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School Of Engineering

Combustion Analysis of a Ford Fox Engine and Calculations for
5 Stroke Cycle

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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

Date:

Abstract

The main purpose of this report is to calculate the current efficiency of the Ford Fox 1.0L engine and to see if changing the engine from a 4-stroke cycle to a 5-stroke cycle has any benefits. This project was completed by doing research into many different topics and by doing calculations on excel.

The emissions produced by a petrol engine are a serious issue during modern times, everything needs to be done to lower these emissions or to start using electric and hybrid engines. The 5 Stroke cycle could be a good option as not only does it decrease the temperature of the exhaust gases by a considerable amount but it also the 5-stroke engine does not loss as much energy down the exhaust. As is shown in this report, the Ford engine loses 118 Kw down the exhaust, but the 5 Stroke engine only loses 89 Kw down the exhaust.

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Abbreviations

BHP – Brake Horse Power

BICERI – British International Combustion Engine, Research Institute

BMEP – Brake Mean Effective Pressure

BSFC – Brake Specific Fuel Consumption

CF – Calorific Value

CO – Carbon Monoxide

CO₂ – Carbon Dioxide

CR – Compression Ratio

EGR – Exhaust Gas Recirculation

EOC – End of Combustion

FMEP – Friction Mean Effective Pressure

HC - Hydrocarbons

HGV – Heavy Goods Vehicle

IMEP – Indicated Mean Effective Pressure

IVC – Intake Valve Closing

MFB – Mass Fraction Burned

MPG – Miles Per Gallon

NoX – Nitrous Oxide

PM – Particulate Matter

PN – Particulate Number

PV – Pressure Volume

RPM – Revolutions Per Minute

SOC – Start of Combustion

TDC – Top Dead Centre

ULEZ – Ultra Low Emission Zone

VCR – Variable Compression Ratio

Introduction

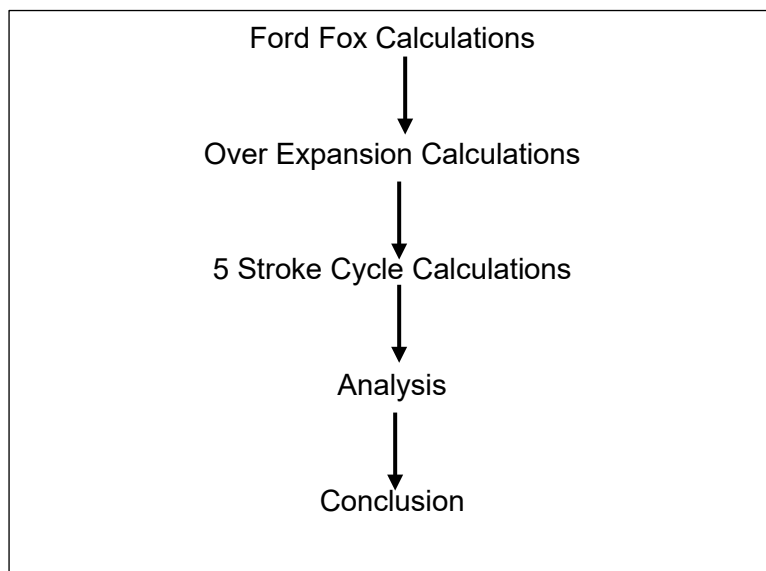
Cars and other motorised vehicles are used by people every day. This means that it is very important that manufacturers make cars and vehicles of all different sizes and these vehicles must also be reliable and provide the driver with a sense of satisfaction. The other obligation that the manufacturers have is to make sure that the vehicle's fuel consumption is as low as possible while maintain low exhaust gas emission. Global warming, fuel shortages and general health of the planet is the reason for this. Companies are looking into alternative fuels for their engines such as Electric, Hybrid and Hydrogen to try and help the planet. The governments across the world are also putting in regulations and rules that are making companies go for alternative fuel sources.

The first vehicle that was propelled by a petrol engine was made in 1886 by Gottlieb Daimler (Oldrich Ruzicka, 2015). This means that petrol vehicles have been used for over 130 years. So, considering the heritage of petrol engines, maybe companies and manufacturers should look at making petrol engines more efficient and make them produce less exhaust emissions. There are a few different methods that companies and manufacturers can employ to make this happen. These methods are Over – Expansion, Variable Compression and 5 Stroke Cycle. All these methods have the possibility to increase the efficiency of the engine and decrease the emissions emitted from the exhaust. These methods would require some specialist research and development to see significant improvements but even with a basic knowledge of the subject, there will still be some improvements. All these methods will be looked at in further detail in the next section.

Unfortunately, there will be a point in time when petrol engines will stop being made as the petrol will be hard to find and procure. So, companies should still pursue the options of alternative fuels. Using the alternative methods above for petrol engines might be the better option to choose at this moment as the technology put into these methods is the same or similar to what is currently being used in standard petrol engines. This will mean that companies and manufacturers will save money when it comes to training current staff or hiring new staff as this will be needed for the alternative fuels.

The project that has been completed leading up to this report is all relevant as it shows a potential outcome from using the 5 Stroke Cycle. There is a portion of this project and report were the Over – Expansion cycle was explored, and calculations were completed to see if this was a possible option for this engine, but the increases were not significant. The choice was then made to stop the calculations for this and start calculating the 5 Stroke Cycle.

There was multiple stages planned for this project to be completed. These are shown below. The research for this project was completed alongside each of the tasks below.



Literature Review

Petrol Engines and Emissions Produced

Petrol cars are very common and there are a lot of them on the road in the UK. According to a news article, 59 percent of all cars on the road in the UK are petrol which means there is a massive 18.3 million petrol vehicles on the road in the UK at the end of 2017 (Hull, 2018). The article also states that there are almost 12.4 million diesel vehicles. From looking at these numbers it is shown that there are more petrol cars than any other type. Looking at this data the best option for companies and manufacturers would be to do some research and development into petrol engines to try and make them more efficient and to produce less harmful exhaust emissions rather than looking for another fuel option to use.

Fuel consumption is one factor that should be looked at for petrol engines. Exhaust gases are produced when fuel is consumed or burned inside the cylinder so by increasing the MPG of a vehicle there will be less fuel being used which in turn would mean that there would be less harmful gases emitted from the exhaust. The average MPG for petrol vehicles in the UK was around 51.7 miles per gallon. This is a 32% increase since 2007. (Transport, 2018) (Foundation, 2018) This does mean that there are improvements being made in this area but there still may be some more room for improvement. Companies are trying to improve this factor by downsizing engines or by making the engines function more effectively and efficiently at lower RPM.

The main issue with petrol engines are the exhaust gases. CO₂ and NO_x are not the only the exhaust gases that are produced by engines but they are the two most harmful gases that need to be decrease so the risk of damage to the planet and to the human beings living on it are lowered. Petrol vehicles do produce less NO_x than diesel vehicles, however they do produce more CO₂. Arguments can be made which gas is better to emit and which gas is more harmful to the environment and to the people but the main point is that both of these gases are harmful to both the environment and the people. NO_x causes acid rain to form in the atmosphere and NO_x on its own can cause some serious health problems (Girard, 2010). CO₂ is considered as a greenhouse gas. There is naturally some CO₂ in the atmosphere but burning of fossil fuels like petrol produces CO₂ which is then emitted into the atmosphere. This extra CO₂ that is being put into the atmosphere is causing issue for the atmosphere and is also causing issues for human health. CO₂ traps heat inside the atmosphere which then in turn heats up the planet. Adding more CO₂ to the atmosphere will mean that more heat will be trapped inside the atmosphere which will cause issues for human health and various issues for the planet. CO₂ can cause some serious health problems and these health problems get more serious the more CO₂ is present (Lindsey, 2018) (Ender Yalcin, 2018)

Companies and manufacturers recognize that the two gases described above are an issue and plans have been put in place to try and lower the amount of the gas that is being emitted into the atmosphere. One of these plans is to start using electric engines as these engines produce zero harmful emissions. Governments recognize this fact and are pushing companies and manufacturers to start produce fully electric vehicles. Hybrid vehicles are also being made which uses both a petrol engine and an electric engine which means that it does produce less harmful emissions than a standard petrol engines. Another plan that is being put into place is for companies and manufacturers to start looking at using hydrogen powered engines. This type of engine is also preferable by various governments due to the fact that they don't produce the harmful emissions like petrol and diesel engine do. However there are a few issues associated with hydrogen and electric engines that are going to be explored further on in this section.

Government Regulations

Governments around the world are putting rules and regulations forward that are making companies and manufacturers reduce the exhaust emissions produce by the engines that they make. Not only are these rules and regulations forcing the companies and manufacturers to reduce the emissions produced by petrol and diesel vehicles, but these rules and regulations are also forcing companies and manufacturers to start making vehicles that are powered by alternative fuel sources (Electric, Hybrid and Hydrogen). These rules and regulations have been put into place not only to reduce the emissions that are emitted into the atmosphere but also to try and combat the fuel shortages as fuels like petrol and diesel are found and are not renewable. Renewable energy is highly recognized as a great thing as it is being produced and used without any serious repercussions. The only problem is all of this technology is still quite young so there are a few issue aligned with them but with enough time and effort focused on this, these issues will be solved. The main reason for this is that something like this cannot be made in a day. It has to be constantly worked on for improvements to be made and for it to adapt. The exact same thing happened to petrol and diesel vehicles as it has taken those over 100 years to get to the point where they are at now.

When it comes to regulations and rules that are being enforced by governments regarding the amount of emissions that can be produced by a vehicle, all companies and manufacturers must comply with the European Emissions Standard or Euro for short. This regulation as different categories for the different type of vehicles such as light duty vehicles such as passenger cars and heavy duty vehicles such as HGV's. For this project and report, the only category that will be looked at and examined is the one that concerns petrol cars so light duty vehicles. The table shown below shows a comparison between the Euro 5 standards for light duty vehicles and Euro 6 standards for light duty vehicles.

Table 1: Euro 5 and Euro 6 Regulations (ICCT, 2016)

Pollutant	Euro 5 Light-Duty		Euro 6 Light-Duty	
	Gasoline	Diesel	Gasoline	Diesel
CO	1.0	0.5	1.0	0.5
HC	0.1*		0.1*	
HC+NO _x		0.23		0.17
NO _x	0.06	0.18	0.06	0.08
PM	0.005 ^c	0.005	0.005 ^c	0.005
PN (#/km)		6.0 x 10 ¹¹	6.0 x 10 ¹¹ ^d	6.0 x 10 ¹¹

This data shows the pollutants that are being limited by the rules and regulations put forth by the European Union. These limits are defined to ensure that the new cars and vehicles that are being made are not polluting the environment too much. As the data shows, the limits have not changed much since Euro 5 was put in place in September of 2009. Euro 6 standards started in September of 2014 and all care made from that date must comply with it. The limits for petrol vehicles have not changed in this category apart from issuing a limit on PN (#/km). This limit governs the amount of particulates can come out of the exhaust of a car per kilometre. When looking at the figures for the diesel vehicles, there are two changes that have been enforced. These are regarding HC + NO_x and NO_x. This is because diesel vehicles are known for emitting a high number of NO_x into the atmosphere due to the higher combustion temperatures. Putting a limit on NO_x not only means that companies and

manufacturers have to do considerable work to lower the exhaust gases produced but it also impacts the amount of diesel vehicles being made and sold.

According to multiple news articles, the government of the UK and the European Union are not only putting rules and regulations forth that control the amount of exhaust gases that are being emitted by petrol and diesel vehicles. According to a news article the UK government is planning a ban on sales being made on petrol and diesel cars by 2032. This is because the plan that the UK government is doing is to try and make sure that all cars in the UK are “effectively zero emission” by 2040 (BBC, 2018). This means that there will be a lot of pressure on companies and manufacturers around the world to make vehicles that are either powered by electric or hydrogen. Hybrid vehicles will still be allowed but if the plan above is being enforced, then it will not be too long after that date that hybrid vehicles will start to be phased out. This only leaves a few options. Either electric vehicle sales will increase to comply with this rule but that will take a lot as in the UK, electric car sales only amount to less than 1% of all cars sold in the UK or the other option is to make petrol and diesel vehicles so efficient and environmentally friendly that they produce almost zero emissions.

Another plan that is put enforced in the UK is to place a ULEZ in London. This has been started in Central London on the 8th April 2019 and will affect all of London from 25th October 2021. This zone means that any car of vehicle driving with London will have to pay an emissions charge on top of the currently enforced congestion charge. This is being enforced to try and tackle the amount of toxic air that is in the air around major cities and the amount of pollutants that are being emitted in the cities. This rule doesn't only affect all passenger vehicles in London but also affects business and industries around the city as they have to pay the charges for the transport trucks. This affects the amount of money that the companies make and could possibly lead to some of the smaller businesses to shut down as they will not be able to afford the charge. This whole plan is effectively trying to force the British public to start buying electric vehicles. (BBC, ULEZ: New pollution charge begins in London, 2019)

London Ultra Low Emission Zone

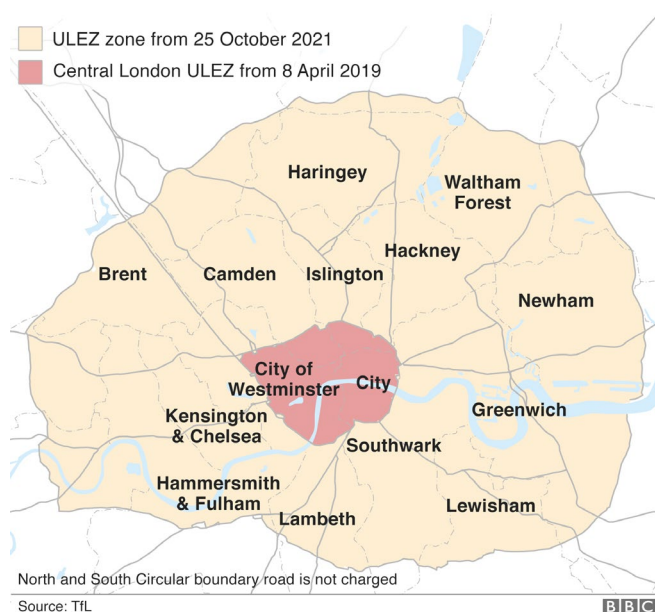


Figure 1: London ULEZ (BBC, ULEZ: New pollution charge begins in London, 2019)

Variable Compression Engine

A Variable Compression Engine is one option for companies and manufacturers to try and employ to make the petrol and diesel vehicles more efficient. There are a few different ways to achieve a variable compression ratio in an engine. The first way that can be employed and used inside an engine is by using some sort of mechanism that uses a control shaft and an oscillating member. This setup works as the control shaft would be running at half speed of the crankshaft and a conventional phasing mechanism between the crankshaft and the control shaft will allow relative angular movement between the two shafts which in turn alters the compression ratio. The compression ratio in this setup will change between two different compression ratios that the company or manufacturer will state. To change the compression ratio limits, the company or manufacturer will have to change the size of the eccentric and angular movement of the control rod. The images below show this type of setup with the mechanisms in place. (Alberto Boretti, 2011)

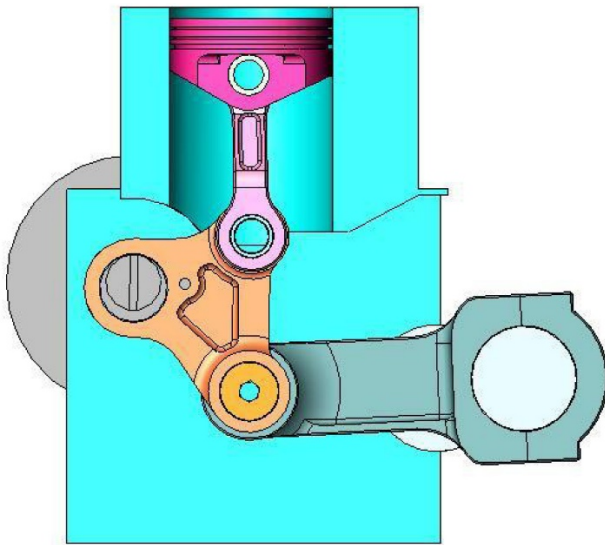


Figure 2: Low CR at TDC (Alberto Boretti, 2011)

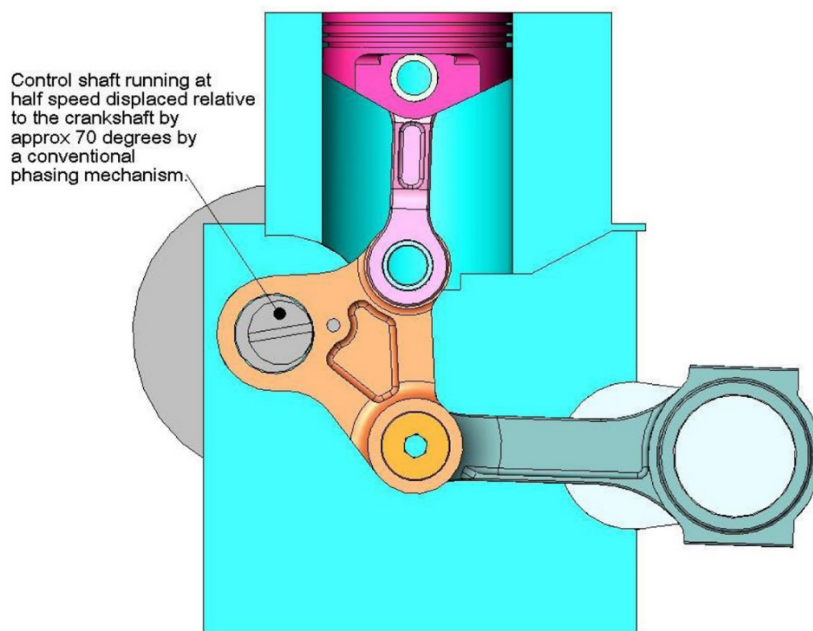


Figure 3: High CR at TDC (Alberto Boretti, 2011)

Using this sort of setup to alter the compression ratio has been proven to work and does offer an increase in efficiency and power output of the engine. However that being said, there are a few issues and disadvantages linked to this setup. First of all to make this setup work, the company or manufacturer will have to design, model and create a new engine block to allow for the extra components to be placed inside the engine along with moving the position of the crankshaft. This would require a lot of work but could possibly pay off. The main disadvantage with using a variable compression ratio is that it does not help a lot with the emissions that are created by the combustion. At the low compression ratio, it does have a possibility of having an increase in HC production due to the risk of unburnt fuel. This does mean that this engine might not comply with the Euro regulations that were showed previously.

However this setup is not the only setup that can be used to have a variable compression ratio. The other ways to achieve a variable compression ratio either requires changing the clearance volume or by changing both the clearance volume and the swept volume of the engine. The first option where the clearance volume is changed requires either raising or lowering the crankshaft and can also be achieved by raising or lowering the piston crown. The second option where both the clearance volume and swept volume is changed requires a variable throw crankshaft. There are a few different mechanisms that can be used to achieve this but the one mechanism that may be the best to choose uses a special piston that lowers or raises the piston skirt. This system was developed by BICERI. (Rajput, 2005)

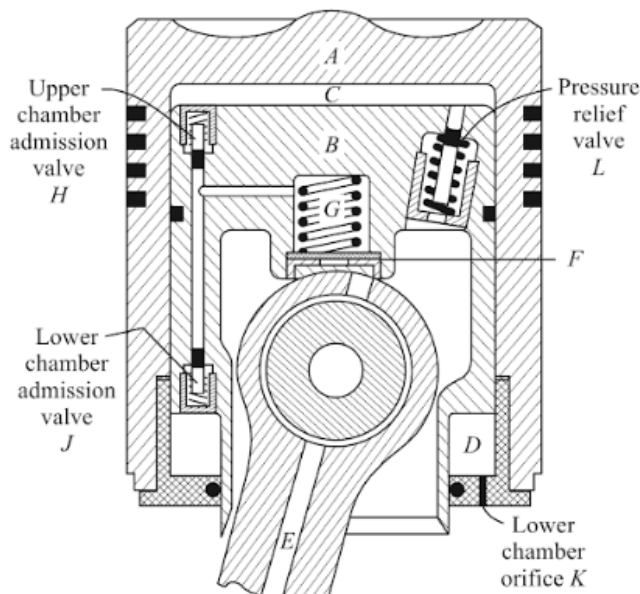


Figure 4: BICERI VCR System (H.N.Gupta, 2012)

The image above shows the BICERI VCR system. However this not the only system that can be used. The other three systems that can be used either includes an auxiliary chamber in the cylinder head, a vertically sliding cylinder head or an adjustable connecting rod length. However all of these systems and setup share the same disadvantages as described above as none of the options help with the amount of emissions produced. All VCR systems will increase the fuel conversion efficiency and power output. There is one option that can be used with VCR systems and that is by using an alternative fuel such as Bio-Fuel or Ethanol as the systems promote a higher compression ratio so the other fuels might work more efficiently. (H.N.Gupta, 2012)

Over – Expansion Principle

Around the same time as the Otto cycle was invented and people started working on the first car, there was a British engineer called James Atkinson. In 1882 Atkinson invented the Atkinson principle which was an engine concept that has a larger expansion ratio than compression ratio. This allowed a higher theoretical thermal efficiency be achieved amongst other advantages. The engine works on the standard 4 stroke cycle but then there will either be an altered crank train or altered valve timing to achieve the longer expansion stroke. In 1918, W.M. Austin patented a design for the IVT Atkinson Crank Train. (Patrick Pertl, 2012)

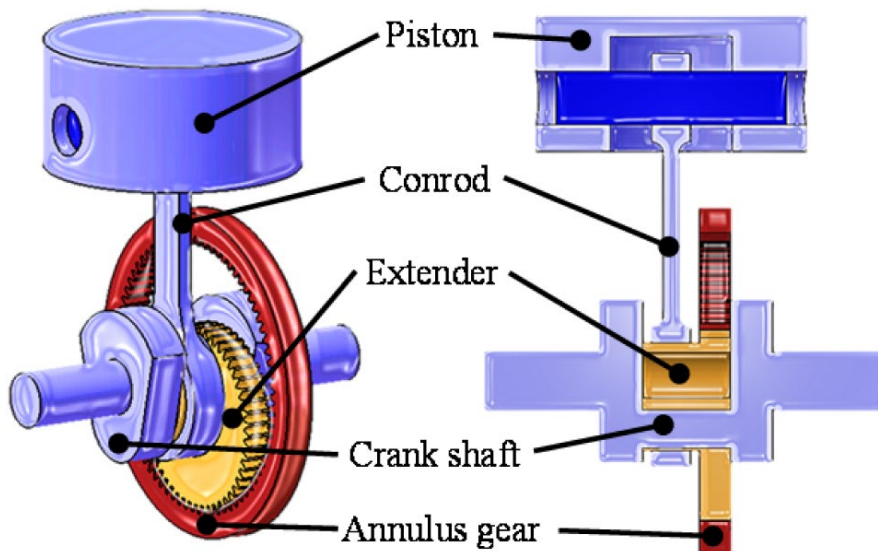


Figure 5: IVT Atkinson Crank Train (Patrick Pertl, 2012)

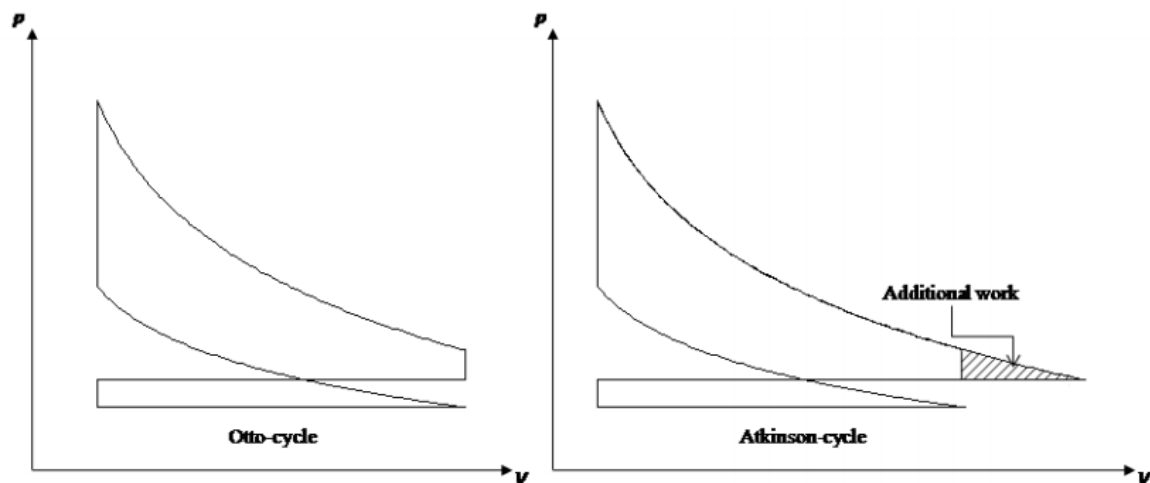


Figure 6: Otto Cycle PV Diagram (Left) and Atkinson Cycle PV Diagram (Right) (Fredrik Holst, 2014)

The crank train that is shown in Figure 5 is based on the Atkinson Cycle. This concept uses a planetary wheel (extender gear) and an annulus gear to make the expansion stroke longer than the combustion stroke. The ratio of the sun gear (crank shaft), planetary wheel and the annulus gear will not only generated the Atkinson cycle but also controls the duration and length of the expansion stroke. Creating a setup like the one shown above in a real world engine does produce a few issues. First of all the cylinder length will have to be increased to allow for the larger expansion stroke. This increase in cylinder length will mean that there will be an increase in friction forces inside the cylinder and this force will affect the overall power output. Another issue is because of the added components to the crank train, there will be a

significant increase in engine weight which of course will lead to an increase in vehicle weight. To counteract this extra weight, most engines that use the Atkinson cycle will be equipped with either a turbocharger or a supercharger.

Figure 6 shows a theoretical PV diagram for the Otto Cycle and the Atkinson Cycle. As it shows, there is a significant amount of extra work that can be provided by the Atkinson cycle if the setup and tuning of the engine is done correctly. This extra work should be larger than the extra friction force generated by the longer expansion stroke for this principle to be viable to use in a real world engine.

The other way an Atkinson cycle is achieved inside of an engine is by closing the intake valve later. This method of achieving the Atkinson cycle is often used in modern engines to increase the engine efficiency. By delaying the IVC, the pressure inside the cylinder is decreased which will then decrease the effective compression stroke. This method makes the engine perform a longer expansion stroke than compression stroke. This method is widely used by Toyota, Ford, Mazda, Mercedes and many other manufacturers to achieve a higher engine efficiency in the hybrid models that are produced. Combining a petrol engine that operates on the Atkinson Cycle with an electric motor is a very effective way of using the Atkinson principle as the increase in efficiency is achieved with the decrease of emissions but without the need for a high power output.

Just now a decrease of emissions was mentioned this is achieved as the gases that are emitted out of the exhaust are at a lower temperature than a normal Otto cycle engine.

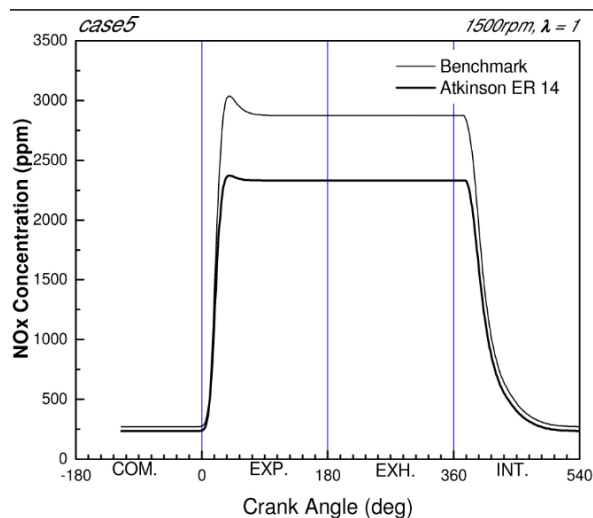


Figure 7: NOx Emissions (Chongming Wang, 2012)

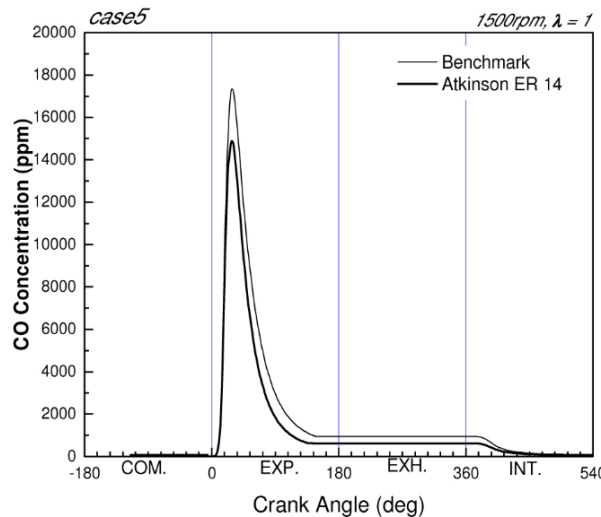


Figure 8: CO Emissions (Chongming Wang, 2012)

Figures 7 and 8 show the results from a study done comparing emissions from a standard engine and an engine using the Atkinson cycle with an expansion ratio of 14:1. The NO_x emissions is lowered due to the increase in formation of other gases like H₂O. The decrease in CO concentration is mainly due to the fact that this engine was equipped with an EGR valve so some of the exhaust gases from the last cycle have been inputted into the cylinder for this combustion which creates an effective lean air/fuel mixture. (Chongming Wang, 2012)

From all of the research shown above, it can be clearly stated that the most optimum way to run an engine that incorporates the Atkinson cycle would be to pair it with an electric motor in a hybrid vehicle but to also equip the engine with an EGR valve. This will provide the decrease of emissions and increase in engine efficiency and MPG.

5 Stroke Cycle

The 5 Stroke Cycle was first invented by as a concept engine in the year 2000 by Gerhard Schmitz. After this a British engineering company called Ilmor adopted this concept to try and make a petrol engine that works on this principle. The overall aim for this engine was to create a petrol engine that has the efficiency and fuel consumption equivalent to a diesel engine or higher than a diesel engine but with lower emissions than a normal petrol engine. The main principle of this engine is very similar to the Atkinson cycle but with a major difference. The way the 5 stroke cycle engine operates is that there are two cylinders that are working on the standard Otto cycle and then one cylinder that acts as an expansion cylinder. (Engineering, 2018)

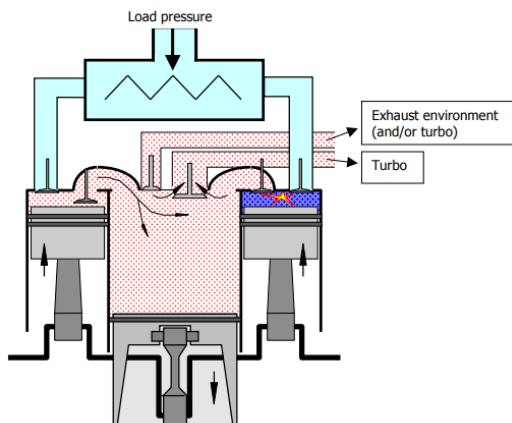


Figure 9: 5 Stroke Cycle Engine (Schmitz, 2011)

The two cylinders that are operating on the standard cycle will be operating alternatively. Once the combustion stroke has been achieved, the exhaust gases are cycled from these two cylinders into the larger 3rd cylinder so the gases can go through another expansion stroke before being emitted out of the engine. Figure 9 shows this in action.

The first issue with this engine can be realized when looking at Figure 9. For this engine to work, the cylinder block, pistons and crankshaft all have to be designed and made. This means that this engine could possibly be quite costly to make and this principle would not be possible by modifying a current engine. However after all of the work that has to be done for this engine to work, it could be worth the cost. The concept engine that Ilmor is working on proves that this is true. According to the data supplied by Ilmor, the engine is a 700cc turbocharged 3 cylinder engine that is pushing out 130 BHP @ 7000 RPM. This engine only has a fuel consumption of 226 g/KwHr. This is quite impressive when looking at the data supplied by Ford for the 1.0L Fox engine that is the focus of this report. The Ford engine uses around 285 g/KwHr on average. This isn't the only advantage of the 5 stroke engine. On a paper written by Schmitz, it is stated that "The fuel consumption is reduced from 16% (at full load) up to 30% (at low load)". (Schmitz, 2011)

Other studies of this 5 stroke concept has shown that this engine does offer improvements compared against a standard Otto cycle engine however this engine is still quite a new concept so it does have a few issues associated with it. First of all due to the different size pistons and cylinders, there can be an issue of engine balancing and there is also a problem with the transfer ports as they are sensitive to pressure drops. As said before though, this engine is still a relatively new concept so with further investigation and studying of the engine should eliminate the issue that are currently associated with it. (Kurt Stuart, 2017)

Methodology

Calculations for Ford Fox Engine

Before any work is explained and evaluated, it should be said that all the calculations that were completed for this project were only regarding the cylinders and the exhaust. Data such as bearing frictions and data regarding the manifolds or crankshaft were not collected or calculated. More about this will be explained later on in this report in the Further Work section.

The first stage was to find out what the Ford Fox engine was producing and how much work and energy was being lost by this engine. To do this data was first collected showing the volume and pressure of the cylinders against the crank angle. These pieces of data are very important and became the basis of all calculations that were completed after this stage. The data was supplied for between 1000 RPM and 2500 RPM (in 250 RPM increments) and then from 2500 RPM to 6500 RPM (in 500 RPM increments). To find a baseline for this engine, the ideal efficiency, engine efficiency and fuel conversion efficiency would need to be calculated to see what this engine was currently performing at. To do this a few pieces of data needed to be calculated first. These are:

- Efficiencies
- Net Work
- Compression Ratio
- Fuel Mass
- IMEP, BMEP and FMEP
- BSFC
- MFB

Before any of the data above could be calculated, PV diagrams and pressure against crank angle graphs were plotted. These graphs allow engineers to see more clearly what the data is saying but also these graphs can be studied to see the duration of the intake, compression, expansion and exhaust strokes. SOC and EOC can also be determined from these graphs and data. The PV diagrams and pressure against crank angle graphs for 1000 RPM (Figures 10 and 11) and 6500 RPM (Figures 12 and 13) are shown below.

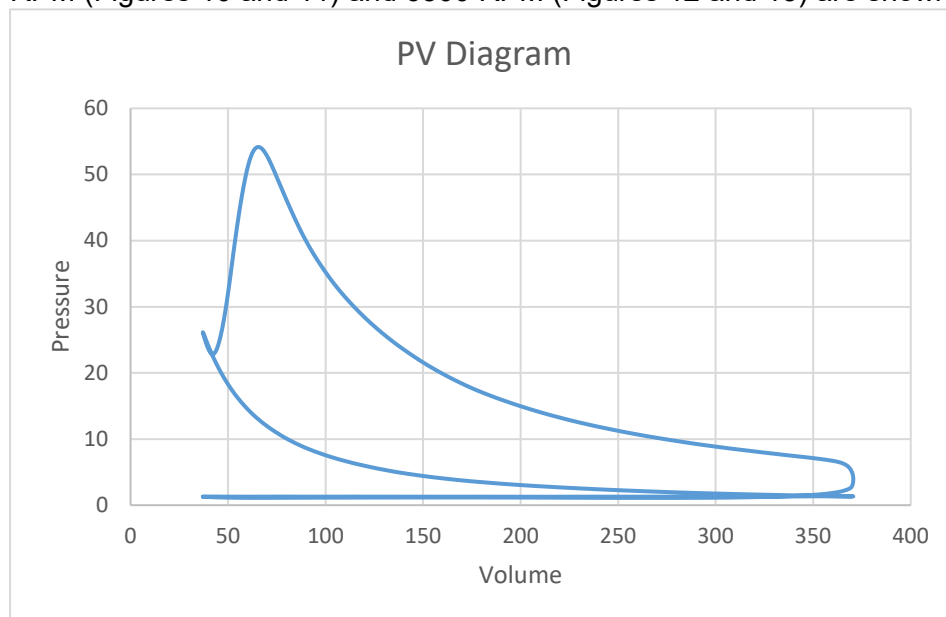


Figure 10: PV Diagram for 1000 RPM

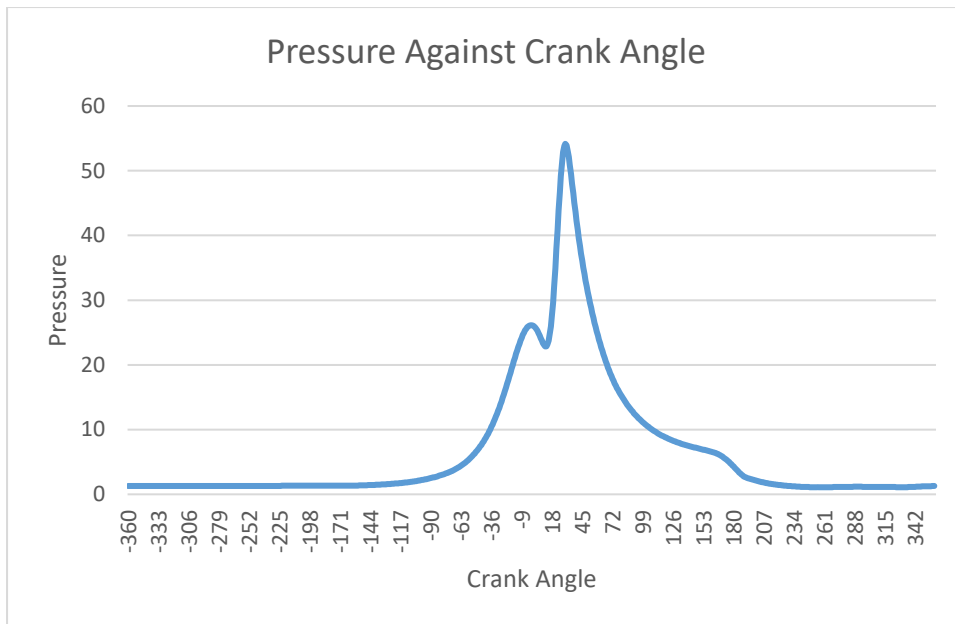


Figure 11: Pressure Against Crank Angle for 1000 RPM

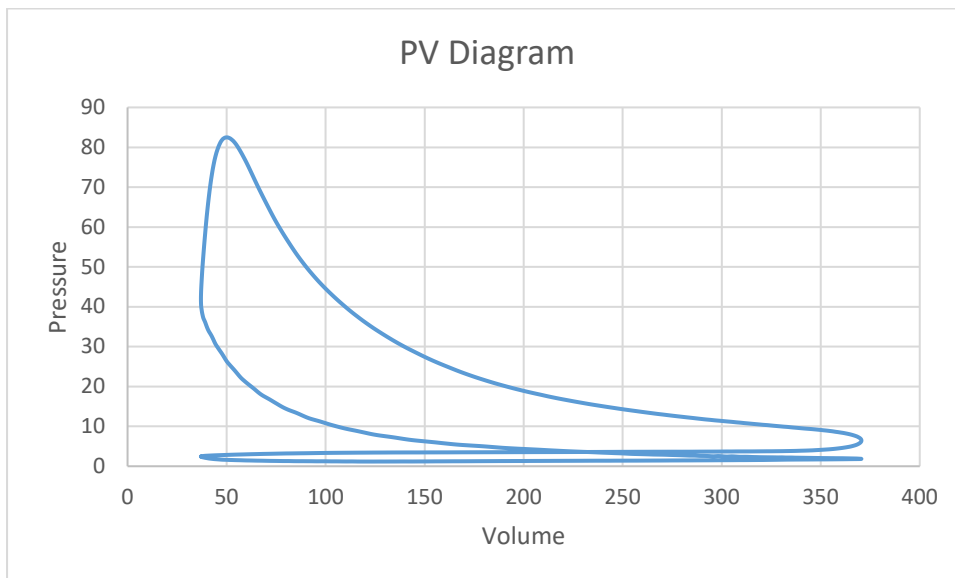


Figure 12: PV Diagram for 6500 RPM

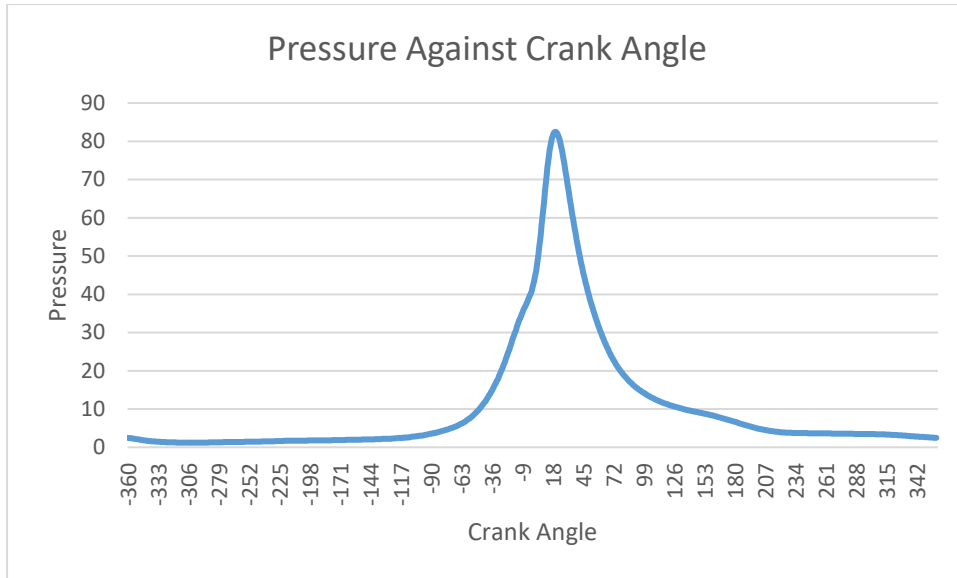


Figure 13: Pressure Against Crank Angle for 6500 RPM

The Net Work is an important piece of data to have when performing the calculations as it shows how much work is available to use after combustion across 720 degrees at a specific RPM. To calculate this, the Work Done /°. The equation for this is:

$$\text{Work Done Per Degree} = \frac{P1 + P2}{2} * (V2 - V1)$$

The pressure is the average pressure across all 3 cylinders and the volume is the absolute volume of the cylinders. With this piece of data calculated in joules, the Net Work can be calculated by adding the values of the Work Done /° for all 720 degrees. This calculation was done for each RPM value that was recorded. The results showed that there was 486.58J at 1000 RPM and 592.74J at 6500 RPM. This value is not the whole amount of joules that is produced by combustion as some of that energy is lost due to pumping work. This figure will be used in later equations when calculating efficiency and IMEP.

The next step is to find out what the Ideal Efficiency of this engine currently is. This will show how efficient this engine can be if it was working 100% efficiently. The equation used for this is:

$$n = 1 - \frac{1}{CR^{\gamma-1}}$$

Gamma in this equation represents the ratio of specific heats. The value that was used for this is 1.4 as this is the ratio of specific heats for air. It is known that there is more than just air inside the cylinder as there is a mixture of air and fuel which in this case is petrol. However this calculation was only completed with this value as the fuel and air mixture inside the cylinder is constantly changing as it depends on load, RPM and also how much exhaust gas is being put back into the cylinder by EGR valve and turbocharger. This value for the ratio of specific heats was used to save time and also because it doesn't fully affect the calculations. It shall be noted that the efficiency figure that was calculated is not 100% accurate but it is close enough to the actual value to be viable.

The CR for this equation was supplied by Ford as part of the technical specifications for the engine, however this value was calculated as a validation study. The value calculated resulted to be 10.00 (across all RPM's) and the technical specifications show that the recorded value for this is 10.0 (across all RPM's). The Ideal Efficiency that was calculated showed that the maximum efficiency that this particular engine could reach is 60.19%. This value shows that the efficiency cannot be higher than this value without changing the compression ratio, engine components or engine operating parameters.

Once it is known how efficient this engine can be, the next step was to narrow down the efficiency to find out exactly how efficient the engine is during a normal cycle. Before this can be done the Fuel Mass in Kg/Hr needed to be known. This value was supplied by Ford in a PDF File that stated all the data that was recorded for this engine. The equation to work out the first efficiency is:

$$\eta = \frac{\text{Net Work} * 60 * \text{RPM} * 1.5}{\text{Fuel Mass} * C_f}$$

The C_f in this equation is the calorific value of the fuel. In the case of this engine, petrol is being used so the average calorific of this fuel was used which is $44 * 10^6$ J/Kg. This equation was completed for each RPM and values are 30.72% at 1000 RPM, 31.39% at 6500 RPM and the peak value was 34.08% at 3500 RPM. This value isn't showing the exact efficiency of this engine as this is still some data that needs to be included that are heat and friction.

Before delving into calculating the forces acting with the cylinder, the course of action that was chosen was to calculate the IMEP, BMEP and FMEP. Before doing this another validation study was carried out to see if the calculated power that is produced by the engine would be the same as the recorded power. The equation that was used for this is shown below.

$$P = \text{Torque} * 2\pi * \frac{\text{RPM}}{60}$$

The torque value was supplied within the data that was recorder by Ford. The calculations was completed for each RPM and the results showed that the recorder data and the calculated data were the same with 92 Kw at 6000 RPM.

The IMEP, BMEP and FMEP are valuable information to have when studying and analysing how an engine performs. The IMEP of an engine is the amount of work output per unit of swept volume. However the calculation that was done for this report was the Net IMEP. This Net IMEP includes the pumping work that is used by components in the engine. Then BMEP is fairly similar to the IMEP except the IMEP is calculated for the cylinder, the BMEP cylinder is the mean effective pressure that is at the flywheel of the engine. The FMEP is the amount of work that is used by friction. (Stone, 2012) (Lumley, 1999)

The three equations that were used to calculate the Net IMEP, BMEP and the FMEP are shown below.

$$\text{Net IMEP} = \frac{\text{Net Work}}{\text{Cylinder Displacement}}$$

$$\text{BMEP} = \frac{\text{Brake Work Out In 2 Revs}}{\text{Engine Displacement}}$$

$$FMEP = Net\ IMEP - BMEP$$

For these equations the engine displacement was provided by Ford as part of the technical specifications and the cylinder displacement was calculated from this. The displacement for this engine is 999cc and the engine is a three cylinder which corresponds to 333cc per cylinder. The Brake Work out in 2 Revs is how many Joules of energy is at the flywheel of the engine after two full revolutions. To calculate this, the equation that was used is shown below:

$$Brake\ Work\ out\ in\ 2\ Revs = T * 4\pi$$

The FMEP that was calculated will be used later during the friction calculations but the Net IMEP and the BMEP were only calculated to be able to obtain the FMEP but also to evaluate and analyse how the engine is performing.

The next for the calculations was to see how much fuel is currently being used by this engine. To do this the BSFC value had to be calculated. BSFC is commonly misunderstood on what it represents. The BSFC value shows how much fuel is used per unit of power per hour. In other words the BSFC statistic of an engine shows how efficient the engine is at turning the fuel into power (Baechtel, 2011). The equation used for this is shown below.

$$BSFC = \frac{Fuel\ Mass}{Power}$$

The Fuel Mass for this equation needs to be in g/Hr and the power should be in KW. This will provide the answer in g/KwHr. The average value for this across all the RPM's is around 285 g/KwHr. By looking at this figure and comparing it to the figure that Ilmor claim to get out of their 5 stroke engine, the Ford engine is using around 60g/KwHr more than the 5 stroke engine. From a fuel consumption point of view, using a 5 stroke cycle would be a better option but there is more variable that need to be considered before deciding. There will be more discussion about the 5 stroke cycle and how it may be viable for this engine during the 5 stroke calculations and also in the analysis and conclusion sections of this report.

The penultimate calculation that was completed on this engine to understand the current engine operating characteristics is the MFB. The MFB or Mass Fraction Burned of an engine is a fraction of the amount of energy released from combustion to the amount of energy released at the end of the combustion process. MFB can be obtained through different equations but can also be obtained by computer software such as Ricardo Wave. The MFB of an engine can also be shown as different results. Sometimes the results will be shown for 50% MFB, 10% - 90% MFB or 0% - 100% MFB. (Michael F.J.Brunt, 1997)

The equation that was used to calculate the MFB in this particular case is shown below.

$$MFB = \frac{P1}{Sum\ of\ SOC\ to\ EOC}$$

The P1 in this equation refers to the first pressure figure from the Sum of SOC to EOC. This pressure figure starts at the SOC and will continually go down the list until it reaches the EOC. The Sum of SOC to EOC is taken from the Extra Pressure from Combustion. To calculate the Extra Pressure from Combustion, the first equation that needs to be completed is:

$$NP1 = OP1 * \left(\frac{V1}{V2}\right)^n$$

The NP1 is the new pressure calculated by using this equation. The OP1 is the original average pressure that was recorded from engine and supplied by Ford. With the figures for this equation calculated for each crank angle, the Extra Pressure from Combustion can be calculated. The equation for this is:

$$EP = OP2 - NP1$$

This equation was used to calculate the Extra Pressure from Combustion for each degree of rotation of the crankshaft. The EP represents the Extra Pressure from Combustion and the OP and NP where previously explained. From the Extra Pressure from combustion, the Sum of SOC to EOC can be calculated by the equation below.

$$\text{Sum of SOC to EOC} = EP1 + EP2$$

This equation was calculated from the start of combustion (SOC) to the end of combustion (EOC) to be able to get figures for MFB for the full combustion. Some people may argue that the first 10% and the last 10% of MFB isn't very useful data to have as the 10% - 90% range of the MFB figure will show how quickly and how effectively the engine is burning the fuel in the mixture but the full range was calculated so all of the data was available to study so a full analysis of the combustion of this engine can be evaluated and analysed. With the full range of data for MFB, the first 10% can be examined and analysed to find out whether the spark timing should be retarded or advanced to get the desired combustion.

The last piece of data that needed to be calculated and evaluated for this engine before moving on to the possibility of improving or modifying the engine was the friction forces that are inside of the cylinder. The final goal for these calculations was to find out how many joules are lost from combustion due to the friction forces. To do this there are many steps that needed to be completed before that final value could be obtained.

The first step is to calculate the radial force for each cylinder. The equation that was used for this is shown below.

CYL Friction Force

$$= (\text{Cyl Pressure} * \pi * \text{Ring Inner Diameter} * \text{Ring Thickness}) * 0.1$$

The Ring Inner Diameter and Ring Thickness for this equation was measured by using a Vernier caliper. The values were measured to 0.069m and 0.005m respectively. With the cylinder friction force calculated for each cylinder, the Work Done/° Against Friction could be calculated. There are a few steps to this as a few different equations are needed. All the equations are shown below in order.

$$\text{Rod Angle} = \left(\sin^{-1} \left(\left(\frac{R}{L} \right) * \sin(CA) - \left(\frac{\text{Net Offset}}{L} \right) \right) \right) * \frac{180}{\pi}$$

For the above equation, R is the radius of the crankshaft, L is the con rod length and CA is the crank angle.

$$F_{\text{gas}} = \text{AVG PR} * \text{Bore Area}$$

$$F_{\text{side}} = F_{\text{gas}} * \tan(\text{Rod Angle})$$

$$F_f = 0.1 * F_{side}$$

$$F_f \text{ Skirt and Ring} = \text{AVG Cyl Friction Force} + F_f$$

The above equation regarding F_f Skirt and Ring was completed for all 720 degrees of crankshaft rotation.

$$S = (L + R) * \cos(CA \text{ at TDC}) - ((R * \cos(CA)) + (L * \cos(Rod \text{ Angle})))$$

$$WD^\circ AF = \left(\frac{F_f \text{ SR1} + F_f \text{ SR2}}{2} \right) * (S2 - S1)$$

$WD^\circ AF$ stands for the Work Done /° Against Friction and the $F_f \text{ SR}$ is the F_f Skirt and Ring.

The values for the Work Done /° Against Friction was calculated at all 720 degrees of crankshaft rotation. However, these values must all be positive so to do this the ABS (Absolute) function was used on Excel. This function removes the minus figure from the value with altering the numbers. The Work Done /° Against Friction was then added up to get a Total Work Done Against Friction. The values for this are 32.27J at 1000 RPM and 43.57J at 6500 RPM. These values show how much energy is lost due to friction inside of the cylinder. This figure does get bigger when the friction forces for the crank train and cylinder head components are taken into consideration. The figures will be used later on when looking at the calculations that were completed for the 5 Stroke Cycle.

Calculations for the Over – Expansion Cycle

The first idea that was explored to try and increase the efficiency of this engine while lowering the emissions and fuel consumption was to make the engine run by using the Atkinson Cycle instead of the Otto Cycle. In this particular case, the Over – Expansion would be achieved by using the method that closes the intake valve later. This method was chosen for two reasons, the first reason being that the modern engines used in the hybrid vehicles uses this method and the second reason is because this project was all theoretical and done by using equations and calculations to get approximate figures for what would happen, changes to the components and hardware inside the engine were not permitted due to time constraints and nature of the project.

The first step to calculate an Over – Expansion cycle in this engine is to calculate the pressure. To do this the first step would be to find out exactly when the expansion stroke started on the Ford engine. This was done by carefully examining the pressure data for each cylinder but also by carefully examining the PV diagrams (the PV diagrams were created on Excel and are shown in the Results section of this Report). With the knowledge of where the expansion stroke starts, the original pressure from this point can be replaced with the new Over – Expansion pressure. To calculate this new pressure, the equation below was used.

$$OEP1 = P1 * \left(\frac{V1}{V2} \right)^{n_{exp}}$$

In this equation, the OEP stands for Over – Expansion Pressure. After completing the calculation to find out how the pressure will be affected by the extended expansion ratio, it was clear from the data that there was not much increase or impact. This is clearly shown when looking at the PV diagram and the graph depicting the pressure against crank angle. These graphs are shown below for 1000 RPM (Figures 14 and 15) and 6500 RPM (Figures 16 and 17).

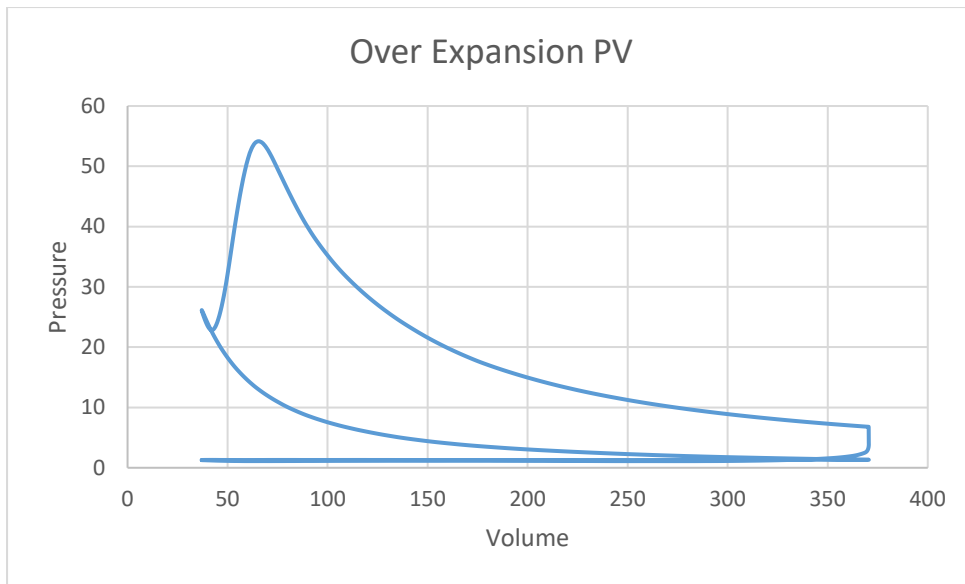


Figure 14: Over Expansion PV for 1000 RPM

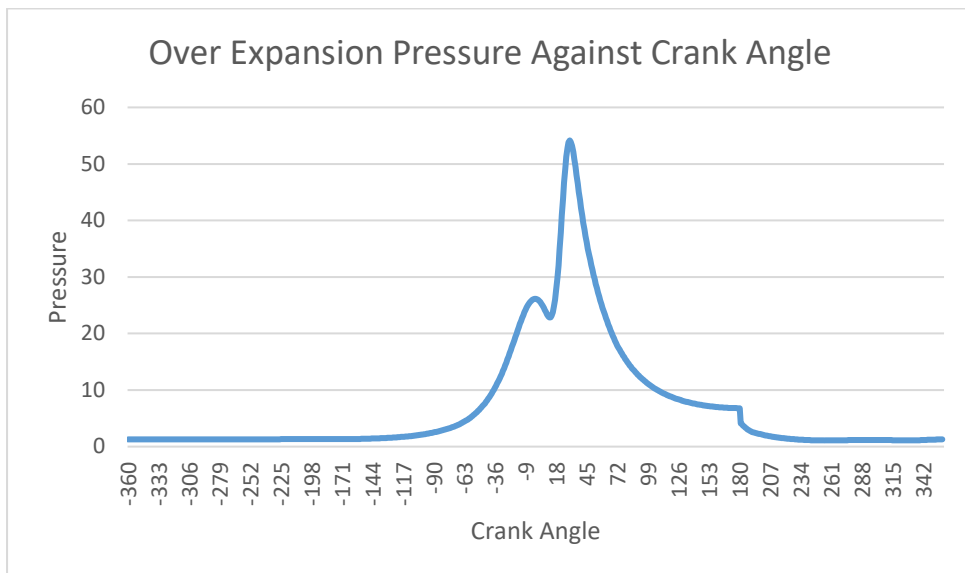


Figure 15: Over Expansion Pressure Against Crank Angle for 1000 RPM

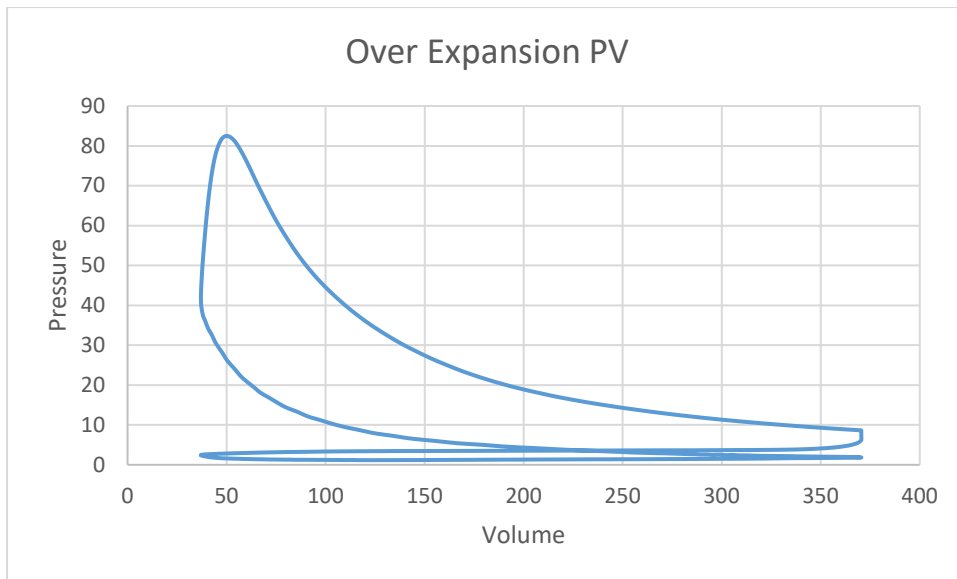


Figure 16: Over Expansion PV for 6500 RPM

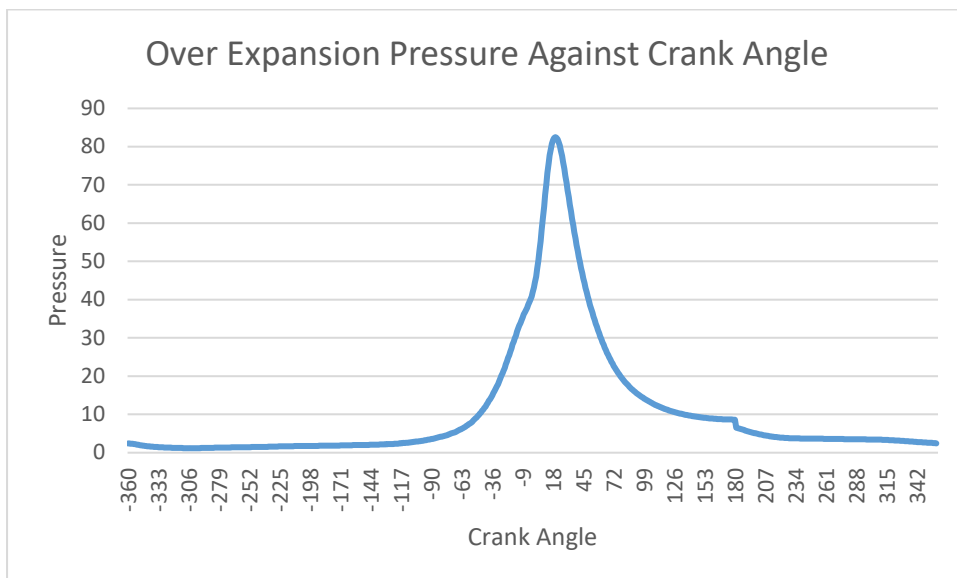


Figure 17: Over Expansion Pressure Against Crank Angle for 6500 RPM

When comparing the graphs shown in figures 10, 11, 12 and 13 to the graphs shown in figures 14, 15, 16, and 17, it is clearly shown that the new extended expansion stroke does not have that much impact on the pressure and area under the graph. The main impact that is made by the extended expansion stroke is that there is a sharper drop off at the point where the expansion stroke ends and the exhaust stroke begins. This was the first sign that this method is not the best option for this engine. However, further calculations were carried before a decision could be made to make sure that the choice was not rushed and all data was evaluated.

To fully decided whether the calculations for the Over – Expansion system should continue, the best course of action would be to calculate an important piece of data using the pressures from the Over – Expansion cycle. The piece of data that was calculated was Net Work. This will show how much extra energy is being generated by the extended expansion stroke. The equations to calculate Work Done /° and Net Work (See Page 19 for the equations) were completed using the new Over – Expansion pressures and the values for

Net Work came out as 490.62J at 1000 RPM and 594.2J at 6500 RPM. When comparing these values to the Net Work values for the standard engine, it is shown that by uses the Over – Expansion principle, the engine is gaining around 1J for the extended expansion stroke. At this point, it was decided that the calculations regarding Over – Expansion should cease and a new focus point for the calculations should be chosen. After careful consideration of the other options available for this, the 5 Stroke Cycle seemed the most promising and the most interesting.

Calculations For 5 Stroke Cycle

Many of the calculations that were completed to simulate the 5-stroke cycle are the same as what has previously been shown. However, these calculations included the pressure from the 5th stroke cylinder.

The first step for this was to calculate what the pressure in this new cylinder would be. As the cylinder is only does an extra expansion and exhaust stroke on the exhaust gases that are transferred from the other cylinders, the pressure for this cylinder is only calculated for a short portion as the pressure during combustion and induction are irrelevant. To calculate the new pressure, the equation that was used is:

$$P2 = P1 * \left(\frac{V1}{V2}\right)^n$$

The value for P1 does not need to be calculated as it was taken as the final pressure of the expansion stroke from the average pressure of the 3 operating cylinders. n in this equation stands for Polytropic Index. The value for this was taken as 1.28. It is understood that in a 5 Stroke engine, the expansion cylinder is normally larger than the other cylinders but as the work that was done on this subject is all theoretical and simulated, the volume was kept the same as the other cylinders. With the pressure for the expansion cylinder calculated, the extra work generated by the additional expansion stroke could now be calculated. Firstly, the extra work out per degree (See Page 19 for equation) was calculated for this cylinder to then find out the total extra work out. The values for this were calculated to be 42.72J at 1000 RPM and 45.40J at 6500 RPM. The maximum value for the extra work out is 89.19J at 2500 RPM.

Because of the added extra work out there will now be a new Net Work. The extra work out from the 5-stroke cylinder was added onto the Net Work for the standard engine. This was completed as the next step that was needed to be completed was to find out how much the extra work out increases the efficiency of the engine. By using the efficiency calculation shown on Page 20, a new efficiency was calculated. The figures for this are 33.67% at 1000 RPM and 34.34% at 6500 RPM. This increase in efficiency shows that the 5 Stroke cylinder is helping and a 3% average increase in efficiency is quite significant.

The next step was to narrow down the efficiency to a more accurate figure which meant including the amount of energy lost due to friction. Firstly, the extra friction was calculated for the 5 Stroke cylinder by using the equations shown on Pages 22 and 23. With the friction work calculated for both the normal engine and the 5 Stroke engine, the Fuel Energy Brake Efficiency could be calculated. the first step to calculating this efficiency is to take the friction work away from the Net Work to have a figure for Brake Work. With the Brake Work, the equation that was used for the Fuel Energy Brake Efficiency is:

$$n = \left(\frac{\text{Brake Work}}{\text{Fuel Energy Per Cycle}} \right) * 100$$

There are a few steps needed to calculate the Fuel Energy Per Cycle. These are shown below:

$$\text{Fuel Mass in 1 Rev} = \frac{\text{Fuel Mass}}{60 * \text{RPM} * 1.5}$$

$$\text{Fuel Energy Per Cycle} = \text{Fuel Mass in 1 Rev} * \text{Calorific Value of Fuel}$$

The Fuel Energy Brake Efficiency was calculated for both the normal engine and the 5 Stroke engine. The values for the normal engine were 28.94% at 1000RPM and 29.16% at 6500 RPM whereas the values for the 5 Stroke engine were 30.95% at 1000RPM and 31.30% at 6500RPM. So, after the friction work has been considered, there is still around a 2% increase in efficiency.

The final part of the calculations for this project was to find out how much energy is being lost done the exhaust pipe of the vehicle. The equations for this were completed for both the normal engine and the 5 Stroke engine. The first step for this was to calculate the exact composition of the exhaust gas for each RPM. The lambda was needed for this stage and the lambda values were collected from the data supplied by Ford. It is understood that when an engine is running lean, the exhaust gases contain CO₂, H₂O, O₂ and N₂. When an engine is running with a rich AFR then the exhaust gas is made up of CO₂, CO, H₂O and N₂. The equation used to calculate each chemical are shown below.

If Lean:

$$\text{CO}_2 = \text{Lambda} * 8$$

$$\text{H}_2\text{O} = \text{Lambda} * 9$$

$$\text{O}_2 = (25 * (1 - \text{Lambda})) / 2$$

$$\text{N}_2 = 47$$

If Rich:

$$\text{CO}_2 = 25 - (17 * \text{Lambda})$$

$$\text{CO} = 25 * (\text{Lambda} - 1)$$

$$\text{H}_2\text{O} = \text{Lambda} * 9$$

$$\text{N}_2 = 47$$

The next stage required some data for each of the chemicals in the exhaust gas. By using some sections from a book called Thermal Fluid Sciences, tables with the enthalpy of formations for each of the gases was acquired. These tables were then plotted into excel for the temperature range of the exhaust gases and a graph was made from this data. This graph was then used to find out the equations for each gas. The equations are shown below.

$$y = 49.935x - 16122 \text{ for CO}_2$$

$$y = 38.528x - 12143 \text{ for H}_2\text{O}$$

$$y = 31.291x - 9646.5 \text{ for N}_2$$

$$y = 33.212x - 10338 \text{ for O}_2$$

$$y = 31.666x - 9791.9 \text{ for CO}$$

The next piece of data that is required for these calculations is the temperature before and after the turbocharger. This data was supplied in the Ford technical specifications. With all the data collected, the energy loss per Kmol for each gas could now be calculated. to calculate this, there will be the equation for the gas with x being replaced with the pre-turbo temperature minus the equation for that gas with x being replaced with the after-turbo temperature.

To calculate the total energy loss for each RPM it will be the amount of the chemical multiplied by the energy loss/Kmol for that chemical. This will have to be done for each chemical in that current mixture and then the four values will be added up to obtain the total energy loss. The total mass is a very similar calculation. To calculate this, it is the amount of that gas multiplied by the gases atomic weight. Once again this will be repeated for each gas in the composition and all four values will be added up to obtain the total mass.

To calculate the total energy loss per KG the equation is:

$$\text{Total Energy Loss Per Kg} = \frac{\text{Total Energy Loss}}{\text{Total Mass}}$$

The total mass in Kg/Sec was obtained by adding the Fuel Mass per second and Air Mass per second. The Fuel Mass and Air Mass was obtained via the Ford technical specifications.

With all the above data, the total energy loss per second across the turbo could be calculated. The equation for this is shown below.

$$\text{Energy Loss Across Turbo Per Sec} = \frac{\text{Total Energy Loss Per Kg}}{\text{Total Mass Kg per Sec}}$$

To calculate the Energy Loss Across Turbo Per Second for the 5 Stroke engine, the temperature before and after the turbo had to be calculated. this was done by using the equation below.

$$T2 = \frac{V1^{\gamma-1}}{V2} * T1$$

With the temperatures calculated the Energy Loss Across Turbo Per Second was calculated to be a maximum of 14.62 Kw for the standard engine and a maximum of 11.88 Kw for the 5 Stroke engine. The above equations can be repeated to calculate the Energy Loss Per Second Across Exhaust. This is done by changing the after-turbo temperature to atmospheric temperature (298K). This calculation was completed for both the normal engine and the 5 Stroke Engine and the data showed that it was a maximum of 118.18 Kw for the normal engine and 89.18 Kw for the 5 Stroke engine.

Results

This section is showing all the graphs and tables produced from work that was completed during this project.

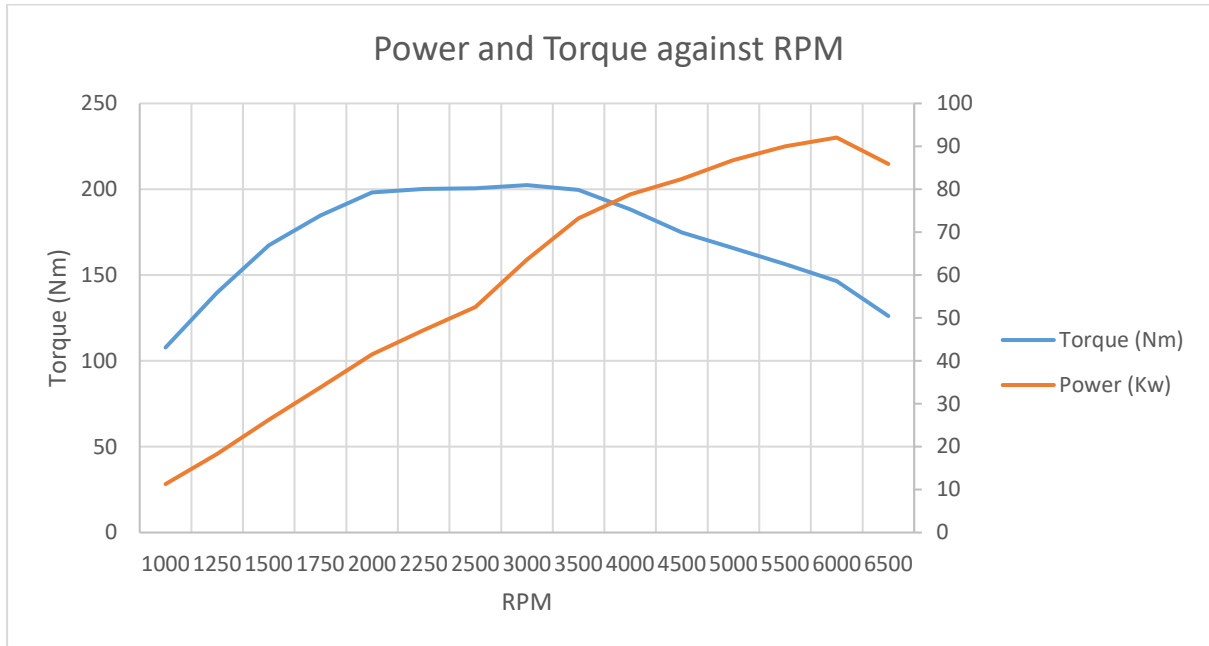


Figure 18: Graph Showing Power and Torque Against RPM

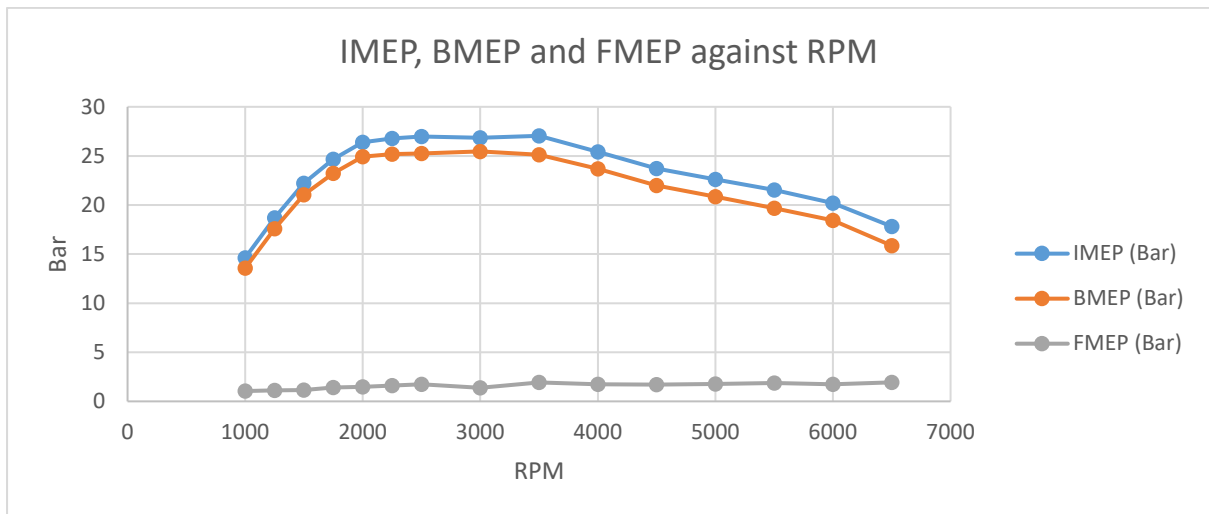


Figure 19: Graph Showing IMEP, BMEP and FMEP Against RPM

Table 2: IMEP, BMEP, FMEP, Power and Torque

RPM	IMEP (Bar)	BMEP (Bar)	FMEP (Bar)	Torque (Nm)	Power (Kw)
1000	14.6119763	13.56010763	1.051868701	107.8	11.28879
1250	18.6803919	17.57279254	1.107599406	139.7	18.286687
1500	22.2103133	21.04458262	1.165730633	167.3	26.279423
1750	24.6470832	23.23331984	1.413763314	184.7	33.848043
2000	26.3984289	24.93147804	1.466950908	198.2	41.510911
2250	26.7910267	25.17047808	1.620548574	200.1	47.147452
2500	26.9796493	25.23337283	1.746276489	200.6	52.516957
3000	26.8453618	25.45979392	1.385567869	202.4	63.585835
3500	27.0474138	25.12016228	1.92725153	199.7	73.193873
4000	25.4209909	23.67358308	1.747407802	188.2	78.833032
4500	23.7215679	22.00058279	1.720985116	174.9	82.419683
5000	22.6111457	20.84331943	1.767826253	165.7	86.760317
5500	21.5179461	19.66089817	1.857047903	156.3	90.022337
6000	20.1802961	18.42816111	1.75213496	146.5	92.048665
6500	17.8001387	15.87463435	1.925504369	126.2	85.901615

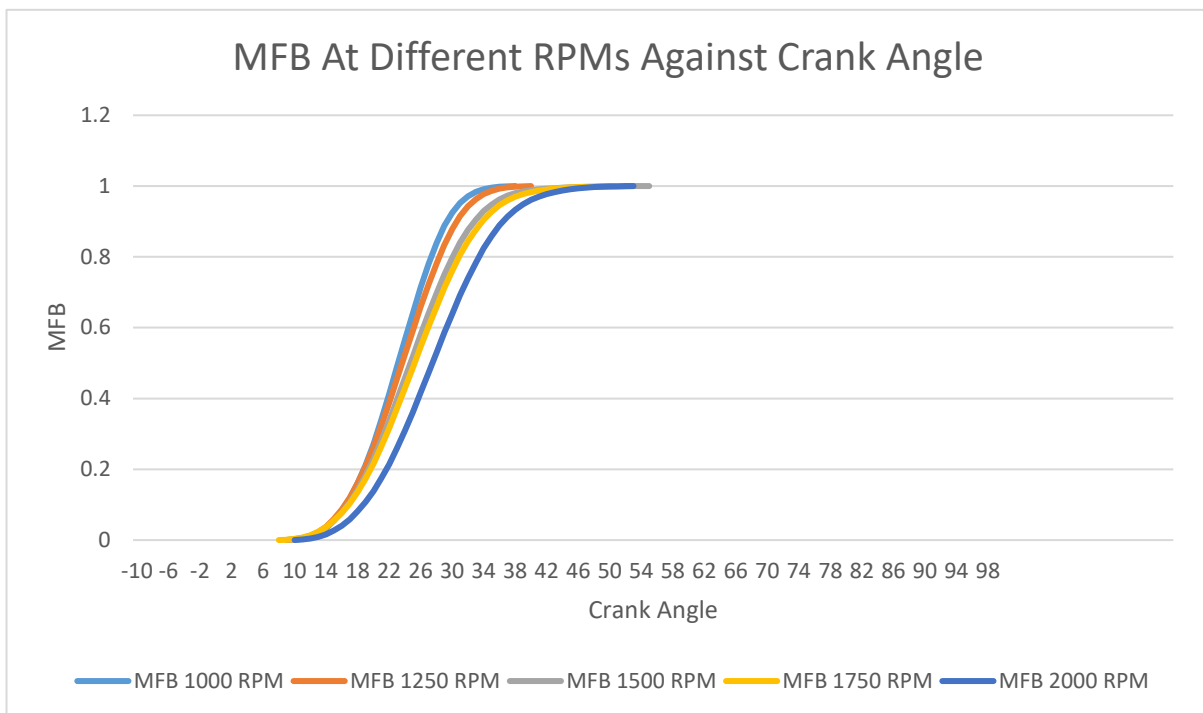


Figure 20: MFB for 1000, 1250, 1500, 1750, 2000 RPM

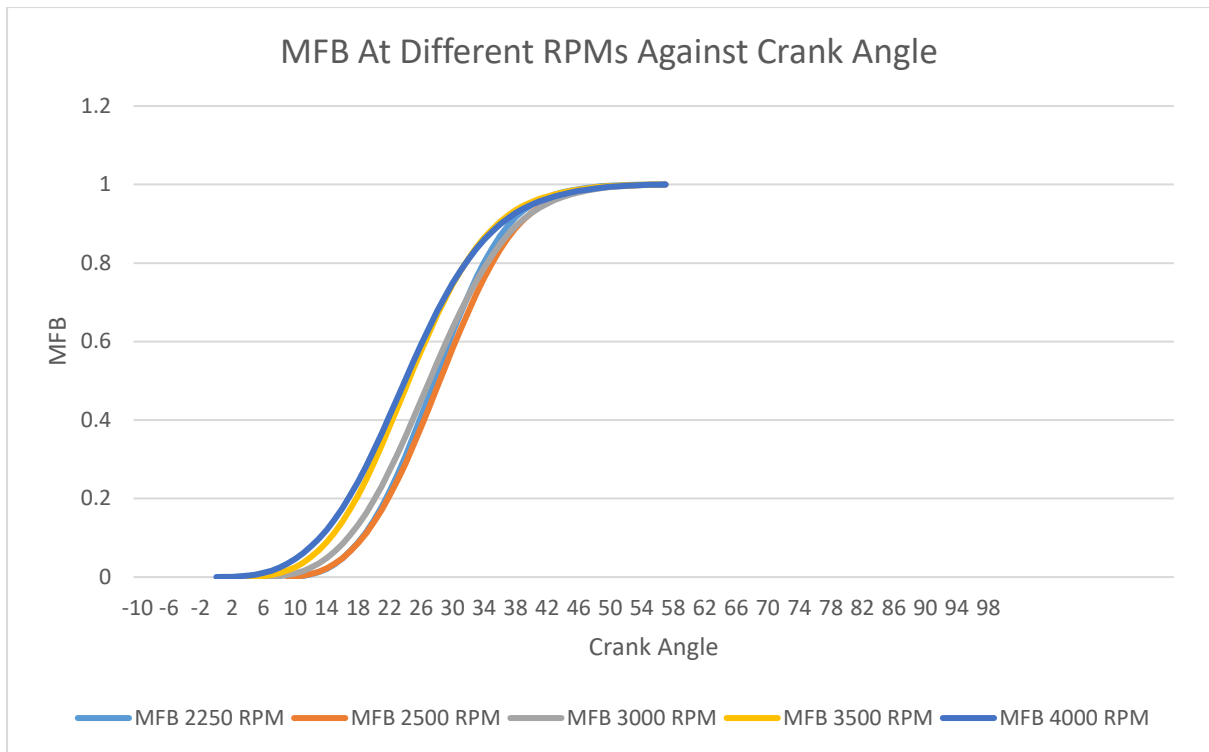


Figure 21: MFB for 2250, 2500, 3000, 3500, 4000 RPM

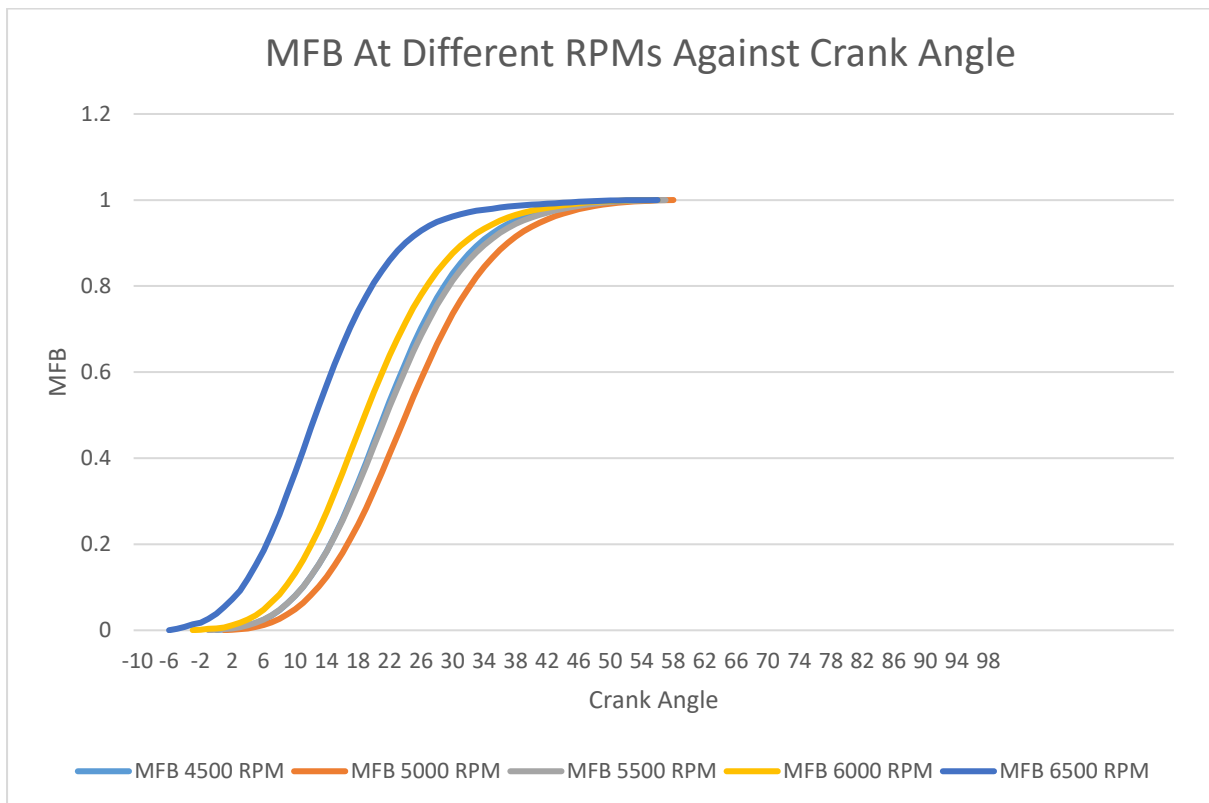


Figure 22: MFB for 4500, 5000, 5500, 6000, 6500

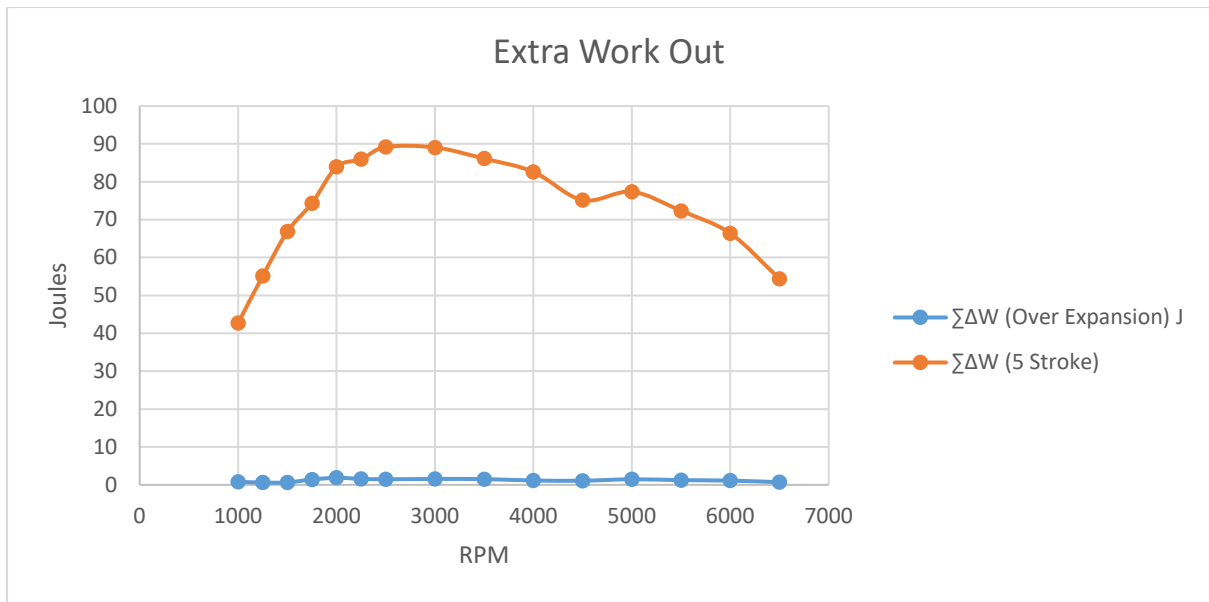


Figure 23: Extra Work Out for Over Expansion and 5 Stroke Engines

Table 3: Extra Work Out and Efficiencies

RPM	$\Sigma\Delta W$ (Over Expansion)	$\Sigma\Delta W$ (5 Stroke)	Original Efficiency	5 Stroke Efficiency	Increase
	J		%	%	%
1000	0.811012351	42.72374681	30.71835933	33.67071617	2.952357
1250	0.593033676	55.13951703	30.46909541	33.22979882	2.760703
1500	0.636279444	66.8661967	30.17603458	32.95766936	2.781635
1750	1.423545879	74.34678599	31.28758578	34.23422322	2.946637
2000	1.857058458	83.92448223	31.68445797	34.84786287	3.163405
2250	1.584169086	85.94766518	31.77923418	34.95788044	3.178646
2500	1.476269575	89.18605483	32.03769217	35.32738116	3.289689
3000	1.552212514	89.06025435	30.34073912	33.47278285	3.132044
3500	1.517826831	86.11107611	34.08056015	37.45799254	3.377432
4000	1.14696613	82.61460095	32.15443136	35.38317438	3.228743
4500	1.092105741	75.14957461	32.54668812	35.73668356	3.189995
5000	1.472667113	77.37248204	30.13947856	33.35863969	3.219161
5500	1.239025769	72.32489995	30.29372622	33.45995633	3.16623
6000	1.119578667	66.38504229	29.85995688	32.91268828	3.052731
6500	0.699817722	54.40287093	31.38514195	34.34274442	2.957602

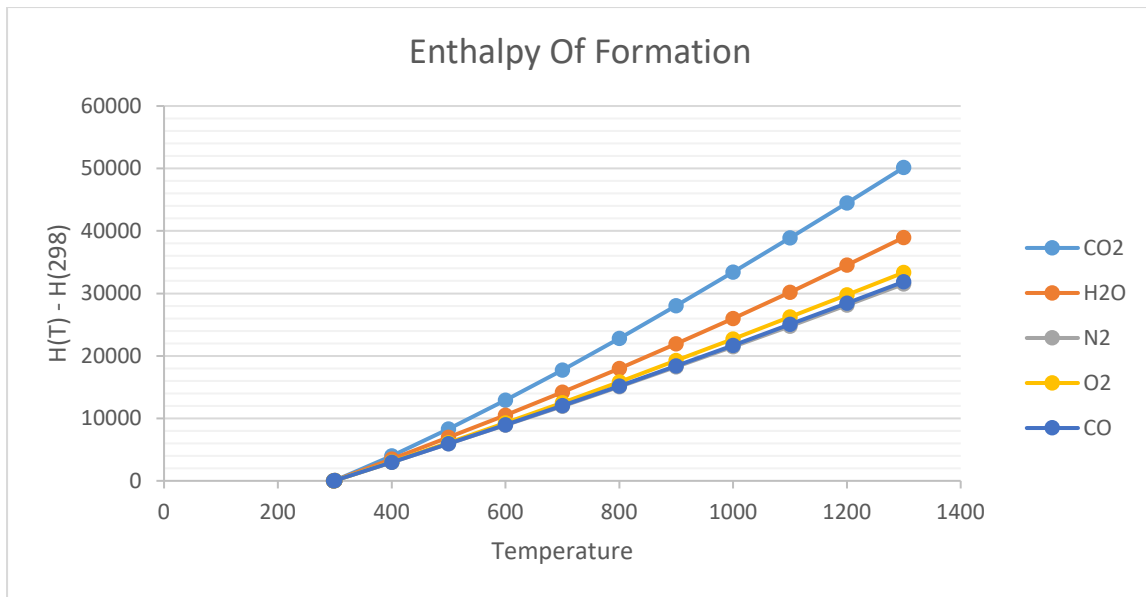


Figure 24: Enthalpy Of Formation

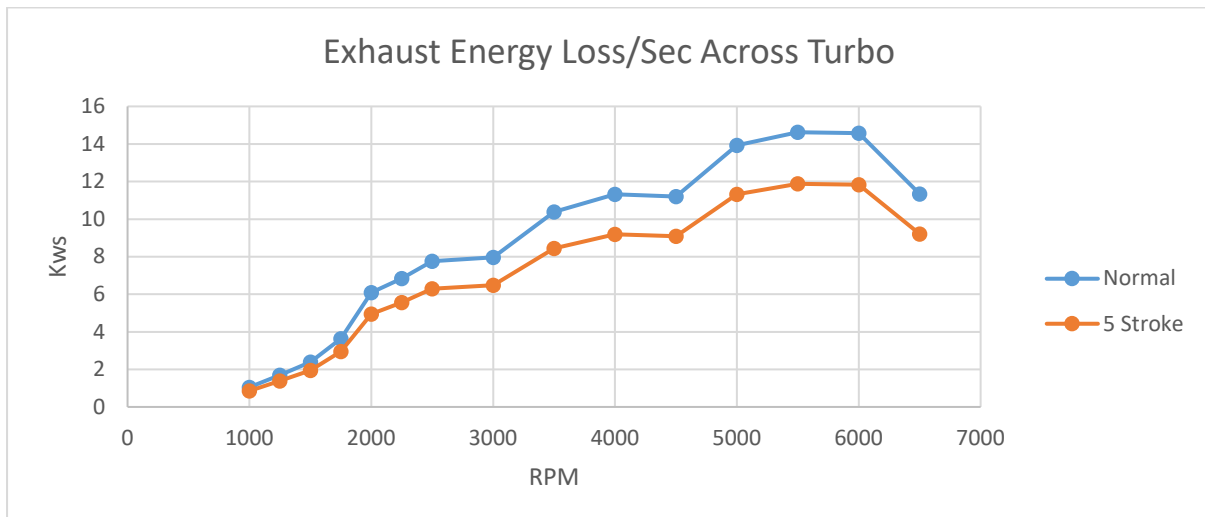


Figure 25: Energy Loss Per Second Across Turbo

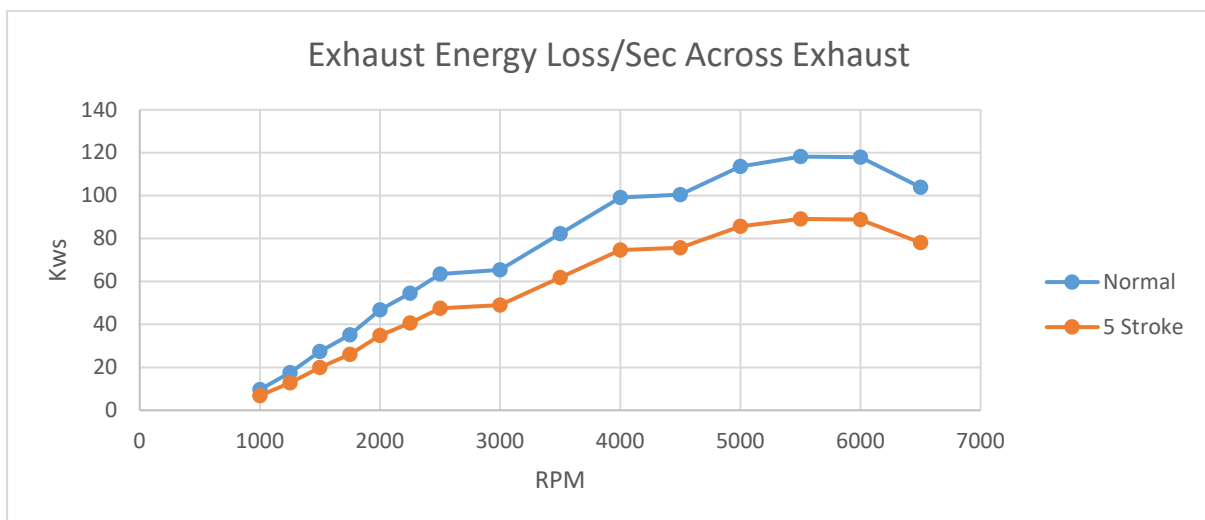


Figure 26: Energy Loss Per Second Across Exhaust

Analysis

There is a lot of data that was acquired and calculated to examine and analyse. There are a few important calculations that will be focused on for this report. Firstly, there is the issue with the Over Expansion calculations. Unfortunately, the calculations for this did not show any improvement. This could be since over expansion engines or engines that use the Atkinson Cycle are primarily used within conjunction of an electric motor. The reason this setup works as a hybrid engine is because the petrol engine is either used to charge the electric motor or it is used for high loads.

The actual performance of the engine is normal as there are no abnormalities or faults with any of the data recorded and calculated. However, compared to the 5 Stroke engine that is being produced by Ilmor it is considerably worse on fuel consumption and emissions. These two factors are the main issue at this current time with petrol and diesel engines. The calculations for the 5 Stroke modification do seem promising on this engine as not only does it drop the temperature off the exhaust gases by a considerable amount, but it also drops the energy loss through the exhaust by a considerable amount.

The 5 Stroke calculations prove that this setup is viable and companies like Ford and Fiat might benefit from using these engines as those companies are putting a lot of effort and attention into downsizing their engines. From research on this topic, the 5 Stroke engine works best as a 3-cylinder engine and works best with a small engine size.

There have been a few issues that were encountered during the calculations for this project and there is one possible issue that wasn't solved. The energy loss across the exhaust for the Ford engine is very high for the size of the engine. It is widely believed that 33% of the fuel power goes down the exhaust as energy lost, 33% is lost to oil and water and then 33% is transferred to the wheels as power. The power transferred to the wheels for this engine is 92 Kw and 118 Kw is being lost down the exhaust. This means that there is considerably more than 33% being lost down the exhaust. With all, the engine could be highly inefficient at transferring power to the wheels however, the author of this report believes that the error is with the chemical composition of the exhaust gases.

Conclusion and Further Work

In summary, the Over Expansion engine or Atkinson Cycle engine should only be used in conjunction with an electric motor, or if it is used in a petrol engine then some modifications should be done to the crank train to make sure that the engine is working at optimal efficiency.

The 5 Stroke engine is a very promising design and concept and could possibly be the best option for small petrol engines since it still produces quite a lot of power and torque but is also fuel efficient and not as harmful to the environment compared to other petrol engines. The 5 Stroke engine typically is equipped with a turbocharger but if the engine is also equipped with an EGR valve then the harmful gases emitted out of the exhaust will decrease even further.

With all the work that has been done for this project, choosing to keep using petrol engines is quite a dangerous risk for all car companies. Due to the health of the environment, the limit of fuels like petrol and diesel and the legislations and regulations being enforced by governments, choosing to develop long range and efficient electric or hybrid vehicle might be the best option to choose from when looking from an outside perspective.

With everything that has just been said, car companies and manufacturers should take every option into careful consideration before deciding which path to take as there is risks and advantages associated with every option.

There are a few extra pieces of work that could be done to make this project complete. These tasks are:

- Research into Thermo – Electric Materials
- Calculate the forces for the crank train and cylinder head
- Create a 3d model for the 5 Stroke engine.

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