ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

INVESTIGATING THE EFFECT OF SPARK ADVANCE, COMPRESSION RATIO AND CHARGE PRESSURE ON PERFORMANCE OF AN ULTRABOOSTED GASOLINE ENGINE

M.Sc. THESIS

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Faculty of Mechanical Engineering

Automotive MSc Programme

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ATEŞLEME AVANSI, SIKIŞTIRMA ORANI VE DOLDURMA BASINCININ AŞIRI DOLDURMALI BENZİNLİ MOTOR PERFORMANSINA ETKİLERİNİN İNCELENMESİ

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Asena Nihan Ebrinç, a **M.Sc.** student of ITU **Faculty of Mechanical Engineering, Automotive MSc Programme** student ID **503131703**, successfully defended the **thesis** entitled "**INVESTIGATING THE EFFECT OF SPARK ADVANCE, COMPRESSION RATIO AND CHARGE PRESSURE ON PERFORMANCE OF AN ULTRABOOSTED GASOLINE ENGINE**", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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FOREWORD

This thesis is written as a completion for the Automotive M.Sc. programme in ITU Faculty of Mechanical Engineering. This thesis covers a validation and optimization of a spark ignition engine by investigating the basic engine parameters. The objective is to determine the critical parameters, which are most effective on the engine performance.

I would like to express my thankfulness to my advisor, Prof. Dr. Cem Soruşbay for his guidance during my study. I would like to thank my all colleagues in Ford Otosan,

A special thankfulness to my husband Ahmet Ebrinç, my supervisor Suphi Ramazanoğlu and my colleague Sedat Çevirgen for their great encouragement and confidence in me in the difficult periods of my thesis.

Last but not least, I would like to present my gratitude to my mother Nurten Çakır and my sister Yağmur Suna Çakır for their assistance, encouragement and love during my thesis and entire education life. I devote this work to my father Şeref Çakır I lost years ago.

Oct 2017 Asena Nihan EBRİNÇ

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ABBREVIATIONS

TDC	**:** Top Dead Center
BDC	**:** Bottom Dead Center
BSFC	**:** Brake Specific Fuel Consumption
CO	**:** Carbon monoxide
CO2	**:** Carbon dioxide
NOX	**:** Nitrogen oxide / dioxide
RPM	**:** Revolutions per Minute
IVO	**:** Intake Valve Opening
IVC	**:** Intake Valve Closing
CA	**:** Crank Angle
SW	**:** Software
Nm	**:** Newton meter
SI	**:** Spark Ignition
CI	**:** Compressed Ignition
NVH	**:** Noise, Vibration and Harshness

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SYMBOL LIST

D : Cylinder bore diameter
n : Engine speed
θ : Crank angle

INVESTIGATING THE EFFECT OF SPARK ADVANCE, COMPRESSION RATIO AND CHARGE PRESSURE ON PERFORMANCE OF AN ULTRABOOSTED GASOLINE ENGINE

SUMMARY

Nowadays, one of the most demanded items in the automotive industry is to get more powerful engines with high performance but with less fuel consumption and cost. As an output of this demand automotive manufacturers are concentrated on the software tools to be able to predict and simulate possible failure modes, reactions and different correlation of engine parameters with a high performance results. A big advantage of these software tools is to get a chance to run a simulation several times by changing the hundreds of engine parameters. It is not only costs save but also time save for manufacturers which allows getting more results with a short time rather than a real time dynamometer tests. Simulation programs are the biggest assistants for that purpose, which allow changing hundreds of engine parameters for different engine operating conditions.

To protect human health and achieve air quality standards, emission standards are getting tighter day by day overall the world, which is limiting specific amount of air pollutants that are released from fixed or mobile specific sources. Thus, suppliers also consider towing the rules for the restrictions. NOx, HC and CO pollutants are most critical ones that are produced by the internal combustion engines. By using the simulation programs this is also achieved to estimate the rate of pollutants that will be released from the system with entered input to the models. In same way it is possible to modify engine model based on these emission outputs by adjusting affecting parameters many times. This is a big advantage of simulation programs rather than usage of real engine setups and waste of time.

There are many parameters that may have impact on the internal combustion engine performance. Key factors could be listed as; compression ratio, spark advance, knocking limit, boost pressure and so on. The purpose of this study is to investigate the effect of these parameters on the engine performance by defining the optimum operating condition of a selected gasoline engine.

As a start point, engine to be run for five different compression ratios by sweeping from 8:1 to 12:1 based on swept spark advance. Spark advance has been swept from 0 to 50 deg CA, but for some of the compression ratios it was not possible to continue until 50 deg CA due to knocking. During this simulation it was important to monitor knocking limits as it will not be possible to continue analysis after a while due to engine knock by increased temperature and pressure with the incremental compression ratios. These datas were checked for 3 different engine speeds; 2000 rpm, 4000 rpm and 6000 rpm.

Based on the analysis results one of the conditions with maximum power and minimum fuel will be selected as optimum operating condition. Right after this selection, boost pressure will be the main factor to force to improve the engine operating conditions. Boost pressure impact to be investigated on the engine outputs by changing when compared to the baseline. In the meantime, as air is increased inside the cylinders, the more fuel will be required to provide appropriate air fuel ratio. So in the second trial there will be change on not only boost pressure where pressure is increased inside the manifold, but also injected fuel amount to be adjusted. Ultra-boost provides better combustion by having more compressed air inside the cylinders which means higher temperature and pressure during combustion process. Thus, challenging point for the ultra-charging is knocking probability again. It will be tracked to understand how charge pressure impacts the spark advance limits with engine knocking limits.

The outcomes from this thesis may contribute to have a perspective for improvement of the engine performance by using simulation programs and possible impacts of come critical parameters to engine performance.

ATEŞLEME AVANSI, SIKIŞTIMA ORANI VE DOLDURMA BASINCININ AŞIRI DOLDURMALI BENZİNLİ MOTOR PERFORMANSINA ETKİLERİNİN İNCELENMESİ

ÖZET

Günümüzde, otomotiv endüstrisinde en çok talep gören öğelerden biri, daha düşük yakıt tüketimiyle daha az maliyetli ve daha yüksek performanslı motorlar elde etmektir. Bu talebin bir sonucu olarak, otomotiv üreticileri muhtemel arıza modlarını, reaksiyonları ve motor parametrelerinin yüksek performans sonuçları ile farklı korelasyonunu tahmin edebilen ve simüle edebilen yazılım araçları üzerinde yoğunlaşmıştır. Bu yazılım araçlarının büyük avantajı yüzlerce motor parametresini değiştirerek bir simülasyonun birkaç kez çalıştırılmasına olanak tanınmasıdır. Bu yazılım programları gerçek zamanlı dinamometre testlerinin yerine, daha kısa sürede daha fazla sonuç alma imkanı veren; imalatçılar için yalnızca maliyet tasarrufu değil, ayrıca zamandan da tasarruf sağlanan araçlar olmuşlardır. Neredeyse tüm motor parçaları için çok kısa sürede, programlara girilen her farklı parametrenin gerçek hayattaki simülasyonu yapılabilir. Motor parçaları haricinde, egzoz emisyon tahminleri, malzeme dayanımları gibi araştırmalar için de bu programlardan faydalanılmaktadır. Simülasyon programlarının bu amaç doğrultusunda, yüzlerce motor parametresinin değiştirilmesine imkan tanıyarak farklı motor koşullarını gözlemlemede en büyük yardımcılardan olduğu söylenebilir. Özetle, analiz programları, geleneksel yöntemlere kıyasla daha uygulanabilir olduğundan tasarım ve analiz sürecinin hızlanması ve ekonomik olması yönünden çok fazla tercih edilmektedir.

Her geçen gün artan araç sayısı çevre kirliliğine yol açmakta ve insan sağlığını tehdit etmektedir. Bu sorundan yola çıkılarak, emisyon standartları, insan sağlığını korumak ve hava kalitesi standartlarını yakalamak amacıyla, sabit veya mobil kaynaklardan salınan belirli hava kirletici miktarlarını sınırlayacak şekilde günden güne sıkılaşmaktadır. Bu nedenle otomotiv üreticileri bu sınırlandırmalara sadık kalmak durumundadırlar. Emisyon standartları açısından önem arzeden kimyasallar, NOx, HC ve CO bileşenleri gibi içten yanmalı motorlar tarafından üretilen kritik kirleticilerdir. Ancak üreticilerin daha yüksek performanslı bir motor geliştirmesi için kullandıkları yöntemler, kimi zaman emisyon seviyelerinde artışa sebep olmaktadır. Güçte elde edilen artış ve yakıtta elde edilen tasarruf, negatif etkileri de beraberinde getirebilir. Yukarıda bahsedilen simülasyon programları kullanılarak, değişik koşullarda motor çalışmalarına ve tanımlanan yüzlerce değişik parametreye göre sistemlerden bu kirleticilerin ne seviyede yayılacağı hesaplanabilir ve emisyon standartlarına uyulacak şekilde veri girdisi sağlanarak doğru seviyeler ayarlanabilir ve böylece sadece dinamometrede test edilen bir motora göre, çok daha ekonomik ve hızlı sonuçlar alınabilir. Ayrıca dinamometre şartlarında aylarca süren bir test, bu program sayesinde, hem daha kısa sürede hem de birbirinden farklı varyasyonlar için oluştururalak koşulabilir.

Son yıllarda yukarıda belirtilen müşteri beklentilerini karşılamak amacıyla, performans ve yakıt ekonomisi dikkate alınarak, aşırı doldurmalı motorlar yaygın olarak kullanılmaya başlanmıştır. İçten yanmalı motorlarda kullanılan aşırı doldurma sistemlerin amacı moto verimini arttırmaya yöneliktir. Turboşarjlı ya da süperşarjlı olarak isimlendirilen bu sistemlerin ana prensibi, silindir içerisine basınçlı hava

gönderilerek yanma veriminin arttırılması, böylece egzoz sırasında dışarı atılan yanmamış yakıt oranın azalmasını sağlamaktır. Aşırı doldurma sırasında elde edilen yüksek basınç, sıcaklık ve daha iyi bir yanma sonucunda vuruntu ihtimali de gündeme gelmektedir.

Vuruntu sebeplerinin başında seçilen yakıttaki oktan sayısı gelir. Oktan sayısı kısaca, yakıtın motor vuruntusuna olan dayanımı olarak tanımlanabilir. Düşük oktan sayılı yakıtların tutuşmaya daha erken başlamasından dolayı, vuruntu ihtimali daha da artar. Bu çalışmada en yaygın olarak kullanılan oktan sayısı 95 olarak seçilmiştir.

İçten yanmalı motor performansını etkileyebilecek birçok parametre vardır. Bu çalışmada, bu parametrelerden ateşleme avansı, sıkıştırma oranı ve doldurma basıncı gibi faktörlerin motor performansı üzerindeki etkisi araştırılacak ve seçilen bir benzinli motor için en ideal çalışma şartları irdelenecektir. Bu sonuçlara varabilmek için, simülasyon programlarından Ricardo Wave isimli program kullanılmıştır. Wave programı motor performansı ve NVH analizlerinde kullanılan, tek boyutlu motor modelleme, gaz dinamik analizleri, denizcilik, yeraltı taşımacılığıı vb. gibi alanlarda kullanılan bir simülasyon SW paketidir. Programda performans ve akustik ile ilgili simülasyonlar, emme, yanma ve egzoz sistem düzenlemeleri, aktarma organları da gözönünde bulundurularak bütün araç simülasyonunu da gösterecek şekilde tamamlanabilir. Buji ateşlemeli motorlardaki ileri seviye yanma modellenmesi, aşırı doldurma için kompressör ve türbin haritalarının motor hacmine göre ayarlanması, gerçek zamanlı simülasyon yetkinliği, egzoz sistemlerinin modellenmesi bu program avantajları arasında gösterilebilir. Programa istenilen tüm girdiler eklenerek motor performansı hakkında yorumlar yapılabilir.

Başlangıç olarak, seçilen motor simülasyonda, 5 farklı sıkıştırma oranı için, 0 derece krank açısından, 50 derece krank açısına kadar koşturulacaktır. Fakat vuruntu limitlerine gelindiğinde her sıkıştırma oranı için 50 derece krank açısına kadar simülasyonu devam ettirmek mümkün olmayacaktır ve alınan grafiklerde 50 derece krank açısına gelmeden eğrilerin sona erdiği görülecektir. Bunun sebebi artan sıkıştırma oranlarında, daha fazla sıcaklık ve basınç değerlerine ulaşılması ve vuruntu sınırının belirlenme ihtiyacıdır. Yukarıda bahsedilen çalışma koşulları 3 farklı motor hızı için irdelenecektir. Bu üç farklı motor hızının verdiği motor çıktılarına göre, elde edilen en yüksek motor gücü ve en düşük yakıt tüketimi için yorumlama yapılacak, sonrasında irdelenen hız ve sıkıştırma oranı verilerinden optimum değerlerin alındığı sıkıştırma oranına ve hıza karar verilecektir.

Belirli bir motor hızı için seçilen optimum çalışma koşullarında bazı değişikliklere gidilerek, motor gücü ve yakıt tüketimi için alınan değerlerde tekrar iyileştirme çalışması yapılacaktır. Bu iyileştirme çalışması halihazırda turboşarjlı olan motorda, aşırı doldurma yapılarak ve yine vuruntu limitleri göz önüne alınarak farklı ateşleme avansları taranacak şekilde yapılacaktır. Doldurma basıncı ilk alınan değere göre yüzdesel olarak arttırılacak ve motor çıktıları tekrar control edilecektir. Motor silindirleri içine daha fazla sıkıştırmış hava gönderildiğinden, optimum hava yakıt karışımını sağlayabilmek adına, silindirler içerisine verilen yakıt miktarı da aynı şekilde belli yüzdelerle arttırılacaktır. Böylelikle sadece doldurma basıncı değil, yakıt miktarının da ayarlanıp, bir artışa gidilerek sonuçların irdelenmesi gerekecektir. Aşırı doldurma silindir içerisine gönderilen sıkıştırlmış ve daha fazla hava miktarı sayesinde daha bir yanma sağlar. Bu da daha yüksek sıcaklık ve basınç verileri anlamına gelir. Yüksek basınç ve sıcaklığın bir ürünü olan vuruntu ihtimali tekrar karşılaşılan bir sorun haline gelir. Bunu yorumlayabilmek için, silindir içinde oluşan

basınç ve sıcaklık verileri baz alınarak vuruntu hesabı yapılacaktır. Elde edilen vuruntu limitlerine göre, her farklı motor hızı için ateşleme avansının hangi noktalarda yapılabileceği araştırılarak, çıktıların değerlendirmesi yapılacaktır.

Son olarak elde edilen veriler başlangıç koşullarına göre incelenerek bir kıyaslama yapılacaktır. Bu sayede seçilen benzinli ve aşırı doldurmalı bir motorda, belli başlı motor parametrelerinin değiştirilerek en iyi çalışma koşullarına nasıl ulaşılabileceği ve aşırı doldurmanın etkileri irdelenecektir.

1. INTRODUCTION

1.1 Motivation

Internal combustion engines are widely used engines in the automotive industry, and also gasoline engine usage is quite much all over the world. So the purpose of the manufacturers is to get high quality and performance with the correct correlation of all vehicle parameters as well as the possible lower fuel consumption as an advantage. This view is a motivation to start this thesis to investigate some of these parameter's impact on a spark ignition engine by getting the optimum engine working conditions.

1.2 Literature Review

A number of considerable studies presented over the last years to explain the method of improvement for the SI engine performance. There are several parameters that have impact on the engine working conditions. Compression ratio, spark advance, boost pressure and so on. In some of the researches, the effect of different compression ratios on both emissions and engine performance was studied to find optimum level of the operating conditions. Increasing the compression ratio could improve the thermal efficiency of an internal combustion engine by producing more engine power. It was also observed as a reduction on BSFC level by increased compression ratio [1]. But there is a limitation for compression ratio which is knocking limit, due to increased temperature and pressure levels. Knocking also directly defines the emission level on an IC engine, durability, BSFC as well as the power. There are different trends of knocking for normal combustion, conventional knock and super knock. These trends can be controlled with correct spark timing by defining optimum operation points [2] [3]. As a function of spark advance angle for various compression ratios, there was a significant decrease on fuel consumption by increased compression ratio. As mentioned above limitation is the knocking limit, which prevents to get more power or lower BSFC with more compression ratio and

boost pressure the more probability of engine knocking occurs [4] [5]. Lately, there is an increasing interest in supercharging on SI engines. At this point, it is necessary to mention about the effect of boost pressure on engine performance and exhaust emissions. Getting more air inside the manifold by creating boost pressure, improves the combustion to give better performance output [6].

1.3 Objective

Literature survey and the background knowledge presented that engine performance improvement is a key factor for the engine production by selecting the correct and optimum engine parameters. To be able to get a wide customer map and high level confident of a production, it is must to create correct design of a vehicle and the engine to be able to satisfy customers as well as to have a good reputation in the market. Thus, the objectives of this thesis are to develop a SI engine model by using the Ricardo-Wave software and investigating the possible performance improvements by adjusting the critical engine parameters. As mentioned in the motivation section, spark advance, compression ratio and boost pressure will be examined to come to a conclusion for engine performance enhancement. Once model is created in the Ricardo Wave SW tool, all compression ratios to be swept from 8:1 to 12:1 for 2000, 4000 and 6000 rpms against to different spark advances. In the meantime, in-cylinder pressure and temperature values to be monitored to calculate knocking integral to recognize at which spark timing knock occurs for each condition. Based on the outputs for these operating conditions, maximum power and lower BSFC point to be selected as second start point. As soon as the optimum point is gathered, boost pressure impact will be investigated to see the impact on engine power, BSFC as well as the emissions. It will be also required to adjust injection flow rate as it is comparative to the boost pressure where to gain AFR as 14.7 (stoichiometric ratio).

2. GENERAL REMARKS

2.1 Internal Combustion Engines

Internal combustion engines generate mechanical power by combustion of a fuel-air mixture. Combustion process is a way of releasing energy from the fuel-air mixture. Working principle of this process is to convert chemical energy of the fuel to mechanical energy by a rotating output shaft. With the combustion of the mixture inside the cylinders, chemical energy of the fuel is converted to thermal energy by raised temperature and pressure inside the cylinders. After then crankshaft is rotated with the expansion of high pressure gasses which generates the mechanical energy as an output of the engine.

There are generally two types of internal combustion engines in automotive industry; compression ignition diesel engines and spark ignition gasoline engines. Usually both of these engines are four-stroke cycle engines which imply that each cycle requires intake, compression, combustion and exhaust events [7].

2.1.1 Spark Ignition Engine Basics

Spark ignition engines are internal combustion engines, which are also called as gasoline engines. The main principle of the SI engines is the usage of spark plug to start combustion process in each cycle. At the end of the compression event, spark plug provides required spark inside the cylinder to start combustion event.

2.1.2 Comparison of Spark Ignition and Compression Ignition Engines

Spark ignition gasoline and compression ignition diesel engines differ in how they supply and ignite the fuel. In a spark ignition engine, spark plugs are used to start combustion with the mixed fuel and air which inducted to the cylinders during intake event. In a diesel engine, vaporized fuel is sent into cylinder with pressurized, hot air which causes the ignition in a different way than SI engines. Because of the high compression ratio and temperatures on CI engines, the torque generated by CI

engines is very high when compared to SI engines. This also brings a negative impact on CI engines as high vibrations.

2.2 Turbocharging

Turbochargers are supply systems that compress the air entering the engine causing it to be extremely dense; with more air in a small area, more gasoline can be coupled with the air creating larger explosions in the cylinder which help the car to progress forward.

As more gas passed through the turbine housing, the faster the turbine wheel rotates. Compressor wheel speed increases with the impact of the increased turbine wheel speed. This creates a sucking process which procures air from the atmosphere into the compressor cover. The faster the wheels spin, the more air is absorbed in. As the air is sucked into the compressor cover, it is forced through a diffuser area which compresses the air and leads it into the engine. This process results the increase temperature in the air, up to 180°C.

Figure 2.1 : Turbocharger [8].

Some of the advantages of turbocharges could be listed as follow:

- By getting more pressurized air inside the cylinders, the more power engine produces.
- İdeal combustion occurs at stoichiometric ratio of about 14.7:1. That means the more air you burn, the more fuel has to be burned.

- Performance of turbocharges are profitable particularly at high altitudes. Because of the high air pressure at high altitudes, the power loss of the ordinary engines is more than turbocharged engines.
- Turbocharged engines consume less fuel when compared to air powered engines with similar power.

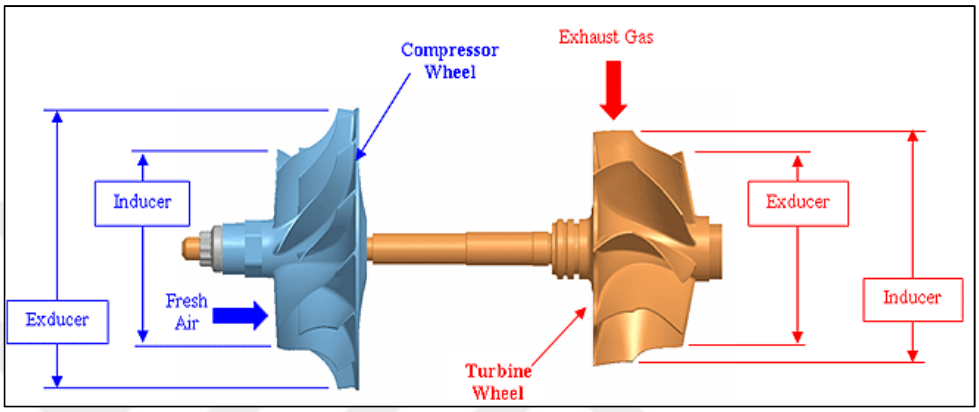


Figure 2.2 : Turbocharger structure [8].

2.3 Boost Pressure

Boost pressure is the pressure that is created by turbocharger system. The air pressure in the inlet manifold could be described as boost pressure. It is proportional with the exhaust thermal energy. Hence higher engine RPM drives higher boost pressure.

Exhaust gases from the engine are used to spin the turbine, which in turn drives the compressor through a shared shaft, which generates boost pressure to be sent to the engine. Based on the experiences typical boost level is 1.0 – 1.8 bar [10].

Turbochargers' basic purpose is to create boost pressure, so when an otherwise strong running engine suddenly becomes powerless usually it may mean turbocharger trouble.

2.4 Spark Advance

Ignition timing (spark advance) is the process of angle setting relative to both crankshaft angular velocity as well as the piston position to start an arc, which will

occur close to end of the compression event in the cylinder. Spark is given before piston position at TDC that allows having better mixture of the fuel-air.

Correct ignition timing is a substantial parameter that needs to be set. Getting the spark too soon or too late may cause different problems in the engine like excessive vibrations or even it may cause engine damage. It also has impact on fuel economy, engine power, knocking and so on. Recent times, older engines used mechanical spark distributors, which are driven by inertia as well as manifold vacuum. Current modern engines use a control unit in order to set spark timing, which is depending on load range, engine RPM etc.

Any greater changes on the engine would drive a change to the ignition timing. There may be many factors that have impact on the spark advance like; engine speed, turbo boost pressure, intake air pressure, engine temperature, fuel type, content of the fuel, and the position of the spark plugs etc.

Spark advance is also used to adjust knocking characteristics for the turbocharged SI engines.

2.5 Engine Knocking

Engine knocking is described as a metallic sound that engine makes during gas pedal is pressed. It is one of the most restrictive factors in increasing the efficiency of gasoline engines as an abnormal combustion process that occurs when part of the unburned air/fuel mixture explodes outside the envelope of the normal combustion front. That drives fuel to burn in mismatched pockets instead of uniform explosion; this may also cause damage to piston and cylinder wall. Possible sources of the knocking are; usages of low octane rating, incorrect spark plug selection, carbon deposits that cause improper combustion process [7].

Octane number is one of the most important parameters of the knocking possibility. It could be defined as a standard measure of the performance of an engine fuel against to knocking. The higher octane number the greater the resistance gas to knocking. The octane requirement of a gasoline engine changes with the compression ratio and other operating conditions, which has results on engine performance by helping increasing the efficiency.

3. ENGINE MODEL

3.1 Engine Specifications

For this study 1.0L 125 PS GTDI engine is modelled on the Ricardo Wave software. Model creation details to be explained in the following section. This gasoline engine to be addressed based on full load conditions for particular RPM values. Basic engine specifications as follow:

Table 3.1 : Engine Specificications

Bore	71,9 mm
Stroke	82 mm
Number of Cylinders	3
Engine Displacement	0,999 L
Rod Length	137 mm
Piston Pin Offset	7,5 mm
Firing Order	1, 2, 3
Fuel	Gasoline
Injection System	GDI
Induction System	Turbocharged
Maximum Power	125 PS

4. METHODS OF USED SOFTWARE – RICARDO WAVE

4.1 Ricardo Wave

Ricardo Wave is 1D gas dynamics and engine simulation software tool which used for the engine performance analysis and NVH. It also procures to analyse mass flows, energy losses at connection points and dynamics of pressure waves.

By using one-dimensional formulation, Wave tool enables performance simulations of any exhaust, combustion and intake system constellations. It allows to get engine performance outputs by creating CI and SI combustion sub-models, NOx, CO and HC emissions sub-models, cylinder pressure heat release analysis, torque response studies, intake and exhaust geometric designs, fuel consumption prediction and so on.

Basically, Wave tool has tree primary types as pre-processors, solvers, post-processors.

Pre-processors are used to establish the simulations. The pre-processors allow user to put all required input to the relevant windows by adding critical parameters of the engine that allows describing simulation and getting analysis results. The provided information to the pre-processor is transformed as an input format for the solver.

Solvers are used to examine the data provided by the pre-processors. The solvers are almost entirely non-interactive; they simply read input data, process it, and create output data from the simulation.

Post-processors are used to view and decode the results provided by the solvers for the simulation. It is possible to create 2-D and 3-D graphs, pictures of results and simple text reporting based on the user input. WavePost tool is used for this study to create all relevant outputs. The WavePost is graphical post processor which enables visualization and report generation by adding multiple plots for the needed outputs [9].

4.2 SI Engine Model Creation

SI engine model creation starts with a single cylinder model creation in the Wave tool. In order to model single cylinder engine intake and exhaust ports are created with duct elements as start point as well as to be able to simulate the real life conditions ambient junctions added. Likewise, all other features added to the model; cylinder, engine, compressor, turbine, injectors, intake-exhaust manifolds, catalyst and so on.

Figure 4.1 : SI engine base components [9].

One of the important parameters is the engine block where geometry, combustion, operating parameters, turbulence and flow are defined.

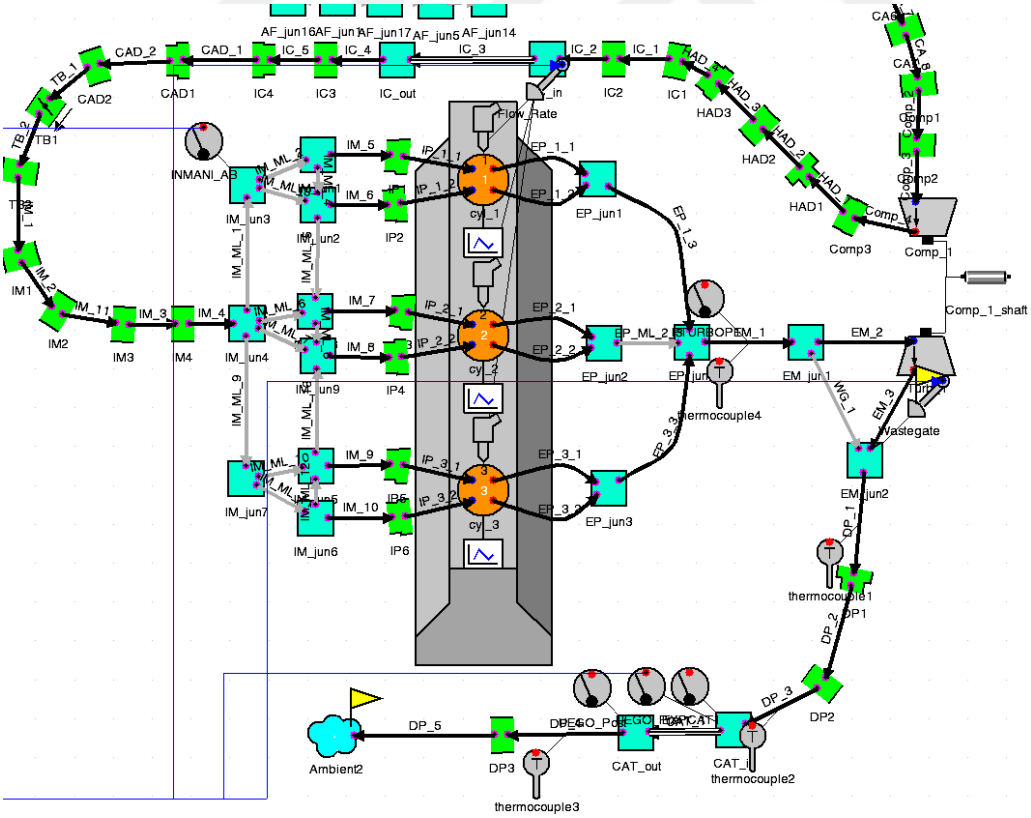


Figure 4.2 : SI engine model in Ricardo Wave software tool.

Geometry tab is used to define number of cylinders, stroke per cycle, engine type, piston details, firing order for each cylinder and some other additional data.

Operating parameters tab is to describe engine speed, reference pressure and reference temperatures. These values are added directly to constants table where they are defined specific for each different case and could be changed manually for each situation. If these values will not be swept or if they will be kept as fixed, then they would be directly added in the Operating Parameters tab.

In Turbulence and Flow tab relevant flow model needs to be added to simulate the turbulent flow inside the cylinders based on cylinder geometry. In the Head Geometry tab turbulent flame CAD file is inserted for correct cylinder modelling.

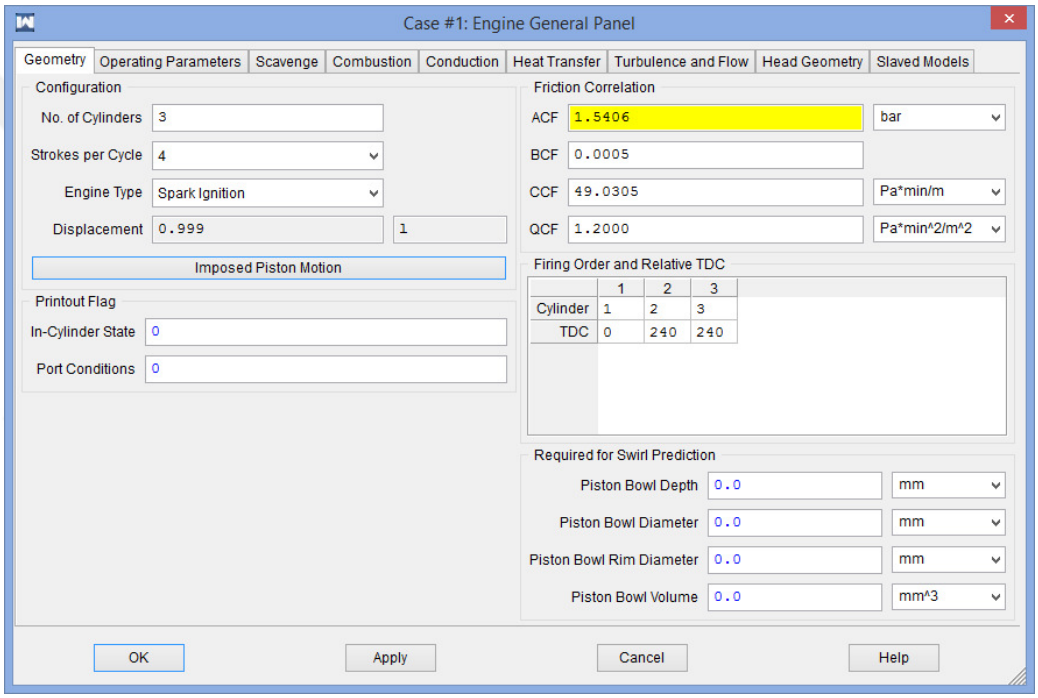
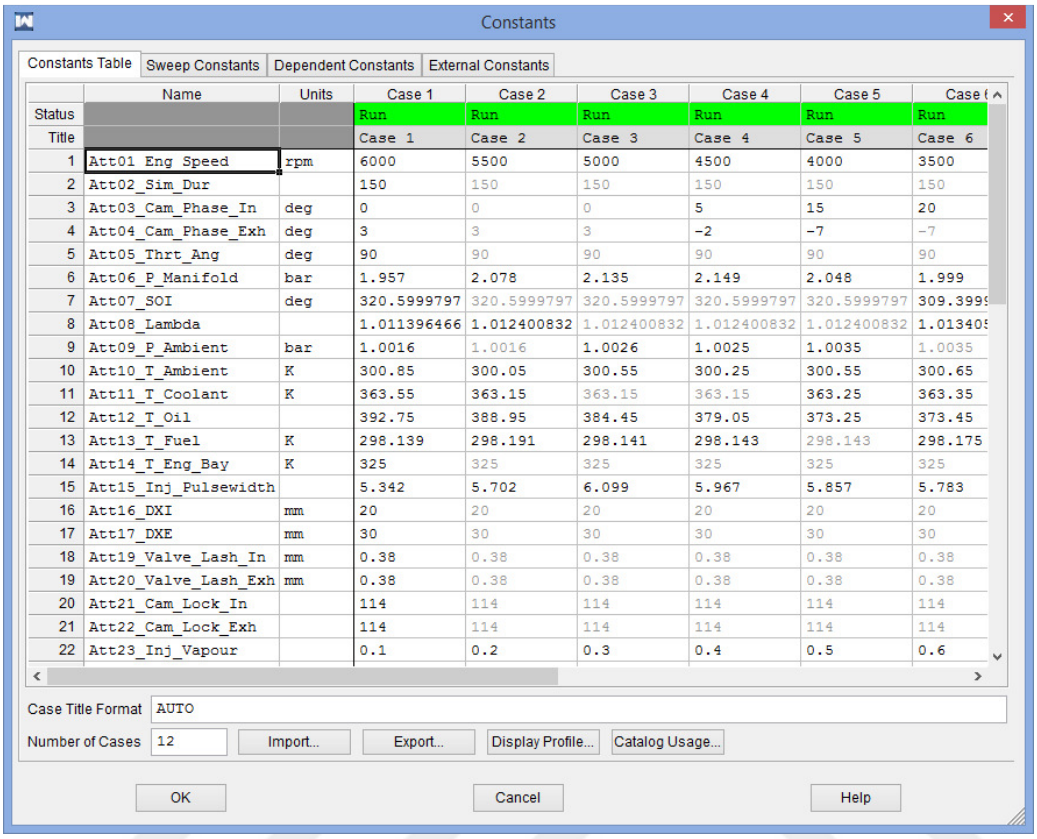


Figure 4.3 : Engine general panel.

Likewise, emission functions could be switched on from the combustion tab to get NOx, CO and HC models. Emissions sub-models are used to calculate the in-cylinder accumulation of common engine emissions forms. These emissions sub-models for SI engines, predicts emissions production during combustion and exhaust. Details of the emission predictions in the simulation program, to be given in the following sections.

A simple knock prediction model is also available in the combustion tab. Ricardo Wave SW does not give exact knocking integral value, hence knocking integral calculation formula is used to find out knock limits. Based on the in-cylinder temperature and pressure it will be easy to find knocking integral with a formula [3].



	Name	Units	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Status			Run	Run	Run	Run	Run	Run
Title			Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
1	Att01_Eng_Speed	rpm	6000	5500	5000	4500	4000	3500
2	Att02_Sim_Dur		150	150	150	150	150	150
3	Att03_Cam_Phase_In	deg	0	0	0	5	15	20
4	Att04_Cam_Phase_Exh	deg	3	3	3	-2	-7	-7
5	Att05_Thrt_Ang	deg	90	90	90	90	90	90
6	Att06_P_Manifold	bar	1.957	2.078	2.135	2.149	2.048	1.999
7	Att07_SOI	deg	320.5999797	320.5999797	320.5999797	320.5999797	320.5999797	309.3995
8	Att08_Lambda		1.011396466	1.012400832	1.012400832	1.012400832	1.012400832	1.013405
9	Att09_P_Ambient	bar	1.0016	1.0016	1.0026	1.0025	1.0035	1.0035
10	Att10_T_Ambient	K	300.85	300.05	300.55	300.25	300.55	300.65
11	Att11_T_Coolant	K	363.55	363.15	363.15	363.15	363.25	363.35
12	Att12_T_Oil		392.75	388.95	384.45	379.05	373.25	373.45
13	Att13_T_Fuel	K	298.139	298.191	298.141	298.143	298.143	298.175
14	Att14_T_Eng_Bay	K	325	325	325	325	325	325
15	Att15_Inj_Pulsewidth		5.342	5.702	6.099	5.967	5.857	5.783
16	Att16_DXI	mm	20	20	20	20	20	20
17	Att17_DXE	mm	30	30	30	30	30	30
18	Att19_Valve_Lash_In	mm	0.38	0.38	0.38	0.38	0.38	0.38
19	Att20_Valve_Lash_Exh	mm	0.38	0.38	0.38	0.38	0.38	0.38
20	Att21_Cam_Lock_In		114	114	114	114	114	114
21	Att22_Cam_Lock_Exh		114	114	114	114	114	114
22	Att23_Inj_Vapour		0.1	0.2	0.3	0.4	0.5	0.6

Figure 4.4 : Constant table.

Cylinder geometry is a critical input to the model. Important inputs could be listed as follow:

- Initial conditions for piston top temperature
- Initial conditions cylinder liner temperature
- Initial conditions cylinder head temperature,
- Valve definitions
- Sub-models:
    - Primary combustion model as Turbulent Flame Model
    - Heat transfer model as Woschni Model

Based on the engine data, all required inputs entered to the software for cylinder details and sub-models. These sub-models should be also part of the cylinder design to be able obtain reasonable data outputs.

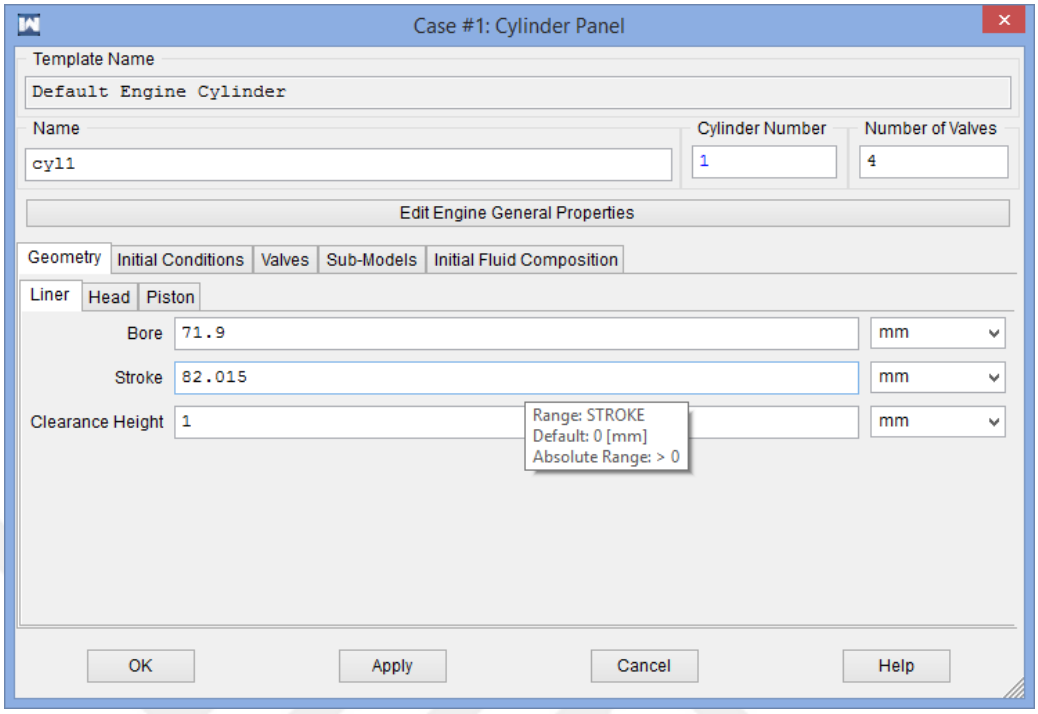


Figure 4.5 : Cylinder panel.

Hence, 1.0L engine model is with turbocharger, compressor and turbine details also entered to the software. Turbine map and compressor map files are get from the manufacturer to provide the data to Wave software. Turbine map gives the turbine performance values based on speed vs pressure ratio. Compressor map gives the compressor performance by pressure ratio vs mass flow rate. These are important inputs to understand the performance range of the turbocharger by commenting on the maps.

Compressor map is mapped on axes of air flow rate versus pressure ratio. Pressure ratio = P1 / P2

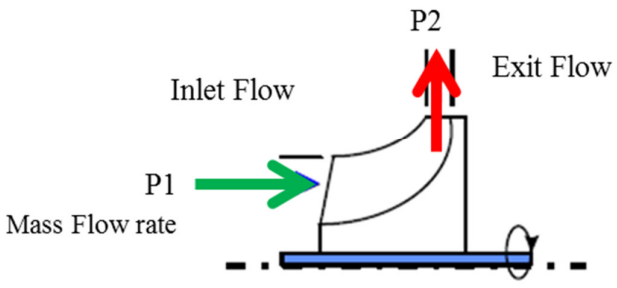


Figure 4.6 : Mass flow rate.

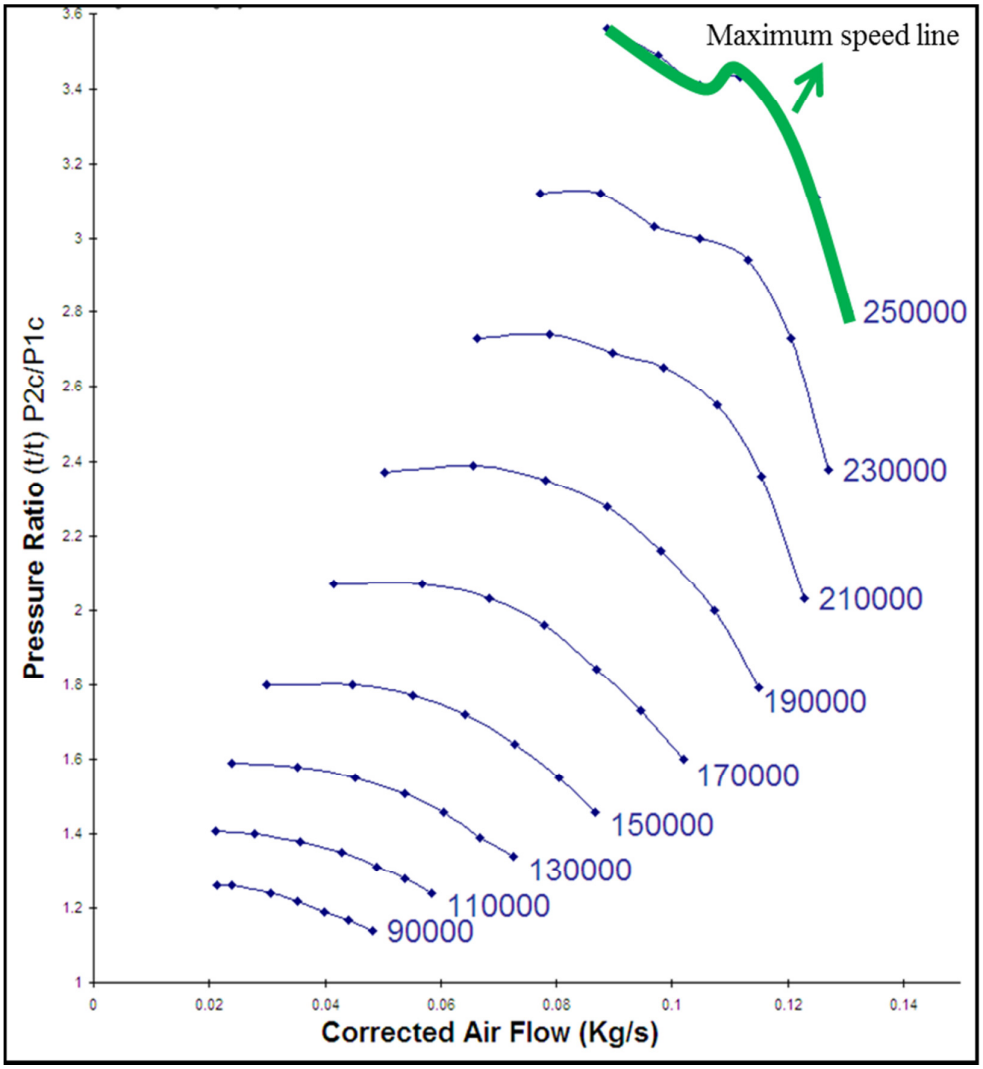


Figure 4.7 : Compression map example [10].

4.2.1 SI Turbulent Flame Model Creation

Combustion is one of the major inputs for a 1-D gas modelling simulations. To be able to start creation of combustion model "Combustion" tab is a used which allows modelling with either Wiebe or turbulent flame model for SI engines. For this study turbulent flame is used, in this way it was able to adjust spark advance for each cases. This primary combustion model could be applied to all cylinder elements in an SI engine and it is required to be used with specified cylinder head geometry as well as flow sub-model. There is another tab inside the "Turbulent Flame Combustion Model" as "Flame" where burned map file should be inserted.

Instead of defining a constant to this function, spark advance was added to the constant table as “Spark Timing”, which is modified during simulation for different compression ratios and engine speeds.

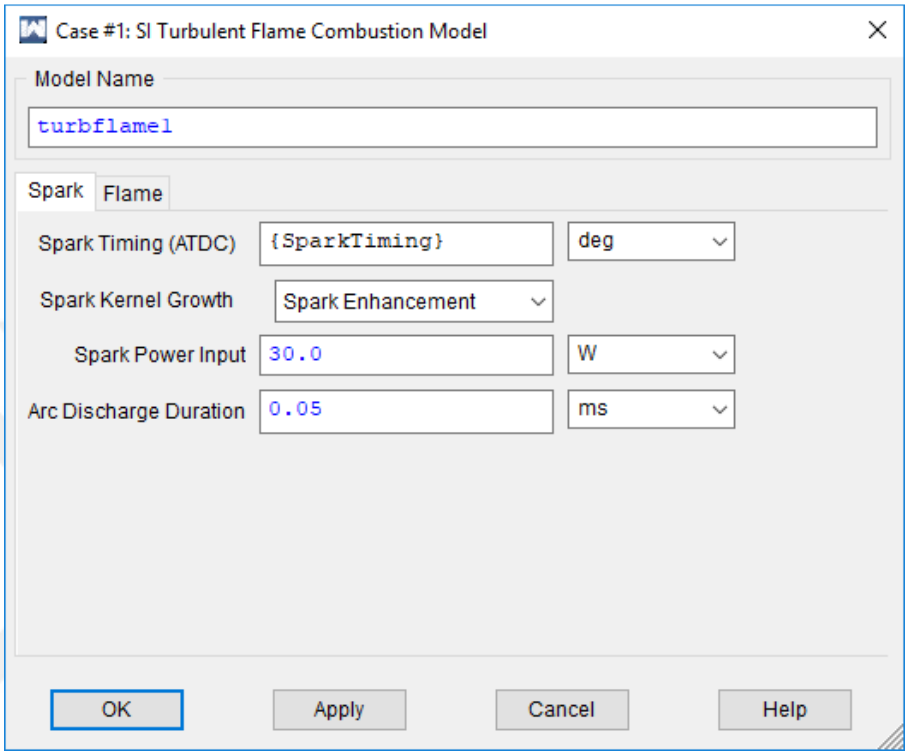


Figure 4.8 : Turbulent flame combustion model and spark timing definition.

Some additional data is required as an input to this combustion sub-model. Stl CAD data is used for the engine cylinder geometry, which is inserted into the flame model during model creation. This CAD file should be imported to Wave Mesher to adjust spark plug, valves and piston boundaries. WaveMesher, is an additional tool inside the Wave program, is used to simulate 3D geometry of the cylinders as well as to predict the burned/unburned zones volumes inside the cylinders. In the Flame tab this meshed CAD model is inserted to help prediction of the turbulent flame based on cylinder geometry.

Predictive model is created with closed valve positions and piston is positioned at TDC. Swirl orientation is around the z axis and the tumble orientation is around the y axis.

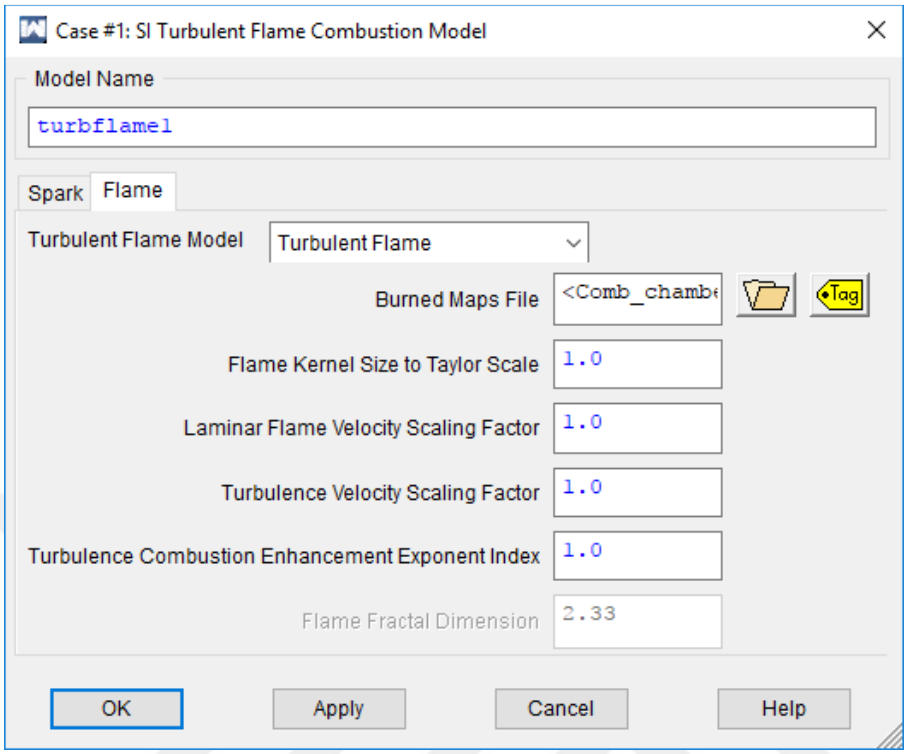


Figure 4.9 : Turbulent flame combustion model and turbulent flame model definition.

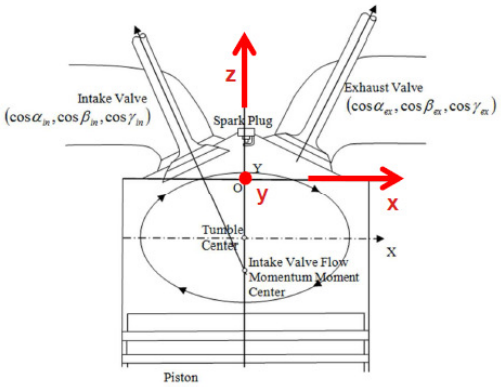


Figure 4.10 : Cylinder geometry and valve position [9].

Cylinder geometry is defined in the WaveMesher tool based on the engine specifications. Boundaries are required to define the 3D model in details, like piston, liner, head, intake valves, spark plug and exhaust valves. WaveMesher tool ensures to define all boundaries for listed details above.

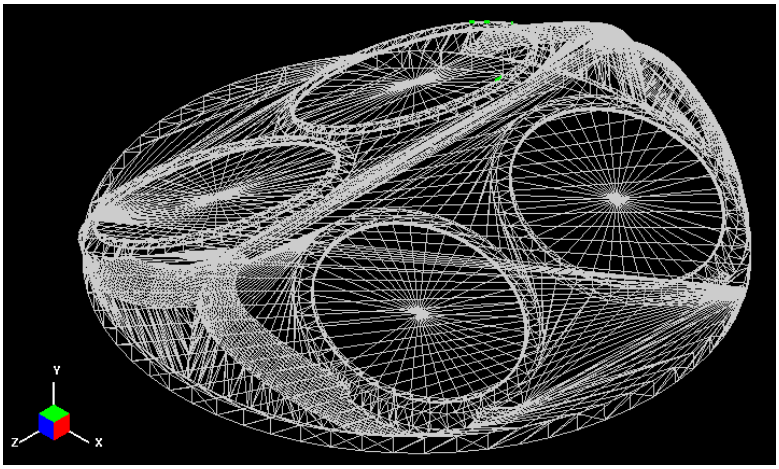


Figure 4.11 : Valve geometry in Wave Mesher tool [9].

Boundary painting is a method to define intake / exhaust valves and cylinder boundaries to be able mesh all geometry and get a better simulation of flame model. After creating all boundaries, SW allows to create a combustion map, which will be used in the turbulent flame combustion model.

4.3 Knock Prediction

Engine knock is one of the challenging event for the internal combustion engines. It is also one of the most definitive factors in increasing the efficiency of gasoline engines. Knowing the knocking limits of an engine and taking into consideration this information in the 1D simulation model is requisite for performance optimization and get real time results. To be able to predict knock behaviour for each individual cycles, following formula is used based on in-cylinder pressure and temperature. Required inputs for this formula are; fuel octane number, activation temperature multiplier, and pre-exponential multiplier. The typical number for fuel octane number is 95 for gasolines.

$$\tau = 17.68\left(\frac{ON}{100}\right)^{3.402} * P^{-1.7} \exp\left(\frac{3800}{T}\right)$$

where: A_p = User-entered pre-exponential multiplier

ON = User-entered fuel octane number

P = Cylinder pressure [kgf/cm^2]

A_T = User entered activation temperature multiplier

T = Unburned gas temperature [K]

4.4 NO_x Emissions Prediction in the Model

NOx emissions sub-model in the Wave tool could calculate the NOx formation during combustion and exhaust events in the engine cylinders. NOx formations are strongly temperature dependent hence non-homogeneity of the flame inside the cylinder combustion chamber should be considered. All the NOx is assumed to be in the form of NO during the prompt formation phase as well as the thermal phase described below by the extended Zeldovich mechanisms of NOx formation [3]:

$$N + NO_2 \rightarrow N_2 + O$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

4.5 HC Emissions Prediction in the Model

HC emissions sub-model in the Wave tool could also calculate the HC emissions. There are several inputs to create the model for the HC prediction like, oil density, molecular weight of the engine oil, array of temperature values corresponding to the viscosity array.

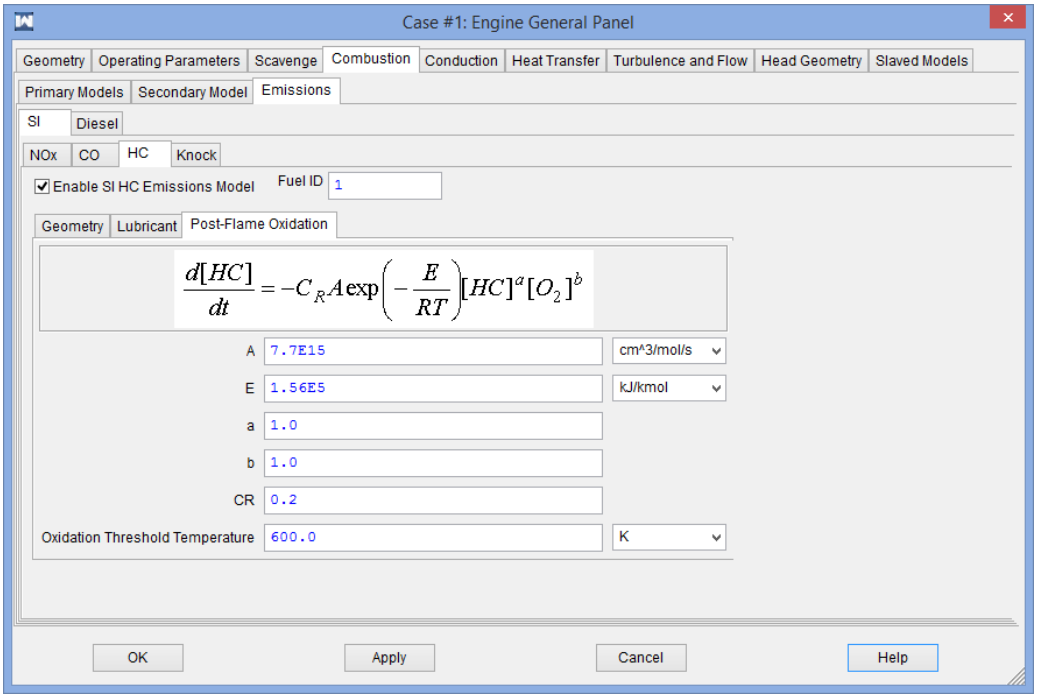


Figure 4.12 : Hydrocarbon emissions calculation in the simulation [9].

5. ANALYSIS AND RESULTS

During this study engine performance outputs investigated based on different engine speeds, compression ratios and spark advances. To this respect; engine power, BSFC, brake specific CO, brake specific NO values examined to come through optimized engine operating conditions by sweeping engine speed from 2000 rpm to 6000 rpm; in the meantime, spark advance has been changed from 0 deg to 50 deg, which will be explained in detailed in the following sections.

Once maximum engine power and minimum BSFC are obtained for a particular compression ratio and spark advance, boost pressure to be increased to come up to push the limits for more power and lower BSFC, this point to be determined as the ideal working conditions for this 3 cylinder, turbocharged, gasoline engine.

5.1 Influence of Spark Advance on Engine Performance for Different Compression Ratios

During engine operation, different rpm values and compression ratios have impact on the performance. After model run in the Ricardo Wave software for the 3-cylinder engine, following plots created to interpret possible impacts on engine performance by changing spark advance as well as engine speed. Compression ratio is swept from 8:1 to 12:1; in the meantime, spark advance is swept from 0 deg to 50 deg.

5.1.1 Model Outputs for Compression Ratio 8:1

As a start point compression ratio is selected as 8:1 and spark advance is swept from 0 to 50 deg CA. During 0 deg CA spark advance, BSFC is captured between 350-400 g/kWh for almost all speeds; once spark advance is reached up to 50 deg CA, BSFC started to drop down for all rpms by increased spark advance prior to the top dead center.

Lowest BSFC value is determined at 45-degree spark advance, where engine maximum power is got at same spark advance for 6000 rpm for 8:1 compression ratio. As purpose of this study, this approach to be applied for all compression ratios

to monitor maximum power with minimum BSFC. At the end the most proper condition to be focused to optimize engine operating conditions with the increased boost pressure. Thus, turbocharger impact on a gasoline engine will come to exist with impact on engine power and BSFC. Turbocharger impact to be applied by increased boost pressure on the manifold side. As more air to be sent inside the cylinders, more fuel injection to be adjusted as well. As explained in the prior sections knocking integral is calculated for each single compression ratio status and each engine speeds, based on the cylinder pressure and temperature. As shown in the engine power and BSFC curves; knock has been detected on different spark advances for each particular rpm value. It was 20 deg CA for 2000 rpm, 30 deg CA for 4000rpm and 48 deg CA for 6000 rpm. It is possible to receive power and fuel consumption datas up to these limits. These knocking limits for different RPMs will be shown in the following sections on the engine power and BSFC curves.

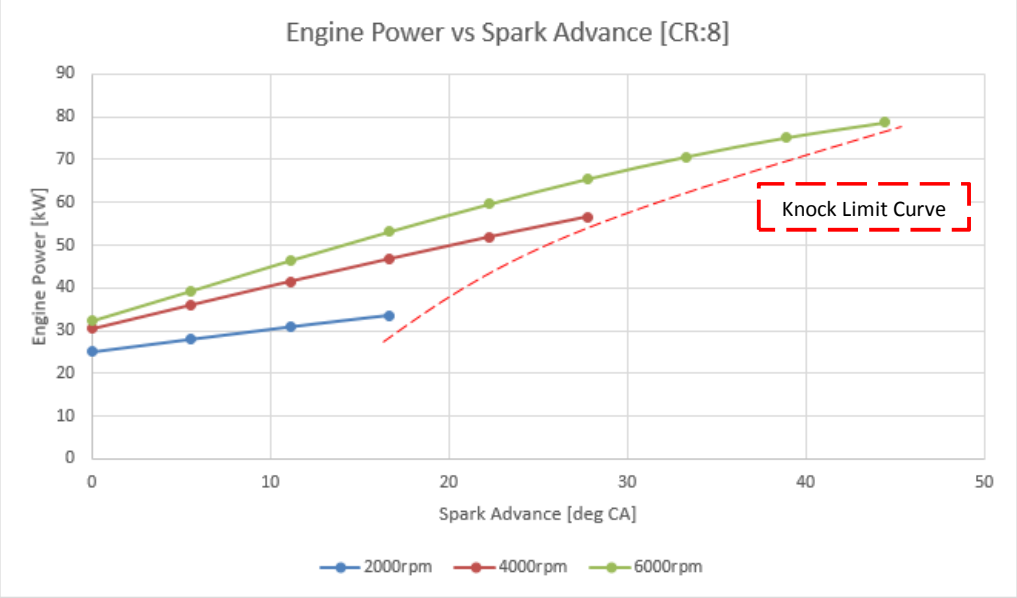


Figure 5.1 : Engine power vs spark advance [CR: 8].

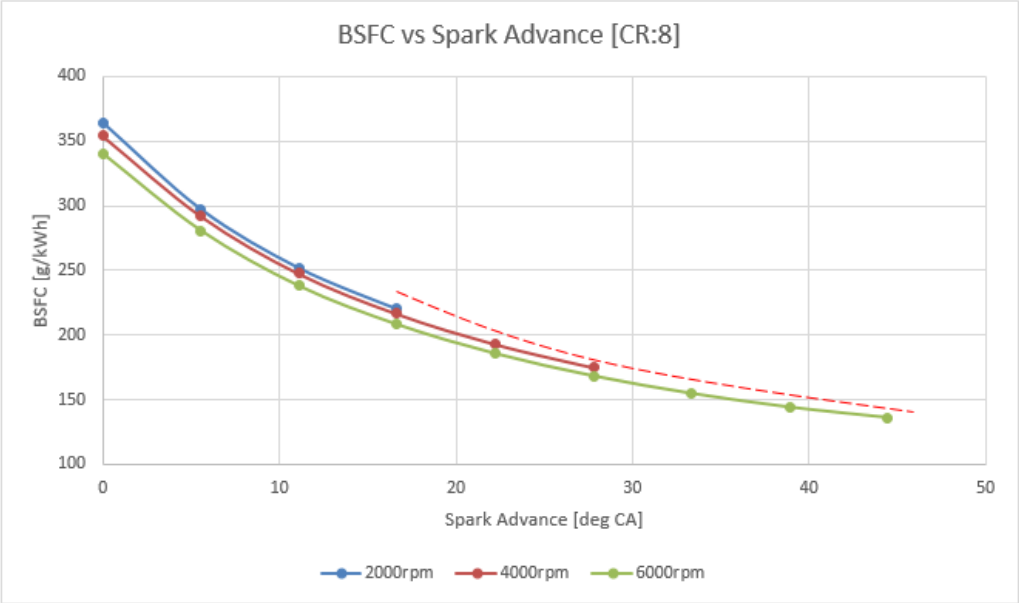


Figure 5.2 : BSFC vs spark advance [CR: 8].

5.1.1.1 **Emission Outputs for Compression Ratio 8:1**

CO and NO levels are critical from emission perspective. Hence following plots are created to investigate.

It has been observed that CO levels for all engine speeds decreases with the increasing spark advance. Similar trend is also captured for brake specific NO. Minimum brake specific CO formation was detected at 6000 rpm and 45 deg CA, which matches with the maximum power and minimum BSFC curves. Alternatively, brake specific NO amount was not minimum at this spot. Once it is checked for same spark advance e.g.: 20 deg CA: highest NO formation was detected at 6000 rpm, which is reasonable as NO formation is a result of high temperature and high pressure by increased engine speeds and an output of better combustion.

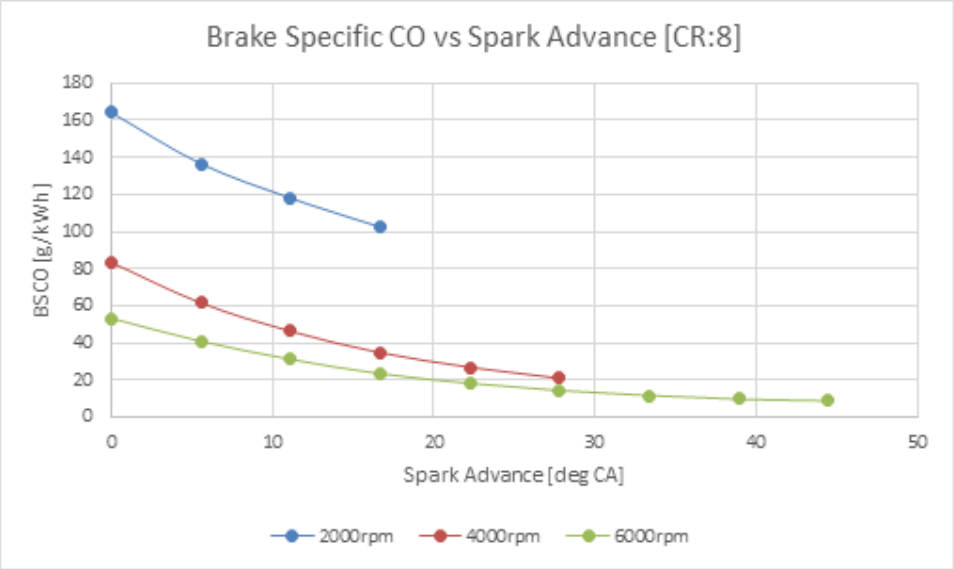


Figure 5.3 : Brake specific CO vs spark advance [CR: 8].

For the other compression ratios, similar tendency observed for the engine power, BSFC and the emission levels which will be shown in the following sections. As the compression ratio increased, there was a significant increase in engine power and a decrease in BSFC which is expected. For the increased engine speeds and compression ratio correlations, more pressure and temperature is able to obtained in general, which procures better combustion. This formation is the reason of getting more power at higher engine speeds. Likewise, with the contribution of satisfied combustion, BSFC get reduces with increased speeds and compression ratios.

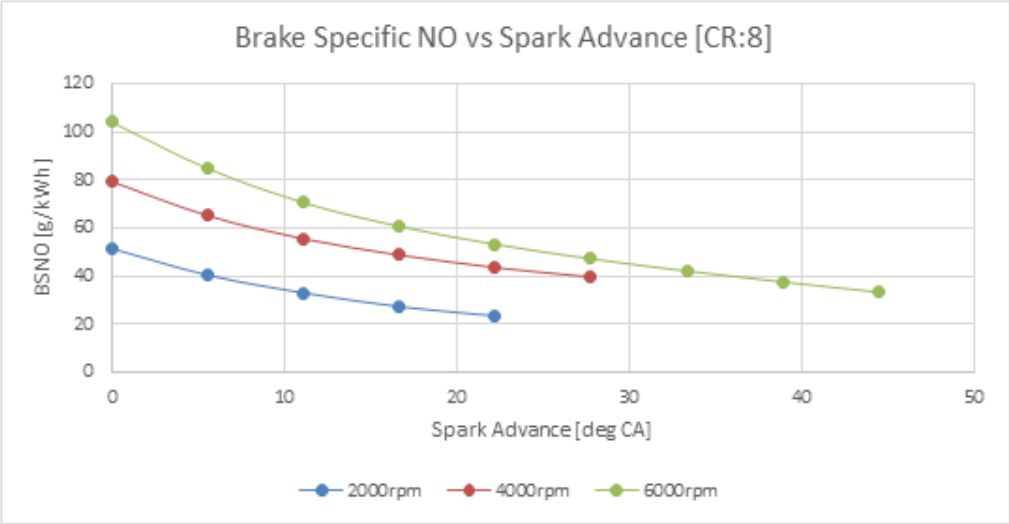


Figure 5.4 : Brake specific NO vs spark advance [CR: 8].

5.1.2 Model Outputs for Compression Ratio 9:1

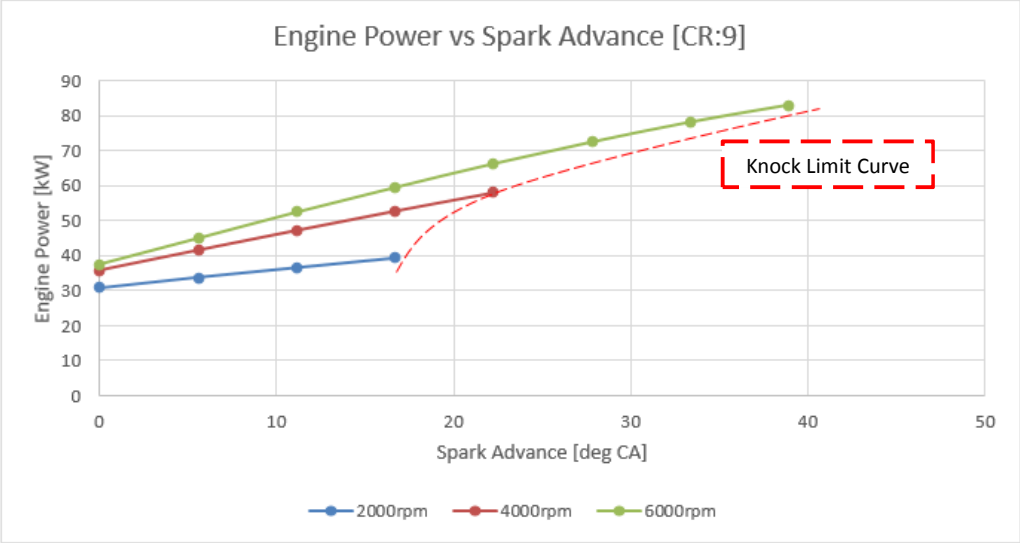


Figure 5.5 : Engine power vs spark advance [CR: 9].

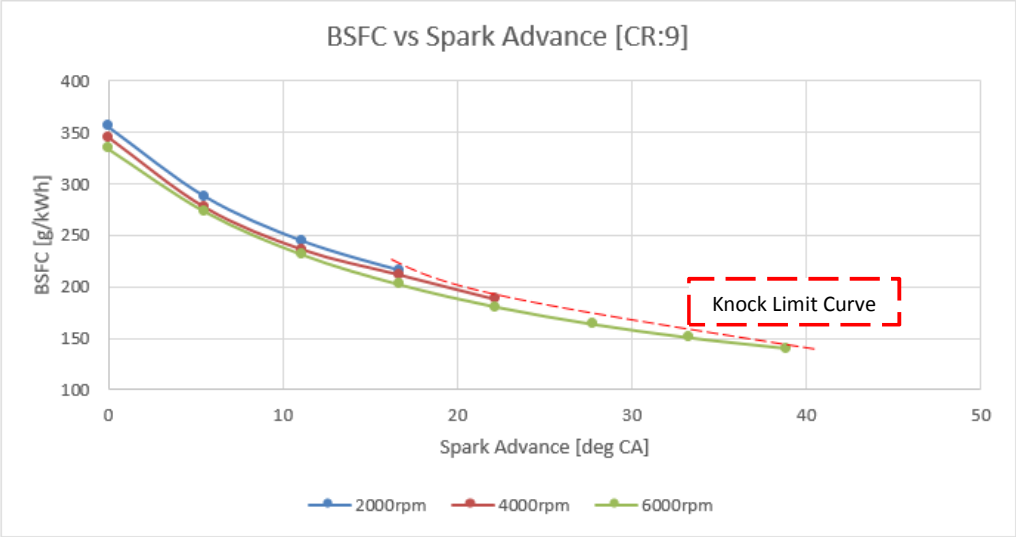


Figure 5.6 : BSFC vs spark advance [CR: 9].

5.1.2.1 **Emission Outputs for Compression Ratio 9:1**

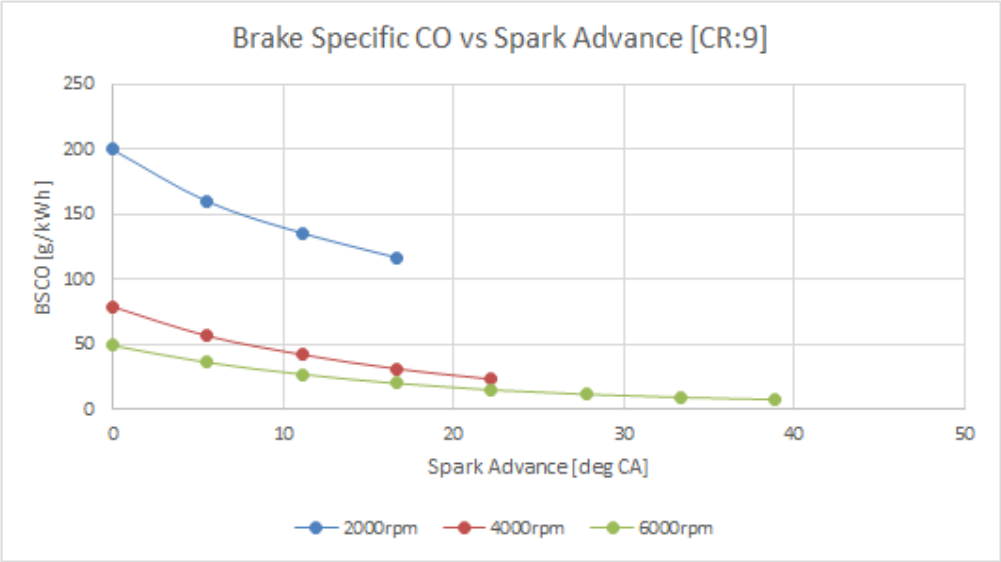


Figure 5.7 : Brake specific CO vs spark advance [CR: 9].

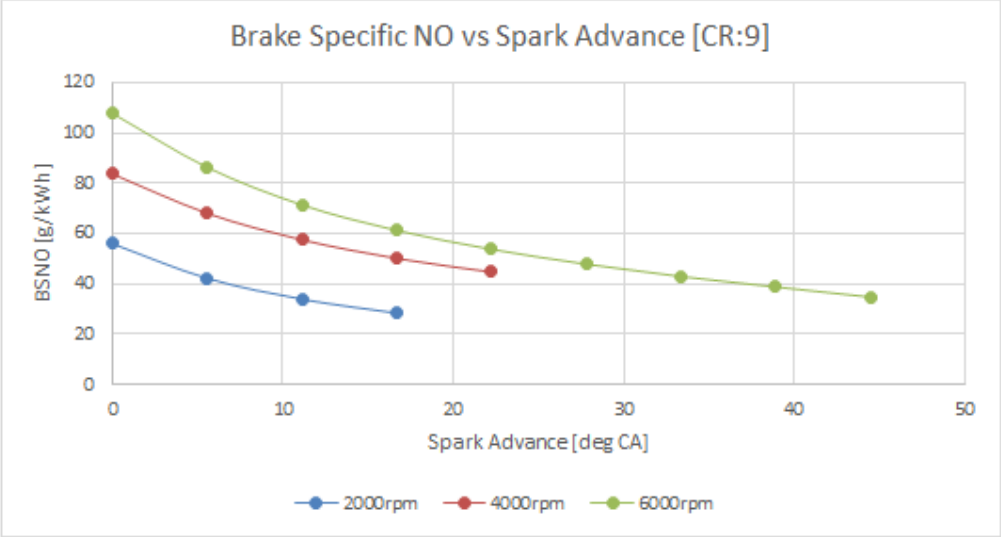


Figure 5.8 : Brake specific NO vs spark advance [CR: 9].

5.1.3 Model Outputs for Compression Ratio 10:1

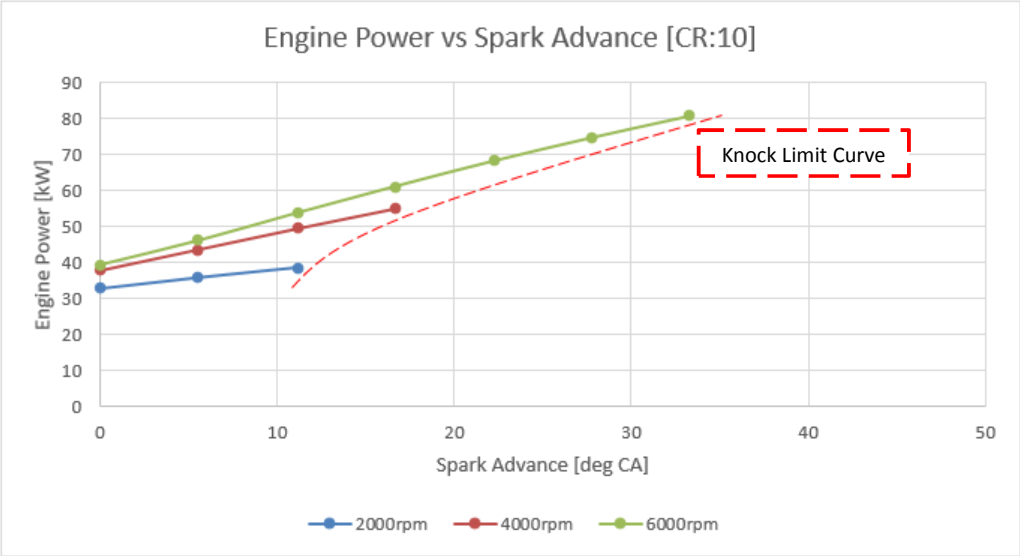


Figure 5.9 : Engine power vs spark advance [CR: 10].

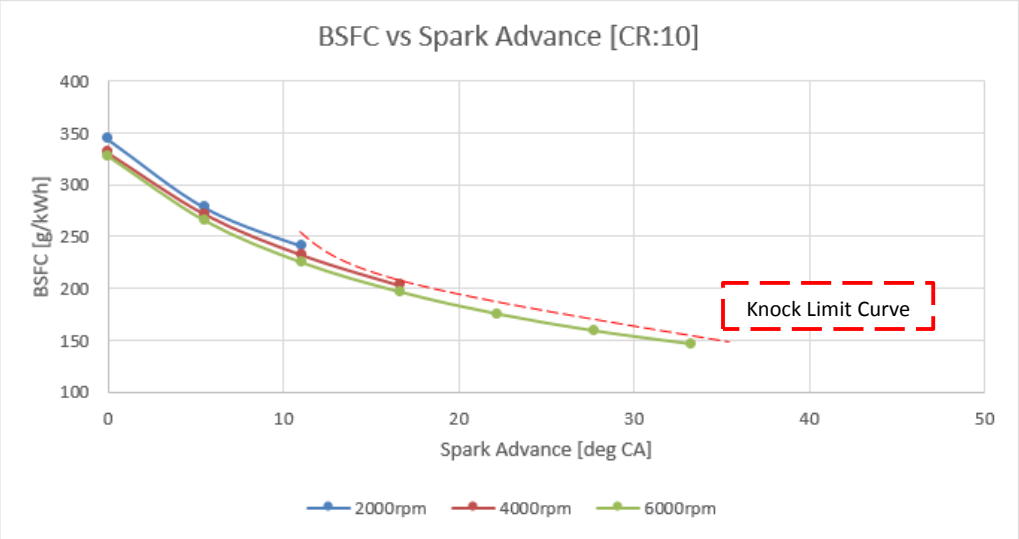


Figure 5.10 : BSFC vs spark advance [CR: 10].

5.1.3.1 **Emission Outputs for Compression Ratio 10:1**

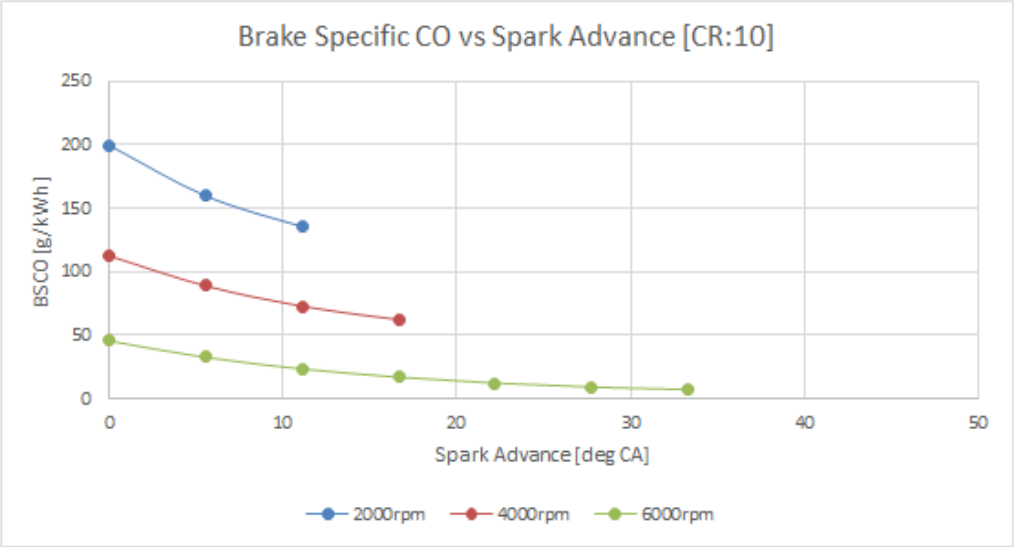


Figure 5.11 : Brake specific CO vs spark advance [CR: 10].

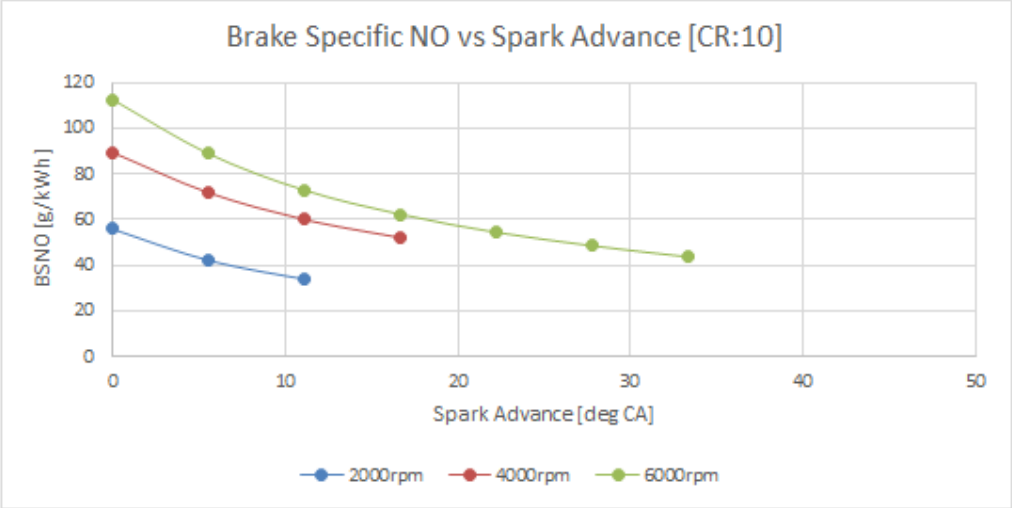


Figure 5.12 : Brake specific NO vs spark advance [CR: 10].

5.1.4 Model Outputs for Compression Ratio 11:1

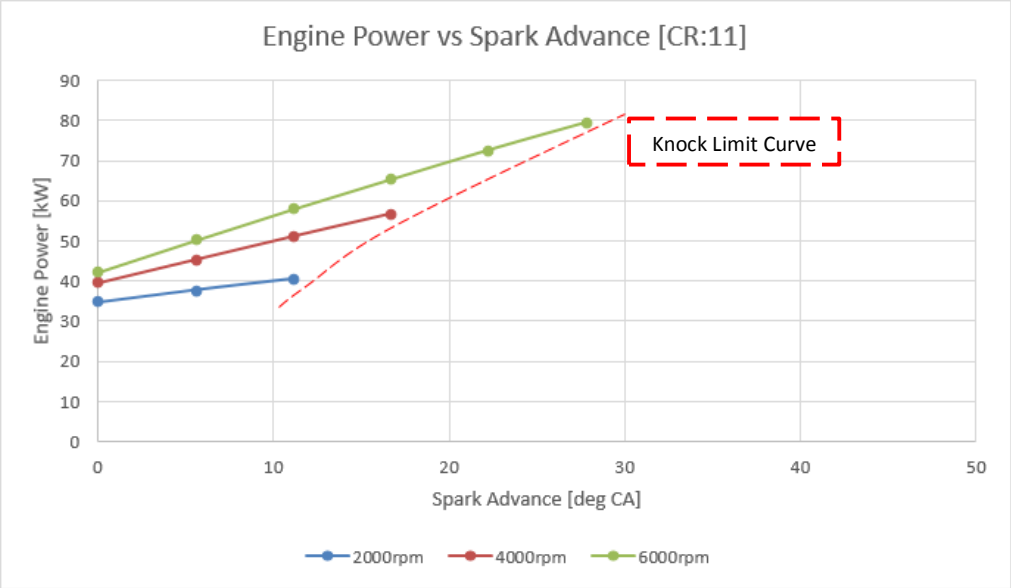


Figure 5.13 : Engine power vs spark advance [CR: 11].

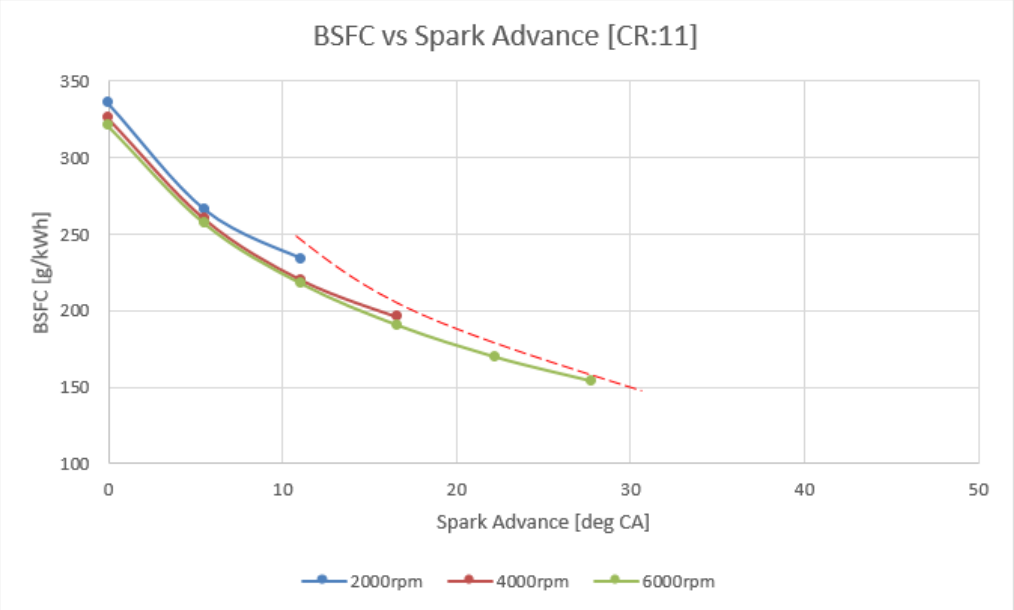


Figure 5.14 : BSFC vs spark advance [CR: 11].

5.1.4.1 **Emission Outputs for Compression Ratio 11:1**

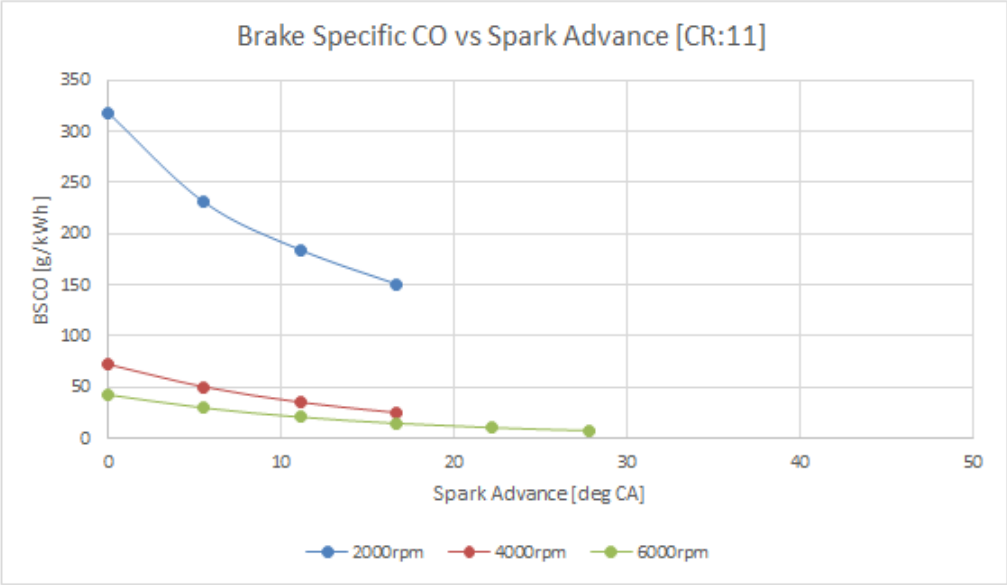


Figure 5.15 : Brake specific CO vs spark advance [CR: 11].

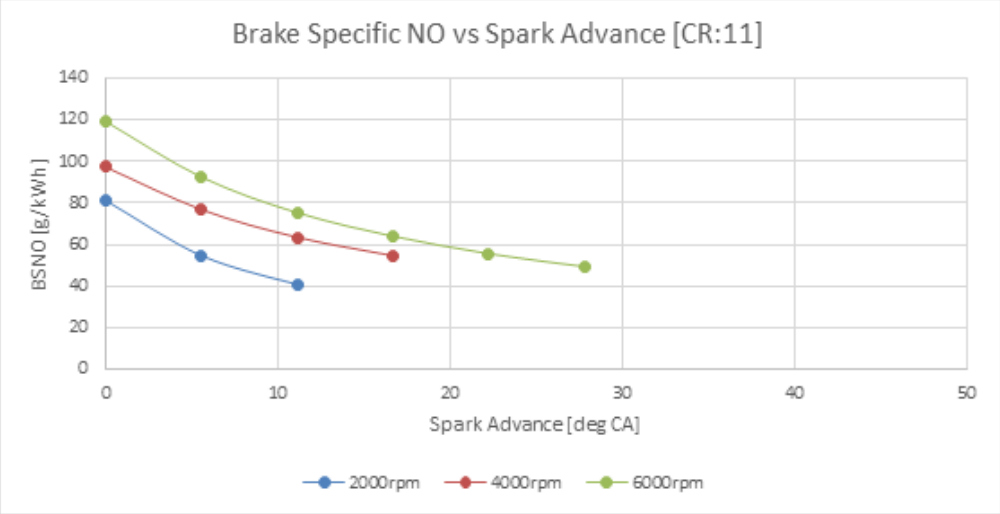


Figure 5.16 : Brake specific NO vs spark advance [CR: 11].

5.1.5 Model Outputs for Compression Ratio 12:1

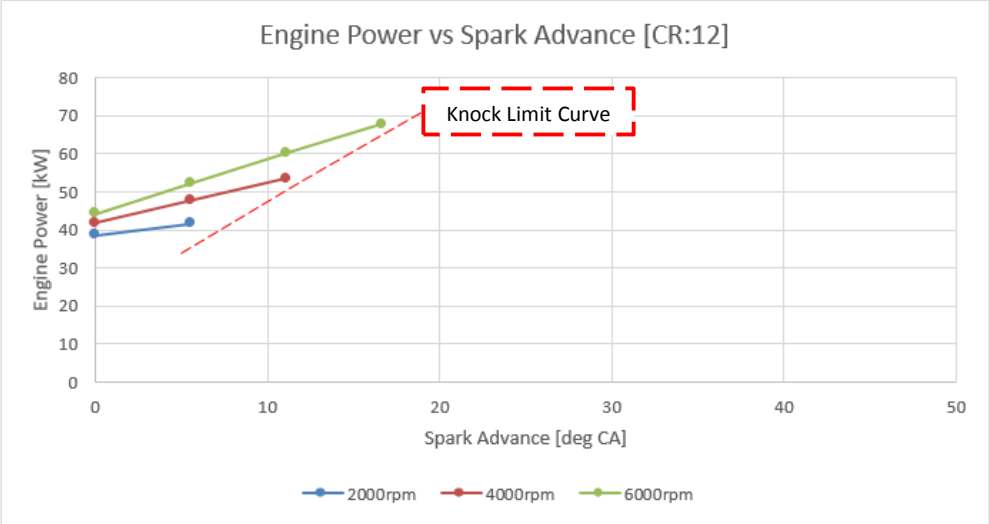


Figure 5.17 : Engine power vs spark advance [CR: 12].

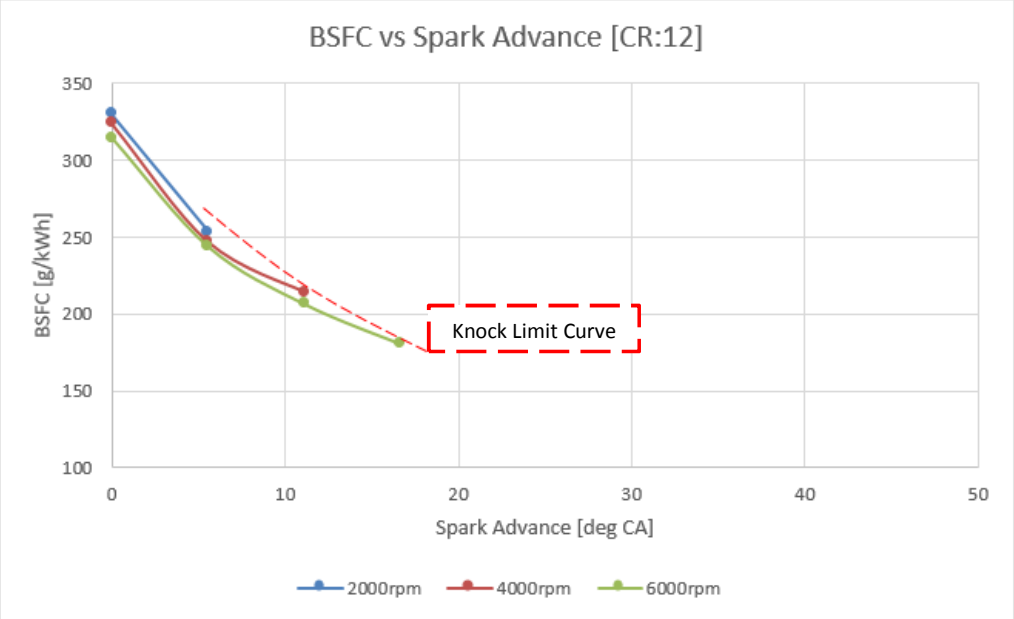


Figure 5.18 : BSFC vs spark advance [CR: 12].

5.1.5.1 **Emission Outputs for Compression Ratio 12:1**

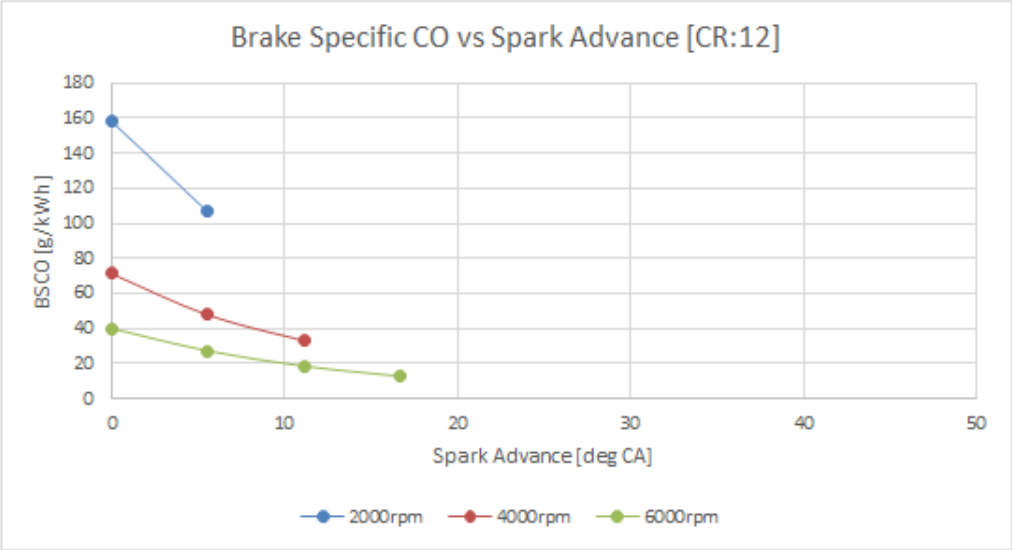


Figure 5.19 : Brake specific CO vs spark advance [CR: 12].

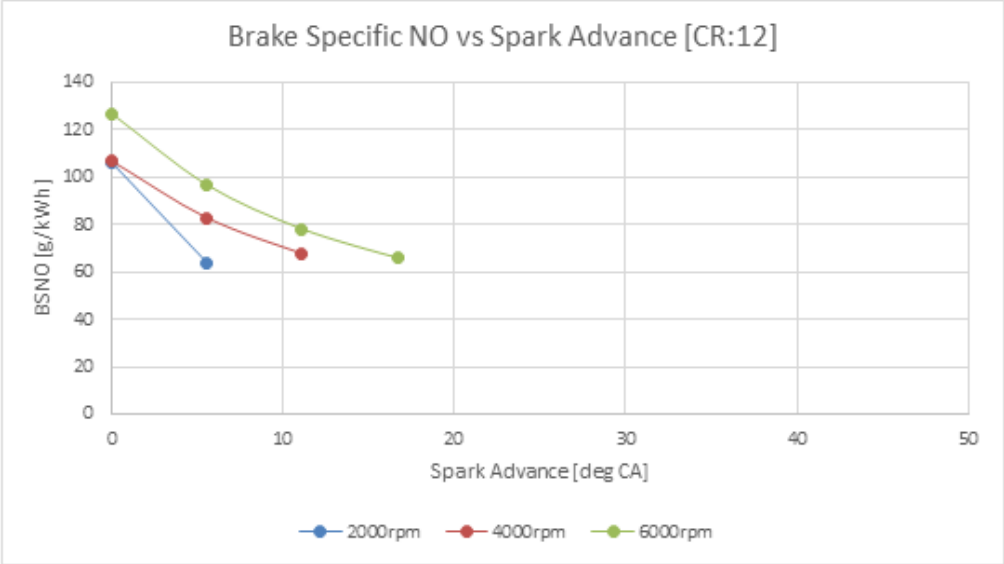


Figure 5.20 : Brake specific NO vs spark advance [CR: 12].

According to the received datas, it has been observed that spark advance decreased against to increased compression ratio. While it was possible to get data up to 45 deg CA for compression ratio 8:1, it was only around 15-20 deg CA when compression is reached up to 12:1. The reason of this, by increased compression ratio levels, in-cylinder pressure and temperatures grow in parallel, which creates knock at these limits.

5.2 Basic Engine Data Outputs for All Compression Ratios

Following graphs show comparison between all compression ratios against to increased spark advance. It could be seen in the next graphs as “possible maximum engine power for different compression ratios” and “possible minimum BSFC for different compression ratios”. With respect to the outputs above for 5 different compression ratios; compression ratio 9:1 has given the better results against to lower fuel consumption and upper limit of engine power at 6000 rpm when it is compared to other compression ratios. It was possible to get lowest BSFC with compression ratio 12:1 but the engine power was not highest at this level. Next step will be to force these 9:1 compression ratio limits by increased boost pressure to understand where it could be got more power with lower BSFC. In the meantime, with same approach like at the beginning of the analysis, knocking will be monitored to catch until which spark advance model could be run. Knocking integral results will direct the study to limit spark advance and understand at which point optimum level of results to be gathered.

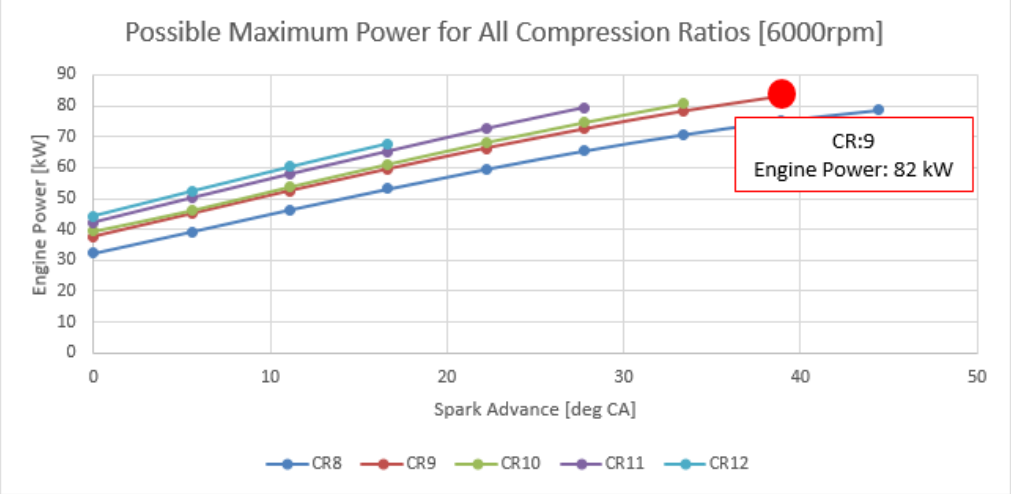


Figure 5.21 : Possible maximum engine power for different compression ratios

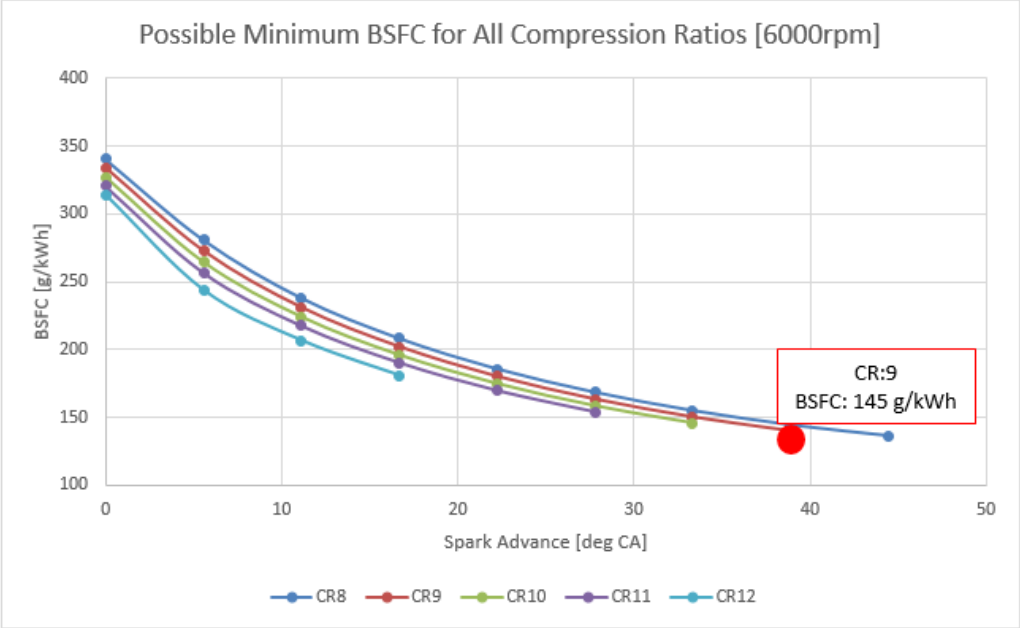


Figure 5.22 : Possible minimum BSFC for different compression ratios

5.3 Boost Pressure Increase for Compression Ratio 9:1 and Optimum Outputs

In this section limits of the 9:1 compression ratio to be forced by increased boost pressure to get enhanced power and BSFC results. The mentioned outputs above are got by setting boost pressure to 1.957 bar at first point where injection fuel rate was 7.8 kg/h for 6000 rpm 9:1 compression ratio. To continue the investigation boost pressure is increased by %60 as 3.13 bar and injection fuel rate is increased by %30 as 10.14 kg/h.

Table 5.1 Comparison of initial values with modified model

	Initial Conditions	**Modified Model**
Boost Pressure [bar]	1.957	3.13
Injection Fuel Rate [kg/h]	7.8	10.14
Engine Power [kW]	82	87
BSFC [g/kWh]	145	132

Same graphs have been created to investigate the impact of boost pressure on power and fuel consumption and see the improvement.

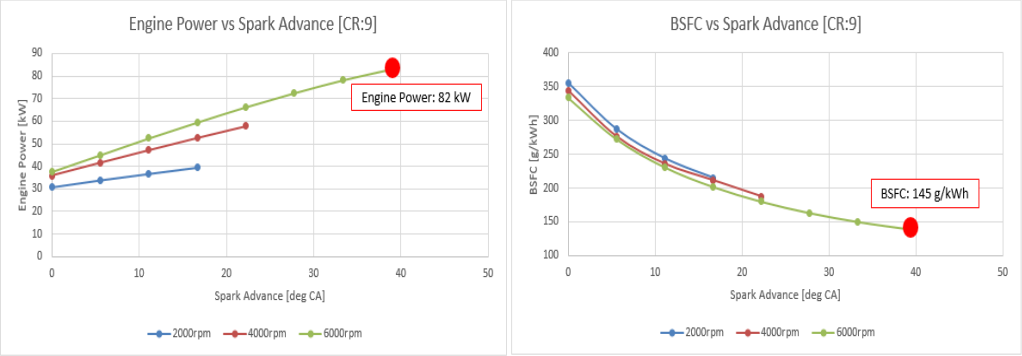


Figure 5.23 : Engine power and BSFC values of CR: 9 for initial conditions

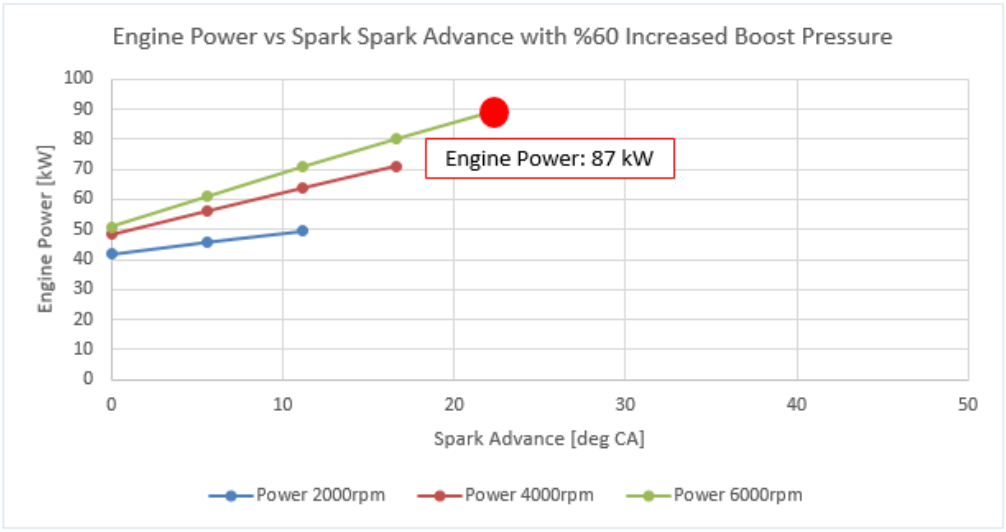


Figure 5.24 : Engine power vs spark advance with increased boost pressure [CR: 9].

It has been observed that, while it was possible to sweep spark advance till 40 deg CA at initial condition; it was only possible to run the model around 22 deg CA with the increased boost pressure and injection fuel rate. This trend was expected as by increasing the turbocharger impact, pressure and temperature values are also elevated. This causes the knocking occurrence earlier when it is compared with initial conditions.

With the new conditions by changing the boost pressure and fuel injection rate, there was an increase on engine power and reduction on BSFC when it is compared with initial conditions.

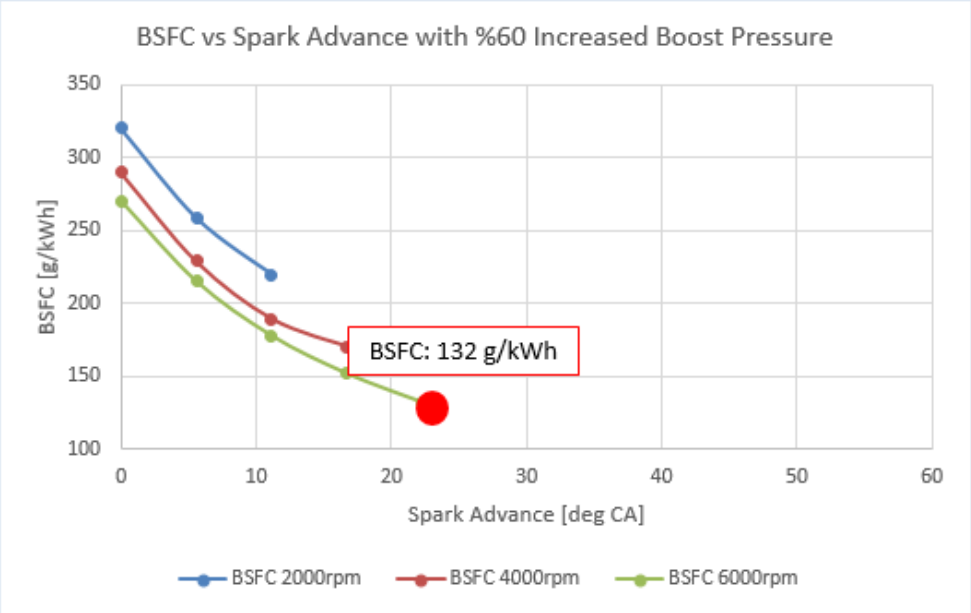


Figure 5.25 : BSFC vs spark advance with increased boost pressure [CR: 9].

5.4 Knock Integral Calculation

Outputs are investigated for all cylinder pressure and temperature values to be able calculate knocking integral based on the following formula, all cylinders had the same trend based on knock formation. With the increased in-cylinder pressure and temperatures knocking detected in early spark advances by increased compression ratios. Maximum cylinder pressure and temperature applied to the formula, based on the combustion duration. Once the knocking integral is calculated as "1", spark advance adjusted as the limit for the condition of each compression ratio.

$$\int_{t=0} \frac{dt}{\tau} = 1$$

$$\tau = 17.68\left(\frac{ON}{100}\right)^{3.402} * P^{-1.7} \exp\left(\frac{3800}{T}\right)$$

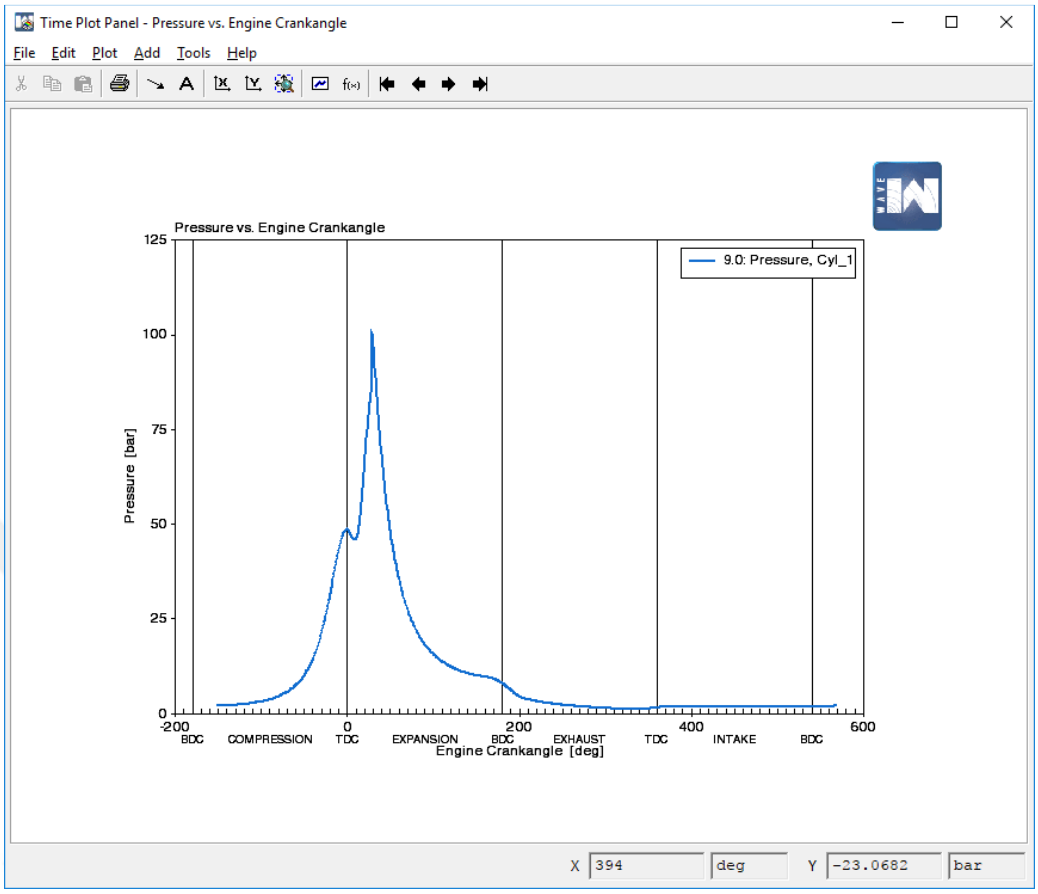


Figure 5.26 : Cylinder pressure vs engine crank angle

6. CONCLUSIONS AND RECOMMENDATIONS

During this study the optimum working circumstances of a turbocharged gasoline engine has been observed. As a result of analysis which is performed in Ricardo Wave SW, it was possible to estimate these conditions. Simulation programs could be used for this kind of studies to be able simulate all possible failure modes as well as to find the optimum operating condition of an engine, prior to any dyno work. Not only the spark advance changes, or emissions analysis but also there are lots of other comprehensive CAE features that may give better understanding of the engine performance for each particular engine components.

Critical points and the summary of the work done during this thesis:

- A deep literature research has been done to able to command the nature of the engine parameters. Information is gathered for the engine performance behaviour with different spark advances and compression ratios with increased boost pressure.
- Ricardo Wave software is used to create engine model and get output of engine performance analysis.
- Knocking integral calculation is considered to interpret correct limits of the engine operation during increased spark timing.
- Spark advance impact is controlled for each individual compression ratio and engine speed. It has been swept from 0 deg CA to 50 deg CA for 2000rpm, 4000rpm and 6000 rpm engine speeds. By considering the knock limits, particular spark advance limits observed for each cases.
- By sweeping different compression ratios from 8:1 to 12:1 maximum power and minimum BSFC point is selected as 9:1 compression ratio with 6000 rpm engine speed.
- After defining the optimum operating condition of the engine as 9:1 compression ratio and 6000 rpm engine speed, boost pressure is increased

%60 based on the initial conditions. In same way, injection flow rate is also increased %30 compared to baseline.

- Once boost pressure has been changed, further improvement was seen in the previous optimized datas. e.g.: engine power increase and fuel consumption reduction.
- Challenging and critical point was, new knock limits against to increased boost pressure. The more increase on the in-cylinder temperature and the pressure with turbocharger impact, the greater the probability of knocking.
- New knock limit was defined for compression ratio 9:1 by decreasing the spark advance. And it is selected as optimum condition of the engine by getting highest engine power and the lowest BSFC.
- Even injection flow rate is changed directly proportional with boost pressure, there was a decrement on BSFC amount. The reason of the reduced fuel consumption is having better combustion conditions which results higher engine power and performance. Thus, it was possible to get lower input of fuel.

It is described in the following tables for initial condition values for all compression ratios and engine speeds. It could be seen that compression ratio 9:1 is the optimum solution between all others. By increasing the boost pressure and injection fuel rate it was possible to improve the power and BSFC values more.

	Compression Ratio					
Engine Speed [kW]	rpm	8:1	9:1	10:1	11:1	12:1
	2000	33,53722	36,37498	35,66356	37,44033	38,58246
	4000	56,65869	54,87704	51,98069	53,85806	50,50853
	6000	78,67915	81,99017	77,6165	76,41019	64,77732

	Compression Ratio					
BSFC [g/kWh]	rpm	8:1	9:1	10:1	11:1	12:1
	2000	220,4606	215,3977	240,0934	233,4482	252,9905
	4000	175,0931	187,5981	202,3219	195,6369	213,9702
	6000	136,2122	144,9787	150,7596	159,7512	180,6219

Figure 6.1 : Engine power and BSFC values for all compression ratios and engine speeds

	Initial Conditions		Modified Model
Boost Pressure [bar]	1.957	%60 increase	3.13
Injection Fuel Rate [kg/h]	7.8	%30 increase	10.14
Engine Power [kW]	**82**	%6,1 increase	**87**
BSFC [g/kWh]	**145**	%9,8 increase	**132**

Figure 6.2 : Initial model and modified model comparison

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