

Analytical Techniques Using Cylinder Pressure

M6X00417 MAJOR PROJECT - MALCOLM MCDONALD

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Abstract

This report utilises the cylinder pressure information from a Spark Ignition (SI) Gasoline Direct injection (GDI) engine, developing from first principals an accurate engine model, culminating in a NO_x model. The Mass Fraction Burned (MFB) is calculated and used to develop a single zone, then two zone temperature model. The molecular weight is used to determine the dissociation in the burned zone. The Zeldovich NO_x model predicts NO_x output in PPM which can be compared against the measured data.

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Abbreviations

W_{ci} - Indicated work per cycle	ICE- Internal Combustion Engine
ΔP - Delta P	IMEP- Indicated Mean Effective Pressure
ABDC - After Bottom Dead Centre	IVC - Inlet Valve Closes
AFR - Air Fuel Ratio	IVO - Inlet Valve Opens
ATDC - After Top Dead Centre	MBT - Maximum Brake Torque
BDC - Bottom Dead Centre	MFB - Mass Fraction Burned
BMEP - Brake Mean Effective Pressure	MW - Molecular Weight
BTDC - Before Top Dead Centre	n - Constant
CYLPR - Cylinder Pressure	NA - Naturally Aspirated
EGR - Exhaust Gas Recirculation	PL - Part Load
EOC - End of Combustion	PPM - Parts per Million
EVC - Exhaust Valve Closes	PS - Pferdestärke (Metric unit = 0.986 HP)
EVO - Exhaust Valve opens	PV -Pressure Volume
EZM - Extended Zeldovich Mechanism	RGF - Residual Gas Fraction
FER - Fuel Equivalence Ratio	RPM - Revolutions per Minute
FL - Full Load	SI - Spark Ignition
GDI - Gasoline Direct Injection	SOC- Start of Combustion
HC- Hydro Carbons	TDC- Top Dead Centre
HP - Horse Power	WLTP- Worldwide Harmonised Light
HCCI - Homogeneous Charge Compression Ignition	Vehicle Test

Engine Specification

The data supplied is from a Ford 1.0 litre turbo charged in line 3-cylinder Fox engine from the EcoBoost range. It is the more powerful version 125 PS; 123hp (Ford, 2012).

Ford Fox 1.0-litre EcoBoost (125PS)		
Type		Inline three cylinder turbo petrol, direct fuel injection and Ti VCT, transverse
Displacement	cm ³	999
Bore	mm	71.9
Stroke	mm	82
Compression ratio		10.0:1
Max power	PS (kW)	125 (92)
at rpm		6000
Max torque	Nm	170 (up to 200 with transient overboost)
	at rpm	1400-4500
Valve gear		DOHC with 4 valves per cylinder, twin independent variable cam timing
Cylinders		3 in line
Cylinder head		Cast aluminium
Cylinder block		Cast iron
Camshaft drive		Low friction Belt-in-Oil with dynamic tensioner
Crankshaft		Cast iron, 6 counterweights, 4 main bearings
Engine management		Bosch MED17 with CAN-Bus and individual cylinder knock control
Fuel injection		High pressure direct fuel injection with 6 hole injectors
Emission control		Close coupled three-way catalyst system with heated universal oxygen sensor and catalyst monitor sensor post catalyst
Emission level		Euro Stage 5
Turbocharger		Continental low inertia turbo
Lubrication system		Electronically controlled variable displacement oil pump for improved fuel economy
System capacity with filter	litres	4.1
Cooling system		Split cooling system with 2 thermostats
Transmission		Durashift 6- speed (B6) manual
Gear Ratios		
		6th 0.690
		5th 0.821
		4th 1.032
		3rd 1.357
		2nd 2.048
		1st 3.727
		Reverse
		3.82
		FDR 4.07

Figure 1 Ford EcoBoost Specifications (Ford, 2013)

Chapter 1 Introduction

The modern motor vehicle industry is driven by increasingly stringent emission legislation. All vehicle manufactures will soon have to develop vehicles capable of passing the new Worldwide Harmonised Light Vehicle Test (WLTP). There is currently an intense focus within the industry to develop more efficient and environmentally friendly powertrains.

Bearing that requirement in mind this report aims to develop an analytical method, from cylinder pressure data to model the Ford Fox 1L Ecoboost engine using first principals. The goal of the model will be to develop a method for predicting the NO_x formation of the engine.

The initial steps will be to consider the work done in the cycle. Then calculate the MFB by establishing the polytropic index and identifying the start and end of combustion. From this information a single zone combustion model can be created. To find the average temperature within the one-zone model the molecular weight of the cylinder charge will need to be identified. This average temperature will then form the basis for a two-zone model which will determine the temperature in the burned and unburned zone of the cylinder.

From these temperatures a dissociation model will be employed to determine the partial pressure equilibrium constants; from which the NO_x production can be calculated using the extended Zeldovich mechanism.

Finally, the valve timing will be calculated from the partial Ford data supplied. To determine if differentiated data can be used to identify the inlet and exhaust valve opening and closing.

Chapter 2 Literature Review

The Gasoline Direct Injection (GDI) is a product of the increasing political pressure on automotive manufacturers to reduce emissions. Over the last decade many engines have become smaller, turbocharged and employ GDI. There are many benefits to this process, Bosch claims its GDI gives fifteen percent greater fuel efficiency along with fifty percent more low-end torque, normally associated with diesel engines.

The drawback to the GDI engines are the NO_x emissions, the automotive manufacturers have been combatting that problem with Exhaust Gas Recirculation (EGR). The Ford Fox used in this report is an excellent example of the a 1.0L turbocharged GDI engine with EGR, the engine has been used extensively throughout the ford range and the other manufactures have similar engines. The known issue with NO_x would give the expectation that considerable research has gone into this problem however the author has not been able to find the in-depth body of research so readily available for Naturally Aspirated (NA) port injection engines.

The reports reviewed in this chapter all consider the issue of NO_x modelling for GDI engines either directly or indirectly. It is also of note that many of the specialist books, relied on as the reference for the field, such as 'Design and simulation of four stroke engines' by Blair and 'Internal combustion engine fundamentals' by Heywood have very little information regarding the turbo charged GDI engine.

A Review of Mixture Preparation and Combustion Control Strategies for Spark-Ignited Direct-Injection Gasoline Engines by Fu-Quan Zhao and Ming-Chia Lai Wayne State University David L. Harrington General Motors Research and Development Centre (Zhao, et al., 1997)

This paper, from 1997, identifies the fact new technology allows the realistic application of GDI for development. In an insightful paper many of their observations and perceptions have proven true over the twenty-one years since it was written. They highlight many of the NO_x issues still encountered today that the GDI engine has greater fuel efficiency as it can operate knock limited higher compression ratios that unfortunately elevate NO_x emissions. The report highlights the issue of NO_x management through EGR, that on a rich or stoichiometric charge there are increased Unburnt Hydrocarbons (UBHC). They also discuss the management of NO_x using the emerging catalyst technology and the possible application of NO_x storage catalysts.

Cooled EGR Modulation: A Strategy to Meet EURO IV Emission Standards in Automotive DI Diesel

Engines by J. L. Lázaro, J. L. García-Bernad and C. Pérez VALEO Engine Cooling Spain J. Galindo, H. Climent and F. J. Arnau CMT - Universidad Politécnica de Valencia (Lázaro, et al., 2002)

This is an older paper focusing on the impact of an EGR cooler on diesel. While not directly relevant to GDI petrol engines, it is useful, as it addresses the different emissions encountered at start up where their prototype reduces HC and CO but slightly increase NOx. By not cooling the EGR on warm up the engine reaches optimal operating temperature earlier, as this occurs at a stage where the engine is cool the slight increase in NOx production is not considered essential. This technology has made its way into petrol engines.

Expansion of HCCI Operating Region by the Combination of Direct Fuel Injection, Negative Valve

Overlap and Internal Fuel Reformation by Tomonori Urushihara, Koji Hiraya, Akihiko Kakuhou and Teruyuki Itoh Nissan Motor Co.,Ltd. (Urushihara, et al., 2003)

This paper focused on an EGR heavy test engine, where the direct injection of fuel into the high temperature residual gas in the cylinder changed the chemical composition of the fuel, a process they called fuel reformation. The paper is aimed at increasing the effective range of Homogeneous Charge Compression Ignition (HCCI) and has little to do with NOx formation other than their method did not increase NOx in the expanded lean limit.

Investigation into the Effect of Injection Timing on Stoichiometric and Lean CAI Operations in a 4-

Stroke GDI Engine by Li Cao, Hua Zhao, Xi Jiang and Navin Kalia Brunel University (Cao, et al., 2007)

The concept examined in this paper is that Controlled Autoignition (CAI) also known as (HCCI) can be achieved with managed direct injection timing in lean and stoichiometric mixtures. Given their assumption that this method can reduce NOx emissions by lowering combustion temperatures and improve fuel efficiency this subject is gaining more attention. The report also includes negative valve overlap where the exhaust valve is closed earlier than standard trapping more exhaust gasses. The most significant conclusion to this is that they found the minor combustion in a lean burn mixture occurring in the negative overlap created relatively high NOx.

Investigation into Controlled Auto-Ignition Combustion in a GDI Engine with Single and Split Fuel

Injections by Li Cao, Hua Zhao and Xi Jiang Brunel University (Cao, et al., 2006)

This paper follows on from the above study and investigates control methods for the CAI. The report goes into detailed analysis of single injection or double injection timing and the impacts of each. The most relevant finding is that best engine efficiency was with a 50/50 injection ratio whereas the best for NO_x and soot production was 10/90 split. Both these reports are informative, however, as the Ford Fox is not a HCCI engine they have limited application.

Isolating the Effects of EGR on HCCI Heat-Release Rates and NO_x Emissions by John E. Dec, Magnus Sjöberg and Wontae Hwang Sandia National Laboratories (Dec, et al., 2009)

This paper examines the effect of EGR heat release and NO_x emissions in HCCI engines. The usual limited of HCCI is rapid Pressure Rate Rises (PRR) and engine knock caused rapid Heat Release Rate (HRR). They discuss how while EGR has benefits it has drawbacks as it can affect the combustion phasing therefore they separate out the functions to better understand how they work. Their work indicates that the combustion phasing is impacted by EGR as is the thermal efficiency. Most relevant to this report is that in an intentionally stratified charge EGR reduces peak temperatures reducing NO_x formation.

Parametric Study on a Gasoline Direct Injection Engine – A CFD Analysis by A Abhilash Reddy and J M Mallikarjuna Indian Institute of Technology Madras (Reddy & Mallikarjuna, 2017)

This report is a Computational Fluid Dynamics (CFD) analysis using CONVERGE. The focus is on soot and particulate matter emissions, but it does look at NO_x modelling. In general, they discovered that NO_x production increase with crank angle after spark ignition, until up to peak temperature after which NO_x production reduces. This is explained through predominantly high gas temperatures in cylinder. The NO_x formation was also increased at higher injection pressure due to increased atomisation creating improved combustion. The study showed increases in NO_x for all tests be it higher pressure injection, increased number of injector holes or multi stage injection. This would seem to highlight the importance of EGR as these tests were to reduce soot and particulate matter by increasing combustion efficiency. Unfortunately, this increases combustion temperatures to the level where NO_x is produced.

Chapter 3 Calculating Work Done

3.1 Full Load

The Ford data is based on two revolutions of the crank, over 720° starting at -360° to 360° with zero being TDC of the power stroke by industry convention. Supplied against this information, in one-degree increments is the cylinder volume in centimetres cubed alongside the cylinder pressure in bar. An example of the supplied data at full load, 1000rpm is shown in Table 1. While data is given for all three cylinders and an average figure could have been used, this report focuses on cylinder one in all instances.

Table 1 1000RPM Full Load Supplied Data

Crank Angle	V_ABS	CYLPR1	CYLPR2	CYLPR3
deg	cm ³	bar	bar	bar
-360	37.05	1.171	1.322	1.35
-359	37.09	1.171	1.326	1.35
-358	37.19	1.175	1.331	1.355
-357	37.35	1.18	1.331	1.36
-356	37.58	1.18	1.336	1.36
-355	37.88	1.185	1.336	1.36
-354	38.24	1.185	1.341	1.36
-353	38.66	1.185	1.346	1.365
-352	39.15	1.19	1.346	1.365
-351	39.71	1.19	1.346	1.365
-350	40.33	1.19	1.351	1.365
-349	41.01	1.195	1.351	1.365
-348	41.76	1.19	1.351	1.365
-347	42.57	1.19	1.351	1.37
-346	43.44	1.19	1.346	1.37
-345	44.38	1.19	1.346	1.37

From the supplied data before any calculations are required, a pressure volume diagram can be plotted (Figure 4). The indicated work per cycle can be ascertained by integrating around the curve to calculating the area enclosed in the graph (Heywood, 1988).

$$W_{ci} = \oint P \times (V_2 - V_1)$$

Equation 1 Indicated work in Joules per degree

W_{ci} = Indicated work per cycle

V = Volume

P = Pressure

By applying Equation 1 to each engine speed the work done could be calculated (Table 2), in order to achieve a value in joules the pressure was converted to pascals and the volume was converted to metres cubed; as the values calculated where for a single cylinder they were multiplied by three to give the engine indicated work done in two revolutions by the 3 cylinder Ford Fox engine.

$$\text{Indicated Torque} = \text{Word done in 2 revs} \times 4\pi$$

Equation 2 Indicated Torque

The indicated work per cycle was over 720° which needs to be convert to radians using Equation 2. This results in a predicted indicated torque which can then be compared to the measured values for torque supplied in the Ford data (Ford, 2012) and the percentage difference determined (Table 2); the results have been plotted on Figure 2 for comparison.

Table 2 Indicated work done and Torque FL

RPM	Work Done	Indicated Work Done 2 Revs	Indicated Torque	Final CVC Clutch Torque	Brake Torque	Torque lost due to Friction
	J	J	Nm	Nm	Nm	%
1000	496.176541	1488.529623	118.4534237	108.9	108	8.82
1250	631.343499	1894.030497	150.722158	145	140	7.11
1500	747.572522	2242.717566	178.4697933	174.1	167	6.43
1750	834.359818	2503.079454	199.188734	190.5	185	7.12
2000	887.253724	2661.761172	211.8162239	201.6	198	6.52
2250	897.233455	2691.700365	214.1987092	200.7	200	6.63
2500	899.688792	2699.066376	214.7848777	199.8	201	6.42
3000	898.766649	2696.299947	214.5647323	200.4	202	5.86
3251	900.930972	2702.792916	215.0814264	200.4	200	7.01
4000	852.366741	2557.100223	203.4875702	190.5	188	7.61
4500	794.453405	2383.360215	189.6617797	176.4	175	7.73
5000	765.404277	2296.212831	182.7268112	165.8	166	9.15
5500	728.88709	2186.66127	174.008975	154.7	156	10.35
6000	684.943168	2054.829504	163.5181364	145.7	146	10.71
6500	609.58283	1828.74849	145.5271809	125.6	126	13.42

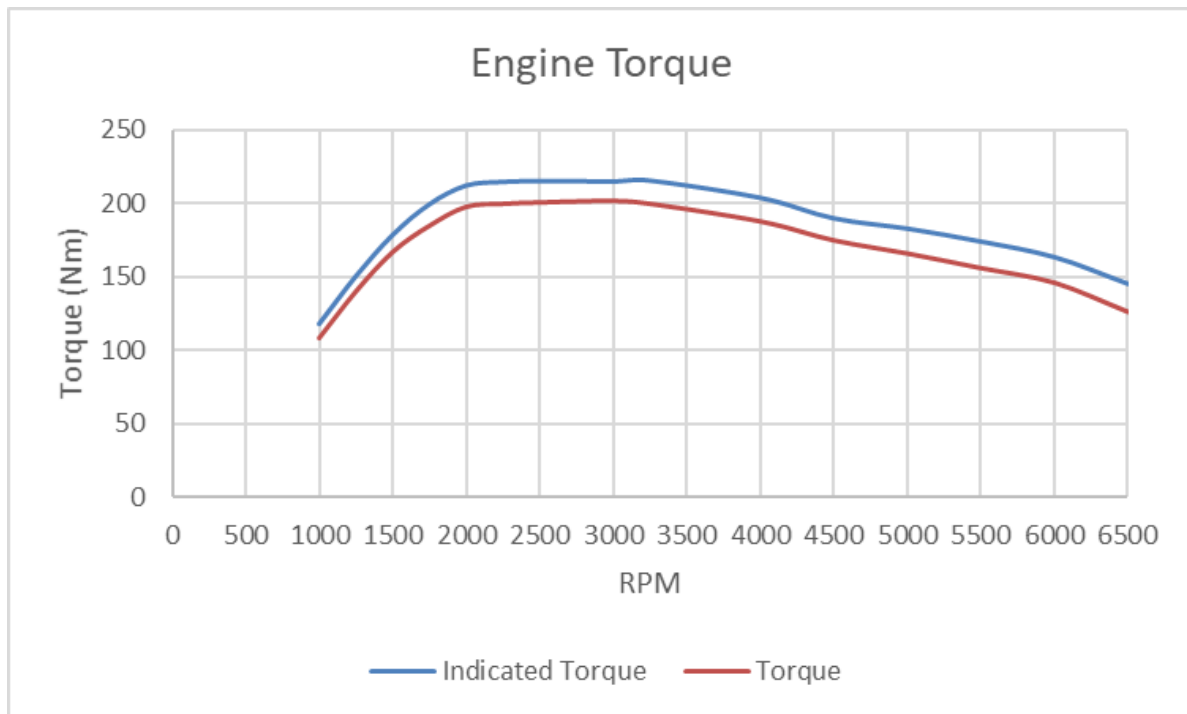


Figure 2 Engine Torque FL

The calculated results follow the trend of the measured results and show a difference of between 5.86% to 13.42% this is assumed to be the losses due to friction within the engine.

3.2 Part Load

Additional data was available for the part load; however, it was for a slightly different engine known as the Ford Fox Classic. This data will have limited value for comparison, but does provides an opportunity to test the model on part load. The data supplied for part load came in the same format as full load a sample at 800RPM is shown in Table 4, as with the full load data this report will focus on cylinder one.

The data also defined the Brake Mean Effective Pressure (BMEP) used across the engine speeds (Table 3). This was essential as part load could be anywhere on the torque demand scale. Using the Ford data for BMEP (Appendix 1) it was possible to determine at what load the engine was measured. Often the BMEP supplied was between two values in this instance the value was calculated through linear interpolation (Appendix 3, Appendix 4); this was cross referenced with the ford Torque data (Appendix 2) to compare against the calculated values in Table 5.

Table 3 BMEP for engine speed

LOGPOINT	DYNO_SPD	BMEP	SPARKADV
	rpm	kN/m ²	°CA
1	800.1	71.3	35.033
3	1500	99.7	40.3
4	1500	261.7	30.367
9	2000	400.4	40.7
14	2500	262.2	36.633
18	3000	750.3	26.633
19	4000	550.3	34.5

Table 4 1000RPM Part Load Supplied Data

Crank Angle	V_ABS	CYLPR1	CYLPR2	CYLPR3
deg	cm ³	bar	bar	bar
-360	37.05	0.943129193	1.000119813	0.986207726
-359	37.09	0.933545943	0.995330045	0.976629573
-358	37.19	0.919171067	0.98575051	0.962262343
-357	37.35	0.904796192	0.976170975	0.947895113
-356	37.58	0.885629691	0.957011905	0.928738807
-355	37.88	0.86646319	0.933063068	0.904793424
-354	38.24	0.842505064	0.913903998	0.880848041
-353	38.66	0.813755313	0.889955161	0.852113581
-352	39.15	0.785005561	0.856426789	0.818590045
-351	39.71	0.74667256	0.822898416	0.785066509
-350	40.33	0.708339558	0.779790509	0.746753896
-349	41.01	0.670006556	0.736682602	0.703652207
-348	41.76	0.631673555	0.688784927	0.655761441
-347	42.57	0.578965677	0.636097485	0.607870675
-346	43.44	0.531049425	0.583410043	0.559979909
-345	44.38	0.483133173	0.530722601	0.507300067

It is immediately apparent that the cylinder pressures are much lower at part load than full load (Table 1). Given that the throttle is only partially open the inlet will be greatly restricting the airflow into the cylinder. The process outlined in section 2.1 for full load was repeated for the part load data using Equation 1 the results are shown in Table 5 and plotted in Figure 3.

Table 5 Indicated work done and Torque PL

RPM	BMEP	Work Done	Indicated Work Done 2 Revs	Indicated Torque	Final CVC Clutch Torque	Brake Torque	Torque lost due to Friction
	kN/m ²	J	J	Nm	Nm	Nm	%
800	71.3	47.711426	143.134278	11.39026393	14.7	6.0234375	47.12
1500	99.7	56.32616731	168.9785019	13.44688193	12.4	8.362903226	37.81
1500	261.7	112.5024677	337.5074031	26.85798577	22.7	20.64166667	23.15
2000	400.4	164.5190866	493.5572598	39.2760388	30.7	31.984375	18.57
2500	262.2	115.5873075	346.7619225	27.59443702	21.4	20.88188976	24.33
3000	750.3	289.6879468	869.0638403	69.15790302	60.5	59.624	13.79
4000	550.3	224.1994134	672.5982401	53.52366731	39.4	43.76422764	18.23

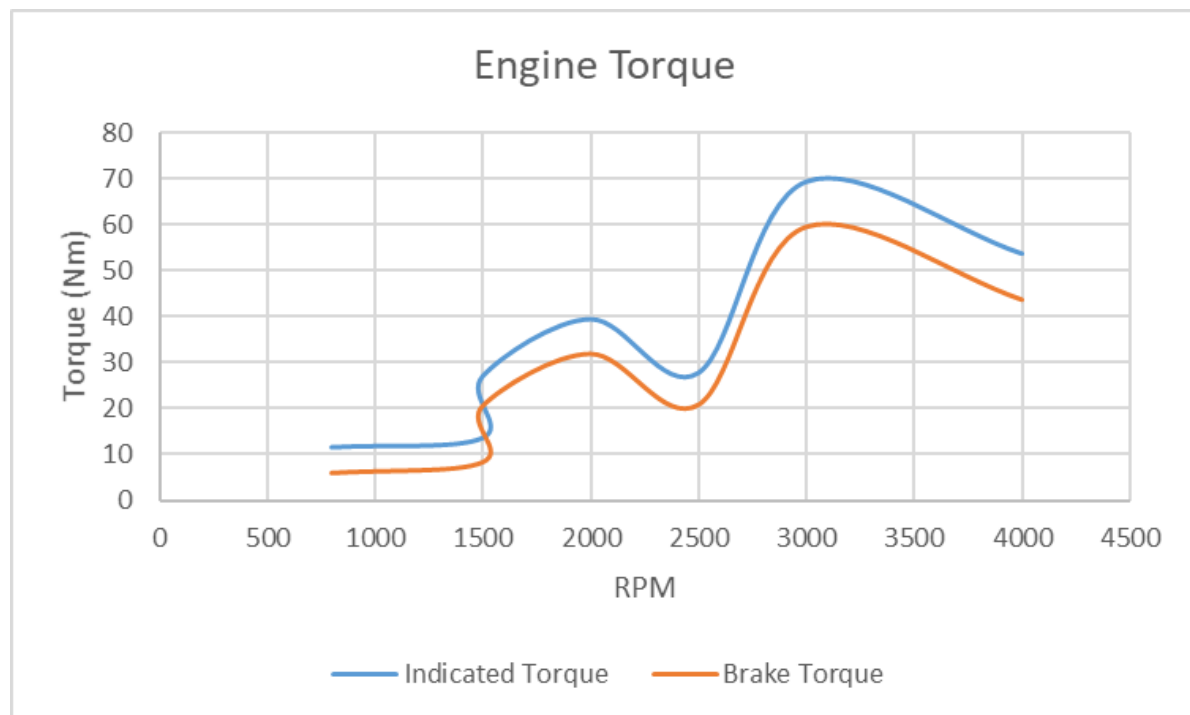


Figure 3 Engine Torque PL

The calculated values follow the trend of the measured results, but show much larger differences than full load. There are several potential reasons for this given that we are comparing the results against a slightly different version of the same engine and that we are using a linear interpolation of the data to get values. This explains the differences of between 13.79% to 47.12% some of which can still be attributed to losses due to friction within the engine. However, given how well the calculated figures follow the measured figures, there is definite value in continued comparison between the part load Ford Fox classic data and the Ford Fox data supplied.

Chapter 4 Mass Fraction Burned (MFB)

4.1 Pressure Volume Diagrams (PV)

The first step to calculating the MFB was to plot the PV diagram Figure 4, two clear pressure spikes can be seen a small spike when the piston reaches Top Dead Centre (TDC) followed by a slight drop. Then a large spike as combustion begins forcing the piston down in the power stroke; the same trend can be seen in Figure 5 at 3000RPM. However, Figure 6 shows no pressure drop before combustion starts.

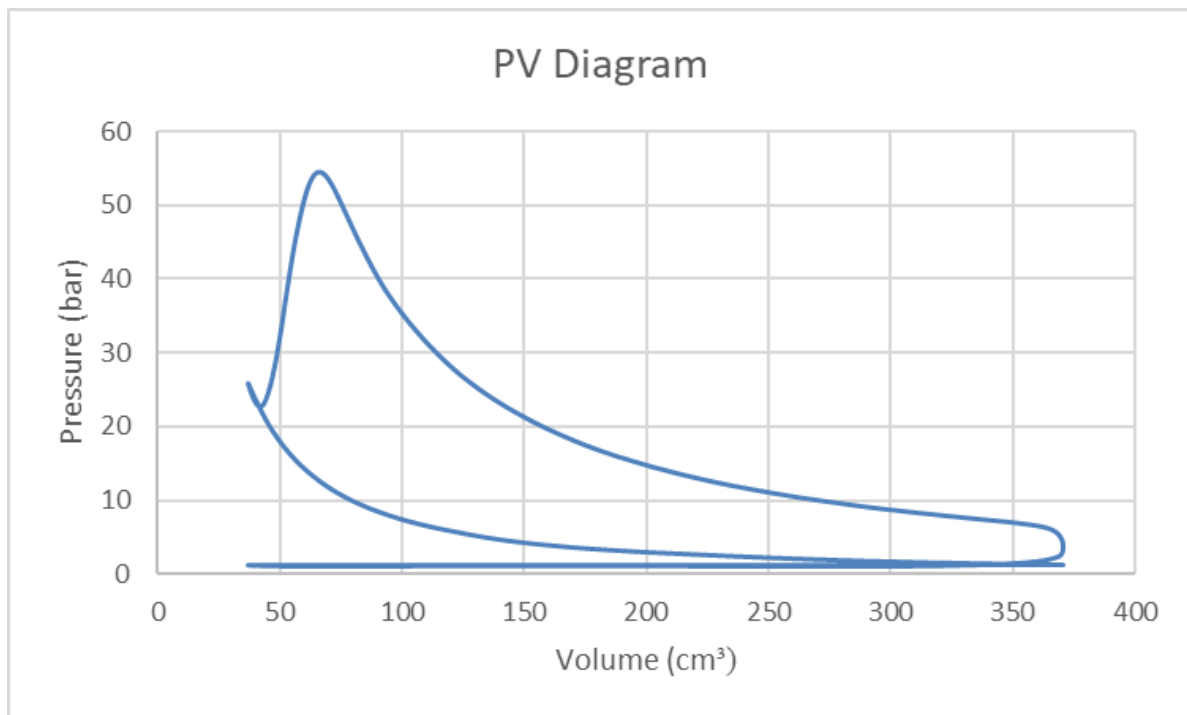


Figure 4 1000RPM PV Diagram FL

On this turbo charged engine at low RPM the initial spike in pressure is caused as the piston reaches TDC compressing the charge, the pressure then drops back down as the piston begins travelling downwards, the retarded ignition timing causes the SOC 9° after TDC as can be seen in Figure 29. This is normally seen in turbo charged engines, but can also be seen in a naturally aspirated engine with retarded ignition timing.

It can also be clearly seen that in Figure 4 the pumping loop is small, as the engine speed increase in Figure 5 the pumping loop can be seen gradually increasing in size; this continues in Figure 6 where the pumping loop has increased significantly. This is due to the increased speed of air flow at high RPM indicating the inlet is choking and increases the power lost to suck the air into the cylinder; coupled with the increased force required to force the exhaust gasses out.

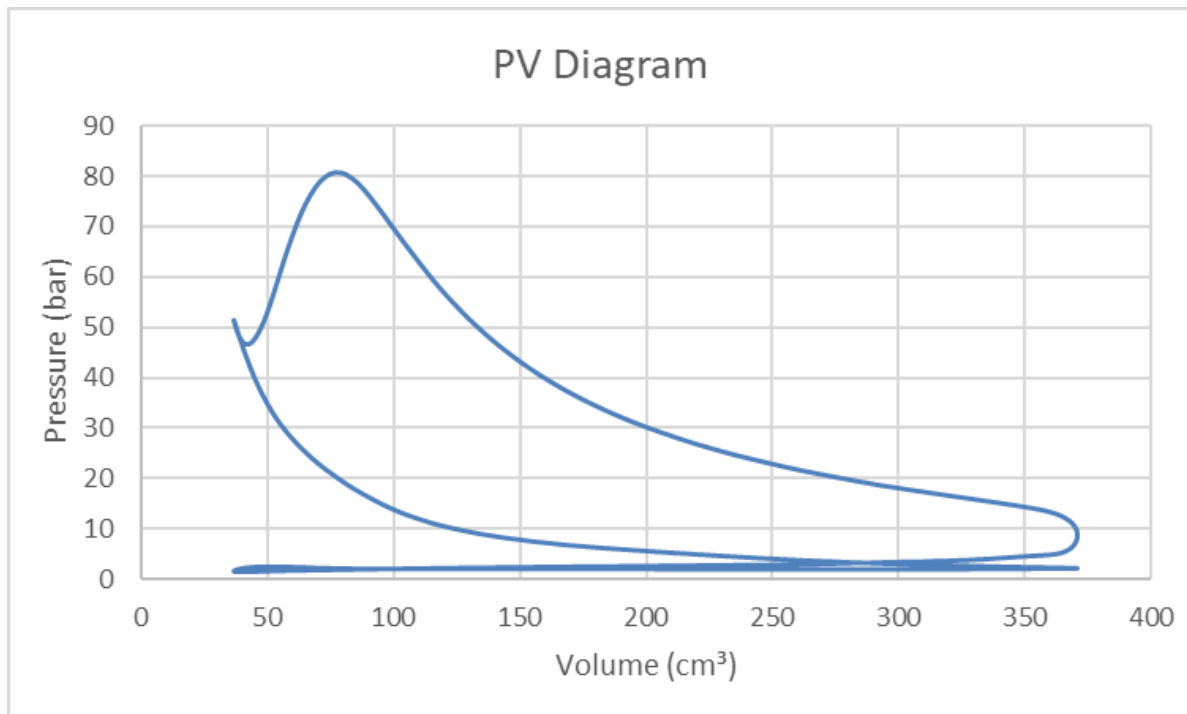


Figure 5 3000RPM PV Diagram FL

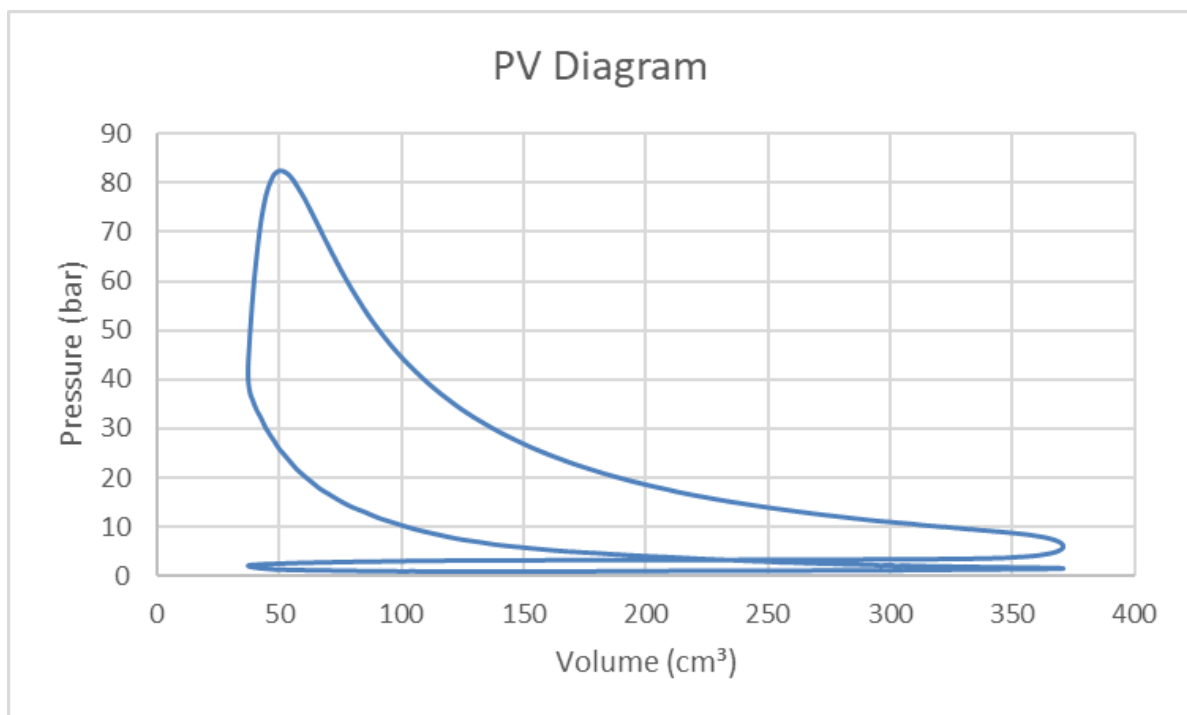


Figure 6 6500RPM PV Diagram FL

4.2 Log P Log V Diagrams

The next step to identify the MFB was to take a log of the pressure and volume data supplied, a sample at 1000RPM is shown in Table 6. The advantage to this process is that the compression and expansion slopes before and after combustion appear in a linear format (Randolph, 1994). Figure 7 plots the data for 1000RPM, the SOC is normally assumed to start at the end of the straight line, however, as the ignition is retarded there is a slight drop in pressure before the SOC. The EOC is said to be when the curve returns to a straight line (Caris & Nelson, 1958). It is impossible to accurately identify the SOC and the EOC from PV diagrams or Log P Log V diagrams (Brunt, et al., 1998). The Log P and Log V diagrams do however give an approximation of where these events occur. These points must be identified to develop an accurate MFB profile at each engine speed.

Table 6 1000RPM Log P, Log V FL

Crank Angle	V_ABS	CYLP1	Work done	Log P	Log V
deg	cm ³	bar	J	log bar	log cm ³
-360	37.05	1.171		0.068556895	1.568788212
-359	37.09	1.171	0.004684	0.068556895	1.569256833
-358	37.19	1.175	0.01171	0.070037867	1.570426178
-357	37.35	1.18	0.0188	0.071882007	1.572290606
-356	37.58	1.18	0.02714	0.071882007	1.574956776
-355	37.88	1.185	0.0354	0.07371835	1.57840997
-354	38.24	1.185	0.04266	0.07371835	1.582517884
-353	38.66	1.185	0.04977	0.07371835	1.58726185
-352	39.15	1.19	0.058065	0.075546961	1.592731766
-351	39.71	1.19	0.06664	0.075546961	1.598899887
-350	40.33	1.19	0.07378	0.075546961	1.605628222
-349	41.01	1.195	0.08092	0.077367905	1.612889769
-348	41.76	1.19	0.089625	0.075546961	1.62076049
-347	42.57	1.19	0.09639	0.075546961	1.62910365
-346	43.44	1.19	0.10353	0.075546961	1.637889817

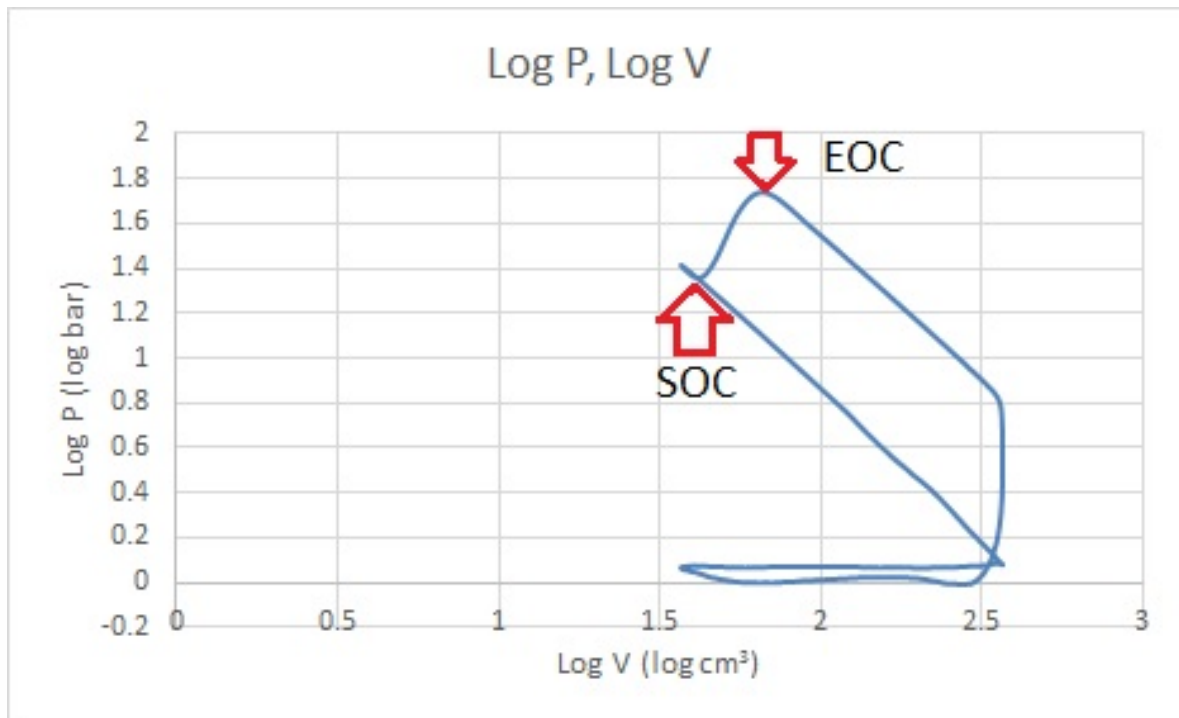


Figure 7 1000RPM Log P, Log V FL

Figure 7, Figure 8 and Figure 9 also reinforce the point made in section 3.1 where the pumping loop is considerably expanded. The early spike from the retarded ignition timing can also be clearly seen in Figure 7 and Figure 8 however as the ignition timing advances, it is gone in Figure 9.

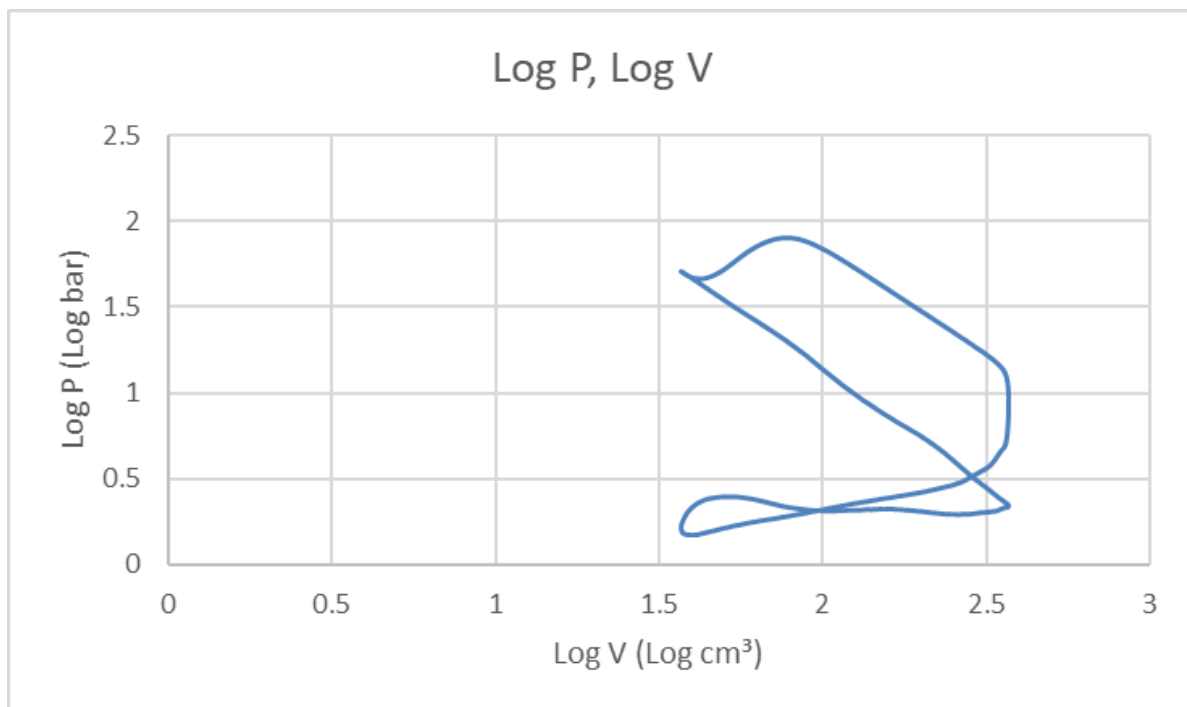


Figure 8 3000RPM Log P, Log V FL

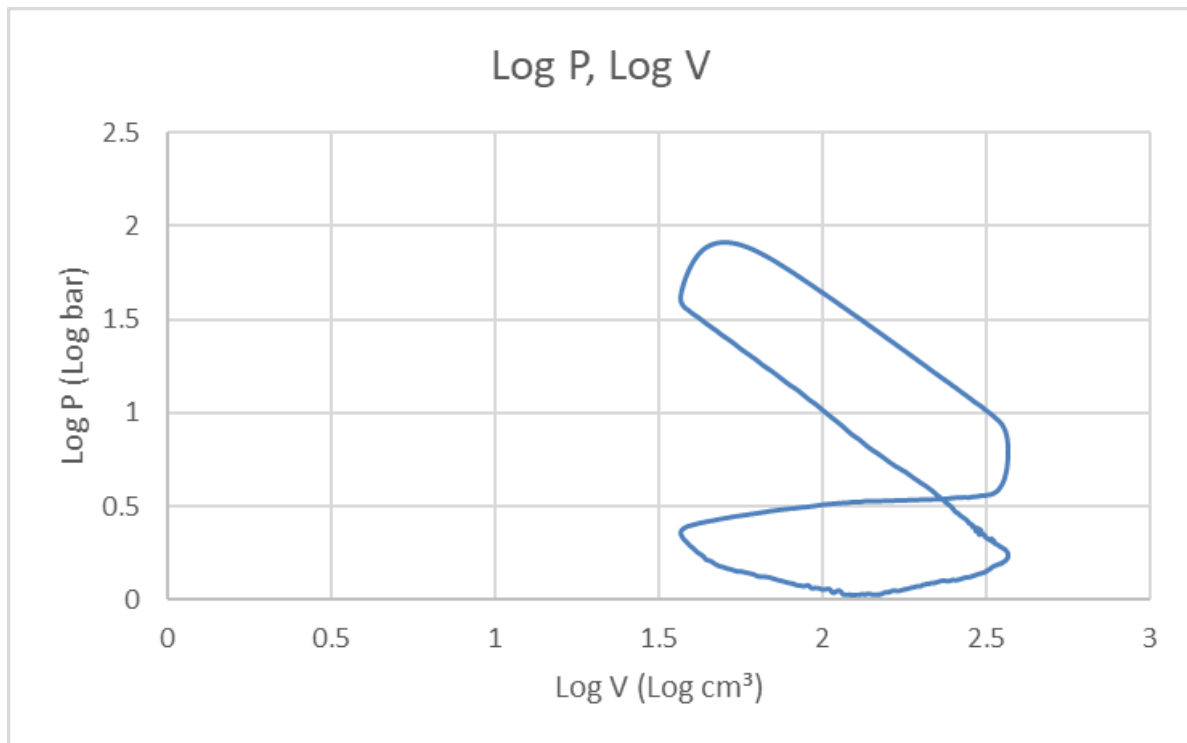


Figure 9 6500RPM Log P, Log V FL

Figure 9 also highlights a common issue with acquiring cylinder pressure data, the transducers can only supply dynamic cylinder data which may often be different from the actual values (Sun, et al., 2017). Also, given the harsh working environment and high stresses the sensors operate in they can suffer from structural oscillations that show in the data (Randolph, 1994). The location and orientation of the sensors can also impact the data. The opening and closing of valves can also cause signal noise all of which make determining the SOC and EOC difficult to define (Brunt & Lucas, 1991) (Shayler & Wiseman, 1990). These issues can make determining the polytropic index that much harder, Figure 10 shows an example of signal noise at 6500rpm (Brunt, et al., 1998); this was a primary reason for the authors choice to adopted the shorter, thirty value data range suggested by Bonatesta, to determine the polytropic index detailed in section 4.3 (Bonatesta, 2013).

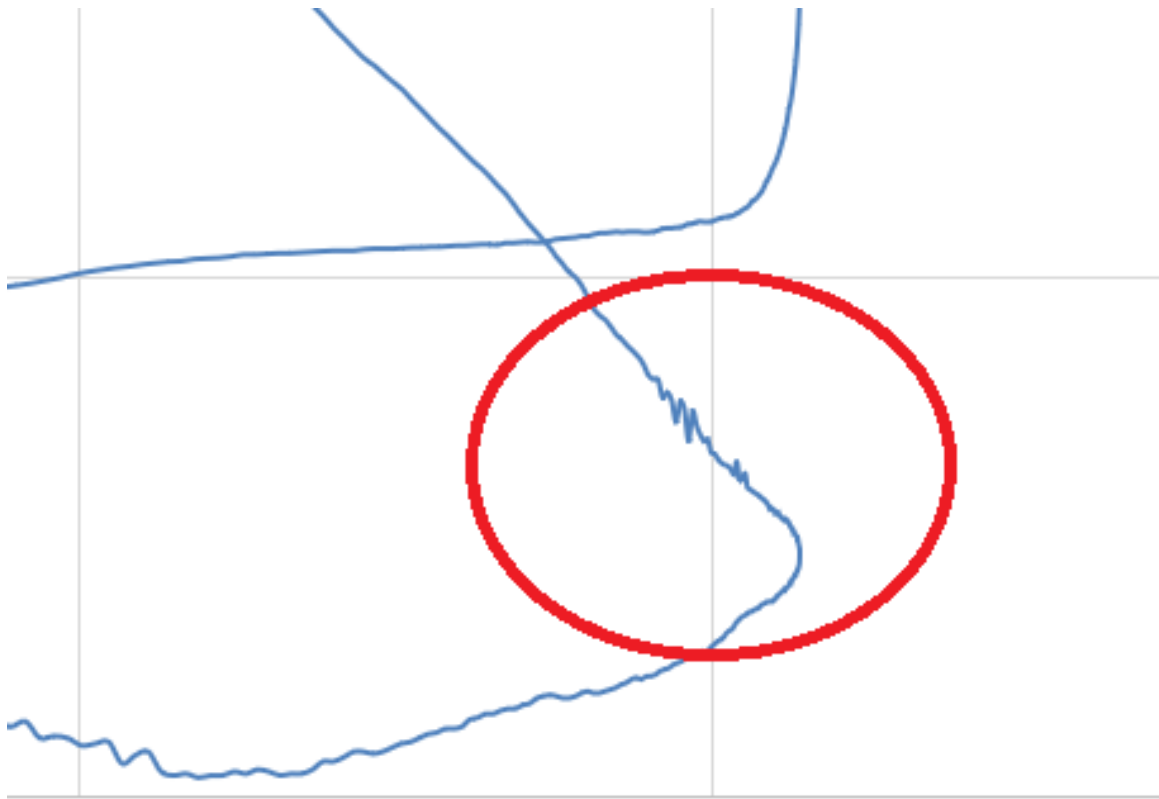


Figure 10 6500RPM Zoom signal noise

4.3 Polytropic Index

To work out the MFB a value for n in expansion and n in compression must be established. As both the compression before combustion and the expansion after combustion, are close to adiabatic isentropic processes, it could be assumed that Equation 3 could be used. However, significant research has shown that the processes are not adiabatic as in a real engine there is a degree of heat loss, and are best fitted using a polytropic relationship (Equation 5) (Lancaster, et al., 1975) (Caris & Nelson, 1958) (Heywood, 1988).

$$pV^\gamma = \text{Constant}$$

Equation 3 Adiabatic Process

$$pV^n = \text{Constant}$$

Equation 4 Polytropic Index (Zammit, 1987)

For use with the cylinder pressure and volume data supplied Equation 4 has to be manipulated to find n as shown in Equation 5, the derivative steps are outlined below.

$$p_1 V_1^n = \text{Constant}$$

$$p_2 V_2^n = \text{Constant}$$

$$\log p_1 V_1^n = \text{Constant}$$

$$\log p_1 V_1^n = \log p_2 V_2^n$$

$$\log p_1 + n \log V_1 = \log p_2 + n \log V_2$$

Therefore, the Polytropic index per degree is

$$n = \frac{(\log P_2 - \log P_1)}{(\log V_1 - \log V_2)}$$

Equation 5 Polytropic index per degree

Equation 5 was used so that the polytropic index could be calculated for every degree of crank angle. The results at 1000RPM are shown over a duration of 40° of crank angle in Table 7, the complete results for every degree are plotted and shown in Figure 11.

Table 7 Polytropic index by Degree and Delta P

Crank Angle	V_ABS	CYLPR1	Work done	Log P	Log V	(logP2-logP1) / (logV1-logV2)	ΔP
deg	cm ³	bar	J	log bar	log cm ³		bar
5	37.88	25.017	0.75933	1.398235229	1.57840997	1.469385861	-0.043068793
6	38.24	24.69	0.900612	1.39252109	1.582517884	1.39100761	-0.032238089
7	38.66	24.305	1.03698	1.385695625	1.58726185	1.438767562	-0.049355235
8	39.15	23.911	1.190945	1.378597739	1.592731766	1.297622312	-0.013425365
9	39.71	23.511	1.339016	1.371271101	1.598899887	1.187823384	0.021772133
10	40.33	23.151	1.457682	1.364569755	1.605628222	0.99598884	0.092018369
11	41.01	22.872	1.574268	1.359304142	1.612889769	0.725136451	0.20100234
12	41.76	22.713	1.7154	1.356274501	1.62076049	0.384925544	0.354550078
13	42.57	22.761	1.839753	1.357191339	1.62910365	-0.10989096	0.588224648
14	43.44	23.074	1.980207	1.363122888	1.637889817	-0.675100976	0.88274912
15	44.38	23.699	2.168956	1.374730021	1.647187298	-1.248416886	1.235748125
16	45.38	24.661	2.3699	1.392010683	1.656864492	-1.785710078	1.614554183
17	46.44	25.946	2.614066	1.414070414	1.666892211	-2.199875108	1.988285093
18	47.55	27.567	2.880006	1.440389506	1.677150521	-2.565636246	2.377695281
19	48.73	29.563	3.252906	1.470748503	1.687796411	-2.85171055	2.829882117
20	49.97	31.949	3.665812	1.504457269	1.698709349	-3.088880902	3.302340587
21	51.27	34.725	4.15337	1.540642254	1.709863317	-3.244135636	3.78781982
22	52.62	37.722	4.687875	1.576594711	1.721150844	-3.185149282	4.109690352
23	54.03	40.758	5.318802	1.610212865	1.732634968	-2.927359096	4.265428761
24	55.5	43.692	5.991426	1.640401925	1.744292983	-2.589553925	4.282155375
25	57.03	46.449	6.684876	1.666976369	1.756103372	-2.250090555	4.22077266
26	58.61	48.897	7.338942	1.689282214	1.767971721	-1.879439547	4.011644863
27	60.24	51.077	7.970211	1.708225381	1.779884963	-1.590093355	3.832173387
28	61.93	52.823	8.632013	1.722823063	1.79190108	-1.214841846	3.486479412
29	63.67	54.006	9.191202	1.732442012	1.80393485	-0.799329682	2.985574136
30	65.46	54.555	9.667074	1.73683456	1.815976001	-0.364794693	2.39305467
31	67.31	54.502	10.092675	1.736412439	1.828079591	0.034875663	1.81929221
32	69.2	53.929	10.300878	1.731822367	1.840106094	0.381663046	1.285766057
33	71.14	52.967	10.462226	1.724005376	1.852113861	0.650994649	0.874407961
34	73.13	51.721	10.540433	1.713666913	1.864095573	0.862853485	0.553803414
35	75.17	50.316	10.551084	1.701706108	1.87604455	1.000989866	0.347745344
36	77.26	48.815	10.516044	1.688553294	1.887954704	1.10433629	0.198686575
37	79.38	47.295	10.34878	1.67481523	1.899711095	1.168561349	0.10805274
38	81.56	45.751	10.31031	1.660400591	1.911477217	1.225096771	0.03464216
39	83.77	44.245	10.110971	1.645864199	1.923088515	1.251917849	0.001345927
40	86.03	42.764	9.99937	1.631078321	1.934649923	1.27889953	-0.029431459
41	88.33	41.325	9.83572	1.616212862	1.94610823	1.297352038	-0.048324917
42	90.67	39.945	9.67005	1.601462425	1.957463616	1.298981617	-0.047995338
43	93.05	38.631	9.50691	1.58693595	1.968716377	1.290925323	-0.037924108
44	95.46	37.458	9.310071	1.573544585	1.97982143	1.205880388	0.045157856
45	97.91	36.313	9.17721	1.56006213	1.990827051	1.225051838	0.02576057

The scale on Figure 11 gives very little information, as the polytropic index only applies in the compression and expansion phases of the engine cycle. Figure 12 Reduces the scale of the polytropic index, ignoring the spike caused by the fact that Equation 4 does not apply at TDC and BDC a definite spike can be seen after TDC. Figure 13 reduces the scale further and the combustion process can clearly be seen. In this instance the fact that Equation 4 does not apply is used to identify combustion. However, it is difficult to identify a specific SOC and EOC from the graph.

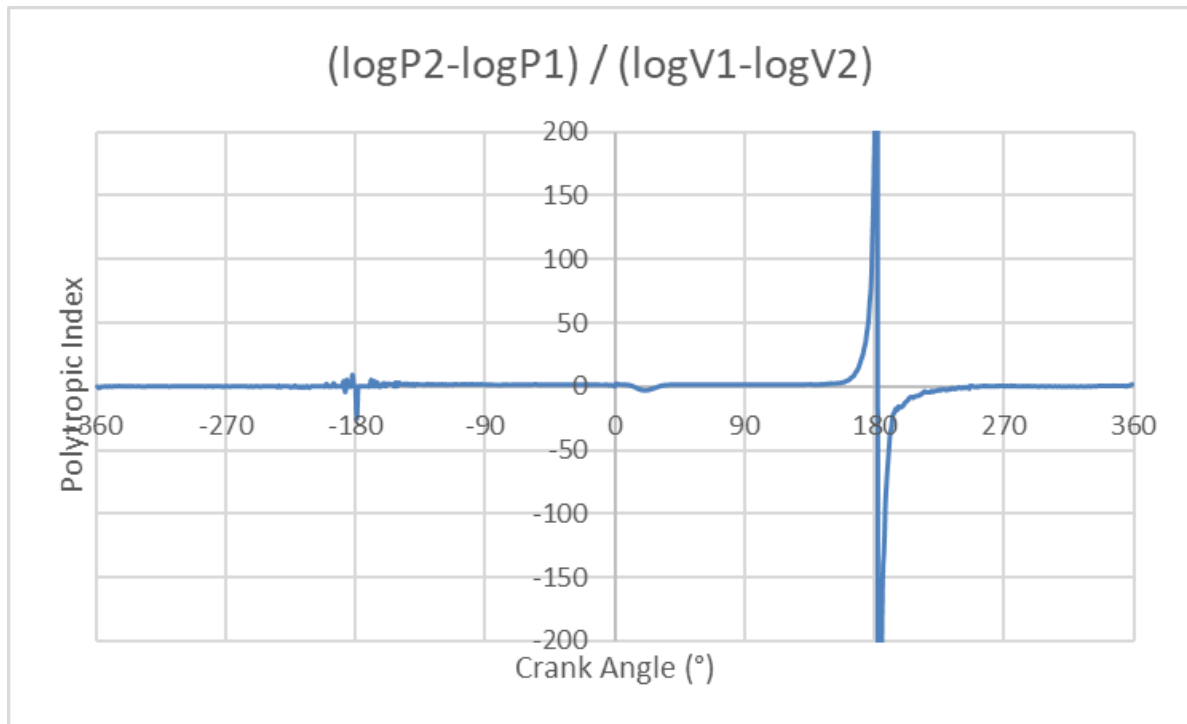


Figure 11 1000RPM Polytropic index

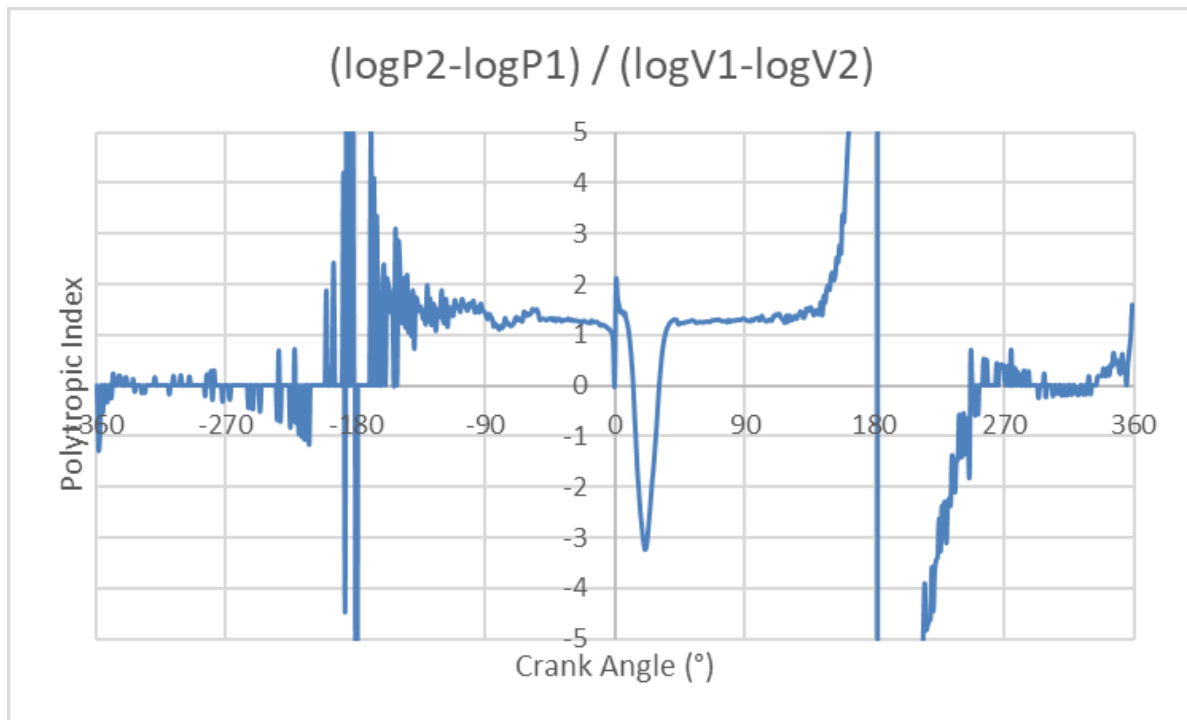


Figure 12 1000RPM Polytropic Index (Zoomed in 1)

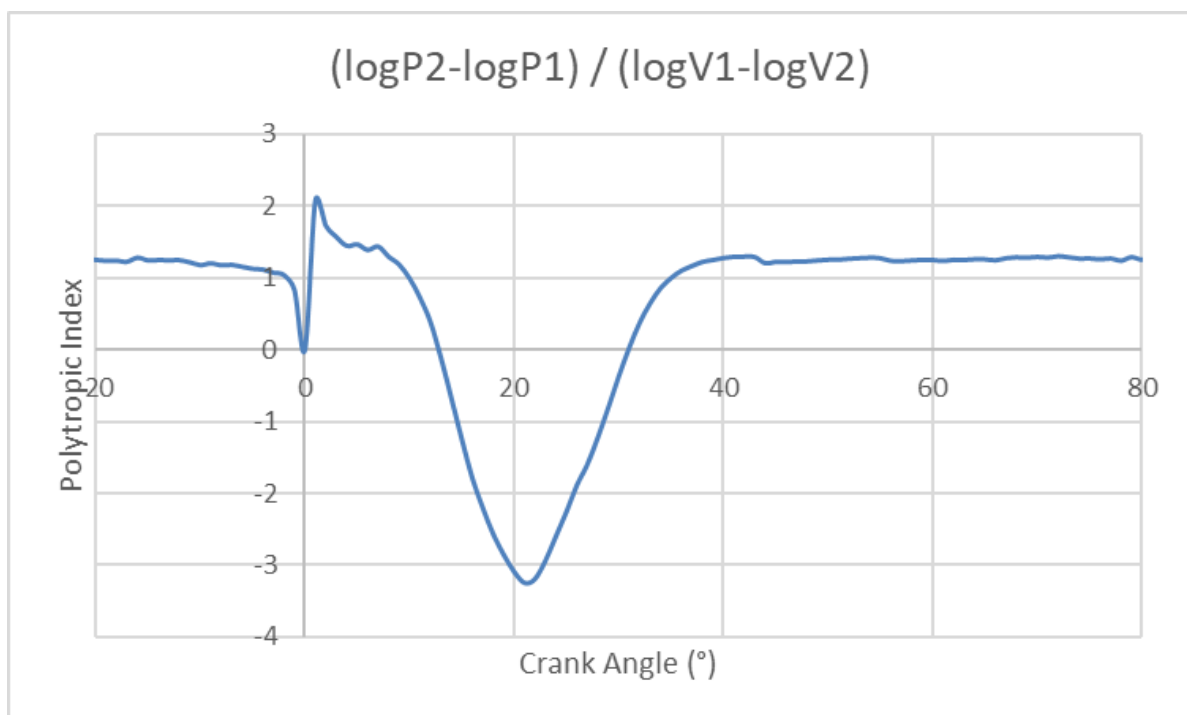


Figure 13 1000RPM Polytropic Index (Zoomed in 2)

At 3000RPM Figure 14 the data spikes at BDC are more pronounced. Reducing the scale in Figure 15 the same spike after TDC can be seen which when magnified for Figure 16 again clearly shows the combustion process, but with no clearly defined SOC or EOC.

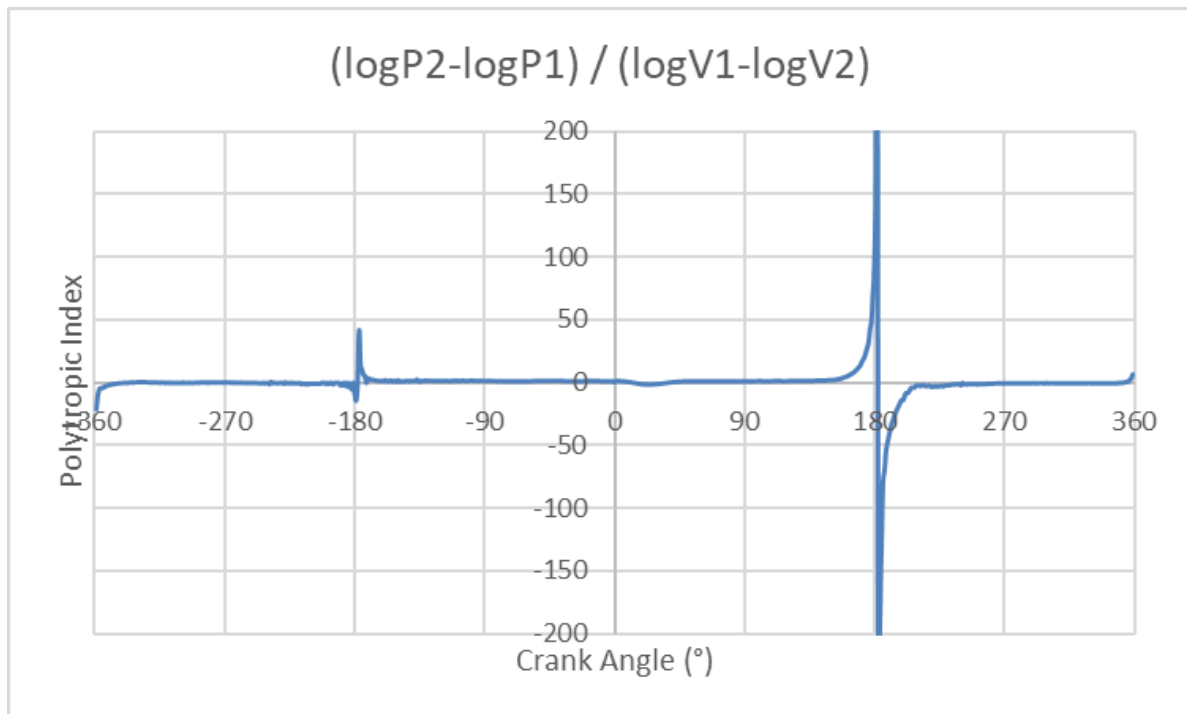


Figure 14 3000RPM Polytropic Index

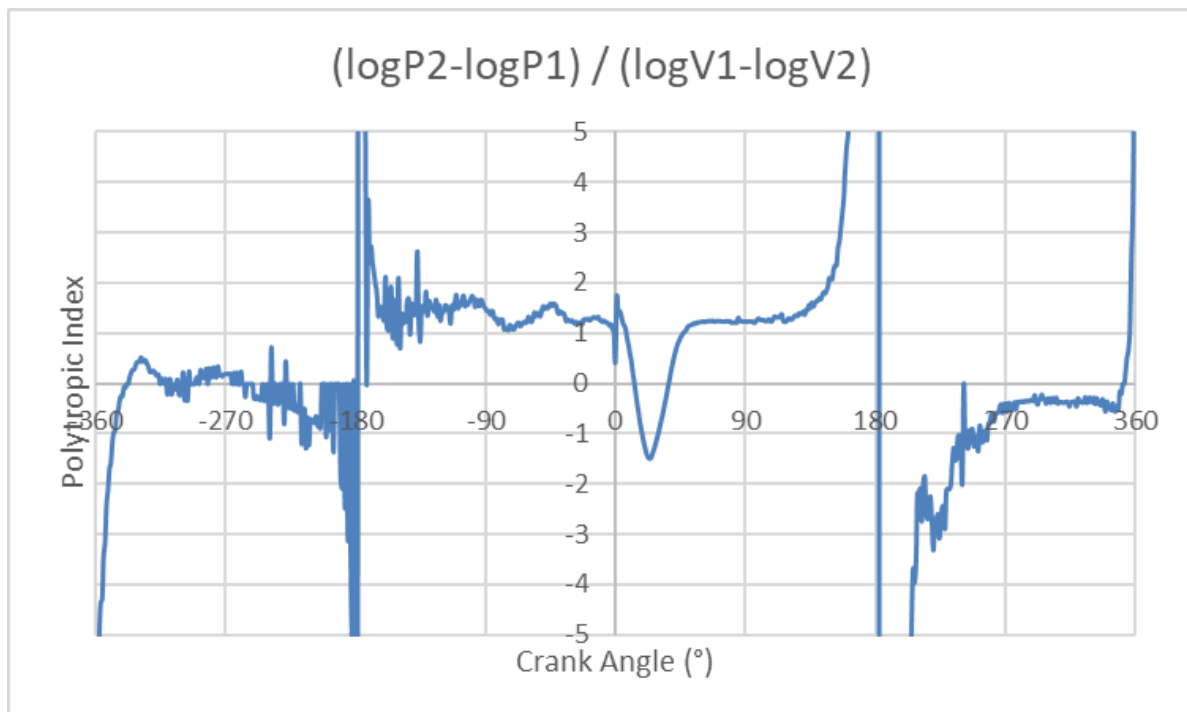


Figure 15 3000RPM Polytropic Index (Zoomed in 1)

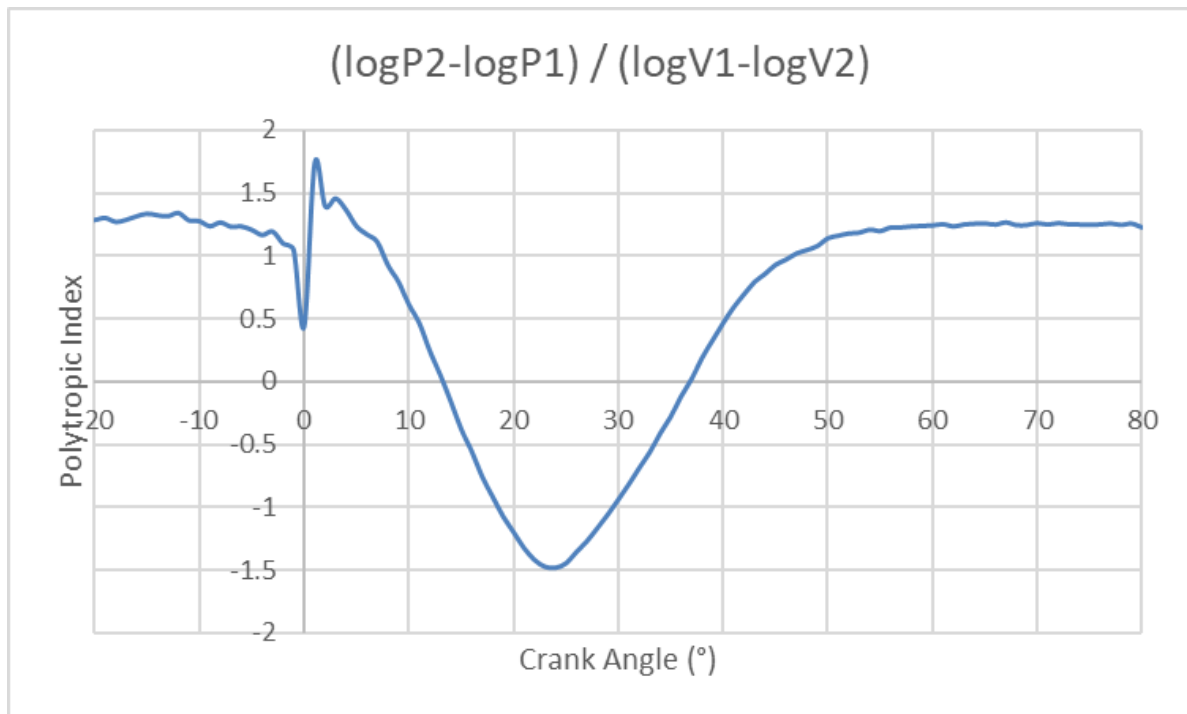


Figure 16 3000RPM Polytropic Index (Zoomed in 2)

At 6500RPM Figure 17 also shows the spikes at BDC but there is also a spike at TDC. When the scale is reduced in Figure 18 the spike at TDC becomes more pronounced. Zooming in further for Figure 19 shows the spike at TDC looking different to 1000RPM and 3000RPM.

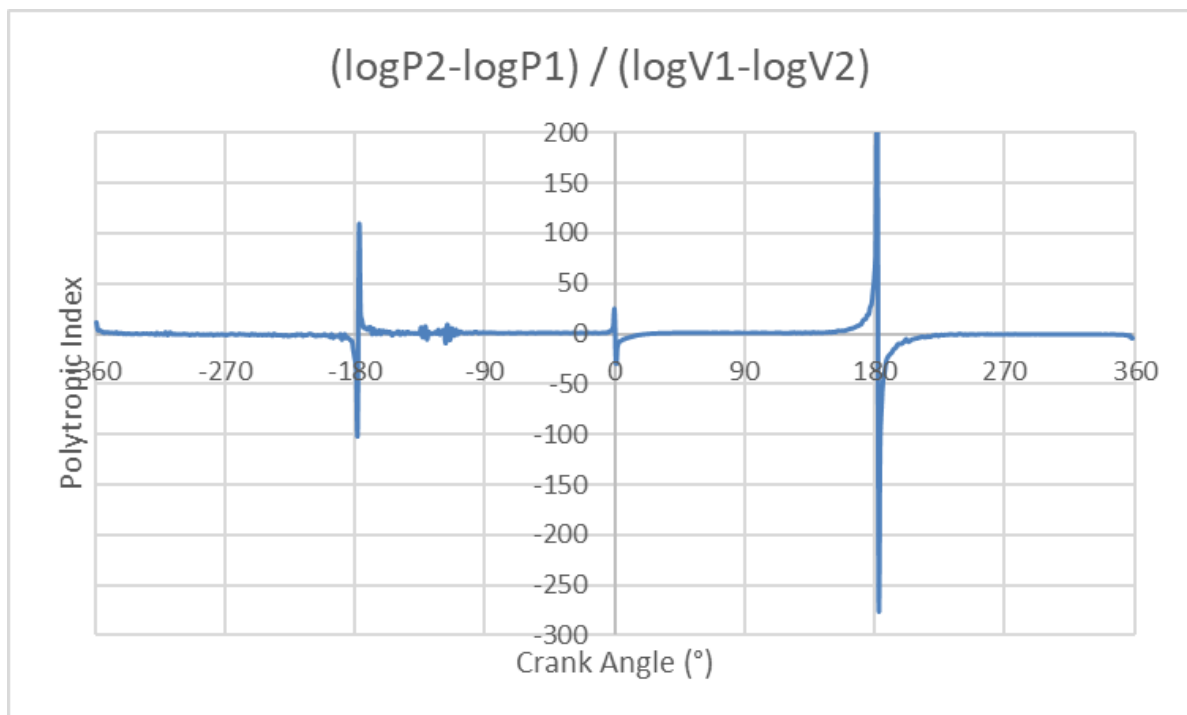


Figure 17 6500RPM Polytropic Index

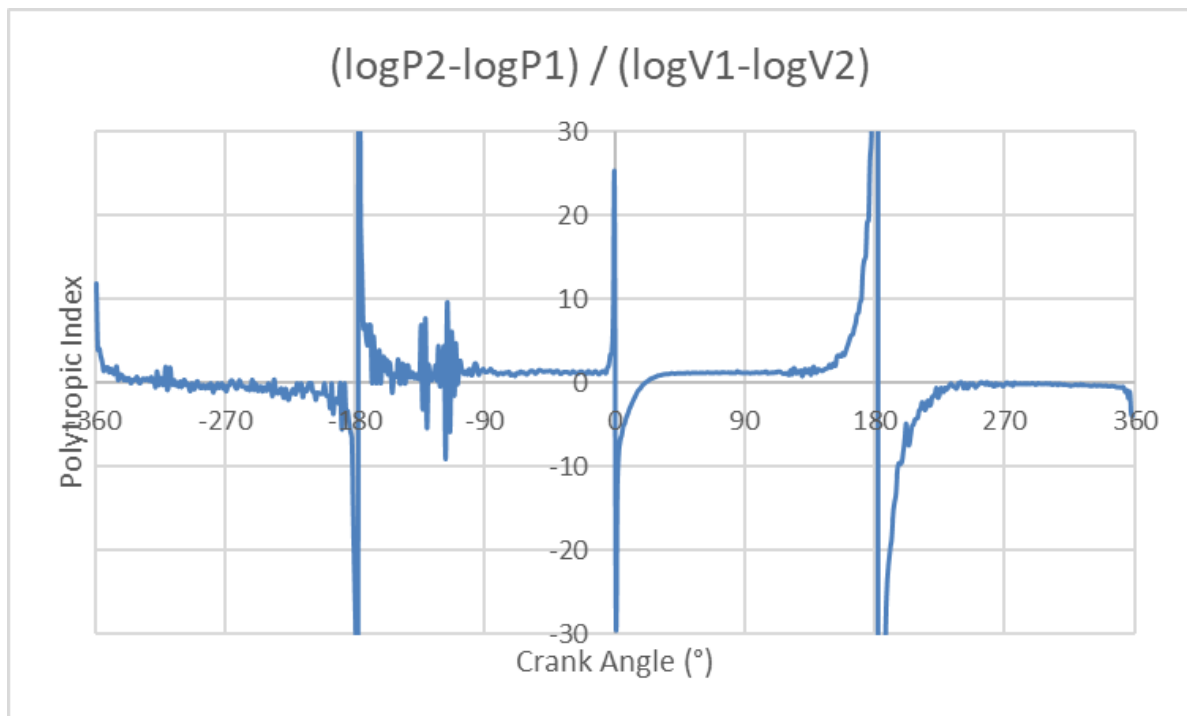


Figure 18 6500RPM Polytropic Index (Zoomed in 1)

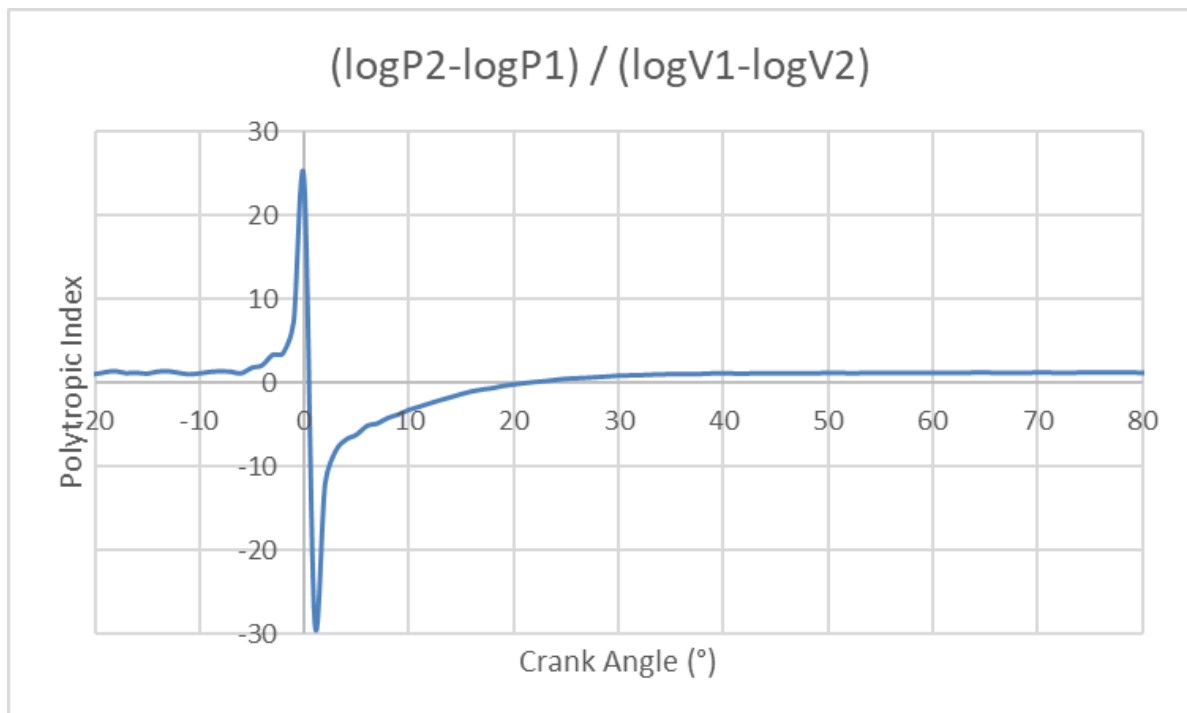


Figure 19 6500RPM Polytropic Index (Zoomed in 2)

It can therefore be assumed that combustion has started before TDC and the combustion has become lost in the signal noise of the data. This highlights the difficulties of using this method to identify the SOC and EOC for MFB as both section where Equation 4 do not apply overlap.

At this stage an exact SOC and EOC is very difficult to discern. However, there is enough information available to work out an approximate value for n in compression and n in expansion as the region the SOC and EOC occur, can be identified. This enables readings to be taken for n close to those regions to give an initial value for n that can be refined at a later stage. Initially the value for n was an average, calculated over most of the slope in both instances as per the Rassweiler and Withrow method (Rassweiler & Withrow, 1938). However, the slope often varies over the data range as can clearly be seen in the compression stroke at 6500RPM on the Log P, Log V diagram shown in Figure 9.

Therefore, a shorter duration of fifty values was taken for the initial estimation of the polytropic index. Taking 3000RPM as an example, it can be seen from the data shown in Figure 20 the region the SOC and the EOC occur can be identified. Comparing this information with the data shown in Figure 21, the SOC of combustion occurs around 5° - 10° of crank angle; the EOC can be identified 50° - 60° of crank angle.

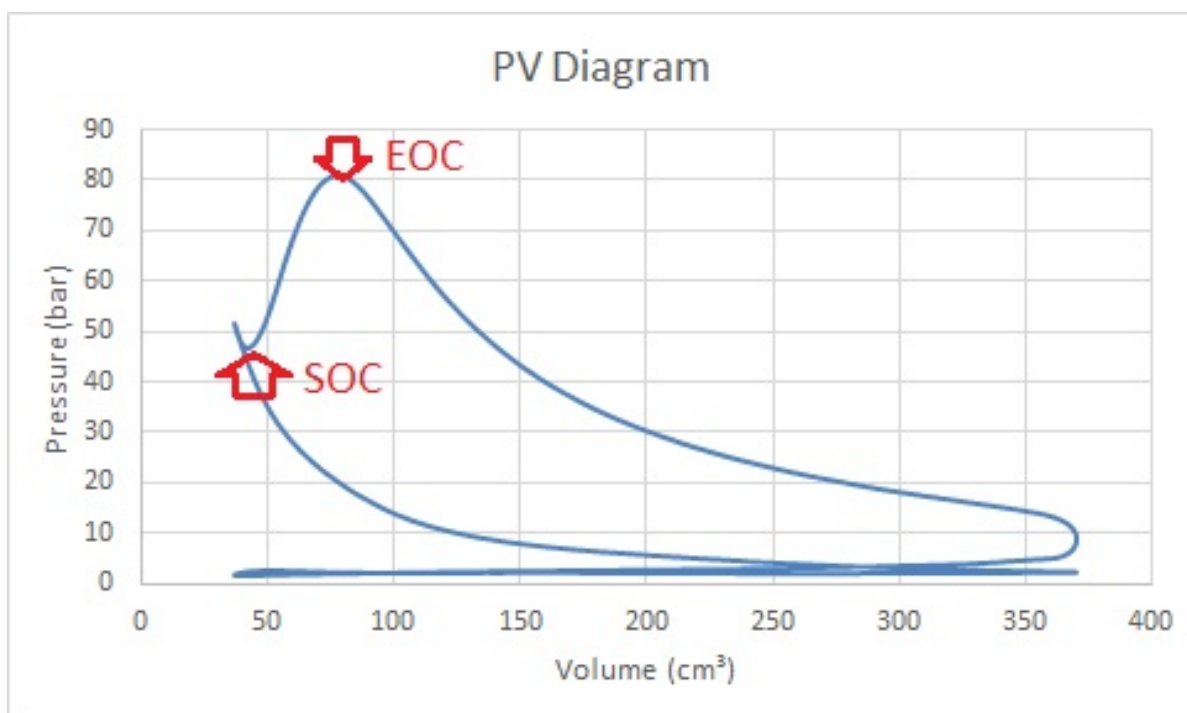


Figure 20 3000RPM PV Diagram SOC, EOC

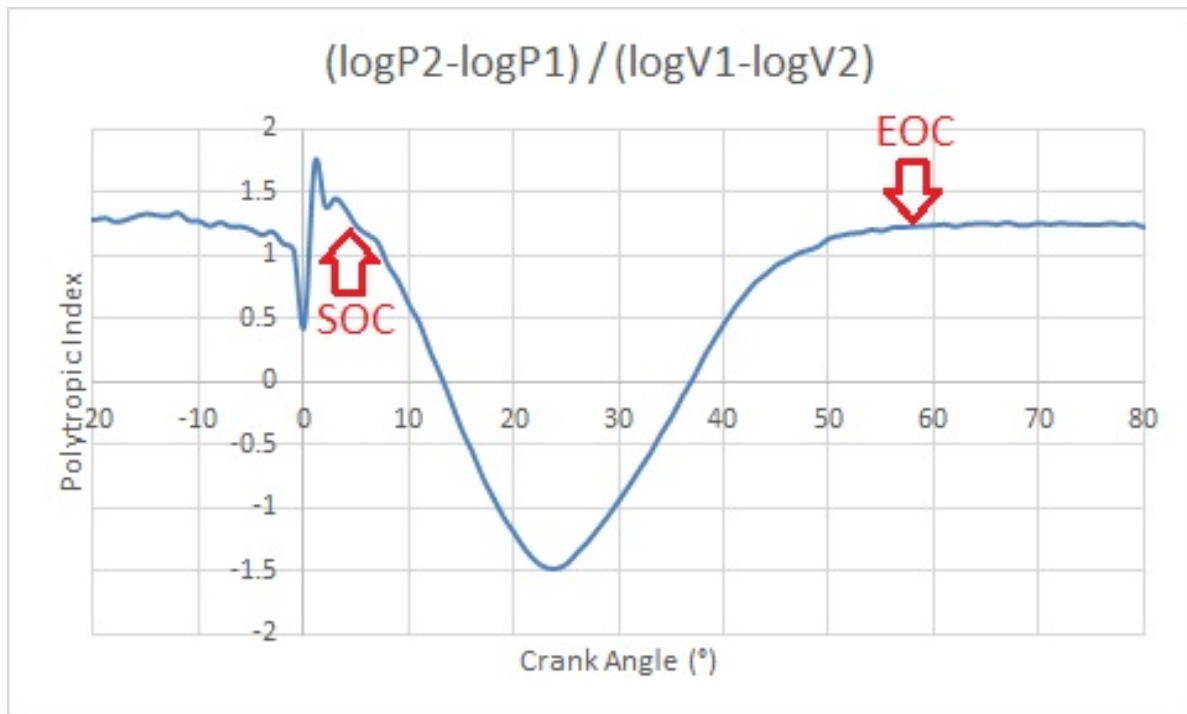


Figure 21 3000RPM Log P Log V Diagram SOC, EOC

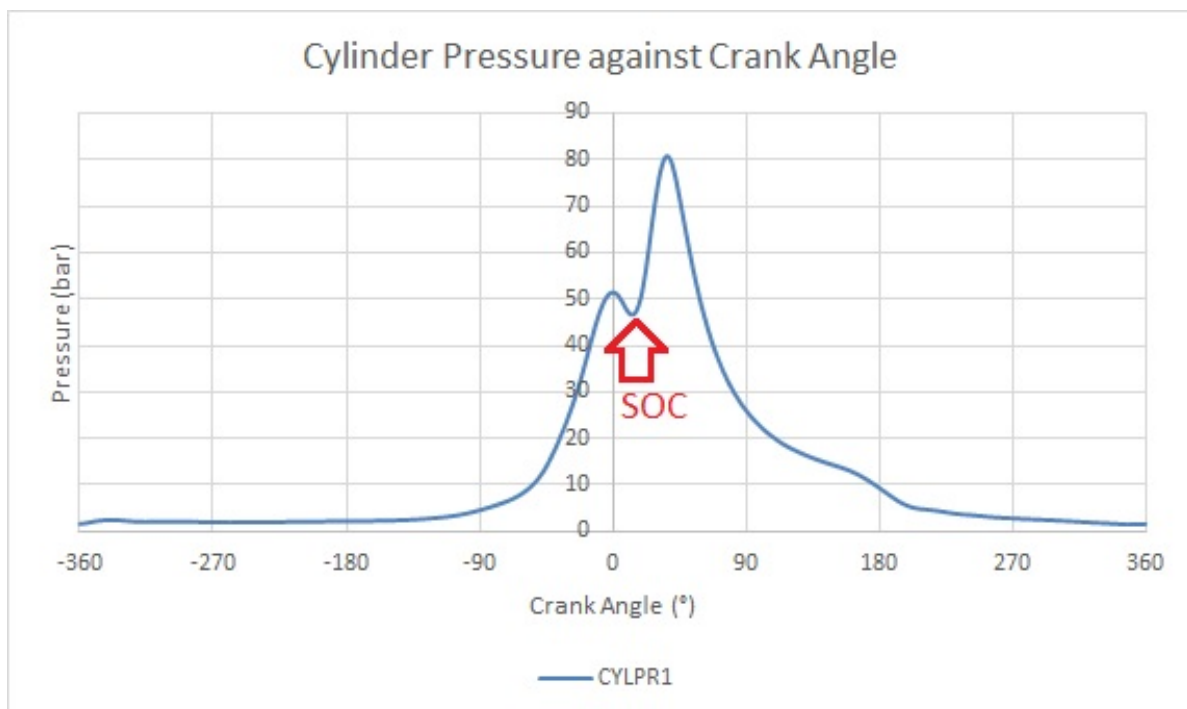


Figure 22 3000RPM Cylinder pressure against Crank Angle SOC

Further comparison with the data identifying the SOC is Figure 22 which plots the cylinder pressure against the crank angle. At 3000RPM this is helpful in confirming the region the SOC occurs, but there is no correlation to identify the EOC.

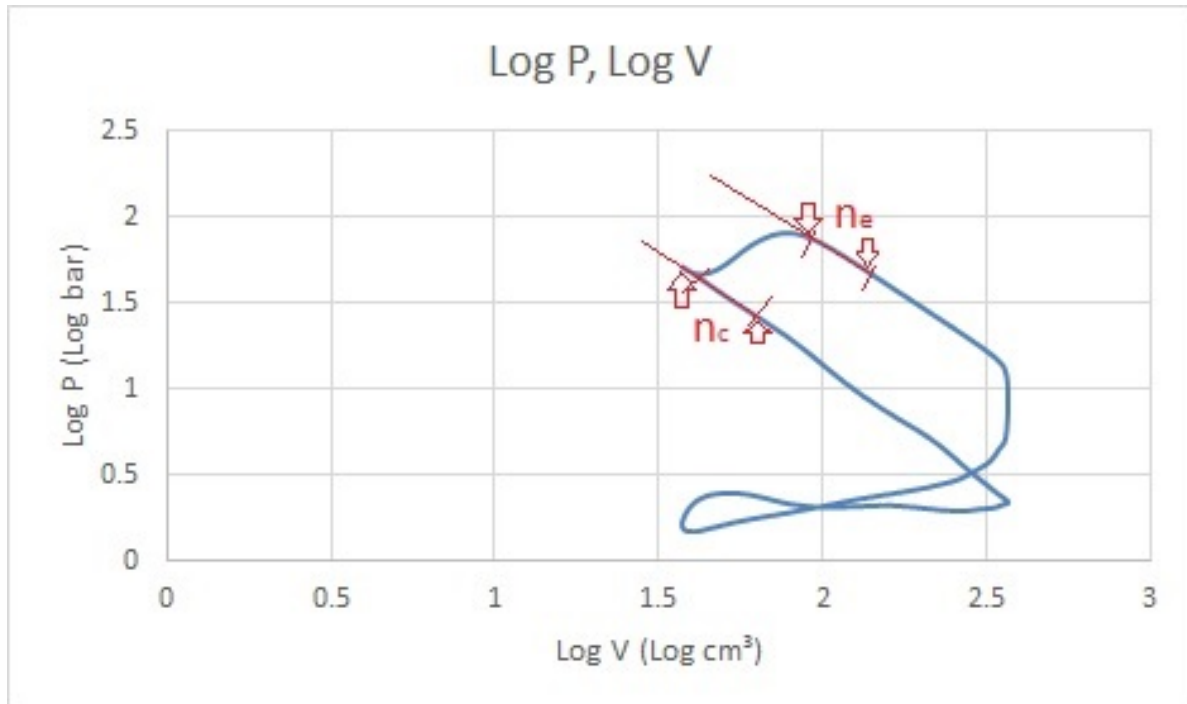


Figure 23 3000RPM Measured n in compressions and n in Expansion

As the region for the SOC and EOC have been identified the slope of the line for the sections shown in Figure 23 can be calculated. These values were calculated across all engine speeds, shown in Table 8 and displayed in Figure 24, these figures in compression are higher than expected, Heywood states they should be in the region of $1.3 (\pm 0.05)$ (Heywood, 1988).

Table 8 Initial Values for N in Compression and Expansion

RPM	N Comp	N Exp
1000	1.309	1.284
1250	1.300	1.274
1500	1.366	1.277
1750	1.387	1.275
2000	1.389	1.266
2250	1.344	1.259
2500	1.373	1.252
3000	1.376	1.249
3251	1.370	1.257
4000	1.396	1.254
4500	1.373	1.256
5000	1.346	1.258
5500	1.357	1.261
6000	1.336	1.266
6500	1.343	1.270

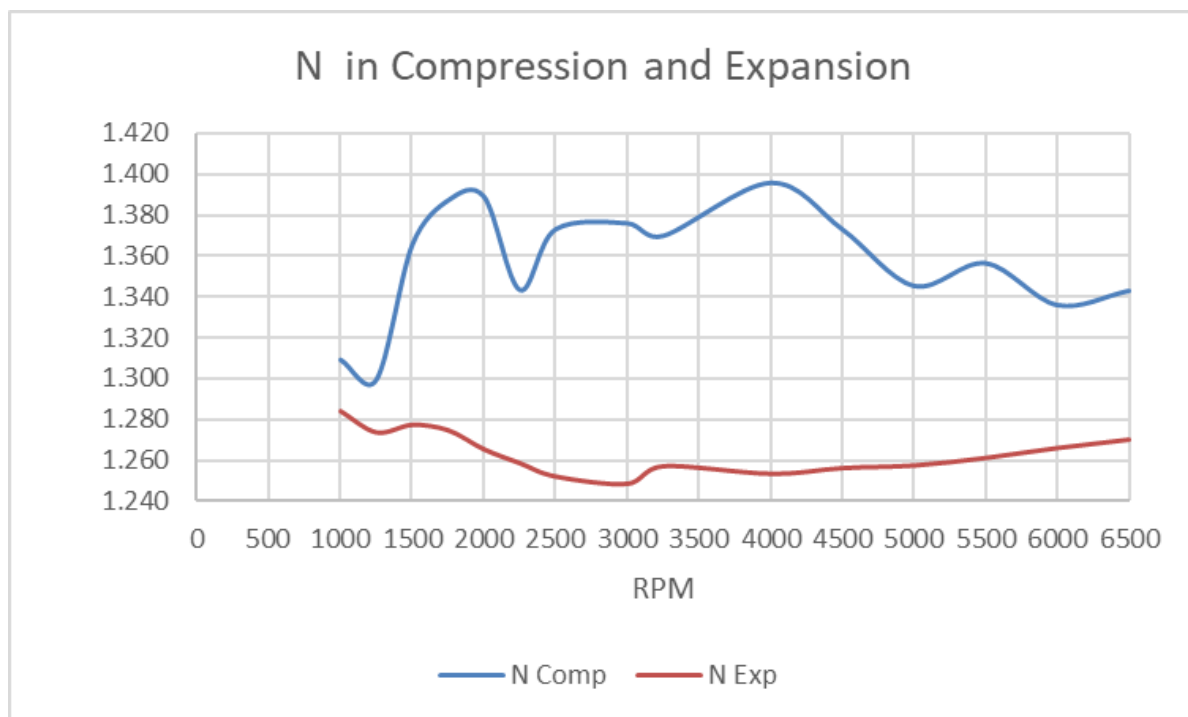


Figure 24 Initial values for N in Compression and Expansion

4.4 Extra pressure from Combustion ΔP

To precisely identify the SOC and EOC so an accurate value for N could be calculated the extra pressure from combustion or ΔP was calculated (Table 7) and an example at 1000RPM shown in Figure 25.

$$p_2 - p_1 \times \left(\frac{V_1}{V_2}\right)^n = \Delta P$$

Equation 6 Delta P (Blair, 1999)

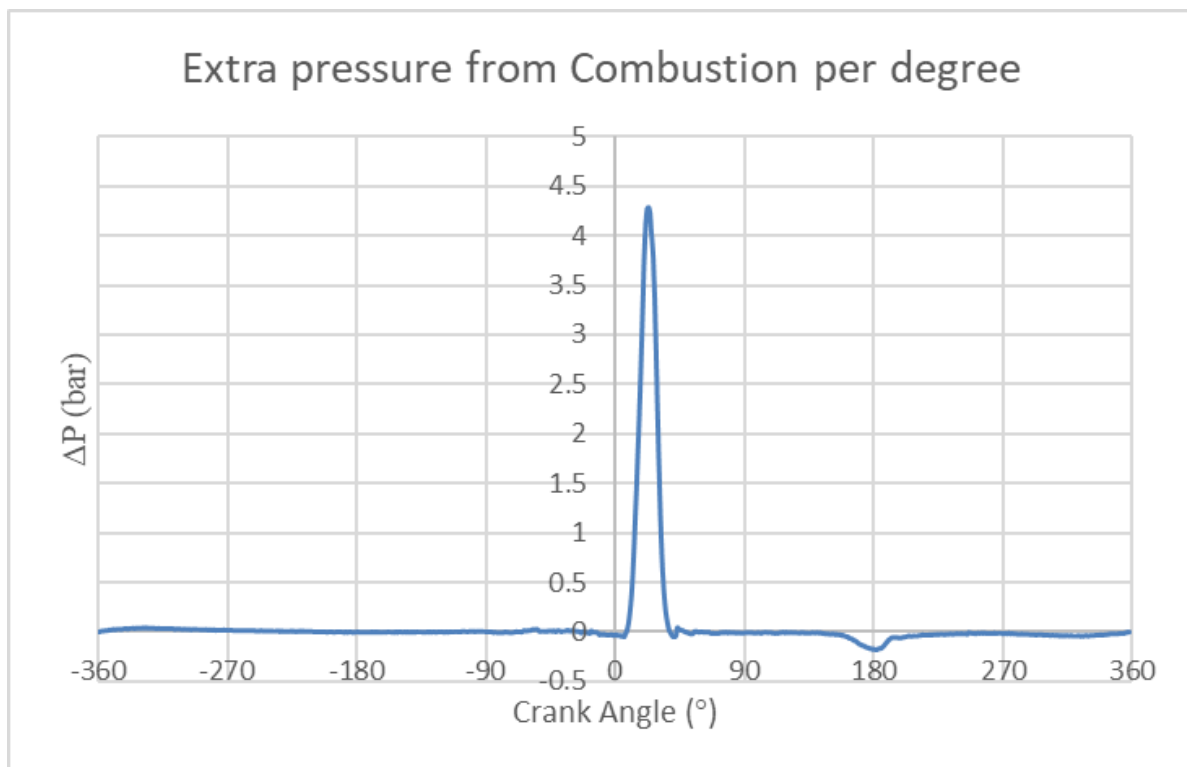


Figure 25 1000RPM Extra pressure from Combustion per degree FL

The Extra pressure from combustion appears to show a sudden increase this should be indicative of the SOC; when compared with the cylinder pressure (Figure 26) the data does correlate and define the SOC. However, closer inspection shown in Figure 27 indicates that while the initial assumption of SOC at around 10° is correct there is still no definitive SOC point readily identifiable. Therefore, the data itself was analysed and a solution was identified to find the SOC and EOC (Table 9).

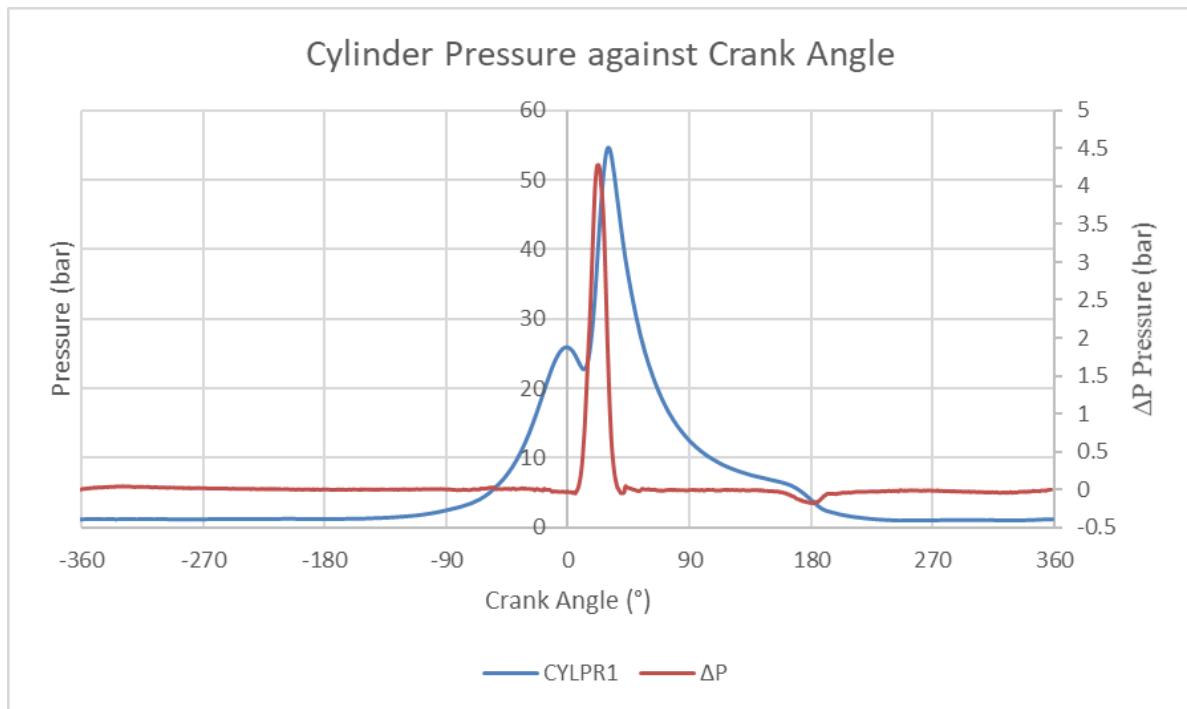


Figure 26 1000RPM Cylinder pressure and Extra pressure from Combustion against Crank Angle

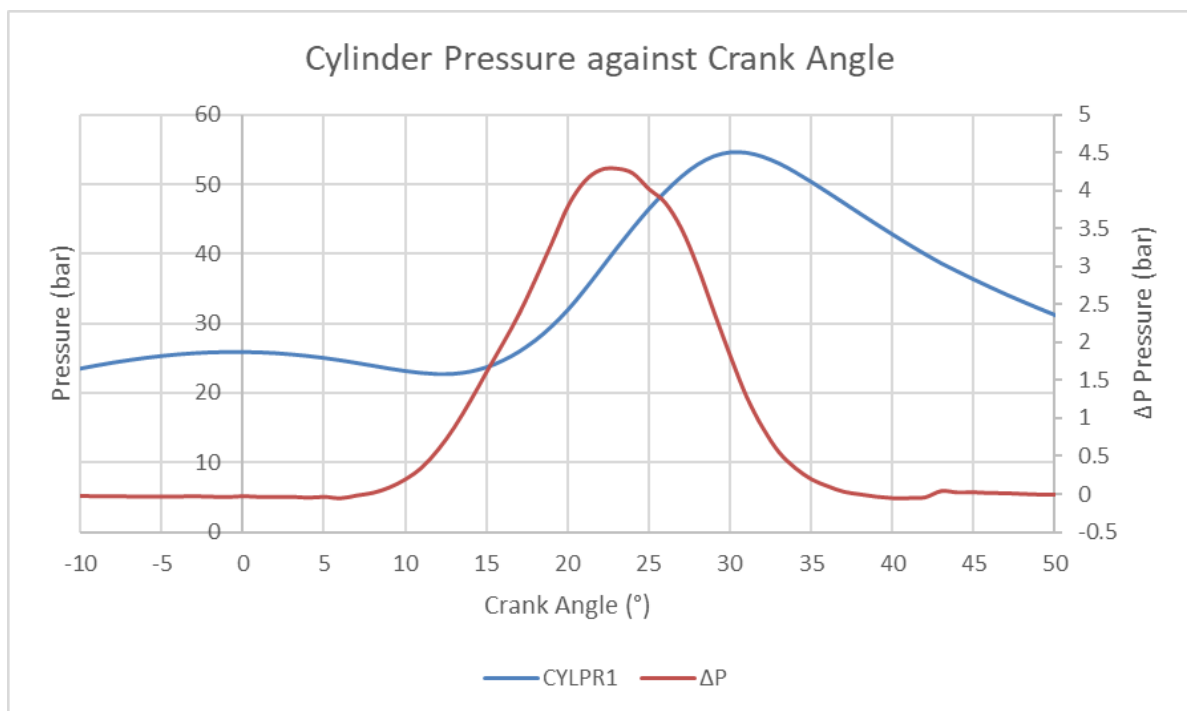


Figure 27 1000RPM Cylinder pressure and Extra pressure from Combustion against Crank Angle (Zoomed In)

Table 9 Identifying the SOC and EOC

Crank Angle	V_ABS	CYLPR1	Work done	Log P	Log V	(logP2-logP1) / (logV1-logV2)	ΔP
deg	cm ³	bar	J	log bar	log cm ³		bar
5	37.88	25.017	0.75933	1.398235229	1.57840997	1.469385861	-0.043068793
6	38.24	24.69	0.900612	1.39252109	1.582517884	1.39100761	-0.032238089
7	38.66	24.305	1.03698	1.385695625	1.58726185	1.438767562	-0.049355235
8	39.15	23.911	1.190945	1.378597739	1.592731766	1.297622312	-0.013425365
9	39.71	23.511	1.339016	1.371271101	1.598899887	1.187823384	0.021772133
10	40.33	23.151	1.457682	1.364569755	1.605628222	0.99598884	0.092018369
11	41.01	22.872	1.574268	1.359304142	1.612889769	0.725136451	0.20100234
12	41.76	22.713	1.7154	1.356274501	1.62076049	0.384925544	0.354550078
13	42.57	22.761	1.839753	1.357191339	1.62910365	-0.10989096	0.588224648
14	43.44	23.074	1.980207	1.363122888	1.637889817	-0.675100976	0.88274912
15	44.38	23.699	2.168956	1.374730021	1.647187298	-1.248416886	1.235748125
16	45.38	24.661	2.3699	1.392010683	1.656864492	-1.785710078	1.614554183
17	46.44	25.946	2.614066	1.414070414	1.666892211	-2.199875108	1.988285093
18	47.55	27.567	2.880006	1.440389506	1.677150521	-2.565636246	2.377695281
19	48.73	29.563	3.252906	1.470748503	1.687796411	-2.85171055	2.829882117
20	49.97	31.949	3.665812	1.504457269	1.698709349	-3.088880902	3.302340587
21	51.27	34.725	4.15337	1.540642254	1.709863317	-3.244135636	3.78781982
22	52.62	37.722	4.687875	1.576594711	1.721150844	-3.185149282	4.109690352
23	54.03	40.758	5.318802	1.610212865	1.732634968	-2.927359096	4.265428761
24	55.5	43.692	5.991426	1.640401925	1.744292983	-2.589553925	4.282155375
25	57.03	46.449	6.684876	1.666976369	1.756103372	-2.250090555	4.22077266
26	58.61	48.897	7.338942	1.689282214	1.767971721	-1.879439547	4.011644863
27	60.24	51.077	7.970211	1.708225381	1.779884963	-1.590093355	3.832173387
28	61.93	52.823	8.632013	1.722823063	1.79190108	-1.214841846	3.486479412
29	63.67	54.006	9.191202	1.732442012	1.80393485	-0.799329682	2.985574136
30	65.46	54.555	9.667074	1.73683456	1.815976001	-0.364794693	2.39305467
31	67.31	54.502	10.092675	1.736412439	1.828079591	0.034875663	1.81929221
32	69.2	53.929	10.300878	1.731822367	1.840106094	0.381663046	1.285766057
33	71.14	52.967	10.462226	1.724005376	1.852113861	0.650994649	0.874407961
34	73.13	51.721	10.540433	1.713666913	1.864095573	0.862853485	0.553803414
35	75.17	50.316	10.551084	1.701706108	1.87604455	1.000989866	0.347745344
36	77.26	48.815	10.516044	1.688553294	1.887954704	1.10433629	0.198686575
37	79.38	47.295	10.34878	1.67481523	1.899711095	1.168561349	0.10805274
38	81.56	45.751	10.31031	1.660400591	1.911477217	1.225096771	0.03464216
39	83.77	44.245	10.110971	1.645864199	1.923088515	1.251917849	0.001345927
40	86.03	42.764	9.99937	1.631078321	1.934649923	1.27889953	-0.029431459
41	88.33	41.325	9.83572	1.616212862	1.94610823	1.297352038	-0.048324917
42	90.67	39.945	9.67005	1.601462425	1.957463616	1.298981617	-0.047995338
43	93.05	38.631	9.50691	1.58693595	1.968716377	1.290925323	-0.037924108
44	95.46	37.458	9.310071	1.573544585	1.97982143	1.205880388	0.045157856
45	97.91	36.313	9.17721	1.56006213	1.990827051	1.225051838	0.02576057

Table 9 shows the delta P values are all negative (highlighted in orange) until 9° after which point they are positive. Given the information obtained earlier it indicates this is the SOC. It should be noted, however, that as the data is per degree and there is a certain amount of inherent error in the data it may well be that SOC is 9° (±1°); for the purposes of this report the SOC will be taken as 9° at 1000RPM. The same pattern was found to occur after 39° indicating that the EOC is at this point. However, later calculations amended this to 38° the details of which are covered in section 3.6. For the purposes of this report the EOC will be taken as 38°.

4.5 Start of combustion SOC, End of combustion EOC

This method was repeated and the SOC and EOC were calculated for all engine speeds along with the duration of combustion (Table 10) and the ignition delay which was calculated from the data in Appendix 5.

Table 10 SOC, EOC, Combustion Duration

RPM	SOC	Spark Advance	Ignition Delay	EOC	Duration
	deg	deg	deg	deg	deg
1000	9	-5.7	3.3	38	29
1250	9	-5	4	39	30
1500	8	-2.9	5.1	46	38
1750	7	-3.6	3.4	47	40
2000	9	-4.2	4.8	50	41
2250	7	-3.1	3.9	51	44
2500	7	-3.2	3.8	56	49
3000	5	-0.1	4.9	59	54
3251	2	3	5	56	54
4000	1	5.3	6.3	54	53
4500	0	7.6	7.6	65	65
5000	0	4.9	4.9	66	66
5500	-2	7.5	5.5	66	68
6000	1	9.5	10.5	61	60
6500	-6	14.5	8.5	52	58

Knowing the SOC and that the supplied data identifies the ignition timing, the ignition delay was calculated. As the time for everything to happen at 3000RPM is double the time available at 6000RPM it would be expected that the Ignition delay in degrees at 6000RPM would be double that at 3000RPM. It is close but not exactly double. The same can be said between 1000RPM and 2000RPM, however, at these lower engine speeds the difference is not at all close to double.

Having identified the SOC and EOC the polytropic index could then be refined so the slope of the line was closer to the values than the initial estimate.

4.6 Refined Polytropic Index

The method defined in section 3.3 was repeated for n in compression. Thirty values were taken to calculate the slope of the line just before the SOC; for n in expansion thirty values were taken as close after the EOC as could be established. The values were calculated across the RPM range (Table 11) and shown in Figure 28, which shows a huge variation in results for n in compression with an average value of 1.279. The variation for n in expansion is much smaller with an average value of 1.252. These values are close to that expected given that Heywood states 'The exponent n for the compression and expansion processes is $1.3 (\pm 0.05)$ for conventional fuels' (Heywood, 1988). The author, therefore, concluded that the shorter duration of thirty values suggested by Bonatesta gave a more accurate value for n ; this was clearly demonstrated with n values returned in the region of 1.28 in compression and 1.25 in expansion compared to initial results in the high 1.30s. This is in line with the modified Rassweiler and Withrow method for establishing a value for n (Shayler & Wiseman, 1990).

Table 11 N in Compression and Expansion

RPM	N Comp	N Exp
1000	1.273	1.253
1250	1.275	1.248
1500	1.266	1.257
1750	1.274	1.253
2000	1.296	1.246
2250	1.281	1.239
2500	1.271	1.240
3000	1.261	1.246
3251	1.276	1.253
4000	1.259	1.253
4500	1.289	1.261
5000	1.293	1.261
5500	1.286	1.266
6000	1.288	1.258
6500	1.293	1.247

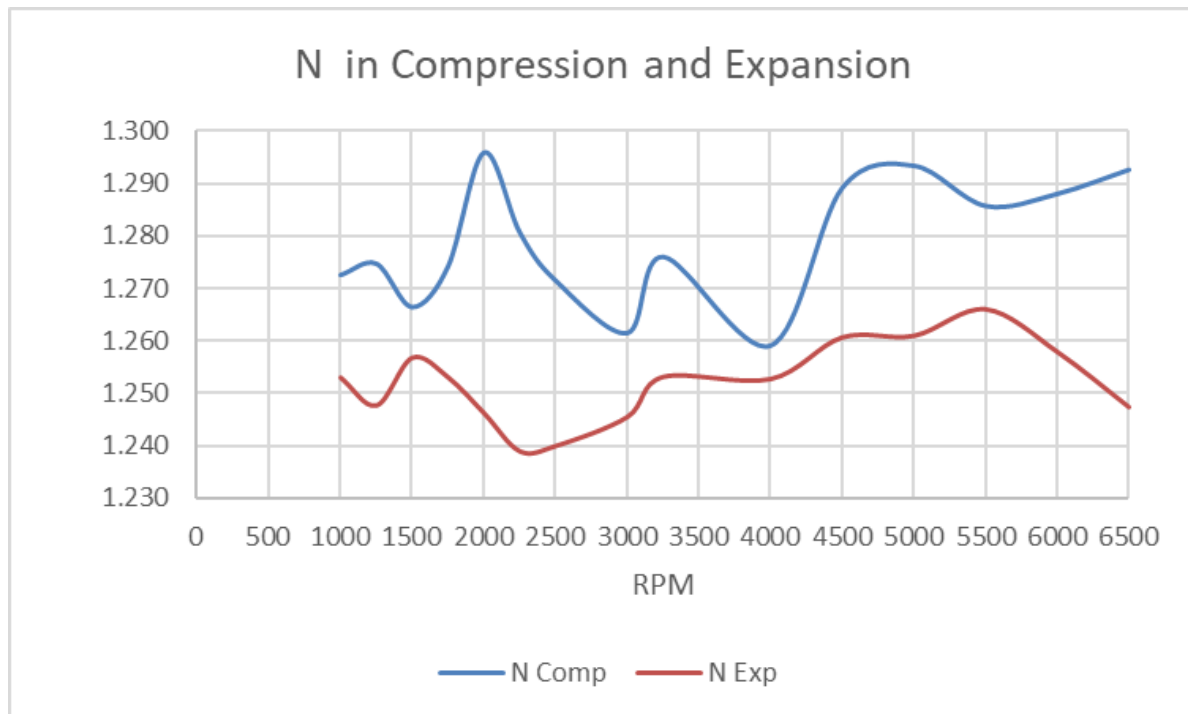


Figure 28 *N in Compression and Expansion*

The revised n values were then used to amend the delta P column. The SOC is after TDC for all engine speeds except 5500RPM and 6500RPM. Therefore, the values for n in expansion have been used to calculate delta P across all engine speeds. For the few measurements BTDC n in compression will be used to calculate delta P.

4.7 MFB Profiles

From the revised delta P values and clearly identified SOC it is now possible to calculate the MFB across all engine speeds. Continuing with the 1000RPM example, Table 12 shows the additional column of cumulative delta P. This column takes the value for delta P from SOC and creates a running total per degree until the EOC normally identified as the value before the first negative value in the delta P column (Brunt, et al., 1998). However, as mentioned in section 3.4 looking at the data, the EOC would appear to be 39° with the first negative value registering at 40°. Given the method employed to define the MFB using Equation 7 the final delta P value for the EOC is needed to calculate it. Therefore, if the value at 39° is used then MFB will show as greater than one which cannot be the case; as the MFB is defined as a normalised quantity with a scale of zero to one, describing the process of chemical energy release as a function of crank angle (Mendera, et al., 2002). This means there is a potential offset of a degree in the EOC.

$$MFB = \frac{\sum_{SOC-\theta} \Delta P}{\sum_{SOC-EOC} \Delta P}$$

Equation 7 MFB

The data for 1000RPM has been plotted in Figure 29. At this low engine RPM, the ignition timing (Table 10) has been retarded well past TDC and is assumed to be knock limited; as is expected given that knock becomes more likely with increased air pressure and compression ratios normally associated with turbo engines (Amer, et al., 2012).

Table 12 1000RPM MFB

Crank Angle	V_ABS	CYLPR1	Log P	Log V	(logP2-logP1) / (logV1-logV2)	ΔP	ΔP Cumulative	MFB
deg	cm ³	bar	log bar	log cm ³		bar	bar	
5	37.88	25.017	1.398235229	1.57840997	1.469385861	-0.043068793		
6	38.24	24.69	1.39252109	1.582517884	1.39100761	-0.032238089		
7	38.66	24.305	1.385695625	1.58726185	1.438767562	-0.049355235		
8	39.15	23.911	1.378597739	1.592731766	1.297622312	-0.013425365		
9	39.71	23.511	1.371271101	1.598899887	1.187823384	0.021772133	0	0
10	40.33	23.151	1.364569755	1.605628222	0.99598884	0.092018369	0.092018369	0.001584734
11	41.01	22.872	1.359304142	1.612889769	0.725136451	0.20100234	0.293020709	0.005046382
12	41.76	22.713	1.356274501	1.62076049	0.384925544	0.354550078	0.647570787	0.011152419
13	42.57	22.761	1.357191339	1.62910365	-0.10989096	0.588224648	1.235795435	0.021282783
14	43.44	23.074	1.363122888	1.637889817	-0.675100976	0.88274912	2.118544554	0.036485427
15	44.38	23.699	1.374730021	1.647187298	-1.248416886	1.235748125	3.354292679	0.057767395
16	45.38	24.661	1.392010683	1.656864492	-1.785710078	1.614554183	4.968846862	0.085573135
17	46.44	25.946	1.414070414	1.666892211	-2.199875108	1.988285093	6.957131955	0.119815242
18	47.55	27.567	1.440389506	1.677150521	-2.565636246	2.377695281	9.334827236	0.160763745
19	48.73	29.563	1.470748503	1.687796411	-2.85171055	2.829882117	12.16470935	0.209499778
20	49.97	31.949	1.504457269	1.698709349	-3.088880902	3.302340587	15.46704994	0.266372458
21	51.27	34.725	1.540642254	1.709863317	-3.244135636	3.78781982	19.25486976	0.331606027
22	52.62	37.722	1.576594711	1.721150844	-3.185149282	4.109690352	23.36456011	0.402382828
23	54.03	40.758	1.610212865	1.732634968	-2.927359096	4.265428761	27.62998887	0.475841745
24	55.5	43.692	1.640401925	1.744292983	-2.589553925	4.282155375	31.91214425	0.549588727
25	57.03	46.449	1.666976369	1.756103372	-2.250090555	4.22077266	36.13291691	0.62227858
26	58.61	48.897	1.689282214	1.767971721	-1.879439547	4.011644863	40.14456177	0.691366849
27	60.24	51.077	1.708225381	1.779884963	-1.590093355	3.832173387	43.97673516	0.757364272
28	61.93	52.823	1.722823063	1.79190108	-1.214841846	3.486479412	47.46321457	0.817408178
29	63.67	54.006	1.732442012	1.80393485	-0.799329682	2.985574136	50.44878871	0.868825528
30	65.46	54.555	1.73683456	1.815976001	-0.364794693	2.39305467	52.84184338	0.910038549
31	67.31	54.502	1.736412439	1.828079591	0.034875663	1.81929221	54.66113559	0.941370273
32	69.2	53.929	1.731822367	1.840106094	0.381663046	1.285766057	55.94690164	0.963513647
33	71.14	52.967	1.724005376	1.852113861	0.650994649	0.874407961	56.8213096	0.97857264
34	73.13	51.721	1.713666913	1.864095573	0.862853485	0.553803414	57.37511302	0.988110203
35	75.17	50.316	1.701706108	1.87604455	1.000989866	0.347745344	57.72285836	0.99409905
36	77.26	48.815	1.688553294	1.887954704	1.10433629	0.198686575	57.92154494	0.997520816
37	79.38	47.295	1.67481523	1.899711095	1.168561349	0.10805274	58.02959768	0.999381693
38	81.56	45.751	1.660400591	1.911477217	1.225096771	0.03464216	58.06423984	0.999978298
39	83.77	44.245	1.645864199	1.923088515	1.251917849	0.001345927	58.06558576	
40	86.03	42.764	1.631078321	1.934649923	1.27889953	-0.029431459	58.0361543	
41	88.33	41.325	1.616212862	1.94610823	1.297352038	-0.048324917	57.98782939	
42	90.67	39.945	1.601462425	1.957463616	1.298981617	-0.047995338	57.93983405	
43	93.05	38.631	1.58693595	1.968716377	1.290925323	-0.037924108	57.90190994	
44	95.46	37.458	1.573544585	1.97982143	1.205880388	0.045157856	57.9470678	
45	97.91	36.313	1.56006213	1.990827051	1.225051838	0.02576057	57.97282837	

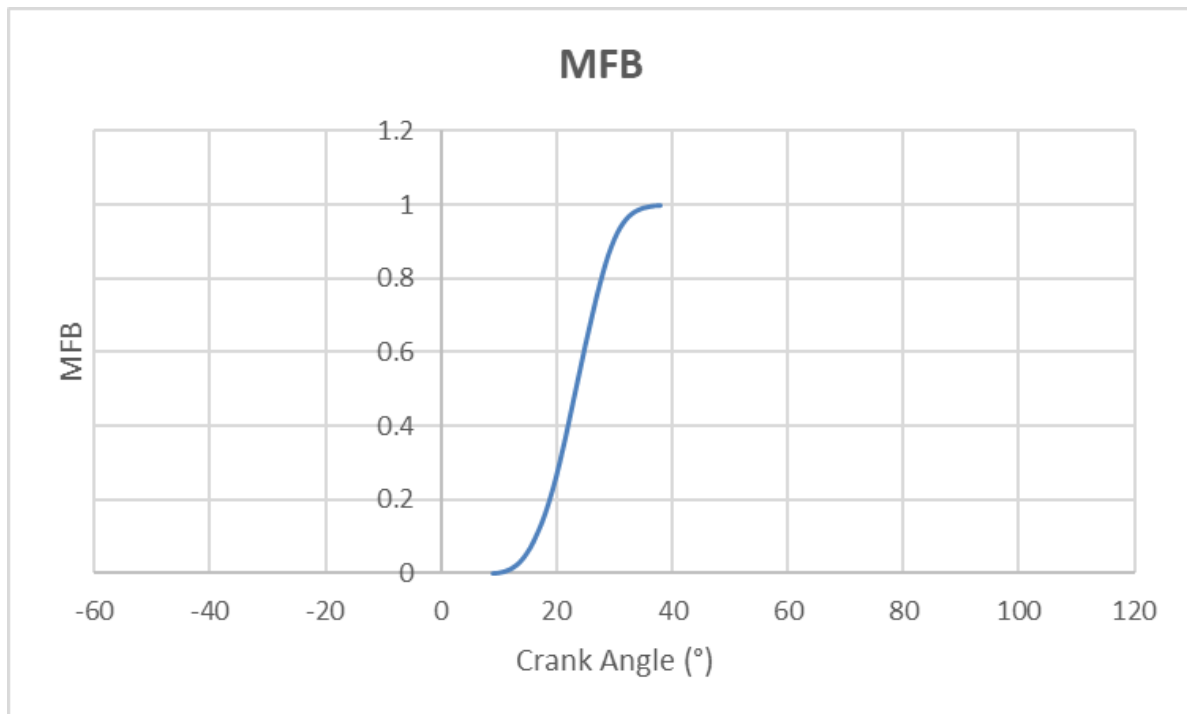


Figure 29 1000rpm MFB FL

The profile of Figure 29 is consistent with the expectations of using the Rassweiler Withrow method with a linear model of the polytropic index (Mittal, et al., 2008). When both the extra pressure from combustion and the MFB are plotted together (Figure 30) there is a clear relationship.

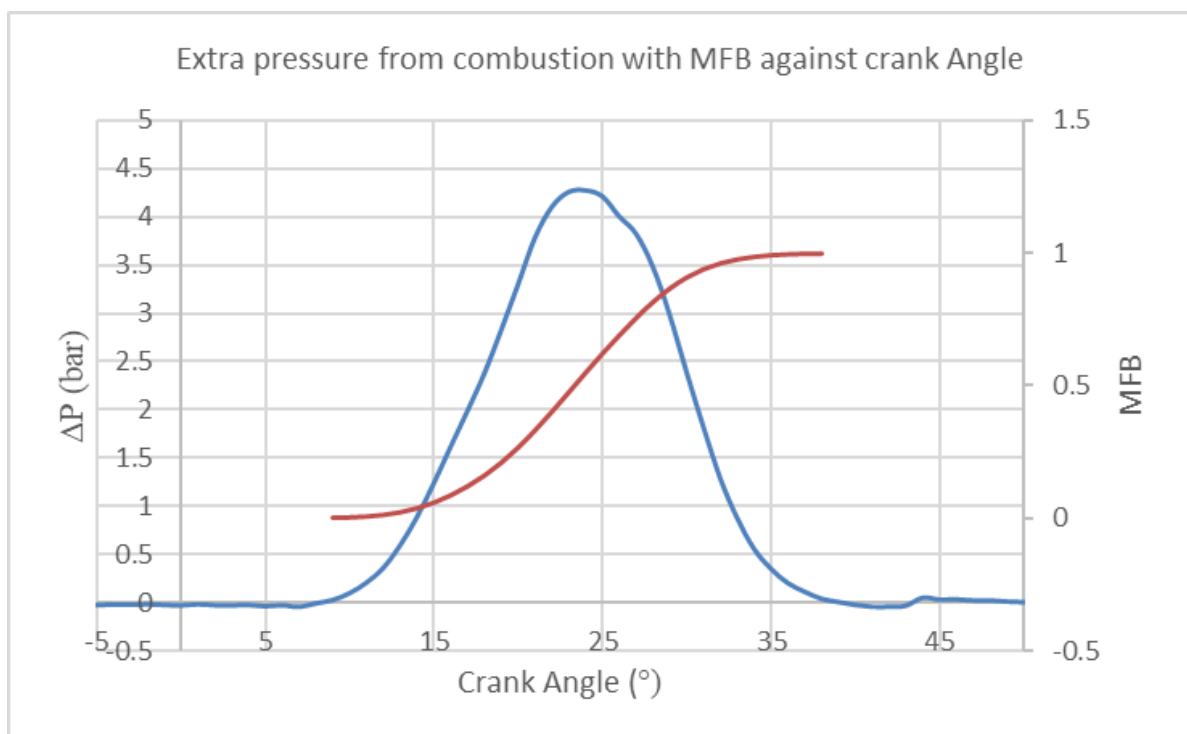


Figure 30 1000RPM ΔP with MFB

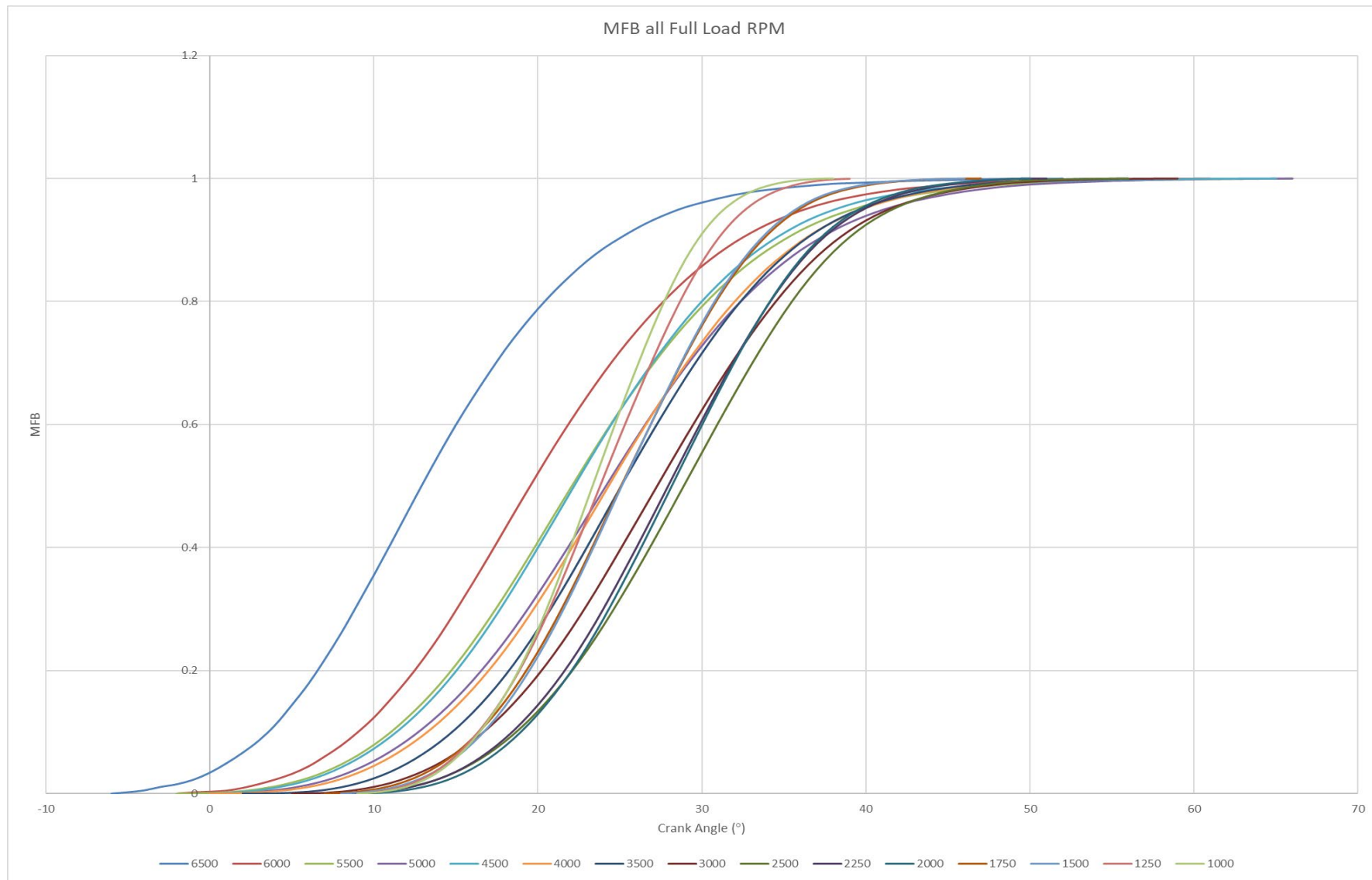


Figure 31 MFB Full Load RPM Range

4.8 Part Load

The processes defined in chapter three section 3.1 to 3.7 were applied to part load data supplied for the Ford Fox classic. As the data was recorded at different engine speeds for part load and full load 3000RPM will be used for examples for direct comparison. A sample of the data at 3000RPM is shown in Table 13 and plotted in Figure 32. The picture at part load is slightly different, the most noticeable thing is much lower pressure throughout the cycle. Following the same process as the full load data we can see significant changes in all aspects of the engine.

Table 13 3000RPM Part Load

Crank Angle	V_ABS	CYLP1	Work done	Log P	Log V	$(\log P_2 - \log P_1) / (\log V_1 - \log V_2)$	ΔP	ΔP Cumulative
deg	cm ³	bar	J	log bar	log cm ³		bar	bar
-360	37.05	0.805054206		-0.094174877	1.568788212			
-359	37.09	0.795470955	0.003220217	-0.099375673	1.569256833	11.09808558	-0.008465728	0
-358	37.19	0.79067933	0.00795471	-0.101999614	1.570426178	2.243941142	-0.002039136	0
-357	37.35	0.78109608	0.012650869	-0.107295542	1.572290606	2.840510946	-0.005225549	0
-356	37.58	0.776304454	0.01796521	-0.109967922	1.574956776	1.002329298	0.001357145	0
-355	37.88	0.771512829	0.023289134	-0.112656848	1.57840997	0.778677803	0.00311413	0
-354	38.24	0.761929579	0.027774462	-0.118085166	1.582517884	1.321429695	-0.000245677	0
-353	38.66	0.757137953	0.032001042	-0.120824983	1.58726185	0.577537158	0.005847783	0
-352	39.15	0.752346328	0.03709976	-0.123582194	1.592731766	0.504068199	0.007385667	0
-351	39.71	0.747554703	0.042131394	-0.126357022	1.598899887	0.449865989	0.008839055	0
-350	40.33	0.742763078	0.046348392	-0.129149693	1.605628222	0.41506122	0.00997013	0
-349	41.01	0.733179827	0.050507889	-0.134789493	1.612889769	0.776666405	0.006233777	0
-348	41.76	0.733179827	0.054988487	-0.134789493	1.62076049	0	0.016907514	0
-347	42.57	0.728388202	0.059387566	-0.137637097	1.62910365	0.341310059	0.013118266	0
-346	43.44	0.723596577	0.063369774	-0.140503496	1.637889817	0.326240021	0.013933738	0
-345	44.38	0.723596577	0.068018078	-0.140503496	1.647187298	0	0.019669897	0

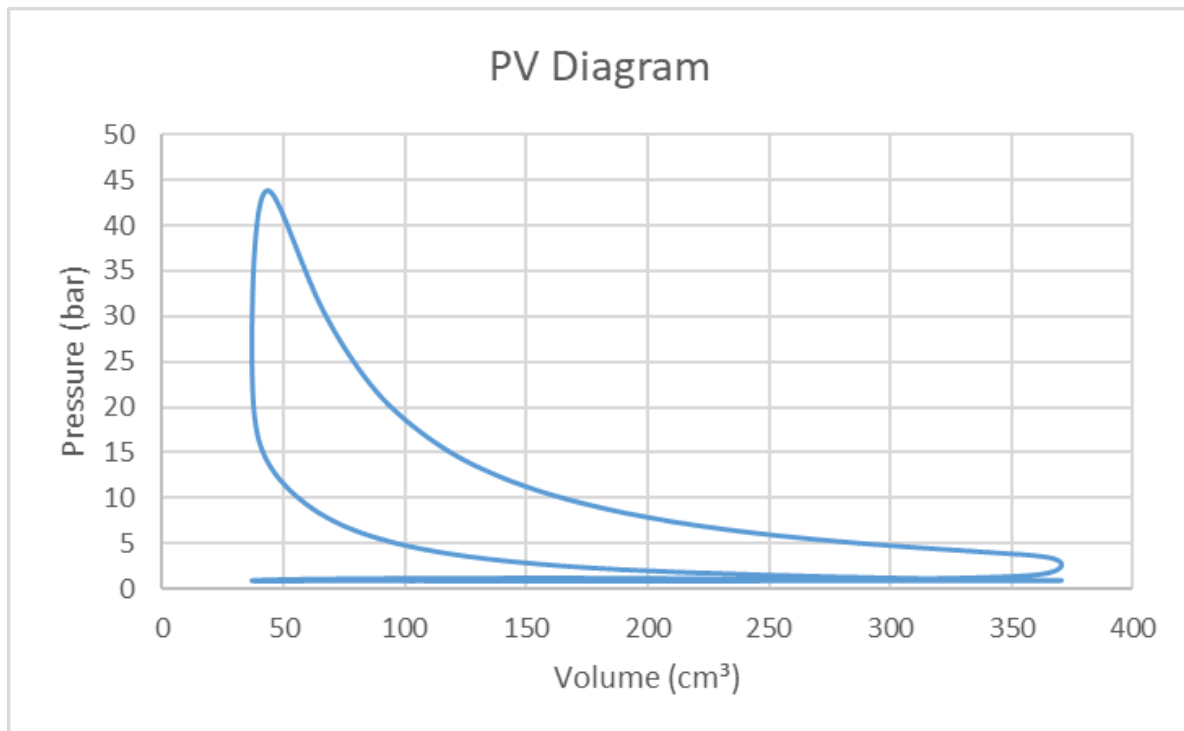


Figure 32 3000RPM PV Diagram PL

The pressure has dropped to 43bar compared to the 80bar at 3000RPM (Figure 33) full load with a much more discernible intake stroke; at such a slow speed and such a low power demand Table 5 the intake is mostly closed. Therefore, the intake stroke is fighting against a vacuum with the throttle mostly closed; the pumping loop is much larger as a result.

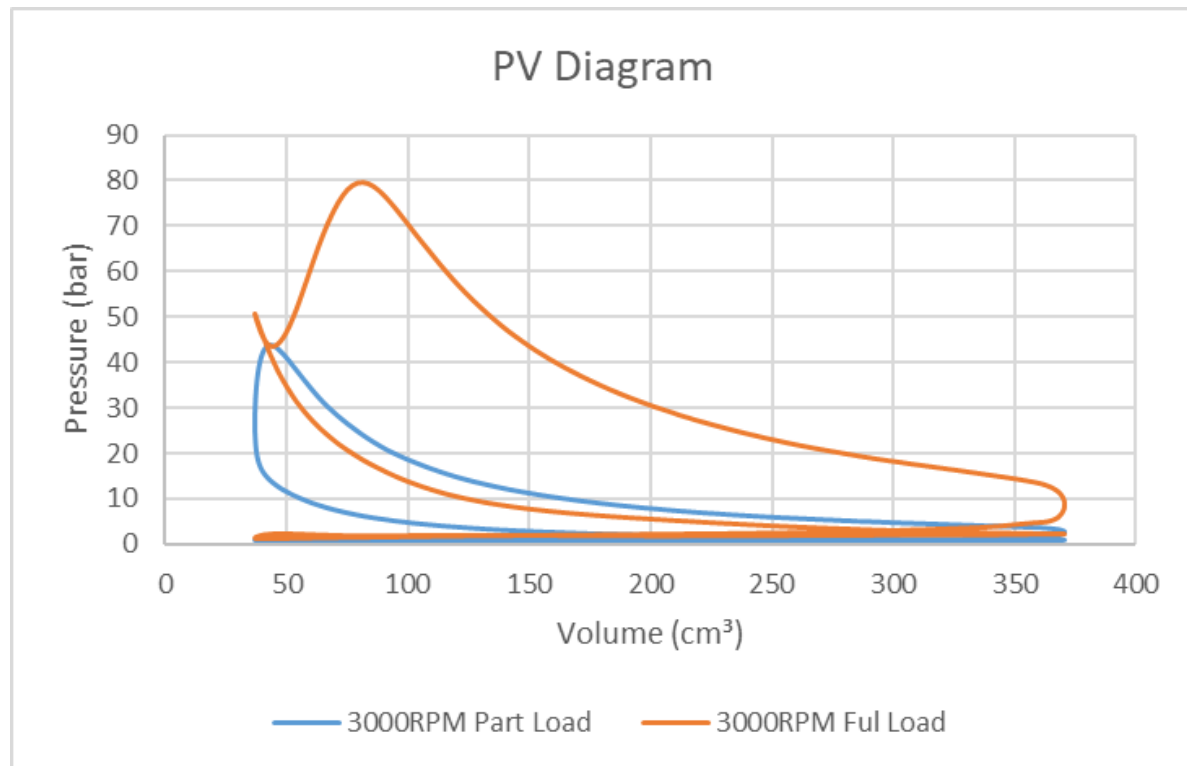


Figure 33 3000RPM PV diagram FL PL

At 3000RPM the demand is 29.8% throttle, (Table 5, Appendix 4) and when compared to the full load in Figure 33 the differences are apparent. The part load is at reduced pressure without the delay after TDC before combustion that is seen in the full load data.

Therefore, the Log P Log V graphs are also reduced, Figure 34 does show the larger pumping loop also seen at full load. The primary reason for the Log P Log V graph is to calculate n in compression and expansion; the lines do appear straighter than in the full load data so potentially less sensitive to values taken over longer durations. However, the same process employed on the full load data was used to calculate the part load n in compression and n in expansion. The issues with identifying the SOC and EOC are still encountered with the part load data.

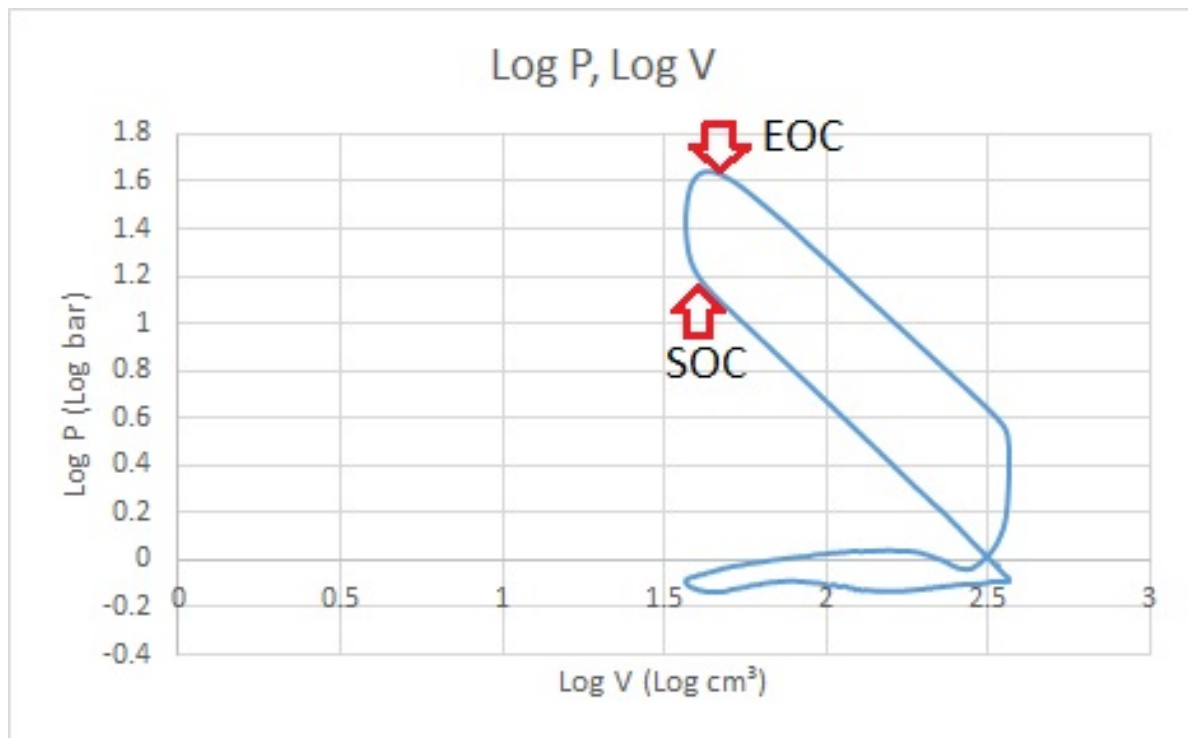


Figure 34 3000RPM Log P, Log V PL

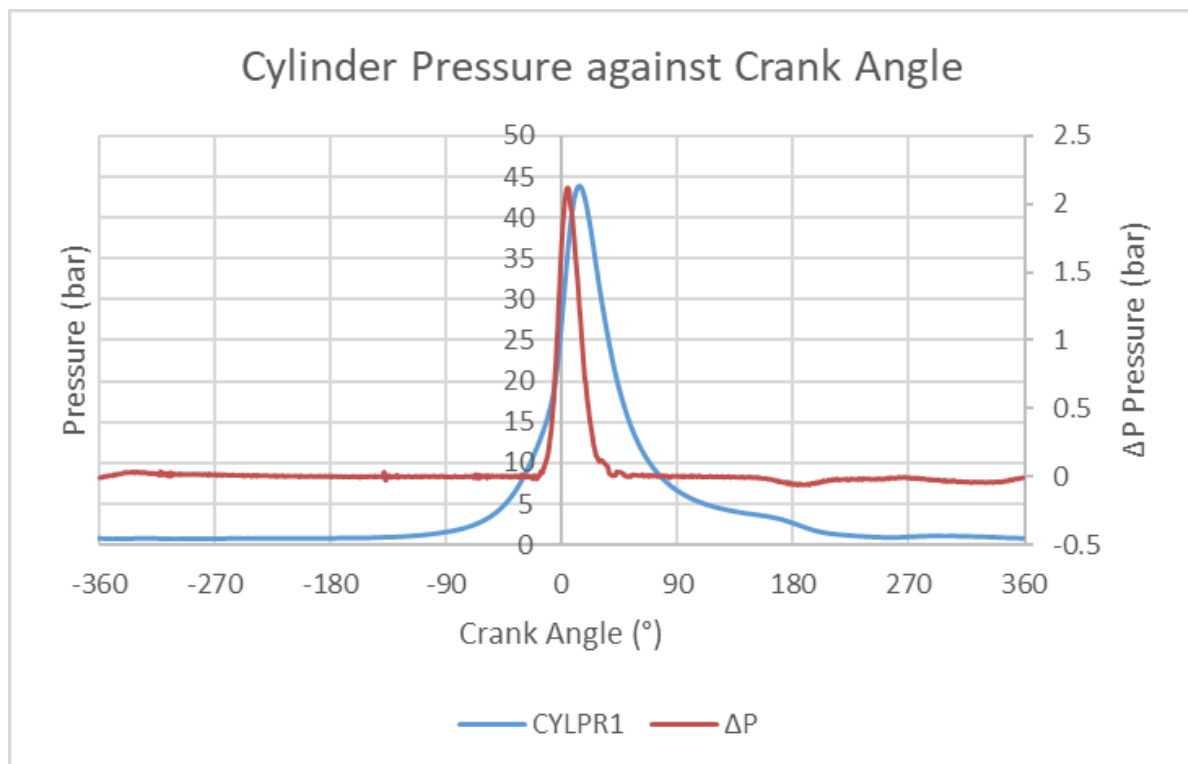


Figure 35 3000RPM Cylinder pressure an Extra pressure from combustion against Crank Angle PL

The delta P (Figure 35) is also much lower as with the PV diagram and Log P Log V graph, although the comparison with the cylinder pressure shows the same indication of SOC and EOC. The results are all in line with expectation given the partial throttle opening and the intake choking issues inherent with this condition.

Therefore, it was possible to calculate the initial values for n at each engine speed. The polytropic index calculated using Equation 5 was used and shown in Figure 36. The pattern at part load is a repeat of the full load data at 6500RPM, so even when the data is zoomed in (Figure 37, Figure 38) the SOC is lost in signal noise over TDC; as the SOC appears to start BTDC (Figure 35) this is to be expected.

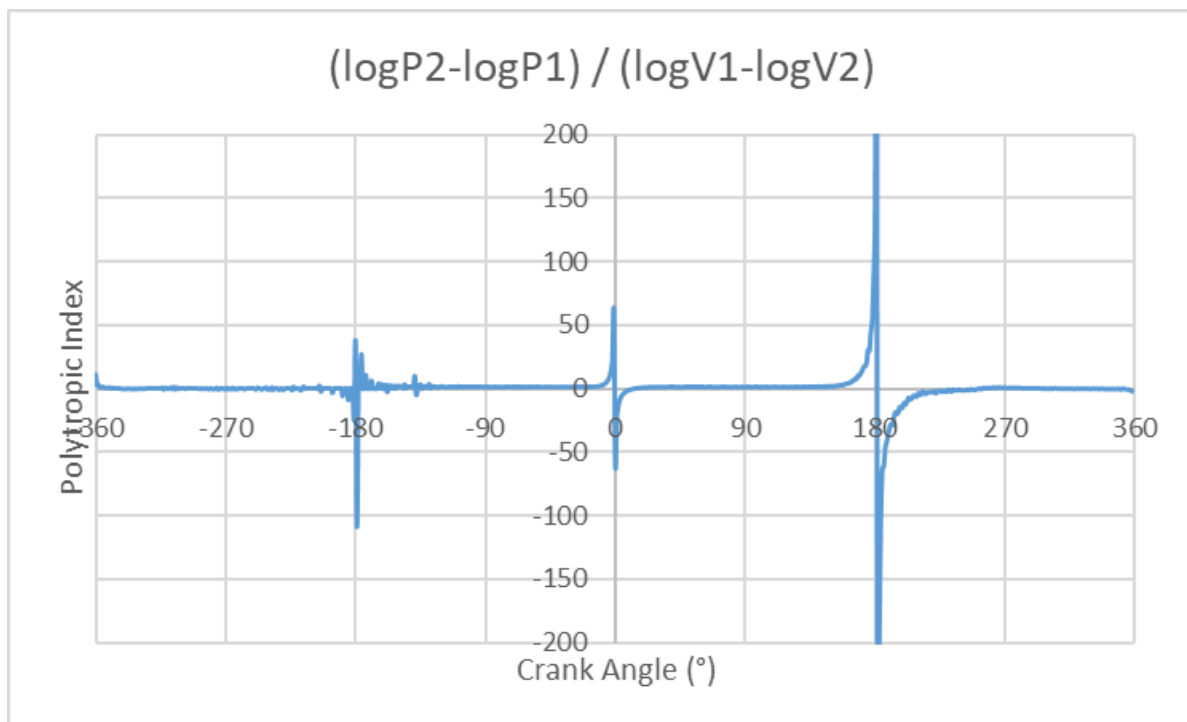


Figure 36 3000RPM Polytropic index PL

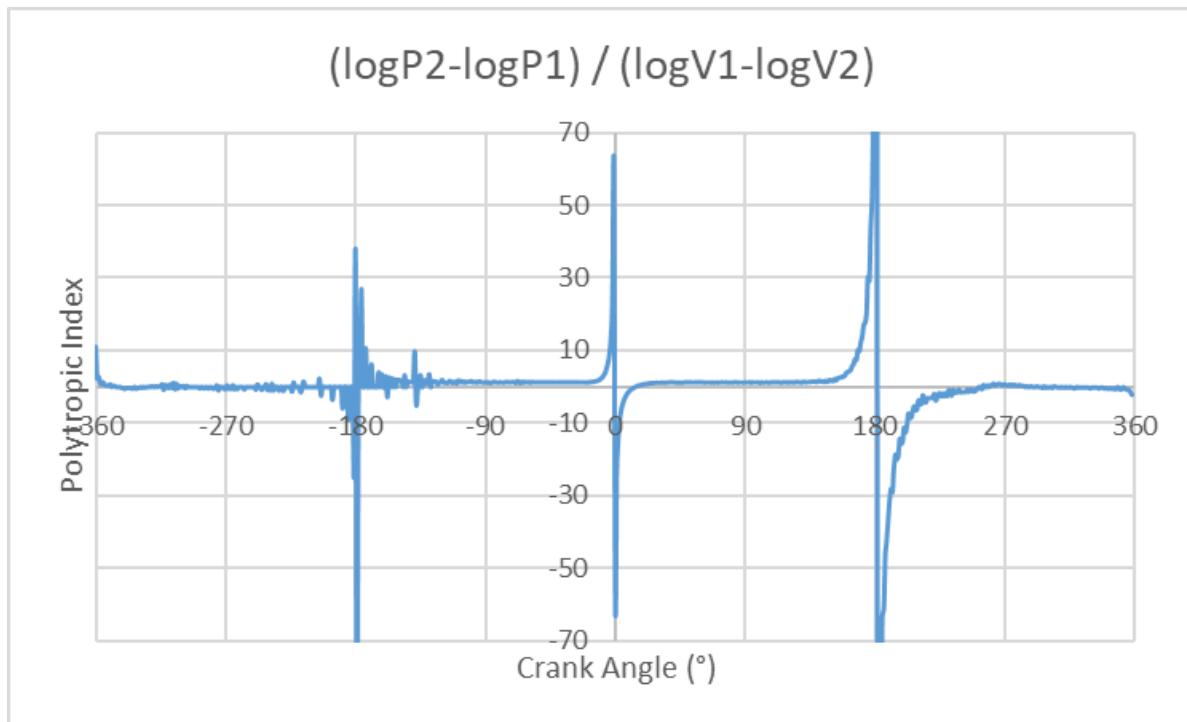


Figure 37 3000RPM Polytropic index (Zoomed in 1)

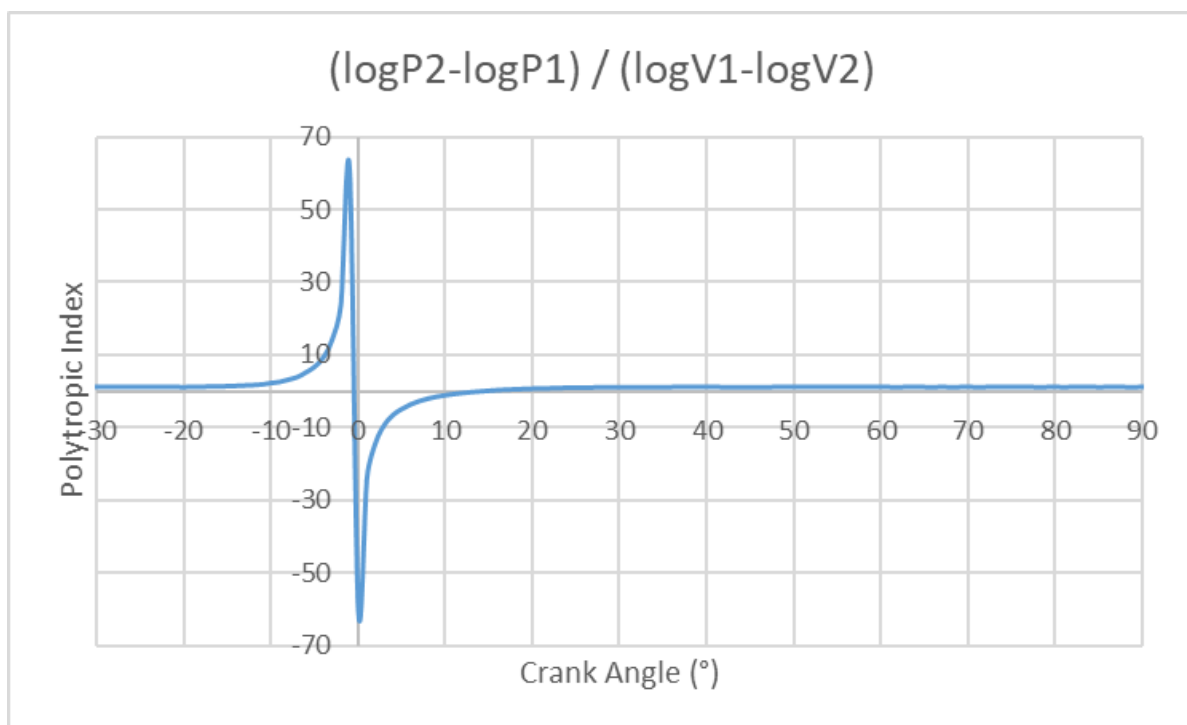


Figure 38 3000RPM Polytropic index (Zoomed in 2)

The refined polytropic index was established from the data shown in Table 14. The method used at full load to identify the SOC is used again with the last negative figure highlighted in orange the SOC can be identified as -18° , or 18° BTDC. However, there is an issue with the part load data regarding the EOC; it is difficult to identify at full load, on the part load data it is even more difficult.

To determine the EOC from the full load data the 'delta P cumulative' column takes the value for delta P from SOC and creates a running total per degree until the EOC, normally identified as the value before the first negative value in the delta P column. However, the part load data in Table 14 and Table 15 indicates that the EOC would appear to be 83° with the first negative value registering at 84° . This is an improbably long combustion duration, this is corroborated by the delta P spike in Figure 35, which indicates the EOC Long before 84° . There is however, considerable signal noise or cyclic variation around the EOC unlike the full load data. Given the method employed to define the MFB using Equation 7 requires the final delta P values up to the EOC, the method employed for full load will not work at part load.

To identify the EOC a measure of judgement is required, examination of the delta P column in Table 14 and Table 15 shows that the EOC has been selected as 35° . After 35° the delta P value highlighted in yellow can be seen to slowly reduce until 54° then bounce up and down over another 30° until the first negative value at 86° highlighted in orange (McDonald, 2017). Given that after 35° the values become very small and prone to potential error the author identified this as the EOC.

Table 14 3000RPM Identifying the SOC and EOC

Crank Angle	V_ABS	CYLPR1	Log P	Log V	(logP2-logP1) / (logV1-logV2)	ΔP	ΔP Cumulative	MFB
deg	cm ³	bar	log bar	log cm ³		bar	bar	
-19	48.83	11.89287494	1.075286852	1.688686724	1.230331641	-0.017151772	0	0
-18	47.64	12.28578821	1.089403024	1.677971753	1.317425089	0.00911401	0	0
-17	46.5	12.6834931	1.103238877	1.667452953	1.315345168	0.008598339	0.008598339	0.000200756
-16	45.44	13.10515612	1.117442199	1.657438323	1.418257261	0.0395015	0.048099839	0.001123049
-15	44.43	13.51723589	1.130887893	1.647676313	1.377348971	0.027318645	0.075418485	0.001760892
-14	43.48	13.9580654	1.144825229	1.638289535	1.48478388	0.059437569	0.134856053	0.003148657
-13	42.6	14.4132698	1.158762516	1.629409599	1.569525579	0.08292032	0.217776373	0.005084705
-12	41.79	14.8876407	1.172825879	1.621072371	1.686815171	0.113731838	0.331508211	0.007740148
-11	41.03	15.39076134	1.187260104	1.613101517	1.81087556	0.147175944	0.478684155	0.011176454
-10	40.34	15.92263174	1.202014851	1.605735894	2.00319061	0.192143182	0.670827337	0.015662667
-9	39.72	16.51679327	1.217925733	1.59900924	2.365348654	0.27348884	0.944316177	0.022048162
-8	39.16	17.15887104	1.23448871	1.592842683	2.68593613	0.33739015	1.281706327	0.029925643
-7	38.67	17.8919897	1.25265864	1.587374172	3.322646506	0.452708617	1.734414945	0.040495613
-6	38.24	18.71135761	1.272105299	1.582517884	4.004428424	0.559947709	2.294362654	0.053569431
-5	37.88	19.67447428	1.293903136	1.57840997	5.306304167	0.733879799	3.028242452	0.070704265
-4	37.58	20.77654808	1.317573393	1.574956776	6.854596929	0.89965079	3.927893242	0.091709567
-3	37.35	22.02237063	1.342864067	1.572290606	9.485770908	1.080972344	5.008865586	0.116948416
-2	37.19	23.42631682	1.369704012	1.570426178	14.39580823	1.281900809	6.290766395	0.1468786
-1	37.09	24.98838664	1.397738217	1.569256833	23.97427952	1.480728605	7.771495	0.181451073
0	37.05	26.68941359	1.426339032	1.568788212	61.0318655	1.666291516	9.437786517	0.22035612
1	37.09	28.48627304	1.454635633	1.569256833	-60.38269773	1.833907921	11.27169444	0.263174723
2	37.19	30.35500687	1.482230336	1.570426178	-23.59842659	1.967302052	13.23899649	0.30910785
3	37.35	32.22853233	1.508240528	1.572290606	-13.95076441	2.040822182	15.27981867	0.356757546
4	37.58	34.07809966	1.532475369	1.574956776	-9.089759378	2.103269603	17.38308827	0.405865282
5	37.88	35.84620936	1.554443237	1.57840997	-6.361607464	2.115155388	19.49824366	0.455250531
6	38.24	37.49932006	1.574023393	1.582517884	-4.766448279	2.086955199	21.58519886	0.503977354
7	38.66	38.96076575	1.590627484	1.58726185	-3.500044186	1.985077532	23.57027639	0.550325508
8	39.15	40.2640878	1.604917864	1.592731766	-2.612540773	1.929940511	25.5002169	0.595386307
9	39.71	41.37095323	1.616695528	1.598899887	-1.909441101	1.836352474	27.33656938	0.638261986
10	40.33	42.28136202	1.626148969	1.605628222	-1.405019424	1.727349512	29.06391889	0.678592633
11	41.01	42.98573092	1.633324316	1.612889769	-0.988129206	1.604744106	30.668663	0.716060654
12	41.76	43.48885157	1.638377939	1.62076049	-0.642078861	1.494394295	32.16305729	0.750952197
13	42.57	43.80509883	1.641524665	1.62910365	-0.377162282	1.378579562	33.54163685	0.783139664
14	43.44	43.91530621	1.642615915	1.637889817	-0.124201019	1.236346405	34.77798326	0.812006231
15	44.38	43.84343183	1.641904541	1.647187298	0.076512575	1.121897929	35.89988119	0.838200622
16	45.38	43.58468407	1.639333902	1.656864492	0.26563887	0.981050373	36.88093156	0.861106465
17	46.44	43.17260431	1.635208247	1.666892211	0.411425038	0.864384199	37.74531576	0.881288353
18	47.55	42.60719253	1.629482919	1.677150521	0.558116168	0.727619036	38.4729348	0.898277009
19	48.73	41.9555315	1.622789227	1.687796411	0.62875827	0.671892497	39.14482729	0.913964545
20	49.97	41.18887147	1.614779893	1.698709349	0.733930152	0.568817398	39.71364469	0.927245456
21	51.27	40.35033706	1.605847167	1.709863317	0.800856347	0.501020817	40.21466551	0.938943432
22	52.62	39.43992827	1.595936116	1.721150844	0.878053366	0.417327385	40.63199289	0.94868731
23	54.03	38.48160323	1.585253157	1.732634968	0.930237187	0.36167515	40.99366804	0.957131804
24	55.5	37.47536193	1.573745836	1.744292983	0.987073778	0.300851776	41.29451982	0.964156177
25	57.03	36.42120439	1.561354303	1.756103372	1.049206203	0.2351046	41.52962442	0.969645466
26	58.61	35.35746359	1.548481103	1.767971721	1.0846664	0.195296989	41.72492141	0.974205316
27	60.24	34.28413954	1.535093254	1.779884963	1.123778812	0.153483551	41.87840496	0.977788893
28	61.93	33.22519037	1.521467478	1.79190108	1.133958357	0.140707481	42.01911244	0.981074171
29	63.67	32.17582445	1.507529684	1.80393485	1.158223434	0.114914127	42.13402657	0.983757219
30	65.46	31.15999991	1.493597448	1.815976001	1.157051843	0.11236285	42.24638942	0.986380699
31	67.31	30.18250836	1.47975533	1.828079591	1.143637427	0.120642207	42.36703162	0.989197487
32	69.2	29.2385582	1.465955953	1.840106094	1.147413807	0.113080655	42.48011228	0.991837727
33	71.14	28.31856616	1.45207126	1.852113861	1.15630938	0.102413272	42.58252555	0.994228901
34	73.13	27.42253224	1.438107556	1.864095573	1.165418068	0.092090755	42.67461631	0.996379062
35	75.17	26.55045645	1.424071992	1.87604455	1.174624751	0.082215163	42.75683147	0.998298645
36	77.26	25.70233879	1.409972644	1.887954704	1.183809083	0.07287618	42.82970765	

Table 15 Continuation of 3000RPM Identifying the SOC and EOC

Crank Angle	V_ABS	CYLPR1	Log P	Log V	(logP2-logP1) / (logV1-logV2)	ΔP	ΔP Cumulative	MFB
deg	cm ³	bar	log bar	log cm ³		bar	bar	
35	75.17	26.55045645	1.424071992	1.87604455	1.174624751	0.082215163	42.75683147	0.998298645
36	77.26	25.70233879	1.409972644	1.887954704	1.183809083	0.07287618	42.82970765	
37	79.38	24.84942951	1.395316423	1.899711095	1.246659929	0.027353666	42.85706131	
38	81.56	24.01568672	1.38049501	1.911477217	1.259668421	0.018001698	42.87506301	
39	83.77	23.21548531	1.365777767	1.923088515	1.267493297	0.012319253	42.88738227	
40	86.03	22.43924203	1.351008183	1.934649923	1.277490139	0.005886861	42.89326913	
41	88.33	21.70133174	1.336486386	1.94610823	1.267359669	0.011440548	42.90470967	
42	90.67	20.99217121	1.32205736	1.957463616	1.270676932	0.009147416	42.91385709	
43	93.05	20.34051018	1.308361842	1.968716377	1.217080604	0.036998532	42.95085562	
44	95.46	19.71280728	1.294748476	1.97982143	1.225871337	0.030962891	42.98181851	
45	97.91	19.11385413	1.281348267	1.990827051	1.21757867	0.03376357	43.01558208	
46	100.4	18.5388591	1.268083004	2.001733713	1.216253258	0.033069665	43.04865175	
47	102.92	17.98303058	1.254862883	2.012499778	1.227943668	0.026461913	43.07511366	
48	105.48	17.44636856	1.241705043	2.023170121	1.233122433	0.023227371	43.09834103	
49	108.06	16.91928978	1.228382129	2.033664963	1.269472549	0.007306253	43.10564728	
50	110.68	16.41137751	1.215145036	2.04406915	1.272285168	0.005920346	43.11156763	
51	113.32	15.92263174	1.202014851	2.054306566	1.282568341	0.001793227	43.11336086	
52	116	15.45305247	1.189014279	2.064457989	1.2806649	0.002413171	43.11577403	
53	118.7	15.00743133	1.176306365	2.074450719	1.271716026	0.00539627	43.1211703	
54	121.42	14.57618506	1.163643873	2.084290229	1.286902685	0.000146488	43.12131679	
55	124.18	14.17368854	1.151482885	2.094051656	1.245820753	0.013222823	43.13453961	
56	126.95	13.79035852	1.139575557	2.103632705	1.242799937	0.013545743	43.14808535	
57	129.75	13.42140338	1.127797929	2.113107367	1.24306584	0.012959233	43.16104459	
58	132.57	13.06682312	1.116170012	2.122445256	1.245240356	0.011824448	43.17286903	
59	135.4	12.72661773	1.104712999	2.131618664	1.248937452	0.010320818	43.18318985	
60	138.26	12.39599559	1.093281413	2.140696553	1.259278155	0.007270557	43.19046041	
61	141.13	12.07974832	1.082057886	2.149619342	1.257849642	0.007318378	43.19777879	
62	144.02	11.77787593	1.071066975	2.158422807	1.248475537	0.009276579	43.20705537	
63	146.93	11.49517005	1.0605154	2.167110479	1.214545749	0.016728336	43.2237837	
64	149.84	11.21246416	1.049701068	2.175627764	1.269692315	0.003881366	43.22766507	
65	152.77	10.94413315	1.039181368	2.184038079	1.250809354	0.007740828	43.2354059	
66	155.72	10.68538539	1.02879019	2.192344395	1.250997099	0.007426049	43.24283195	
67	158.67	10.4410125	1.018742616	2.200494822	1.232766699	0.010689227	43.25352117	
68	161.63	10.19663962	1.00845707	2.208521973	1.281344452	0.001131078	43.25465225	
69	164.6	9.971433231	0.998757586	2.216429831	1.226562823	0.01103004	43.26568229	
70	167.57	9.751018471	0.989049979	2.22419627	1.249943082	0.006520049	43.27220234	
71	170.55	9.535395337	0.979338704	2.231851724	1.268543373	0.003159934	43.27536227	
72	173.53	9.334147078	0.97007464	2.239374567	1.231457808	0.009032006	43.28439428	
73	176.52	9.137690444	0.960836441	2.246793919	1.245148945	0.006584858	43.29097914	
74	179.51	8.946025436	0.951630129	2.254088647	1.262050158	0.003800286	43.29477943	
75	182.5	8.759152053	0.942462065	2.261262869	1.277917432	0.001364195	43.29614362	
76	185.49	8.58186192	0.933581523	2.268320501	1.258289233	0.004051398	43.30019502	
77	188.48	8.414155038	0.92501051	2.275265273	1.234167618	0.007152153	43.30734717	
78	191.47	8.246448155	0.916266933	2.282100737	1.27914898	0.00106388	43.30841105	
79	194.45	8.093116149	0.908115773	2.288807947	1.215283178	0.009002115	43.31741317	
80	197.43	7.939784142	0.899808695	2.295413146	1.257657638	0.003584283	43.32099745	
81	200.4	7.791243761	0.891606792	2.301897717	1.264833482	0.002618544		
82	203.37	7.65228663	0.883791229	2.308286889	1.223251447	0.007212231		
83	206.32	7.513329498	0.875832435	2.314541329	1.272502885	0.001605916		
84	209.27	7.369580742	0.867442781	2.320706974	1.360709815	-0.007679687		
85	212.22	7.235415236	0.85946346	2.32678631	1.312531743	-0.002551303		
86	215.15	7.115624606	0.852213028	2.33274135	1.217528608	0.006808804		
87	218.06	6.995833976	0.844839494	2.338576008	1.263747555	0.002217634		
88	220.97	6.880834971	0.837641142	2.344333316	1.250298316	0.003378577		

This amended method was used to identify the EOC and along with the SOC calculations, it was possible to determine combustion durations and Ignition delay Table 17. The Ford Fox classic along with the BMEP data also supplied the spark advance timing Table 3. This data was compared to the Ford Fox data available and is shown in Table 16. There is a difference at 800RPM and 4000RPM, however, the other engine speeds are very close in both cases, the data supplied with the classic engine will be used for comparison.

Table 16 Spark advance comparison

RPM	SPARKADV Fox Ecoboost	SPARKADV Fox Classic
rpm	°CA	°CA
800.1	28.3	35.033
1500	39.1	40.3
1500	30.4	30.367
2000	41.1	40.7
2500	36.7	36.633
3000	26.9	26.633
4000	37.9	34.5

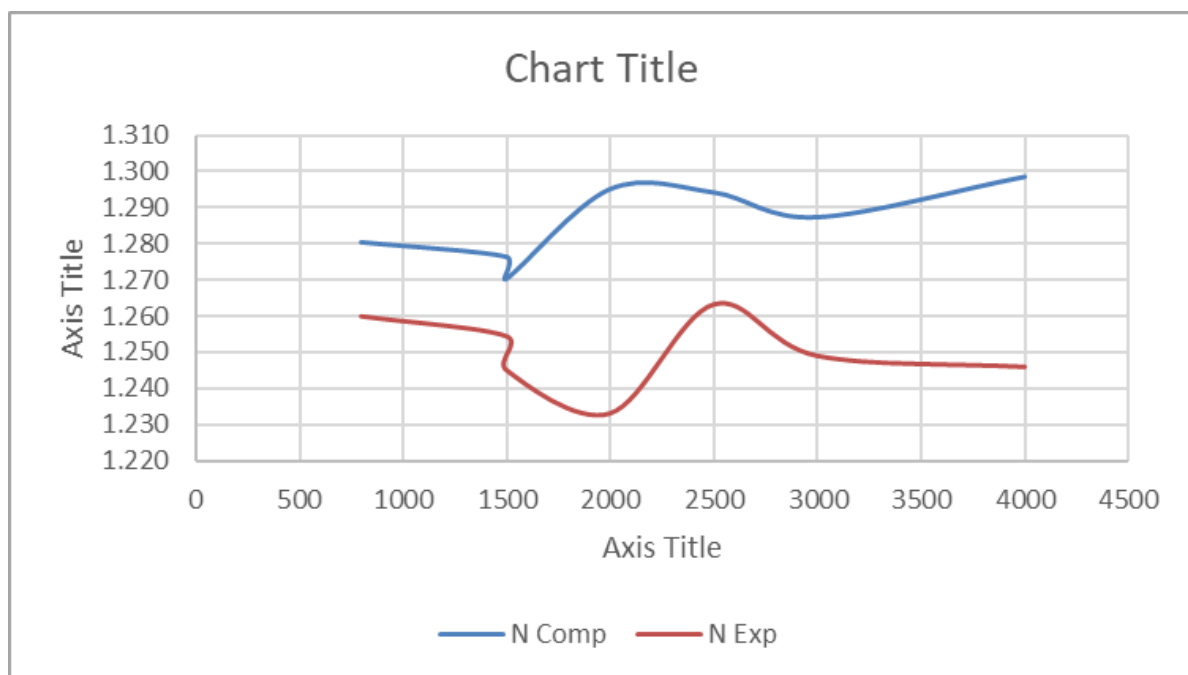
Table 17 SOC, EOC Combustion Duration PL

RPM	SOC	Spark Advance	Ignition Delay	EOC	Duration
	deg	deg	deg	deg	deg
800	-18	35.033	17.033	28	46
1500	-21	40.3	19.3	50	71
1500	-17	30.367	13.367	46	63
2000	-21	40.7	19.7	41	62
2500	-18	36.633	18.633	39	57
3000	-18	26.633	8.633	35	53
4000	-18	34.5	16.5	35	53

The ignition delay is much longer than at full load. This is to be expected as at reduced load the mixture is less dense. The spark advance is vastly different than full load, it is particularly interesting the difference at 1500RPM with the two different power requirements. With the SOC and EOC identified the revised n in compression and n in expansion values could be calculated and are shown in Table 18 and plotted in Figure 39.

Table 18 n in Compression and Expansion PL

RPM	N Comp	N Exp
800	1.280	1.260
1500	1.276	1.254
1500	1.270	1.245
2000	1.295	1.233
2500	1.294	1.263
3000	1.287	1.249
4000	1.299	1.246


Figure 39 n in Compression and Expansion PL

The revised n values were used to amend the delta P column Table 14. The SOC is BTDC, therefore, the value for n in compression will be used up to TDC and the value for n in expansion will be used ATDC. From the revised n values, the MFB profiles across all engine speeds were calculated using Equation 7, Figure 40 shows an example at 3000RPM.

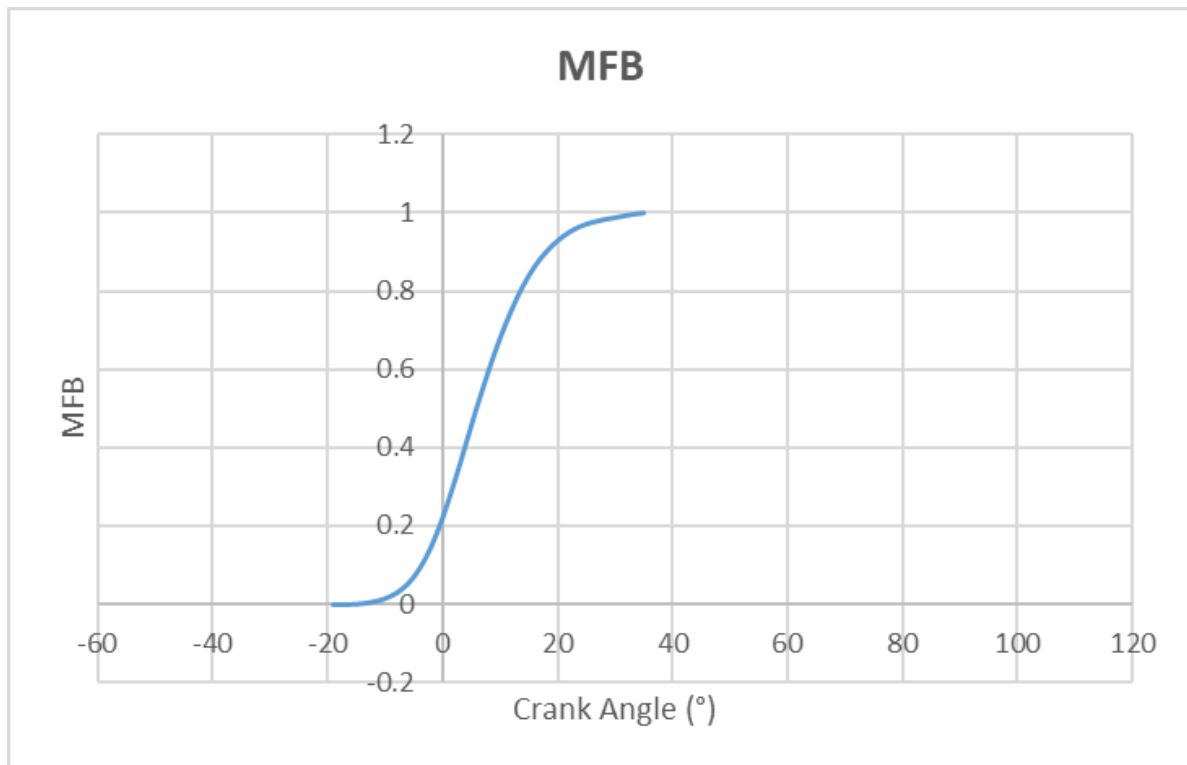


Figure 40 3000RPM MFB PL

The MFB at part load is also consistent with the Rassweiler Withrow method with a linear model of the polytropic index (Mittal, et al., 2008) seen at full load. There is no clear pattern in the part load data when all the MFB profiles are plotted together (Figure 41). However, it is a very small snap shot at inconsistent loads if the data had been at the same load every time a pattern would have been expected.

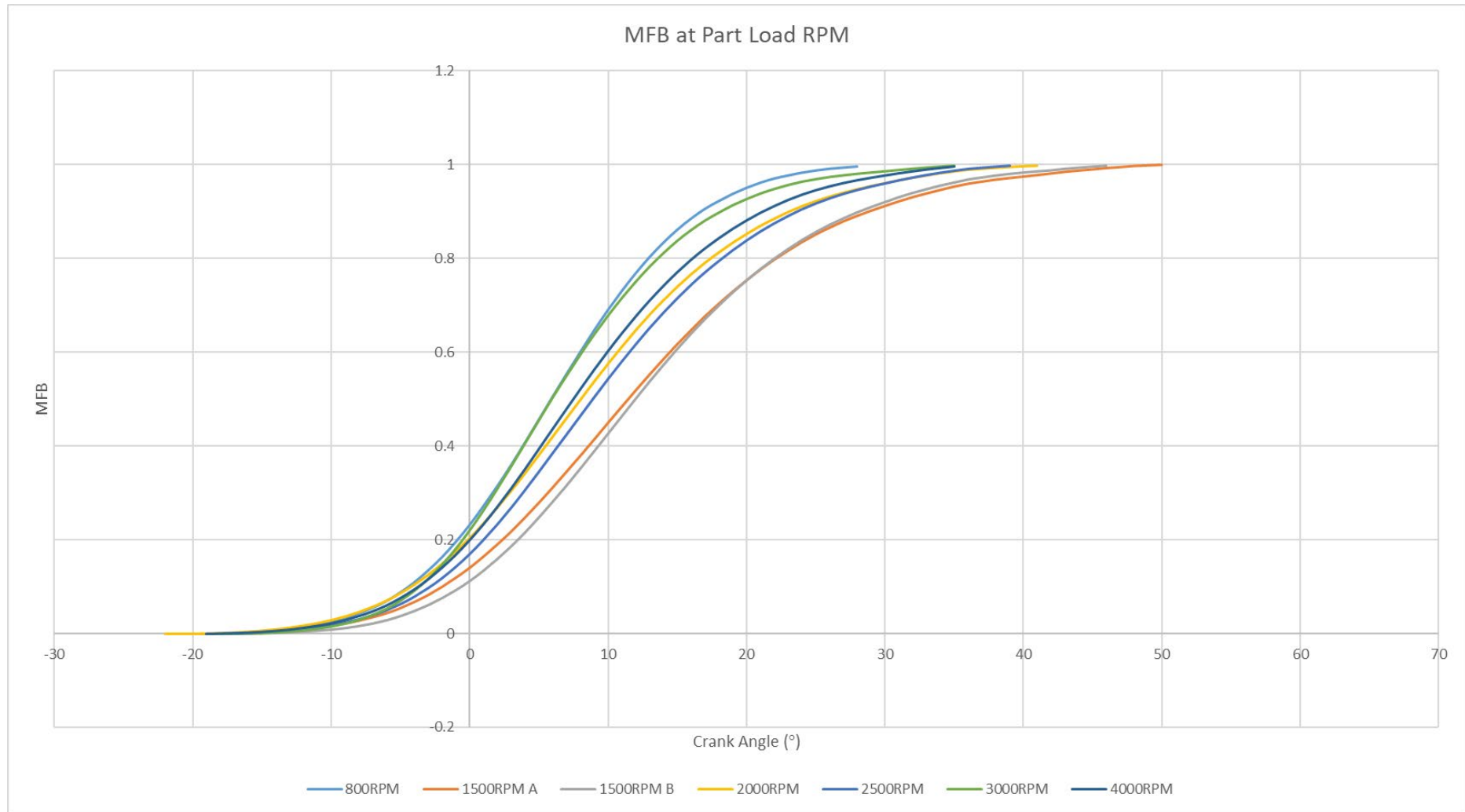


Figure 41 MFB Part Load RPM Range

Chapter 5 Single Zone Temperature Model

The next step in the process is to calculate the temperature of the gas in the cylinder throughout the cycle. It is assumed to be a single entity with the whole volume seen as an ideally mixed homogenous charge, where the volume changes with crank angle but not the mass (Merker, et al., 2006). Thus, calculating the average temperature throughout; this is an unrealistic situation but is the basis for the two-zone model. The temperature can be calculated using Equation 10, which is the ideal gas law (Equation 8) rearranged to find temperature. The pressure and the volume are already known (Table 1) however, the value for m and R (Equation 9) need to be calculated; R_u is the universal gas constant defined as 8314.472 J/kmol.K (Turns, 2006)

$$PV = mRT = nR_uT$$

Equation 8 Ideal Gas Law (Twigg, 1996)

$$R = \frac{R_u}{\text{Molecular Weight}}$$

Equation 9 Gas Constant

$$T = \frac{PV}{mR}$$

Equation 10 Gas Temperature

T = Temperature

m = Mass

P = Pressure

n = Number of Moles

V = Volume

R_u = Universal Gas Constant

5.1 Cylinder Mass

To calculate the total mass in the cylinder, it needs to be deconstructed into its constituent parts and the weight of each constituent must be calculated. Starting with the fuel flow which is given in kilograms per hour from the Ford data sheet shown in Appendix 6. The data was collated and is shown in Table 19.

Table 19 Cylinder Mass

RPM	Fuel Mass	Residual Gas Ratio	lambda	Air mass	Fuel Mass Per cylinder	Air mass per cylinder	Air and fuel mass per cylinder	Residual gas mass per cylinder	Total cylinder mass
	Kg/h				Kg	Kg	Kg	Kg	Kg
1000	3.24	0.005	1.11	13.76	0.0000360000	0.0004953600	0.0005313600	0.0000026568	0.0005340168
1250	5.22	0.002	1.11	13.7	0.0000464000	0.0006356800	0.0006820800	0.0000013642	0.0006834442
1500	7.52	0.001	1.1	13.78	0.0000557037	0.0007675970	0.0008233007	0.0000008233	0.0008241240
1750	9.39	0.004	1.03	13.9	0.0000596190	0.0008287048	0.0008883238	0.0000035533	0.0008918771
2000	11.35	0.008	0.99	14.1	0.0000630556	0.0008890833	0.0009521389	0.0000076171	0.0009597560
2250	12.92	0.008	0.99	14.08	0.0000638025	0.0008983388	0.0009621412	0.0000076971	0.0009698384
2500	14.34	0.01	0.99	14.33	0.0000637333	0.0009132987	0.0009770320	0.0000097703	0.0009868023
3000	18.08	0.015	1	13.42	0.0000669630	0.0008986430	0.0009656059	0.0000144841	0.0009800900
3251	18.92	0.017	0.94	13.6	0.0000646639	0.0008794286	0.0009440924	0.0000160496	0.0009601420
4000	21.54	0.022	0.97	14.06	0.0000598333	0.0008412567	0.0009010900	0.0000198240	0.0009209140
4500	22.34	0.027	0.95	13.91	0.0000551605	0.0007672825	0.0008224430	0.0000222060	0.0008446489
5000	25.55	0.031	0.92	13.36	0.0000567778	0.0007585511	0.0008153289	0.0000252752	0.0008406041
5500	26.61	0.033	0.92	13.35	0.0000537576	0.0007176636	0.0007714212	0.0000254569	0.0007968781
6000	27.62	0.036	0.9	13.02	0.0000511481	0.0006659489	0.0007170970	0.0000258155	0.0007429125
6500	25.11	0.041	0.9	13.1	0.0000429231	0.0005622923	0.0006052154	0.0000248138	0.0006300292

The fuel mass per hour is converted to KG per cycle using Equation 11. As the Ford Fox is a three-cylinder engine, every two revolutions all three cylinders have an intake stroke; therefore, the equivalent of one and a half cylinders per revolution have an intake stroke.

$$\text{Fuel per Cycle} = \frac{\text{Fuel Mass}}{60 \times \text{RPM} \times 1.5}$$

Equation 11 Fuel mass

Once the fuel mass per cylinders has been calculated for each RPM (Table 19), the air mass per cylinder needs to be calculated; given the AFR is provided in the data sheet (Appendix 7) as a ratio for example at 1000RPM 13.76:1 means that for every one unit of fuel there are 13.76 units of air. Equation 12 can then be used to give the air mass in the cylinder.

$$\text{Air per cycle} = \frac{\text{Fuel Mass}}{60 \times \text{RPM} \times 1.5} \times \text{AFR}$$

Equation 12 Air Mass

The final consideration in calculating the total cylinder mass is the Residual Gas Fraction (RGF), which is the amount of gas not fully expelled from the last combustion cycle; within the Ford data this figure is combined with the Exhaust Gas Recirculation (EGR) (Appendix 8). EGR is the amount of exhaust gas intentionally returned to the intake to reduce emissions (Ferguson & Kirkpatrick, 2001). Therefore, the residual gas mass per cylinder can be calculated using Equation 13 and the total mass per cylinder can be calculated using Equation 14. The result for all engine speeds are shown in Table 19.

$$\text{Residual Gas mass per cylinder} = (\text{Air} + \text{Fuel}) \times \text{Residual Gas Ratio}$$

Equation 13 Residual Gas mass per Cylinder

$$\text{Total Mass in the cylinder} = \text{Air} + \text{Fuel} + \text{RGF}$$

Equation 14 Total cylinder mass

5.2 Gas Constant

Once the total cylinder mass (m Equation 10) has been identified the gas constant R needs to be calculated using Equation 9. Therefore, the molecular weight at each engine speed, must be calculated from the mass obtained in Table 19. The lambda (λ) figure needed for Equation 15 is supplied from the data sheet (Ford, 2012) (Appendix 9) and shown in Table 20 to get the fuel equivalence ratio Phi (ϕ) (Appendix 10).

$$\phi = \frac{1}{\lambda}$$

Equation 15 Phi

Table 20 Lambda λ and Fuel equivalence ratio ϕ

RPM	Fuel Mass	Residual Gas ratio	lambda	Air mass	Total cylinder mass	Fuel Equivalence Ratio
	Kg/h				Kg	
1000	3.24	0.005	1.11	13.76	0.0005340168	0.901
1250	5.22	0.002	1.11	13.7	0.0006834442	0.901
1500	7.52	0.001	1.1	13.78	0.0008241240	0.909
1750	9.39	0.004	1.03	13.9	0.0008918771	0.971
2000	11.35	0.008	0.99	14.1	0.0009597560	1.010
2250	12.92	0.008	0.99	14.08	0.0009698384	1.010
2500	14.34	0.01	0.99	14.33	0.0009868023	1.010
3000	18.08	0.015	1	13.42	0.0009800900	1.000
3500	18.92	0.017	0.94	13.6	0.0009601420	1.064
4000	21.54	0.022	0.97	14.06	0.0009209140	1.031
4500	22.34	0.027	0.95	13.91	0.0008446489	1.053
5000	25.55	0.031	0.92	13.36	0.0008406041	1.087
5500	26.61	0.033	0.92	13.35	0.0007968781	1.087
6000	27.62	0.036	0.9	13.02	0.0007429125	1.111
6500	25.11	0.041	0.9	13.1	0.0006300292	1.111

The molecular weight is a sum of the atomic weight values of the atoms in a molecule (Helmenstine, 2018). The molecular weight is calculated by multiplying by the fuel equivalence ratio ϕ indicating a lean, rich or stoichiometric mixture (Turns, 2006).

The ratio of nitrogen N_2 to oxygen in the atmosphere is 1:3.7687 (Goodger, 2000), however, Heywood uses a ratio of 1:3.773. Given the figures in Appendix 11 the author cannot recreate either figure, hence, has decided to use the value specified by Heywood (Equation 16). Each individual molecule has its own atomic weight, which is shown in Table 21.

Table 21 Molecular weight (Turns, 2006)

Molecule	Symbol	Molecular weight
		Kg/Mol
Hydrogen	H	1.008
Carbon	C	12.011
Oxygen	O	15.999
Nitrogen	N	14.007

The fuel used in testing the Ford Fox was stated as 95 Ron gasoline (Ford, 2012) commonly known as unleaded, which falls under the heading of Isooctane with a chemical composition of C_8H_{18} ; this hydrocarbon fuel can be completely oxidised if sufficient oxygen is available in the cylinder. If the mixture is stoichiometric this is described as the condition with the correct amount of oxygen to convert all the fuel to oxidised products. These products would be carbon to carbon dioxide CO_2 and hydrogen to water H_2O (Heywood, 1988). Therefore, using 3000RPM, which is stoichiometric, (Table 20) the reactants are stated in Equation 16. The value of x cannot be calculated without the products for a balanced equation.

$$Reactants = FER \times C_8H_{18} + (x(O_2 + 3.773N_2))$$

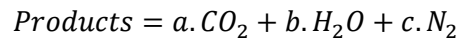
Equation 16 Reactants

As the FER is one it can be omitted for the rest of this example. Equation 16 expands to Equation 17 where the C_8 is eight carbon atoms with a molecular weight of 12.011 plus, the H_{18} is eighteen hydrogen atoms with a molecular weight of 1.008. Then O_2 which is two oxygen atoms with a molecular weight of 15.999 plus, the oxygen to nitrogen ratio of 3.773 times N_2 which is two nitrogen atoms with a molecular weight of 14.007 both multiplied by x.

$$Reactants = ((8 \times 12.011) + (18 \times 1.008)) + (x \times (2 \times 15.99) + (3.773 \times (2 \times 14.007)))$$

Equation 17 Reactants (expanded)

The products to balance Equation 16 are shown in Equation 18.



Equation 18 Products

Where

$$C = 8$$

$$H = 18$$

Therefore, we can calculate the unknown values: -

$$a = C \therefore a = 8$$

$$2b = H \therefore b = 9$$

$$O = 2a + b \therefore O = 25$$

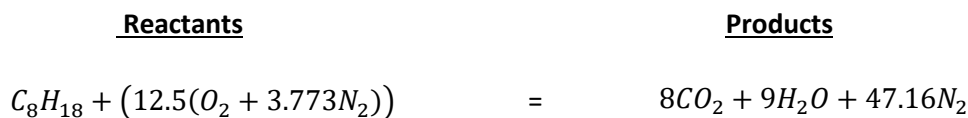
Therefore, in Equation 16: -

$$x = 12.5$$

Allowing the calculation of a value for N

$$N = 12.5 \times 3.773 \therefore N = 47.16$$

These values calculated are consistent with the examples by Heywood and Turns are the figures the author will use (Equation 19).



Equation 19 Balanced equation at 3000RPM Stoichiometric

Having used the products to calculate the value of x in the reactants for Equation 16 it now possible to determine the molecular weight by completing Equation 17 as shown in Equation 20. From this the molecular weights for the reactants across all engine speeds where calculated (Appendix 12).

$$Molecular\ Weight = \frac{(1 \times 114.232) + (12.5 \times (31.998 + 3.773 \times 28.014))}{FER + 12.5(1 + 3.773)}$$

Equation 20 Reactant Molecular weight

The mass of the products from Equation 19 were also calculated; expanding Equation 19 out in Equation 21 allows the molecular weight to be calculated across all engine speeds using Equation 22, this also enables the calculation of a value for R for burned and unburned using Equation 9, the results are shown in Table 22.

$$(8 \times (12.011 + (2 \times 15.999))) + (9 \times ((2 \times 1.008) + 15.999)) + (47.16 \times (2 \times 14.007))$$

Equation 21 Products (expanded)

$$MW = \frac{(8 \times 44.009) + (9 \times 18.015) + (47.16 \times 28.014)}{8 + 9 + 47.16}$$

Equation 22 Products Molecular weight

Table 22 Molecular weight and R

RPM	Fuel Mass	Residual Gas ratio	lambda	Air mass	Total cylinder mass	Fuel Equivalence Ratio	Molecular weight Unburned	R_un Unburned	Molecular weight Burned	R_B Burned	Corrected Molecular Weight Unburned + RGF	Corrected R_un Unburned
	Kg/h				Kg		Kg/mol	J/Kg/K	Kg/mol	J/Kg/K	Kg/mol	J/Kg/K
1000	3.24	0.005	1.11	13.76	0.0005340168	0.901	30.119	276.040	28.562	291.091	30.111	276.113
1250	5.22	0.002	1.11	13.7	0.0006834442	0.901	30.119	276.040	28.562	291.091	30.116	276.070
1500	7.52	0.001	1.1	13.78	0.0008241240	0.909	30.130	275.936	28.565	291.053	30.129	275.951
1750	9.39	0.004	1.03	13.9	0.0008918771	0.971	30.216	275.153	28.593	290.770	30.209	275.215
2000	11.35	0.008	0.99	14.1	0.0009597560	1.010	30.270	274.660	28.547	291.235	30.256	274.791
2250	12.92	0.008	0.99	14.08	0.0009698384	1.010	30.270	274.660	28.547	291.235	30.256	274.791
2500	14.34	0.01	0.99	14.33	0.0009868023	1.010	30.270	274.660	28.547	291.235	30.252	274.824
3000	18.08	0.015	1	13.42	0.0009800900	1.000	30.256	274.787	28.606	290.641	30.230	275.021
3500	18.92	0.017	0.94	13.6	0.0009601420	1.064	30.344	273.987	28.242	294.386	29.668	280.238
4000	21.54	0.022	0.97	14.06	0.0009209140	1.031	30.299	274.398	28.428	292.459	29.610	280.780
4500	22.34	0.027	0.95	13.91	0.0008446489	1.053	30.329	274.127	28.305	293.731	29.648	280.425
5000	25.55	0.031	0.92	13.36	0.0008406041	1.087	30.376	273.699	28.113	295.736	29.709	279.847
5500	26.61	0.033	0.92	13.35	0.0007968781	1.087	30.376	273.699	28.113	295.736	29.709	279.847
6000	27.62	0.036	0.9	13.02	0.0007429125	1.111	30.410	273.399	27.980	297.142	29.754	279.429
6500	25.11	0.041	0.9	13.1	0.0006300292	1.111	30.410	273.399	27.980	297.142	29.754	279.429

The gas constant was the final component needed to calculate the average temperature of the single zone model per degree using Equation 10. The calculations were carried out across all engine speeds (Table 22) and a sample at 3000RPM is shown in Table 23. The peak temperature is highlighted in yellow and occurs at 46° at 2,589.78K. The values were then corrected to include the RGF, which has an impact on the molecular weight and the gas constant (R) (Table 22). The example data at 3000RPM (Table 23) has also changed with the inclusion of the RGF all the temperatures calculated are slightly lower, but the highest temperature occurs at the same crank angle at 2587.57K.

Table 23 3000RPM Single Zone Average Temperature

Crank Angle	V_ABS	CYLPR1	Log P	Log V	(logP2-logP1) / (logV1-logV2)	ΔP	ΔP Cumulative	MFB	Single Zone Temperature	Corrected Temperature
deg	cm³	bar	log bar	log cm³		bar	bar		K	K
3	37.35	50.827	1.706094477	1.572290606	1.452835119	-0.045239893	0		704.8936671	704.29318
4	37.58	50.404	1.702465003	1.574956776	1.361306445	-0.035817634	0		703.3318822	702.7327255
5	37.88	49.913	1.698213674	1.578409997	1.231129342	0.005740911	0	0	702.040505	701.4424484
6	38.24	49.365	1.693419141	1.582517884	1.167145475	0.036617481	0.036617481	0.000370172	700.9314566	700.3343448
7	38.66	48.773	1.68817947	1.58726185	1.104491817	0.075117419	0.1117349	0.001129545	700.1318668	699.5354362
8	39.15	48.21	1.683137131	1.592731766	0.921830883	0.196190437	0.307925337	0.003112863	700.8215113	700.2244931
9	39.71	47.672	1.678263372	1.598899887	0.790153002	0.307370151	0.615295488	0.006220113	702.9133398	702.3145396
10	40.33	47.224	1.67416277	1.605628222	0.609452745	0.463129413	1.078424901	0.010901957	707.1792646	706.5768304
11	41.01	46.863	1.670830087	1.612889769	0.458949446	0.612352297	1.690777198	0.017092318	713.6058182	712.9979093
12	41.76	46.661	1.668954042	1.62076049	0.238357475	0.844031318	2.534808516	0.025624756	723.5241936	722.9078354
13	42.57	46.618	1.668553638	1.62910365	0.047991943	1.060294945	3.595103462	0.036343435	736.8783784	736.2506441
14	43.44	46.772	1.669985941	1.637889817	-0.163018023	1.31407293	4.909176391	0.049627593	754.4218939	753.7792145
15	44.38	47.157	1.673546169	1.647187298	-0.382923884	1.615740286	6.524916678	0.065961351	777.0912027	776.4292117
16	45.38	47.749	1.678964281	1.656864492	-0.55988463	1.882348726	8.407765404	0.084995349	804.5764157	803.9145396
17	46.44	48.595	1.686591586	1.666892211	-0.760622173	2.199720264	10.60748567	0.107232648	837.9581387	837.2442961
18	47.55	49.663	1.696032951	1.677150521	-0.920362501	2.476922065	13.08440773	0.13227222	876.8433198	876.0963516
19	48.73	50.991	1.707493529	1.687796411	-1.076526107	2.82146245	15.90587018	0.160794803	922.6319003	921.8459256
20	49.97	52.554	1.720605777	1.698709349	-1.201532302	3.134263919	19.0401341	0.192479543	975.1100938	974.2794138
21	51.27	54.378	1.73542323	1.709863317	-1.32844685	3.478625709	22.51875981	0.227645486	1035.201932	1034.32006
22	52.62	56.427	1.751486961	1.721150844	-1.423140053	3.781223274	26.2998308	0.265870434	1102.494244	1101.555048
23	54.03	58.674	1.768445697	1.732634968	-1.476711298	4.075289293	30.37527238	0.307068138	1177.115802	1176.113037
24	55.5	61.06	1.7857568	1.744292983	-1.48490996	4.315401968	34.69067434	0.350693178	1258.311915	1257.23998
25	57.03	63.513	1.802862627	1.756103372	-1.448371234	4.486663089	39.17733743	0.396049521	1344.944999	1343.799263
26	58.61	65.914	1.818977668	1.767971721	-1.357816467	4.526568447	43.70390588	0.441809274	1434.458258	1433.236267
27	60.24	68.256	1.834140834	1.779884963	-1.272799323	4.556124079	48.26002996	0.487867808	1526.737324	1525.436722
28	61.93	70.498	1.848176796	1.79190108	-1.168094722	4.554254332	52.81428429	0.533907442	1621.124623	1619.743614
29	63.67	72.6	1.860936621	1.80393485	-1.060334745	4.493653132	57.30793742	0.579334448	1716.36637	1714.904226
30	65.46	74.52	1.872272846	1.815976001	-0.941456961	4.384448527	61.69238595	0.623657489	1811.287429	1809.744424
31	67.31	76.242	1.88219428	1.828079591	-0.819710055	4.264514847	65.9569008	0.666768103	1905.515109	1903.891833
32	69.2	77.709	1.89047132	1.840106094	-0.688233258	4.051984071	70.00888487	0.707730212	1996.714357	1995.013389
33	71.14	78.931	1.897247605	1.852113861	-0.564325167	3.852688023	73.86157289	0.746677607	2084.970871	2083.194719
34	73.13	79.836	1.902198769	1.864095573	-0.413226775	3.571357833	77.43293073	0.782780994	2167.86817	2166.021399
35	75.17	80.456	1.905558437	1.87604455	-0.281167808	3.309686664	80.74261739	0.816239108	2245.647124	2243.734095
36	77.26	80.721	1.906986533	1.887954704	-0.119905787	2.96691723	83.70953462	0.846232114	2315.686496	2313.713802
37	79.38	80.678	1.906755124	1.899711095	0.019683754	2.633406096	86.34294072	0.872853608	2377.96109	2375.935344
38	81.56	80.273	1.904569494	1.911477217	0.18575615	2.272157535	88.61509825	0.895823185	2431.001557	2428.930627
39	83.77	79.576	1.900782105	1.923088515	0.326181353	1.932248291	90.54734654	0.91535657	2475.193445	2473.084869
40	86.03	78.604	1.895444647	1.934649923	0.461661608	1.623404389	92.17075093	0.931767806	2510.921271	2508.782259
41	88.33	77.397	1.888724127	1.94610823	0.586519407	1.334213776	93.50496471	0.945255571	2538.463268	2536.300794
42	90.67	76.011	1.880876446	1.957463616	0.691097738	1.094080808	94.59904551	0.956315797	2559.048918	2556.868907
43	93.05	74.472	1.871993017	1.968716377	0.789444321	0.87500946	95.47405497	0.965161397	2573.048193	2570.856257
44	95.46	72.865	1.862518969	1.97982143	0.853129511	0.727578789	96.20163376	0.972516599	2582.729512	2580.529328
45	97.91	71.176	1.852333578	1.990827051	0.925471821	0.575070793	96.77670456	0.978330075	2587.611985	2585.407642
46	100.4	69.469	1.841791047	2.001733713	0.966613803	0.48501362	97.26171818	0.98323315	2589.782465	2587.576272
47	102.92	67.742	1.830858015	2.012499778	1.015508735	0.38528712	97.6470053	0.987128075	2588.786993	2586.581649
48	105.48	66.029	1.81973472	2.023170121	1.042449518	0.328740976	97.97574627	0.990451366	2586.088404	2583.885359
49	108.06	64.336	1.808454056	2.033664963	1.074876987	0.26486888	98.24061515	0.993128965	2581.413309	2579.214246
50	110.68	62.609	1.796636767	2.04406915	1.135820438	0.164434774	98.40504993	0.994791261	2573.027593	2570.835674
51	113.32	60.925	1.784795538	2.054306566	1.156662002	0.127588679	98.5326386	0.996081073	2563.543136	2561.359296
52	116	59.275	1.772871563	2.064457989	1.174611162	0.09826909	98.6309077	0.99707449	2553.101482	2550.926538
53	118.7	57.687	1.761077954	2.074450719	1.180218901	0.08671096	98.71761866	0.997951064	2542.536516	2540.370572
54	121.42	56.134	1.74922599	2.084290229	1.204527904	0.052205129	98.76982378	0.998478814	2530.782045	2528.626115
55	124.18	54.647	1.737566325	2.094051656	1.194463187	0.062768514	98.8325923	0.99911335	2519.744503	2517.597975
56	126.95	53.194	1.725862649	2.103632705	1.221544251	0.028217283	98.86080958	0.999398603	2507.459228	2505.323166
57	129.75	51.794	1.714279452	2.113107367	1.22254465	0.026039819	98.8868494	0.999661843	2495.314814	2493.189097
58	132.57	50.442	1.702792298	2.122445256	1.230166017	0.016731626	98.90358103	0.999830985	2482.996343	2480.88112
59	135.4	49.144	1.691470502	2.131618664	1.234197302	0.011830514	98.91541154	0.999950582	2470.743677	2468.638891
60	138.26	47.888	1.680226699	2.140696553	1.238592343	0.00700961	98.92242115		2458.452252	2456.357938
61	141.13	46.676	1.669093631	2.149619342	1.247711712	-0.002029381	98.92039177		2445.972098	2443.888415
62	144.02	45.526	1.658259494	2.158422807	1.230667362	0.013774343	98.93416611		2434.56193	2432.487967
63	146.93	44.405	1.647431874	2.167110479	1.246320032	-0.000643528	98.93352258		2422.595348	2420.531579

Chapter 6 Two Zone Temperature Model

6.1 Temperature unburned

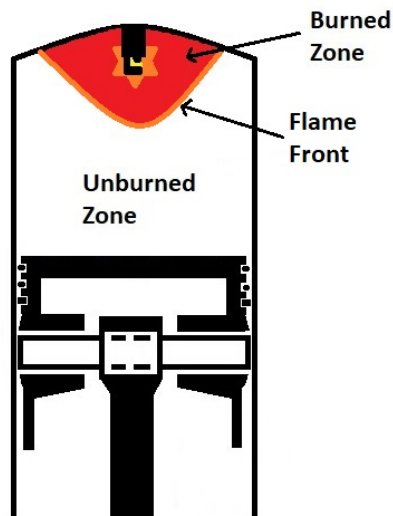


Figure 42 Two Zone Temperature Model

The two-zone combustion model separates the cylinder into a burned and unburned zone separated by the flame front. This method also assumes an ideally mixed homogenous charge where the volume, temperature and mass will change with crank angle, but not the pressure as the pressure exerted by the flame front is said to keep both zones at the same pressure. The flame front is assumed to be very thin ($\sim 0.1\text{mm}$) with a short residence in any given zone. While NO_x forms in the flame front, the dominant NO_x production is within the post flame gasses, under increased pressure, as the combustion process compresses them to a higher temperature than experienced at their combustion (Heywood, 1988).

The first step in the two-zone model is to identify, which gas constant (R) value to employ in each condition and then calculate those values, to define the temperature unburned at each degree of crank angle. Figure 43 shows that R unburned (corrected) should be used up to the SOC, then R burned should be used from the EOC, both are fixed values calculated and shown in Table 22; the R average calculated using Equation 23 should be used throughout the combustion process.

$$R_{avg} = MFB \times R_B + (1 - MFB) \times R_{Un}$$

Using the three R values for the gas constant the unburned temperature can be calculated using Equation 24, to use this formula the value for Gamma (γ) must be determined. To calculate gamma using Equation 25 the value for the specific heat C_p needs to be calculated using Equation 26.

$$T_{Un2} = T_{Un1} \times \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\gamma = \frac{C_p}{C_v}$$

$$\frac{\tilde{C}_{p,i}}{\tilde{R}} = a_{i1} + a_{i2}.T + a_{i3}.T^2 + a_{i4}.T^3 + a_{i5}.T^4$$

T_{Un} = Temperature Unburned

 $C_{P,i}$ = Specific Heat (Species)

P = Pressure

$$\tilde{R} = R_u = \text{Universal Gas Constant}$$

γ = Gamma

a_i = Coefficients for species

 $C_p = \text{Specific Heat}$

T = Temperature (Before SOC)

 C_v = Specific Heat (Constant Volume)

Equation 26 is modified slightly as the Universal Gas constant is known so Equation 27 is used to calculate the values for oxygen and nitrogen; the values for a_i are taken from Appendix 13 which is taken from Heywood . A separate formula (Equation 28) based on polynomial functions is used to determine the specific heat of the fuel with the A_f values taken from Appendix 14 also taken from Heywood; the values were calculated and are shown in Table 24. The temperatures shown in the first column 'Corrected Temperature' are the values at each engine speed taken before the SOC, this is from the corrected temperature that includes the RGF (Table 23); this is value needed for the first value of the T_{Un} (Equation 24) (Heywood, 1988).

$$\tilde{C}_{p,i} = \tilde{R} \times (a_{i1} + a_{i2} \cdot T + a_{i3} \cdot T^2 + a_{i4} \cdot T^3 + a_{i5} \cdot T^4)$$

Equation 27 Modified Specific approximation

$$\tilde{C}_{p,f} = A_{f1} + A_{f2} + A_{f3}t^2 + A_{f4}t^3 + \frac{A_{f5}}{t^2}$$

Equation 28 Polynomial function for Fuel

Table 24 Specific heat and Gamma

Corrected Temperature	O2	N2	C8H18	cpav	Cvav	γ_{un}
°K	j/kmol/K	j/kmol/K	j/kmol/K	j/kmol/K	j/kmol/K	
634.8732024	32395.13935	30312.98343	336737.0918	35314.31	27000.31	1.307922377
631.9711734	32368.35014	30294.99653	335734.8839	35279.82	26965.82	1.308316201
621.2827834	32268.96905	30229.46652	332007.2976	35192.91	26878.91	1.309313108
637.1199638	32415.82075	30326.96423	337510.1243	35690.65	27376.65	1.303689454
652.3156525	32554.29095	30422.73389	342672.9191	36075.49	27761.49	1.29947963
666.7745525	32683.639	30515.68266	347480.6355	36254.66	27940.66	1.297559189
684.5634665	32839.31279	30632.19896	353257.9011	36473.76	28159.76	1.29524399
702.7327255	32994.115	30753.32674	359004.7842	36641.94	28327.94	1.293491125
694.1648506	32921.66121	30695.96436	356313.9695	36874.96	28560.96	1.291096708
706.7943062	33028.11483	30780.65911	360268.5003	36856.42	28542.42	1.291285753
724.6835668	33175.14679	30901.9889	365744.8273	37192.06	28878.06	1.287900183
758.9532765	33443.98563	31137.63917	375836.0425	37797.51	29483.51	1.281988103
771.57433	33538.6286	31225.07859	379423.5694	37949.23	29635.23	1.280544454
789.9329078	33672.03832	31352.48805	384521.3268	38305.08	29991.08	1.277215778
793.637	33698.34028	31378.1926	385532.692	38348.97	30034.97	1.276810622

The $C_p A v$ is calculated using Equation 29 which accounts for the AFR in the cylinder. The $C_p A v$ is calculated using Equation 30. Thus these values defined Equation 25 is used to calculate the gamma value at all engine speeds which is shown in Table 24.

$$C_p A v = \frac{\left((FER \times Fuel C_p) + 12.5 \times (O_2 C_p + (3.76 \times N_2 C_p)) \right)}{(FER + (12.5 \times (1 + 3.76)))}$$

Equation 29 Average Specific Heat

$$C_v A v = \frac{C_p}{\bar{R}}$$

Equation 30 Average Specific heat constant volume

The unburned temperature can now be calculated using Equation 24 throughout the combustion process for all engine speeds. An example of the values for 3000RPM are shown in Table 25. The temperatures are significantly lower than the single zone which is to be expected. The highest temperature within the unburned zone now occurs at 35° crank angle at 781.32K.

The process can also be carried out throughout combustion so a value for gamma can be found for every degree of crank angle which is shown in Table 26.

Table 25 Temperature Unburned

Crank Angle deg	V_ABS cm³	CYLPR1 bar	ΔP bar	MFB	Single Zone Temperature K	Corrected Temperature K	T un K
3	37.35	50.827	-0.045239893		704.8936671	704.29318	
4	37.58	50.404	-0.035817634		703.3318822	702.7327255	
5	37.88	49.913	0.005740911	0	702.040505	701.4424484	699.6875916
6	38.24	49.365	0.036617481	0.000370172	700.9314566	700.3343448	697.7729023
7	38.66	48.773	0.075117419	0.001129545	700.1318668	699.5354362	695.9341045
8	39.15	48.21	0.196190437	0.003112863	700.8215113	700.2244931	694.1603064
9	39.71	47.672	0.307370151	0.006220113	702.9133398	702.3145396	692.6705223
10	40.33	47.224	0.463129413	0.010901957	707.1792646	706.5768304	691.461486
11	41.01	46.863	0.612352297	0.017092318	713.6058182	712.9979093	690.7815458
12	41.76	46.661	0.844031318	0.025624756	723.5241936	722.9078354	690.6364798
13	42.57	46.618	1.060294945	0.036343435	736.8783784	736.2506441	691.1555671
14	43.44	46.772	1.31407293	0.049627593	754.4218939	753.7792145	692.4473111
15	44.38	47.157	1.615740286	0.065961351	777.0912027	776.4292117	694.4169285
16	45.38	47.749	1.882848726	0.084995349	804.5764157	803.8910105	697.1973121
17	46.44	48.595	2.199720264	0.107232648	837.9581387	837.2442961	700.6511961
18	47.55	49.663	2.476922065	0.132727222	876.8433198	876.0963516	704.8619171
19	48.73	50.991	2.82146245	0.160794803	922.6319003	921.8459256	709.7037564
20	49.97	52.554	3.134263919	0.192479543	975.1100938	974.2794138	715.2064876
21	51.27	54.378	3.478625709	0.227645486	1035.201932	1034.32006	721.2093732
22	52.62	56.427	3.781223274	0.265870434	1102.494244	1101.555048	727.5888397
23	54.03	58.674	4.075289293	0.307068138	1177.115802	1176.113037	734.1454245
24	55.5	61.06	4.315401968	0.350693178	1258.311915	1257.23998	740.6684366
25	57.03	63.513	4.486663089	0.396049521	1344.944999	1343.799263	746.8536523
26	58.61	65.914	4.526568447	0.441809274	1434.458258	1433.236267	752.7090993
27	60.24	68.256	4.556124079	0.487867808	1526.737324	1525.436722	758.1600297
28	61.93	70.498	4.554254332	0.533907442	1621.124623	1619.743614	763.1410408
29	63.67	72.6	4.493653132	0.579334448	1716.36637	1714.904226	767.5868222
30	65.46	74.52	4.384448527	0.623657489	1811.287429	1809.744424	771.4935856
31	67.31	76.242	4.264514847	0.666768103	1905.515109	1903.891833	774.7640786
32	69.2	77.709	4.051984071	0.707730212	1996.714357	1995.013389	777.4491854
33	71.14	78.931	3.852688023	0.746677607	2084.970871	2083.194719	779.4153438
34	73.13	79.836	3.571357833	0.782780994	2167.86817	2166.021399	780.7515272
35	75.17	80.456	3.309686664	0.816239108	2245.647124	2243.734095	781.3199608
36	77.26	80.721	2.96691723	0.846232114	2315.686496	2313.713802	781.2278393
37	79.38	80.678	2.633406096	0.872853608	2377.96109	2375.935344	780.3582773
38	81.56	80.273	2.272157535	0.895823185	2431.001557	2428.930627	778.8533401
39	83.77	79.576	1.932248291	0.91535657	2475.193445	2473.084869	776.7364279
40	86.03	78.604	1.623404389	0.931767806	2510.921271	2508.782259	774.0774318
41	88.33	77.397	1.334213776	0.945255571	2538.463268	2536.300794	770.981463
42	90.67	76.011	1.094080808	0.956315797	2559.048918	2556.868907	767.4884951
43	93.05	74.472	0.87500946	0.965161397	2573.048193	2570.856257	763.7767283
44	95.46	72.865	0.727578789	0.972516599	2582.729512	2580.529328	759.8017169
45	97.91	71.176	0.575070793	0.978330075	2587.611985	2585.407642	755.7040442
46	100.4	69.469	0.48501362	0.98323315	2589.782465	2587.576272	751.472512
47	102.92	67.742	0.38528712	0.987128075	2588.786993	2586.581649	747.1859625
48	105.48	66.029	0.328740976	0.990451366	2586.088404	2583.885359	742.8578907
49	108.06	64.336	0.26486888	0.993128965	2581.413309	2579.214246	738.3446316
50	110.68	62.609	0.164434774	0.994791261	2573.027593	2570.835674	733.8432718
51	113.32	60.925	0.127588679	0.996081073	2563.543136	2561.359296	729.3317004
52	116	59.275	0.09826909	0.99707449	2553.101482	2550.926538	724.8903096
53	118.7	57.687	0.08671096	0.997951064	2542.536516	2540.370572	720.4478325
54	121.42	56.134	0.052205129	0.998478814	2530.782045	2528.626115	716.0977493
55	124.18	54.647	0.062768514	0.99911335	2519.744503	2517.597975	711.7515185
56	126.95	53.194	0.028217283	0.999398603	2507.459228	2505.323166	707.4699324
57	129.75	51.794	0.026039819	0.999661843	2495.314814	2493.189097	703.2433592
58	132.57	50.442	0.016731626	0.999830985	2482.996343	2480.88112	699.0965767
59	135.4	49.144	0.011830514	0.999950582	2470.743677	2468.638891	694.9969535
60	138.26	47.888	0.00700961		2458.452252	2456.357938	
61	141.13	46.676	-0.002029381		2445.972098	2443.888415	
62	144.02	45.526	0.013774343		2434.56193	2432.487967	
63	146.93	44.405	-0.000643528		2422.595348	2420.531579	

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Table 26 3000RPM Gamma through combustion

Crank Angle	V_ABS	CYLPR1	T un	O2	N2	C8H18	cpav	Cvav	γun
deg	cm³	bar	K	j/kmol/K	j/kmol/K	j/kmol/K	j/kmol/K	j/kmol/K	
5	37.88	49.913	699.6875916	32968.47693	30732.89229	358052.332	36605.02862	28291.02862	1.29387408
6	38.24	49.365	697.7729023	32952.29249	30720.06997	357451.2603	36581.78851	28267.78851	1.294115686
7	38.66	48.773	695.9341045	32936.70332	30707.77544	356872.4111	36559.44873	28245.44873	1.294348306
8	39.15	48.21	694.1603064	32921.62252	30695.93405	356312.5333	36537.87959	28223.87959	1.294573252
9	39.71	47.672	692.6705223	32908.92417	30686.00299	355841.1681	36519.74976	28205.74976	1.294762595
10	40.33	47.224	691.461486	32898.59727	30677.95319	355457.8694	36505.02703	28191.02703	1.294916535
11	41.01	46.863	690.7815458	32892.78116	30673.43001	355242.009	36496.74354	28182.74354	1.295003217
12	41.76	46.661	690.6364798	32891.5395	30672.46536	355195.9269	36494.97591	28180.97591	1.295021721
13	42.57	46.618	691.1555671	32895.98123	30675.91777	355360.7762	36501.30044	28187.30044	1.294955525
14	43.44	46.772	692.4473111	32907.01908	30684.51618	355770.4553	36517.0323	28203.0323	1.294790997
15	44.38	47.157	694.4169285	32923.8069	30697.64605	356393.6236	36541.00123	28227.00123	1.294540675
16	45.38	47.749	697.1973121	32947.41755	30716.21939	357270.2348	36574.79777	28260.79777	1.29418844
17	46.44	48.595	700.6511961	32976.60341	30739.3531	358354.1905	36616.71618	28302.71618	1.293752725
18	47.55	49.663	704.8619171	33011.96671	30767.64436	359668.206	36667.72024	28353.72024	1.293224308
19	48.73	50.991	709.7037564	33052.33117	30800.29022	361169.083	36726.22914	28412.22914	1.292620475
20	49.97	52.554	715.2064876	33097.81208	30837.53166	362861.7958	36792.53611	28478.53611	1.291939163
21	51.27	54.378	721.2093732	33146.94402	30878.31539	364692.655	36864.63271	28550.63271	1.291201953
22	52.62	56.427	727.5888397	33198.59927	30921.82255	366620.5294	36940.96992	28626.96992	1.290425428
23	54.03	58.674	734.1454245	33251.08169	30966.69751	368582.9143	37019.11105	28705.11105	1.289634831
24	55.5	61.06	740.6684366	33302.67842	31011.4857	370516.2694	37096.52195	28782.52195	1.288855855
25	57.03	63.513	746.8536523	33351.02969	31054.06993	372332.1506	37169.6084	28855.6084	1.288124232
26	58.61	65.914	752.7090993	33396.28485	31094.47307	374035.7655	37238.50513	28924.50513	1.287437934
27	60.24	68.256	758.1600297	33437.95791	31132.15136	375608.2756	37302.37791	28988.37791	1.286804595
28	61.93	70.498	763.1410408	33475.65239	31166.62814	377033.9869	37360.51511	29046.51511	1.28623055
29	63.67	72.6	767.5868222	33508.98406	31197.43107	378297.4933	37412.21578	29098.21578	1.285721986
30	65.46	74.52	771.4935856	33538.03068	31224.51859	379400.8343	37457.49738	29143.49738	1.285278046
31	67.31	76.242	774.7640786	33562.17096	31247.20535	380319.4877	37495.29382	29181.29382	1.284908546
32	69.2	77.709	777.4491854	33581.87054	31265.83702	381070.3231	37526.24867	29212.24867	1.284606642
33	71.14	78.931	779.4153438	33596.22691	31279.4824	381618.188	37548.87102	29234.87102	1.284386409
34	73.13	79.836	780.7515272	33605.95027	31288.75654	381989.5826	37564.22344	29250.22344	1.284237145
35	75.17	80.456	781.3199608	33610.07862	31292.70208	382147.352	37570.74929	29256.74929	1.284173745
36	77.26	80.721	781.2278393	33609.4099	31292.06265	382121.7927	37569.69192	29255.69192	1.284184015
37	79.38	80.678	780.3582773	33603.09139	31286.02702	381880.3561	37559.70692	29245.70692	1.284281041
38	81.56	80.273	778.8533401	33592.12923	31275.58185	381461.7535	37542.40853	29228.40853	1.284449288
39	83.77	79.576	776.7364279	33576.65186	31260.89086	380871.3122	37518.03852	29204.03852	1.284686654
40	86.03	78.604	774.0774318	33557.11595	31242.44153	380126.9909	37487.36681	29173.36681	1.284985962
41	88.33	77.397	770.981463	33534.23608	31220.96692	379256.5719	37451.56972	29137.56972	1.285336083
42	90.67	76.011	767.4884951	33508.25006	31196.74954	378269.6399	37411.07428	29097.07428	1.285733195
43	93.05	74.472	763.7767283	33480.43645	31171.03092	377215.1708	37367.91867	29053.91867	1.286157613
44	95.46	72.865	759.8017169	33450.4224	31143.51003	376079.3564	37321.56377	29007.56377	1.2866149
45	97.91	71.176	755.7040442	33419.23612	31115.16772	374901.3564	37273.63125	28959.63125	1.287089291
46	100.4	69.469	751.472512	33386.76975	31085.93393	373677.2326	37223.97933	28909.97933	1.287582357
47	102.92	67.742	747.1859625	33353.61155	31056.3607	372429.2359	37173.52617	28859.52617	1.288085118
48	105.48	66.029	742.8578907	33319.85796	31026.54773	371160.9833	37122.42894	28808.42894	1.288596092
49	108.06	64.336	738.3446316	33284.36816	30995.51481	369829.6788	37068.98309	28754.98309	1.289132495
50	110.68	62.609	733.8432718	33248.67672	30964.6262	368492.9016	37015.51722	28701.51722	1.289671098
51	113.32	60.925	729.3317004	33212.61038	30933.73605	367144.0422	36961.773	28647.773	1.290214531
52	116	59.275	724.8903096	33176.81968	30903.3992	365807.2687	36908.71533	28594.71533	1.290753026
53	118.7	57.687	720.4478325	33140.73913	30873.13283	364461.2917	36855.5004	28541.5004	1.291295128
54	121.42	56.134	716.0977493	33105.1388	30843.57684	363134.6611	36803.25632	28489.25632	1.291829309
55	124.18	54.647	711.7515185	33069.30536	30814.13225	361800.6166	36750.92809	28436.92809	1.292366319
56	126.95	53.194	707.4699324	33033.74868	30785.21401	360477.9779	36699.25446	28385.25446	1.292898554
57	129.75	51.794	703.2433592	32998.40191	30756.75827	359164.0799	36648.12798	28334.12798	1.293427065
58	132.57	50.442	699.0965767	32963.48647	30728.93218	357866.9781	36597.85738	28283.85738	1.29394859
59	135.4	49.144	694.9969535	32928.74089	30701.51699	356576.7933	36548.05542	28234.05542	1.294467085

6.2 Temperature Burned

The second zone can now be addressed. The temperature burned is calculated using Equation 31. To calculate temperature burned the volume burned first needs to be identified using Equation 32. However, to calculate the volume burned the volume unburned must be identified using Equation 33.

$$T_B = \frac{P \times V_B}{MFB \times m \times R_B}$$

Equation 31 Temperature Burned

$$V_B = V - V_{Un}$$

Equation 32 Volume Burned

$$V_{Un} = \frac{((1 - MFB) \times m \times R_{Un} \times T_{Un})}{P}$$

Equation 33 Volume Unburned

T_B = Temperature Burned

R_B = Gas Constant Burned

P = Pressure

V = Cylinder Volume

V_B = Volume Burned

V_{Un} = Volume Unburned

MFB = Mass Fraction Burned

R_{Un} = Gas Constant Unburned

m = Total Cylinder Mass

T_{Un} = Temperature Unburned

The calculations were carried out across all engine speeds and an example of 3000RPM is shown in Table 27. It is noted that the maximum temperature in the burned zone (highlighted in yellow) is at 43° of crank angle at 2,545.96K. The burned zone maximum temperature is only 3° earlier than calculated in the one-zone model but 8° after the maximum temperature in the unburned zone. The values have been plotted in Figure 44 and show a correlation in line with expectation as do the volumes, which have been plotted in Figure 45.

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Table 27 Volume Burned and Unburned, Temperature Unburned

Crank Angle	V_ABS	CYLPR1	MFB	Corrected Temperature	T un	γun	V un	V b	T B
deg	cm³	bar		K	K		m³	m³	K
5	37.88	49.913	0	701.4424484	699.6875916	1.29387408			
6	38.24	49.365	0.000370172	700.3343448	697.7729023	1.294115686	0.0000380860	0.0000001540	7288.023809
7	38.66	48.773	0.001129545	699.5354362	695.9341045	1.294348306	0.0000384175	0.0000002425	3720.103278
8	39.15	48.21	0.003112863	700.2244931	694.1603064	1.294573252	0.0000386901	0.0000004599	2529.463489
9	39.71	47.672	0.006220113	702.3145396	692.6705223	1.294762595	0.0000389211	0.0000007889	2146.531137
10	40.33	47.224	0.010901957	706.5768304	691.461486	1.294916535	0.0000390370	0.0000012930	1984.921742
11	41.01	46.863	0.017092318	712.9979093	690.7815458	1.295003217	0.0000390531	0.0000019569	1898.100527
12	41.76	46.661	0.025624756	722.9078354	690.6364798	1.295021721	0.0000388735	0.0000028865	1853.208449
13	42.57	46.618	0.036343435	736.2506441	691.1555671	1.294955525	0.0000385102	0.0000040598	1829.818134
14	43.44	46.772	0.049627593	753.7792145	692.4473111	1.294790997	0.0000379251	0.0000055149	1818.651867
15	44.38	47.157	0.065961351	776.4292117	694.4169285	1.294540675	0.0000370741	0.0000073059	1818.64621
16	45.38	47.749	0.084995349	803.8910105	697.1973121	1.29418844	0.0000360119	0.0000093681	1824.648925
17	46.44	48.595	0.107232648	837.2442961	700.6511961	1.293752725	0.0000346961	0.0000117439	1835.815007
18	47.55	49.663	0.13227222	876.0963516	704.8619171	1.293224308	0.0000331960	0.0000143540	1851.282799
19	48.73	50.991	0.160794803	921.8459256	709.7037564	1.292620475	0.0000314835	0.0000172465	1869.989682
20	49.97	52.554	0.192479543	974.2794138	715.2064876	1.291939163	0.0000296218	0.0000203482	1892.4037
21	51.27	54.378	0.227645486	1034.32006	721.2093732	1.291201953	0.0000276113	0.0000236587	1917.414553
22	52.62	56.427	0.265870434	1101.555048	727.5888397	1.290425428	0.0000255155	0.0000271045	1946.13583
23	54.03	58.674	0.307068138	1176.113037	734.1454245	1.289634831	0.0000233700	0.0000306600	1977.891194
24	55.5	61.06	0.350693178	1257.23998	740.6684366	1.288855855	0.0000212299	0.0000342701	2012.84924
25	57.03	63.513	0.396049521	1343.799263	746.8536523	1.288124232	0.0000191428	0.0000378872	2050.583904
26	58.61	65.914	0.441809274	1433.236267	752.7090993	1.287437934	0.0000171816	0.0000414284	2090.75824
27	60.24	68.256	0.487867808	1525.436722	758.1600297	1.286804595	0.0000153332	0.0000449068	2129.929364
28	61.93	70.498	0.533907442	1619.743614	763.1410408	1.28623055	0.0000135998	0.0000483302	2169.059987
29	63.67	72.6	0.579334448	1714.904226	767.5868222	1.285721986	0.0000119884	0.0000516816	2207.810076
30	65.46	74.52	0.623657489	1809.744424	771.4935856	1.285278046	0.0000105021	0.0000549579	2245.943645
31	67.31	76.242	0.666768103	1903.891833	774.7640786	1.284908546	0.0000091275	0.0000581825	2282.801099
32	69.2	77.709	0.707730212	1995.013389	777.4491854	1.284606642	0.0000078816	0.0000613184	2318.96945
33	71.14	78.931	0.746677607	2083.194719	779.4153438	1.284386409	0.0000067426	0.0000643974	2352.79734
34	73.13	79.836	0.782780994	2166.021399	780.7515272	1.284237145	0.0000057259	0.0000674041	2386.006225
35	75.17	80.456	0.816239108	2243.734095	781.3199608	1.284173745	0.0000048101	0.0000703599	2415.930375
36	77.26	80.721	0.846232114	2313.713802	781.2278393	1.284184015	0.0000040113	0.0000732487	2444.818253
37	79.38	80.678	0.872853608	2375.935344	780.3582773	1.284281041	0.0000033149	0.0000760651	2469.495766
38	81.56	80.273	0.895823185	2428.930627	778.8533401	1.284449288	0.0000027245	0.0000788355	2492.484599
39	83.77	79.576	0.91535657	2473.084869	776.7364279	1.284686654	0.0000022270	0.0000815430	2510.405529
40	86.03	78.604	0.931767806	2508.782259	774.0774318	1.284985962	0.0000018112	0.0000842188	2525.000561
41	88.33	77.397	0.945255571	2536.300794	770.981463	1.285336083	0.0000014699	0.0000868601	2535.674885
42	90.67	76.011	0.956315797	2556.868907	767.4884951	1.285733195	0.0000011889	0.0000894811	2542.330066
43	93.05	74.472	0.965161397	2570.856257	763.7767283	1.286157613	0.0000009631	0.0000920869	2545.964349
44	95.46	72.865	0.972516599	2580.529328	759.8017169	1.2866149	0.0000007725	0.0000946875	2545.46231
45	97.91	71.176	0.978330075	2585.407642	755.7040442	1.287089291	0.0000006202	0.0000972898	2543.776407
46	100.4	69.469	0.98323315	2587.576272	751.472512	1.287582357	0.0000004889	0.0000999111	2539.035549
47	102.92	67.742	0.987128075	2586.581649	747.1859625	1.288085118	0.0000003827	0.0001025373	2533.246033
48	105.48	66.029	0.990451366	2583.885359	742.8578907	1.288596092	0.0000002896	0.0001051904	2525.684037
49	108.06	64.336	0.993128965	2579.214246	738.3446316	1.289132495	0.0000002125	0.0001078475	2517.194997
50	110.68	62.609	0.994791261	2570.835674	733.8432718	1.289671098	0.0000001646	0.0001105154	2509.12874
51	113.32	60.925	0.996081073	2561.359296	729.3317004	1.290214531	0.0000001265	0.0001131935	2497.707927
52	116	59.275	0.99707449	2550.926538	724.8903096	1.290753026	0.0000000964	0.0001159036	2486.237603
53	118.7	57.687	0.997951064	2540.370572	720.4478325	1.291295128	0.0000000690	0.0001186310	2473.65146
54	121.42	56.134	0.998478814	2528.626115	716.0977493	1.291829309	0.0000000523	0.0001213677	2461.61483
55	124.18	54.647	0.99911335	2517.597975	711.7515185	1.292366319	0.0000000311	0.0001241489	2448.679304
56	126.95	53.194	0.999398603	2505.323166	707.4699324	1.292898554	0.0000000216	0.0001269284	2436.488885
57	129.75	51.794	0.999661843	2493.189097	703.2433592	1.293427065	0.0000000124	0.0001297376	2423.557773
58	132.57	50.442	0.999830985	2480.88112	699.0965767	1.29394859	0.0000000063	0.0001325637	2410.76754
59	135.4	49.144	0.999950582	2468.638891	694.9969535	1.294467085	0.0000000019	0.0001353981	2397.75213

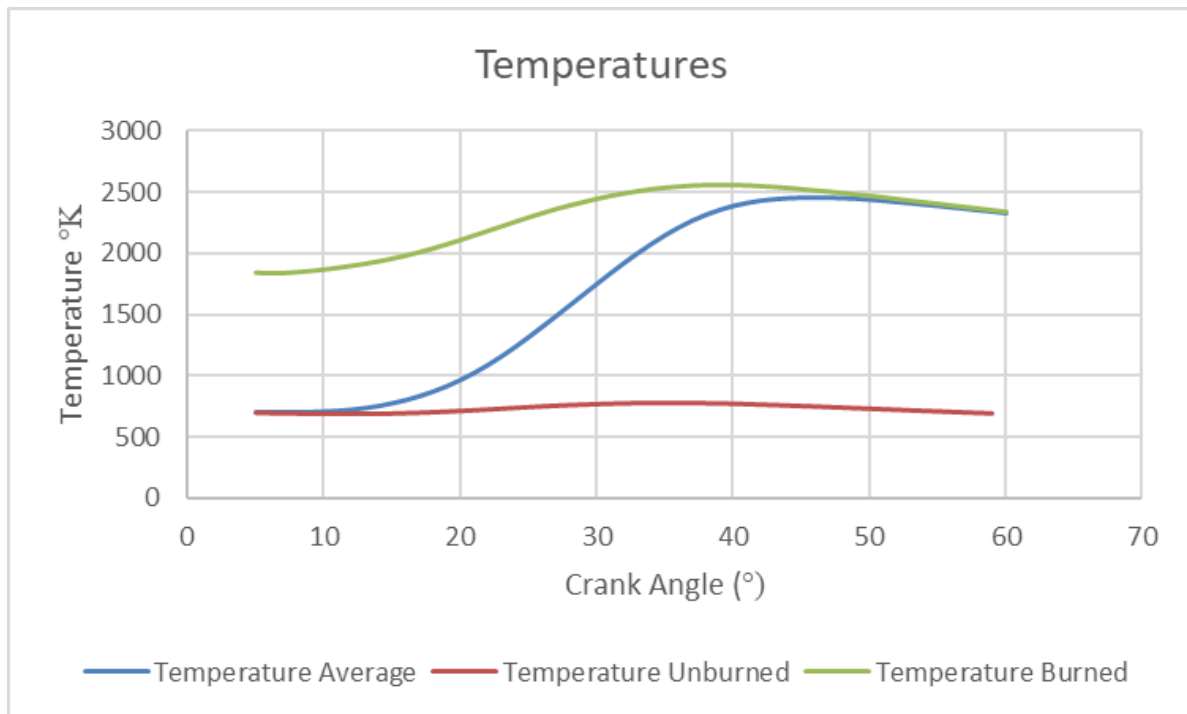


Figure 44 Temperatures average, Burned and Unburned

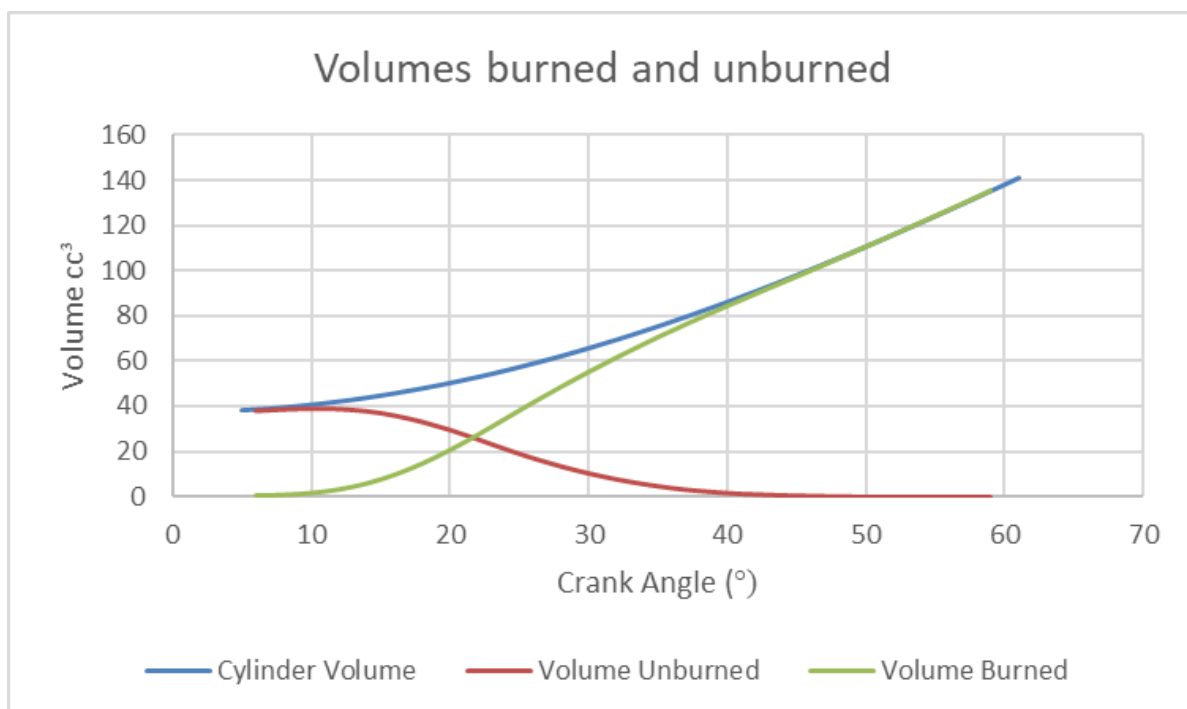
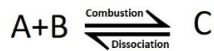


Figure 45 Volumes Cylinder, Burned and Unburned

Chapter 7 Dissociation

Dissociation is an equilibrium process that causes the products that would be obtained from complete combustion to dissociate or break down partially towards their reactants, this gives reversibility to the combustion reaction at temperatures of 1800K and above as shown in Equation 34.



Equation 34 Principal of Dissociation

As the engine was tested using a Hydrocarbon fuel C_8H_{18} there are numerous products from the combustion process. At sub 1000K CO_2 , H_2O , N_2 , O_2 , and H_2 , the exact concentrations will depend on variables, such as, temperature and the fuel air ratio; as the Ford Fox runs rich through much of the engine range, it is creating carbon monoxide, due to a shortage of oxygen in the cylinder prohibiting all of the carbon from converting to carbon dioxide. However, above 1000K additional species are produced such as OH, NO, H, CO, C, CH_4 , O_3 , and O. NO or NO_x has a very slow decomposition rate below 2000K a state known as frozen. This is an issue as dissociation is desirable in the creation of reverse reactions but the creation of NO_x is undesirable, the ultimate measure of which is the aim of the model (Goodger, 2000) (Glassman & Yetter, 2008) (Kirkpatrick, n.d.) (Heywood, 1988).

Partial pressure equilibrium constants are the determination of the point at which combustion and dissociation are exactly balanced, occurring at specific constant high temperatures also known as dynamic equilibrium. In this condition the reactants and products coexist in constant proportions.

The charge is a mixture of gases, each gas has a partial pressure this ideally equals the number of atoms or molecules, which assumes a hypothetical volume containing only that gas at a constant temperature; the sum of these pressures in an ideal gas mix is the total pressure of the charge. This is calculated using Equation 35.

$$\frac{\text{mol } X}{n_T} \times p = \text{Partial Pressure}$$

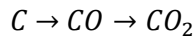
Equation 35 Partial Pressure

mol X= Number of molecules in the gas

P = Pressure

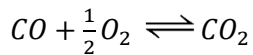
n_t = Number of molecules in total in the charge

Carbon oxidation occurs in two stages



Equation 36 First stage Carbon Oxidation

The second stage occurring at high temperatures dissociates as: -

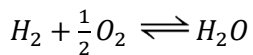


Equation 37 Second stage Carbon Oxidation

$$\frac{p_{CO_2}}{p_{CO}(p_{O_2})^{\frac{1}{2}}} = K_{CO_2} = \frac{n_{CO_2}}{n_{CO}(p_{O_2})^{\frac{1}{2}}}$$

Equation 38 Equilibrium Constant CO_2

Hydrogen oxidises in a similar fashion

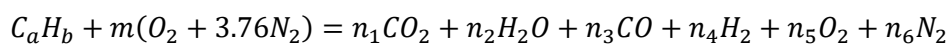


Equation 39 Hydrogen Oxidation

$$\frac{p_{H_2O}}{p_{H_2}(p_{O_2})^{\frac{1}{2}}} = K_{H_2O} = \frac{n_{H_2O}}{n_{H_2}(p_{O_2})^{\frac{1}{2}}}$$

Equation 40 Equilibrium Constant H_2O

Given these dissociative formulas and the data shown in Table 28 it possible to determine the product concentrations from first principals using the following iterative steps laid out by Goodger. Although, dissociation at higher temperatures proceeds further to create radicals, the author has followed Goodger with a first approximation by only considering dissociation restricted to CO, H_2 , and O_2 , which gives the general equation for any mixture strength (Equation 41).



Equation 41 Combustion Equation for any general mixture strength

Table 28 Partial pressure Equilibrium constants for oxidation reaction $\text{atm}^{-0.5}$ (Goodger, 2000)

Temperature	K _{CO2}	K _{H2O}	K _{H2}
K	$\text{atm}^{-0.5}$	$\text{atm}^{-0.5}$	$\text{atm}^{-0.5}$
298.15	1.1641E+45	1.1169E+40	9.5945E-06
300	5.7544E+44	6.1094E+39	0.000010617
500	1.0593E+25	7.6913E+22	0.0072607
1000	16634000000	11353000000	0.6935
1500	207010	530880	2.5645
2000	765.6	3467	4.5285
2100	345.94	1686.6	4.8754
2200	168.27	874.98	5.1999
2300	87.097	480.84	5.5207
2400	47.753	277.43	5.8097
2500	27.543	167.49	6.081
2700	10.351	68.077	6.5769
3000	3.0549	22.029	7.211

The solution for Equation 41 by iteration on values of $\frac{n_5}{n_t}$ is outlined in Appendix 15 for C, H, O and N are provided by molar balances the remaining two equations are derived from the values in Table 28 dependant on temperature using Equation 42 and Equation 43 with the process laid out in Appendix 15 the product concentrations can be determined.

$$K_{CO_2} = \frac{n_1}{n_3 \left(P \frac{n_5}{n_t} \right)^{\frac{1}{2}}}$$

Equation 42

$$K_{H_2O} = \frac{n_2}{n_4 \left(P \frac{n_5}{n_t} \right)^{\frac{1}{2}}}$$

Equation 43

Table 28 gives the values at temperature intervals, as all the values are likely to be between these values a linear interpolation model, as used to calculate actual torque in Table 5 was initially considered. However, this was likely to introduce a large margin of error into an equation that was already producing an approximation. Therefore, the author took a polynomial approach to the data to provide a formula to interpolate accurate values between those given. Initially it was hoped a single polynomial would suffice, but as Figure 46 clearly shows it was not going to give accurate results, it would in fact be less accurate than a linear interpolation.

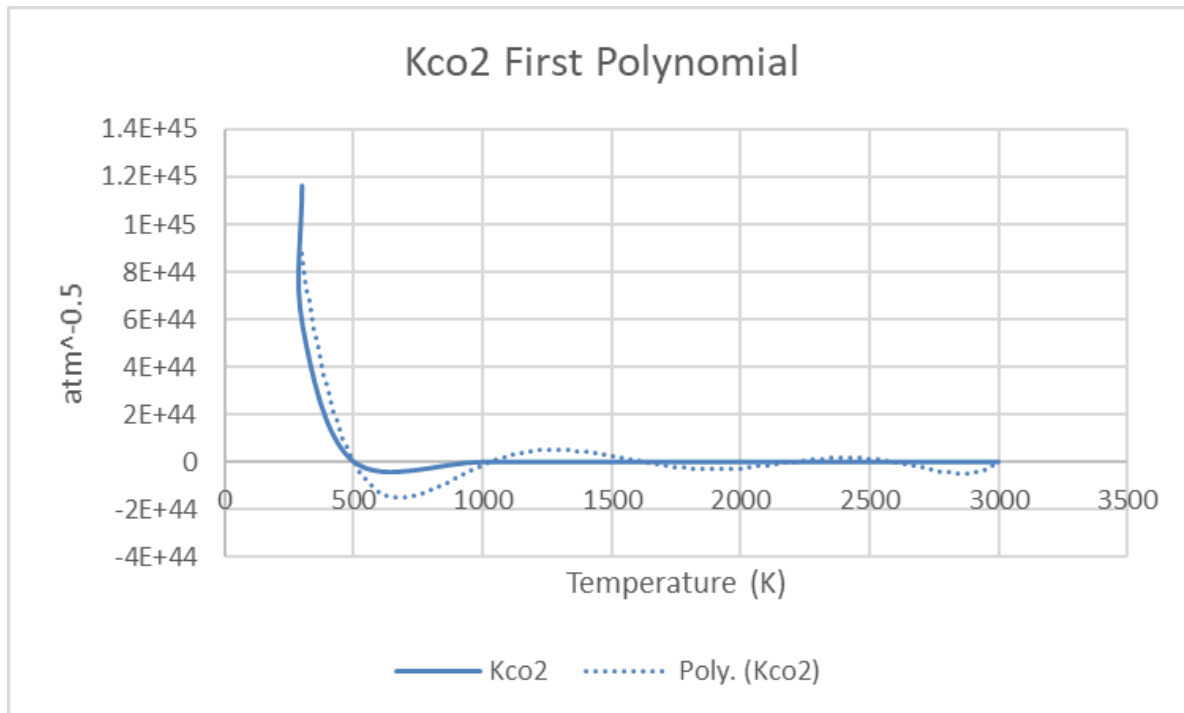


Figure 46 KCO_2 First polynomial

Therefore, after some experimentation the author settled on breaking the data up into three different polynomials the first from 1500K-2000K (Figure 47) the second from 2000K-2700K (Figure 48) the third from 2700K-3000K (Figure 49). The three graphs for $K H_2O$ are shown in Appendix 16. Using the polynomials from the graphs the values for $K CO_2$ and $K H_2O$ were calculated at all engine speeds and at every temperature throughout the combustion process, an example of 3000RPM is shown in Table 29.

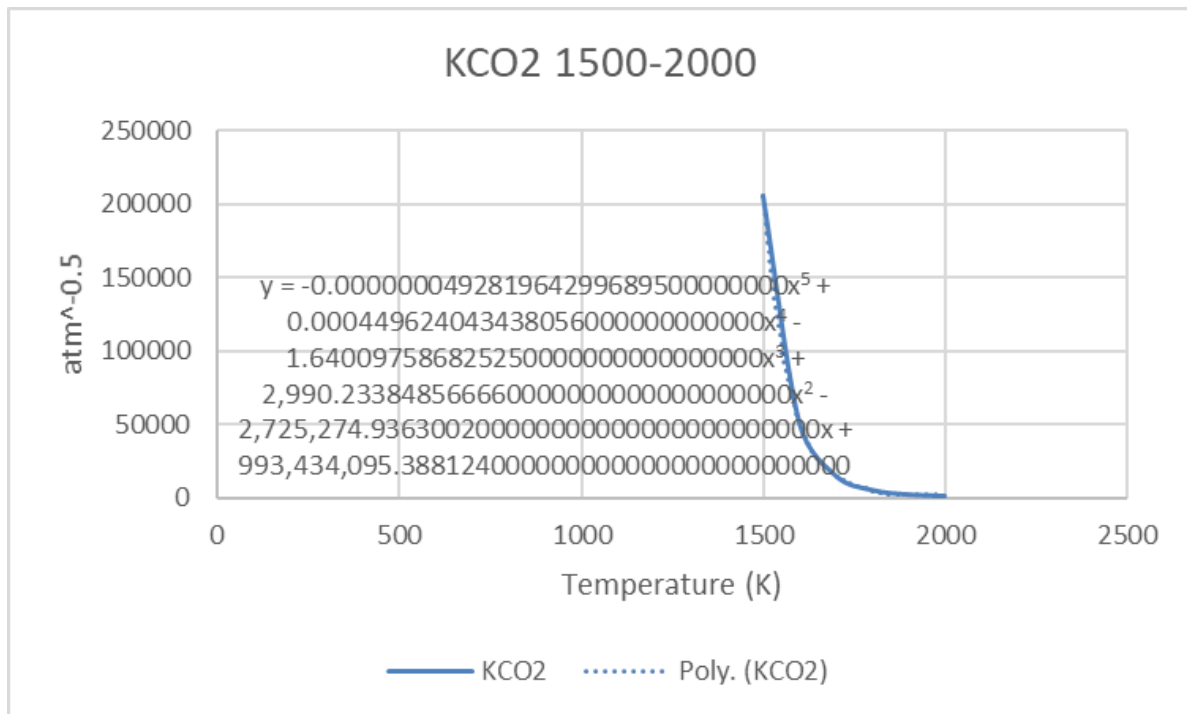


Figure 47 KCO₂ Polynomial 1500K-2000K

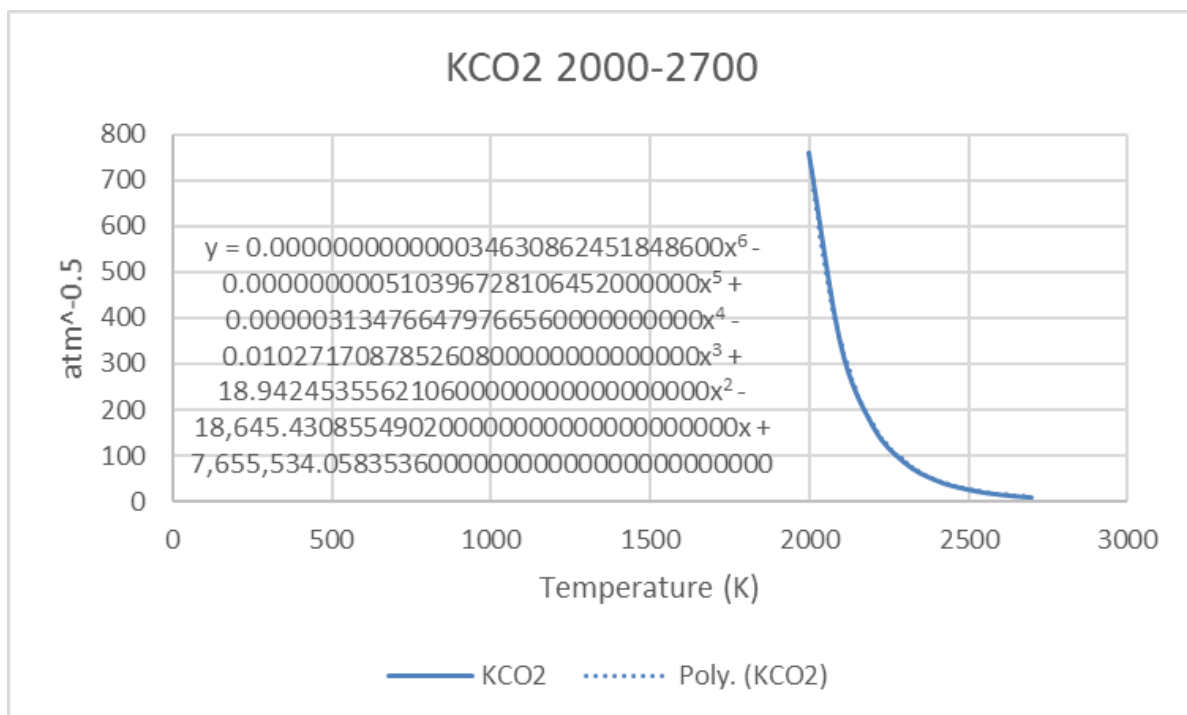


Figure 48 KCO₂ Polynomial 2000K-2700K

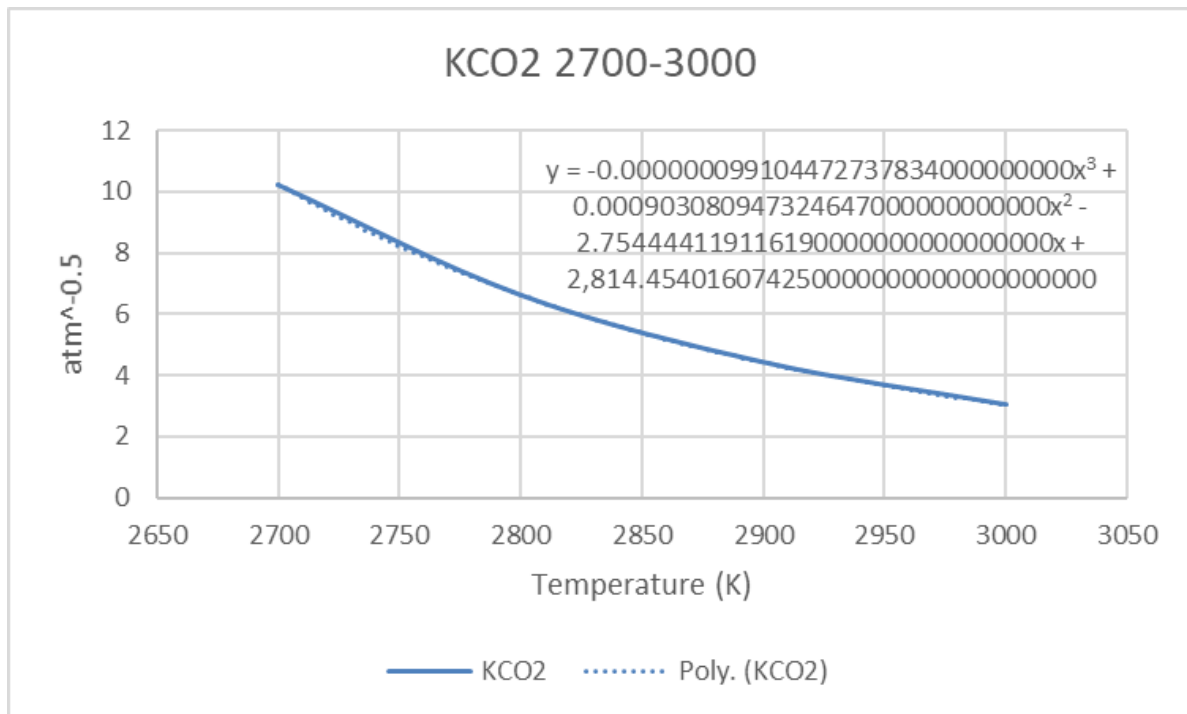


Figure 49 KCO₂ Polynomial 2700K-3000K

To ensure as much accuracy as possible the polynomial had to be set to a sixth order with thirty decimal places; even with this the polynomial can be seen deviating slightly from the line in all three graphs. Applying the polynomials as dictated by the temperatures in Table 29, the values highlighted by a yellow border use the polynomials from 1500K-2000K. The temperature then jumps above 2000K, thus, the polynomial for 2000K-2700K was applied thereafter, at no point does the temperature at any engine speed go above 2700K so the third polynomial was not needed.

Table 29 also has no values recorded for the first 8° of crank angle from SOC, this is because the temperature is very sensitive to the MFB value and any small error is compounded. The first temperature of 7288.02K clearly illustrates this point. Therefore, the first value is taken at 13° crank angle where the temperature has reached reasonable levels and starts to rise just after that point.

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Table 29 K CO₂ and K H₂O

Crank Angle	V_ABS	CYLPR1	MFB	Corrected Temperature	T un	Yun	T B	Kco2	K H2O
deg	cm ³	bar		K	K		K	atm ^{-0.5}	atm ^{-0.5}
5	37.88	49.913	0	701.4424484	699.6875916	1.29387408			
6	38.24	49.365	0.000370172	700.3343448	697.7729023	1.294115686	7288.023809		
7	38.66	48.773	0.001129545	699.5354362	695.9341045	1.294348306	3720.103278		
8	39.15	48.21	0.003112863	700.2244931	694.1603064	1.294573252	2529.463489		
9	39.71	47.672	0.006220113	702.3145396	692.6705223	1.294762595	2146.531137		
10	40.33	47.224	0.010901957	706.5768304	691.461486	1.294916535	1984.921742		
11	41.01	46.863	0.017092318	712.9979093	690.7815458	1.295003217	1898.100527		
12	41.76	46.661	0.025624756	722.9078354	690.6364798	1.295021721	1853.208449		
13	42.57	46.618	0.036343435	736.2506441	691.1555671	1.294955525	1829.818134	3244.943825	13433.75268
14	43.44	46.772	0.049627593	753.7792145	692.4473111	1.294790997	1818.651867	3795.438999	15180.11866
15	44.38	47.157	0.065961351	776.4292117	694.4169285	1.294540675	1818.64621	3795.737985	15181.05968
16	45.38	47.749	0.084995349	803.8910105	697.1973121	1.29418844	1824.648925	3489.793288	14214.49261
17	46.44	48.595	0.107232648	837.2442961	700.6511961	1.293752725	1835.815007	2983.33902	12588.64176
18	47.55	49.663	0.13227222	876.0963516	704.8619171	1.293224308	1851.282799	2426.024282	10715.16839
19	48.73	50.991	0.160794803	921.8459256	709.7037564	1.292620475	1869.989682	1990.92876	9048.069345
20	49.97	52.554	0.192479543	974.2794138	715.2064876	1.291939163	1892.4037	1814.961223	7887.736791
21	51.27	54.378	0.227645486	1034.32006	721.2093732	1.291201953	1917.414553	1987.604393	7487.865581
22	52.62	56.427	0.265870434	1101.555048	727.5888397	1.290425428	1946.13583	2358.626864	7544.899881
23	54.03	58.674	0.307068138	1176.113037	734.1454245	1.289634831	1977.891194	2135.137268	6520.869056
24	55.5	61.06	0.350693178	1257.23998	740.6684366	1.288855855	2012.84924	684.2980981	3150.393892
25	57.03	63.513	0.396049521	1343.799263	746.8536523	1.288124232	2050.583904	504.890267	2390.827036
26	58.61	65.914	0.441809274	1433.236267	752.7090993	1.287437934	2090.75824	368.4340414	1797.464829
27	60.24	68.256	0.487867808	1525.436722	758.1600297	1.286804595	2129.929364	274.0963311	1374.995442
28	61.93	70.498	0.533907442	1619.743614	763.1410408	1.28623055	2169.059987	206.5788722	1063.51932
29	63.67	72.6	0.579334448	1714.904226	767.5868222	1.285721986	2207.810076	158.0271326	833.093501
30	65.46	74.52	0.623657489	1809.744424	771.4935856	1.285278046	2245.943645	122.628163	660.8125558
31	67.31	76.242	0.666768103	1903.891833	774.7640786	1.284908546	2282.801099	96.67329655	531.7990049
32	69.2	77.709	0.707730212	1995.013389	777.4491854	1.284606642	2318.96945	76.96323947	432.042586
33	71.14	78.931	0.746677607	2083.194719	779.4153438	1.284386409	2352.79734	62.4606483	357.3918794
34	73.13	79.836	0.782780994	2166.021399	780.7515272	1.284237145	2386.006225	51.14710633	298.1023004
35	75.17	80.456	0.816239108	2243.734095	781.3199608	1.284173745	2415.930375	42.97302347	254.3950199
36	77.26	80.721	0.846232114	2313.713802	781.2278393	1.284184015	2444.818253	36.572242	219.4163841
37	79.38	80.678	0.872853608	2375.935344	780.3582773	1.284281041	2469.495766	32.05316514	194.1925399
38	81.56	80.273	0.895823185	2428.930627	778.8533401	1.284449288	2492.484599	28.47595143	173.8785605
39	83.77	79.576	0.91535657	2473.084869	776.7364279	1.284686654	2510.405529	26.02516021	159.8072521
40	86.03	78.604	0.931767806	2508.782259	774.0774318	1.284985962	2525.000561	24.20333554	149.3017663
41	88.33	77.397	0.945255571	2536.300794	770.981463	1.285336083	2535.674885	22.95158659	142.0840505
42	90.67	76.011	0.956315797	2556.868907	767.4884951	1.285733195	2542.330066	22.20035302	137.7607804
43	93.05	74.472	0.965161397	2570.856257	763.7767283	1.286157613	2545.964349	21.7985541	135.4528578
44	95.46	72.865	0.972516599	2580.529328	759.8017169	1.2866149	2545.46231	21.85372262	135.7695284
45	97.91	71.176	0.978330075	2585.407642	755.7040442	1.287089291	2543.776407	22.0397663	136.837949
46	100.4	69.469	0.98323315	2587.576272	751.472512	1.287582357	2539.035549	22.56964176	139.8848423
47	102.92	67.742	0.987128075	2586.581649	747.1859625	1.288085118	2533.246033	23.23109268	143.6946298
48	105.48	66.029	0.990451366	2583.885359	742.8578907	1.288596092	2525.684037	24.12129927	148.8284816
49	108.06	64.336	0.993128965	2579.214246	738.3446316	1.289132495	2517.194997	25.16033296	154.8224924
50	110.68	62.609	0.994791261	2570.835674	733.8432718	1.289671098	2509.12874	26.19142122	160.7647288
51	113.32	60.925	0.996081073	2561.359296	729.3317004	1.290214531	2497.707927	27.73430746	169.6313377
52	116	59.275	0.99707449	2550.926538	724.8903096	1.290753026	2486.237603	29.39542688	179.1283089
53	118.7	57.687	0.997951064	2540.370572	720.4478325	1.291295128	2473.65146	31.36539973	190.310566
54	121.42	56.134	0.998478814	2528.626115	716.0977493	1.291829309	2461.61483	33.41254203	201.8312784
55	124.18	54.647	0.99911335	2517.597975	711.7515185	1.292366319	2448.679304	35.81238504	215.2084928
56	126.95	53.194	0.999398603	2505.323166	707.4699324	1.292898554	2436.488885	38.28435674	228.8515411
57	129.75	51.794	0.999661843	2493.189097	703.2433592	1.293427065	2423.557773	41.15264534	244.5255074
58	132.57	50.442	0.999830985	2480.88112	699.0965767	1.29394859	2410.76754	44.26259738	261.353381
59	135.4	49.144	0.999950582	2468.638891	694.9969535	1.294467085	2397.75213	47.73130896	279.9468231

This was an uncommon approach normally the values were calculated in ranges as shown in Figure 50 and Table 30.

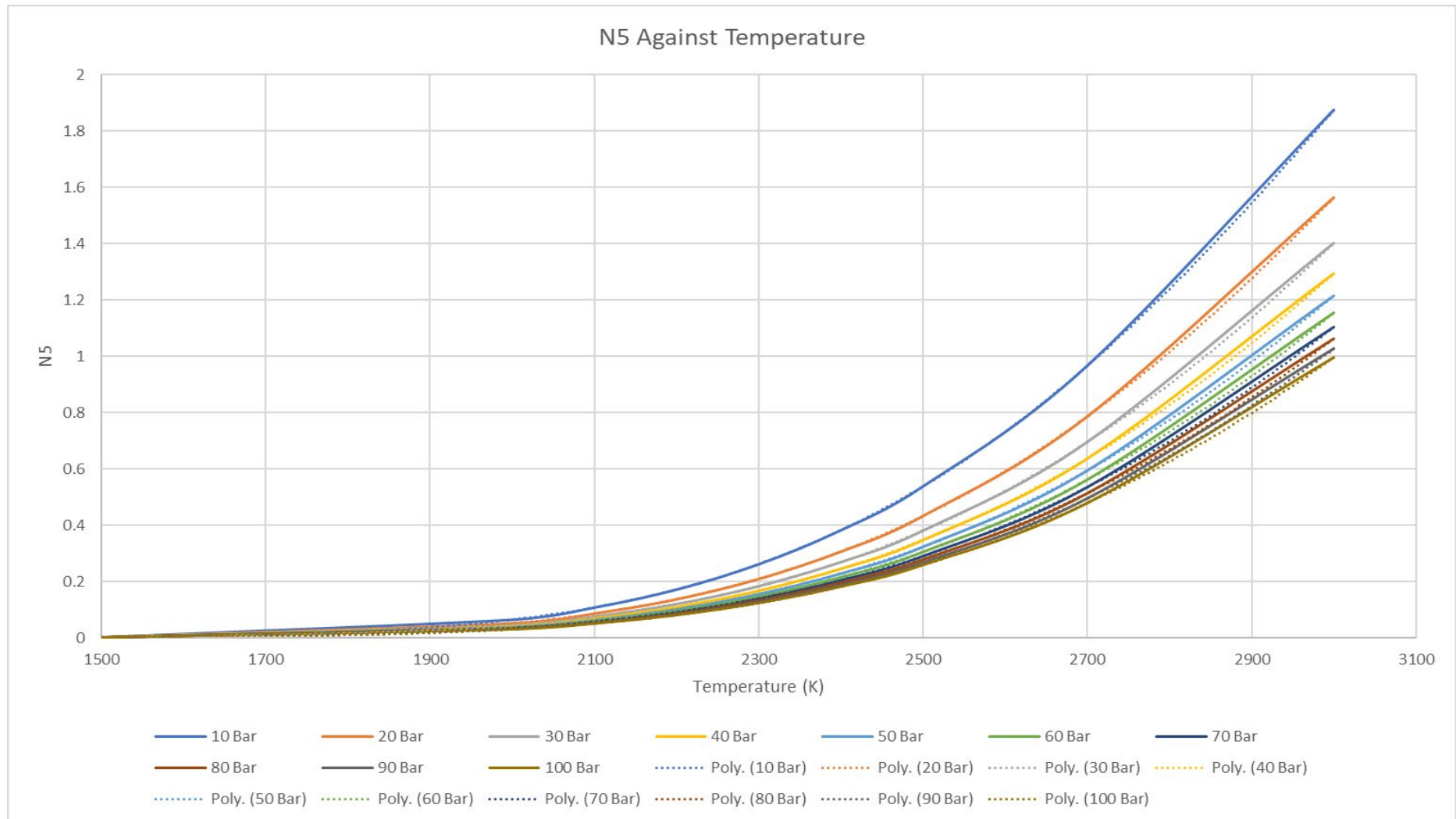


Figure 50 N5 Values against temperature

UWTSW Swansea BEng Motorcycle Engineering Programme

Table 30 Standard Stoichiometric Dissociation model

	Temperature	Guessed			Working									Calculated	Error Guessed
		N5/NT	(N5/NT)*P	((N5/NT)*P) ^{^0.5}	(N1/N3)	N3	N1	N2/N4	N4	N2	N6	N5	NT	N5/NT	Error Guessed calculated
10 Bar	1500	2.65503E-05	0.000265503	0.016294252	3373.073032	0.002371022	7.997628978	8650.292311	0.001040307	8.998959693	47	0.001705664	64.00170566	2.66503E-05	0.000000100030729
	2000	0.001004634	0.010046342	0.100231444	76.73719334	0.102910842	7.897089158	347.5024155	0.025824785	8.974175215	47	0.064367813	64.06436781	0.001004737	0.000000102342142
	2100	0.001680478	0.016804778	0.129633243	44.84532424	0.174499802	7.825500198	218.6394284	0.040976249	8.959023751	47	0.107738026	64.10773803	0.001680578	0.000000099775496
	2200	0.002672982	0.026729823	0.163492577	27.51089593	0.280594479	7.719405521	143.052735	0.06247712	8.93752288	47	0.1715358	64.1715358	0.002673082	0.000000100074822
	2300	0.004067398	0.040673985	0.201677924	17.56554214	0.430905811	7.569094189	96.97481293	0.091860344	8.908139656	47	0.261383078	64.26138308	0.004067498	0.00000009975216
	2400	0.0059362	0.059361995	0.243643172	11.63469238	0.633177268	7.366822732	67.59392513	0.131206954	8.868793046	47	0.382192111	64.38219211	0.005936302	0.000000102102668
	2500	0.0083359	0.083358998	0.288719584	7.95220349	0.893634736	7.106365264	48.35764305	0.18234258	8.81765742	47	0.537988658	64.53798866	0.008336	0.000000099968901
	2700	0.014874696	0.148746964	0.385677279	3.992145515	1.60251739	6.39748261	26.25575212	0.330205527	8.669794473	47	0.966361459	64.96636146	0.014874797	0.000000100955013
	3000	0.028450601	0.284506013	0.53339105	1.62945632	3.042454039	4.957545961	11.75007145	0.705878397	8.294121603	47	1.874166218	65.87416622	0.028450701	0.000000099914397
20 Bar	1500	2.10601E-05	0.000421202	0.020523197	4248.506982	0.001882571	7.998117429	10895.35475	0.000825964	8.999174036	47	0.001354268	64.00135427	2.116E-05	0.000000099906344
	2000	0.000798667	0.015973331	0.126385644	96.76084872	0.08183235	7.91816765	438.1790263	0.020492782	8.979507218	47	0.051162566	64.05116257	0.000798777	0.000000109994821
	2100	0.001337518	0.026750359	0.163555369	56.58034445	0.1389363	7.8610637	275.8524858	0.032508287	8.967491713	47	0.085722293	64.08572229	0.001337619	0.000000101270193
	2200	0.002131172	0.042623442	0.206454455	34.74009117	0.223838265	7.776161735	180.6435192	0.049547598	8.950452402	47	0.136692931	64.13669293	0.002131275	0.000000102914384
	2300	0.003251039	0.065020784	0.254991734	22.20901503	0.344693646	7.655306354	122.6102252	0.072809511	8.927190489	47	0.208751578	64.20875158	0.003251139	0.000000099813763
	2400	0.004760917	0.095218345	0.3085747	14.73536764	0.508408839	7.491591161	85.60787898	0.103916643	8.896083357	47	0.306162741	64.30616274	0.004761017	0.000000099838673
	2500	0.006715344	0.134306876	0.366479025	10.09393178	0.721114944	7.278885056	61.38157189	0.144273376	8.855726624	47	0.43269416	64.43269416	0.006715444	0.000000100383340
	2700	0.012134032	0.24268063	0.492626258	5.099174398	1.311652935	6.688347065	33.53651777	0.26059373	8.73940627	47	0.786123333	64.78612333	0.012134131	0.000000099878214
	3000	0.023850629	0.477012578	0.690660972	2.109900204	2.572429813	5.427570187	15.21457056	0.555056328	8.444943672	47	1.563743071	65.56374307	0.023850729	0.000000100115337
30 Bar	1500	1.83874E-05	0.000551622	0.023486627	4861.966737	0.001645086	7.998354914	12468.58075	0.000721756	8.999278244	47	0.001183421	64.00118342	1.84906E-05	0.000000103228058
	2000	0.000698253	0.020947597	0.144732846	110.8074671	0.071551572	7.928448428	501.788778	0.017900161	8.982099839	47	0.044725866	64.04472587	0.000698354	0.000000100395969
	2100	0.001170016	0.03510047	0.187351194	64.81227199	0.121557876	7.878442124	315.9865235	0.028392374	8.971607626	47	0.074975125	64.07497513	0.001170116	0.000000099894945
	2200	0.001865865	0.055975949	0.236592369	39.81139787	0.19602367	7.80397633	207.0135907	0.043266404	8.956733596	47	0.119645037	64.11964504	0.001865965	0.000000100403978
	2300	0.002849798	0.085493934	0.292393457	25.46659291	0.302267845	7.697732155	140.5944698	0.063561804	8.936438196	47	0.182914825	64.18291482	0.002849899	0.000000101210087
	2400	0.004180314	0.125409429	0.354131938	16.91086243	0.446656326	7.553343674	98.24682352	0.090683003	8.909316997	47	0.268669664	64.26866966	0.004180414	0.000000099964486
	2500	0.005909391	0.177281725	0.421048364	11.59693509	0.635075115	7.364924885	70.52139046	0.12583648	8.87416352	47	0.380455797	64.3804558	0.005909492	0.000000101315261
	2700	0.010744928	0.322347854	0.567756861	5.876851272	1.163323109	6.836676891	38.65118385	0.226979352	8.773020648	47	0.69515123	64.69515123	0.010745028	0.000000099837374
	3000	0.021420814	0.642624422	0.801638586	2.448925716	2.319562861	5.680437139	17.65929641	0.482333299	8.517666701	47	1.40094808	65.40094808	0.021420914	0.000000099858318
40 Bar	1500	1.67022E-05	0.000668087	0.025847371	5350.664323	0.001494862	7.998505138	13721.85245	0.00065584	8.99934416	47	0.001075351	64.00107535	1.68021E-05	0.000000099915116
	2000	0.000634719	0.025388772	0.159338546	121.9895912	0.065046155	7.934953845	552.4267407	0.016262315	8.983737685	47	0.040654235	64.04065423	0.000634819	0.000000099859983
	2100	0.001063936	0.042557425	0.206294511	71.36552326	0.110549881	7.889450119	347.9363229	0.025792672	8.974207328	47	0.068171276	64.06817128	0.001064043	0.000000107165641
	2200	0.001697619	0.067904759	0.260585417	43.84870809	0.17837749	7.82162251	228.007028	0.039300104	8.960699896	47	0.108838797	64.1088388	0.001697719	0.000000100068059
	2300	0.002594841	0.103793658	0.322170231	28.06006065	0.275291924	7.724708076	154.9123341	0.057724747	8.942275253	47	0.166508335	64.16650834	0.002594941	0.000000100047377
	2400	0.003810369	0.152414747	0.390403314	18.64292943	0.407271228	7.592728772	108.3095913	0.082334952	8.917665048	47	0.24480309	64.24480309	0.003810473	0.0000001004364268
	2500	0.005393997	0.215759887	0.464499609	12.79371273	0.579974381	7.420025619	77.7990395	0.11421459	8.88578541	47	0.347094486	64.34709449	0.005394097	0.000000100085168
	2700	0.009847346	0.393893842	0.627609626	6.496387237	1.06718073	6.93281927	42.72578049	0.20582823	8.79417177	47	0.63650448	64.63650448	0.009847446	0.000000099820158
	3000	0.019813542	0.792541667	0.890248093	2.719618899	2.150757972	5.849242028	19.61127524	0.436654205	8.563345795	47	1.293706088	65.29370609	0.019813642	0.000000099881553

UWTSD Swansea BEng Motorcycle Engineering Programme

	Temperature	Guessed			Working									Calculated	Error Guessed calculated
		N5/NT	(N5/NT)*P	((N5/NT)*P) ^0.5	(N1/N3)	N3	N1	N2/N4	N4	N2	N6	N5	NT	N5/NT	
50 Bar	1500	1.55002E-05	0.000775012	0.02783904	5762.959724	0.001387935	7.998612065	14779.18969	0.000608923	8.999391077	47	0.000998429	64.00099843	1.56002E-05	0.000000099965905
	2000	0.000589428	0.029471404	0.171672373	131.4323685	0.060408192	7.939591808	595.188116	0.015095906	8.984904094	47	0.037752049	64.03775205	0.000589528	0.000000099953106
	2100	0.000988276	0.049413799	0.222292147	76.89974542	0.102696099	7.897303901	374.9179355	0.023941396	8.976058604	47	0.063318747	64.06331875	0.000988378	0.000000101598356
	2200	0.001577498	0.078874918	0.280846787	47.25808886	0.165775317	7.834224683	245.7353217	0.036476334	8.963523666	47	0.101125826	64.10112583	0.001577598	0.000000099921916
	2300	0.002412571	0.120628526	0.347316176	30.25019695	0.255998387	7.744001613	167.0035099	0.053570309	8.946429691	47	0.154784348	64.15478435	0.00241267	0.000000099863997
	2400	0.003545412	0.177270594	0.421035145	20.1056913	0.37904468	7.62095532	116.8077804	0.076395633	8.923604367	47	0.227720157	64.22772016	0.003545512	0.000000100188916
	2500	0.005023967	0.25119835	0.501196917	13.80446669	0.540377453	7.459622547	83.94547168	0.105950321	8.894049679	47	0.323163887	64.32316389	0.005024067	0.000000100030305
	2700	0.00919841	0.4599205	0.678174387	7.019783084	0.997533215	7.002466785	46.16807777	0.190807012	8.809192988	47	0.594170113	64.59417011	0.00919851	0.000000099907082
	3000	0.018632719	0.931635932	0.965212895	2.948628872	2.02601973	5.97398027	21.26267486	0.40426409	8.59573591	47	1.21514191	65.21514191	0.018632819	0.000000099969258
60 Bar	1500	1.45794E-05	0.000874767	0.029576454	6122.62168	0.001306416	7.998693584	15701.54774	0.000573155	8.999426845	47	0.000939786	64.00093979	1.46839E-05	0.000000104495765
	2000	0.000554821	0.033289237	0.182453384	139.6863105	0.056864097	7.943135903	632.5658809	0.01420531	8.98579469	47	0.035534704	64.0355347	0.000554922	0.000000101016451
	2100	0.000930437	0.055826209	0.236275705	81.73721723	0.096691674	7.903308326	398.5026033	0.022528013	8.977471987	47	0.059609843	64.05960984	0.000930537	0.000000100289414
	2200	0.001485606	0.089136344	0.298557104	50.23820385	0.156133498	7.843866502	261.2314947	0.03432082	8.96567918	47	0.095227159	64.09522716	0.001485714	0.000000107995091
	2300	0.002273004	0.136380268	0.369296992	32.1646601	0.241220624	7.758779376	177.5727656	0.050399623	8.949600377	47	0.145810123	64.14581012	0.002273104	0.000000099930944
	2400	0.003342257	0.200535443	0.447811839	21.38435877	0.357392413	7.642607587	124.2364386	0.071864068	8.928135932	47	0.214628241	64.21462824	0.003342357	0.000000100055326
	2500	0.004739744	0.284384629	0.533277253	14.68805538	0.509942106	7.490057894	89.31860714	0.099647241	8.900352759	47	0.304794673	64.30479467	0.004739844	0.000000099847481
	2700	0.008697376	0.521842554	0.722386707	7.477424804	0.943682803	7.056317197	49.17791985	0.17936176	8.82063824	47	0.561522281	64.56152228	0.008697476	0.000000099949592
	3000	0.017709994	1.062599615	1.030824726	3.149066454	1.928144581	6.071855419	22.70803788	0.379618088	8.620381912	47	1.153881334	65.15388133	0.017710094	0.000000099981072
70 Bar	1500	1.38489E-05	0.000969421	0.031135529	6445.365785	0.001241009	7.998758991	16529.22945	0.000544457	8.999455543	47	0.000892733	64.00089273	1.39488E-05	0.000000099887956
	2000	0.000527145	0.036900125	0.192094053	147.0672068	0.054029519	7.945970481	665.9900811	0.013493454	8.986506546	47	0.033761487	64.03376149	0.000527245	0.000000100449919
	2100	0.000884164	0.061891472	0.248779967	86.06294187	0.091887545	7.908112455	419.5922927	0.021398395	8.978601605	47	0.05664297	64.05664297	0.000884264	0.000000099905364
	2200	0.001412058	0.098844081	0.314394786	52.90321061	0.148414165	7.851585835	275.0891497	0.032598166	8.967401834	47	0.090506166	64.09050617	0.001412162	0.000000103512609
	2300	0.002161202	0.151284149	0.38895263	33.87660725	0.22938011	7.77061989	187.0239828	0.047866234	8.952133766	47	0.138623172	64.13862317	0.002161306	0.000000103579006
	2400	0.003179348	0.222554393	0.471756709	22.52779815	0.340023318	7.659976682	130.8794639	0.068244135	8.931755865	47	0.204133727	64.20413373	0.003179448	0.000000099877089
	2500	0.004511507	0.315805522	0.561965765	15.47822308	0.48548924	7.51451076	94.12364605	0.094613699	8.905386301	47	0.290051469	64.29005147	0.004511607	0.000000099910908
	2700	0.008293404	0.580538277	0.761930625	7.886743898	0.900217233	7.099782767	51.86995115	0.170229021	8.829770979	47	0.535223127	64.53522313	0.008293504	0.000000099971788
	3000	0.016958904	1.187123269	1.089551866	3.328471996	1.848227275	6.151772725	24.00173806	0.359974974	8.640025026	47	1.104101124	65.10410112	0.01695901	0.000000106501260
80 Bar	1500	1.32431E-05	0.001059446	0.032549133	6737.996087	0.00118712	7.99881288	17279.68389	0.000520813	8.999479187	47	0.000853967	64.00085397	1.3343E-05	0.000000099973792
	2000	0.000504284	0.040342745	0.200855034	153.7746137	0.051688063	7.948311937	696.3644014	0.012905735	8.987094265	47	0.032296899	64.0322969	0.000504385	0.000000100207250
	2100	0.000845932	0.067674528	0.260143283	89.99396729	0.087917916	7.912082084	438.7576609	0.020465817	8.979534183	47	0.054191867	64.05419187	0.000846032	0.000000099948834
	2200	0.001351264	0.108101121	0.328787349	55.32504724	0.142032726	7.857967274	287.6823547	0.031176135	8.968823865	47	0.08660443	64.08660443	0.001351366	0.000000101552786
	2300	0.002068734	0.165498718	0.406815337	35.43239539	0.219584793	7.780415207	195.6130866	0.045775183	8.954224817	47	0.132679988	64.13267999	0.002068836	0.000000101878476
	2400	0.003044492	0.243559337	0.493517312	23.5669322	0.325640985	7.674359015	136.9165078	0.065256873	8.934743127	47	0.195448929	64.19544893	0.003044592	0.000000099953201
	2500	0.004322358	0.345788628	0.588037947	16.19632919	0.465215565	7.534784435	98.49047581	0.09046092	8.90953908	47	0.277838243	64.27783824	0.004322458	0.000000099946239
	2700	0.007957502	0.636600172	0.797872278	8.258775951	0.864045101	7.135954899	54.31675108	0.16269936	8.83730064	47	0.51337223	64.51337223	0.00795761	0.000000107450684
	3000	0.016329491	1.306359287	1.142960755	3.49163081	1.781090285	6.218909715	25.17828247	0.343796428	8.656203572	47	1.062443357	65.06244336	0.016329595	0.000000104019731

	Temperature	Guessed			Working									Calculated	Error Guessed calculated
		N5/NT	(N5/NT)*P	((N5/NT)*P) ^0.5	(N1/N3)	N3	N1	N2/N4	N4	N2	N6	N5	NT	N5/NT	
90 Bar	1500	1.2727E-05	0.001145434	0.033844267	7006.101776	0.001141699	7.998858301	17967.24463	0.000500884	8.999499116	47	0.000821291	64.00082129	1.28325E-05	0.000000105461861
	2000	0.000484941	0.043644709	0.208913161	159.9439159	0.049706756	7.950293244	724.3019286	0.012408625	8.987591375	47	0.031057691	64.03105769	0.000485041	0.000000099832442
	2100	0.000813574	0.073221638	0.270594971	93.60962421	0.084557994	7.915442006	456.3854778	0.019677057	8.980322943	47	0.052117525	64.05211753	0.000813674	0.000000099968748
	2200	0.001299792	0.116981269	0.342025247	57.55258824	0.136629315	7.863370685	299.2652502	0.029973498	8.970026502	47	0.083301407	64.08330141	0.001299893	0.000000100675857
	2300	0.001990405	0.179136418	0.423245104	36.86337879	0.211285951	7.788714049	203.5131756	0.044006945	8.955993055	47	0.127646448	64.12764645	0.001990506	0.000000101091496
	2400	0.00293017	0.263715331	0.51353221	24.52270365	0.313446417	7.686553583	142.4692412	0.062731216	8.937268784	47	0.188088816	64.18808882	0.002930276	0.000000105658037
	2500	0.004161864	0.374567759	0.612019411	16.85685064	0.448007331	7.551992669	102.5071311	0.086950531	8.913049469	47	0.267478931	64.26747893	0.004161964	0.000000099966790
	2700	0.007671705	0.690453488	0.830935309	8.601011382	0.833245549	7.166754451	56.56758302	0.156337986	8.843662014	47	0.494791768	64.49479177	0.00767181	0.000000104259979
	3000	0.015790413	1.421137168	1.192114578	3.641790826	1.72347275	6.27652725	26.26109205	0.330140846	8.669859154	47	1.026806798	65.0268068	0.015790515	0.000000102482958
100 Bar	1500	1.22872E-05	0.001228725	0.03505317	7256.356733	0.00110233	7.99889767	18609.02692	0.00048361	8.99951639	47	0.00079297	64.00079297	1.239E-05	0.000000102755274
	2000	0.000468264	0.046826399	0.216394082	165.6713094	0.047998663	7.952001337	750.2382834	0.01198022	8.98801978	47	0.029989442	64.02998944	0.000468366	0.000000101566068
	2100	0.000785672	0.078567189	0.280298393	96.96642612	0.081660629	7.918339371	472.7512698	0.018997311	8.981002689	47	0.05032897	64.05032897	0.000785772	0.000000100339131
	2200	0.001255395	0.125539466	0.354315489	59.62066736	0.131968194	7.868031806	310.0189667	0.028937142	8.971062858	47	0.080452668	64.08045267	0.001255495	0.000000100031745
	2300	0.001922808	0.192280817	0.438498366	38.19189216	0.204123852	7.795876148	210.8475542	0.042483379	8.957516621	47	0.123303616	64.12330362	0.001922914	0.000000106104433
	2400	0.002831466	0.28314659	0.532115203	25.4100973	0.302914446	7.697085554	147.6247209	0.060555202	8.939444798	47	0.181734824	64.18173482	0.002831566	0.000000100197563
	2500	0.004023172	0.402317199	0.634284793	17.47010605	0.433132326	7.566867674	106.23636	0.083926758	8.916073242	47	0.258529542	64.25852954	0.004023272	0.000000100001542
	2700	0.007424144	0.742414394	0.861634722	8.918781009	0.806550724	7.193449276	58.65750698	0.150861148	8.849138852	47	0.478705936	64.47870594	0.007424249	0.000000104555718
	3000	0.015320805	1.532080486	1.237772389	3.78127087	1.673195311	6.326804689	27.26688795	0.318393734	8.681606266	47	0.995794522	64.99579452	0.015320907	0.000000102128758

These calculations are based on C_8H_{18} Isooctane fuel at $\phi = 1$. A table like this would be made for each FER and then many 'If' statements would be needed in the Excel to calculate the product concentrations for each RPM across all engines speeds. The method employed by the author removes the need for these tables and the FER at a given engine speed is incorporated into the process laid out in Appendix 15.

The process stated in Appendix 15 (Goodger, 2000), is expanded and applied by Equation 44 to Equation 54: -

Initially a value for $\frac{n_5}{n_t}$ is guessed at a value of 0.0000001:

$$\frac{n_5}{n_t} = 0.0000001$$

Equation 44 $\frac{n_5}{n_t}$ Guessed Value

This allows a basis for calculation, so the guessed value is multiplied:

$$\left(\left(\frac{n_5}{n_t} \right) \times P \right)^{\frac{1}{2}}$$

Equation 45 Guessed value times pressure

Therefore, the carbon balance can be found assuming the guessed value from Equation 44 is correct:

$$\frac{n_1}{n_3} = K CO_2 \times \left(\left(\frac{n_5}{n_t} \right) \times P \right)^{\frac{1}{2}}$$

Equation 46 $\frac{n_1}{n_t}$ Carbon Balance

From the carbon balance the carbon monoxide concentration can be calculated based on the value C_T (Appendix 12):

$$n_3 = \frac{C_T}{\left(\frac{n_1}{n_3} + 1 \right)}$$

Equation 47 Carbon Monoxide concentration

The carbon dioxide concentration can also be calculated from the carbon balance:

$$n_1 = C_T - n_3$$

Equation 48 Carbon Dioxide concentration

Repeating the process for hydrogen and water; the hydrogen balance can be found assuming the guessed value from Equation 44 is correct:

$$\frac{n_2}{n_4} = K H_2O \times \left(\left(\frac{n_5}{n_t} \right) \times P \right)^{\frac{1}{2}}$$

Equation 49 $\frac{n_2}{n_4}$ Hydrogen Balance

From the hydrogen balance the hydrogen concentration can be determined based on the value H_T (Appendix 12):

$$n_4 = \frac{H_T}{\left(\frac{n_2}{n_4} + 1\right)}$$

Equation 50 Hydrogen concentration

The water concentration can also be determined from the carbon balance:

$$n_2 = H_T - n_4$$

Equation 51 Water concentration

The oxygen concentration can be calculated as the values for n_1, n_2, n_3 have all been determined based on the value O_T (Appendix 12):

$$n_5 = \frac{O_T - 2n_1 - n_2 - n_3}{2}$$

Equation 52 Oxygen concentration

The nitrogen concentration is the value N_T (Appendix 12):

$$n_6 = N_T$$

Equation 53 Nitrogen Concentration

Therefore, all six n values have been calculated and can be added together to find n_t value; however, the logic is based on the guessed value from Equation 44:

$$n_t = n_1 + n_2 + n_3 + n_4 + n_5 + n_6$$

Equation 54 n Total

The initial value guessed in Equation 44 is unlikely to be correct, therefore, none of the values are correct; however, by adding another column to calculate $\frac{n_5}{n_t}$ an error calculation column can be added, by subtracting the calculated value for $\frac{n_5}{n_t}$ from the guessed value for $\frac{n_5}{n_t}$. This enables implementation of the Excel 'Goal Seek' function; this function will change the guessed value for $\frac{n_5}{n_t}$ until the difference reaches a specific threshold, which has been predetermined as 0.0000001. This process would have to run on every row at every engine speed, which is manually intensive to avoid this the author automated the process with a macro this is shown in Appendix 17. This enables changes to be made

to the earlier stages of the model, the macro can then be initiated and it will recalculate new values based on the changes. This macro was also used to calculate the values in Table 30 for the traditional method as a baseline comparison. The values were calculated across all engine speeds for every degree of crank angle through the combustion process. An example at 3000RPM is shown in Table 31.

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Table 31 3000RPM Dissociation

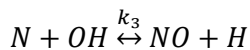
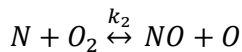
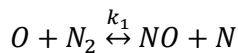
Crank Angle	V_ABS	CYLPR1	MFB	T B	Kco2	K H2O	N5/NT	(N5/NT)*P	((N5/NT)*P) ^0.5	(N1/N3)	N3	N1	N2/N4	N4	N2	N6	N5	NT	N5/NT	Error Guessed calculated
deg	cm³	bar		K	atm^0.5	atm^0.5		atm	atm^0.5		kmol	kmol		kmol	kmol	kmol	kmol	kmol		atm^0.5
5	37.88	49.913	0																	
6	38.24	49.365	0.000370172	7288.023809																
7	38.66	48.773	0.001129545	3720.103278																
8	39.15	48.21	0.003112863	2529.463489																
9	39.71	47.672	0.006220113	2146.531137																
10	40.33	47.224	0.010901957	1984.921742																
11	41.01	46.863	0.017092318	1898.100527																
12	41.76	46.661	0.025624756	1853.208449																
13	42.57	46.618	0.036343435	1829.818134	3244.943825	13433.75268	0.000233471	0.010883955	0.104326197	338.5326482	0.023561799	7.976438201	1401.492327	0.006417147	8.993582853	47.16	0.014989473	64.17498947	0.000233572	0.000000100792284
14	43.44	46.772	0.049627593	1818.651867	3795.438999	15180.11866	0.000211163	0.009876512	0.099380641	377.1931618	0.021153212	7.978846788	1508.609928	0.005961805	8.994038195	47.16	0.013557508	64.17355751	0.000211263	0.000000100241325
15	44.38	47.157	0.065961351	1818.64621	3795.737985	15181.05968	0.000210577	0.009930175	0.099650265	378.2462957	0.021094471	7.978905529	1512.796619	0.005945316	8.994054684	47.16	0.013519894	64.17351989	0.000210677	0.000000100233138
16	45.38	47.749	0.084995349	1824.648925	3489.793288	14214.49261	0.000221183	0.010561256	0.102767974	358.6389856	0.022244529	7.977755471	1460.794606	0.006156816	8.993843184	47.16	0.014200673	64.17420067	0.000221283	0.000000100423482
17	46.44	48.595	0.107232648	1835.815007	2983.33902	12588.64176	0.000242859	0.011801721	0.108635728	324.097205	0.024608025	7.975391975	1367.576257	0.006576177	8.993423823	47.16	0.015592101	64.1755921	0.00024296	0.000000101227800
18	47.55	49.663	0.13227222	1851.282799	2426.024282	10715.16839	0.000274939	0.013654296	0.116851597	283.4848123	0.028121009	7.971878991	1252.084541	0.007182277	8.992817723	47.16	0.017651643	64.17765164	0.000275043	0.000000104448922
19	48.73	50.991	0.160794803	1869.989682	1990.92876	9048.069345	0.000309652	0.015789446	0.125656062	250.1722687	0.03185065	7.96814935	1136.944767	0.007908995	8.992091005	47.16	0.019879823	64.17987982	0.000309752	0.000000100009138
20	49.97	52.554	0.192479543	1892.4037	1814.961223	7887.736791	0.000327993	0.01723737	0.131291165	238.2883735	0.034342464	7.966567536	1035.590153	0.008682313	8.991317687	47.16	0.021057389	64.18105739	0.000328094	0.000000100020060
21	51.27	54.378	0.227645486	1917.414553	1987.604393	7487.865581	0.000311683	0.016948724	0.130187265	258.7607801	0.030797567	7.969202433	974.8247414	0.008222968	8.990777032	47.16	0.020010267	64.18001027	0.000311783	0.000000100010063
22	52.62	56.427	0.265870434	1946.13583	2358.626864	7544.899881	0.000282179	0.015922539	0.126184545	297.6222586	0.026789698	7.973210302	952.0497616	0.009443368	8.990556632	47.16	0.018116533	64.17811653	0.000282285	0.000000105764016
23	54.03	58.674	0.307068138	1977.891194	2135.137268	6520.869056	0.000300063	0.017605912	0.132687271	283.3055382	0.028138741	7.971861259	865.2363226	0.010389774	8.989610226	47.16	0.019264258	64.17926426	0.000300163	0.000000100005926
24	55.5	61.06	0.350693178	2012.84924	684.2980981	3150.393892	0.000591993	0.036147076	0.190123843	130.1013841	0.061021476	7.938978524	598.9649931	0.015000875	8.984999125	47.16	0.038011176	64.19801118	0.000592093	0.000000100008763
25	57.03	63.513	0.396049521	2050.583904	504.890267	2390.827036	0.000712255	0.045237483	0.21269105	107.3856409	0.073810515	7.926189485	508.5075122	0.017664116	8.982335884	47.16	0.045737316	64.20573732	0.000712356	0.000000100103200
26	58.61	65.914	0.441809274	2090.75824	368.430414	1797.464829	0.000863585	0.056922323	0.238583996	87.90246603	0.089986255	7.910013745	428.8463425	0.020937715	8.979062285	47.16	0.055461985	64.21546198	0.000863686	0.000000101112543
27	60.24	68.256	0.487867808	2129.929364	274.0963311	1374.995442	0.001034587	0.070616762	0.265738145	72.83785048	0.108345516	7.891654484	365.3887377	0.024564074	8.975435926	47.16	0.066454795	64.22645479	0.001034695	0.000000108177839
28	61.93	70.498	0.533907442	2169.059987	206.5788722	1063.51932	0.001229948	0.086708884	0.294463722	60.82998363	0.129387063	7.870612937	313.1678574	0.028647106	8.971352894	47.16	0.079017085	64.23901708	0.001230048	0.000000100020407
29	63.67	72.6	0.579334448	2207.810076	158.0271326	833.093501	0.001449327	0.105221135	0.324378074	51.26053686	0.153079178	7.846920822	270.2372649	0.033818128	8.966818719	47.16	0.093130229	64.25313023	0.001449427	0.000000100196254
30	65.46	74.52	0.623657489	2245.943645	122.628163	660.8125558	0.001693525	0.126201484	0.355248482	43.56346882	0.179519239	7.820480761	234.7526576	0.038175604	8.961824396	47.16	0.108847421	64.26884742	0.001693626	0.000000101453763
31	67.31	76.242	0.666768103	2282.801099	96.67329655	531.7990049	0.001960233	0.1494521	0.386590352	37.37296375	0.208480118	7.791519882	205.5883645	0.043564893	8.956435107	47.16	0.126022505	64.28602251	0.001960341	0.000000107476277
32	69.2	77.709	0.707730212	2318.96945	76.96323947	432.042586	0.002256554	0.175354516	0.418753527	32.22862797	0.240756254	7.759243746	180.9193567	0.04947247	8.95052753	47.16	0.145114362	64.30511436	0.002256654	0.000000100009308
33	71.14	79.831	0.746677607	2352.79734	62.4606483	357.3918794	0.002567528	0.202661482	0.450179388	28.11849645	0.27473946	7.75226054	160.8904577	0.055593147	8.944406853	47.16	0.165166304	64.3251663	0.002567768	0.0000001000052901
34	73.13	79.836	0.782789994	2386.006225	51.14710633	298.1023004	0.002907678	0.232133418	0.480180226	24.64279141	0.311978516	7.688021484	143.626362	0.062229319	8.937770681	47.16	0.187103917	64.34710392	0.002907729	0.000000100286243
35	75.17	80.456	0.816239108	2415.930375	42.97302347	254.3950199	0.003241928	0.26083257	0.510717701	21.94708376	0.348628178	7.651371822	129.9240398	0.06874215	8.93125785	47.16	0.208685164	64.36868516	0.003242029	0.000000101172559
36	77.26	80.721	0.846232114	2444.818253	36.572242	219.4163841	0.003589582	0.289754637	0.538288619	19.68642163	0.386727107	7.613272893	118.1093423	0.075560824	8.924439176	47.16	0.231143965	64.39114397	0.003589686	0.0000001003794043
37	79.38	80.678	0.872853608	2469.495766	32.05316514	194.1925399	0.003905	0.315047552	0.561290969	17.99115212	0.421248798	7.578751202	108.9985189	0.081819283	8.918180717	47.16	0.251534041	64.41153404	0.003905109	0.000000109151952
38	81.56	80.273	0.895823185	2492.484599	28.47595143	173.8785605	0.004217215	0.338528503	0.581832023	16.56822042	0.455367693	7.544632307	101.1681146	0.088809106	8.911909894	47.16	0.271728899	64.4317289	0.004217315	0.000000100003075
39	83.77	79.576	0.91535657	2510.405529	26.02516021	159.8072521	0.004477772	0.356323207	0.596928143	15.53515054	0.48381779	7.51618221	95.39344615	0.093367344	8.906632656	47.16	0.288592567	64.44859257	0.004477872	0.000000100007085
40	86.03	78.604	0.931767806	2525.000561	24.20333554	149.3017663	0.004706943	0.369984542	0.608263546	14.72200671	0.508840897	7.491159103	90.81482181	0.098023389	8.901976611	47.16	0.303432143	64.46343214	0.004707043	0.000000100013662
41	88.33	77.397	0.945255571	2535.674885	22.95158659	142.0840505	0.004891701	0.37860297	0.615307216	14.12227685	0.529020866	7.470979134	87.42534162	0.101780777	8.898219223	47.16	0.315400822	64.47540082	0.004891801	0.000000100022661
42	90.67	76.011	0.956315797	2542.330066	22.0035302	137.7607804	0.005024308	0.381902651	0.617982727	13.7194347	0.543499133	7.456500867	85.13378276	0.104488619	8.895511381	47.16	0.323993876	64.48399388	0.005024408	0.000000100035120
43	93.05	74.472	0.965161397	2545.964349	21.7985541	135.4528578	0.00511565	0.380972664	0.617229831	13.45471787	0.553452518	7.446547482	83.60554456	0.106376007	8.893623993	47.16	0.329914262	64.48991426	0.00511575	0.000000100046723
44	95.46	72.865	0.972516599	2545.46231	21.85372262	135.7695284	0.005143145	0.37475523	0.616172549	13.37824909	0.55639598	7.44360402	83.11437832	0.106997165	8.893002835	47.16	0.331696573	64.49169657	0.005143245	0.000000100050800
45	97.91	71.176	0.978330075	2543.776407	22.0397663	136.837949	0.005145158	0.366852335	0.60583362	13.34911975	0.557525488	7.442474512	82.88046903	0.107295537	8.892704463	47.16	0.332410513	64.49241051	0.005145258	0.000000100052523
46	100.4	69.469	0.98323315	2539.035549	22.56964176	139.8848423	0.005117099	0.355479766	0.596221239	13.45649978	0.553384299	7.446615701	83.40231402	0.106632148	8.893367852	47.16	0.330008223	64.49000822	0.005117199	0.000000100046964
47	102.92	67.742	0.987128																	

Chapter 8 NOx Model

The term NO_x is used to cover seven compounds, from an emissions point of view NO is of primary concern as a product of combustion. It has become a primary concern for legislation as in 1999 fifty percent of global NO_x emissions came from mobile sources (Clean Air Technology Center, 1999).

In combustion the production of NO is dominant followed by smaller quantities of NO₂. NO_x is produced in all combustion processes, which can be subdivided to 'Thermal NO_x' formed amongst the combustion products at high temperatures according to the Zeldovich mechanism. 'Prompt NO_x', which develops in the flame front via the Fenimore mechanism and Fuel NO_x which is produced by the nitrogen in the fuel.

Thermal NO_x first described by Zeldovich in 1946 occurs within the burned zone after the flame front has passed. This reaction mechanism has been extensively investigated most notably by Baulch et al. (1991) which developed what is known as the extended Zeldovich mechanism, which defines three reactions with experimentally determined speed constants k_i ; despite the extensive research there is still disagreement on the correct speed constants to apply.



Equation 55 Extended Zeldovich Mechanism

The debate regarding the correct speed coefficients is beyond the scope of this report. However, the values defined by Heywood are shown in Appendix 18. Therefore, the author has chosen to use Equation 56, which provides an estimation of the NO_x concentration. It should be noted that this equation cannot take into account the negative values that would be created by reverse reactions.

$$\frac{d[NO]}{dt} = (4.7 \times 10^{13}) \times [N_2] \times [O_2]^{\frac{1}{2}} \times \exp\left(\frac{-67837}{T_B}\right)$$

Equation 56 Extended Zeldovich Model (Merker, et al., 2006)

Reverse reactions, while excluded from this report are important for consideration of the results especially as Equation 56 is expected to overpredict. The formation of NO_x is exponentially dependant on temperature, if the NO_x concentration is below the temperature at which the equilibrium constant occurs, a common occurrence in combustion engines. Then the forward reaction has a much greater influence on the total conversion (Schwerdt, 2006).

It is only when the NO_x is above the temperature at which the equilibrium constant occurs that the reverse reaction has significant impact. Therefore, the maximum temperature is of greater significance than average temperature; as is the residence time, which is the duration the combustion gases are experiencing high temperatures. The excess oxygen in the system is another consideration, which should be helped with the EGR system the Ford Fox employs as is the turbulence within the cylinder. The excess oxygen and turbulence are issues that can easily be exacerbated by the GDI Ford Fox engine. The two-zone model used to create the dissociation model assumes homogenous charge, however, in reality the cylinder far from homogeneous.

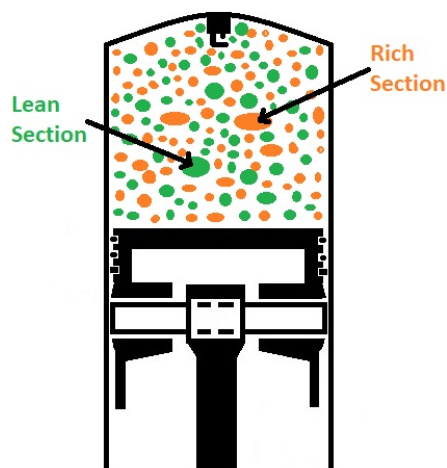
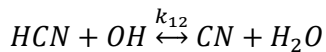
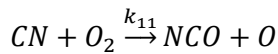
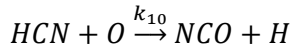
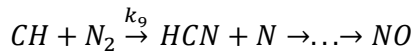


Figure 51 Non-homogeneous charge

Figure 51 is a theoretical representation of rich and lean patches within a homogeneous charge, while the surrounding area and much of the charge are evenly mixed, rich and lean patches will impact flame speed, availability of oxygen for dissociation and ultimately the NO_x produced. This is a problem in GDI engines as port injection engines normally achieved greater mixing in the intake and a more homogeneous charge.

Prompt NOx is formation is in the flame front itself, analogous to the formation of CH radical, which can react in a variety of ways. Prompt NOx first described by Fenimore in (1979); briefly stated as an intermediate CH reacts with N_2 which forms HCN (hydrocyanic acid) before NO.



Equation 57 Prompt NOx

Prompt NOx generally accounts for five to ten percent of the emissions, it has not been considered further in this report (Merker, et al., 2006). As the Zeldovich mechanism accounts for 90% - 95% of the nitrogen from the combustion model it will be used to model the NOx formation.

Fuel NOx where nitrogen bound in fuel converts to nitrogen oxide is not applicable to this report as isooctane fuel hardly contains any nitrogen.

8.1 Extended Zeldovich Mechanism

The next step was to calculate concentrations for nitrogen (Equation 58) and oxygen (Equation 59). Both formulas require the value for alpha (α) which is the number of kilomoles in the cylinder. This is calculated using Equation 60, the value for each RPM was calculated and is shown in Table 32.

Table 32 Alpha

RPM	α
1000	0.00000031537451
1250	0.00000040648270
1500	0.00000048798689
1750	0.0000005228688
2000	0.00000055239208
2250	0.00000055893534
2500	0.00000055832968
3000	0.00000058662254
3251	0.00000056648151
4000	0.00000052416411
4500	0.00000048322815
5000	0.00000049739621
5500	0.00000047093803
6000	0.00000044807839
6500	0.00000037602345

$$[N_2] = \frac{\alpha \times MFB \times n_6}{V_b}$$

Equation 58 Concentration of [N₂]

$$[O_2] = \frac{\alpha \times MFB \times n_5}{V_b}$$

Equation 59 Concentration of [O₂]

$$\alpha = \frac{m}{MW}$$

Equation 60 Alpha (α)

m = Fuel mass in the cylinder

MW = molecular weight of Isooctane (114.2
(Heywood, 1988))

Once the concentrations had been determined across all engine speeds for the duration of combustion, the value had to be converted to per degree using Equation 61, then for the volume burned that degree using Equation 62. An example of the values returned at 3000RPM are shown in Table 33.

$$\frac{d[NO]}{dt} \text{ per degree} = \frac{d[NO]}{dt} \times \frac{1}{6 \times RPM}$$

Equation 61 Concentrations per degree

$$\frac{d[NO]}{dt} \text{ per degree} \times V_b$$

Equation 62 concentrations per degree volume burned

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Table 33 oxygen and nitrogen concentrations per degree volume burned

Crank Angle	V_ABS	CYLPR1	MFB	T B	N5	NT	N5/NT	Error Guessed calculated	[N2]	[O2]	[O2]^0.5	d[NO]/dt	[NO] per degree	[NO]^VB
deg	cm³	bar		K	kmol	kmol		atm^0.5	kmol/m3	kmol/m3	(kmol/m3)^0.5	kmol.m^-3.s^-1	kmol/m3/degree	kmol
5	37.88	49.913	0											
6	38.24	49.365	0.000370172	7288.023809										
7	38.66	48.773	0.001129545	3720.103278										
8	39.15	48.21	0.003112863	2529.463489										
9	39.71	47.672	0.006220113	2146.531137										
10	40.33	47.224	0.010901957	1984.921742										
11	41.01	46.863	0.010792318	1898.100527										
12	41.76	46.661	0.025624756	1853.208449										
13	42.57	46.618	0.036343435	1829.818134	0.014989473	64.17498947	0.000233572	0.000000100792284	0.247660394431435	0.000078717108604	0.0088722662608963	0.000008191312746	0.000000000455073	0.000000000000002
14	43.44	46.772	0.049627593	1818.651867	0.013557508	64.17355751	0.000211263	0.000000100241325	0.248951364105584	0.000071568282257	0.0084598039135971	0.000006252900916	0.000000000347383	0.000000000000002
15	44.38	47.157	0.065961351	1818.64621	0.013519894	64.17351989	0.000210677	0.000000100233138	0.249774538220022	0.000071605708689	0.0084620156398341	0.000006274488627	0.000000000348583	0.000000000000003
16	45.38	47.749	0.084995349	1824.648925	0.014200673	64.17420067	0.000221283	0.000000100423482	0.251002067446385	0.000075580962148	0.0086937311982951	0.000007323740930	0.000000000406874	0.000000000000004
17	46.44	48.595	0.107232648	1835.815007	0.015592101	64.1755921	0.00024296	0.000000101227800	0.252607249810760	0.000083517339328	0.0091387821578349	0.000009713837722	0.000000000539658	0.000000000000006
18	47.55	49.663	0.13227222	1851.282799	0.017651643	64.17765164	0.000275043	0.000000104448922	0.254934883954737	0.000095420261779	0.0097683295285705	0.000014268899295	0.000000000792717	0.000000000000011
19	48.73	50.991	0.160794803	1869.989682	0.019879823	64.17987982	0.000309752	0.00000010009138	0.257931382478536	0.000108728374692	0.0104272899016026	0.00002233895516	0.000000001235216	0.000000000000021
20	49.97	52.554	0.192479543	1892.4037	0.021057389	64.18105739	0.000328094	0.000000100020060	0.261691843311744	0.000116847897151	0.0108096205831274	0.000035937110131	0.000000001996506	0.000000000000041
21	51.27	54.378	0.227645486	1917.414553	0.020010267	64.18001027	0.000311783	0.000000100010063	0.266195188504802	0.000112948195190	0.0106277088401095	0.000057365948743	0.000000003186997	0.000000000000075
22	52.62	56.427	0.265870434	1946.13583	0.018116533	64.17811653	0.000282285	0.000000105764016	0.271369183182407	0.000104246580996	0.0102101214975974	0.000094703337475	0.000000005261297	0.000000000000143
23	54.03	58.674	0.307068138	1977.891194	0.019264258	64.17926426	0.000300163	0.000000100005926	0.277073512221328	0.000113180992202	0.0106386555636388	0.000176320922059	0.000000009795607	0.000000000000300
24	55.5	61.06	0.350693178	2012.84924	0.038011176	64.19801118	0.000592093	0.000000100008763	0.283103275452124	0.000228182535231	0.0151057120067699	0.000464088761895	0.000000025782709	0.000000000000884
25	57.03	63.513	0.396049521	2050.583904	0.045737316	64.20573732	0.000712356	0.000000100103200	0.289194281784547	0.000280470105979	0.0167472417424261	0.000977212593336	0.0000000054289589	0.000000000002057
26	58.61	65.914	0.441809274	2090.75824	0.055461985	64.21546198	0.000863686	0.000000101112543	0.295032089720883	0.000346969153894	0.0186271080389226	0.002093823952452	0.000000116323553	0.0000000000004819
27	60.24	68.256	0.487867808	2129.29364	0.066454795	64.22645479	0.01034695	0.000000108177839	0.300554276814893	0.000423521475905	0.0205796374094528	0.004279905376773	0.00000237772521	0.00000000010678
28	61.93	70.498	0.533907442	2169.059987	0.079017085	64.23901708	0.01230047	0.000000100024047	0.305618553864521	0.000512067157926	0.0226289009438370	0.008500635845455	0.000000472257547	0.000000000022824
29	63.67	72.6	0.579334448	2207.810076	0.093130229	64.25313023	0.01449427	0.000000100196254	0.310116969245576	0.000612410188742	0.0247469228135854	0.016332258749689	0.000000907347708	0.0000000000046893
30	65.46	74.52	0.623657489	2245.943645	0.108847421	64.26884742	0.01693626	0.000000101453763	0.313941125958108	0.000724590872495	0.0269182163691312	0.030301325227335	0.000001683406957	0.000000000092517
31	67.31	76.242	0.666768103	2282.801099	0.126022505	64.28602251	0.01960341	0.000000107476277	0.317040846399002	0.000847206992611	0.0291068203796184	0.053885140785564	0.000002993618933	0.000000000174176
32	69.2	77.709	0.707730212	2318.96945	0.145114362	64.30511436	0.02256654	0.000000100093008	0.319307925754663	0.000982531086176	0.0313453519070370	0.092902898972119	0.000005161272165	0.000000000316481
33	71.14	79.931	0.746677607	2352.79734	0.165166304	64.3251663	0.02567768	0.000000100052901	0.320772585947543	0.001123427106118	0.0335175641435584	0.151976806485168	0.000008443155916	0.000000000543717
34	73.13	79.836	0.782780994	2386.006225	0.187103917	64.34710392	0.02907729	0.000000100286243	0.321282061789740	0.001274663534657	0.0357024303746526	0.24219906380582	0.000013455505354	0.000000000906956
35	75.17	80.456	0.816239108	2415.930375	0.208685164	64.36868516	0.03242029	0.000000101172559	0.320940703970844	0.001420177342072	0.0376852403743364	0.363180760570275	0.000020176708921	0.000000001419631
36	77.26	80.721	0.846232114	2444.818253	0.231143965	64.39114397	0.03589686	0.000000103794043	0.319611430842728	0.001566502407621	0.0395790652696705	0.529303979203277	0.000029405776622	0.000000002153934
37	79.38	80.678	0.872853608	2469.495766	0.251534041	64.41153404	0.03905109	0.000000109151952	0.317459766993504	0.001693213272510	0.0411486727916009	0.721242861719674	0.000040069047873	0.000000003047855
38	81.56	80.273	0.895823185	2492.484599	0.271728899	64.4317289	0.04217315	0.000000100003075	0.314364202363987	0.001811319734395	0.0425596021409433	0.951708566556889	0.000052872420364	0.000000004168223
39	83.77	79.576	0.91535657	2510.405529	0.288592567	64.44859257	0.04477872	0.000000100007085	0.310553234435812	0.001900410413710	0.0435936969493263	1.169526199813570	0.000064973677767	0.000000005298150
40	86.03	78.604	0.931767806	2525.000561	0.303432143	64.46343214	0.04707043	0.000000100013662	0.306077264706443	0.001969331645336	0.0443771522896174	1.371750733757640	0.000076208374098	0.000000006418180
41	88.33	77.397	0.945255571	2535.674885	0.315400822	64.47540082	0.04891801	0.000000100022661	0.301065868894976	0.002013494963009	0.0448719841661711	1.527703244604960	0.000084872402478	0.000000007372024
42	90.67	76.011	0.956315797	2542.330066	0.323993876	64.48399388	0.05024408	0.000000100035120	0.295666853323096	0.002031260598860	0.0450695085269458	1.616227488325180	0.000089790416018	0.000000008034544
43	93.05	74.472	0.965161397	2545.964349	0.329914262	64.48991426	0.0511575	0.000000100046723	0.289957651673582	0.002028438608982	0.0450381905607055	1.645411149473240	0.000091411730526	0.000000008417824
44	95.46	72.865	0.972516599	2545.46231	0.331696573	64.49169657	0.05143245	0.000000100050800	0.284142889036896	0.001998499203092	0.0447045769814661	1.592081992059930	0.000088448999559	0.000000008375017
45	97.91	71.176	0.978330075	2543.776407	0.332410513	64.49241051	0.05154258	0.000000100052523	0.278195742849662	0.001960881882438	0.0442818459691812	1.516987810059990	0.000084277100559	0.000000008199305
46	100.4	69.469	0.98323315	2539.035549	0.330008223	64.49000822	0.05117199	0.000000100046964	0.272254609631492	0.001905136980931	0.0436478748730226	1.392255806723700	0.00007734754488	0.000000007727880
47	102.92	67.742	0.987128075	2533.246033	0.326651729	64.48665173	0.050065416	0.000000100040027	0.266332472968458	0.001844740515851	0.0429504425571067	1.260822857178880	0.000070045714288	0.000000007182299
48	105.48	66.029	0.990451366	2525.684037	0.321587788	64.48158788	0.04987282	0.000000100031200	0.260489031346661	0.001776295913428	0.0421461257226374	1.116835543491600	0.000062046419083	0.000000006526690
49	108.06	64.336	0.993128965	2517.194997	0.315715534	64.47571553	0.04896658	0.000000100023077	0.254758278560368	0.001705495034806	0.0412976395791079	0.977591782473158	0.000054310654582	0.000000005857266
50	110.68	62.609	0.994791261	2509.12874	0.310463307	64.47046331	0.04815559	0.000000100018294	0.24902401610217	0.001699373985486	0.0404891835616112	0.859130233586039	0.000047729457421	0.000000005274842
51	113.32	60.925	0.996081073	2497.707927	0.302003005	64.462003	0.04684977	0.000000100012905	0.243447635439234	0.001558988918808	0.0394840337200730	0.723796936886371	0.000040210940938	0.000000004551619
52	116	59.275	0.99707449	2486.237603	0.293611276	64.45361128	0.04555389	0.000000100008948	0.237992544725727	0.001481706841345	0.0384929453451503	0.608577923730242	0.000033809884652	0.000000003918686
53	118.7	57.687	0.997951064	2473.65146	0.284207044	64.44420704	0.04410126	0.000000100005782	0.232725247695178	0.001402050400530	0.0374500387253509	0.503935648170042	0.000027996424898	0.000000003321245
54	121.42	56.134	0.998478814	2461.61483	0.275400947	64.43540095	0.04274063	0.000000100003738	0.227597925975907	0.001329106967034	0.0364569192435978	0.419556842644626	0	

The values were then combined in two versions, the first to the EOC using Equation 63, the second to the maximum temperature (T_B) using Equation 64 calculated from the two-zone model.

$$To\ EOC = \sum [NO]V_B SOC - EOC$$

Equation 63 Cumulative to EOC

$$To\ T_B = \sum [NO]V_B SOC - Max\ T_B$$

Equation 64 Cumulative to max T_B

To calculate the Parts Per Million (PPM) to the EOC Equation 65 was used, Equation 66 was used to calculate the PPM to the maximum temperature burned.

$$PPM = \frac{To\ EOC \times 10^6}{\alpha \times Avg\ N_T}$$

Equation 65 PPM to EOC

$$PPM = \frac{To\ Max\ T_B \times 10^6}{\alpha \times Avg\ N_T}$$

Equation 66 PPM to Max T_B

The values were calculated for all engines speeds and the results are shown in Table 34, and plotted in Figure 52 this shows both values to EOC and to Max T_B . Figure 53 Shows the PPM to Max T_B .

Table 34 NOx PPM

	1000	1250	1500	1750	2000	2250	2500	3000	3251	4000	4500	5000	5500	6000	6500
Actual	1518	1064	871	1053	1553	1577	2169	1787	1979	2467	2404	1695	1690	1335	1668
To EOC	6140.40	4013.17	2644.11	2794.09	2297.60	2718.84	2898.16	3202.66	801.24	1152.20	1037.49	732.32	825.98	638.72	1123.76
To Max Temp	3342.83	2640.89	1221.18	1462.28	1072.00	1414.81	1256.98	1284.88	332.59	499.51	598.03	324.94	448.39	295.99	536.89

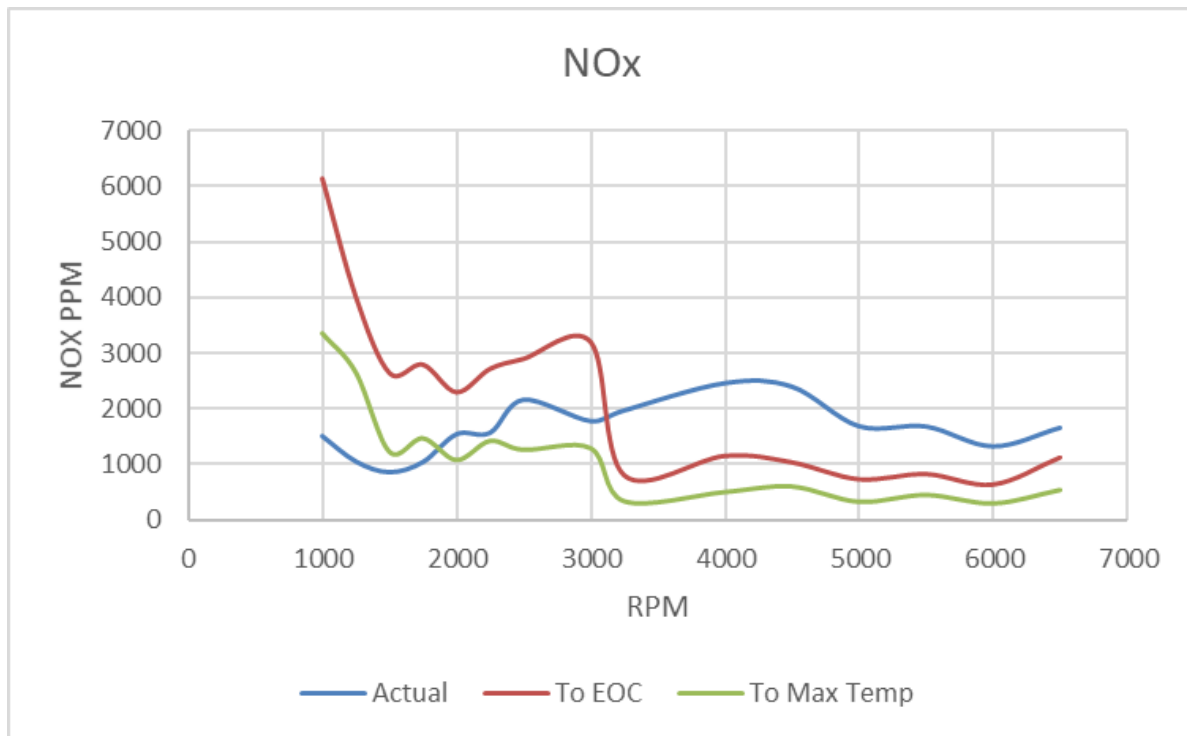


Figure 52 NOx PPM to EOC and Max TB

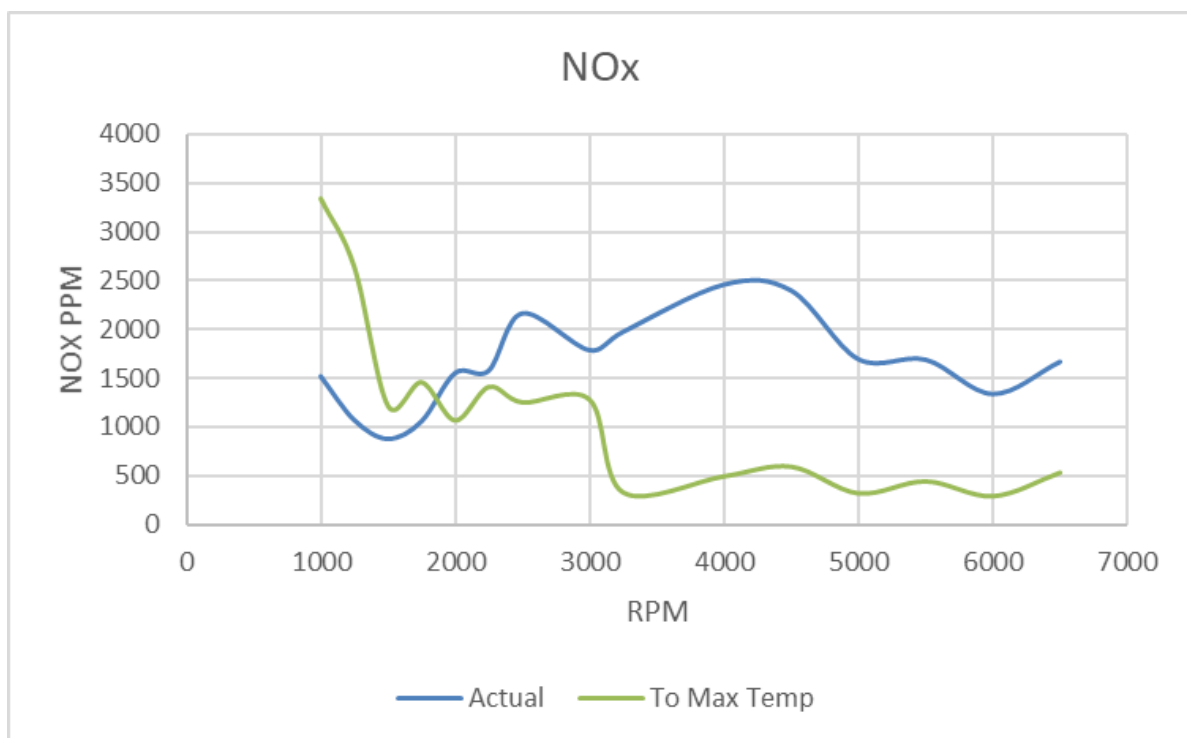


Figure 53 PPM to Max TB

The results show some interesting features the values to the EOC shown in Figure 52 are consistently higher than the figures to the maximum temperature. This is assumed to be because of reverse reactions occurring towards the EOC. The results to maximum temperature shown in Figure 53 have produced some mixed results when the mixture is lean at 1000-1750RPM the model over predicts the NO_x produced. When the mixture becomes rich the model drastically under predicts. At 2000-2500RPM the mixture is rich, but only just at 0.99 λ . At 3000rpm the mixture is stoichiometric and predicts closely to the expected values. From 3251RPM the mixture becomes rich and the model significantly under predicts. However, from 4000-6500RPM the trends follow with the peaks and troughs of the data series being synchronised.

Chapter 9 Valve Timing

The valve timing for the Ford Fox was not fully stated on the data supplied. As timing can have a significant impact on multiple facets of engine performance, it needed to be considered. The in-depth analysis of valves and all their various influences is mostly beyond the scope of this report. However, the author decided to calculate the timing from the cylinder pressure data. To determine if the data correlates with expectations. As cylinder filling can be compromised by breathing limitations and high gas velocities at high RPM. The Ford Fox also employs Variable Valve Timing (VVT) to improve volumetric efficiency across a wide range of engine speeds. It also utilises direct injection into the cylinder making the turbulence and air flow from the valves vitally import. Many engines use the gas exchange or overlap TDC region to increase the EGR, this is known to reduce NOx emissions which the supplied data (Table 37) shows is also used by the Ford Fox engine (Ford, 2012) (Manning, 2012).

The data supplied for the intake is shown in Table 35, given the minus figures it was taken to mean that at 1000RPM the intake valve opened at 29.3°. The top column is titled 'cam request', which is what the VVT asked for the next row down 'cam actual' has been taken as the point the cam opens.

Table 35 Intake Valve Timing

Intake																
wnwse_w Grad KW (intake cam request)																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		-29.3	-31	-31	-30.5	-20	-19.5	-14	-14	-14	-10.2	-5.5	-0.2	4.5	5	5
wnwe_w Grad KW (intake cam actual)																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		-29.3	-31	-31	-30.5	-20	-19.5	-14	-13.4	-14	-10.1	-5.5	-0.3	4.5	4.2	4.1

Table 36 Exhaust Valve Timing

Exhaust																
wnwsa_w Grad KW (exhaust cam request)																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		20.8	27.5	29	16.4	15	15	15	12	11	10	7	5	5	5	5
wnwa_w Grad KW (exhaust cam actual)																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		20.8	27.5	29	16.3	15	15	15	12.3	11	9.9	7	5	5	4	4.8

Table 37 Valve overlap

VCT_OVERLAP Grad KW n>30 n>50																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		50.1	58.5	60	46.8	35	34.5	29	25.6	25	20	12.5	5.3	0.5	-0.2	0.7

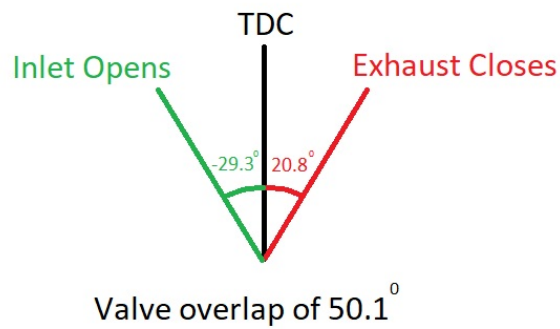


Figure 54 1000RPM Valve overlap

The exhaust data is shown in Table 36, given the positive figures it was taken to indicate that at 1000RPM the exhaust valve closed at 20.8°. Figure 54 shows how this would apply to TDC in the pumping loop, this coincides with the data shown in Table 37, which shows an overlap of 50.1°.

After examining the pressure and volume information, then the log of the pressure and the log of the volume there was no clear indication of the valve opening and closing time. It was therefore, decided to look at the rate of change of each by differentiating the data. The calculations were carried out and values for rate of change of pressure, rate of change of log P and rate of change of log V were found to be most useful an example at 1000RPM is plotted in Figure 55.

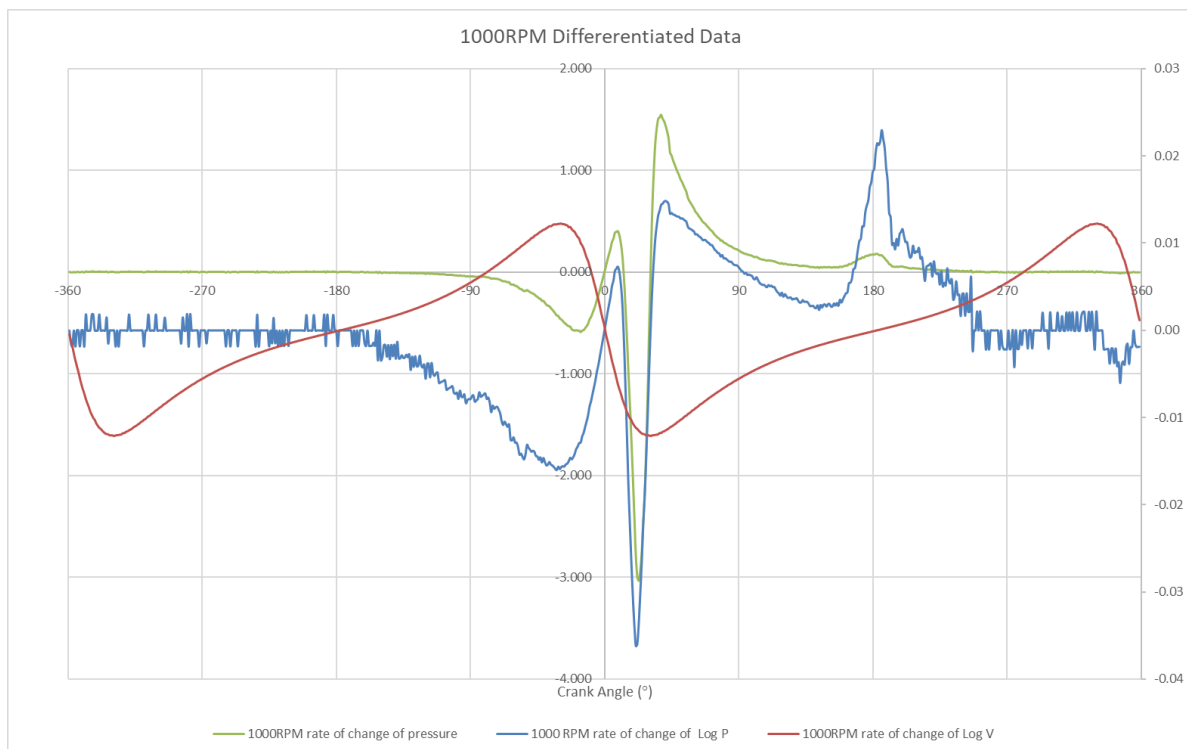


Figure 55 1000RPM Differentiated Data

When this data was compared to the information supplied in Table 35, Table 36 and Table 37 there is a definite change in the rate of change of the log P data around 330° where the inlet is due to open. However, there is no clear change in the data around the -340° where the exhaust closes. When the values were checked it was indeterminate whether these opening and closing points could be positively identified.

Therefore, further information was required, given the inlet opening times and exhaust closing timing only provide half of the information required. To calculate the inlet closing time and exhaust opening times the duration of each valve would be needed. The valve clearances would also be an important consideration, research showed that the Ford Fox Ecoboost engine could potentially be fitted with two different exhaust camshafts each with different clearances. The author was able to contact Ford who confirmed the camshaft fitted to the 125HP version for which the data was supplied is CM5G6A269AB (Wilson, 2018). The valve clearances were then confirmed as, inlet valve clearance 0.21mm-0.30mm and exhaust valve clearance 0.38mm-0.47mm (Randall, 2017). Given these suggested tolerances the author selected a middle approximate value for each clearance as the exact clearance on the tested engine is unknown, thus the inlet valve clearance for this report is assumed to be 0.25mm and the exhaust valve clearance is assumed to be 0.42mm.

Fortunately, the valves had been measured previously (Killen, 2015) and the data was made available to the author. The inlet and exhaust valve lift profiles are shown in Figure 56 and Figure 57.

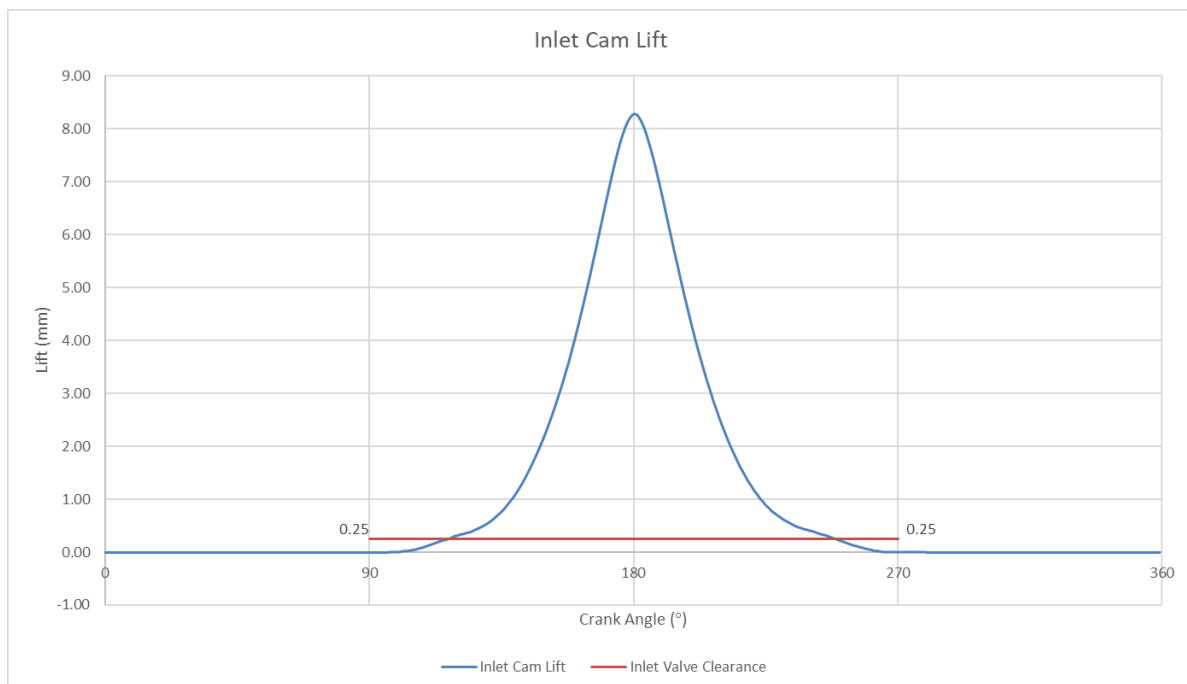


Figure 56 Inlet Valve lift and Clearance

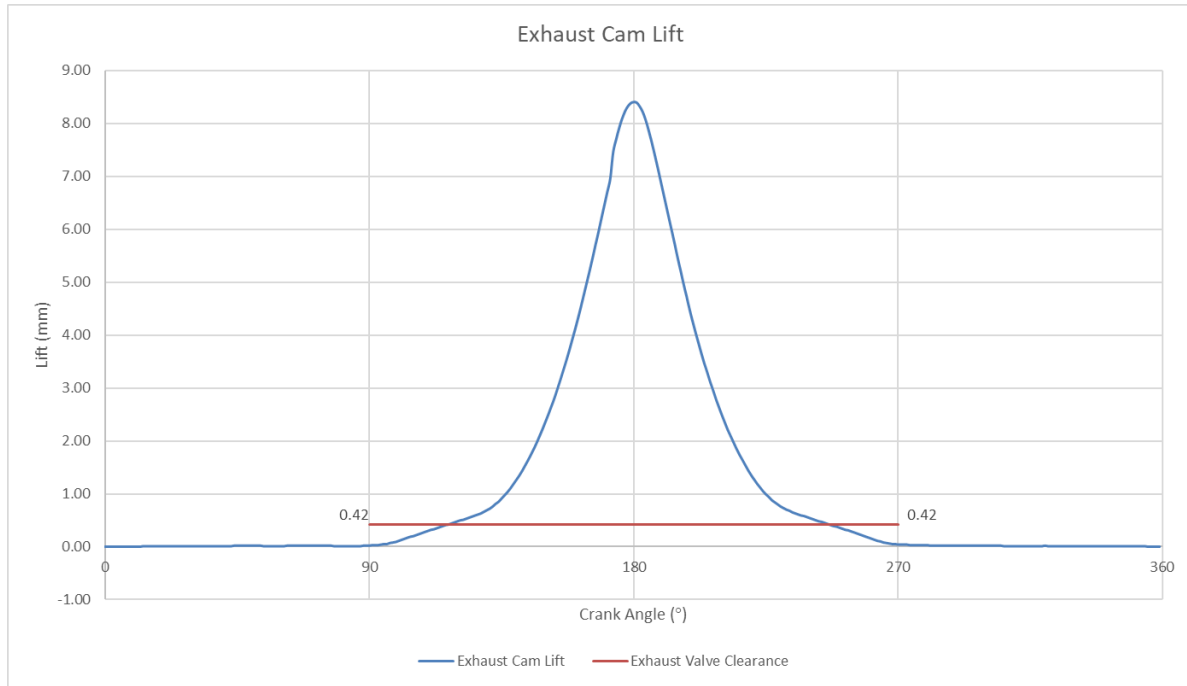


Figure 57 Exhaust Valve lift and Clearance

From this data the valve duration could be calculated as 256° of crank angle for the inlet valve and 259° of crank angle for the exhaust valve. This enabled the inlet closing times and the exhaust opening times to be defined as shown in Table 38. The values were then plotted in Figure 58 which shows the progressive reduction of the overlap as the engine speed increase.

Table 38 Valve opening and closing timing

Intake															
RPM	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
Intake Open	330.7	329	329	329.5	340	340.5	346	346.6	346	349.9	354.5	359.7	364.5	364.2	364.1
Intake Close	586.7	585	585	585.5	596	596.5	602	602.6	602	605.9	610.5	615.7	620.5	620.2	620.1
Intake Duration	256	256	256	256	256	256	256	256	256	256	256	256	256	256	256
Exhaust															
Exhaust Open	121.8	128.5	130	117.3	116	116	116	113.3	112	110.9	108	106	106	105	105.8
Exhaust Close	380.8	387.5	389	376.3	375	375	375	372.3	371	369.9	367	365	365	364	364.8
Exhaust Duration	259	259	259	259	259	259	259	259	259	259	259	259	259	259	259

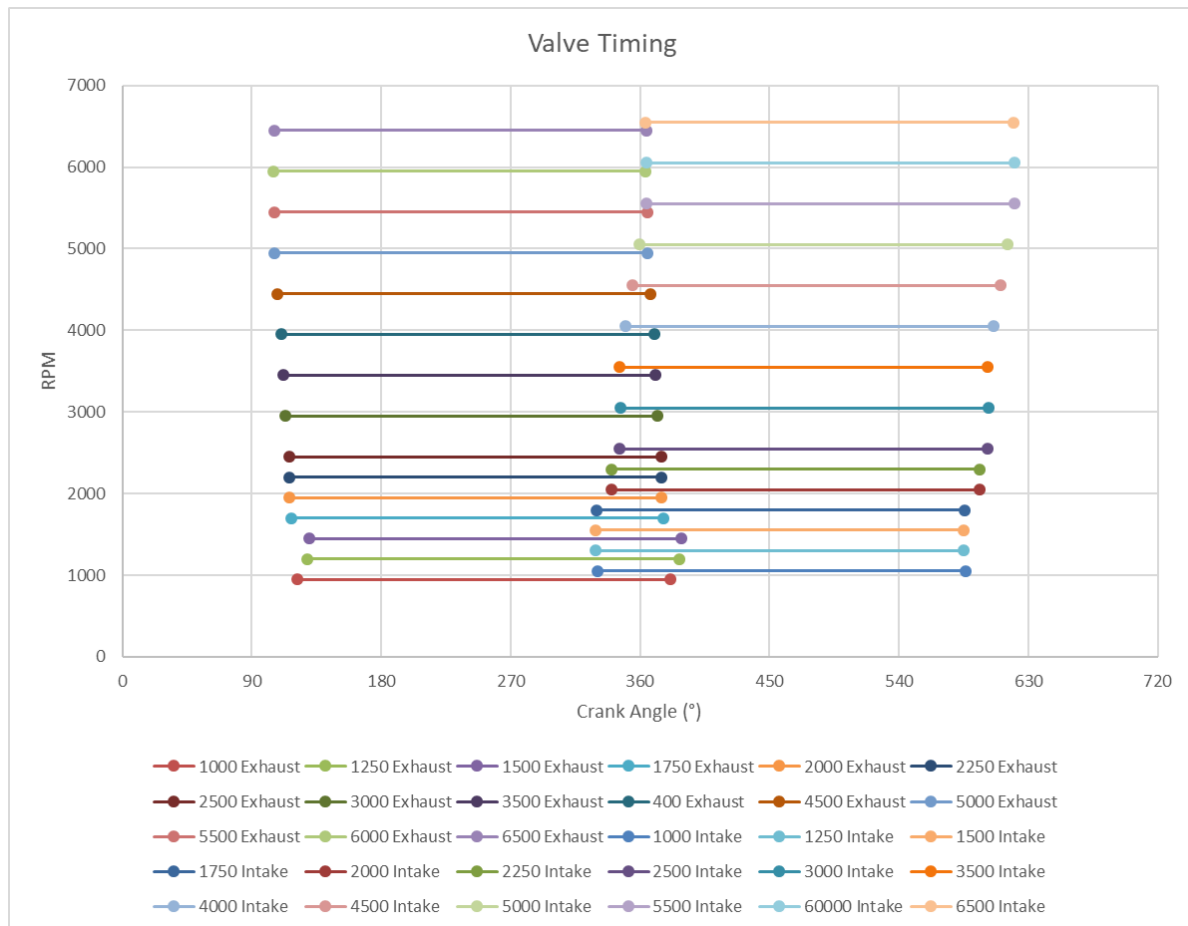


Figure 58 Exhaust and Inlet overlap and timing

These values were then compared to the data calculated for Figure 55 to see if there is a correlation. The data was collated and plotted for 1000RPM (Figure 59), 3000RPM (Figure 60) and 6500RPM (Figure 61).

Figure 59 1000RPM Rate of change data and valve timing

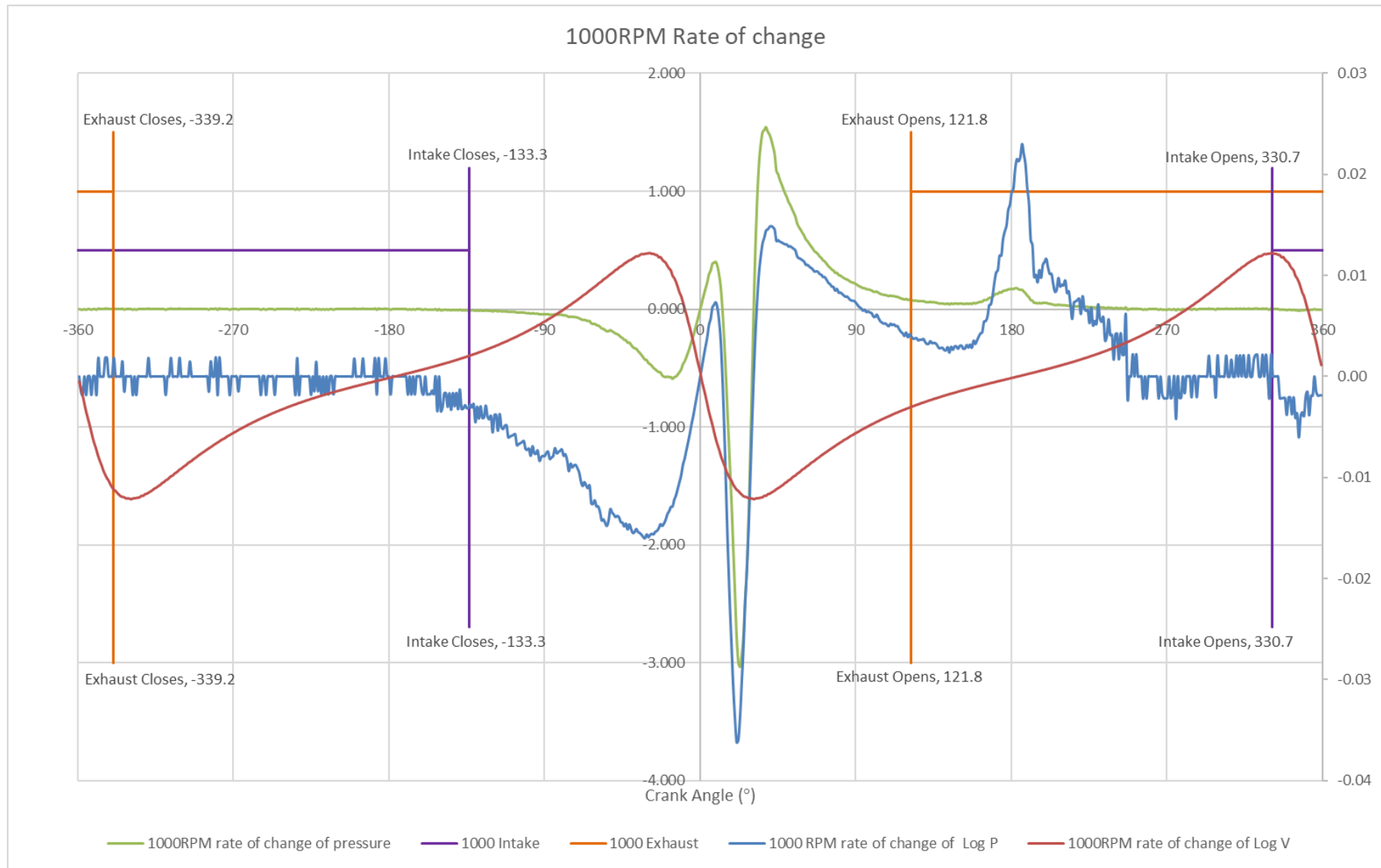


Figure 60 3000rpm Rate of change data and valve timing

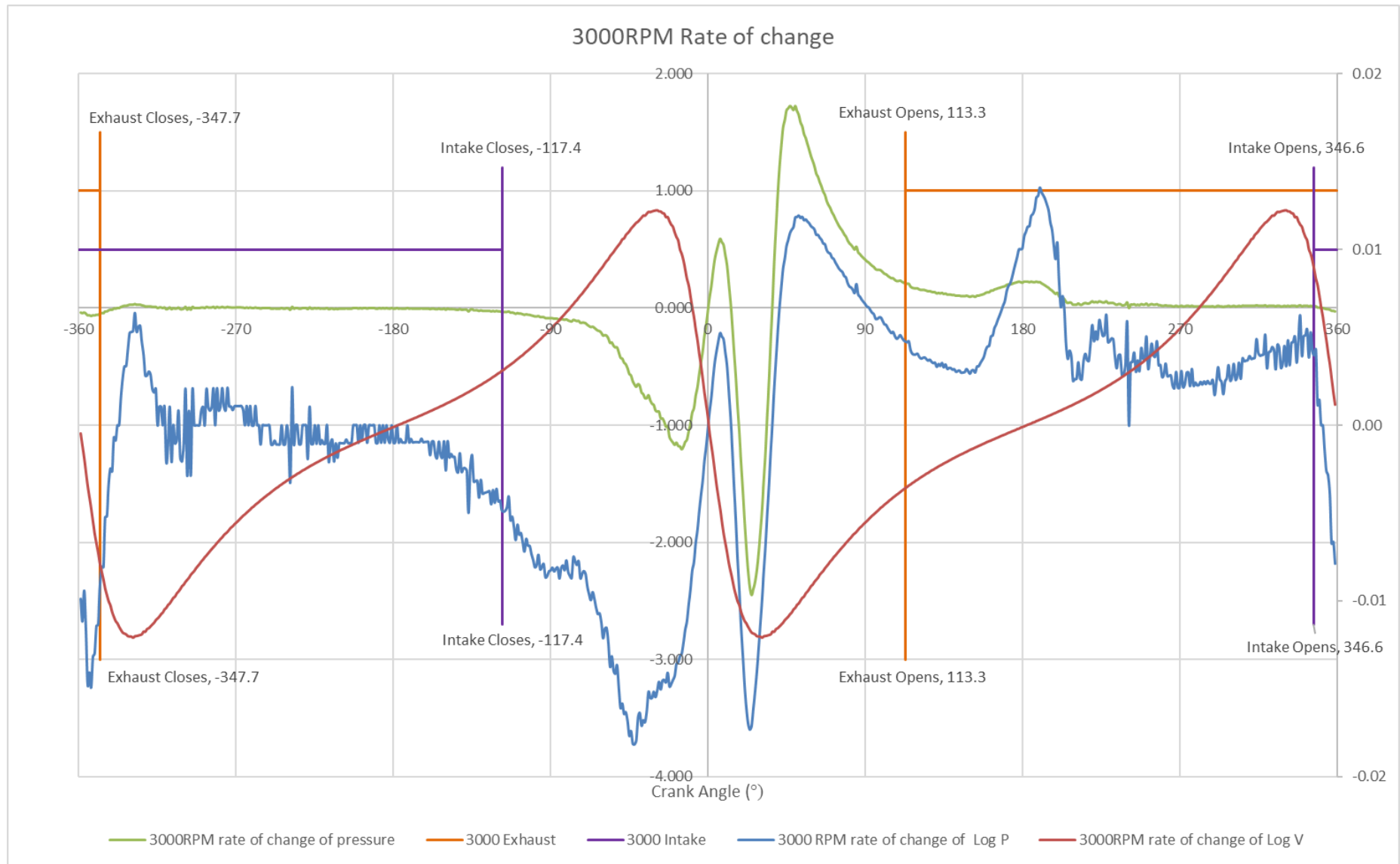
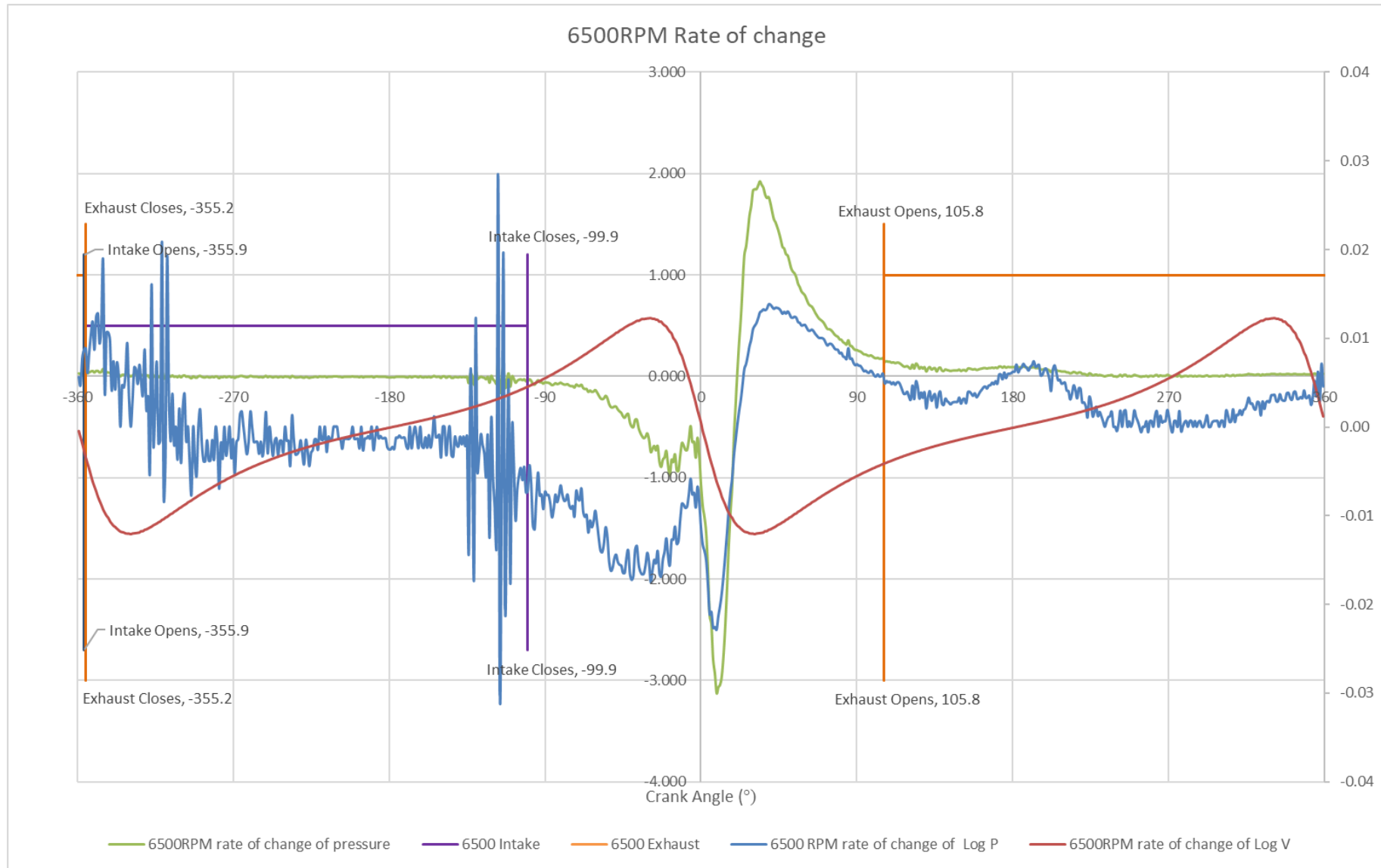


Figure 61 6500RPM Rate of change data and valve timing



Once the data was analysed it was not coincident as expected the exhaust seemed to be opening much sooner in the power stroke across all engine speeds than would realistically be expected. Added to this the inlet stays open long into the compression stroke. The valve timing data then does not directly correlate with the differentiated pressure change data. It was then considered that the effective opening of the valves may have a role to play as design dependency aside the valve opening can be such that the pressure change is negligible. Therefore, a general rule of thumb for effective valve opening of 1mm was applied to the data (McDonald, 2017).

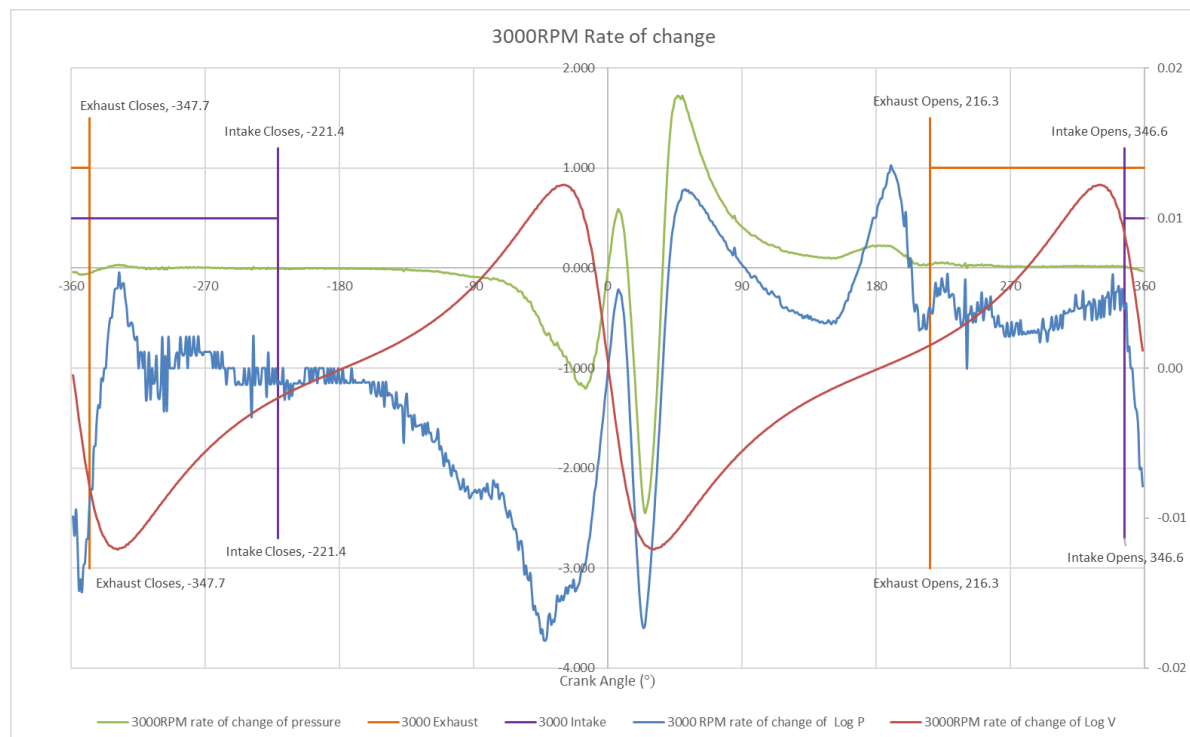


Figure 62 3000RPM with 1mm Effective valve opening

When this amendment to the data was added the inlet was closing too early and the exhaust opening too late as stated by Heywood the inlet valve should open 10°-25° BTDC and close 40°-60° ABDC, while the exhaust valve should open 50°-60° BBDC and close 8°-20° ATDC. Therefore, the effective opening of the valves was set to 0.5mm for comparison

Figure 63 1000RPM with 0.5mm valve opening

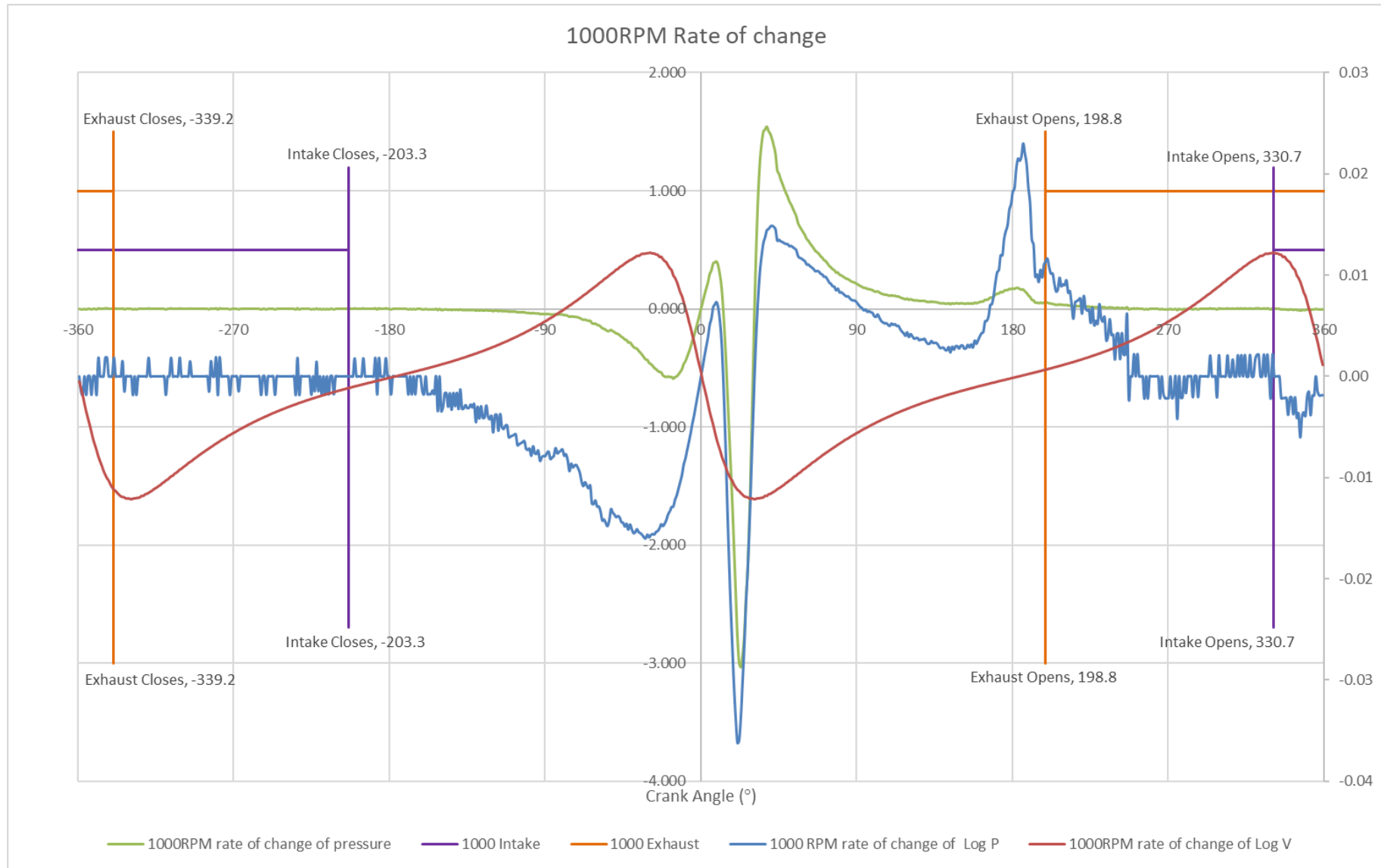


Figure 64 3000RPM with 0.5mm valve opening

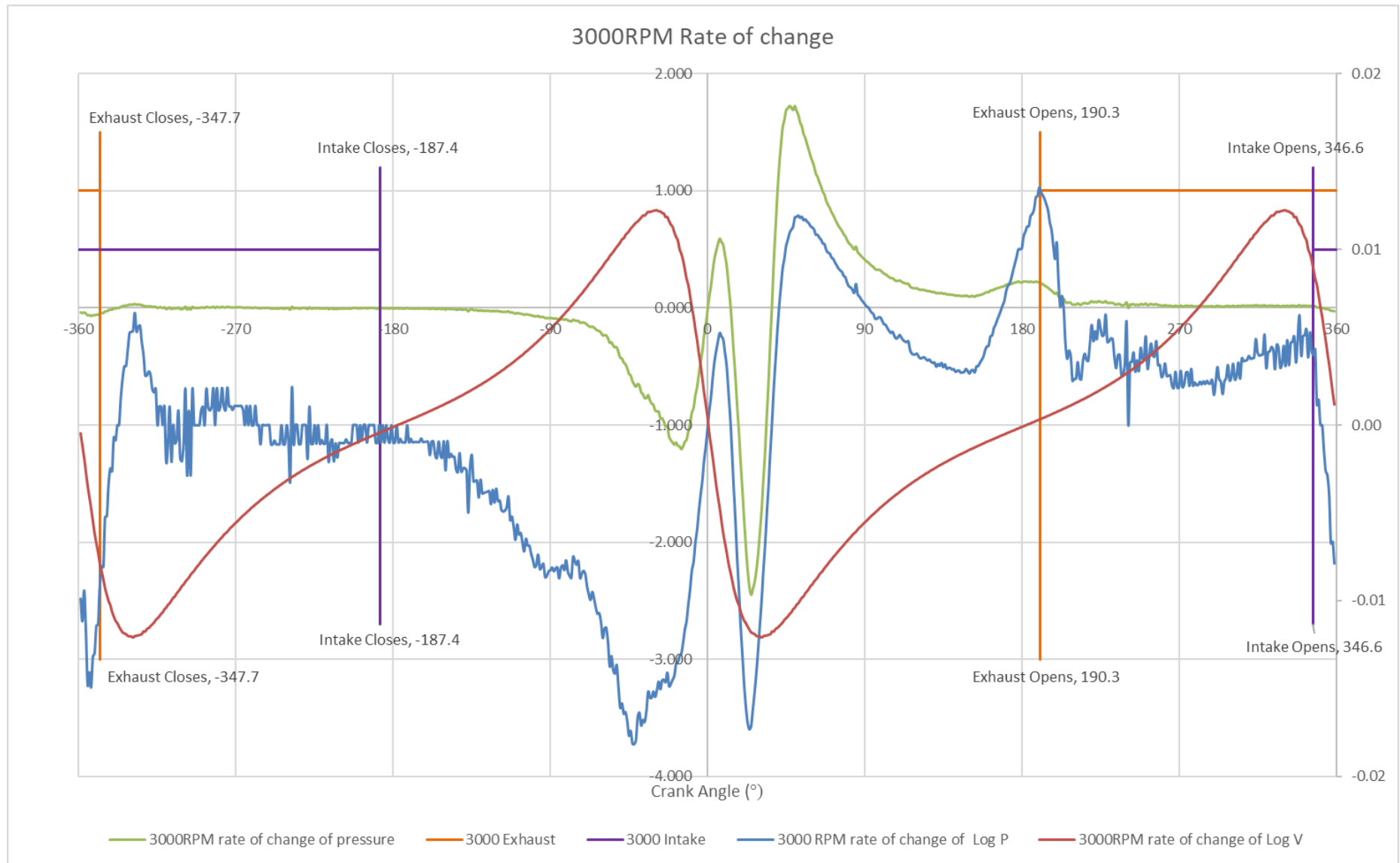


Figure 65 6500RPM with 0.5mm valve opening

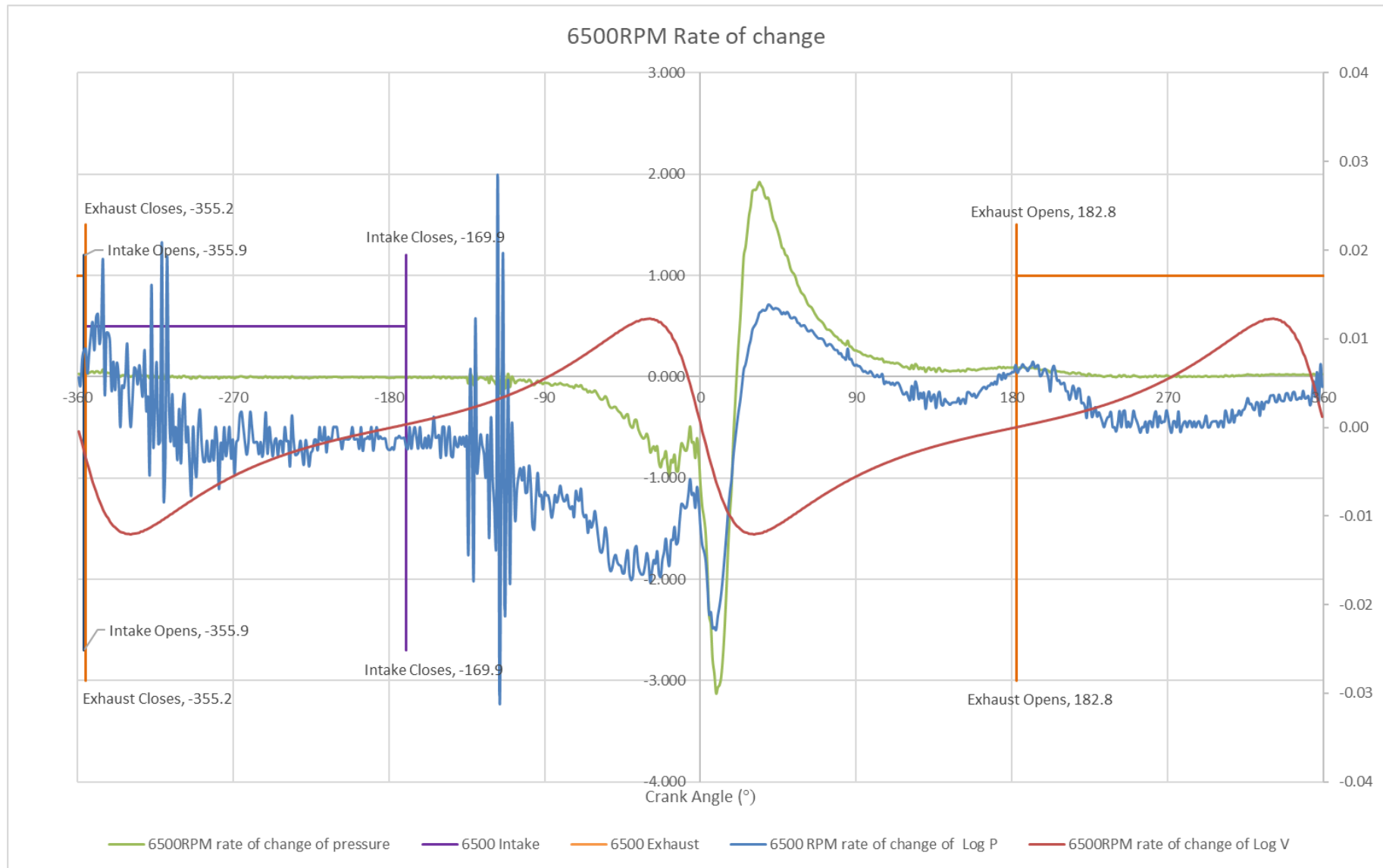


Table 39 Valve opening and closing timing with 0.5mm effective opening adjustment

Intake															
RPM	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
Intake Open	330.7	329	329	329.5	340	340.5	346	346.6	346	349.9	354.5	359.7	364.5	364.2	364.1
Intake Close	516.7	515	515	515.5	526	526.5	532	532.6	532	535.9	540.5	545.7	550.5	550.2	550.1
Intake Duration	186	186	186	186	186	186	186	186	186	186	186	186	186	186	186
Exhaust															
Exhaust Open	198.8	205.5	207	194.3	193	193	193	190.3	189	187.9	185	183	183	182	182.8
Exhaust Close	380.8	387.5	389	376.3	375	375	375	372.3	371	369.9	367	365	365	364	364.8
Exhaust Duration	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182

Table 39 shows the amended results to include the 0.5mm effective valve opening correction. When plotted for 1000RPM in Figure 63 the EVO perfectly coincides with a small peak in the data, although, there is no discernible change when the EVC. The IVO also lines up with an obvious change in the data, while a small change is noticeable when the IVC. At 3000RPM shown in Figure 64 the EVO is coincident with the spike in change of pressure and the EVC is just after a major change. The IVO is also perfectly aligned with a major change in the rate of change of pressure with no major changes at the IVC. At 6500RPM shown in Figure 65 the EVO at the top of a change and just before another at the EVC. The IVO is almost at the same time, therefore, it is difficult to separate any effect each may have had, while there is a change when the IVC.

These adjust show that there is a way to correlate the data against the valve timing, but it is very subjective to determine them from the data alone.

Chapter 10 Analysis

This report has taken the cylinder pressure data for the Ford Fox and developed a NO_x model through calculations from first principals. The part load data was examined up to the MFB, however, as there was not sufficient information available it was not used for later stages of the model.

10.1 Calculating Work Done

The work done calculation was the first process examined to determine the indicated torque. The results (Table 2, Figure 2) show that at full load the calculated figure closely tracks with the measured values supplied. The amount of torque lost due to friction increases with engine speed as would be expected.

When the work done is compared at 3000RPM full load (Table 2) to the part load data (Table 5) the part load is doing 298.69J of work compared to 989.77J of work at full load; less than a third of the work is being done at part load.

The results for part load (Table 5, Figure 3) also closely track with the measured data however the torque lost due to friction is at 47.12% at 800RPM a very high value. The percentage of torque lost due to friction then drops which is counterintuitive. While validating the data it was determined that the friction loss is a high percentage of a very small number. Therefore, the overall percentage loss due to friction is increasing with engine speed, this was validated by further analysis.

10.2 Mass Fraction Burned

The MFB was calculated in several steps. The PV diagrams identified the initial spike at low RPM caused by the piston reaching TDC before the SOC. The second larger spike was caused by the combustion process before dropping into the exhaust and intake collectively known as the pumping loop. It was noted that as the RPM increased the pumping loop increased in size, a trend further confirmed in the Log P Log V diagram. It was therefore examined further to see if the loss was greater in the intake or exhaust section of the loop.

Table 40 shows the Indicated Mean Effective Pressure (IMEP) at full load calculated using Equation 67 for the whole stroke and then the intake measured from -360° to -180° and the exhaust measured from 180° to 360°. The IMEP for the intake stroke is larger at the low engine speeds, after 2250RPM the exhaust loop has a bigger impact working to expel the hot gasses. The IMEP for the exhaust loop steadily increases with engine speed, whereas, the intake peaks at 3251RPM before dropping off again indication that at higher engine speeds the intake may be struggling to get sufficient air into the cylinder.

Table 40 IMEP, BMEP and FMEP FL

RPM	Work Done	Work Done Intake	Work Done Exhaust	IMEP Intake	IMEP Intake	IMEP Exhaust	BMEP	FMEP
	J	J	J	bar	bar	bar	kN/m ²	Bar
1000	496.176541	39.431745	-36.554573	14.9001964	1.18413649	-1.09773492	1355	1.350196426
1250	631.343499	51.021857	-48.402624	18.9592642	1.5321879	-1.45353225	1757	1.389264234
1500	747.572522	55.062381	-56.321236	22.4496253	1.65352495	-1.69132841	2104	1.409625285
1750	834.359818	59.090579	-55.800708	25.0558504	1.77449186	-1.67569694	2324	1.81585039
2000	887.253724	65.249458	-64.276012	26.644256	1.95944318	-1.93021057	2493	1.714255976
2250	897.233455	67.63785	-74.124659	26.9439476	2.03116667	-2.22596574	2517	1.773947598
2500	899.688792	64.82375	-81.445531	27.0176814	1.94665916	-2.44581174	2523	1.787681441
3000	898.766649	69.876912	-95.844896	26.9899895	2.09840577	-2.87822511	2546	1.529989459
3251	900.930972	70.526448	-100.885822	27.0549841	2.11791135	-3.02960426	2513	1.924984144
4000	852.366741	66.213365	-111.777181	25.5965988	1.98838934	-3.3566721	2368	1.916598829
4500	794.453405	61.880526	-112.342444	23.8574596	1.85827405	-3.37364697	2200	1.85745961
5000	765.404277	64.669166	-127.491678	22.9851134	1.942017	-3.82857892	2085	2.135113423
5500	728.88709	59.875697	-131.685982	21.8885012	1.79806898	-3.95453399	1966	2.228501201
6000	684.943168	54.783273	-132.862368	20.5688639	1.64514333	-3.9898609	1843	2.138863904
6500	609.58283	42.719125	-114.19435	18.3057907	1.28285661	-3.42925976	1587	2.435790691

$$IMEP = \frac{\oint \text{Work Done}}{\text{Cylinder Displacement (m}^3\text{)}}$$

Equation 67 IMEP

$$FMEP = IMEP - BMEP$$

Equation 68 FMEP

As the BMEP was supplied in the Ford data it was also possible to determine the Friction Mean Effective Pressure (FMEP) using Equation 68. The results are shown in Table 40, as FMEP is the friction loss within an engine the results show FMEP increasing with engine speed as expected.

The process was repeated for the part load data the results are shown in Table 41, the main point taken from this is that the actual FMEP in figure does increase with engine speed. This reinforces the earlier assumption that the apparent high percentage of friction loss at low engine speeds was due to the calculations showing a high percentage of a small number.

Table 41 IMEP, BMEP and FMEP PL

RPM	Work Done	Work Done Intake	Work Done Exhaust	IMEP Intake	IMEP Intake	IMEP Exhaust	BMEP	FMEP
	J	J	J	bar	bar	bar	kN/m ²	Bar
800	47.711426	9.98083802	-31.8227918	1.43277556	0.29972487	-0.95563939	71.3	0.719776
1500	56.3261673	11.3577129	-32.75949	1.6914765	0.34107246	-0.98376847	99.7	0.694476
1500	112.502468	17.2218891	-31.5301873	3.37845248	0.51717385	-0.94685247	261.7	0.761452
2000	164.519087	21.4276722	-31.8755597	4.94051311	0.64347364	-0.95722402	400.4	0.936513
2500	115.587307	15.8136889	-33.252277	3.47109032	0.47488555	-0.99856688	262.2	0.84909
3000	289.687947	25.6183266	-35.0793562	8.69933774	0.76931912	-1.05343412	750.3	1.196338
4000	224.199413	21.8103323	-34.9891296	6.73271512	0.65496493	-1.05072461	550.3	1.229715

The exhaust loop at part load is higher in all instances across the part load. It is of note that the two values for 1500RPM show that the lower torque demand has a lower IMEP than the higher, which indicates the intake stroke is struggling to suck air in.

When using Equation 5 to look at the polytropic index graphs, aside from the usable information there are spikes at TDC and BDC that get progressively bigger as the engine speed increases. This is because as the piston reaches these points it slows, stops and then changes direction. Therefore, $V_1 \sim V_2$ giving a value close to zero. This causes the polytropic index in these regions to become unreliable. This can cause issues especially at TDC on the power stroke (0°), which is often straddled by the SOC process, fortunately only briefly at 5500RPM and 6500RPM in the Ford Fox at full load; the part load data shows combustion starting well BTDC. As the engine speeds increase the spikes become larger and they are different sizes at the BDC at -180° , which is the end of the intake stroke about to start to the compression stroke; thus, the pressures are relatively low. Hence, the smaller spike than BDC at 180° , which is at the end of combustion and starting the exhaust stroke with very high pressures.

Therefore, as stated in section 4.4 this is not an effective method to determine SOC and EOC. The graphs did provide a region providing an initial value was determined, which could then be used for Equation 6. The exact SOC is difficult to identify, however, the method defined by the author of using the negative values in the delta P column has proven efficient both at full and part load. The EOC is far more subjective and difficult to define, especially at part load (section 4.8) where there is a potential error of over 50° of crank angle in some instances. It is common to refer to an Estimated End of Combustion (EEOC) in many papers as exact location by crank angle is difficult to determine (Brunt & Emtage, 1997). However, as the method was applied consistently it has given consistent results.

When the duration of combustion and ignition delay were calculated from these figures for full load they did not follow a pattern that might have been expected this is because within combustion as the engine speed increases so does the burning rate. When the calculations were carried out at part load

the delay was bigger, which is to be expected as the mixture is less dense, so there is more space between the charge components for reaction. Potentially as there is less air coming in it may be less turbulent. The other interesting aspect at part load is that SOC is between 17° and 21° BTDC, given the less dense mixture the timing can be brought closer to Max Brake Torque (MBT) timing as the engine is not knock limited in this condition, hence, the manufacturer can make best use of the available power. At 6500RPM full load the engine is also less knock limited as the unburned zone is not waiting long enough to detonate as everything is moving much faster. The ignition can be advanced closer to MBT timing. This is because the intake is not completely filling the cylinder with air and raising the pressure beyond the hardware limits.

The final values were then calculated for n in expansion and n in compression. These values (Table 11, Figure 28) were very different than the initial values achieved (Figure 24, Table 8) with estimation. The final figures calculated were taken over 30° of crank angle. For SOC the values had to be taken 20° before the identified SOC otherwise a result in the high thirties was returned. For EOC the degree immediately after EOC was taken as the first point for the calculation. Although the first graph seems smoother the final values are more accurate for the Ford Fox engine. When the value for n was changed from the value in expansion to the value in compression the MFB and the EOC were changed. The EOC could change by as much as 3° depending on the value used for n .

When the full load MFB for all engine speeds are plotted together (Figure 31) several patterns become evident. At 6500RPM the ignition has been advanced significantly before TDC as everything is moving so much faster. The slope for 6000rpm has also been advanced but not beyond TDC.

At the lower end of the rev range 1000RPM and 1250RPM the ignition has been retarded and the combustion takes place over a much shorter crank duration shown by the steepening of the MFB. The 1500RPM and 1750RPM can be seen in a transitional state from the steep low RPM to a gentler slope, more consistent with the higher engine speeds.

It shows that as the engine speed increase the burn duration takes longer by degrees of crank which is to be expected as the engine is moving faster, and the burn takes a specific amount of time, therefore, to keep the engine in an ideal power range as the engine accelerates the ignition is advanced.

The part load MFB showed no such pattern and as it was such a random and inconsistent data set it was decided not to develop it beyond this point.

10.3 Single Zone Temperature Model

The single model is based on the ideal gas and is unrealistic as it is based on assumptions, but it provides a starting point for the two-zone model. It is assumed the charge acts like an ideal gas which a hypothetical term, it assumes a constant mass, this is not necessarily the case as a valve may not seal properly or be completely closed and there is almost certainly blowdown where some of the cylinder contents escape past the piston rings. It assumes the charge is homogenous, which is very unlikely even though it is based on those assumptions it has been used effectively.

The calculations to determine the molecular weights were initially carried out for the products and reactants so that the average temperature could be calculated, that was then corrected to include the RGF Figure 66 shows how difference between the corrected temperatures at 3000RPM. While not huge we know from Dec, et al. that the reduction of peak temperature through EGR reduces NO_x formation.

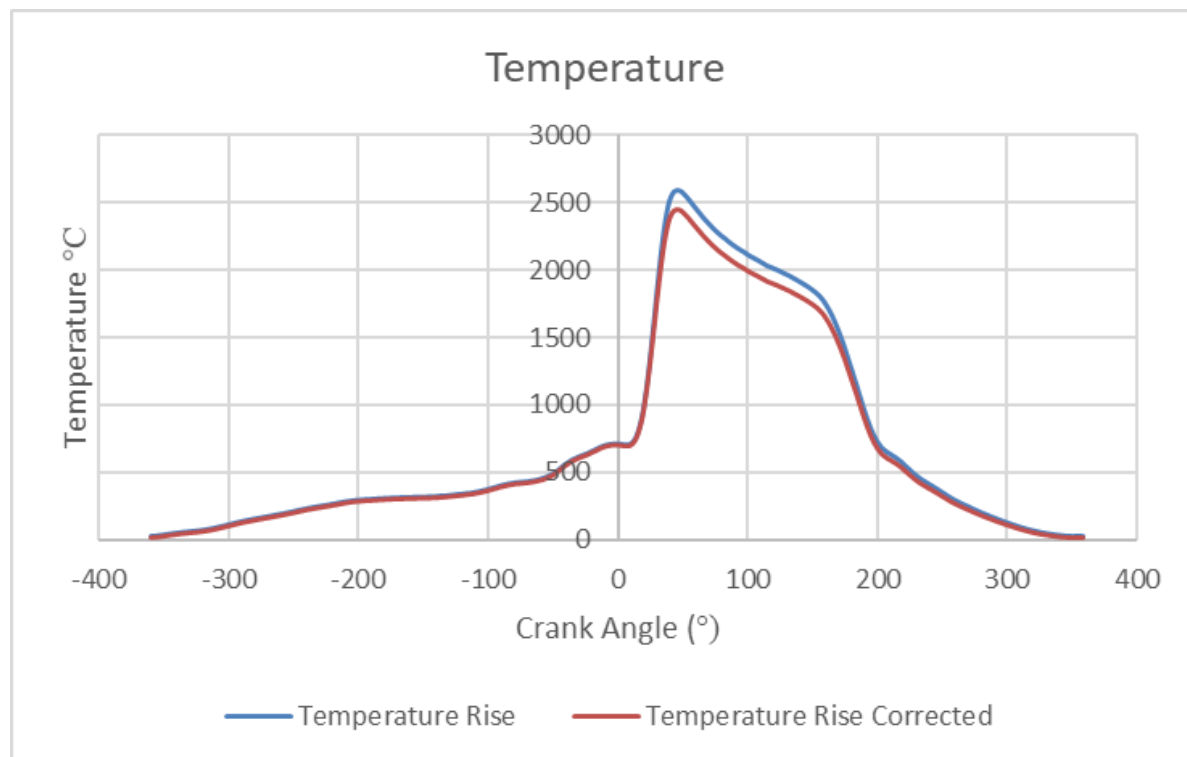


Figure 66 3000RPM Temperature difference accounting for EGR

The molecular weights calculated are all dependant on the FER the importance of which potentially for GDI NO_x modelling will be addressed later. However, given how sensitive the model is to changes in FER it is surprising it provides such accurate results as it is unlikely the charge is ever homogenous.

10.4 Two Zone Model

This model uses the temperature defined before the SOC as its starting point for temperature throughout combustion. Based on a burned and unburned zone it has the same potential inaccuracies as the one-zone model in reality computer simulations of hundreds of zones, are the only way to get truly accurate results, as this combustion model is over simplified.

As the specific heat is be calculated using Equation 27, which is identified as an approximation the potential error is further compounded. It is also noted that the fuel Isooctane C_8H_{18} Is an approximation and many books use different values. Once the unburned temperature has been determined it is used to calculate the burned temperature. When complete and compared as shown in Figure 44 and Figure 45 the volumes and temperatures are consistent with expectation.

10.5 Dissociation

For the dissociation process the only specific method available was following Goodger's process to model the break down towards their reactants. The author did make a modification to the usual method employed by using a series of polynomial equations to calculate the Partial pressure equilibrium constants between the values shown in Table 28. The standard method was carried out for a stoichiometric volume (Table 30, Figure 50) and the result shown for reference as these values were known they could verify the accuracy of the model.

Despite the efforts made to ensure accuracy the first seven temperatures calculated for temperature burned had to be discarded from the calculations as they gave unfeasibly high values unless perhaps the engine was experiencing uncontrolled combustion. This also entered a subjective element into the calculation. As the calculation of the concentrations is an iterative process and to ensure maximum accuracy in this section the excel sheet was set to 32,750 iteration and maximum change of 0.00000001.

The dissociation part of the model was an implementation of an established process that depends on the accuracy of the data calculated previously and entered to provide accurate results.

10.6 NO_x Model

The NO_x model is based on the extended Zeldovich equation which only considers thermal NO_x. This means another error has been inputted into the model. Nor are the reverse reactions taken into consideration and there is even disagreement on which reaction speeds should be applied. The values were calculated, and the result shown in Figure 52 show some interesting trends at 1000RPM the model massively over predicts the NO_x formation, this is assumed to be down to the slow engine speed giving reverse reactions time to occur and as the model does not account for these it overpredicts, it is not helped by the fact that the turbos has little to no effect at these low engine speeds. At 1500RPM, 1750RPM where the mixture is still lean the model slightly overpredicts to maximum temperature and significantly over predicts to EOC, but both follow the trends of the measure data. From 2000RPM to 3000RPM the model under predicts to Maximum temperature, but over predicts to EOC and neither follows the pattern of the measured data. At these values the mixture has gone slightly rich, but only just at 0.99 λ , it is assumed that the inconsistency of the mixture is causing the lack of consistency. It is especially possible when it must be considered that this data is the average of 300 cycles and at all engine speeds the values are potentially inaccurate. Especially considering the potential variance that cyclic variation could cause within the measured data.

After 3000RPM the model changes to under predicting for all values and both to the EOC and maximum temperature. However, it should be noted that the trend follows the measured data through the peaks and troughs which indicates that with further adjustment and refinement the model could be made more accurate.

When the model was initially tested all the values for the FER were set to stoichiometric. The results are shown in Figure 67 . Concentrating on the maximum temperature calculation it very closely tracks with the measured data up until 3000RPM matching the changing trends as well. This model works far more accurately than the model with correct FER. There is a divergence in data from measured after 3000RPM until 4500RPM. Interestingly the data to the EOC comes in line with the measured values. After 4500RPM the maximum temperature figures closely follow the values measured until a final spike at 6500RPM where there is a massive over prediction of NO_x formation.

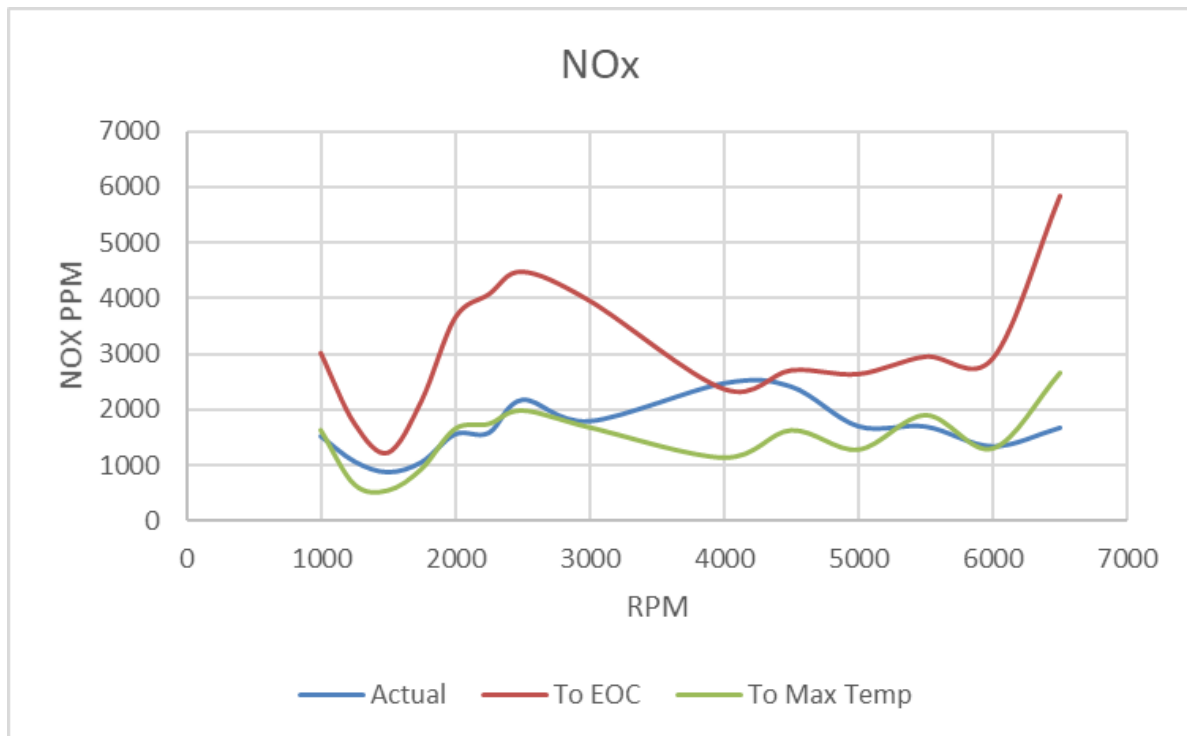


Figure 67 NOx Model at Stoichiometric

Given the way the stoichiometric values work so well up to 3000RPM and after 4500RPM it must be considered that the assumptions currently accepted may not be accurate for a GDI and that further modelling is required to test the data and accuracy of the model.

10.7 Valve Timing

The Ford Fox supplied limited data for the valve timing and as the engine employs VVT it was challenging to calculate. Had the data not been made available for the measured Cams it would have been very difficult to determine the exact point at which the exhaust valve opened, and the inlet Valve closed. However, when the effective opening area was considered, and the data compared as with the polytropic index giving a region to identify SOC and EOC the differentiated data gave clear indications of these regions; all the valve timing graphs are shown in Appendix 19

Chapter 11 Conclusion

This report takes simple cylinder pressure data and with access to measured results and data sheets, is able to generate a NO_x model that follows the trends of the measured data. The importance of the initial assumptions cannot be overstated as any error is carried over and amplified throughout the process. The method to identify the SOC and EOC to develop an accurate value for n are essential and the model is sensitive to changes in these values. From this the MFB calculations showed nice profiles that allow the rest of the model to be calculated. The MFB is a very subjective matter especially around the first and last ten percent that is why many papers and report focus on the MFB from ten percent to ninety percent. However, given the model employed in this report those sections can have a significant impact on NO_x production.

The NO_x model itself does not account for reverse, however, as it under predicts there are other process going on that have not adequately been accounted for perhaps the prompt NO_x formed in the flame front has more impact on emissions in a GDI engine. When the FER was set to stoichiometric it followed very well in the lean mixture phase up to 3000RPM perhaps the charge in a GDI engine is not at all homogenous and the reactions of rich and lean patches creating inconsistent availability of oxygen are creating more NO_x than the standard model can account for.

The valve timing data calculations are often unnecessary as the author was able to look at the factory supplied data for a Volkswagen 1.4L engine which supplied all the valve timing information. However, as the data was not available for the Ford Fox it was an interesting experiment and showed that measured calculations, and data could be used to confirm assumptions. If the valve data had been included it is possible that the impact of changing volumes as the valves open and close has an impact on the emissions as well. This is something given more time the author would like to pursue.

Overall the model has been able to create a method of predicting NO_x emissions that with refinement would reduce the need for testing as it could predict the emission for a given situation. Unfortunately, to be truly accurate each model would need to be refined specifically to each engine.

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Appendixes

Appendix 1 BMEP



Engine: CM13929 / SCE3539 / C022 Test Date: 2012-06-19

125PS_C344_TJ01A_02_Non_PATS_200Nm_CM13929

BMEP kN/m ²	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		1355	1757	2104	2324	2493	2517	2523	2546	2513	2368	2200	2085	1966	1843	1587
200						2489	2517	2518	2520	2482						
190						2392	2391	2394	2387	2379						
180					2266	2263	2266	2266	2261	2257	2267					
170				2108	2137	2136	2138	2141	2140	2149	2138	2138				
160				2015	2012	2013	2014	2012	2013	2014	2012	2010	2014			
150				1883	1887	1891	1887	1887	1886	1887	1893	1896	1888	1888		
140			1754	1756	1761	1771	1759	1761	1759	1762	1752	1762	1762	1760	1761	
130			1634	1638	1635	1636	1636	1635	1635	1636	1638	1636	1636	1635	1637	
120			1510	1505	1510	1502	1509	1510	1511	1509	1514	1510	1510	1509	1510	1510
110		1346	1384	1386	1383	1384	1384	1384	1385	1384	1377	1384	1385	1384	1385	1384
100		1243	1258	1258	1258	1258	1258	1259	1258	1258	1264	1259	1260	1259	1260	1259
90		1128	1133	1129	1132	1125	1132	1132	1131	1133	1128	1132	1135	1132	1132	1132
80		1004	1007	1009	1006	1009	1007	1007	1006	1006	1006	1006	1006	1006	1008	1006
70		878	884	877	880	878	881	881	881	881	885	881	880	880	880	881
60		754	755	758	754	750	754	755	755	755	753	755	755	755	755	755
50		627	629	628	629	630	629	629	630	629	627	629	629	629	629	628
40	473	494	503	506	502	503	503	503	502	503	504	503	503	505	503	502
30	393	368	376	374	377	375	378	377	377	379	377	377	377	378	378	378
20	251	236	250	242	251	251	251	250	252	252	251	251	251	252	253	251
10	135	109	120	121	126	122	122	121	132	125	125	121	125	130	134	135
5	71	52	59	58	74	64	60	62	55	62	63	62	61	71	66	69
2	26	32	12	25	23	29	26	26	28	25	25	26				

Appendix 2 Torque



Engine: CM13929 / SCE3539 / C022 Test Date: 2012-06-19

125PS_C344_TJ01A_02_Non_PATS_200Nm_CM13929

TORQUE Nm	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		108	140	167	185	198	200	201	202	200	188	175	166	156	146	126
200						198	200	200	200	197						
190						190	190	190	190	189						
180					180	180	180	180	180	179	180					
170				168	170	170	170	170	170	171	170	170				
160				160	160	160	160	160	160	160	160	160	160			
150				150	150	150	150	150	150	150	150	150	150	150		
140			139	140	140	141	140	140	140	140	139	140	140	140	140	
130			130	130	130	130	130	130	130	130	130	130	130	130	130	
120			120	120	120	119	120	120	120	120	120	120	120	120	120	120
110		107	110	110	110	110	110	110	110	110	109	110	110	110	110	110
100		99	100	100	100	101	100	100	100	100	100	100	100	100	100	100
90		90	90	90	90	89	90	90	90	90	90	90	90	90	90	90
80		80	80	80	80	80	80	80	80	80	80	80	80	80	80	80
70		70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
60		60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
50		50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
40	38	39	40	40	40	40	40	40	40	40	40	40	40	40	40	40
30	31	29	30	30	30	30	30	30	30	30	30	30	30	30	30	30
20	20	19	20	19	20	20	20	20	20	20	20	20	20	20	20	20
10	11	9	10	10	10	10	10	10	11	10	10	10	10	10	11	11
5	6	4	5	5	6	5	5	5	4	5	5	5	5	6	5	6
2	2	3	1	2	2	2	2	2	2	2	2	2				

Appendix 3 Formula for Linear interpolation

$$X2 = \frac{(Y2 - Y1) \times (X3 - X1)}{(Y3 - Y1)} + X1$$

Appendix 4 Actual Torque calculated through Linear Interpolation

RPM	BMEP Stated	Load Range	BMEP Range	Actual Load equals	Torque Range	Load Range	Actual Torque
	kN/m ²		kN/m ²		Nm		Nm
800		10	135	5.023438	11	10	6.023438
	71.3	5	71		6	5	
1500		10	120	8.362903	10	10	8.362903
	99.7	5	58		5	5	
1500		30	374	21.49242	30	30	20.64167
	261.7	20	242		19	20	
2000		40	503	31.98438	40	40	31.98438
	400.4	30	375		30	30	
2500		30	378	20.88189	30	30	20.88189
	262.2	20	251		20	20	
3000		60	755	59.624	60	60	59.624
	750.3	50	630		50	50	
4000		50	627	43.76423	50	50	43.76423
	550.3	40	504		40	40	

Appendix 5 Spark Advance



Engine: CM13929 / SCE3539 / C022 Test Date: 2012-06-19
125PS_C344_TJ01A_02_Non_PATS_200Nm_CM13929

SPARKADV °CA (Taken from Cyl 1 (TR104))

	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		-5.7	-5.0	-2.9	-3.6	-4.2	-3.1	-3.2	-0.1	3.0	5.3	7.6	4.9	7.5	9.5	14.5
200						-4.6	-3.7	-2.7	-0.1	2.5						
190						-3.4	-2.4	-1.2	-0.4	4.3						
180					-3.5	-2.7	-1.5	-1.2	1.5	4.1	4.6					
170				-3.9	-1.7	-2.9	-1.6	-0.5	3.7	6.3	6.3	7.9				
160				-3.9	-1.1	-0.4	0.7	0.9	4.9	6.7	7.7	8.8	8.0			
150				-3.3	0.3	0.2	2.1	3.0	7.1	8.3	10.0	11.3	10.2	8.8		
140			-4.9	-1.2	0.7	2.4	4.3	5.2	8.9	10.5	12.6	13.8	13.7	12.2	12.3	
130			-3.7	0.6	2.5	4.5	6.5	9.3	11.9	11.8	14.1	17.1	17.4	17.0	12.7	
120			-3.3	1.9	4.7	7.3	9.3	11.1	14.9	13.8	15.1	18.9	19.5	19.7	17.9	16.5
110	-5.7	-3.7	1.5	6.0	7.6	10.6	12.7	15.4	16.1	18.0	21.9	23.1	24.3	22.5	20.4	
100	-2.6	-0.1	4.0	8.1	11.5	13.1	14.2	17.1	18.3	21.0	24.0	25.2	24.5	23.9	22.4	
90	0.5	4.1	6.8	11.1	13.1	14.5	15.7	19.2	20.5	23.6	27.0	28.0	25.5	25.3	24.5	
80	3.7	6.1	8.7	13.0	16.9	16.9	17.6	20.3	22.7	26.2	30.9	30.3	25.3	26.1	25.5	
70	6.8	10.0	11.8	16.2	19.5	19.6	20.5	23.7	27.7	29.2	33.4	33.2	28.6	27.4	26.9	
60	10.9	13.6	15.3	20.3	23.4	23.3	24.1	26.9	30.3	30.9	36.6	35.5	31.1	28.5	28.5	
50	16.1	18.6	18.9	24.1	28.3	29.8	29.0	29.9	33.3	34.1	39.1	38.4	35.1	30.5	29.9	
40	22.7	20.4	22.2	25.8	31.3	37.4	35.1	34.1	35.1	36.9	37.9	40.3	40.5	34.3	28.9	30.0
30	21.8	24.7	25.6	28.5	34.5	41.1	38.7	35.6	39.3	41.1	41.1	42.5	42.0	35.7	31.1	31.4
20	26.5	26.7	28.5	30.4	34.6	40.7	38.6	36.7	39.8	41.6	44.1	43.3	43.2	36.3	33.5	33.0
10	34.6	34.7	35.0	39.1	37.5	44.4	47.7	49.5	45.5	47.3	44.3	44.4	43.0	39.1	35.5	34.7
5	28.3	27.9	34.3	35.6	42.2	37.7	38.8	41.5	43.7	51.1	45.7	45.9	44.1	40.0	37.4	35.4
2	26.7	29.9	33.6	38.3	40.7	39.7	41.0	43.4	43.8	46.4	46.4	45.9				

Appendix 6 Fuel Mass kg/h

FUELMASS kg/h

	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		3.24	5.22	7.52	9.39	11.35	12.92	14.34	18.08	18.92	21.54	22.34	25.55	26.61	27.62	25.11
200						11.34	12.96	14.25	17.78	19.47						
190						10.77	12.04	13.39	16.91	18.46						
180					9.11	10.05	11.26	12.52	15.24	17.76	20.61					
170				7.51	8.77	9.38	10.52	11.72	14.06	17.14	18.91	21.41				
160				7.10	8.08	8.74	9.77	10.88	13.05	15.06	17.46	19.80	23.68			
150				6.52	7.46	8.17	9.12	10.19	11.98	14.00	16.18	18.15	20.99	24.47		
140			5.19	6.04	6.84	7.63	8.45	9.44	11.01	12.93	14.87	16.65	18.92	21.63	25.58	
130			4.73	5.46	6.16	6.96	7.73	8.55	10.05	11.89	13.84	15.40	17.30	19.71	22.93	
120			4.35	4.93	5.75	6.39	7.07	7.79	9.15	10.95	12.86	14.24	15.88	18.00	20.45	23.30
110	3.22	3.91	4.52	5.24	5.78	6.43	7.13	8.42	9.97	11.65	13.06	14.58	16.31	18.66	20.90	
100	2.97	3.43	4.13	4.66	5.20	5.78	6.48	7.71	9.03	10.53	11.88	13.38	15.00	16.78	19.21	
90	2.56	3.00	3.60	4.11	4.55	5.13	5.77	6.90	8.05	9.36	10.70	12.11	13.59	15.15	16.95	
80	2.20	2.66	3.15	3.59	4.05	4.55	5.13	6.11	7.13	8.39	9.56	10.95	12.32	13.64	15.25	
70	1.89	2.33	2.77	3.21	3.60	4.07	4.56	5.40	6.32	7.45	8.44	9.71	10.92	12.18	13.69	
60	1.63	2.02	2.42	2.78	3.12	3.54	4.02	4.75	5.54	6.50	7.39	8.51	9.60	10.76	12.04	
50	1.38	1.73	2.08	2.38	2.70	3.03	3.41	4.09	4.80	5.60	6.41	7.31	8.25	9.33	10.42	
40	1.04	1.16	1.46	1.76	2.01	2.28	2.57	2.87	3.46	4.10	4.77	5.48	6.27	7.10	7.94	8.92
30	0.89	0.95	1.19	1.42	1.67	1.88	2.13	2.36	2.85	3.41	3.94	4.55	5.21	5.94	6.62	7.51
20	0.61	0.73	0.93	1.10	1.30	1.48	1.65	1.84	2.21	2.67	3.13	3.64	4.18	4.76	5.37	6.08
10	0.44	0.51	0.65	0.78	0.93	1.05	1.16	1.29	1.63	1.92	2.38	2.72	3.18	3.64	4.18	4.79
5	0.36	0.42	0.53	0.63	0.79	0.98	1.09	1.32	1.60	1.99	2.35	2.73	3.14	3.56	4.08	
2	0.32	0.39	0.46	0.56	0.66	0.78	0.86	0.98	1.22	1.44	1.83	2.09				

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Appendix 7 Air fuel ratio in cylinder

AFR IN CYL																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		13.76	13.70	13.78	13.90	14.10	14.08	14.33	13.42	13.60	14.06	13.91	13.36	13.35	13.02	13.10
200						14.10	14.05	14.33	13.78	14.39						
190						14.07	14.12	14.31	13.38	13.85						
180					13.88	14.07	14.18	14.29	13.89	13.65	14.03					
170				13.77	13.72	14.08	14.18	14.27	14.32	13.49	14.22	13.92				
160				13.81	13.81	14.10	14.17	14.21	14.30	14.32	14.37	13.97	13.54			
150				13.85	13.93	14.03	14.10	14.09	14.24	14.30	14.35	14.16	13.98	13.65		
140			13.74	13.88	13.97	13.93	14.03	14.04	14.21	14.27	14.33	14.38	14.34	13.94	13.25	
130			13.83	13.98	14.09	13.91	13.96	14.02	14.22	14.23	14.29	14.33	14.42	13.99	13.55	
120			13.98	14.01	13.58	13.87	13.93	13.97	14.20	14.21	14.29	14.35	14.36	14.18	13.70	13.47
110		13.71	14.13	14.10	13.61	13.92	14.02	14.00	14.20	14.23	14.28	14.34	14.32	14.36	13.85	13.74
100		13.34	14.33	13.74	13.93	14.16	14.20	14.09	14.17	14.32	14.31	14.36	14.34	14.38	14.29	13.71
90		14.04	14.57	14.21	14.31	14.53	14.49	14.30	14.37	14.44	14.40	14.40	14.36	14.40	14.44	14.48
80		14.46	14.56	14.55	14.62	14.62	14.63	14.54	14.58	14.62	14.53	14.47	14.36	14.43	14.45	14.48
70		14.59	14.65	14.61	14.59	14.63	14.60	14.56	14.59	14.65	14.62	14.56	14.39	14.39	14.43	14.46
60		14.65	14.66	14.66	14.65	14.69	14.66	14.53	14.63	14.67	14.68	14.65	14.49	14.42	14.42	14.42
50		14.66	14.64	14.64	14.67	14.68	14.66	14.64	14.64	14.69	14.69	14.67	14.65	14.57	14.48	14.45
40	14.54	14.62	14.66	14.69	14.68	14.64	14.62	14.67	14.67	14.66	14.67	14.65	14.65	14.59	14.59	14.54
30	14.56	14.59	14.60	14.67	14.68	14.62	14.61	14.64	14.66	14.66	14.66	14.65	14.64	14.61	14.63	14.60
20	14.63	14.57	14.50	14.59	14.62	14.56	14.65	14.67	14.68	14.69	14.68	14.65	14.62	14.58	14.59	14.57
10	14.65	14.61	14.55	14.60	14.57	14.64	14.68	14.66	14.69	14.68	14.67	14.67	14.58	14.59	14.59	14.56
5	14.62	14.57	14.60	14.58	14.59	14.66	14.67	14.64	14.67	14.67	14.68	14.66	14.58	14.55	14.58	14.55
2	14.70	14.56	14.58	14.58	14.67	14.69	14.62	14.60	14.66	14.65	14.68	14.63				

Appendix 8 EGR

EGR % (Residual gas ratio by internal and external EGR)																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		0.5	0.2	0.1	0.4	0.8	0.8	1.0	1.5	1.7	2.2	2.7	3.1	3.3	3.6	4.1
200						0.8	0.8	1.0	1.4	1.8						
190						0.8	0.9	1.1	1.5	1.8						
180					0.4	0.9	0.9	1.1	1.5	1.9	2.2					
170				0.1	0.2	1.0	1.0	1.2	1.6	2.0	2.2	2.7				
160				0.2	0.2	1.1	1.1	1.3	1.7	2.0	2.2	2.6	3.0			
150				0.2	0.2	1.2	1.2	1.3	1.8	2.2	2.3	2.6	3.1	3.3		
140			0.2	0.2	0.3	1.0	1.2	1.3	2.1	2.4	2.6	2.7	3.1	3.4	3.6	
130			0.3	0.3	0.5	1.1	1.2	1.5	2.3	2.5	2.7	2.9	3.2	3.4	3.7	
120			0.3	0.5	0.8	1.2	1.4	1.7	2.5	2.7	2.9	3.0	3.2	3.5	3.8	4.2
110		0.6	0.5	0.8	1.0	1.3	1.5	1.9	2.6	3.0	3.1	3.1	3.2	3.7	3.9	4.3
100		1.1	0.9	1.1	1.4	1.6	1.8	2.1	2.8	3.4	3.4	3.3	3.3	3.7	4.1	4.5
90		1.8	1.5	1.8	2.1	2.5	2.5	2.8	3.4	3.8	3.6	3.6	3.4	3.7	4.2	4.5
80		3.5	3.0	3.2	3.3	3.2	3.5	4.7	4.9	4.6	4.3	4.1	3.6	3.8	4.4	4.6
70		5.7	5.4	6.0	6.0	5.7	6.5	6.9	6.7	6.2	5.6	5.4	4.2	4.2	4.6	4.8
60		9.7	9.9	10.0	9.9	10.3	10.4	9.4	9.0	8.5	8.0	7.6	5.5	4.6	5.0	5.1
50		14.1	14.7	14.7	14.4	14.6	14.2	12.9	11.5	11.1	10.3	9.6	7.3	5.1	5.4	5.6
40	18.6	18.1	18.4	18.6	19.3	19.5	17.0	15.2	15.1	14.3	12.7	11.2	8.9	5.7	5.9	6.0
30	19.9	19.3	18.6	20.7	21.7	21.3	18.6	16.5	17.7	17.1	14.2	12.5	10.6	6.7	6.7	6.7
20	20.6	19.0	19.0	20.1	19.8	19.5	18.5	17.4	18.0	17.2	15.5	13.1	11.4	8.6	8.3	8.2
10	25.6	24.7	23.4	23.1	21.9	21.3	21.4	21.8	19.9	17.9	16.5	14.5	13.3	11.7	10.8	10.4
5	28.0	27.8	26.1	25.7	23.9	23.8	23.7	24.0	21.7	19.7	17.2	16.1	14.9	13.4	12.8	12.1
2	33.3	29.1	27.3	27.6	26.2	25.8	25.2	25.3	23.1	21.3	18.3	17.3				

Appendix 9 Lambda



Engine: CM13929 / SCE3539 / C022 Test Date: 2012-06-19

125PS_C344_TJ01A_02_Non_PATS_200Nm_CM13929

LAMBDA																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		1.11	1.11	1.10	1.03	0.99	0.99	0.99	**	0.94	0.97	0.95	0.92	0.92	0.90	0.90
200						0.99	0.98	0.99	**	0.99						
190						0.99	0.99	0.99	0.93	0.96						
180					1.02	0.99	0.99	0.99	0.96	0.95	0.97					
170				1.10	1.07	0.99	0.99	0.99	0.99	0.94	0.98	0.96				
160				1.11	1.07	1.00	1.00	0.99	0.99	0.99	0.99	0.96	0.93			
150				1.11	1.08	1.00	1.00	0.99	0.99	0.99	0.99	0.98	0.96	0.94		
140			1.11	1.11	1.08	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.96	0.91	
130			1.10	1.10	1.07	1.00	1.00	1.00	1.00	0.99	0.99	0.99	1.00	0.96	0.93	
120			1.09	1.07	1.01	1.01	1.00	1.00	1.00	0.99	0.99	1.00	1.00	0.98	0.95	0.93
110		1.09	1.09	1.06	1.01	1.01	1.01	1.00	1.00	0.99	1.00	1.00	1.00	1.00	0.96	0.95
100		1.03	1.08	1.01	1.02	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.95
90		1.02	1.05	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00
80		1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00
70		1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00
60		1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00
50		1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
40	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
30	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
20	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
10	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.01	1.01	1.00
5	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1.00
2	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01				

Appendix 10 Lambda and Phi

Because the GDI runs both rich and lean and since the combustion products from each mixture have significantly different compositions and because the stoichiometric fuel/air ratio is dependent on fuel consumption; a more useful parameter defining the charge composition is the ratio of actual fuel/air ratio to the stoichiometric ratio, its inverse is also applicable. Therefore, it can be stated that: -

For lean fuel composition: $\phi < 1, \lambda > 1$

For Stoichmetric composition: $\phi = \lambda = 1$

For Rich Composition: $\phi > 1, \lambda < 1$

(Heywood, 1988) (Turns, 2006)

Appendix 11 Gaseous composition of dry air (Mackenzie, 1998)

Constituent	Chemical symbol	Mole percent
Nitrogen	N ₂	78.084
Oxygen	O ₂	20.947
Argon	Ar	0.934
Carbon dioxide	CO ₂	0.0350
Neon	Ne	0.001818
Helium	He	0.000524
Methane	CH ₄	0.00017
Krypton	Kr	0.000114
Hydrogen	H ₂	0.000053
Nitrous oxide	N ₂ O	0.000031
Xenon	Xe	0.0000087
Ozone*	O ₃	trace to 0.0008
Carbon monoxide	CO	trace to 0.000025
Sulfur dioxide	SO ₂	trace to 0.00001
Nitrogen dioxide	NO ₂	trace to 0.000002
Ammonia	NH ₃	trace to 0.0000003

Appendix 12 Molecular Calculations

RPM	Multiplier	Carbon	Hydrogen	Balance Multiplier	Oxygen	Nitrogen	Molecular Weight Unburned	Molecular Weight Unburned + RGF	Carbon Dioxide	Water	Carbon Monoxide	Nitrogen	Molecular Weight Burned
		C	H		O ₂	N ₂	Kg/mol	Kg/mol	CO ₂	H ₂ O	CO	N ₂	Kg/mol
				OT					CT	HT		NT	
1000	0.900901	8	18	12.5	1	3.773	30.11880046	30.11080945	7.207207	8.108108		47.16	28.56151715
1250	0.900901	8	18	12.5	1	3.773	30.11880046	30.11559418	7.207207	8.108108		47.16	28.56151715
1500	0.909091	8	18	12.5	1	3.773	30.13017357	30.12855756	7.272727	8.181818		47.16	28.56526604
1750	0.970874	8	18	12.5	1	3.773	30.21586982	30.20908238	7.76699	8.737864		47.16	28.59301816
2000	1.010101	8.080808	18.18182	25	1	3.773	29.57509399	30.25569867	7.828283	9.090909	0.252525	47.16	28.54736636
2250	1.010101	8.080808	18.18182	25	1	3.773	29.57509399	30.25569867	7.828283	9.090909	0.252525	47.16	28.54736636
2500	1.010101	8.080808	18.18182	25	1	3.773	29.57509399	30.25211396	7.828283	9.090909	0.252525	47.16	28.54736636
3000	1	8	18	12.5	1	3.773	30.25620894	30.23043418	8	9		47.16	28.60578616
3500	1.06383	8.510638	19.14894	25	1	3.773	29.66762592	30.3067597	6.914894	9.574468	1.595745	47.16	28.24179079
4000	1.030928	8.247423	18.5567	25	1	3.773	29.61032146	30.25613385	7.474227	9.278351	0.773196	47.16	28.42789222
4500	1.052632	8.421053	18.94737	25	1	3.773	29.64789518	30.2720901	7.105263	9.473684	1.315789	47.16	28.30477133
5000	1.086957	8.695652	19.56522	25	1	3.773	29.70911566	30.30305229	6.521739	9.782609	2.173913	47.16	28.11287857
5500	1.086957	8.695652	19.56522	25	1	3.773	29.70911566	30.29848237	6.521739	9.782609	2.173913	47.16	28.11287857
6000	1.111111	8.888889	20	25	1	3.773	29.7535156	30.31825144	6.111111	10	2.777778	47.16	27.97987545
6500	1.111111	8.888889	20	25	1	3.773	29.7535156	30.30608673	6.111111	10	2.777778	47.16	27.97987545

Appendix 13 Coefficients for species thermodynamic properties

TABLE 4.10
Coefficients for species thermodynamic properties

Species	T range, K	a_{i1}	a_{i2}	a_{i3}	a_{i4}	a_{i5}	a_{i6}	a_{i7}
CO ₂	1000–5000	0.44608(+1)	0.30982(–2)	–0.12393(–5)	0.22741(–9)	–0.15526(–13)	–0.48961(+5)	–0.98636(0)
	300–1000	0.24008(+1)	0.87351(–2)	–0.66071(–5)	0.20022(–8)	0.63274(–15)	–0.48378(+5)	0.96951(+1)
H ₂ O	1000–5000	0.27168(+1)	0.29451(–2)	–0.80224(–6)	0.10227(–9)	–0.48472(–14)	–0.29906(+5)	0.66306(+1)
	300–1000	0.40701(+1)	–0.11084(–2)	0.41521(–5)	–0.29637(–8)	0.80702(–12)	–0.30280(+5)	–0.32270(0)
CO	1000–5000	0.29841(+1)	0.14891(–2)	–0.57900(–6)	0.10365(–9)	–0.69354(–14)	–0.14245(+5)	0.63479(+1)
	300–1000	0.37101(+1)	–0.16191(–2)	0.36924(–5)	–0.20320(–8)	0.23953(–12)	–0.14356(+5)	0.29555(+1)
H ₂	1000–5000	0.31002(+1)	0.51119(–3)	0.52644(–7)	–0.34910(–10)	0.36945(–14)	–0.87738(+3)	–0.19629(+1)
	300–1000	0.30574(+1)	0.26765(–2)	–0.58099(–5)	0.55210(–8)	–0.18123(–11)	–0.98890(+3)	–0.22997(+1)
O ₂	1000–5000	0.36220(+1)	0.73618(–3)	–0.19652(–6)	0.36202(–10)	–0.28946(–14)	–0.12020(+4)	0.36151(+1)
	300–1000	0.36256(+1)	–0.18782(–2)	0.70555(–5)	–0.67635(–8)	0.21556(–11)	–0.10475(+4)	0.43053(+1)
N ₂	1000–5000	0.28963(+1)	0.15155(–2)	–0.57235(–6)	0.99807(–10)	–0.65224(–14)	–0.90586(+3)	0.61615(+1)
	300–1000	0.36748(+1)	–0.12082(–2)	0.23240(–5)	–0.63218(–9)	–0.22577(–12)	–0.10612(+4)	0.23580(+1)
OH	1000–5000	0.29106(+1)	0.95932(–3)	–0.19442(–6)	0.13757(–10)	0.14225(–15)	0.39354(+4)	0.54423(+1)
NO	1000–5000	0.31890(+1)	0.13382(–2)	–0.52899(–6)	0.95919(–10)	–0.64848(–14)	0.98283(+4)	0.67458(+1)
O	1000–5000	0.25421(+1)	–0.27551(–4)	–0.31028(–8)	0.45511(–11)	–0.43681(–15)	0.29231(+5)	0.49203(+1)
H	1000–5000	0.25(+1)	0.0	0.0	0.0	0.0	0.25472(+5)	–0.46012(0)

Source: NASA Equilibrium Code.*

Appendix 14 Coefficients for polynomials

TABLE 4.11
Coefficients for polynomials [Eqs. (4.42) and (4.43)] for fuel enthalpy and specific heat

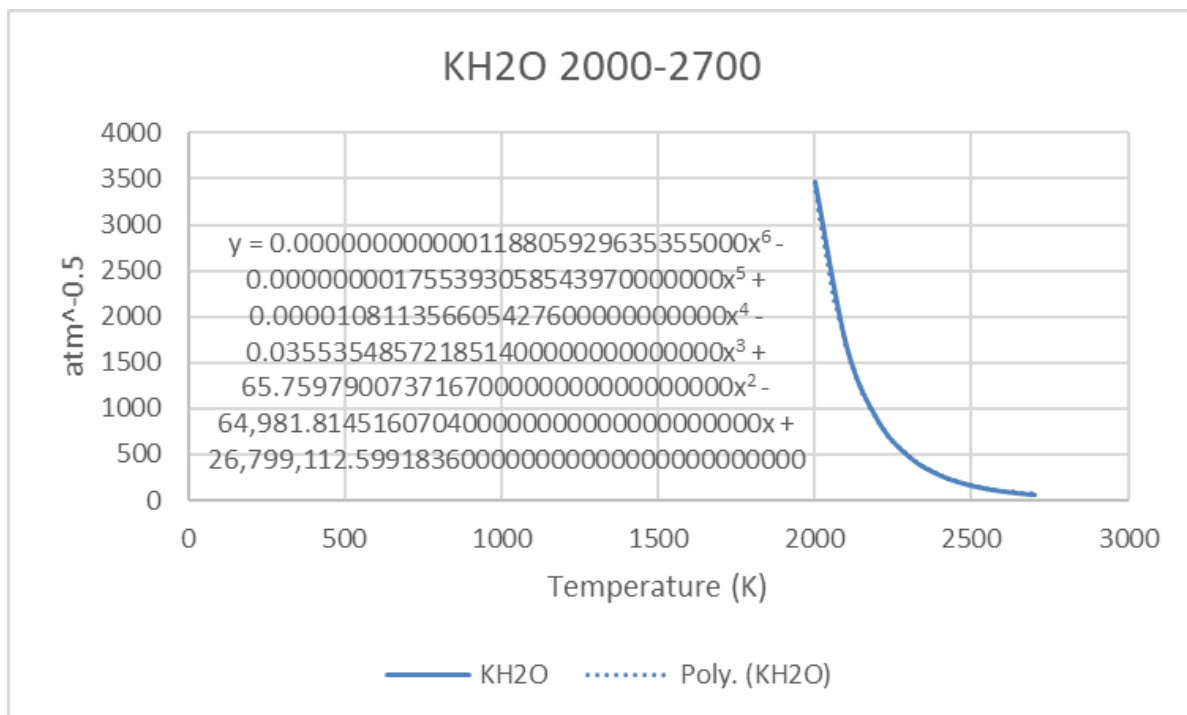
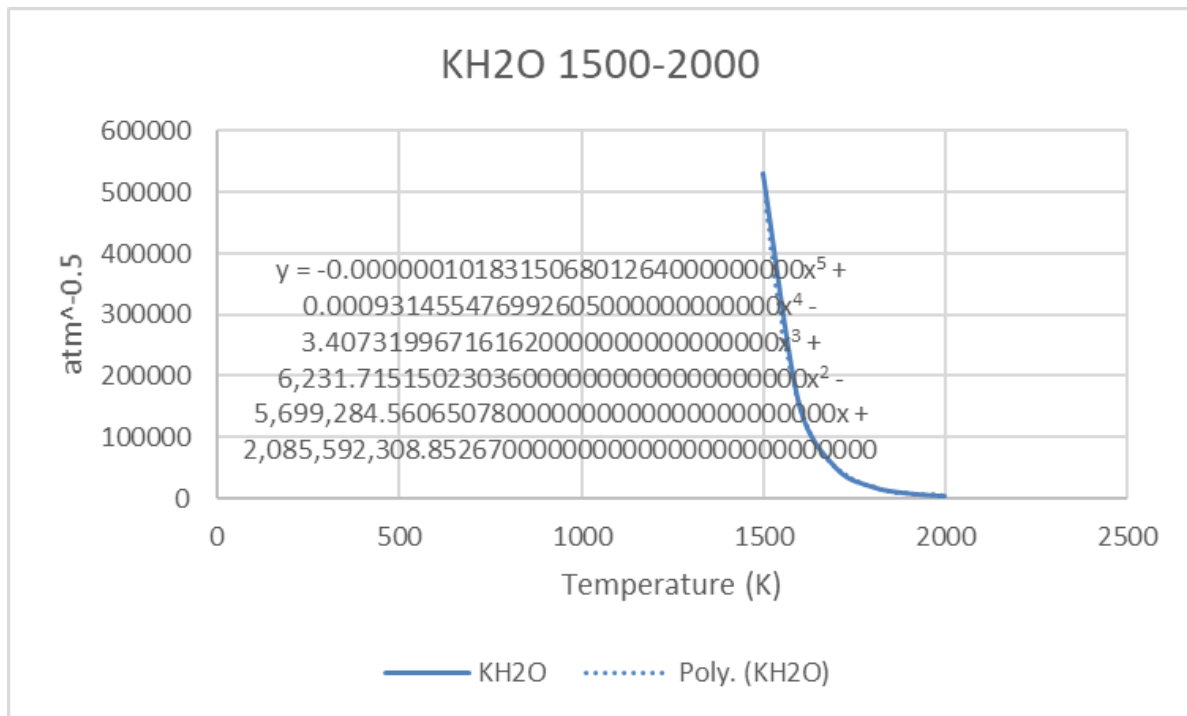
Fuel	Formula	Molecular weight	$(A/F)_s$	$(F/A)_s$	A_{f1}	A_{f2}	A_{f3}	A_{f4}	A_{f5}	A_{f6}	A_{f8}
Methane	CH ₄	16.04	17.23	0.0580	-0.29149	26.327	-10.610	1.5656	0.16573	-18.331	4.3000
Propane	C ₃ H ₈	44.10	15.67	0.0638	-1.4867	74.339	-39.065	8.0543	0.01219	-27.313	8.852
Hexane	C ₆ H ₁₄	86.18	15.24	0.0656	-20.777	210.48	-164.125	52.832	0.56635	-39.836	15.611
Isooctane	C ₈ H ₁₈	114.2	15.14	0.0661	-0.55313	181.62	-97.787	20.402	-0.03095	-60.751	20.232
Methanol	CH ₃ OH	32.04	6.47	0.1546	-2.7059	44.168	-27.501	7.2193	0.20299	-48.288	5.3375
Ethanol	C ₂ H ₅ OH	46.07	9.00	0.1111	6.990	39.741	-11.926	0	0	-60.214	7.6135
Gasoline	C _{8.26} H _{15.5}	114.8	14.64	0.0683	-24.078	256.63	-201.68	64.750	0.5808	-27.562	17.792
	C _{7.76} H _{13.1}	106.4	14.37	0.0696	-22.501	227.99	-177.26	56.048	0.4845	-17.578	15.235
Diesel	C _{10.8} H _{18.7}	148.6	14.4	0.0694	-9.1063	246.97	-143.74	32.329	0.0518	-50.128	23.514

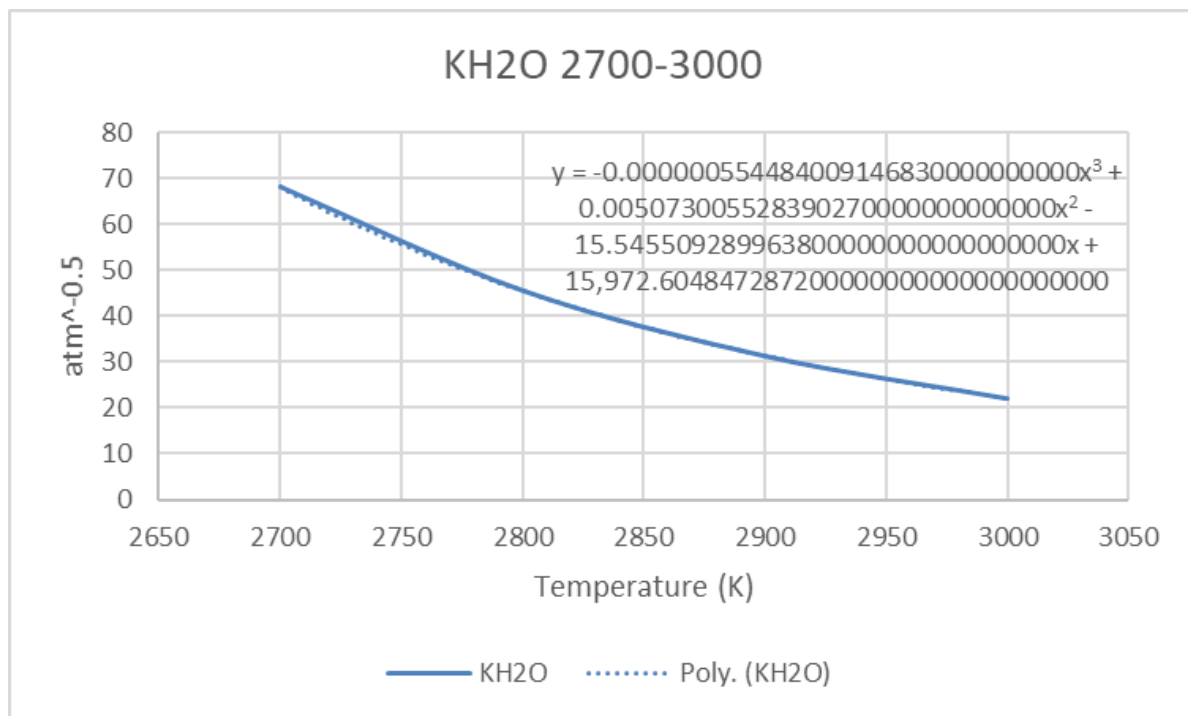
Units of A_{fi} such that $\bar{h}_f$ is in kcal/gmol and $\bar{c}_{p,f}$ is in cal/gmol · K with $t = T(K)/1000$.
 A_{f6} gives enthalpy datum at 298.15 K; $(A_{f6} + A_{f8})$ gives enthalpy datum at 0 K.

Appendix 15 Determination of product concentrations

1. At Given temperature read K_{CO_2} and K_{H_2O} from Table 28.
2. Assume value for $\frac{n_5}{n_t}$ and evaluate $(p \frac{n_5}{n_t})^{\frac{1}{2}}$.
3. Evaluate $\frac{n_1}{n_3}$ and $\frac{n_2}{n_4}$ from K_{CO_2} and K_{H_2O} expressions respectively using the step 2 value
4. Evaluate n_1 and n_3 from carbon balance, and n_2 and n_4 from hydrogen balance using step 3 value.
5. Evaluate n_5 from oxygen balance.
6. Evaluate n_6 from nitrogen balance.
7. Evaluate $n_t = \frac{n_5}{\text{assumed } \frac{n_5}{n_t}}$ and compare with $\sum n_j$ with $j = 1$ to 6.
8. Repeat from step 2 until $n_t = \sum n_j$.

(Goodger, 2000)





```

Sub goalseekdis()
'
' goalseekdis Macro
'
'

    Dim i As Long

    For i = 379 To 401
        Worksheets("1000").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 379 To 402
        Worksheets("1250").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 376 To 409
        Worksheets("1500").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 376 To 410
        Worksheets("1750").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 378 To 413
        Worksheets("2000").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 376 To 414
        Worksheets("2250").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 379 To 419
        Worksheets("2500").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 376 To 422
        Worksheets("3000").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 368 To 419
        Worksheets("3251").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 365 To 417
        Worksheets("4000").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 364 To 428
        Worksheets("4500").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 364 To 429
        Worksheets("5000").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 362 To 429
        Worksheets("5500").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 370 To 424
        Worksheets("6000").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i
    For i = 358 To 415
        Worksheets("6500").Range("AD" & i).FormulaR1C1 = "0.0000001"
    Next i

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```

For i = 379 To 401
    Worksheets("1000").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("1000").Range("AD" & i)
Next i
For i = 379 To 402
    Worksheets("1250").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("1250").Range("AD" & i)
Next i
For i = 376 To 409
    Worksheets("1500").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("1500").Range("AD" & i)
Next i
For i = 376 To 410
    Worksheets("1750").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("1750").Range("AD" & i)
Next i
For i = 378 To 413
    Worksheets("2000").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("2000").Range("AD" & i)
Next i
For i = 376 To 414
    Worksheets("2250").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("2250").Range("AD" & i)
Next i
For i = 379 To 419
    Worksheets("2500").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("2500").Range("AD" & i)
Next i
For i = 376 To 422
    Worksheets("3000").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("3000").Range("AD" & i)
Next i
For i = 368 To 419
    Worksheets("3251").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("3251").Range("AD" & i)
Next i
For i = 365 To 417
    Worksheets("4000").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("4000").Range("AD" & i)
Next i
For i = 364 To 428
    Worksheets("4500").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("4500").Range("AD" & i)
Next i
For i = 364 To 429
    Worksheets("5000").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("5000").Range("AD" & i)
Next i
For i = 362 To 429
    Worksheets("5500").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("5500").Range("AD" & i)
Next i
For i = 370 To 424
    Worksheets("6000").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("6000").Range("AD" & i)
Next i
For i = 358 To 415
    Worksheets("6500").Range("AQ" & i).GoalSeek Goal:=0.0000001, ChangingCell:=Worksheets("6500").Range("AD" & i)
Next i
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End Sub

```

Appendix 18 Constants rate for NO formation Mechanism

TABLE 11.1
Rate constants for NO formation mechanism¹

Reaction	Rate constant, cm ³ /mol·s	Temperature range, K	Uncertainty, factor of or %
(1) $O + N_2 \rightarrow NO + N$ (-1) $N + NO \rightarrow N_2 + O$	$7.6 \times 10^{13} \exp [-38,000/T]$ 1.6×10^{13}	2000–5000 300–5000	2 ±20% at 300 K
(2) $N + O_2 \rightarrow NO + O$	$6.4 \times 10^9 T \exp [-3150/T]$	300–3000	2 at 2000–5000 K ±30% 300–1500 K
(-2) $O + NO \rightarrow O_2 + N$	$1.5 \times 10^9 T \exp [-19,500/T]$	1000–3000	2 at 3000 K ±30% at 1000 K
(3) $N + OH \rightarrow NO + H$ (-3) $H + NO \rightarrow OH + N$	4.1×10^{13} $2.0 \times 10^{14} \exp [-23,650/T]$	300–2500 2200–4500	±80% 2

Appendix 19 Valve timing from 1000RPM to 6500RPM

