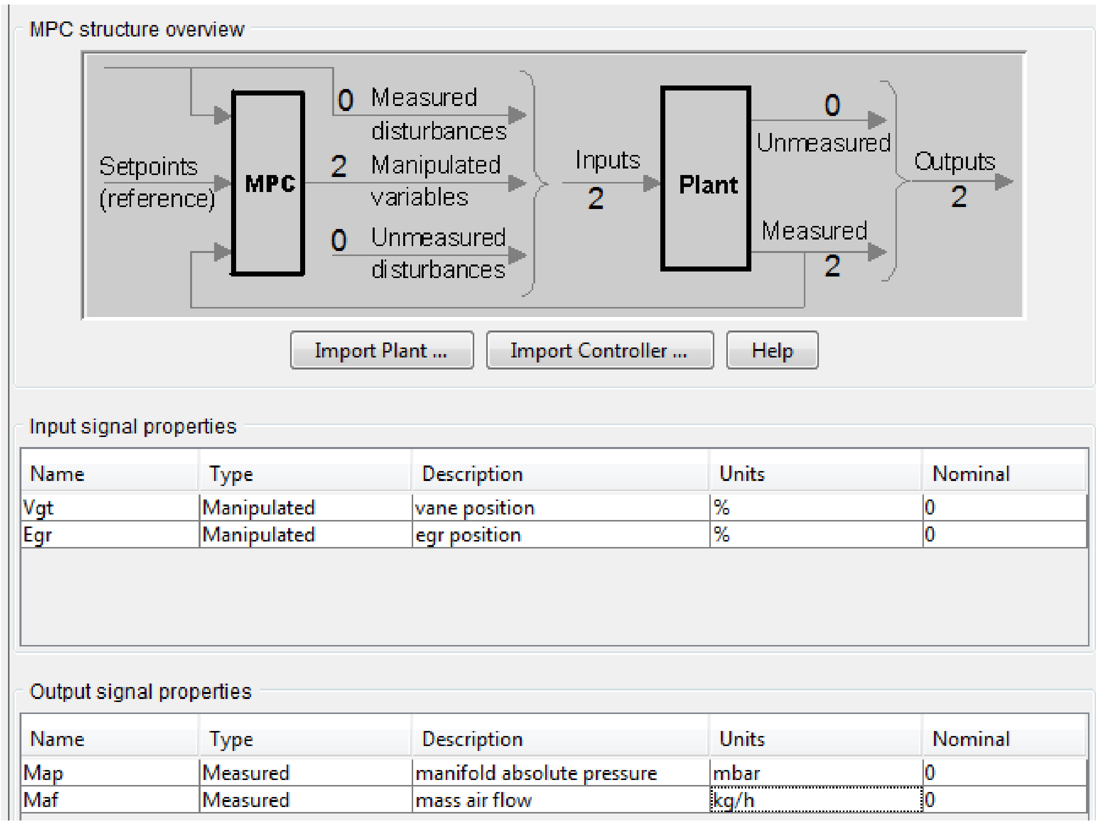

Figure 5.4 : Imported system view inside MPC controller block.

Depending on the plant model, it is also possible to define measured and unmeasured disturbance model within the system, which is not the case in this study. Controller block has four tabs, which fills the all free parameters in the optimization equations. In figure 5.5, prediction horizon, control interval and sampling time of the controller together with plant model are selected. Prediction horizon determines the number of future samples to be predicted by plant model. On the other hand, control horizon defines the number of control actions to be calculated. The greater the number of both horizons increases computational efforts.

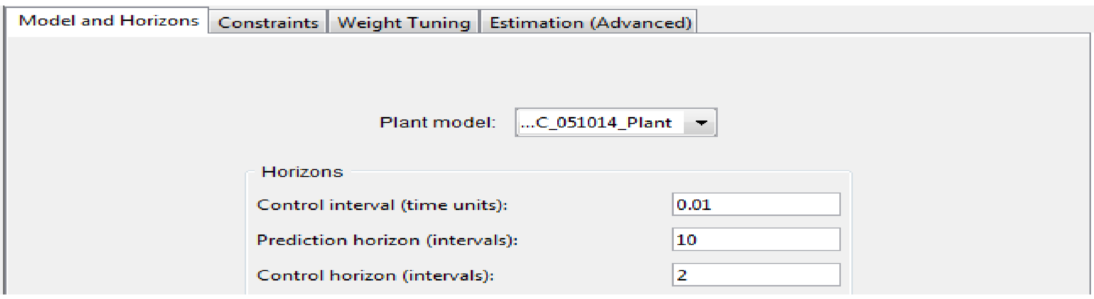

Figure 5.5 : Model and horizons for the controller.

In the second tab which is shown in figure 5.6, constraints of the system are defined in terms of input limits, input rate limits and output limits. In the Weight Tuning tab which is presented in figure 5.7, weighting factors, which shape the controller reponse, are entered. Priority of the factors should be considered according to table 5.1.

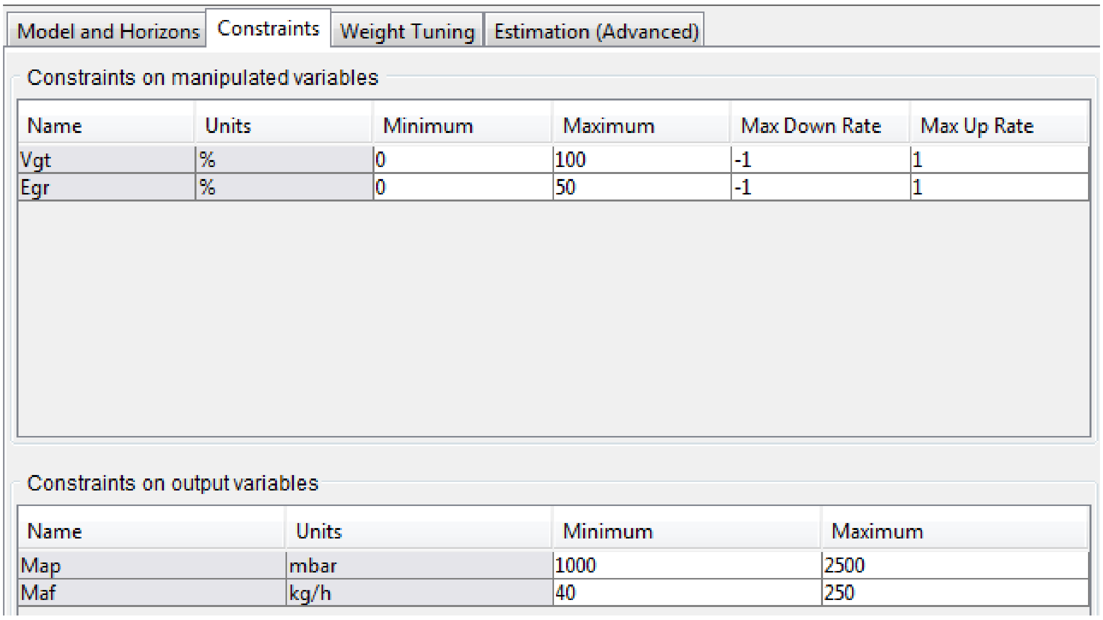

Figure 5.6 : System constraints.

Table 5.1. Weigthing Factor Prioritization [23].

Factor	Priority
0.05	Low priority: large tracking error acceptable
0.2	Below-average priority
1	Average priority – the default. Use this if nyc = 1.
5	Above average priority
20	High priority: small tracking error desired

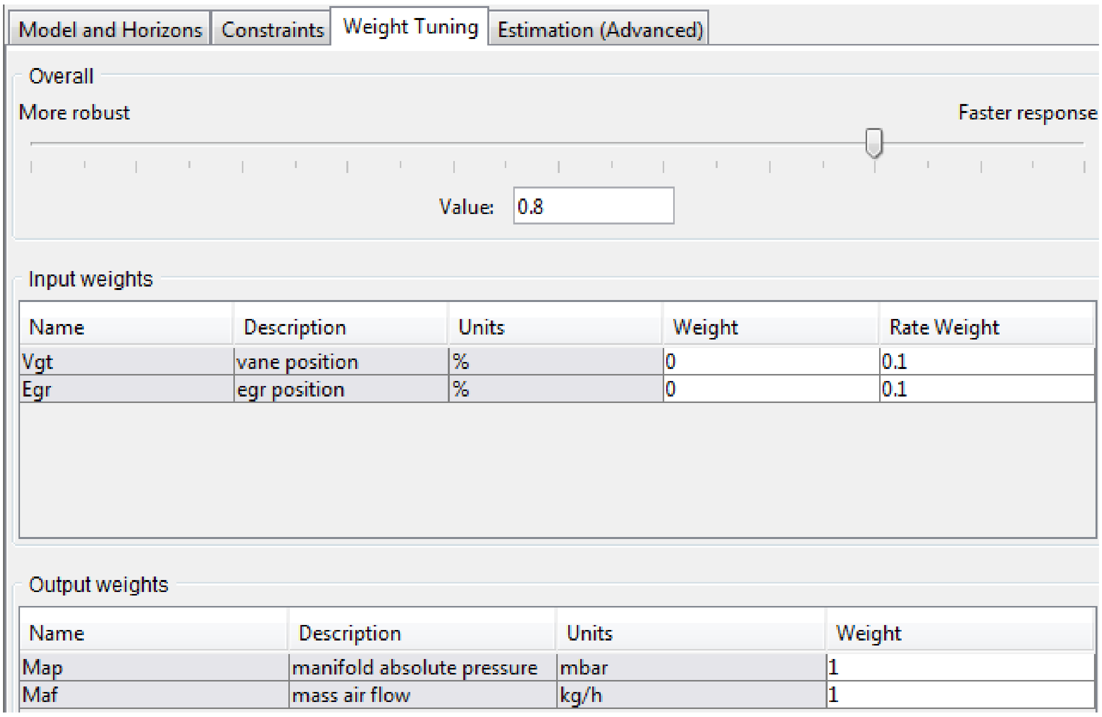

Figure 5.7 : Weighting Factors of the Controller.

The last tab in the controller tab is Estimation (Advanced). This section determines measurement noise and output disturbances on the plant model to cope with unmeasured disturbances. Figure 5.8 shows addition of white noise signals as unmeasured disturbances to the controller structure to find out controller states.

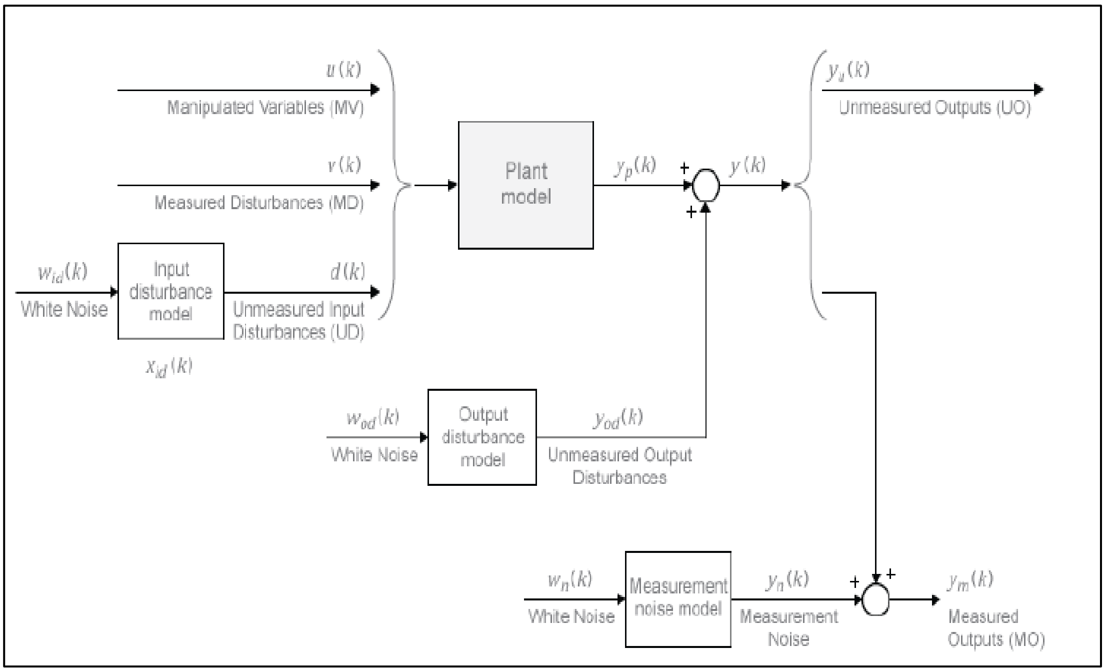

Figure 5.8 : Disturbance Models with the plant model [23].

Each of the disturbance models, as input, output and measurement noise, there are three different predefined models are available. If a different model is designed for the disturbances, it can be imported from workspace. Moreover, white noise, step like or ramp like disturbance models can be selected from the standart definitions shown in figure 5.9. White noise with zero mean model for the disturbance assumps that impact of the disturbance is short-term. Hence, the controller reacts modestly. If more aggressive controller response to the disturbance, step or ramp like models may be employed.

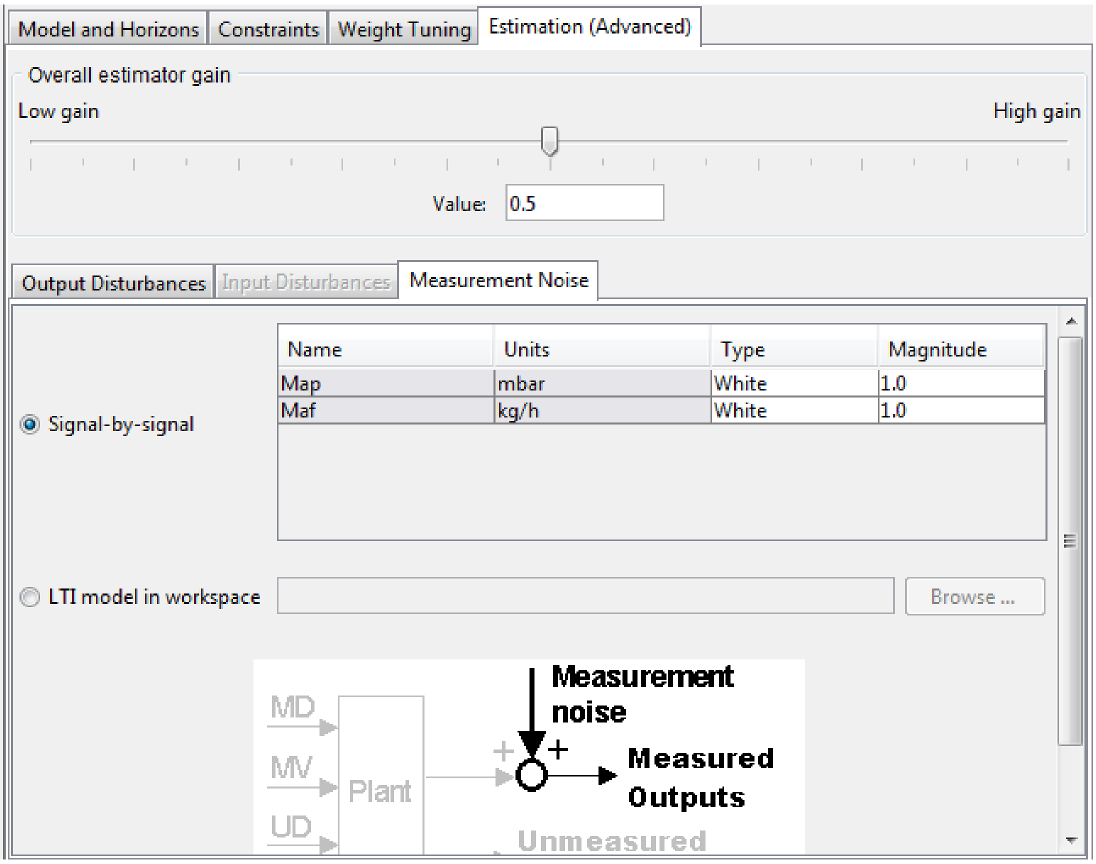

Figure 5.9 : Disturbance models of the controller.

Two different MPC controllers tuned and found as successful after the calibration efforts on the weighting factors. Figure 5.10 shows the response of the two controllers. As one can see, MPC1 controller has a slower response but zero MAP overshoot and robust MAF increase. On the other hand, MPC2 has more aggressive response which may make it desirable for certain applications where there is an immediate demand in the system output. For example, map control affects greatly the engine torque and driveability. Thus, in a project where the performance of the vehicle is more important then its economy MPC2 might be chosen. In the chapter, these two MPC controllers are compared with the PID relatives.

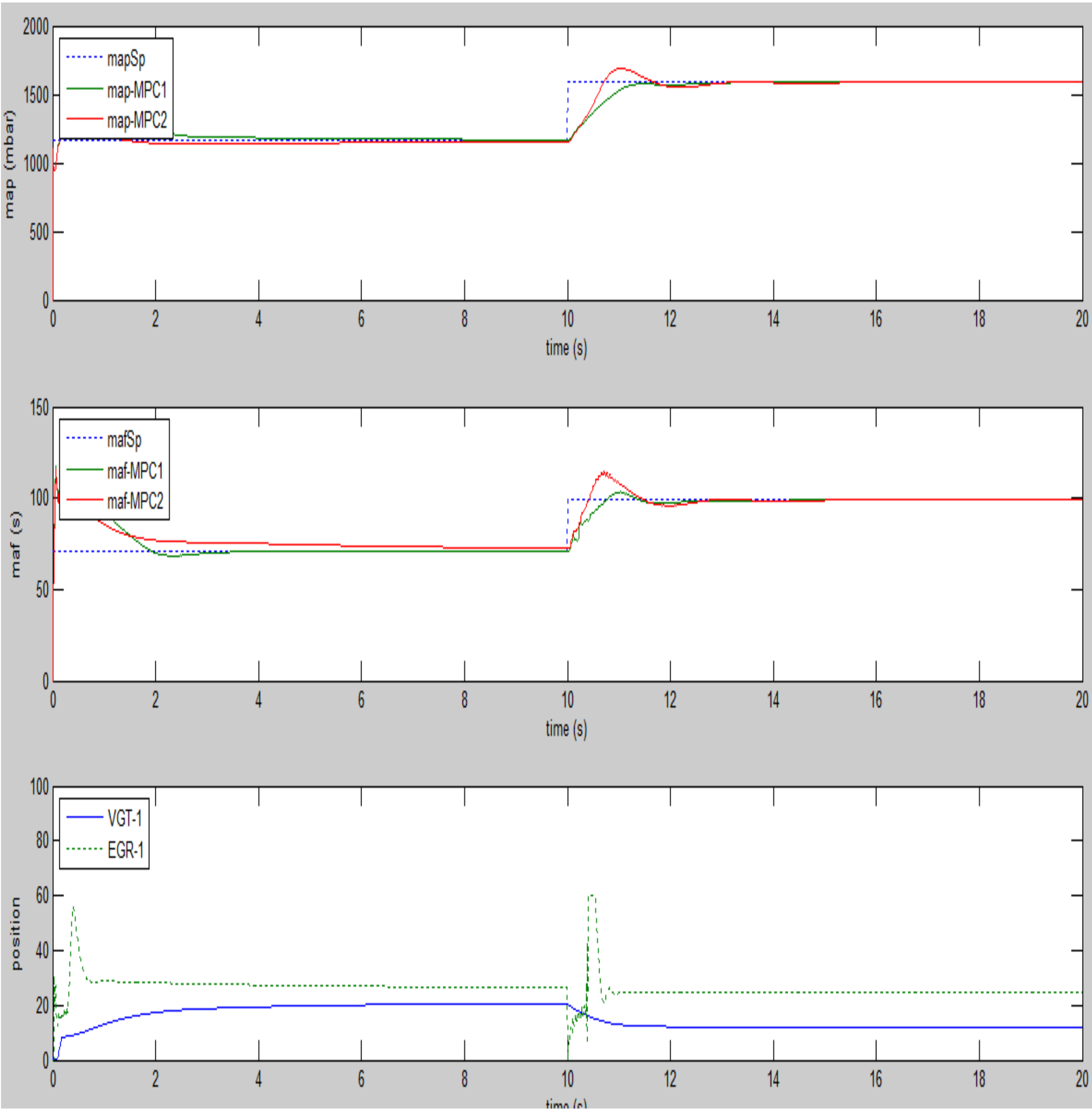

Figure 5.10 : Results with two different MPC controller design.

5.4. Comparison of the All Air Path Controllers

Figure 5.11 and 5.12 show the system outputs as MAP and MAF. Figure 5.13 and 5.14 show the system inputs or in other words controller outputs as VGT and EGR position. When the response of all controllers are compared, two different MPC controllers perform better than the PID controllers. If only the MAP response is compared, best response is belong to controller tuned by genetic algorithm. PID tuned by Ziegler Nichols is faster but it is slow to reach final setpoint. On the other hand, the real difficulty of handling with air path system is to control mass air flow in the same time. PID controllers with Ziegler Nichols cannot cope with system coupling and give very poor mass airflow controller. Moreover, despite the success in the MAP control, PID controller tuned by genetic algorithm is also not good as MPC controllers. Important aspect of air path control is to keep mass airflow stabilized just because oscilalations in the intake air easily cause engine speed fluctiaons. Therefore, MPC controllers are promising alternative to PID controllers to use in air path.

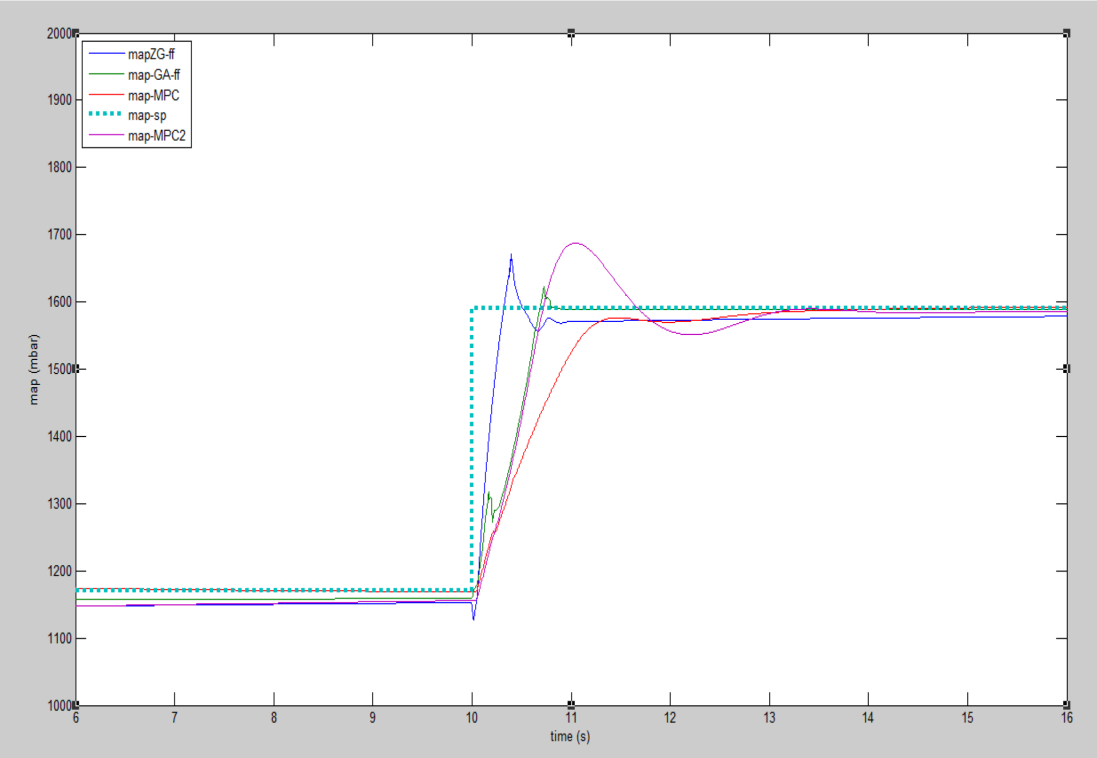

Figure 5.11 : MAP response of the different controllers.

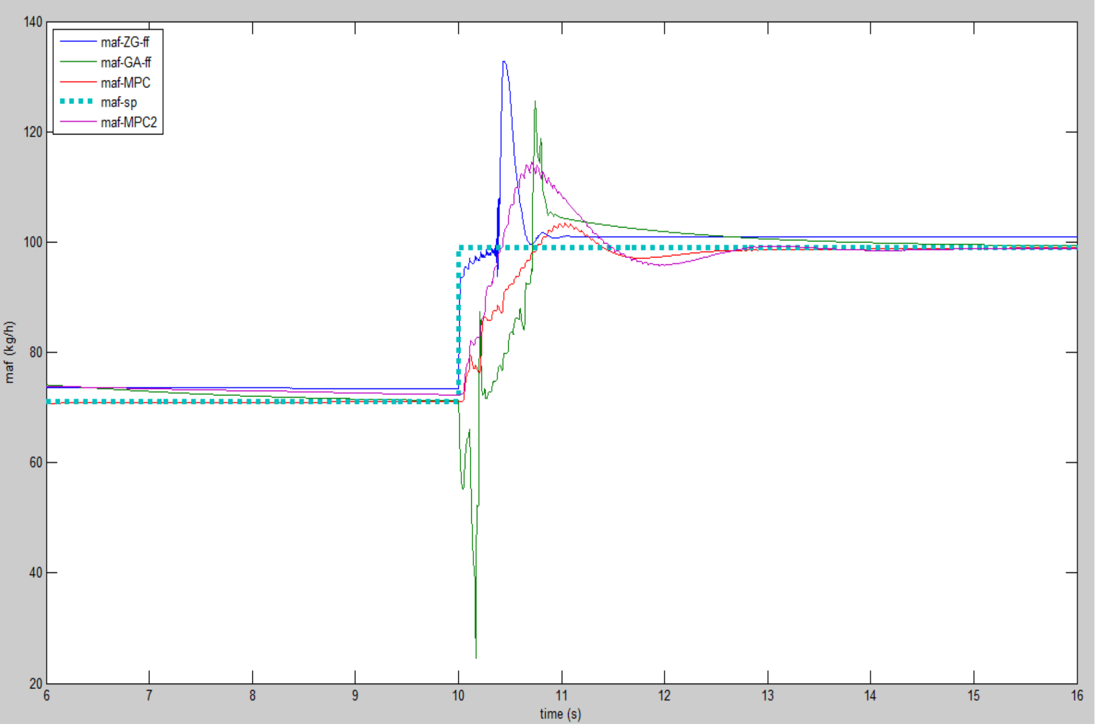

Figure 5.12 : MAF response of the different controllers.

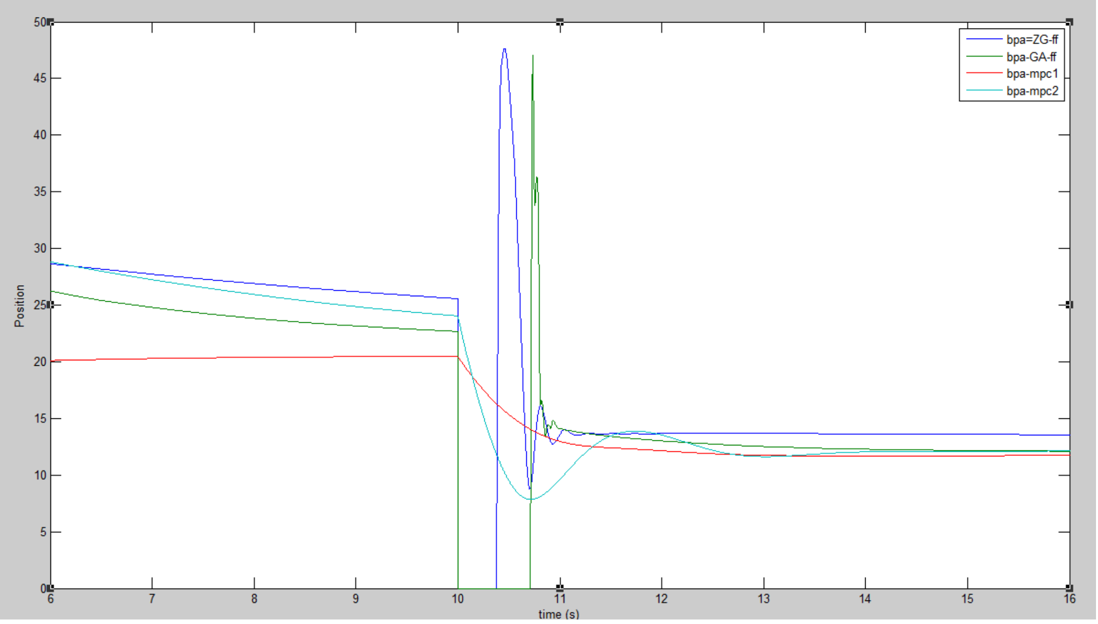

Figure 5.13 : Controller output as Vane positions of different controllers.

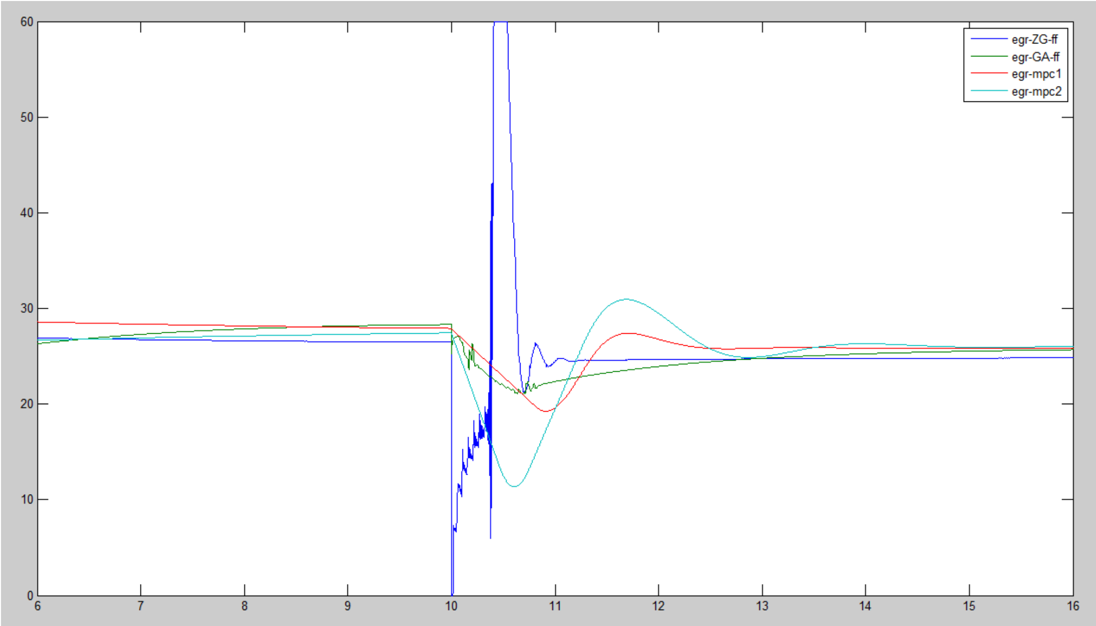

Figure 5.14 : Controller output as EGR position of different controllers.

5.5.Simulations with Same Controllers in Different Engine Speeds

All simulation efforts so far covers only the 2250 rpm of the engine since linear plant model was derived in that range for MPC. However, in this section, the designed controllers were applied to different rpm sets as 1250 rpm and 1750 rpm to show system variation n in different rpm and the change in controller response. Next figures would display the results starting from 1250 rpm with MAP, MAF, VGT position and EGR position which are coverd in figures 5.15, 5.16, 5.17 and 5.18 to 1750 rpm which is displayed with the figures 5.19, 5.20, 5.21 and 5.22.

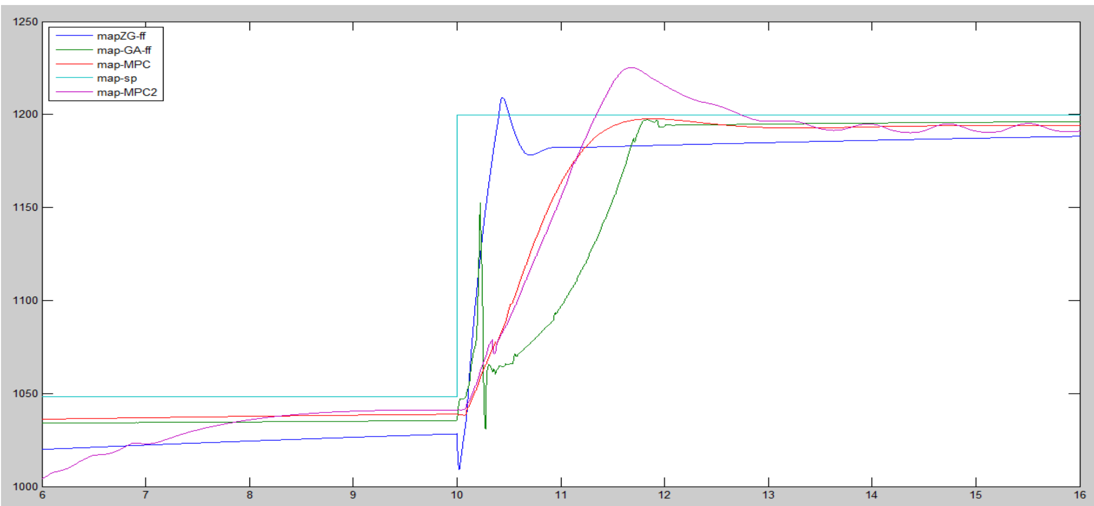

Figure 5.15 : MAP response of the controllers @1250 rpm.

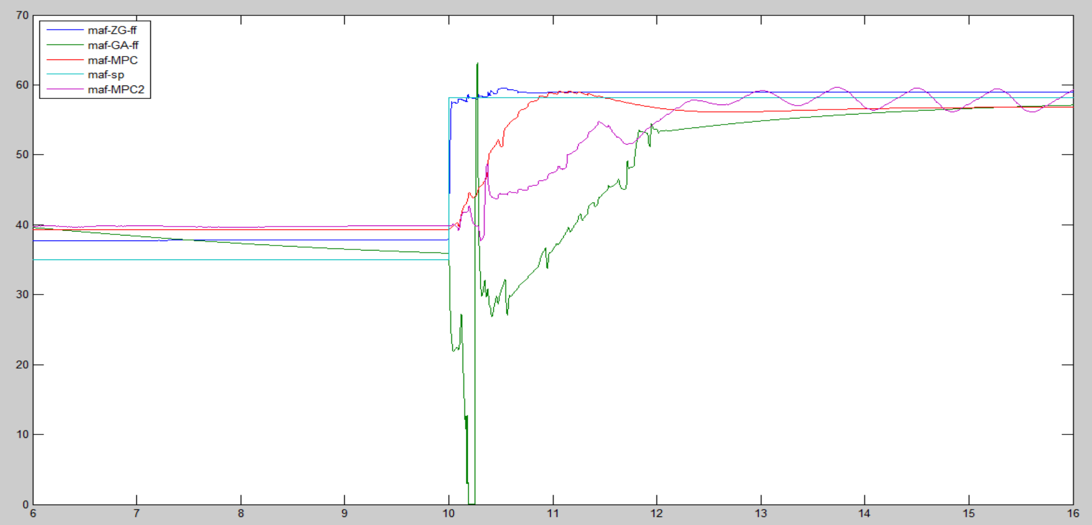

Figure 5.16 : MAF response of the controllers @1250 rpm.

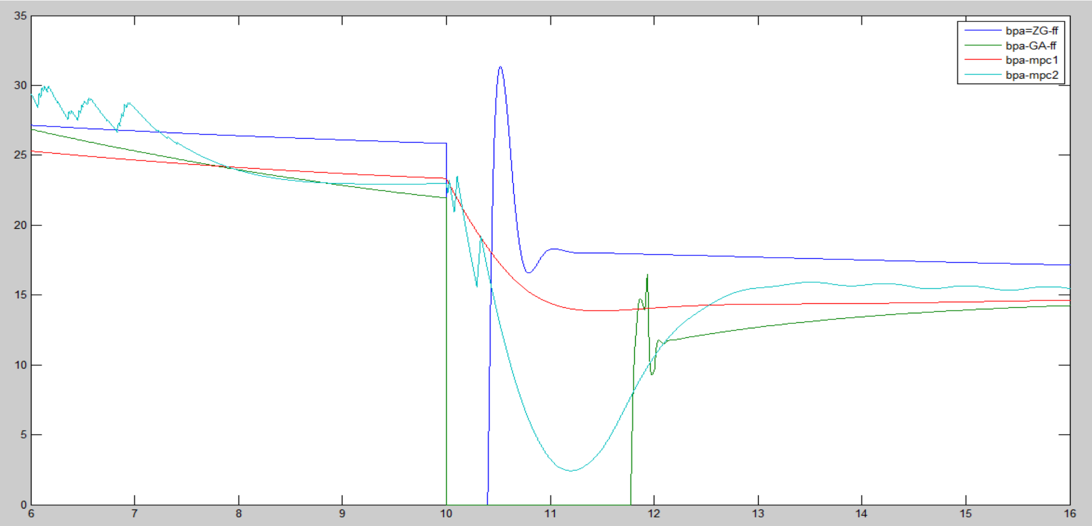

Figure 5.17 : VGT positions as controller output @ 1250 rpm.

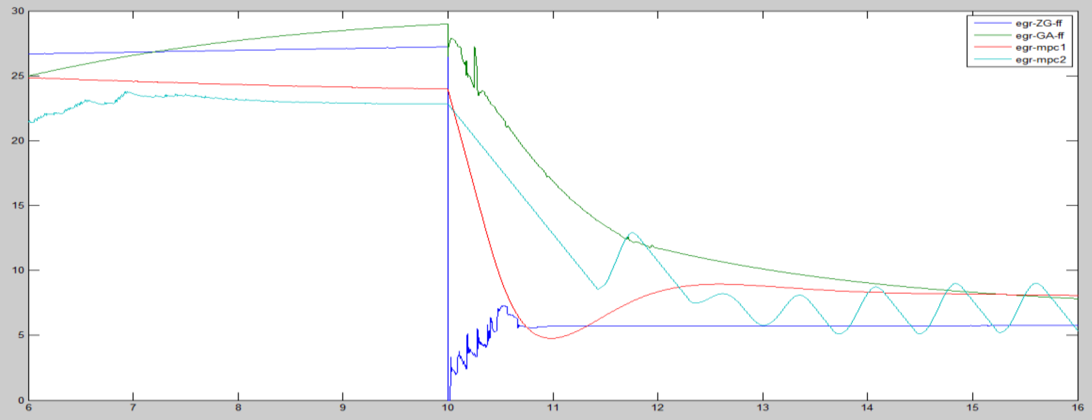

Figure 5.18 : EGR positions as controller output @ 1250 rpm.

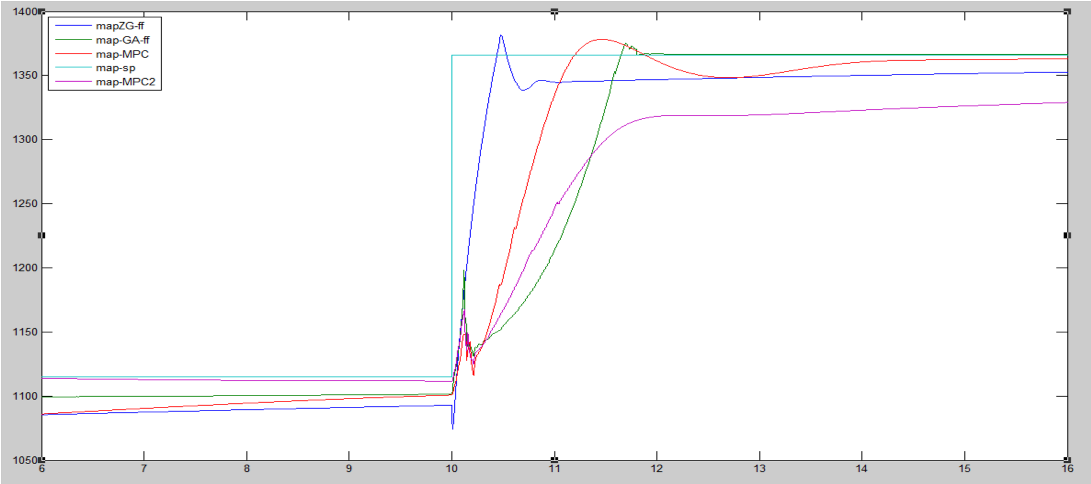

Figure 5.19 : MAP response of the controllers @ 1750 rpm.

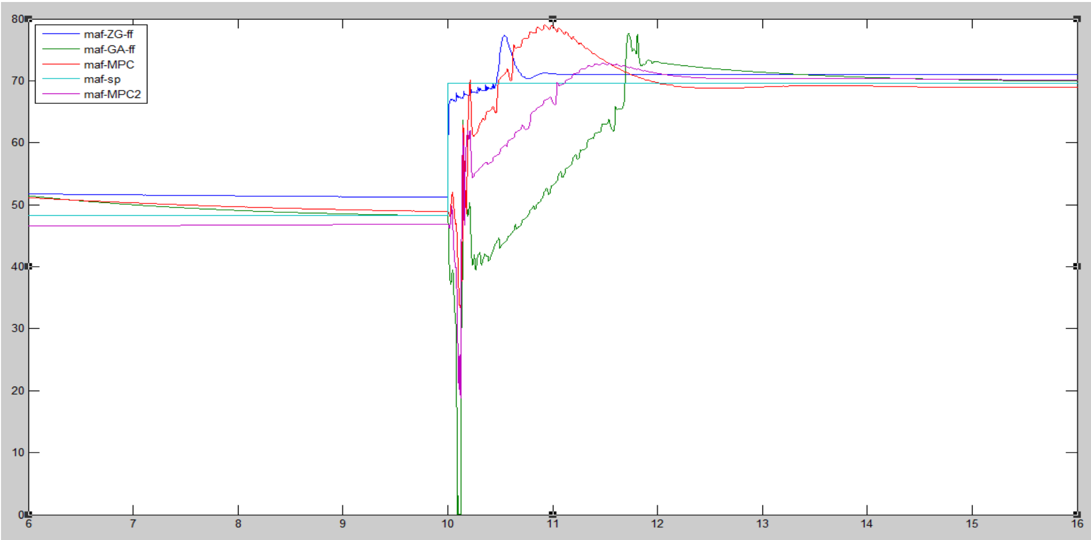

Figure 5.20 : MAF response of the controllers @ 1750 rpm.

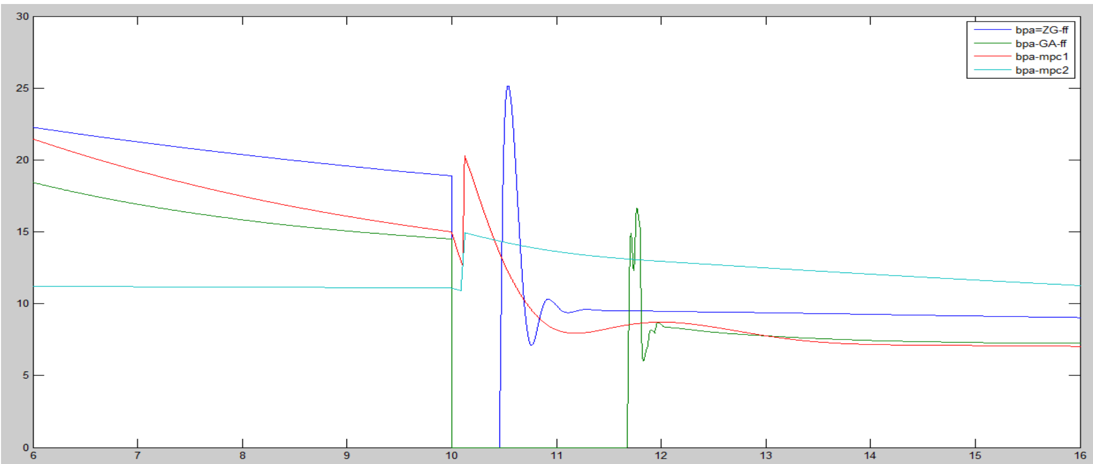

Figure 5.21 : VGT positions as controller output @ 1750 rpm.

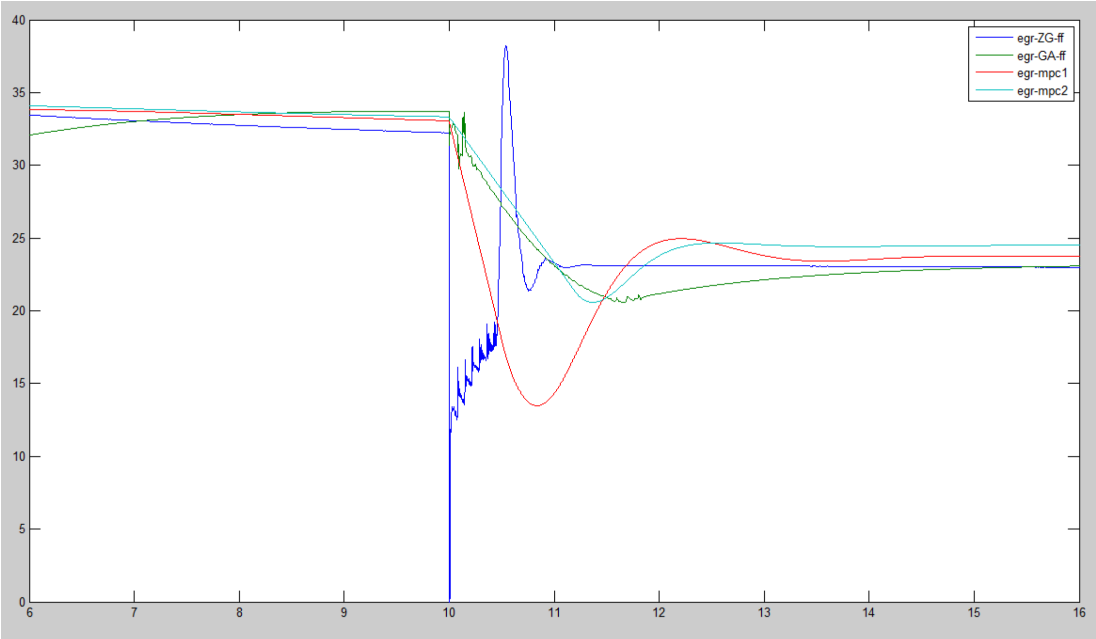

Figure 5.22 : EGR positions as controller output @ 1750 rpm.

Simulation in different rpm ranges showed that performance of MPC controller drops much. However, this is natural due to controller still uses the plant model identified in 2250 rpm. On the other hand, PID controllers also give worse response than the designed operating setpont. Working in the controllers designed for 2250 rpm in the other speed ranges, give the example of how complex the system. In real world, automitve control systems have gain scheduling PID parameter sets that have different controller calibration for different engine operating point. Certainly, similar approach may be applied to model predictive controller to optimize the system further.

6. CONLUSIONS AND RECOMMENDATIONS

In this research, one of the main targets was the development of a diesel engine model, which has exhaust gas recirculation and turbocharger. Use of AVL Boost RT software was proven as a succesful modeling environment due to its block based modeling approach, good handle of the physical phenomena, cooperation with matlab and so on. In order to test and develop controller algorithms for the automotive applications, modeling is crucial part especially for the researchers who are more focused on the controls. Thus, first outputs of this work is that Boost RT software provides the ease in modeling complex phenomena happening in the combustion engines.

Apart from modeling, another focus of the study is to evaluate single input single output approach to the diesel engine air path system. Particularly, to create an alternative controller tunning method and perhaps even controller structure, first system to be tested on the model was generic PID controllers tuned by Ziegler Nichols method. Weakness of the PID controller by only tunning of Ziegler Nichols was shown. Additionally, popular industry solution to cope with air path system so called pre-control or open loop feedforward controller as in the controls terminology was introduced to the system. The contrubition of the feedforward part was shown to prove its efficiency. However, open loop control is a time consuming activity.

Calibration of PID controllers is always a challenging task and may not be straightforward as it is described in Ziegler Nichols method. Hence, in industry, PID controllers are tuned by ZG oscillations method then calibration engineers try to improve the performance until its meet with design specifications. This study comes up with different and fully automized approach to employ genetic algorithms and use of cost functions to tune controllers. This method may take more time then ZG and manual work, however, there is no operator effect and it gives the optimum performance. Thus, use of genetic algorihm to tune PID controllers is one of the important output of the study.

The real mission of this reaearch is actually use of model predictive control, which copes with multi input multi output systems successfully, instead of two separate PID loops. As it is shown in the previous chapter, MPC scheme gave the best controller output in terms of stable robust air intake system. Its multi input multi output approach handles the coupling of the air path very well. Hence, the final conclusion of this work is to encourage use of model predictive controllers for the diesel engine air path. Today's automotive development, meeting with production plan is a already a big challenge. Hence, model predictive control requires quite less time than calibrating the PID plus open loop feedforward approach besides it is more accurate control.

Finally, this study has the potential to be developed further. The transient reponse and all operating points of engine might be tested by the use of adaptive MPC or gain scheduling methods. Another important step would be that implementation of the model and its control algorithm to the microcontrollers to run real time applications. Moreover, scope of the MPC scheme might be extended to test of different set of controllers, plant models and observers.

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