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COMBUSTION MODELLING BASED ON THE FORD FOX ENGINE

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

Signed: _____

Date: _____

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Abstract

This dissertation will explore the modelling of processes within spark-ignition internal combustion engines, with particular focus being applied to the modelling and analysis of the combustion phase to gain an understanding of the accuracy and limitations of such modelling as well as building an understanding of the process of combustion.

This dissertation will take as its initial data cylinder pressure data for several logpoints (representing different engine speeds and BMEPs) at both part load and full load. Polytropic indices for the compression and expansion phases will be calculated. These will be used to calculate pressure reached without combustion and, in turn, MFB profiles will be generated from experimental data. Wiebe function coefficients will be calculated, theoretical MFB profiles will be generated and compared with their experimental counterparts, and variations in Wiebe coefficients will be explored using data from one logpoint as a baseline for this comparison. This will allow an understanding of the function of the Wiebe coefficients and the application of the Wiebe function as a whole to develop. Finally, a two-zone combustion model will be produced that will allow the calculation of temperatures, specific heats and ratios thereof, masses and volumes of the unburned and burned regions. Specific heats and ratios thereof will also be calculated for the overall mixture within the cylinder. This will allow the calculation of both experimental and theoretical heat release and, therefore, combustion efficiency. The above calculations will be repeated for each logpoint of both part load and full load applications.

The modelling outlined above will take place entirely in Microsoft Excel due to its versatility and usability and a dissertation report will be constructed in Microsoft Word presenting the methodology, application and results of the models and calculations previously outlined.

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0. Nomenclature

Table 1: Nomenclature

ABBREVIATION / SYMBOL	MEANING
ABDC	After bottom dead centre
AFR	Air-fuel ratio
ATDC	After top dead centre
B	Bore diameter (m)
BBDC	Before bottom dead centre
BDC	Bottom dead centre
BMEP	Brake mean effective pressure
BTDC	Before top dead centre
C_p	Specific heat at constant pressure (J/kmol.K or J/kg.K)
C_v	Specific heat at constant volume (J/kmol.K or J/kg.K)
dQ_r	Heat released (J)
EOC	End of combustion
l	Connecting rod length (m)
LHV	Lower heating value (For Isooctane: 44MJ/kg)
MBT	Maximum brake torque timing
MFB	Mass fraction burned
r	Crankshaft radius (m)
RPM	Revolutions per minute
SOC	Start of combustion
TDC	Top dead centre
V_c	Clearance volume (cc or m ³)
γ	Ratio of specific heats
θ	Crankshaft angle (°)

1. Introduction

1.1. Background Information

Modelling of the processes occurring within the internal combustion engine has always been of significant importance to engineers and engine manufacturers. Heywood (1988, pp. 2-3) remarked that the early atmospheric internal combustion engine developed by Nicolaus A. Otto (1832-1891) and Eugen Langen (1833-1895) “obtained thermal efficiencies of up to 11 percent.” and that Otto’s four-stroke engine, first operated in 1876 achieved thermal efficiency of 14%. While Otto’s four-stroke engine achieved comparable thermal efficiency to that of his atmospheric engine, it achieved this with dramatically less displacement (310in³ compared to 4900in³) and weight (1250lb compared to 4000lb) (Heywood, 1988, p. 3). Around this time Alphonse Beau de Rochas also listed four conditions necessary to improve the efficiency of internal combustion engines in an albeit unpublished French patent, discovered in 1884 (Heywood, 1988, p. 2). This illustrates that even at the dawn of internal combustion engine development, particular attention was being paid to the importance of improving engine efficiency through a variety of parameters.

In recent years increasing attention has been paid by authorities worldwide on the environmental impact of internal combustion engines, whether spark-ignition or compression-ignition. In Europe this attention culminated in the implementation of the ‘Euro’ European Emissions Standards between 1992 and 1993 (Automobile Association Developments Ltd., 2018). Since then the Euro emissions standards have progressed through multiple iterations and are currently enforced through ‘Euro 6’ with the addition of Worldwide harmonised Light duty Test Procedures (WLTP) and Real Driving Emissions (RDE) tests to bolster their application to closer approximate real-world driving conditions.

The two cases mentioned above illustrate both that engine manufacturers have always been under pressure to improve and develop their engines and that the pressure to ensure an engine operates in the cleanest, most efficient manner possible is increasing steadily with the implementation of stricter regulations regarding their operation in the modern world. This is where modelling of the processes of the internal combustion engine can prove invaluable to engineers and engine manufacturers. Working, testable engines are expensive to manufacture. They require costly materials, complex manufacturing processes and expensive development procedures to reach production, even if for the sole purpose of testing. The use of rigorous, accurate modelling allows the effect of further research and development ideas to be visualised and assessed without manufacturing testable engines.

Mathematical modelling of internal processes is especially useful when considering the two most important phases of the four-stroke cycle, the compression phase and the expansion (or combustion) phase. While, in recent years, developments in manufacturing materials have allowed the production of clear cylinders and cylinder heads, thereby facilitating the observance of the process of combustion, for much of history the only method of analysing the process of combustion was through simple recording of cylinder pressure and application of mathematical modelling. Therefore, considerable research has been performed on the application of mathematical and analytical models on the combustion process and, broadly, on the operation of internal combustion engines.

Arguably the most extensively used model when analysing the process of combustion is the Wiebe (also referred to as Wiebe, Vibe or Viebe) function, developed by Russian engineer Ivan Ivanovitch Wiebe during the 1950s and displayed below as found in Heywood (1988):

$$x_b = 1 - e^{-a\left(\frac{\theta - \theta_0}{\Delta\theta}\right)^{m+1}}$$

Where x_b denotes MFB, $\Delta\theta$ denotes burn duration, θ denotes instantaneous crankshaft angle and θ_0 denotes crankshaft angle at SOC. The parameters a and m are parameters that dictate the shape of the MFB profile and are both different and calculable depending on individual engines, engine speeds and loads, as well as other engine characteristics.

1.2. Objectives

This dissertation will seek to explore the processes and limitations of modelling of internal combustion engine operation. In particular, this dissertation will endeavour to explore the calculation and effect of the Wiebe function a and m coefficients for differing engine speeds and loads through the processing of cylinder pressure data and the subsequent calculation of polytropic indices and MFB profiles. MFB profiles will be generated both from experimental cylinder pressure data and from theoretical MFB calculations. MFB profiles will also be generated from one set of data with varying values of a and m in order to compare the effect of changes in individual coefficients on the overall MFB profile generated. Finally, a two-zone combustion model will be produced to calculate temperatures, specific heats and ratios thereof for both the burned and unburned zones and, through the calculation of heat release, the combustion efficiency of each logpoint of both part load and full load will be calculated. The engine considered in this dissertation was the Ford Fox 1.0L and the original dataset consisted of several logpoints, corresponding to several engine speeds, at both part load and full load. The analytical and modelling stages of the creation of this dissertation took place entirely in Microsoft Excel due to its versatility and usability.

2. Literature Review

Multiple publications have been produced regarding the modelling of the combustion process within the internal combustion engine.

Ghojel (2010) provided a detailed overview of the history of the Wiebe function and, in particular of the engineer responsible for its creation, Ivan Wiebe. Ghojel explored in this paper the origins of the Wiebe function in the fundamental thermodynamic process of combustion and detailed the steps by which Wiebe constructed the final function. This paper highlights applications of the Wiebe function, stressing Wiebe's belief that this function was "universal" and that it was able to "adequately predict the burn rate in SI and CI engines" (Ghojel, 2010, p. 301). This paper continues to present applications of the Wiebe function used in modern engineering and highlights three separate approaches. This paper explains how, while the standard form of the Wiebe function (referred to in this paper as the "single-Wiebe function") is still widely used, at least four applications exist for "double-Wiebe" functions designed for analysis of diesel engines while "multi-Wiebe" functions have been applied to dual-fuel engines and HCCI diesel engines. This paper finally assesses the use of Wiebe functions in combustion modelling software and concludes that while these software packages provide the user with multi-zone combustion models and predictive thermodynamic capabilities, the Wiebe functions utilised by these packages are almost universally single-Wiebe functions.

Yeliana *et al.* (2008) built on the concept that the standard single-Wiebe function was insufficient to accurately model MFB profiles, specifying cases of non-symmetric combustion profile as key cases where this is true. This paper obtained experimental data from a fuel injected engine with variable compression ratio ranging for 8:1 to 16:1 and a single-cylinder direct injection SI Hydra engine with variable compression ratio ranging from 11:1 to 18.5:1, both using ethanol-gasoline blended fuel. In this paper Yeliana *et al.* propose an additional "amplitude correction factor" b to the standard Wiebe function as follows:

$$x_b = b \left(1 - e^{-a \left(\frac{\theta - \theta_0}{\Delta \theta} \right)^{m+1}} \right)$$

The effect of the amplitude correction factor on the standard Wiebe function is shown in the paper to refine the MFB profile generated. However, this refinement is only reliably shown in one of five methods demonstrated to calculate the remaining two Wiebe function coefficients. This paper also explores the use of the double-Wiebe function and assesses its accurate correlation with experimental data. The double-Wiebe function utilised is shown below:

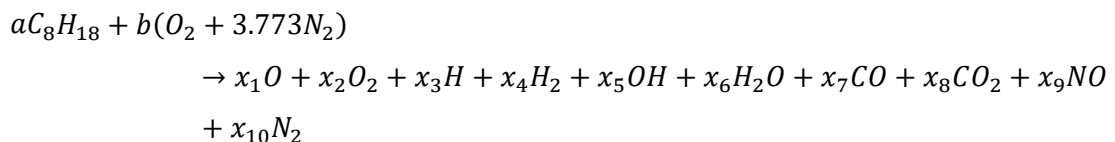
$$x_b = p \left(1 - e^{-\left(\frac{\theta - \theta_0}{\alpha_1}\right)^{\beta_1}} \right) + (1 - p) \left(1 - e^{-\left(\frac{\theta - \theta_0}{\alpha_2}\right)^{\beta_2}} \right)$$

$$\text{where } \alpha = \frac{-1}{a^{m+1}} \cdot \Delta\theta$$

Yeliana *et al.* also performed single-zone and two-zone combustion models focussing on MFB and heat release profiles and the effect thereupon of differing ignition timing. Notably, this paper states that by defining the combustion duration as that of 0-90% MFB the Wiebe coefficient a “has a fixed value of 2.3026” while for a combustion duration of 0-99.9% MFB the Wiebe coefficient a has a fixed value of 6.9078 (Yeliana *et al.*, 2008, p. 104).

Galindo *et al.* (2010) focussed on MFB and heat release rate calculations for small two-stroke engines such as those found within agricultural and industrial applications. While two-stroke engines are outside of the scope of this dissertation the combustion process within the cylinder is identical between two-stroke and four-stroke engines. Hence this study was deemed to be applicable to this dissertation. Galindo *et al.* performed MFB and heat release rate calculations for two engines (one of 50cc displacement and one of 125cc displacement) while varying exhaust system configuration, engine speed and ignition timing. Mentioned specifically in the paper was the lack of verified data regarding the Wiebe function coefficients which led the authors to use coefficients regarding 1600cc four-stroke engines. However, consistent with Yeliana *et al.*, this paper states that for a combustion duration of 0-99.9% MFB the Wiebe coefficient a had “been fixed to 6.9” (Galindo *et al.*, 2010, p. 7). The paper concludes on this matter that these coefficients were insufficient in yielding accurate correlation of the MFB profile with experimental data. Additionally, this paper approaches heat release rate calculations in greater depth than this dissertation, considering Nusselt and Reynold’s numbers for their engines and factoring heat loss through the piston, cylinder head and cylinder liner into their calculations of heat release rate.

Klein and Eriksson (2004) explored the accuracy of specific heats obtained through two-zone combustion modelling. This paper utilised a full combustion model including complete dissociation and so used the following combustion equation:



This level of dissociation modelling is beyond the scope of this dissertation, which fails to consider dissociation upon combustion. The paper begins by outlining three methods for the calculation of γ and subsequently concluding that there are discrepancies between the

accuracy of differing methods of calculation. The chemistry of the full combustion equation is now presented followed by analysis of the two-zone combustion model utilised in the paper, first by unburned region and followed by burned region. For each region considered graphs of produced illustrating how γ changes as a function of temperature at varying temperatures and AFRs. These graphs would be useful for this dissertation in providing verification and comparison between Klein and Eriksson's paper and this dissertation regarding the relationship between γ and temperature.

Ballinger (2015) also explored the application of a two-zone combustion model in assessing the performance of internal combustion engines, albeit as part of an aim to increase engine performance overall. The engine chosen by Ballinger as the focus of his work was the 1.6L four-cylinder Ford Sigma engine. Ballinger used Matlab as the predominant computational program with limited focus on Microsoft Excel for the purposes of model validation. A key focus of Ballinger's work was on the detection and prevention of detonation (alternatively referred to as engine knock) and the optimisation of useful work produced by an engine. Applicable to this dissertation was Ballinger's work in constructing a two-zone combustion model, in the calculation of specific heats and in the use of cylinder pressure data to ascertain subsequent information such as polytropic indices.

Additionally, two other resources provided valuable background information regarding all areas of investigation in this dissertation. The works of Heywood (1988) and Blair (1999) provide a detailed overview of the operation of both spark-ignition and compression-ignition internal combustion engines. In particular, Heywood provided a method for calculation of specific heats for fuels while Blair provided detailed examples of MFB profiles for various engines along with their respective Wiebe function coefficients. This information proved useful in validating the results found through the creation of this dissertation.

Finally, the works of Borman and Ragland (1998), Merker *et al.* (2004), Warnatz, Maas and Dibble (2006) and Turns (2006) all provided detailed information on the physical and mathematical processes of combustion. While much of this information was outside of the scope of this dissertation, such as that regarding the process of chemical dissociation, it was still valuable in building an effective knowledge of the processes surrounding combustion.

3. Methodology

3.1. Initial Data

The engine considered for this dissertation is the Ford Fox 1.0L turbocharged three-cylinder. This engine was selected primarily due to the availability of verified data through the University of Wales Trinity Saint David. Its engine specifications are as displayed in table 2:

Table 2: Ford Fox Engine Geometry

Bore	71.9mm
Stroke	82mm
Compression Ratio	10:1
Connecting Rod Length	86mm
Crankshaft Radius	41mm
Cylinders	3
Crankshaft Offset	6mm

For the purposes of this dissertation a pre-recorded dataset was sourced from the University of Wales Trinity Saint David (Ford Motor Company, 2018). This dataset contained cylinder pressure data for each cylinder for a full four-stroke engine cycle. The phases of the 720° crankshaft angle four-stroke cycle are shown below in table 3:

Table 3: Phases of the Four-Stroke Engine Cycle and their Corresponding Crankshaft Angles

CRANKSHAFT ANGLE (°)	PHASE
-360 → -181	Intake
-180 → -1	Compression
0 → 179	Expansion
180 → 359	Exhaust

Between 0° and 60° crankshaft angle cylinder pressures were recorded at intervals of 0.2° crankshaft angle. Outside of this range cylinder pressures were recorded at intervals of one degree crankshaft angle. This data contained the aforementioned cylinder pressure data for both part load and full load at a range of engine speeds as detailed in table 4 below:

Table 4: Data Logpoint Numbers and Corresponding Engine Speeds

	LOGPOINT #	ENGINE SPEED (RPM) (FIGURES IN ITALICS SHOW EXACT ENGINE SPEEDS LISTED IN DATASET)
PART LOAD	Logpoint 1	800
	Logpoint 3	1500
	Logpoint 4	1500
	Logpoint 9	2000
	Logpoint 14	2500
	Logpoint 18	3000
	Logpoint 19	4000
FULL LOAD	Logpoint 1	1000 (<i>999.8</i>)
	Logpoint 5	2000 (<i>1999.8</i>)
	Logpoint 7	3000 (<i>2999.8</i>)
	Logpoint 10	4500 (<i>4500.4</i>)
	Logpoint 14	6000 (<i>6000.1</i>)

This dataset also included other test parameters relating to each data logpoint such as BMEP, spark advance, specific air consumption and intake manifold pressure.

Throughout the creation of the Excel workbook utilised in this dissertation, in order to facilitate usability and easy identification of errors in complex functions, names were applied to any cells that could be used in Excel functions. These included engine geometry parameters and performance parameters as well as results such as polytropic indices and Wiebe function coefficients.

3.2. Cylinder Pressure

The first stage in processing the dataset was to condense the cylinder pressure data from three cylinders to one range of average pressures throughout the four-stroke cycle according to the arithmetic mean as shown in the following equation:

$$Average = \frac{1}{n} \times \sum_{i=1}^n x_i$$

Where n denotes the number of terms being averaged and x denotes the numerical value of each term being averaged. This action was deemed appropriate as cylinder pressures at a given crankshaft angle show little variation between cylinders and the use of average pressures reduced the amount of redundant and unnecessary calculation.

3.3. Cylinder Volume

Cylinder volume can be calculated as the sum of the cylinder clearance volume and the instantaneous swept volume as shown below (Heywood, 1988, p. 43):

$$V = V_c + \frac{\pi B^2}{4} (l + r - s)$$

Clearance volume V_c can be calculated from total swept volume V_s and compression ratio CR as shown below:

$$V_c = \frac{V_s}{CR - 1}$$

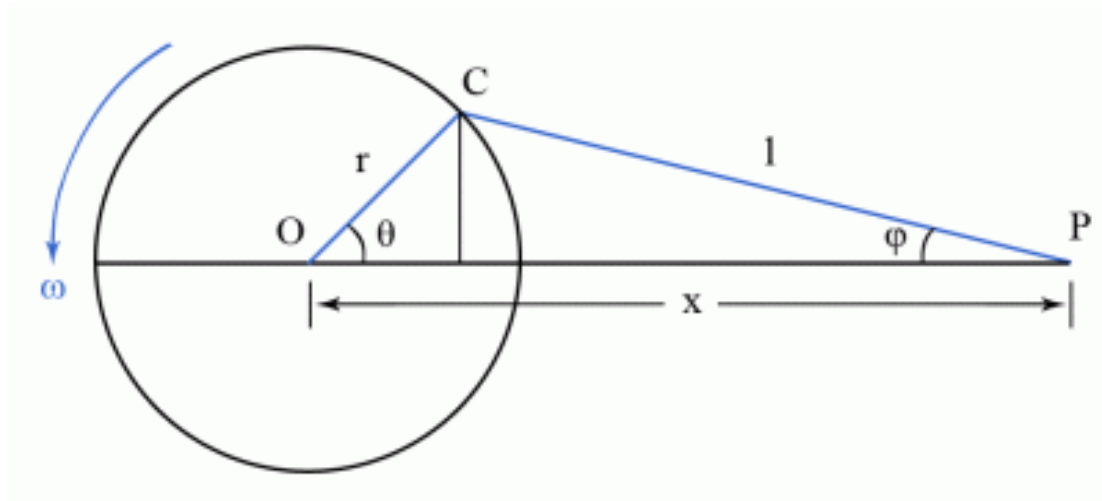


Figure 1: Cylinder, Crankshaft and Piston Geometry for Cylinder Volume Calculation without Crankshaft Offset

Instantaneous swept volume can be calculated as a function of crankshaft angle by first calculating the vertical distance the piston has moved through that crankshaft angle rotation.

Figure 1 (CodeCogs, 2018) shows the common method of visualising and calculating cylinder volume for an engine without crankshaft offset, albeit displayed horizontally rather than vertically. Vertical piston position can be calculated as the piston position at TDC, that is the connecting rod length plus the crankshaft radius, minus the vertical distance travelled by the piston. From figure 1 the distance between the piston and TDC s can be calculated as follows:

$$s = r + l - x = r + l - l \cos \theta - r \cos \phi$$

$$\text{However, } l \sin \theta = r \sin \phi$$

$$\therefore \sin \phi = \frac{l}{r} \sin \theta \text{ and } \cos \phi = \sqrt{(1 - \sin^2 \phi)}$$

$$\therefore s = r + l - l \cos \theta - r \sqrt{(1 - \sin^2 \phi)}$$

$$\therefore s = r + l - l \cos \theta - r \sqrt{1 - \frac{r^2}{l^2} \sin^2 \theta}$$

While the method shown previously is applicable to engines where the bore centreline and crankshaft centre are aligned, a different equation is required for engines, such as the Ford Fox, where the crankshaft is offset from the bore centreline. Figure 2 (Rollins, no date) shows a visualisation of an engine with crankshaft offset d .

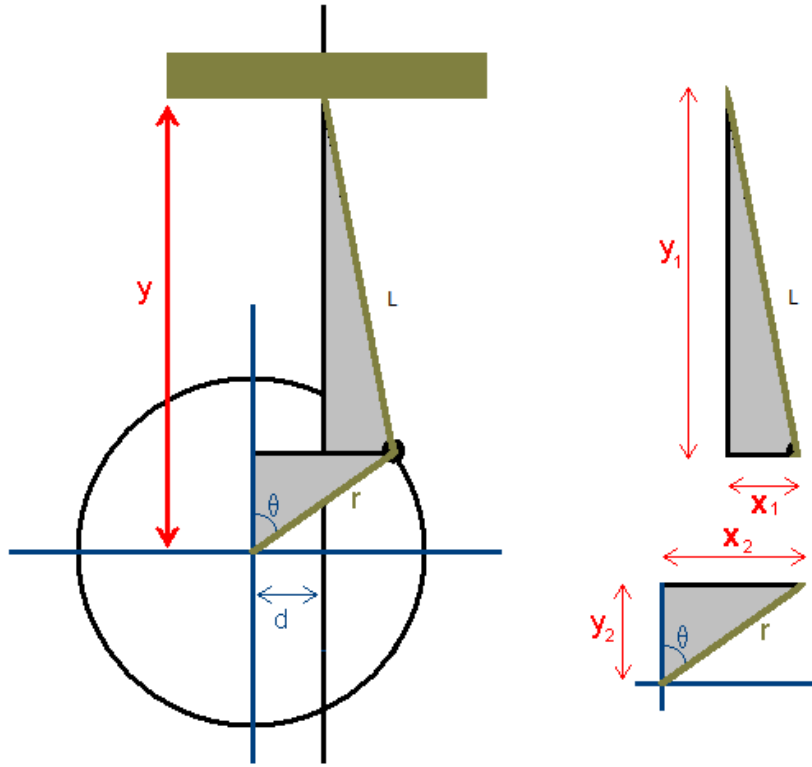


Figure 2: Cylinder, Crankshaft and Piston Geometry for Cylinder Volume Calculation with Crankshaft Offset

Calculating instantaneous piston position y in this case is more complex and requires the derivation of several equations from the two triangles detailed on the right-hand side of figure #. From the connecting rod triangle the following equation can be seen:

$$l^2 = x_1^2 + y_1^2$$

From the lower, crankshaft triangle the following equations can be seen:

$$\sin \theta = \frac{x_2}{r}$$

$$\cos \theta = \frac{y_2}{r}$$

$$x_2 = x_1 + d$$

These four previous equations can now be rearranged and substituted to give an equation for instantaneous piston position as follows:

$$y = y_1 + y_2$$

$$\therefore y = \sqrt{l^2 - x_1^2} + y_2$$

$$\therefore y = \sqrt{l^2 - (x_2 - d)^2} + y_2$$

$$\therefore y = \sqrt{l^2 - (r \sin \theta - d)^2} + y_2$$

$$\therefore y = \sqrt{l^2 - (r \sin \theta - d)^2} + r \cos \theta$$

The final equation for instantaneous piston position calculates the vertical piston position from BDC. However, to calculate cylinder volume, the vertical piston position from TDC is required. In order to calculate this position an expression for piston position at TDC must also be derived. Piston position from BDC can then be subtracted from piston position at TDC to calculate instantaneous cylinder volume.

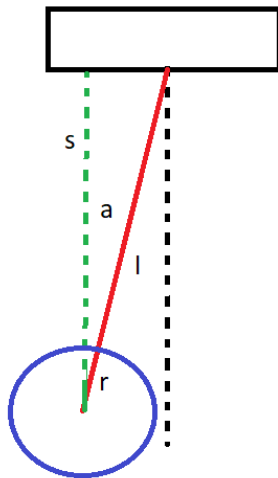


Figure 3: Relationship between Crankshaft Radius, Connecting Rod Length and Vertical Piston Position

Figure 3 shows the piston of an engine with an offset crankshaft at TDC. Since TDC is the highest point in the piston's reciprocal vertical motion, TDC can be seen to be reached when both the crankshaft radius and the connecting rod form a straight line. Since the crankshaft is offset from the cylinder bore centreline, this point is reached at an angle of crankshaft rotation a . The vertical position of the piston s at this point can now be calculated by the following equation:

$$s = (r + l) \cos \theta_{TDC}$$

$$\text{where } \theta_{TDC} = \sin^{-1} \frac{\text{offset}}{r + l}$$

Combining the equations above for instantaneous vertical piston position with respect to BDC y and vertical piston position with respect to TDC s allows the instantaneous cylinder volume V_{cyl} to be calculated as follows:

$$V_{cyl} = V_c + \frac{\pi B^2}{4} (s - y)$$

$$\therefore V_{cyl} = V_c + \frac{\pi B^2}{4} ((r + l) \cos \theta_{TDC} - (\sqrt{l^2 - (r \sin \theta - d)^2} + r \cos \theta))$$

3.4. Logp against logV and Polytropic Indices

Graphs of logp against logV are especially useful in the analysis of engine operation and performance as they allow the identification of the start and end points of the combustion process as well as enable the calculation of the polytropic indices of the compression and expansion phases of the operation of the engine in question.

Polytropic indices are key pieces of information in the modelling process as the fuel-air mixture within the cylinder is treated as an ideal gas and the compression and expansion phases are treated as polytropic thermodynamic processes. That is, processes that obey the following relationship:

$$pV^n = C$$

Where n denotes the polytropic index of the process and C denotes a constant. Hence, the next stage in processing the dataset was to calculate logarithms ($\log_{10}$) of both cylinder pressure and cylinder volume.

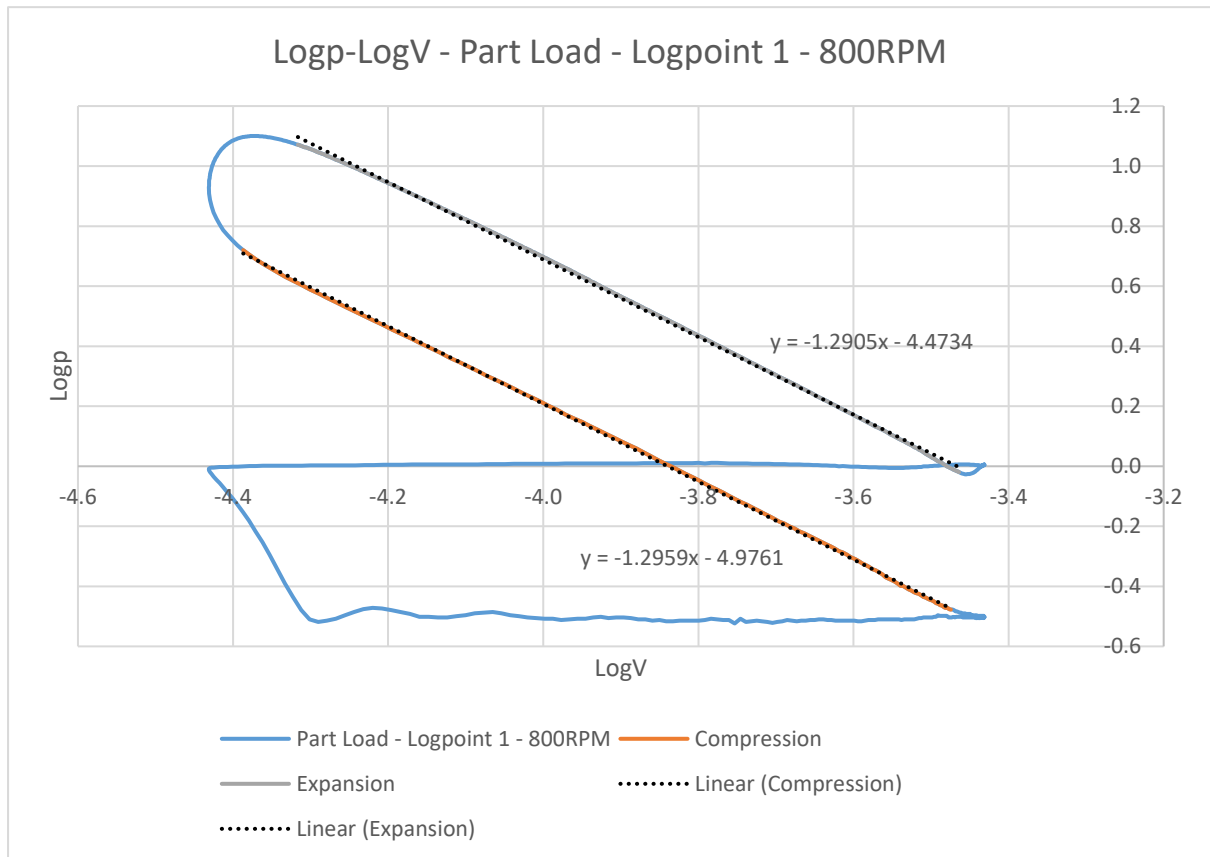


Figure 4: Logp-LogV Graph - Part Load - Logpoint 1 - 800RPM

Figure 4 shows a typical graph of logp against logV, in this case of part load logpoint 1 at 800RPM engine speed. The graph shows logp and logV data for the entire four-stroke cycle

of the logpoint with the compression and expansion phases also displayed. Linear trendlines for the compression and expansion phases allow the gradients of the compression and expansion phases to be shown. The magnitudes of these gradients indicate the polytropic indices of their respective phases. The points in the upper left quadrant of the graph where the data deviates from a straight line and resumes a straight line indicate the points of SOC and EOC respectively.

3.5. Pressure Without Combustion

As the cylinder rises through the compression stroke with both inlet and exhaust valves closed, the pressure within the cylinder rises before combustion has begun. It is possible to calculate the instantaneous pressure without combustion through the equation below:

$$p_{2n} = p_1 \times \left(\frac{V_1}{V_2}\right)^n$$

Where p_{2n} denotes the instantaneous pressure rise without combustion and n denotes the polytropic index. As discussed previously, the polytropic index differs between the compression and expansion phases so the data processing in Excel required a function to accommodate this as follows:

$$=IF(M7<0,Q7*(L7/L8)^{n_{compression_PL_LP1}},Q7*(L7/L8)^{n_{expansion_PL_LP1}})$$

The logical test in the first portion of the above equation differentiates between before and at or after TDC. In this way Excel can be commanded to use different equations based on the crankshaft angle considered and, in this case, is commanded to use the polytropic index of compression before TDC and the polytropic index of expansion after TDC.

3.6. Actual Mass Fraction Burned

MFB can be calculated both through algebraic means, introduced in section 1.1 and further discussed in sections 3.7 through 3.8, and through pressure data processing by utilising p_{2n} data. The first stage in calculating MFB was to calculate Δp , the difference between the pressure reached in the cylinder and p_{2n} as follows in both mathematical form and Excel function form:

$$\Delta p = p_{actual} - p_{2n}$$

$$=Q8-V7$$

Δp can now be utilised to calculate instantaneous MFB through the following equation, again shown in both mathematical form and Excel function form:

$$MFB = \frac{\sum_{\theta_{SOC}}^{\theta} \Delta p}{\sum_{\theta_{SOC}}^{\theta_{EOC}} \Delta p}$$

$$=(SUM(\$W\$349:W349))/(SUM(\$W\$349:\$W\$532))$$

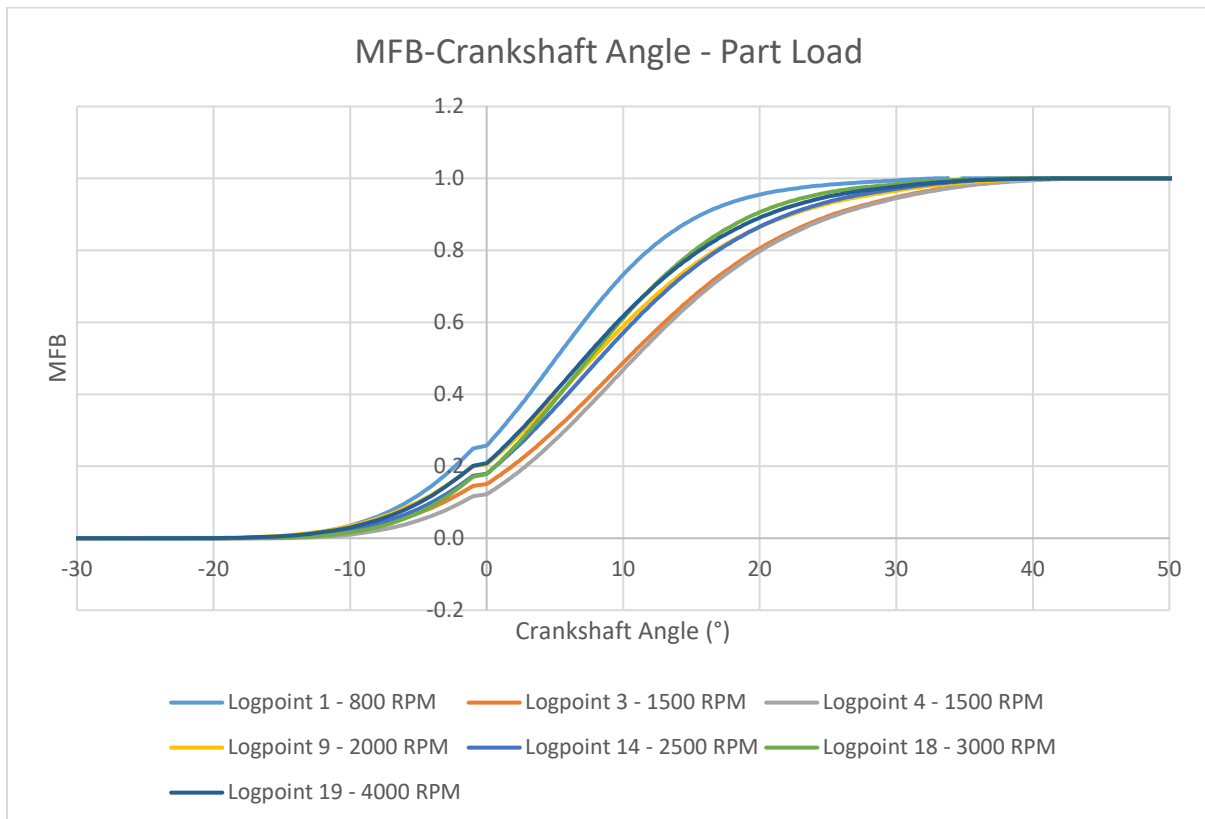


Figure 5: MFB-Crankshaft Angle - Part Load - All Logpoints

Figure 5 shows a graph of MFB against crankshaft angle, in this case of all logpoints at part load. The typical shape of the MFB curve can be observed below, characterised by a relatively slow burn rate for the first and last ~10% and a relatively sharp mid-burn section. Also observed from figure 5 is the difference in SOC and EOC points between different data logpoints. This could be attributed to the Fox's use of variable spark timing for each logpoint.

3.7. Wiebe Function Coefficients

The algebraic function for calculating MFB, commonly known as the Wiebe function and introduced in section 1.1, features two parameters undefined by engine performance characteristics. These are the a and m terms which were referred to by Heywood as “adjustable parameters” that can change “the shape of the curve significantly” (1988, p. 390), while Blair (1999, p. 82) referred to these coefficients as simply “assigned numbers”. However, since MFB has already been calculated previously, and all other parameters are known, the Wiebe function can be rearranged with respect to these coefficients to calculate their value. Both coefficients will differ between part load and full load and between each logpoint within those loads. These coefficients also differ between individual engines and vary across engine speeds. The rearrangement of the Wiebe function is displayed below:

$$MFB = 1 - e^{\left(-a\left(\frac{\theta - \theta_{SOC}}{\theta_D}\right)^{m+1}\right)}$$

Rearranging the Wiebe function to make the exponent term the subject gives:

$$e^{\left(-a\left(\frac{\theta - \theta_{SOC}}{\theta_D}\right)^{m+1}\right)} = 1 - MFB$$

Taking natural logarithms on both sides gives:

$$-a\left(\frac{\theta - \theta_{SOC}}{\theta_D}\right)^{m+1} = \ln(1 - MFB)$$

Multiplying both sides by -1 changes the sign of both sides:

$$a\left(\frac{\theta - \theta_{SOC}}{\theta_D}\right)^{m+1} = -\ln(1 - MFB)$$

Finally, taking natural logarithms of both sides a second time splits the left-hand side and is the final manipulation of the Wiebe function needed to calculate the a and m parameters:

$$\ln a + \ln\left(\frac{\theta - \theta_{SOC}}{\theta_D}\right)^{m+1} = \ln(-\ln(1 - MFB))$$

Although the previous equation is the last manipulation of the base formula, it is not the last step in calculating the Wiebe coefficients. Graphs can now be created of $\ln(-\ln(1-\text{MFB}))$ against $\ln(\theta-\theta_{\text{SOC}}/\theta_{\text{D}})$ and the gradient and y-axis intercept used to calculate the Wiebe coefficients in the following manner:

$$\text{Wiebe } a \text{ coefficient} = e^{y\text{-axis intercept}}$$

$$\text{Wiebe } m \text{ coefficient} = \text{gradient} - 1$$

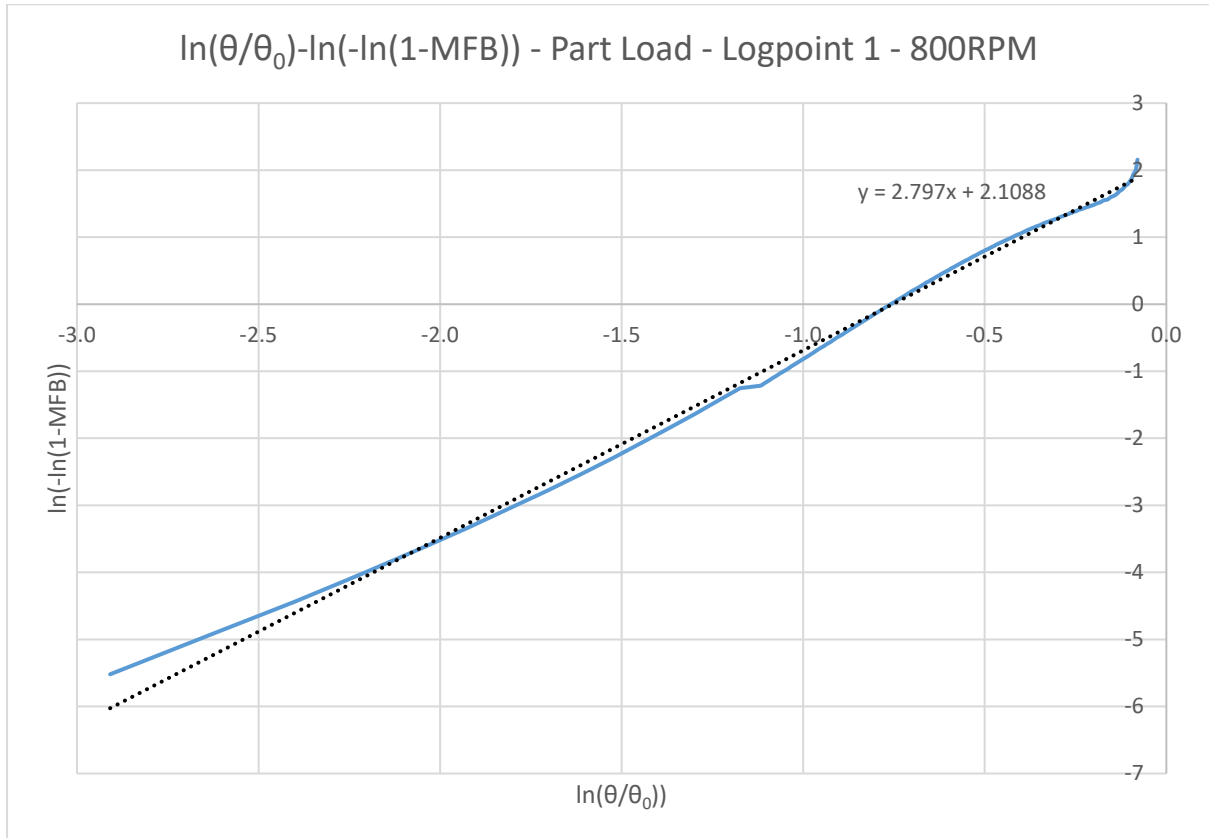


Figure 6: $\ln(\theta/\theta_0)-\ln(-\ln(1-\text{MFB}))$ - Part Load - Logpoint 1 - 800RPM

Figure 6 above shows a typical Wiebe coefficients graph with linear trendline displayed in order to identify the gradient and y-axis intercept. Figure 6 is the Wiebe coefficient graph for part load, logpoint 1 at an engine speed of 800RPM. In this case the Wiebe coefficient calculations are as follows:

$$\text{Wiebe } a \text{ coefficient} = e^{y\text{-axis intercept}} = e^{2.1088} = 8.2383 \text{ (4 d.p.)}$$

$$\text{Wiebe } m \text{ coefficient} = \text{gradient} - 1 = 2.797 - 1 = 1.797 \text{ (3 d.p.)}$$

3.8. Theoretical Mass Fraction Burned

Following the calculation of the Wiebe function coefficients the MFB for each logpoint can now be recalculated and a theoretical MFB curve can be produced and compared to the MFB curves obtained from cylinder pressure data. This provides the opportunity for the Wiebe function coefficients calculated in section 3.7 to be verified by observing the correlation between the traces of actual MFB and theoretical MFB. By comparing the differences in MFB traces the accuracy of the Wiebe function in combustion modelling can also be assessed as opposed to MFB calculation through cylinder pressure data alone. Calculating MFB by this method also allows the easy variation of Wiebe function coefficients in order to assess and analyse the effect of these coefficients on the MFB curve. This will be further explored in section 4.7.

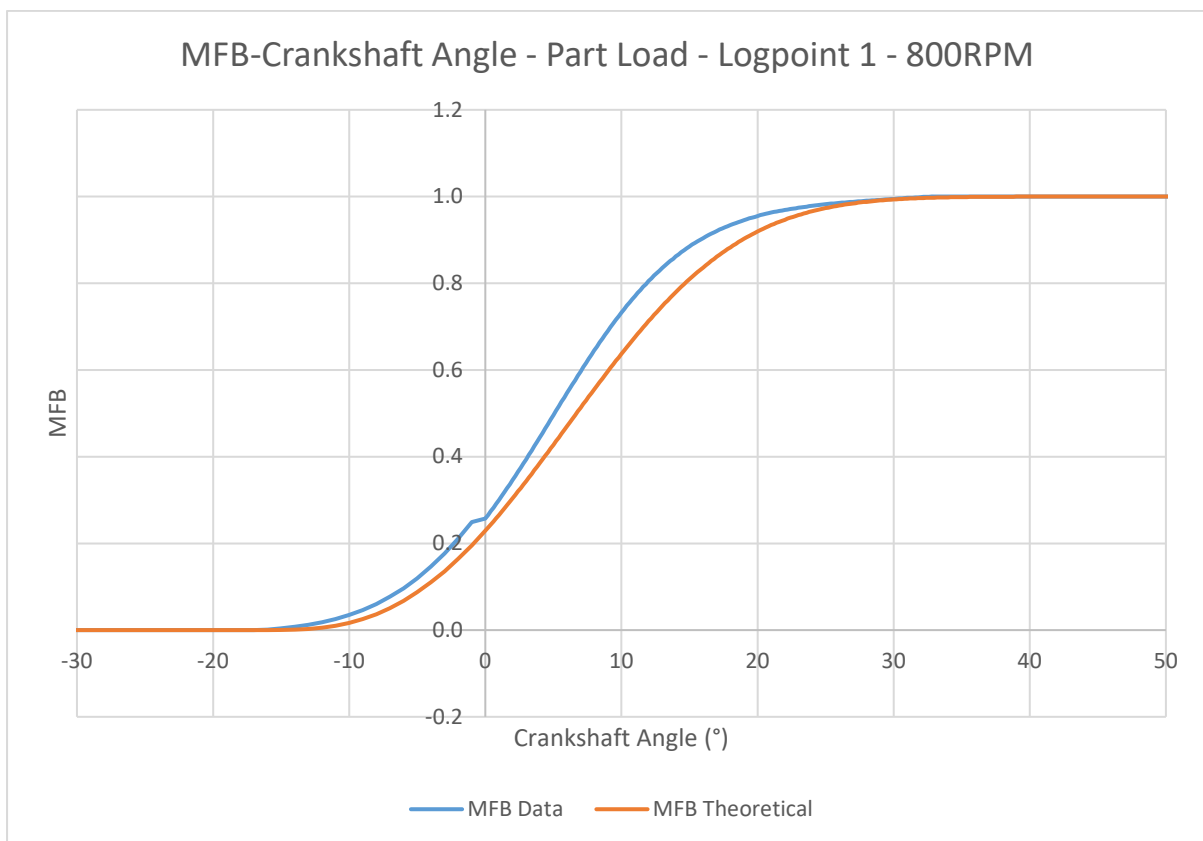


Figure 7: MFB-Crankshaft Angle - Part Load - Logpoint 1 - 800RPM

Figure 7 shows an example of the MFB curves generated by cylinder pressure data and by the Wiebe function, in this case for part load logpoint 1. This illustrates that while the points of SOC and EOC remain identical between the actual and theoretical MFB curves, the mid-burn characteristics differ between these two. Notably, the actual MFB trace experiences a slight deviation from a smooth burn characteristic approximately one degree BTDC. As will

be explored in section 4.5, this potential anomaly is present in MFB curves for all logpoints at part load but does not feature in full load MFB curves.

3.9. Variations in Wiebe Function Coefficients

At this point in the dissertation MFB profiles were generated with varying values of a and m , using the theoretical MFB profile of part load logpoint 1 as a baseline profile to explore the effect of variance of these coefficients on the MFB profile. All other parameters of the Wiebe function remained unchanged. Table 5 displays the a and m coefficients used in the different variations of the Wiebe function, as well as their associated series names.

Table 5: MFBvary# Fields and Corresponding Values of Wiebe Function Coefficients

SERIES NAME	WIEBE a	WIEBE m
MFBvary1	6	2
MFBvary2	12	2
MFBvary3	6	0
MFBvary4	6	4

3.10. Two-Zone Combustion Model

At this point in the dissertation it was deemed appropriate to create a two-zone combustion model to aid in the accuracy of calculations of temperatures, specific heats C_p and C_v and the ratio thereof γ .

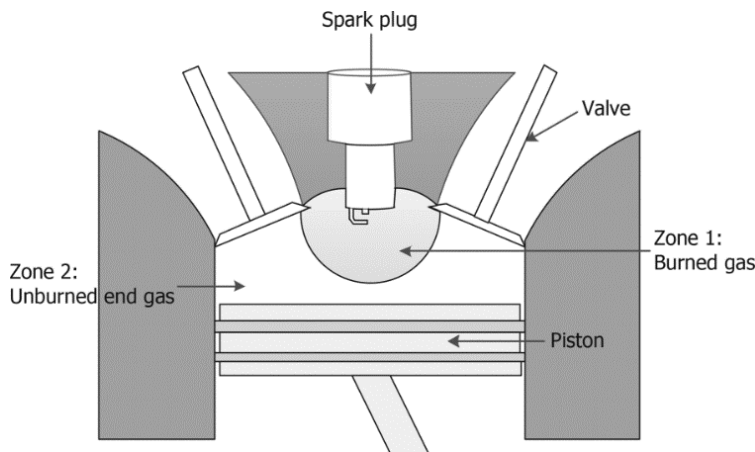


Figure 8: Visualisation of a Two-Zone Combustion Model

A two-zone combustion model can be visualised as illustrated in figure 8 (Amador, G. *et al.*, 2017). The gas within the cylinder can be considered as an unburned region, consisting of fuel and air with a temperature T_b , a volume V_b , a mass m_b and a pressure p , and a burned region, consisting of the products of the combustion reaction with a

temperature T_{un} , a volume V_{un} , a mass m_{un} and a pressure p . Each of these parameters must be considered separately, with the exception of m_b , and pressure which can be assumed to be identical across the regions as the pressure of both regions equalises at the speed of sound i.e. functionally instantaneously.

Temperatures can be calculated by two methods. The first method by which temperature may be calculated is obtained from the ideal gas law displayed below:

$$pV = nR_uT$$

Where: p = pressure (Pa)

V = volume (m^3)

n = number of moles of gas

R_u = universal gas constant (8314 J/mol.K)

T = absolute temperature (K)

The ideal gas law can also be expressed in terms of the mass of gas being considered as below. This variation of the ideal gas law was used in this dissertation as amounts of fuel and air within the cylinder were calculated as masses rather than moles.

$$pV = mRT$$

Where: m = mass of the gas (kg)

$$R = \text{specific gas constant} = \frac{8314}{\text{molecular weight of gas}} \text{ (J/kg.K)}$$

Rearranging this equation with respect to temperature gives:

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

Since this method of calculating temperatures requires the mass within the cylinder, this also has to be calculated. The Ford Fox takes advantage of variable AFRs in order to achieve optimum combustion. AFRs for set engine speeds and torque loads can be found from experimental testing reports (Ford Motor Company, 2012) as displayed in table 6. These values were identified by first converting BMEP values contained in the original dataset of this dissertation into torque values. An expression relating torque and BMEP can be derived as follows:

$$BMEP \times \text{engine displacement} = \text{engine work in 2 revolutions}$$

$$\text{Power} = \text{work per second}$$

$$\text{Power} = BMEP \times \text{engine displacement} \times \frac{RPM}{120}$$

$$\text{Torque} \times 4\pi = BMEP \times \text{engine displacement}$$

$$\text{Torque} = \frac{BMEP \times \text{engine displacement}}{4\pi}$$

Also included in the original dataset was air flow rate data (in kg/hr) for each logpoint as also displayed in table 6. This data, along with each logpoint's corresponding engine speed, allowed the air mass within a single cylinder to be calculated as follows in both mathematical form and Excel form:

$$m_{air} = \frac{\dot{m}_{air}}{60} \times \frac{1}{RPM \times 1.5}$$

$$=((Air_Mass_PL_LP1/60)/RPM_PL_LP1)/1.5$$

From calculating the air mass within a single cylinder, the fuel mass within a single cylinder could now be calculated as follows:

$$m_{fuel} = \frac{m_{air,cyl}}{AFR}$$

Hence, total mass within the cylinder could be calculated as the sum of air and fuel within the cylinder:

$$m_{total} = m_{air,cyl} + m_{fuel,cyl}$$

Table 6: Data Logpoint Numbers and Corresponding BMEP, Torque, Air Mass Flow Rate and AFR

	LOGPOINT #	BMEP (kN/m ²)	TORQUE (Nm)	AIR MASS FLOW RATE (KG/HR)	AFR
PART LOAD	Logpoint 1	71.3	6.30	5.59	14.56
	Logpoint 3	99.7	8.80	10.62	14.70
	Logpoint 4	261.7	23.11	16.56	14.75
	Logpoint 9	400.4	35.36	28.34	14.72
	Logpoint 14	262.2	23.16	27.66	14.76
	Logpoint 18	750.3	66.26	69.22	14.71
FULL LOAD	Logpoint 19	550.3	48.60	73.65	14.71
	Logpoint 1	1269.3	100.91	46.82	16.15
	Logpoint 5	2237.3	177.86	141.19	14.45
	Logpoint 7	2288.1	181.9	217.06	13.56
	Logpoint 10	2175.2	172.93	307.93	13.89
	Logpoint 14	1846.2	146.77	364.92	13.04

Temperatures can be calculated by a second method between the points of SOC and EOC. This method assumes an adiabatic process between these points. That is, a process where no transfer of either heat or mass occurs. This can be visualised as both intake and exhaust valves are closed between these points, eliminating the transfer of matter, and as heat is lost to the piston and cylinder walls, heat is also released through the process of combustion. Hence, heat loss can be assumed to be approximately equal to heat release. During this phase the equation for temperature can be viewed as a simplification of the ideal gas law as shown below:

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}}$$

3.10.1. The Unburned Region

3.10.1.1. Temperature of the Unburned Region

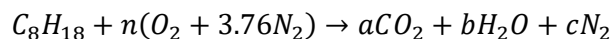
Displayed below is the Excel formula for the unburned temperature of part load logpoint 1 showing the embedded IF and statements to differentiate equations used based on whether temperature is calculated between SOC and EOC or not:

$$=IF(AND(ROW(P7)>SOC_PL_LP3,ROW(P7)<EOC_PL_LP3),AE6*(R7/R6)^{(AH6-1)/AH6),(R7*100000*\$M7)/(Total_Mass_Rev_PL_LP1*280))$$

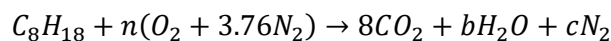
3.10.1.2. Specific Heats and γ of the Unburned Region

The specific heat of a substance indicates how much energy is required to raise the temperature of one kilomole of that substance by one degree kelvin. C_p and hence, C_v can be calculated for any gas or fuel based on the temperature of that gas or fuel and a combination of coefficients.

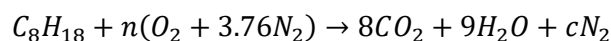
Intrinsic to the calculation of specific heats is the combustion equation, as this dictates how average specific heats are calculated based on the coefficients of the respective reactants and products. The balancing of the combustion equation of isooctane is shown below:



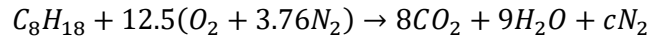
Balancing the products of this equation with respect to carbon gives:



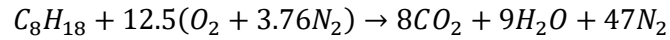
Further balancing the products of this equation with respect to hydrogen gives:



Balancing the reactants of the equation with respect to oxygen gives:



Finally, balancing the reactants of the equation with respect to nitrogen gives:



Since the unburned region consists of both fuel and air, the specific heats of fuel and air must be calculated separately before the overall specific heats of the unburned region can be calculated. Table 7 shows the coefficients for calculating $C_{p,fuel}$ for a range of common fuels as well as fuel specific characteristics such as molecular weight and stoichiometric air-fuel ratio and fuel-air ratio (Heywood, 1988, table 4.11, p. 133), while table 8 shows the corresponding coefficients for the calculation of C_p for various other gaseous species (Turns, 2006, Table B.14, p. 656).

Table 7: Coefficients for Calculating C_p of Various Fuels

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	0.058	-0.29149	26.327	-10.61	1.5656	0.16573	-18.331	4.3
Propane	C ₃ H ₈	44.1	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	0.1111	6.99	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	64.75	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

Table 8: Coefficients for Calculating C_p of Various Gaseous Species

Species	T (K)	a_1	a_2	a_3	a_4	a_5	a_6	a_7
CO	1000-5000	3.02507800E+00	1.44268850E-03	-5.63082700E-07	1.01858130E-10	-6.91095100E-15	-1.42683500E-14	6.10821700E+00
	300-1000	3.26245100E+00	1.51194090E-03	-3.88175500E-06	5.58194400E-09	-2.47495100E-12	-1.43105390E+04	4.84889700E+00
CO ₂	1000-5000	4.45362300E+00	3.14016800E-03	-1.27841050E-06	2.39399600E-10	-1.66903330E-14	-4.89669600E+04	-9.55395900E-01
	300-1000	2.27572400E+00	9.92207200E-03	-1.04091130E-05	6.86668600E-09	-2.11728000E-12	-4.83731400E+04	1.01884880E+01
H ₂	1000-5000	2.99142300E+00	7.00064400E-04	-5.63382800E-08	-9.23157800E-12	1.58275190E-15	-8.35034000E+02	-1.35511010E+00
	300-1000	3.29812400E+00	8.24944100E-04	-8.14301500E-07	9.47543400E-11	4.13487200E-13	-1.01252090E+03	-3.29409400E+00
H	1000-5000	2.50000000E+00	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.00000000E+00	2.54716200E+04	-4.60117600E-01
	300-1000	2.50000000E+00	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.00000000E+00	2.54716200E+04	-4.60117600E-01
OH	1000-5000	2.88273000E+00	1.01397470E-03	-2.27687700E-07	2.17468300E-11	-5.12630500E-16	3.88688800E+03	5.59571200E+00
	300-1000	3.63726600E+00	1.85091000E-04	-1.67616460E-06	2.38720200E-09	-4.31442000E-13	3.60678100E+03	1.35886050E+00
H ₂ O	1000-5000	2.67214500E+00	3.05629300E-03	-8.73026000E-07	1.20099640E-10	-6.39161800E-15	-2.98992100E+04	6.86281700E+00
	300-1000	3.38684200E+00	3.47498200E-03	-6.35469600E-06	6.96858100E-09	-2.50658800E-12	-3.02081100E+04	2.59023200E+00
N ₂	1000-5000	2.92664000E+00	1.48797680E-03	-5.68476000E-07	1.00970380E-10	-6.75335100E-15	-9.22797700E+02	5.98052800E+00
	300-1000	3.29867700E+00	1.40824040E-03	-3.96322200E-06	5.64151500E-09	-2.44485400E-12	-1.02089990E+03	3.95037200E+00
N	1000-5000	2.45026800E+00	1.06614580E-04	-7.46533700E-08	1.87965200E-11	-1.02598390E-15	5.61160400E+04	4.44875800E+00
	300-1000	2.50307100E+00	-2.18001800E-05	5.42052900E-08	-5.64756000E-11	2.09990400E-14	5.60989000E+04	4.16756600E+00
NO	1000-5000	3.24543500E+00	1.26913830E-03	-5.01589000E-07	9.16928300E-11	-6.27541900E-15	9.80084000E+03	6.41729300E+00
	300-1000	3.37654100E+00	1.25306340E-03	-3.30275000E-06	5.21781000E-09	-2.44626200E-12	9.81796100E+03	5.82959000E+00
NO ₂	1000-5000	4.68285900E+00	2.46242900E-03	-1.04225850E-06	1.97690200E-10	-1.39171680E-14	2.26129200E+03	9.88598500E-01
	300-1000	2.67060000E+00	7.83850000E-03	-8.06386400E-06	6.16171400E-09	-2.32015000E-12	2.89629000E+03	1.16120710E+01
O ₂	1000-5000	3.69757800E+00	6.13519700E-04	-1.25884200E-07	1.77528100E-11	-1.13643540E-15	-1.23393010E+03	3.18916500E+00
	300-1000	3.21293600E+00	1.12748640E-03	-5.75615000E-07	1.31387730E-09	-8.76855400E-13	-1.00524900E+03	6.03473700E+00
O	1000-5000	2.54205900E+00	-2.75506100E-05	-3.10280300E-09	4.55106700E-12	-4.36805100E-16	2.92308000E+04	4.92030800E+00
	300-1000	2.94642800E+00	-1.63816650E-03	2.42103100E-06	-1.60284310E-09	3.89069600E-13	2.91476400E+04	2.96399500E+00

$C_{p,fuel}$ is calculated through table 7 and the following equation, displayed in units of both kcal/gmol.K and J/kmol.K, as a function of temperature (Heywood, 1988, p. 130):

$$\overline{C_{p_{fuel}}}(kcal.gmol^{-1}K^{-1}) = A_{f1} + A_{f2}t + A_{f3}t^2 + A_{f4}t^3 + \frac{A_{f5}}{t^2} \text{ where, } t = \frac{T}{1000}$$

$$\overline{C_{p_{fuel}}}(J.kmol^{-1}K^{-1}) = 4184(A_{f1} + A_{f2}t + A_{f3}t^2 + A_{f4}t^3 + \frac{A_{f5}}{t^2}) \text{ where, } t = \frac{T}{1000}$$

C_p of any other gaseous species can be calculated from table 8 as a function of temperature and the coefficients shown in table 8 through the following equation (Turns, 2006, p. 656):

$$\frac{\overline{C_{p_{air}}}}{R_u} = a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4$$

$$\therefore \overline{C_{p_{air}}} = R_u(a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4)$$

Since the reactants are a combination of fuel and air, the reactants side of the combustion equation can be combined with the calculations of C_p shown above to give the average $C_{p,un}$ for the unburned region as follows:

$$\overline{C_{p_{un}}} = \frac{\overline{C_{p_{un}}} \text{ of the reactants}}{\text{coefficients of the reactants}} = \frac{\overline{C_{p_{fuel}}} + 12.5(\overline{C_{p_{O_2}}} + 3.76\overline{C_{p_{N_2}}})}{1 + 12.5(1 + 3.76)}$$

The following Excel function is the above $C_{p,un}$ equation as used in the Excel dataset:

```
=((((('NASA TABLES'!$F$38+('NASA TABLES'!$G$38*(AE7/1000))+('NASA TABLES'!$H$38*(AE7/1000)^2)+('NASA TABLES'!$I$38*(AE7/1000)^3)+('NASA TABLES'!$J$38/(AE7/1000)^2))*4184)+12.5*((IF(AE7>1000,8314*('NASA TABLES'!$C$26+('NASA TABLES'!$D$26*AE7)+('NASA TABLES'!$E$26*(AE7)^2)+('NASA TABLES'!$F$26*(AE7)^3)+('NASA TABLES'!$G$26*(AE7)^4)),8314*('NASA TABLES'!$C$27+('NASA TABLES'!$D$27*AE7)+('NASA TABLES'!$E$27*(AE7)^2)+('NASA TABLES'!$F$27*(AE7)^3)+('NASA TABLES'!$G$27*(AE7)^4)))))+3.76*(IF(AE7>1000,8314*('NASA TABLES'!$C$18+('NASA TABLES'!$D$18*AE7)+('NASA TABLES'!$E$18*(AE7)^2)+('NASA TABLES'!$F$18*(AE7)^3)+('NASA TABLES'!$G$18*(AE7)^4)),8314*('NASA TABLES'!$C$19+('NASA TABLES'!$D$19*AE7)+('NASA TABLES'!$E$19*(AE7)^2)+('NASA TABLES'!$F$19*(AE7)^3)+('NASA TABLES'!$G$19*(AE7)^4))))))/(1+12*4.76)
```

C_p and C_v are related simply by the following equation:

$$\overline{C_v} = \overline{C_p} - 8314$$

Hence:

$$\overline{C}_{vun} = \overline{C}_{Pun} - 8314$$

And γ , the ratio of specific heats is simply:

$$\gamma = \frac{\overline{C}_p}{\overline{C}_v}$$

Hence:

$$\gamma_{un} = \frac{\overline{C}_{Pun}}{\overline{C}_{vun}}$$

3.10.1.3. Mass and Volume of the Unburned Region

The mass of the unburned region can be calculated through the relationship between MFB and the total mass within the cylinder as follows:

$$m_{un} = (1 - MFB)m_{tot}$$

The volume of the unburned region can be calculated by rearranging the ideal gas law with respect to volume and, where applicable, using corresponding values for the unburned region as follows in both mathematical and Excel format:

$$V_{un} = \frac{(1 - MFB) \cdot m_{tot} \cdot R_{un} \cdot T_{un}}{p}$$

$$=(((1-Y7)*Total_Mass_Rev_PL_LP1*280*AE7)/R7)/100000$$

The Excel format function above features an additional parameter to convert V_{un} into cubic metres.

3.10.2. The Burned Region

3.10.2.1. Volume of the Burned Region

The volume of the burned region can be expressed simply as the difference between the instantaneous volume of the cylinder and the instantaneous volume of the unburned region as follows:

$$V_b = V_{cyl} - V_{un}$$

3.10.2.2. Temperature of the Burned Region

Similarly to that of the unburned region, the temperature of the burned region can be calculated using the ideal gas law and corresponding regional values as shown below in both mathematical and Excel function form:

$$T_b = \frac{pV_b}{MFB \cdot m_{tot} \cdot R_b}$$

$$=IF(ROW(N7)<SOC_PL_LP1,0,(T7*100000*AK7)/(Y7*Total_Mass_Rev_PL_LP1*280))$$

The IF statement in the above Excel function ensures that T_b is only calculated after combustion begins and there is a burned region to calculate the temperature of.

3.10.2.3. Specific Heats and γ of the Burned Region

C_p of the burned region can be calculated in an identical manner to that of the unburned region except, in this case, the products of the combustion equation are considered. Since in this case there is no fuel to be considered, only coefficients from table 8 are used in the following equation:

$$\overline{C}_{p_b} = \frac{\overline{C}_{p_b} \text{ of the products}}{\text{coefficients of the products}} = \frac{8\overline{C}_{p_{CO_2}} + 9\overline{C}_{p_{H_2O}} + 47\overline{C}_{p_{N_2}}}{8 + 9 + 47}$$

The previous equation is shown below in Excel function format:

$$\begin{aligned} &=(8*(IF(AL7>1000,8314*('NASA TABLES'!\$C\$8+('NASA TABLES'!\$D\$8*AL7)+('NASA \\ &\quad TABLES'!\$E\$8*(AL7)^2)+('NASA TABLES'!\$F\$8*(AL7)^3)+('NASA \\ &\quad TABLES'!\$G\$8*(AL7)^4)),8314*('NASA TABLES'!\$C\$9+('NASA \\ &\quad TABLES'!\$D\$9*AL7)+('NASA TABLES'!\$E\$9*(AL7)^2)+('NASA \\ &\quad TABLES'!\$F\$9*(AL7)^3)+('NASA TABLES'!\$G\$9*(AL7)^4))))+9*(IF(AL7>1000,8314*('NASA \\ &\quad TABLES'!\$C\$16+('NASA TABLES'!\$D\$16*AL7)+('NASA TABLES'!\$E\$16*(AL7)^2)+('NASA \\ &\quad TABLES'!\$F\$16*(AL7)^3)+('NASA TABLES'!\$G\$16*(AL7)^4)),8314*('NASA \\ &\quad TABLES'!\$C\$17+('NASA TABLES'!\$D\$17*AL7)+('NASA TABLES'!\$E\$17*(AL7)^2)+('NASA \\ &\quad TABLES'!\$F\$17*(AL7)^3)+('NASA \\ &\quad TABLES'!\$G\$17*(AL7)^4))))+47*(IF(AL7>1000,8314*('NASA TABLES'!\$C\$18+('NASA \\ &\quad TABLES'!\$D\$18*AL7)+('NASA TABLES'!\$E\$18*(AL7)^2)+('NASA \\ &\quad TABLES'!\$F\$18*(AL7)^3)+('NASA TABLES'!\$G\$18*(AL7)^4)),8314*('NASA \\ &\quad TABLES'!\$C\$19+('NASA TABLES'!\$D\$19*AL7)+('NASA TABLES'!\$E\$19*(AL7)^2)+('NASA \\ &\quad TABLES'!\$F\$19*(AL7)^3)+('NASA TABLES'!\$G\$19*(AL7)^4)))))/(8+9+47) \end{aligned}$$

Identically to that of the unburned region, C_v is calculated by the method shown below:

$$\begin{aligned}\overline{C_v} &= \overline{C_p} - 8314 \\ \therefore \overline{C_{v_b}} &= \overline{C_{p_b}} - 8314\end{aligned}$$

Also identically to that of the unburned region, γ is calculated by the method shown below:

$$\begin{aligned}\gamma &= \frac{\overline{C_p}}{\overline{C_v}} \\ \therefore \gamma_b &= \frac{\overline{C_{p_b}}}{\overline{C_{v_b}}}\end{aligned}$$

3.10.3. Specific Heats and γ Overall

C_p for the overall gas within the cylinder can be calculated by relating the respective values of C_p of the unburned and burned regions with MFB values in the following equation:

$$\overline{C_{p_{overall}}} = MFB \cdot \overline{C_{p_b}} + (1 - MFB) \cdot \overline{C_{p_{un}}}$$

As discussed previously, C_v and γ can both be calculated by the methods shown below:

$$\begin{aligned}\overline{C_v} &= \overline{C_p} - 8314 \\ \therefore \overline{C_{v_{overall}}} &= \overline{C_{p_{overall}}} - 8314 \\ \gamma &= \frac{\overline{C_p}}{\overline{C_v}} \\ \therefore \gamma_{overall} &= \frac{\overline{C_{p_{overall}}}}{\overline{C_{v_{overall}}}}\end{aligned}$$

3.10.4. Heat Release and Combustion Efficiency

3.10.4.1. Actual Heat Release

The heat released during combustion, dQ_r , can be calculated from cylinder pressures, volumes and γ through the following equation:

$$dQ_r = \frac{V_2 \cdot \Delta p}{(\gamma_{overall} - 1)}$$

However, the above equation calculates the instantaneous heat released per degree of crankshaft rotation and so, in order to calculate the total heat released by the engine throughout combustion a running total of the above equation must also

be calculated.

3.10.4.2. Theoretical Heat Release

The heat released during combustion can also be calculated theoretically through the following equation:

$$dQr = MFB \cdot m_{fuel} \cdot LHV_{isooctane}$$

This form of the heat release equation calculates the theoretical maximum heat energy that can be released by the amount of fuel undergoing combustion.

3.10.4.3. Combustion Efficiency

Since both actual heat release and theoretical maximum heat release can be calculated, the combustion efficiency of the engine can also be calculated. That is, what proportion of the theoretical heat energy available is released during combustion. This can be calculated as a percentage by the following equation:

$$Combustion\ efficiency = \frac{dQr_{actual}}{dQr_{theoretical}} \times 100\%$$

4. Results and Analysis

This section of this dissertation will display the results gained throughout the creation of this dissertation. Where applicable full results will be displayed and discussed. However, where results between logpoints of data exhibit sufficient similarity as not to warrant individual analysis (in logp-logV graphs, for example) an example graph will be displayed and analysed along with numerical results gained. Complete sets of graphs will in these cases be displayed in appendices.

4.1. Cylinder Pressure

4.1.1. Part Load

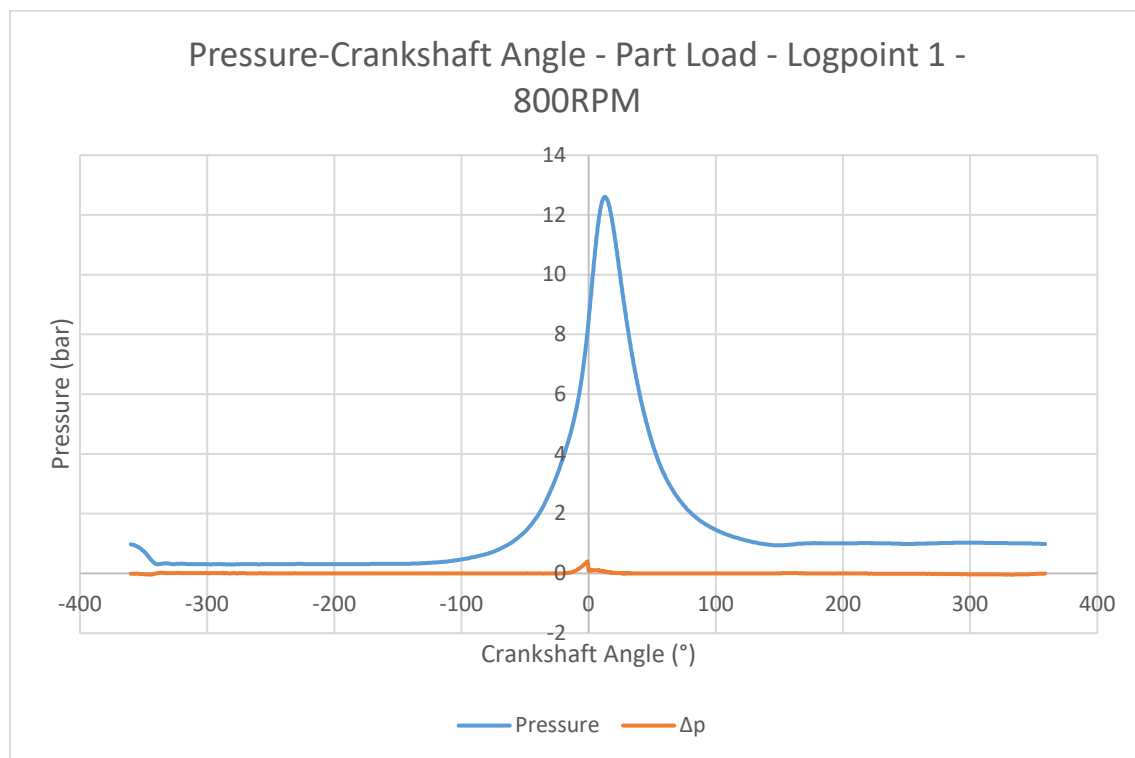


Figure 9: Pressure-Crankshaft Angle - Part Load - Logpoint 1 - 800RPM

Figure 9 shows cylinder pressure and Δp against crankshaft angle for part load logpoint 1. This figure illustrates the typical characteristics of pressure-crankshaft angle graphs for logpoints in the part load dataset. Cylinder pressure can be seen to fall to its minimum value through BDC of the intake stroke, rise increasingly through the compression stroke, reach its maximum value shortly after TDC and fall to around 1bar of pressure shortly before BDC on the exhaust stroke. Δp fluctuates throughout the four-stroke cycle but, for part load logpoints, only exhibits noticeable change around TDC where combustion takes place and shortly before the end of the exhaust stroke where the exhaust valve is open. A complete set of pressure-crankshaft graphs for part load logpoints can be found in Appendix A.

4.1.2. Full Load

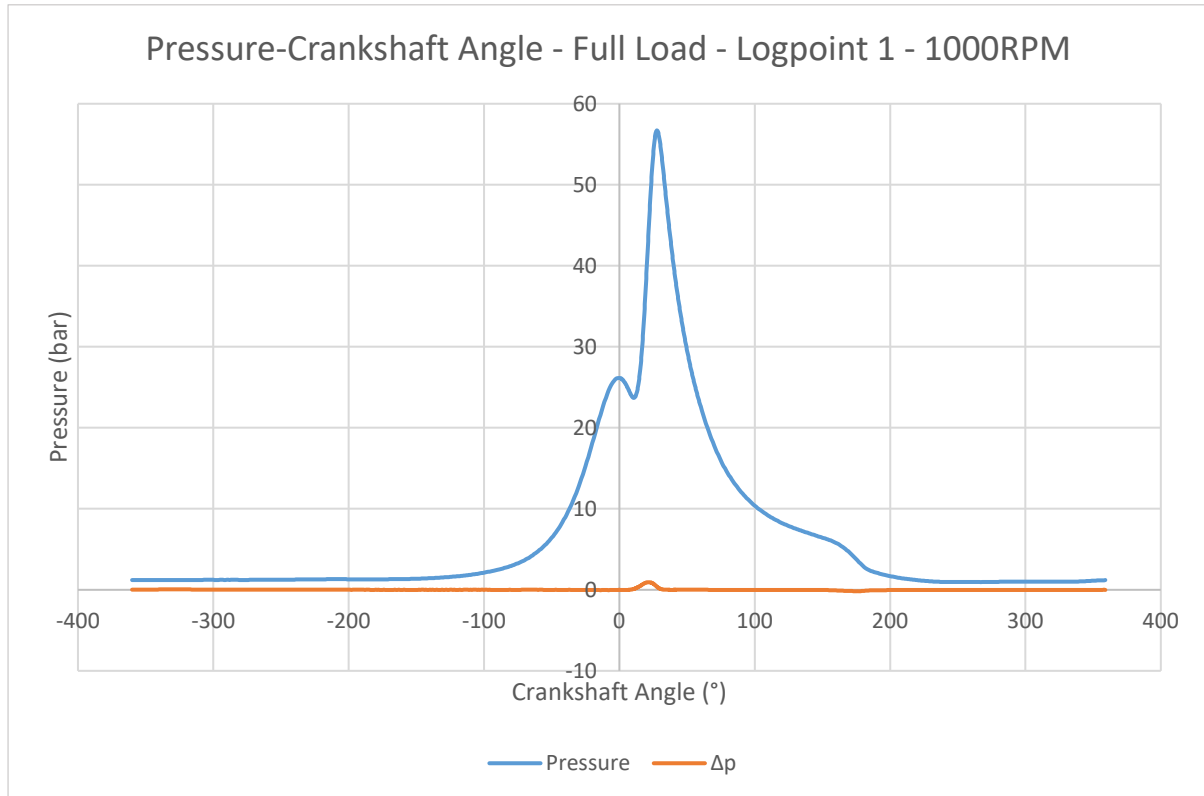


Figure 10: Pressure-Crankshaft Angle - Full Load - Logpoint 1 - 1000RPM

Figure 10 shows cylinder pressure and Δp against crankshaft angle for full load logpoint 1 and illustrates the typical characteristics of pressure-crankshaft angle graphs for full load logpoints. This graph illustrates several differences from figure 9 shown for part load logpoints. Firstly, the minimum cylinder pressure during the intake and exhaust phases appear to be functionally identical. Secondly, the cylinder pressure experiences two noticeable peaks. One of these peaks appears at TDC and the other appears shortly after TDC. Between these two pressure peaks the pressure falls slightly before rising sharply to the second peak. This could be attributed to the Ford Fox's use of variable ignition timing. Thirdly, where the cylinder pressure at part load falls steadily after combustion the cylinder pressure shown in figure 10 experiences a reduction in the rate of decrease at approximately 150-175° crankshaft angle. This could be attributed to the exhaust valve opening after this point in crankshaft rotation, disallowing the release of cylinder pressure as the piston is passing BDC. A complete set of pressure-crankshaft graphs for full load logpoints can be found in Appendix B.

4.2. Logp-LogV Polytropic Indices

4.2.1. Part Load

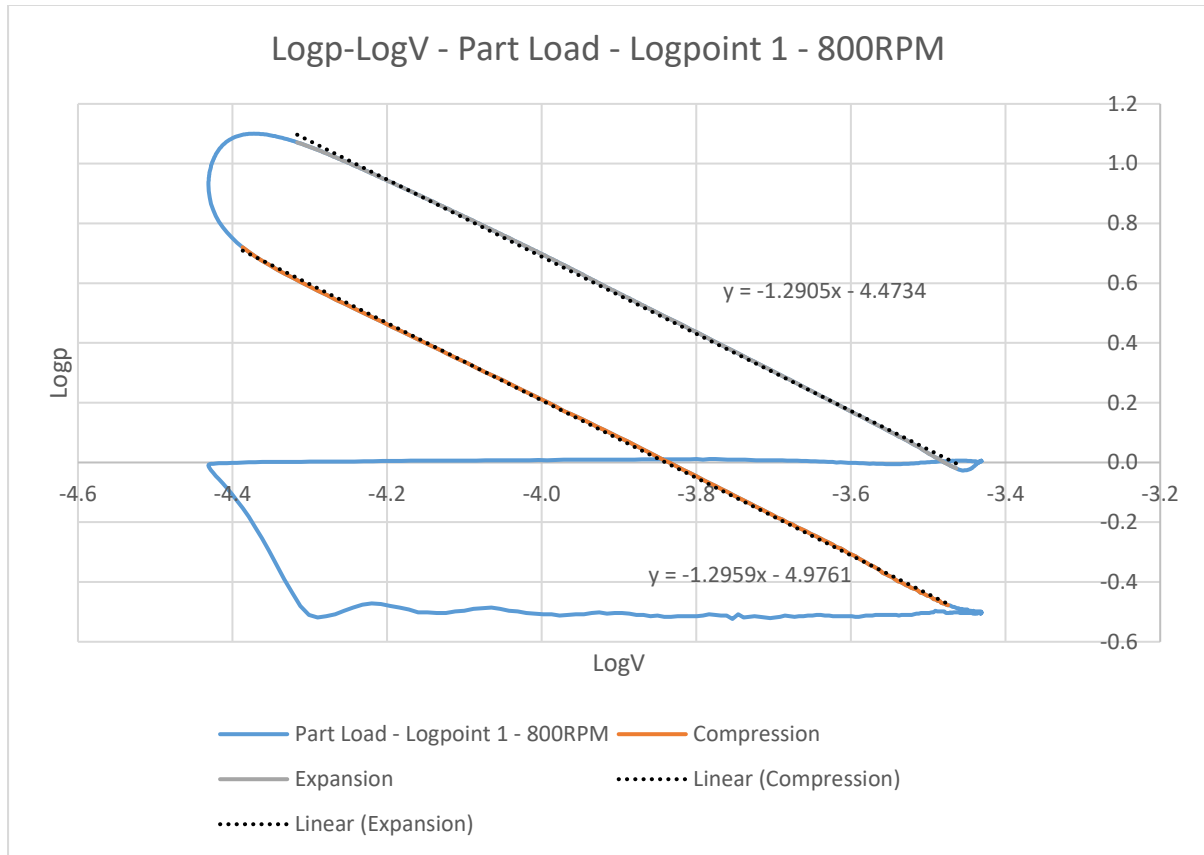


Figure 11: Logp-LogV - Part Load - Logpoint 1 - 800RPM

Figure 11 (reproduction of figure 4) shows the log-logV graph created for part load logpoint 1 and illustrates the typical characteristics of logp-logV graphs for internal combustion engines. The logp-logV trace is displayed for the complete four-stroke cycle with the compression and expansion phases separately displayed as the two straight-line segments. The points in the lower right-hand quadrant where the graph assumes and deviates from a straight line denote the start and end of the compression and expansion phases respectively. The points in the upper left-hand quadrant where the graph deviates from and resumes a straight line denote the points of SOC and EOC respectively. A complete set of logp-logV graphs for the part load dataset can be found in Appendix C.

Table 9: Part Load Logpoint Numbers and Corresponding Engine Speeds and Polytropic Indices

LOGPOINT #	ENGINE SPEED (RPM)	$n_{\text{compression}}$	$n_{\text{expansion}}$
LOGPOINT 1	800	1.2959	1.2905
LOGPOINT 3	1500	1.2986	1.1859
LOGPOINT 4	1500	1.3008	1.196
LOGPOINT 9	2000	1.3107	1.218
LOGPOINT 14	2500	1.3073	1.2083
LOGPOINT 18	3000	1.3086	1.2291
LOGPOINT 19	4000	1.3127	1.2195

Table 9 shows that the polytropic indices for both the compression and expansion phases follow identical correlations through the range of logpoints in the part load dataset. Minimum and maximum values for both polytropic indices are seen at the lowest and highest engine speeds respectively and both polytropic indices rise steadily from their lowest values through a slight decrease between 2000RPM and 3000RPM.

4.2.2. Full Load

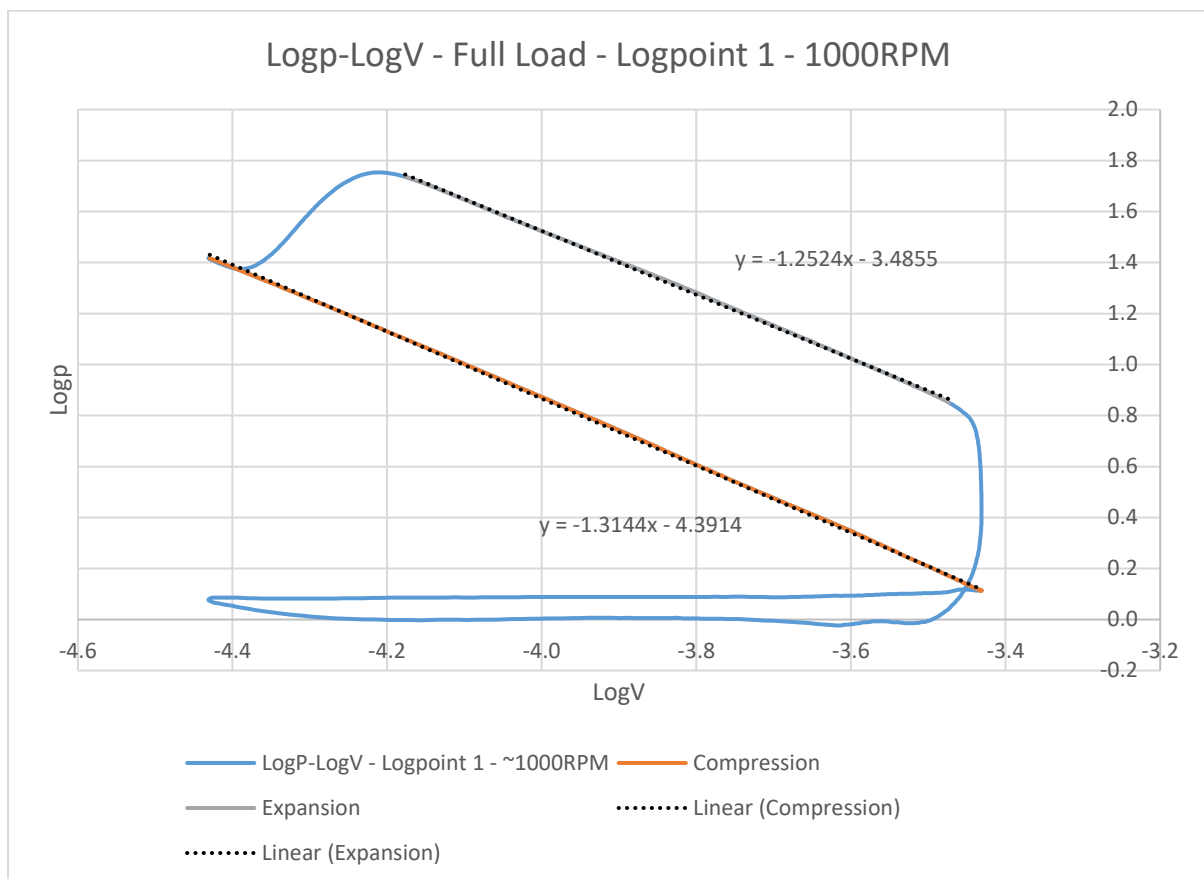


Figure 12: Logp-LogV - Full Load - Logpoint 1 - 1000RPM

Figure 12 shows the logp-logV graph of full load logpoint 1 (1000RPM). A complete set of logp-logV graphs for full load logpoints can be found in Appendix D. Figure 12 shows the same typical characteristics shown in figure 11 while also exhibiting several notable differences from log-logV graphs generated for part load logpoints. Firstly, logp-logV graphs generated for full load logpoints show consistently higher values of logp. This is due to full load applications generating higher cylinder pressures than part load applications. Secondly, where log-logV graphs for part load logpoints exhibit a predominantly smooth radius between the points of SOC and EOC, this region in logp-logV graphs generated for full load logpoints are typically characterised by a sharp deviation from a straight-line at the point of SOC. This deviation can be so extreme, as in figure 12, that the trace appears to reverse direction completely before resuming a path characteristic of that for the combustion process. Thirdly, in logp-logV graphs generated for full load applications, the logp differential between the compression and expansion phases appears greater than that exhibited in part load applications. Since this is characteristic of all logp-logV graphs generated for full load application this can be attributed to a greater differential between cylinder pressures between the compression and expansion phases due to greater fuel mass in the cylinder.

Table 10 shows the polytropic indices calculated for all logpoints at full load:

Table 10: Full Load Logpoint Numbers and Corresponding Polytropic Indices

LOGPOINT #	ENGINE SPEED (RPM)	$n_{\text{compression}}$	$n_{\text{expansion}}$
LOGPOINT 1	1000	1.3144	1.2524
LOGPOINT 5	2000	1.3027	1.227
LOGPOINT 7	3000	1.3029	1.204
LOGPOINT 10	4500	1.3016	1.2177
LOGPOINT 14	6000	1.2938	1.2401

Table # shows that for full load applications the polytropic indices of both the compression and expansion phases are at their maximum values at the lowest engine speed considered and their minimum values at the highest engine speed considered. The polytropic index of the compression phase shows the least variation (from 1.3144 to 1.2938) while the polytropic index for the expansion phase shows greater variation (from 1.2524 to 1.2040).

4.3. Actual Mass Fraction Burned

4.3.1. Part Load

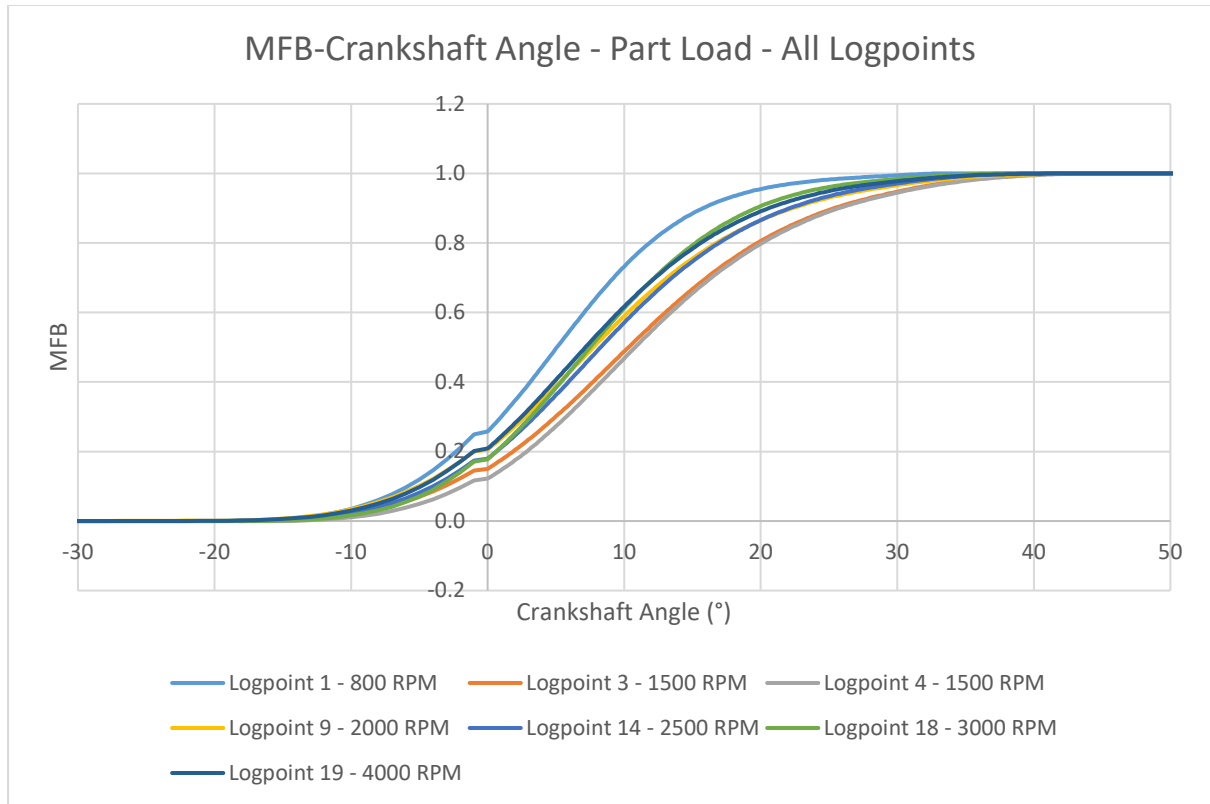


Figure 13: MFB-Crankshaft Angle - Part Load - All Logpoints

Figure 13 shows the MFB profiles for all logpoints at part load. All logpoints at part load can be seen to follow similar MFB profiles, with combustion starting for all logpoints between 20° and 10° BTDC and finishing for all logpoints between 30° and 40° ATDC. Notably, figure 13 shows a decrease of the burn rate between approximately 1° BTDC and TDC. This is characteristic of all logpoints at part load and appears to represent an identical decrease in burn rate of all logpoints, irrespective of features of individual logpoints. This could be attributed to the effect of changing polytropic indices in the calculation of $p2n$ as the crankshaft angle considered transitions from BTDC to ATDC. Accordingly, the polytropic index is changed in the $p2n$ calculation from that of compression to that of expansion.

4.3.2. Full Load

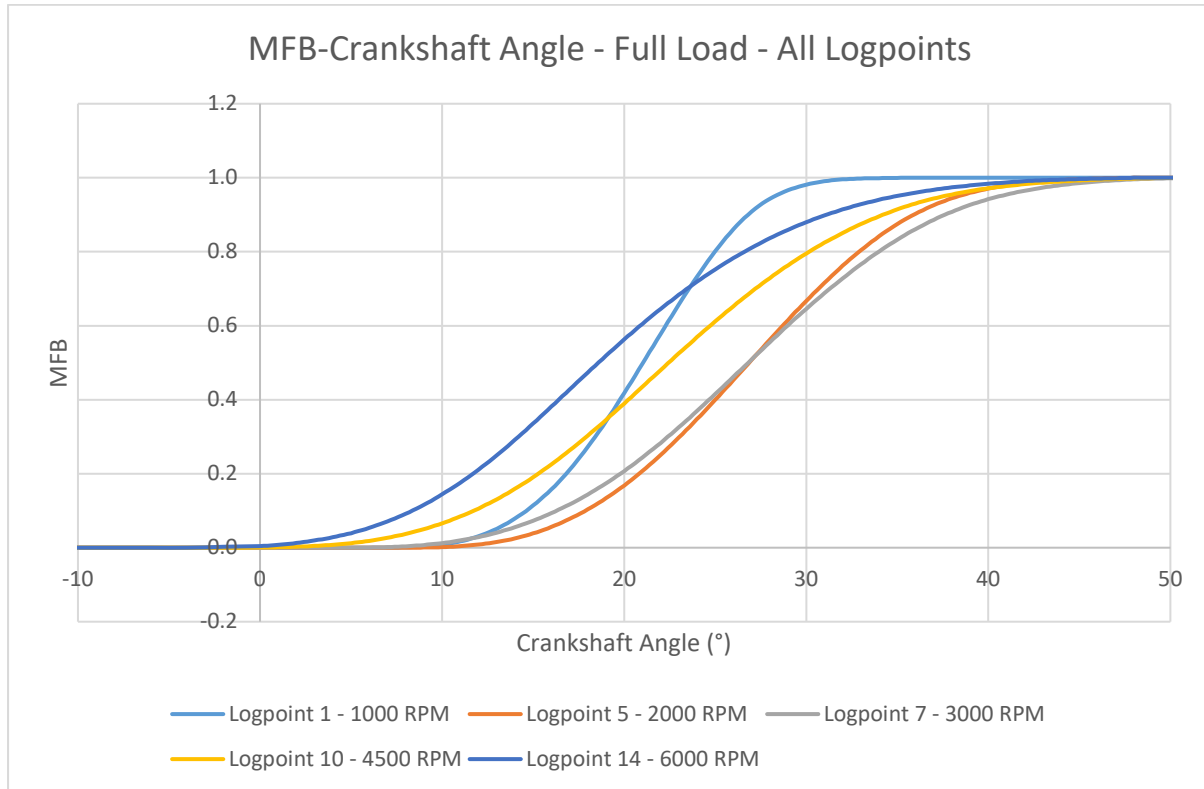


Figure 14: MFB-Crankshaft Angle - Full Load - All Logpoints

Figure 14 shows the MFB profiles generated for all logpoints at full load. As in figure 13 the MFB profile of the lowest engine speed is again shown to exhibit the fastest burn rate. However, figure 14 shows notable differences to figure 13. Firstly, and most noteworthy, all logpoints at full load either begin combustion after TDC or so close to TDC that their value at TDC is essentially negligible. Assuming that the decrease in burn rate exhibited in the MFB profiles at part load is due to the changing polytropic index in the calculation of $p_2 n$ as the crankshaft angle considered transitions from BTDC to ATDC, this would lend an explanation as to why the same decrease is not observed in figure 14. Since the MFB profile does not cross TDC, this change in polytropic index would have no effect on the MFB profiles of full load logpoints. Additionally, figure 14 shows that while all logpoints reach EOC between 40° and 50° ATDC, almost all logpoints experience SOC at different crankshaft angles.

4.4. Wiebe Function Coefficients

4.4.1. Part Load

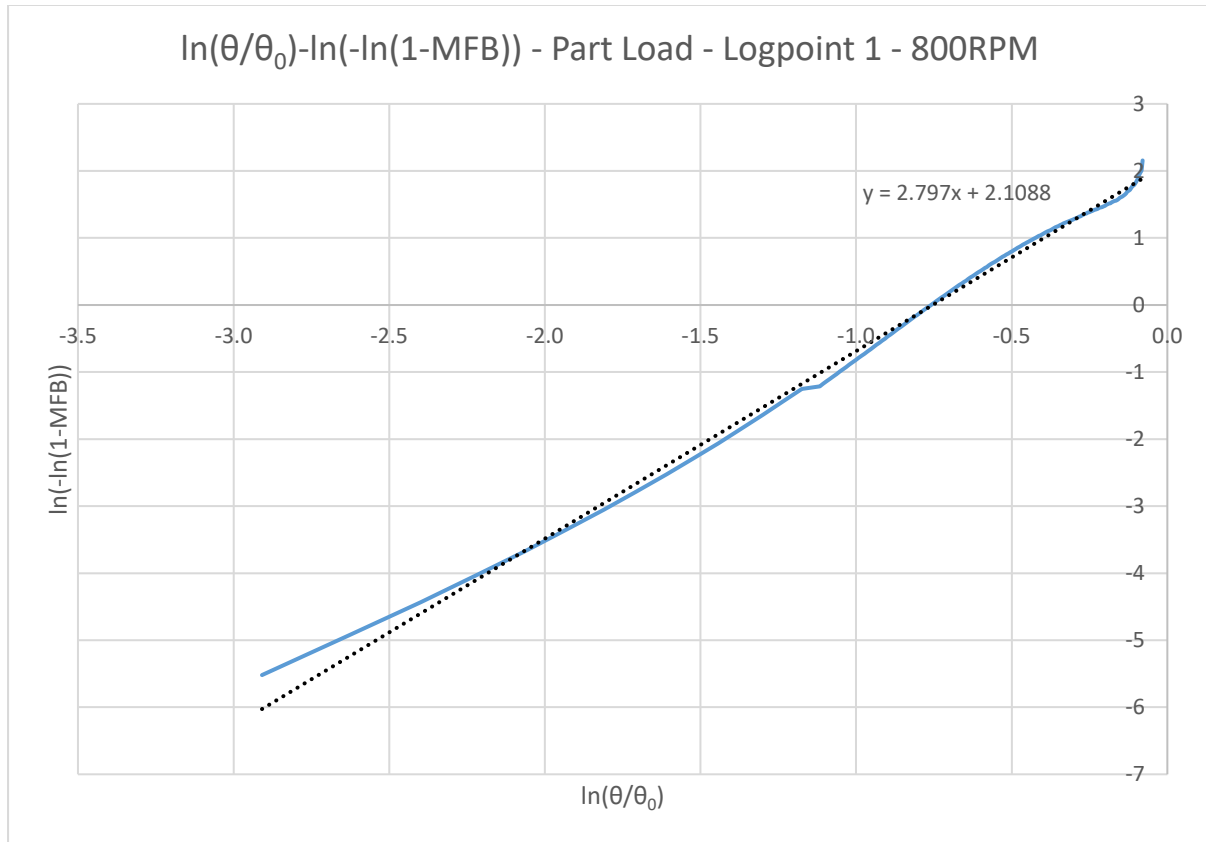


Figure 15: $\ln(\theta/\theta_0)-\ln(-\ln(1-MFB))$ - Part Load - Logpoint 1 - 800RPM

Figure 15 shows the graph utilised for the calculation of the Wiebe function coefficients for part load logpoint 1. The graph shows $\ln(\theta/\theta_0)$ on the x-axis and $\ln(-\ln(1-MFB))$ on the y-axis as well as the linear trendline used to ascertain the gradient and y-axis intercept of the data series. The data range considered for these graphs is from SOC to EOC, as this includes as much data from the combustion phases as possible. Figure 15 shows a slight deviation in the trace above at approximately $(\ln(\theta/\theta_0)=-1.1, \ln(-\ln(1-MFB))=-1.25)$. This can be seen to be a key characteristic of part load Wiebe function coefficient graphs generated for part load logpoints. A full set of Wiebe function coefficient graphs for part load logpoints can be found in Appendix E.

Table 11: Part Load Logpoint Numbers and Corresponding Graph Characteristics, Graph Values, Corresponding Wiebe Function Coefficients and Coefficient Values

LOGPOINT #	GRAPH CHARACTERISTIC	GRAPH VALUE	WIEBE COEFFICIENT	VALUE
LOGPOINT 1	Intercept	2.1088	a	8.2383
	Gradient	2.7970	m	1.7970
LOGPOINT 3	Intercept	1.5766	a	4.8385
	Gradient	2.3806	m	1.3806
LOGPOINT 4	Intercept	1.6824	a	5.3784
	Gradient	2.4072	m	1.4072
LOGPOINT 9	Intercept	1.7983	a	6.0394
	Gradient	2.5014	m	1.5014
LOGPOINT 14	Intercept	1.6819	a	5.3758
	Gradient	2.4727	m	1.4727
LOGPOINT 18	Intercept	1.8892	a	6.6141
	Gradient	2.7492	m	1.7492
LOGPOINT 19	Intercept	1.9121	a	6.7673
	Gradient	2.7100	m	1.7100

Table 11 above shows the values attained from the Wiebe function coefficient graphs and, consequently, the Wiebe function coefficients calculated for each logpoint at part load.

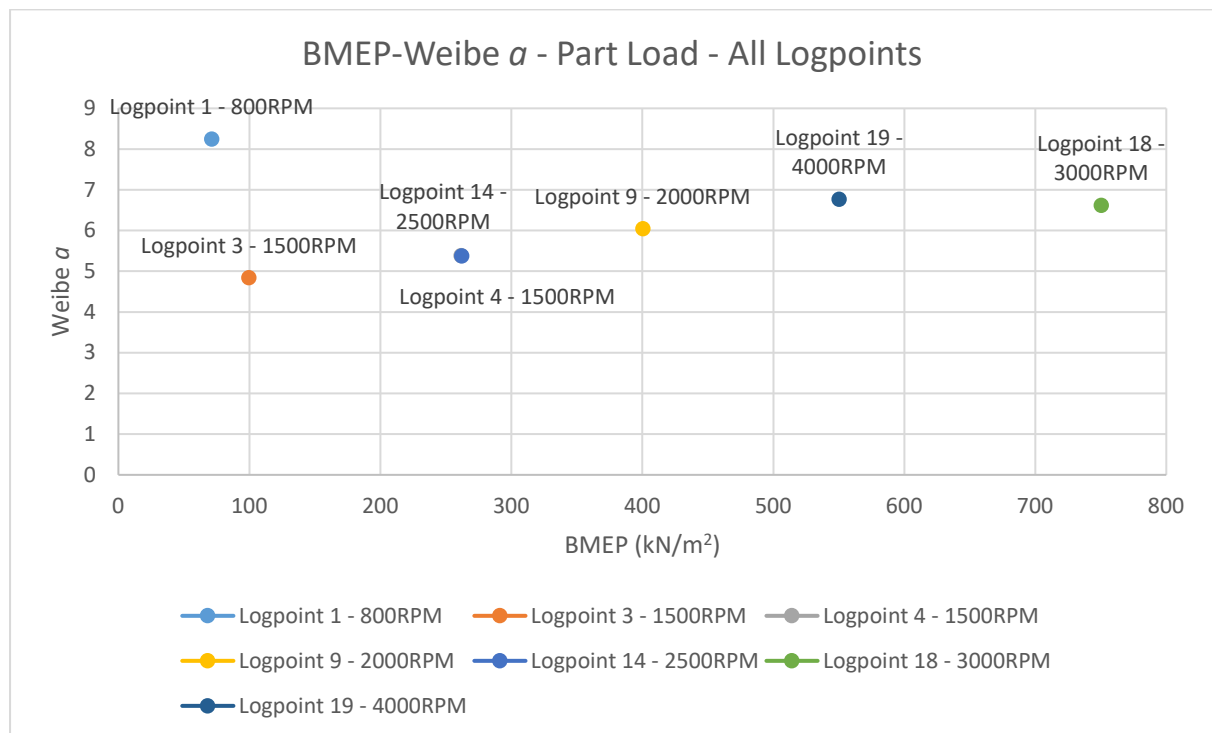


Figure 16: BMEP-Weibe a Coefficients - Part Load - All Logpoints

In order to visualise the effect of changing Wiebe function coefficients, figures 16 and 17 show the relationship between the calculated coefficients and BMEP for all logpoints at part load. These figures illustrate how, similarly to the case of polytropic indices and MFB profiles, logpoint 1 provides something of an anomalous case. Logpoint 1 exhibits a much higher a coefficient and a m coefficient more aligned with those of the higher engine speeds considered in the part load logpoints. From logpoint 3 both a and m coefficients can be seen to rise almost linearly with BMEP from a minimum value of a of 4.8385 to a maximum value of 6.7673, and from a minimum value of m of 1.3806 to a maximum value of 1.7492.

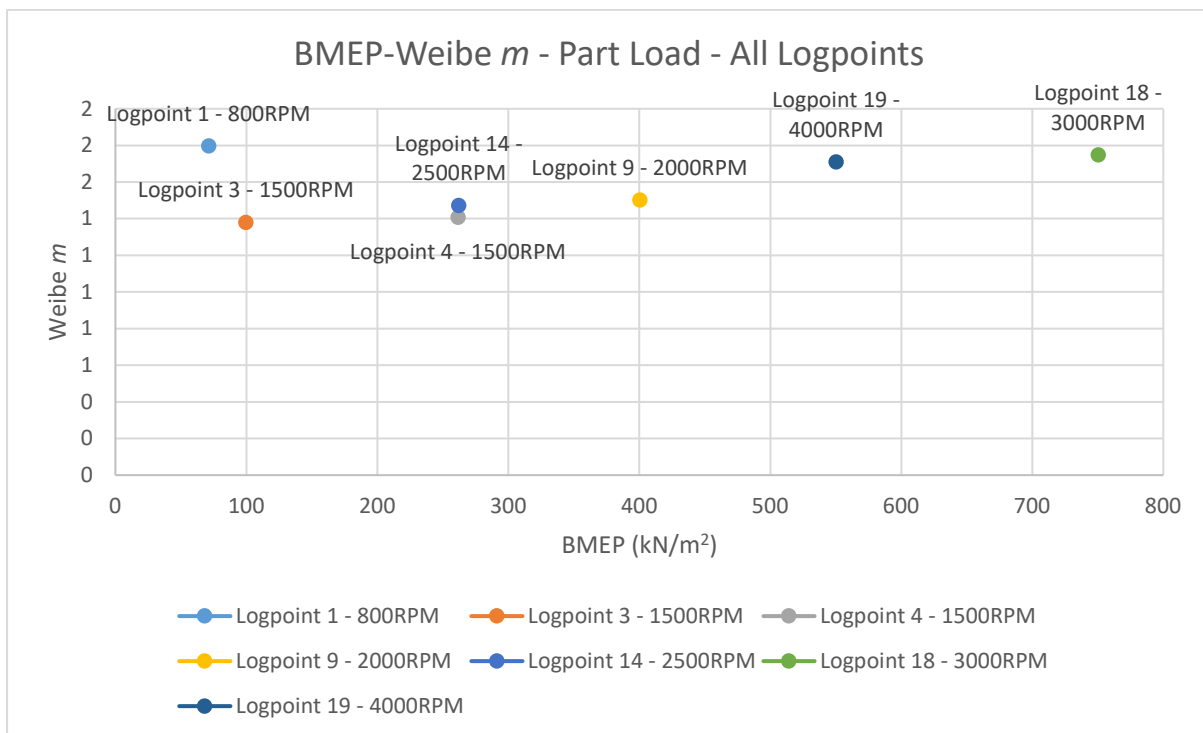


Figure 17: BMEP-Weibe m Coefficients - Part Load - All Logpoints

4.4.2. Full Load

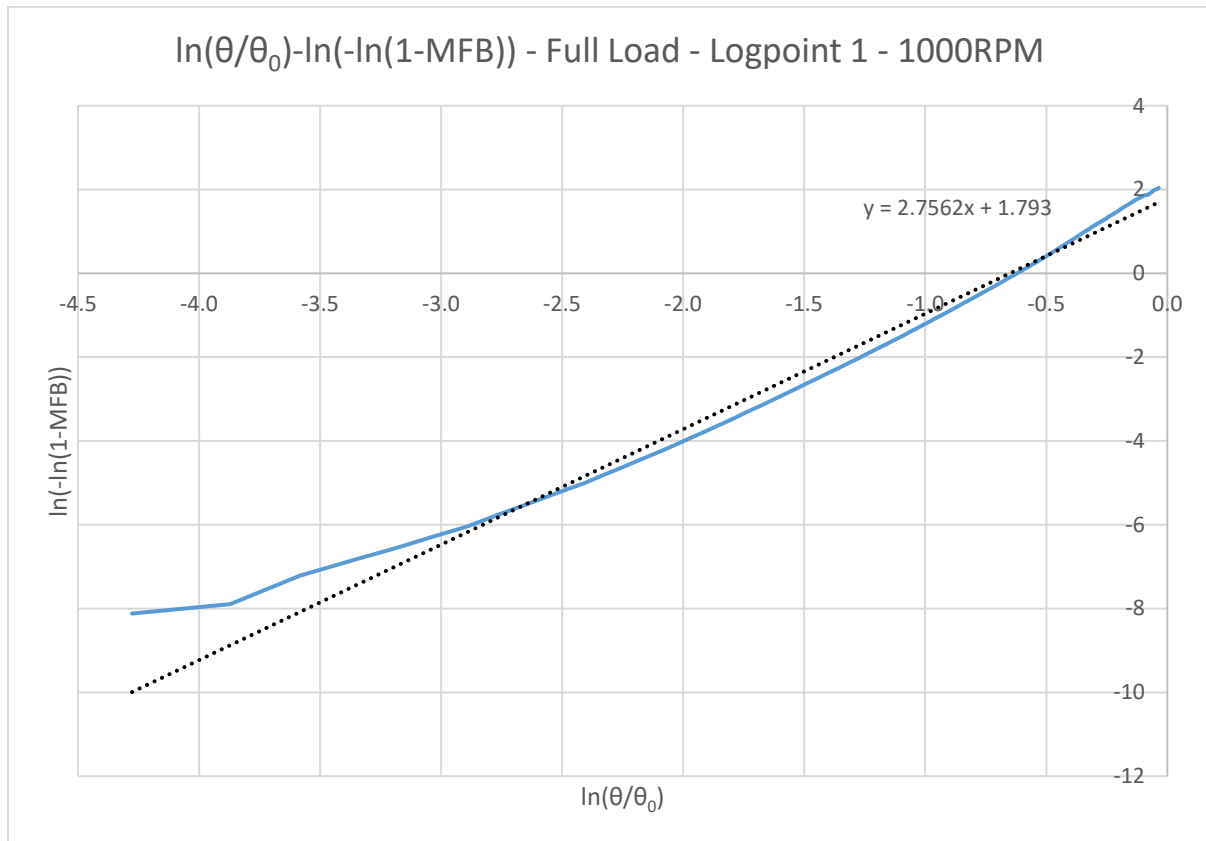


Figure 18: $\ln(\theta/\theta_0)-\ln(-\ln(1-MFB))$ - Full Load - Logpoint 1 - 1000RPM

Figure 18 shows the graph utilised to calculate the Wiebe function coefficients for full load logpoint 1. As in section 4.4.1, the graph shows $\ln(\theta/\theta_0)$ on the x-axis and $\ln(-\ln(1-MFB))$ on the y-axis as well as the linear trendline used to ascertain the gradient and y-axis intercept of the data series. The data range considered in the full load graphs is also the range between SOC and EOC for their respective logpoints. Figure 18 shows that full load Wiebe function coefficient graphs generated typically lack the slight deviation from a linear relationship noted in section 4.4.1. Rather, full load Wiebe function coefficient graphs generated tended to follow a curved correlation of approximately constant radius. A full collection of Wiebe function coefficient graphs for full load logpoints can be found in Appendix F.

Table 12: Full Load Logpoint Numbers and Corresponding Graph Characteristics, Graph Values, Corresponding Wiebe Function Coefficients and Coefficient Values

LOGPOINT #	GRAPH CHARACTERISTIC	GRAPH VALUE	WIEBE COEFFICIENT	VALUE
LOGPOINT 1	Intercept	1.793	a	6.0074
	Gradient	2.7562	m	1.7562
LOGPOINT 5	Intercept	1.6714	a	5.3196
	Gradient	2.5367	m	1.5367
LOGPOINT 7	Intercept	1.6808	a	5.3699
	Gradient	2.3615	m	1.3615
LOGPOINT 10	Intercept	1.9508	a	7.0343
	Gradient	2.7766	m	1.7766
LOGPOINT 14	Intercept	2.1233	a	8.3587
	Gradient	3.4571	m	2.4571

Table 12 above shows the values indicated by the Wiebe function coefficient graphs and, consequently, the Wiebe function coefficients calculated for each logpoint of the full load dataset. Figures 19 and 20 show the relationship between these coefficients and the BMEP of the full load logpoints. Similarly to part load, logpoint 1 of full load appears to be slightly anomalous in its relationship between Wiebe function coefficients and BMEP. Between logpoint 5 and logpoint 14 the relationship between Wiebe function coefficients and BMEP appears to follow a tentatively linear relationship. The minimum and maximum values of a can be seen to be 5.3196 at logpoint 5 and 8.3587 at logpoint 14 respectively while the minimum and maximum values of m can be seen to be 1.3615 at logpoint 7 and 2.4571 at logpoint 14 respectively.

Interestingly, in comparing the correlation between BMEP and Wiebe function coefficients two characteristics can be observed. Firstly, the values of the coefficients follow broadly identical correlations, albeit with different values. Secondly, this can be observed at both part load and full load. This is indicative of the similarity in burn durations between part load and full load logpoints as burn duration was one of the parameters in the Wiebe function that remained unchanged for these analyses.

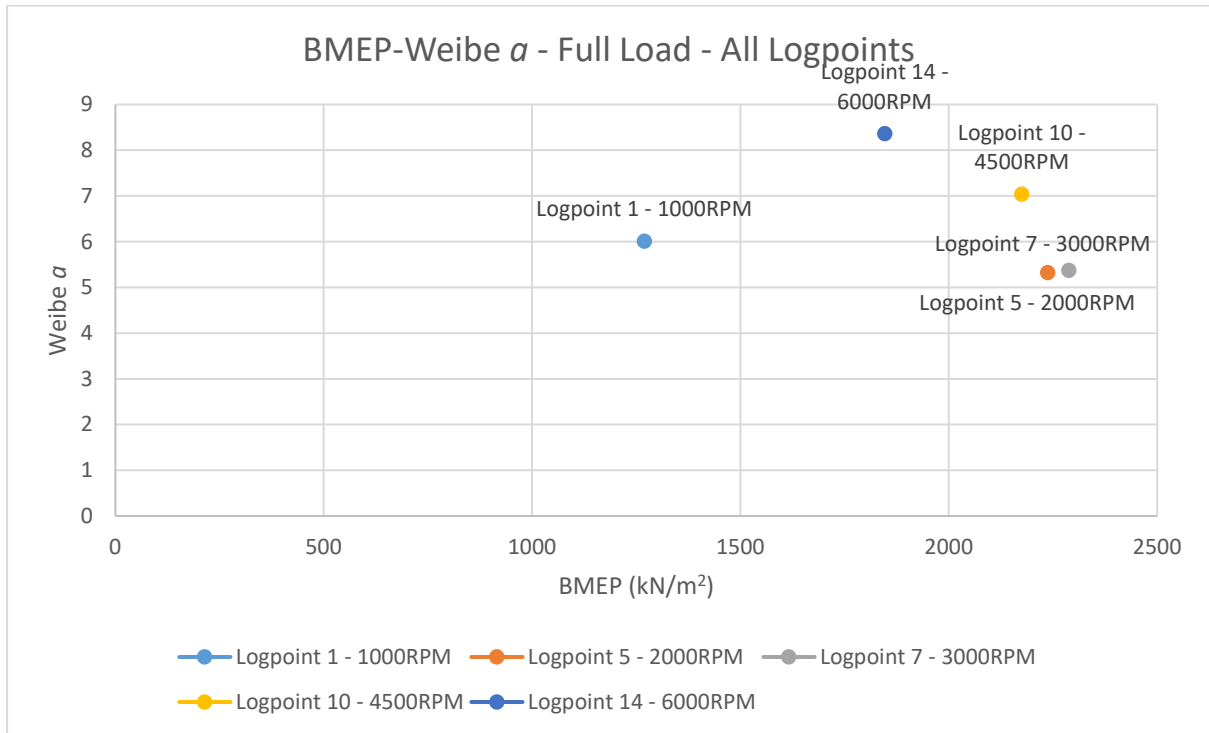


Figure 19: BMEP-Weibe α - Full Load - All Logpoints

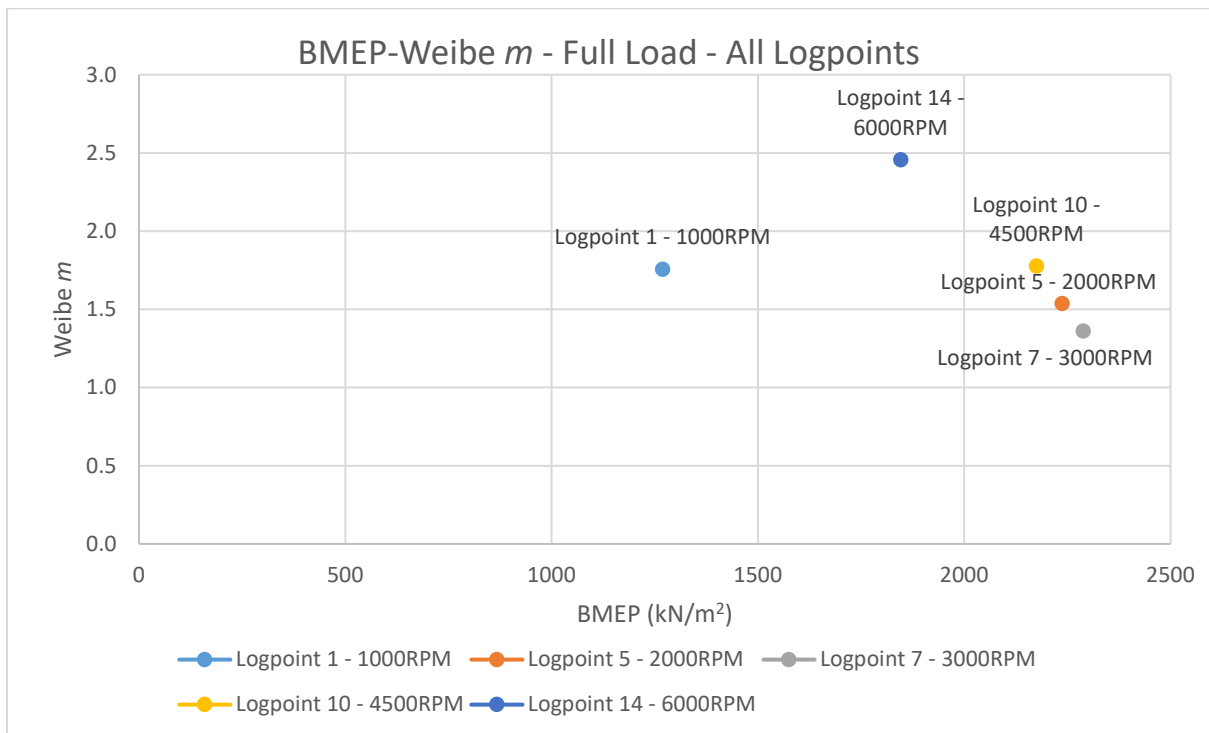


Figure 20: BMEP-Weibe m - Full Load - All Logpoints

4.5. Theoretical Mass Fraction Burned

4.5.1. Part Load

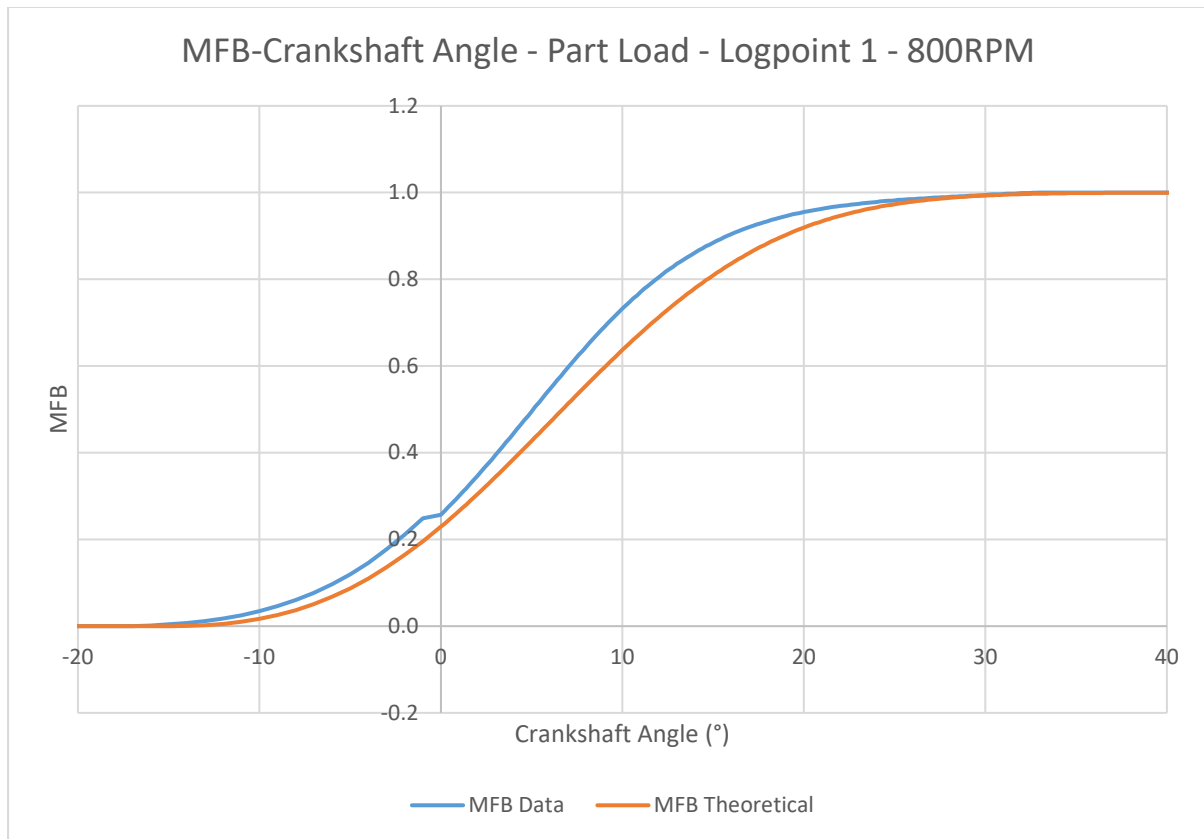


Figure 21: MFB-Crankshaft Angle - Part Load - Logpoint 1 - 800RPM

Figure 21 above shows the experimental MFB profile for part load logpoint 1 and the theoretical MFB profile generated from the previously calculated Wiebe function coefficients. Characteristically of theoretical MFB profiles generated for the part load logpoints, these profiles lack the decrease in burn rate shortly before TDC. This could be attributed to the fact that theoretical MFB profiles are generated entirely mathematically, with no connection to experimental pressure data. MFB profiles generated from pressure data are, however, based on $p2n$ calculations which are affected by experimental pressure data through logp-logV graphs. As shown in figure 21, the theoretical MFB profile is consistently lower than the experimental MFB profile and its correlation decreases throughout the burn duration. This suggests that at least one of the Wiebe coefficients used in generating the theoretical MFB profile would benefit from recalculation and/or the use of increased numerical accuracy.

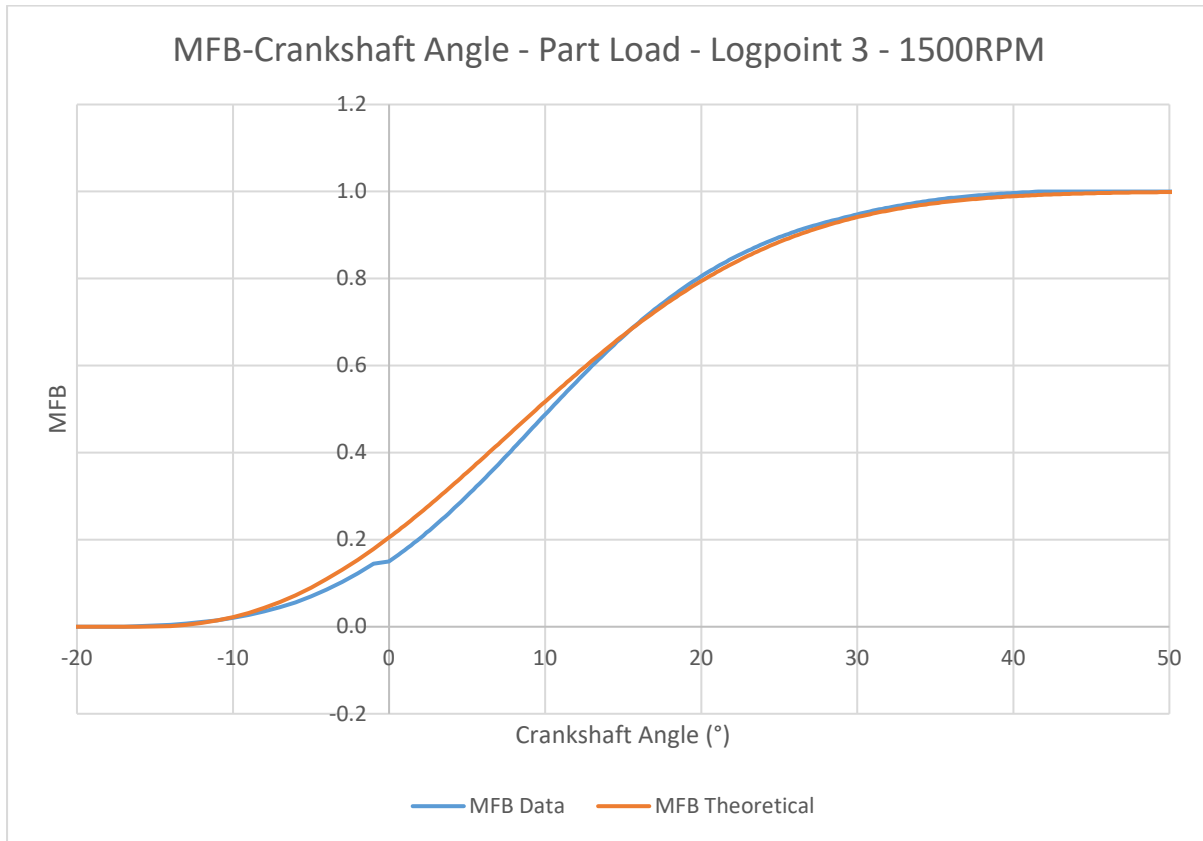


Figure 22: MFB-Crankshaft Angle - Part Load - Logpoint 3 - 1500RPM

Figure 22 above shows both the experimental and theoretical MFB profiles for part load logpoint 3, and illustrates the typical correlation achieved between experimental and theoretical MFB profiles for part load logpoints. Figure 22 shows close correlation between experimental and theoretical MFB profiles from 60%-100%MFB. However, below 15%MFB the theoretical MFB profile exhibits a faster initial burn rate and so does not correlate closely with the experimental MFB profile through the first 50% of the burn duration. These characteristics of correlation are typical for each part load logpoint with the exception of logpoint 1 as previously discussed in section 4.5.1. Therefore, a full collection of experimental and theoretical MFB profiles for all part load logpoints can be found in Appendix G.

4.5.2. Full Load

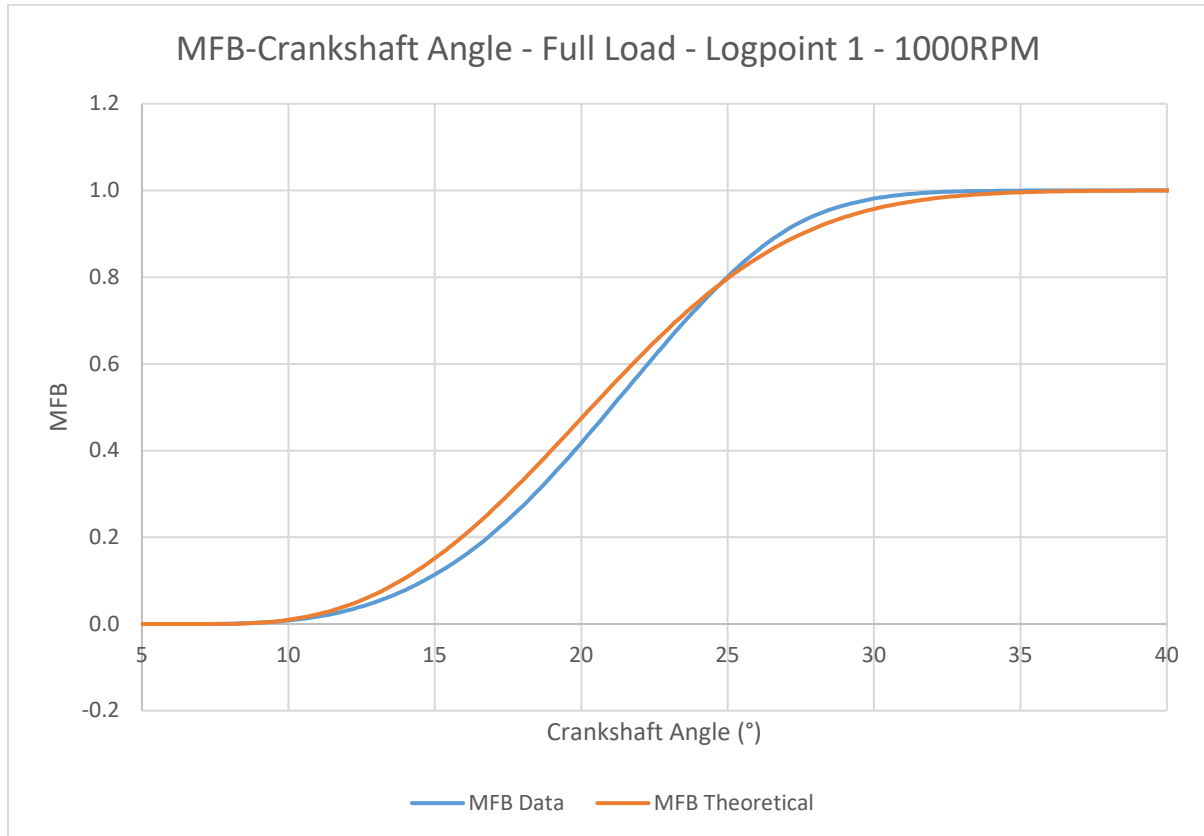


Figure 23: MFB-Crankshaft Angle - Full Load - Logpoint 1 - 1000RPM

Figure 23 shows the experimental and theoretical MFB profiles for full load logpoint 1. In this case, both experimental and theoretical MFB profiles show similar profiles through approximately 0%-60%MFB, albeit separated by approximately 1° crankshaft angle. At approximately 80%MFB the two profiles intersect, with the theoretical MFB profile exhibiting a slower, more gradual end to combustion while the experimental MFB profile exhibits a faster, sharper end-burn region. In order to improve correlation between the experimental and theoretical MFB profiles, both a and m coefficients could be increased in order to lengthen the duration of the early-burn region and increase the gradient of the mid-burn region.

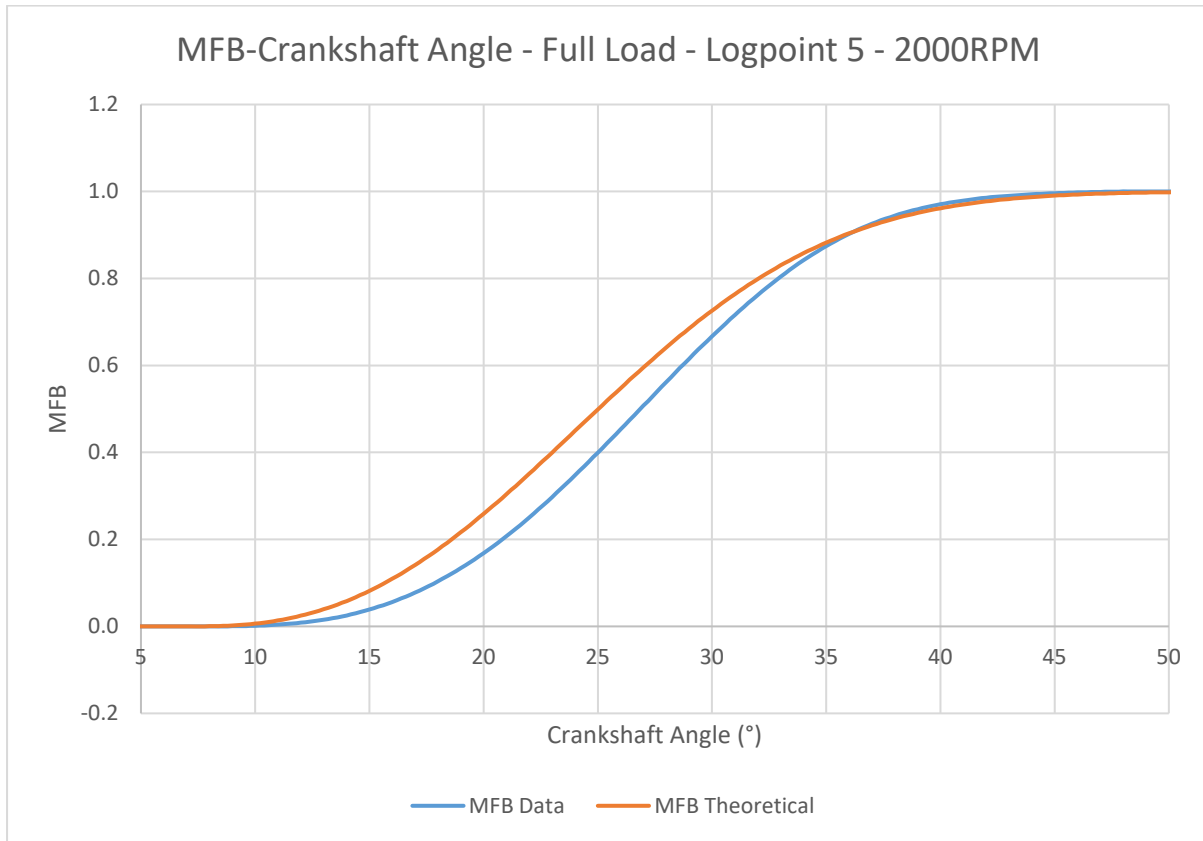


Figure 24: MFB-Crankshaft Angle - Full Load - Logpoint 5 - 2000RPM

Figure 24 shows the experimental and theoretical MFB profiles for full load logpoint 5 and exhibits the least accurate correlation between the two profiles. The two profiles show accurate correlation from approximately 90%-100%MFB. However, outside of this range the theoretical MFB profile shows no correlation with the experimental MFB profile. In order to improve correlation between the experimental and theoretical MFB profiles, both a and m coefficients could be increased in order to lengthen the duration of the early-burn region and increase the gradient of the mid-burn region.

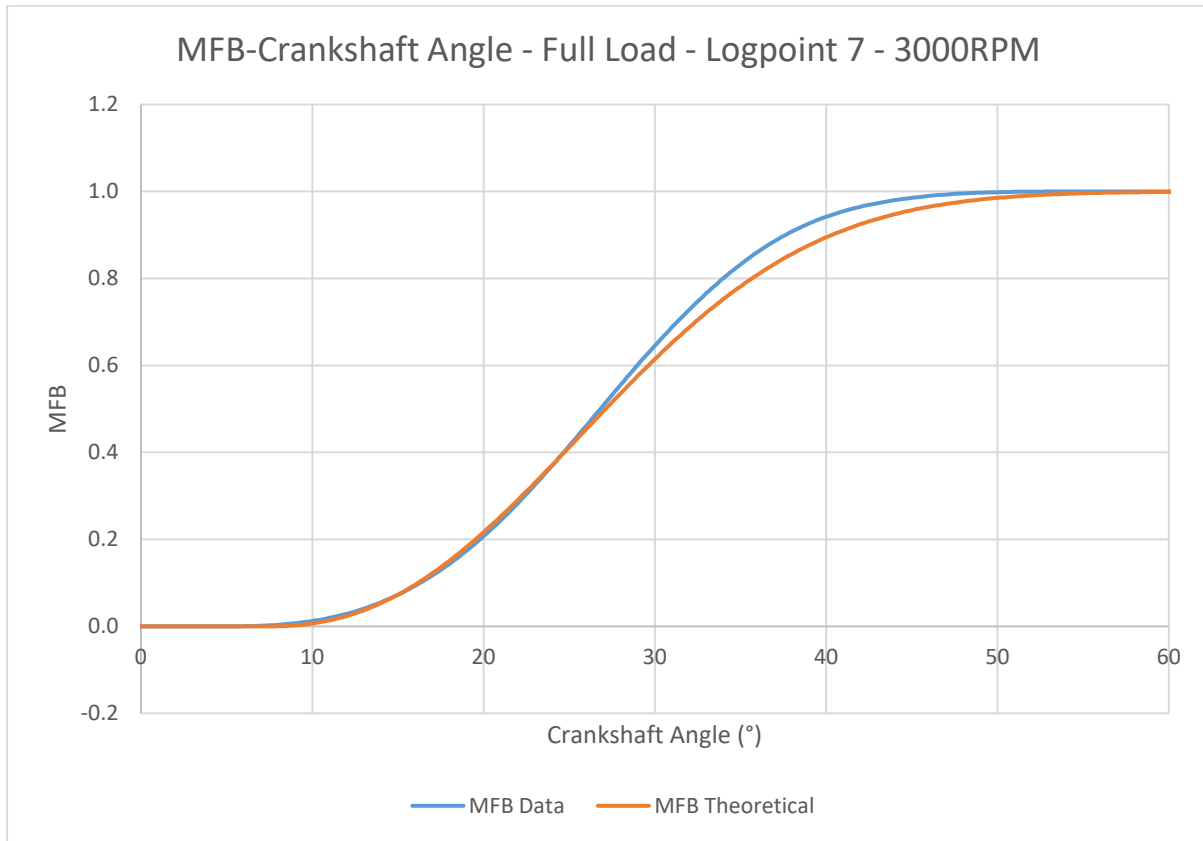


Figure 25: MFB-Crankshaft Angle - Full Load - Logpoint 7 - 3000RPM

Figure 25 shows correlation figuratively opposite to that shown in figure 24. That is, correlation between the two MFB profiles is consistently accurate below approximately 50%MFB and inaccurate above 50%MFB. Despite this, the two MFB profiles in this case do appear to show approximately identical burn rates between 80%-100%MFB. In order to improve correlation between the experimental and theoretical MFB profiles, the m coefficient could be increased in order to increase the gradient of the mid-burn region, although this may necessitate further changes to the a and m coefficients.

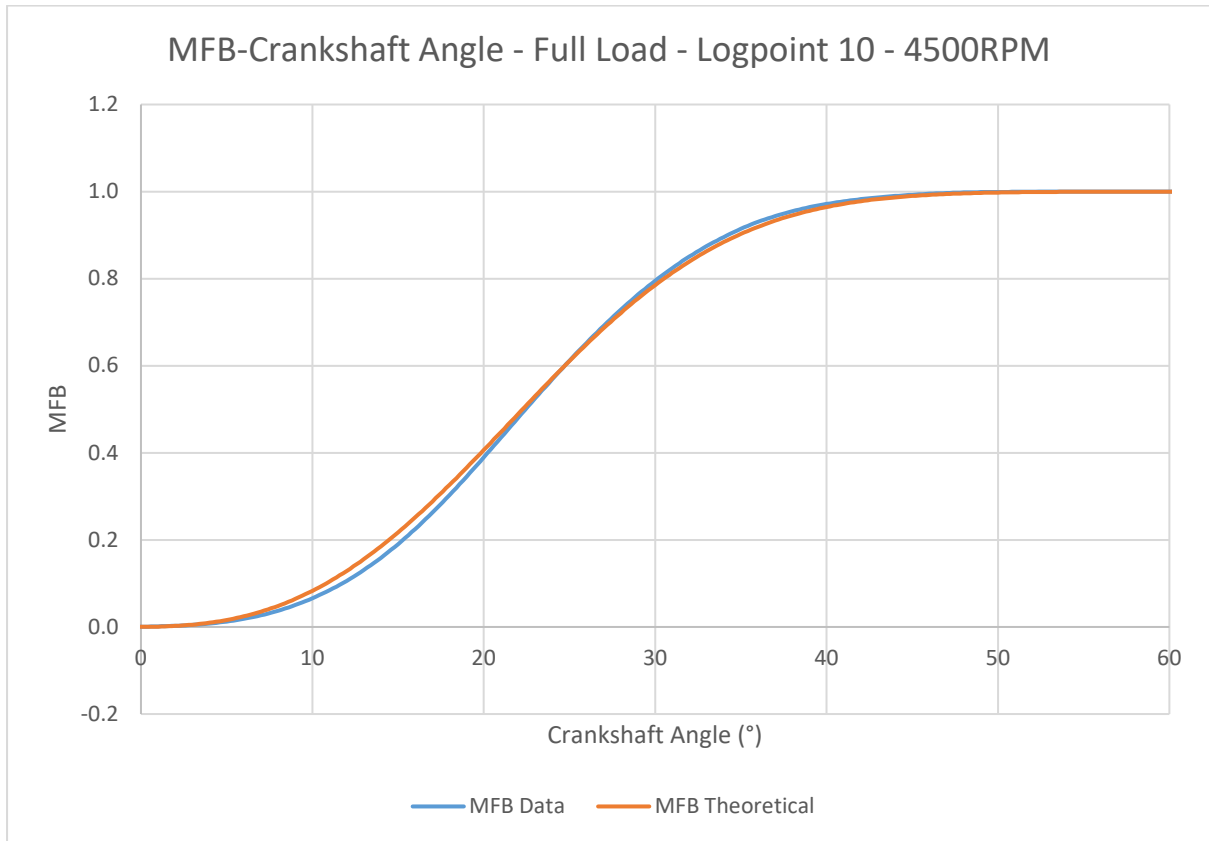


Figure 26: MFB-Crankshaft Angle - Full Load - Logpoint 10 - 4500RPM

Figure 26 shows the experimental and theoretical MFB profiles for full load logpoint 10. This case shows the most accurate correlation of all logpoints considered in this dissertation, with only minor deviation between experimental and theoretical MFB profiles in the early-burn and late-burn regions.

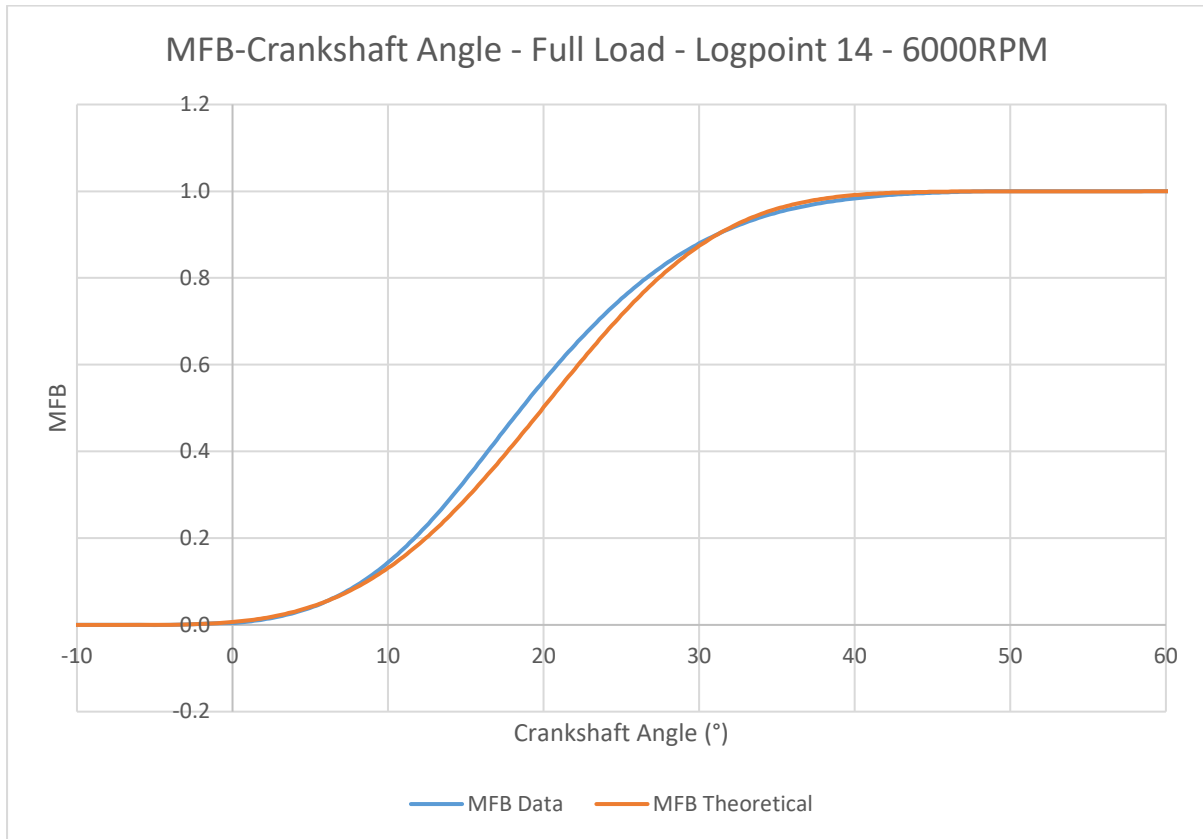


Figure 27: MFB-Crankshaft Angle - Full Load - Logpoint 14 - 6000RPM

Figure 27 shows the experimental and theoretical MFB profiles for full load logpoint 14. Correlation remains favourable in this case although the mid-burn region shows deviation between the two MFB profiles with the theoretical profile displaying slightly slower burn rate. In order to improve correlation between the experimental and theoretical MFB profiles, both a and m coefficients could be increased in order to lengthen the duration of the early-burn region and increase the gradient of the mid-burn region. This could have the effect of closing the discrepancy between the theoretical and experimental MFB profiles.

Shown in all MFB comparisons at full load applications is the characteristic that prior to the intersection of the theoretical and experimental MFB profiles, the theoretical profile exhibits faster burn rates, while after the intersection of the MFB profiles, the theoretical profile exhibits slower burn rates. This could suggest that, at full load applications, additional parameters are required to fit the Wiebe function more accurately. This would be consistent with the findings of Yeliana (2010) as outlined in section 2.

4.6. Variations in Wiebe coefficients a and m

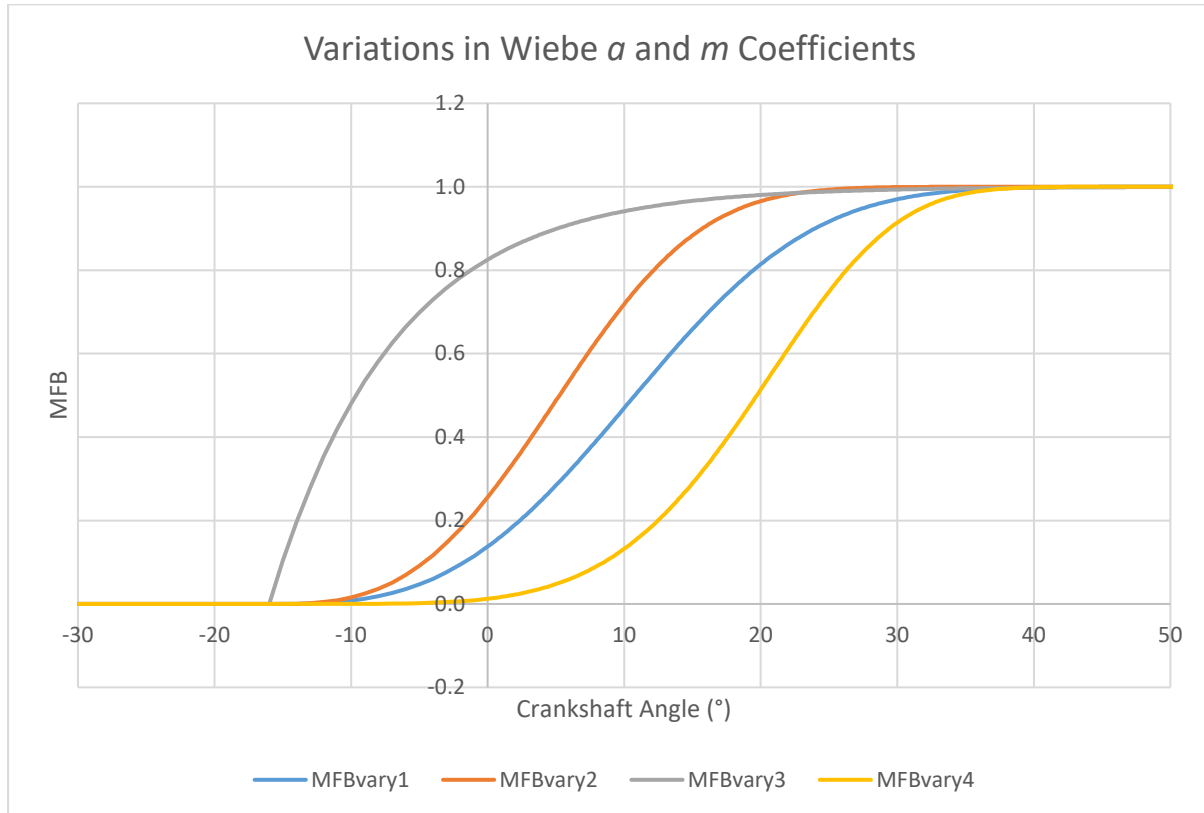


Figure 28: Variations in Wiebe a and m Coefficients (Part Load Logpoint 1 Baseline Data)

Figure 28 shows the plots of the four Wiebe functions generated with varying values of a and m as specified in section 3.9. In the interests of readability, table 5 from section 3.9 has been reproduced in table 13.

Table 13: MFBvary# Fields and Corresponding Values of Wiebe Function Coefficients (Reproduction of Table 5)

SERIES NAME	WIEBE a	WIEBE m
MFBvary1	6	2
MFBvary2	12	2
MFBvary3	6	0
MFBvary4	6	4

From the effects of the different values of Wiebe function coefficients in figure #, it can be seen that the a coefficient controls the gradient of the mid-burn section. As a is increased the mid-burn region of the Wiebe function increases in gradient. This also has the effect of increasing the sharpness of the late-burn curved region. The m coefficient controls the early-burn region. As m is increased the early-burn region increases in duration through a larger-radius curve being produced on the Wiebe profile.

4.7. Specific Heats and γ

4.7.1. Part Load

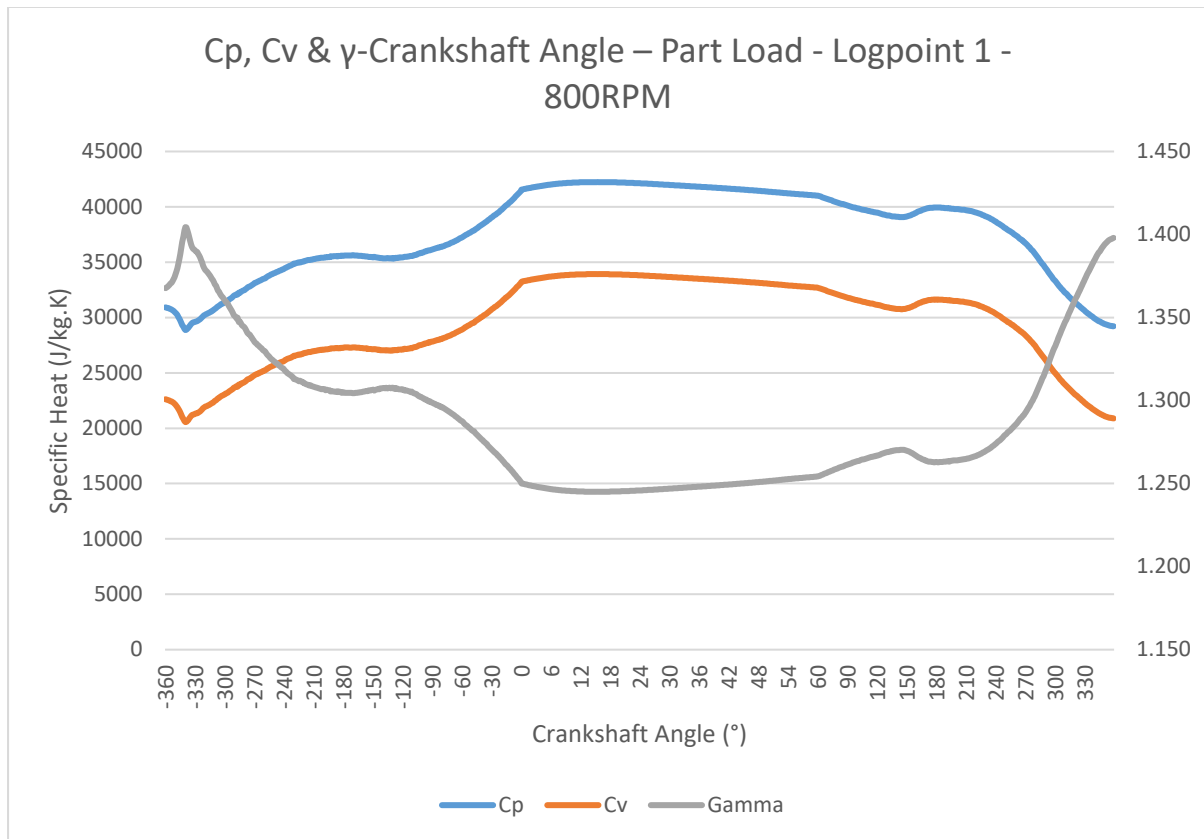


Figure 29: Cp, Cv & γ -Crankshaft Angle – Part Load - Logpoint 1 - 800RPM

Figures 29 and 30 show graphs of C_p and C_v (on the primary y-axis) and γ (on the secondary y-axis) against crankshaft angle for logpoint 1 of part load and full load respectively. Both figures show fundamental characteristics of specific heats and γ . As C_p and C_v are related by a simply numerical relationship, C_p and C_v both follow identical paths through figures 29 and 30, separated by a set numerical value at all times. Both figures also illustrate that as the temperature within the cylinder rises (such as during combustion shortly after TDC) the value of γ falls, as this is related to specific heats as a simple ratio. Both figures also illustrate the typical characteristics of these graphs, with specific heats rising through intake, compression and a portion of the expansion stroke and decreasing through the remainder of the expansion stroke and the exhaust stroke, while γ displays the inverse of these characteristics. A complete collection of these graphs for part load can be found in Appendix H while a complete collection of these graphs for full load can be found in Appendix I.

4.7.2. Full Load

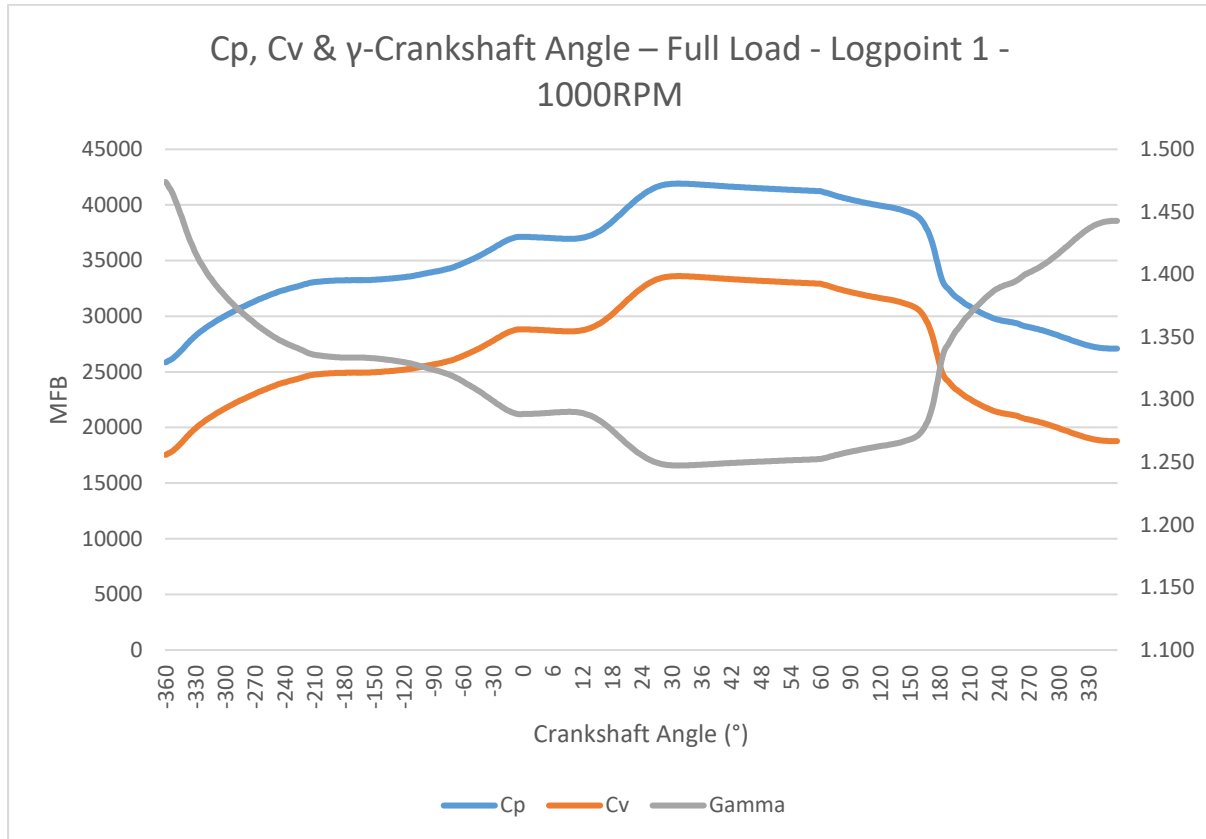


Figure 30: Cp, Cv & γ -Crankshaft Angle – Full Load - Logpoint 1 - 1000RPM

4.8. Heat Release and Combustion Efficiency

4.8.1. Part Load

Table 14: Part Load Logpoint Numbers and Corresponding Engine Speeds and Combustion Efficiencies

LOGPOINT #	ENGINE SPEED (RPM)	COMBUSTION EFFICIENCY
LOGPOINT 1	800	80.20
LOGPOINT 3	1500	75.83
LOGPOINT 4	1500	80.64
LOGPOINT 9	2000	85.17
LOGPOINT 14	2500	82.90
LOGPOINT 18	3000	88.30
LOGPOINT 19	4000	87.43

Table 14 shows the combustion efficiency calculated for each logpoint at part load. Maximum combustion efficiency of 88.3% is found at logpoint 18 (3000RPM) while minimum combustion efficiency of 75.83% is found at logpoint 3 (1500RPM). This shows that, at part load, as engine speed increases to approximately 3000RPM combustion efficiency increases and remains higher than 85% for three of the four highest engine speeds considered in the part load data.

4.8.2. Full Load

Table 15: Full Load Logpoint Numbers and Corresponding Engine Speeds and Combustion Efficiencies

LOGPOINT #	ENGINE SPEED (RPM)	COMBUSTION EFFICIENCY
LOGPOINT 1	1000	82.76
LOGPOINT 5	2000	86.87
LOGPOINT 7	3000	86.48
LOGPOINT 10	4500	87.40
LOGPOINT 14	6000	81.92

Table 15 shows the combustion efficiency calculated for each logpoint at part load. Maximum combustion efficiency of 87.4% is found at logpoint 10 (4500RPM) while minimum combustion efficiency of 81.92% is found at logpoint 14 (6000RPM). Table 15 also shows that while combustion efficiency decreases slightly at the highest engine speed considered at full load, all logpoints at full load exhibit higher combustion efficiency than three of the seven logpoints considered at part load. Additionally, while full load combustion efficiency fails to reach the maximum value shown at part load, the logpoints at full load do exhibit greater consistency in combustion efficiency between logpoints than those at part load. This could be interpreted as contraindicative to modern assumptions regarding ideally efficient vehicle operation, where light engine loads are assumed to be more efficient.

5. Conclusion

In conclusion, this dissertation has met its ambitions and objectives as outlined in section 1.2. Background research has provided the necessary information required to fulfil these objectives and the data used, supplied by Ford Motor Company, has been appropriately processed to facilitate all necessary calculations. Microsoft Excel has been used to create a complete workbook of all calculations and graphical representations of results and these have also been reproduced in this document.

Polytropic indices have been calculated and the values thereof have been seen to be realistic and in keeping with literature already published on the subject. MFB profiles based on cylinder pressure data have been generated for all logpoints of both part load and full load and can be seen to be consistent with MFB profiles generated in previous dissertations and resources referenced in section 2. From these profiles Wiebe function coefficients have been calculated and have also been consistent with findings from resources referenced in section 2, particularly that of Blair (1999). The relationship between these coefficients and BMEP has also been displayed visually and critically analysed. Theoretical MFB profiles have been generated from these coefficients and their correlations with experimental MFB profiles have been analysed and compared and, where appropriate, necessary corrections to improve their correlation have been suggested. The effect of variations in Wiebe function a and m coefficients has been explored based on parameters of a single data logpoint and the effects of such variations have been analysed. Finally, a two-zone combustion model has been produced, allowing the calculation of temperatures, specific heats and γ for both the unburned and burned regions. Specific heats and γ of the overall mixture within the cylinder have also been calculated. These results have been displayed graphically and the characteristics of these results have been assessed. Finally, and possibly most relevant to the concerns of modern engineers and engine manufacturers, the combustion efficiency of each logpoint of both part load and full load has been calculated. These results have been analysed and the efficiencies of part load and full load have been compared.

While the outcomes of this dissertation as outlined above are consistent with the objectives outlined in section 1.2, there are several recommendations to be made regarding further work in these areas to be undertaken in the future.

6. Recommendations

There are several areas of further work to be recommended regarding this dissertation. Firstly, since this dissertation is based in large part on the application of purely mathematical formulae as opposed to experimental analyses, the accuracy of such calculations can always be increased. Further research into the applications of the Wiebe function, for example, has previously yielded new methods of implementing it in combustion modelling, such as the inclusion of Yeliana's 'amplitude correction factor' or the development of double-Wiebe and multi-Wiebe functions as outlined in section 2.

Secondly, if further work is to be undertaken, regarding the calculation of Wiebe function coefficients in particular, there are notable advantages to analysing data from an older engine than that used in this dissertation. The Ford Fox utilises several technologies to optimise engine performance such as variable ignition timing and variable AFR as well as forced induction. These systems, while improving performance, introduce variables that can have significant implications regarding the analysis of and calculations based upon simple cylinder pressure data. Further work undertaken in this field may benefit from the consideration of an older engine platform that does not incorporate these systems and, therefore, does not introduce these additional variables into the analysis and calculation stages.

Thirdly, the two-zone combustion model created in this dissertation neglects several key factors in the modelling of the combustion process. Fuel equivalence ratio is not considered in this dissertation and neither is the full combustion equation incorporating dissociation upon combustion. These two factors have significant impacts on the composition of the balanced combustion equation and, therefore, significant impacts on the specific heats and ration thereof of the burned and unburned regions of the two-zone combustion model. Also neglected in this dissertation is a full heat exchange model incorporating heat exchange between the cylinder head, cylinder wall and piston. Incorporation of this heat exchange model would yield more accurate heat release rate calculations and, therefore, more accurate combustion efficiency results.

Finally, this dissertation may benefit from the incorporation of other software packages such as Matlab and Ricardo Wave. The inclusion of additional software could improve the accuracy of produced models, provide additional validation of results and improve the academic rigour of work undertaken.

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Appendix A: Pressure-Crankshaft Angle Graphs for Part Load Logpoints

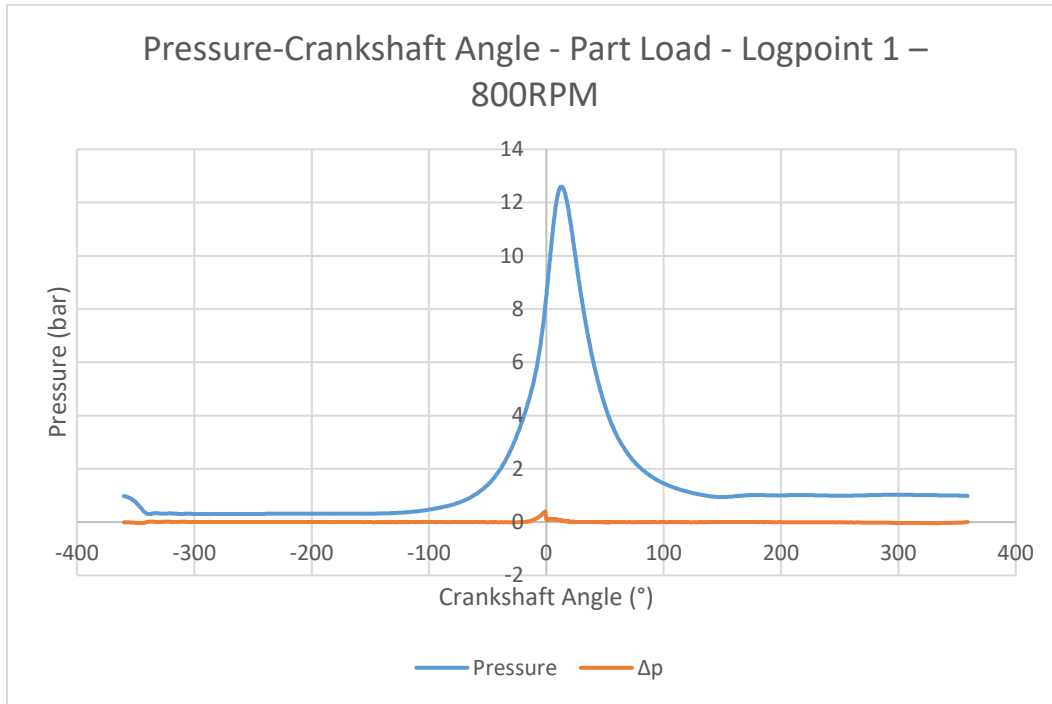


Figure 31: Pressure-Crankshaft Angle - Part Load - Logpoint 1 – 800RPM

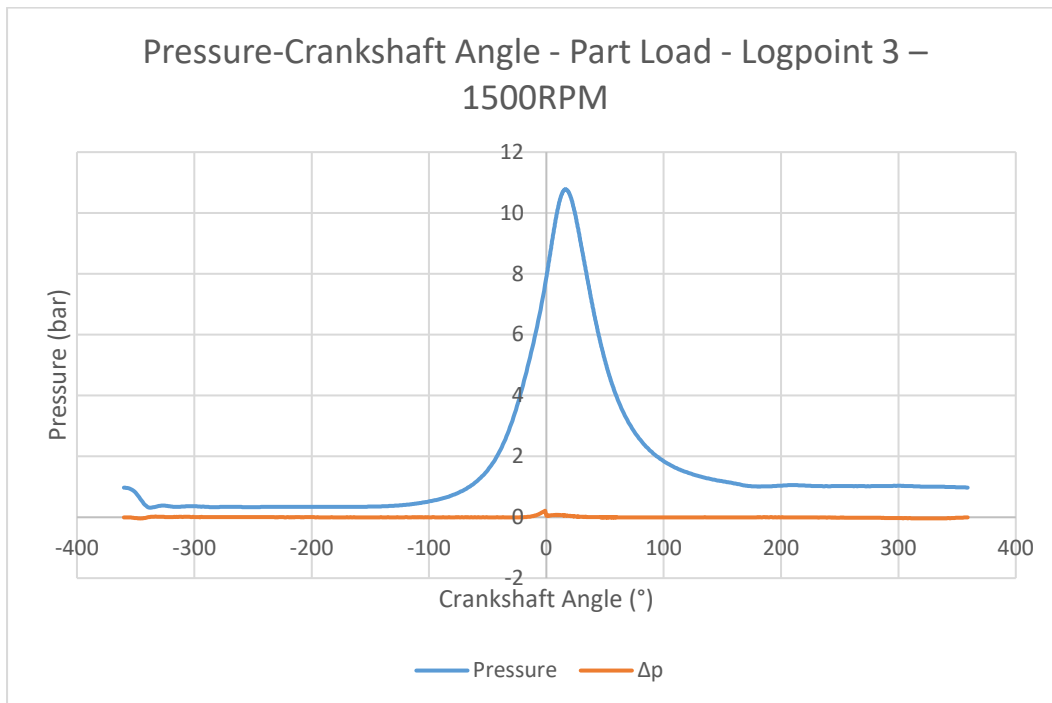


Figure 32: Pressure-Crankshaft Angle - Part Load - Logpoint 3 – 1500RPM

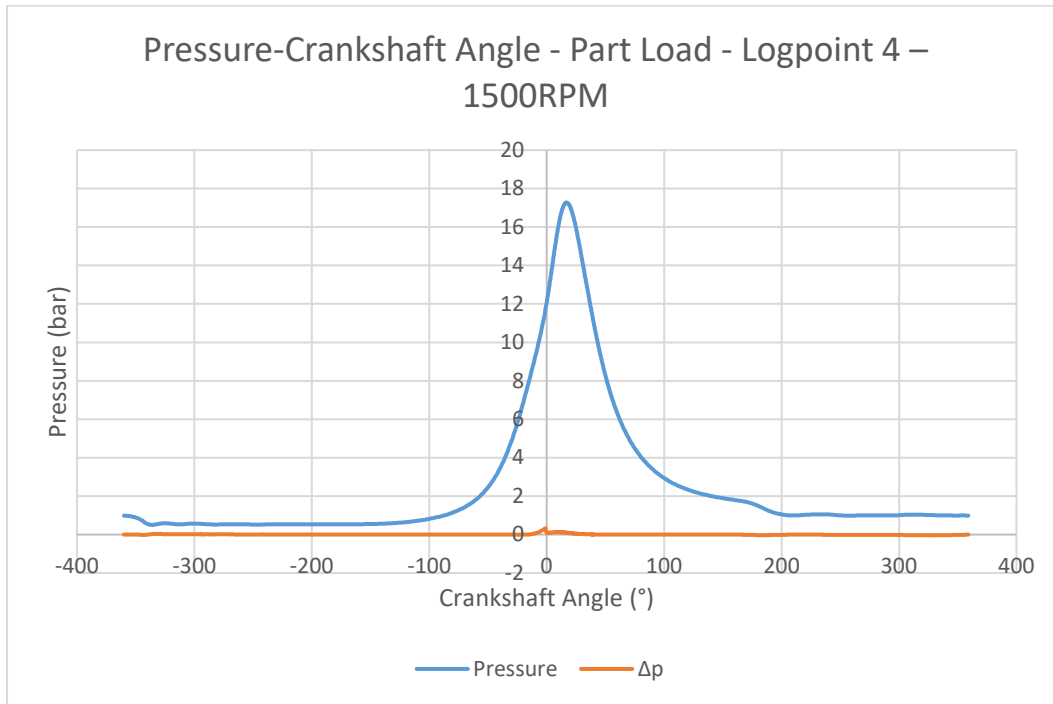


Figure 33: Pressure-Crankshaft Angle - Part Load - Logpoint 4 – 1500RPM

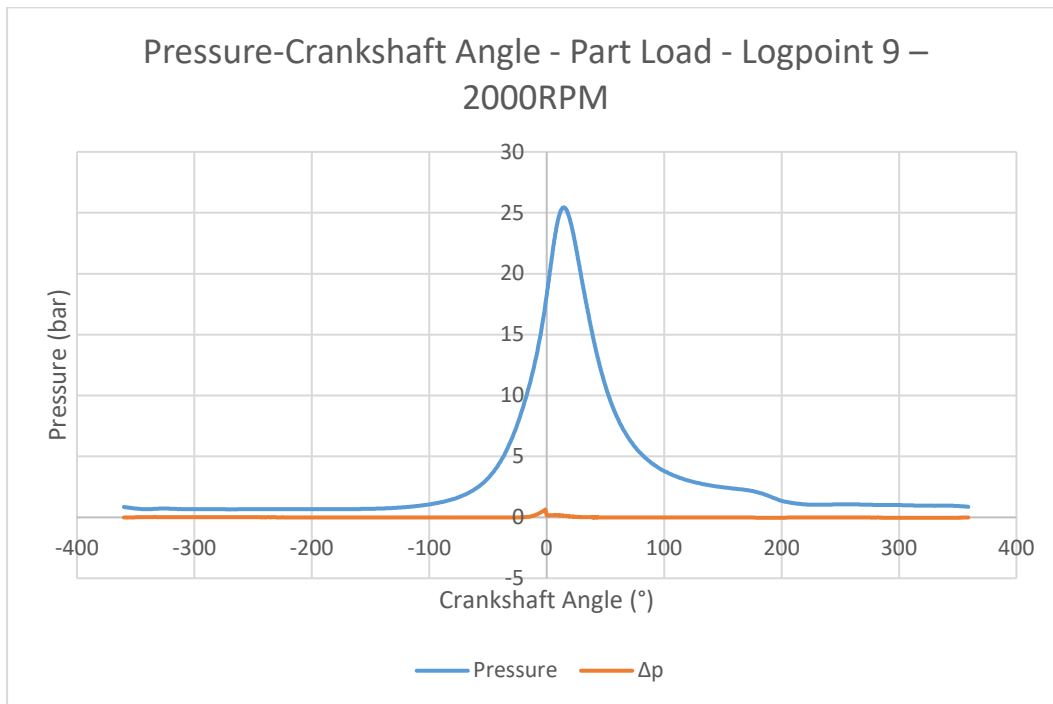


Figure 34: Pressure-Crankshaft Angle - Part Load - Logpoint 9 – 2000RPM

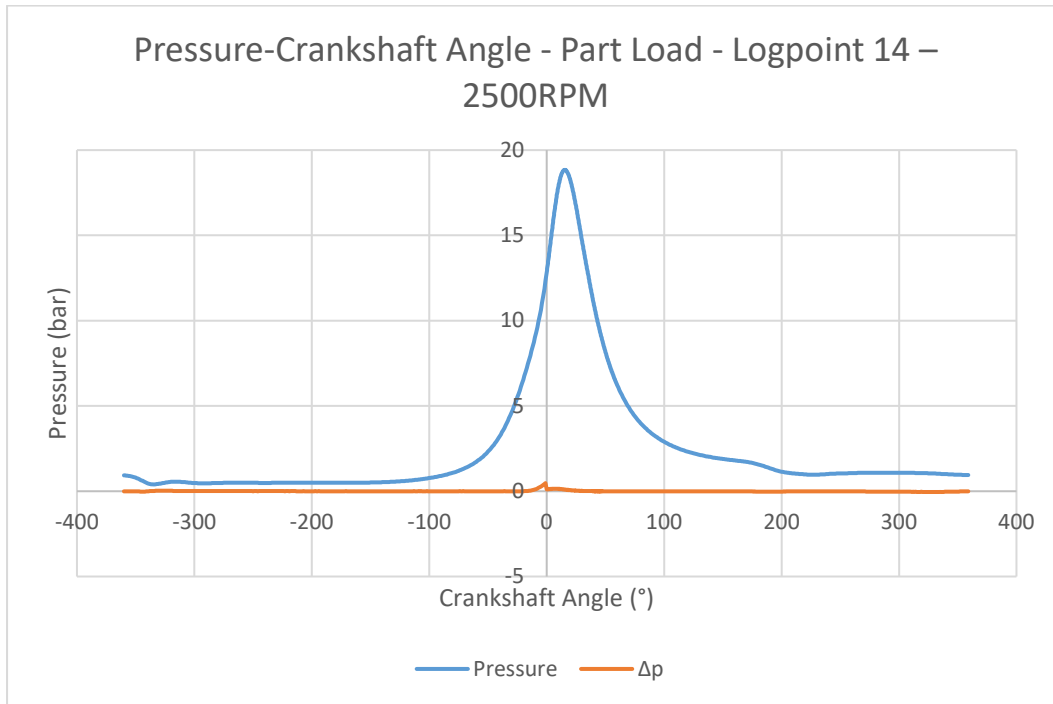


Figure 35: Pressure-Crankshaft Angle - Part Load - Logpoint 14 – 2500RPM

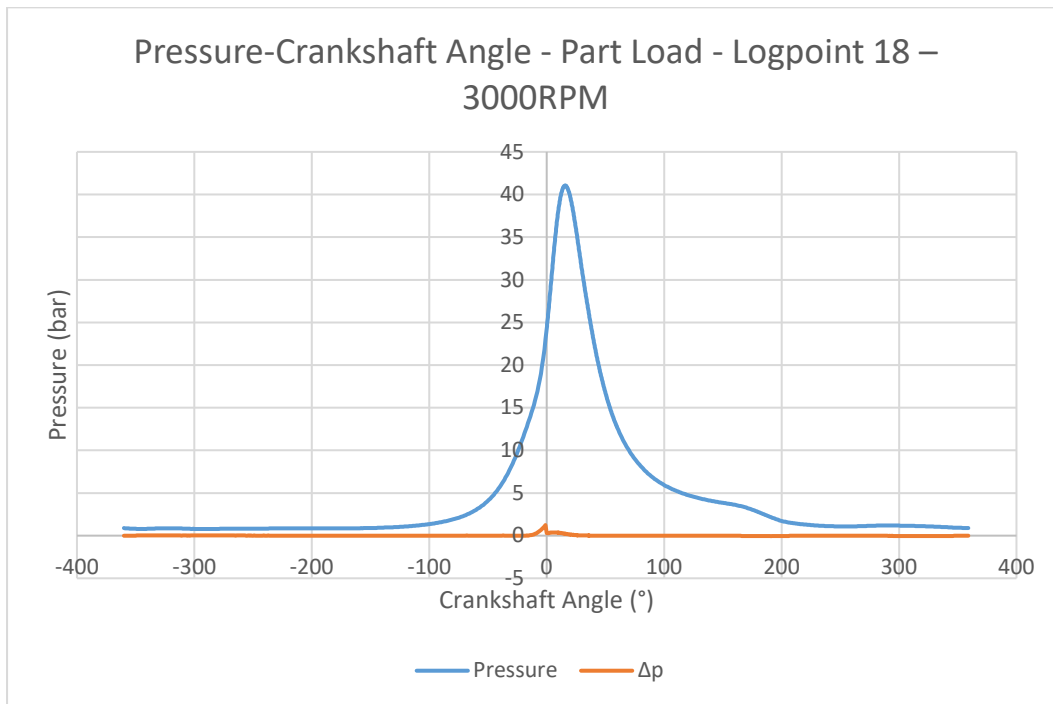


Figure 36: Pressure-Crankshaft Angle - Part Load - Logpoint 18 – 3000RPM

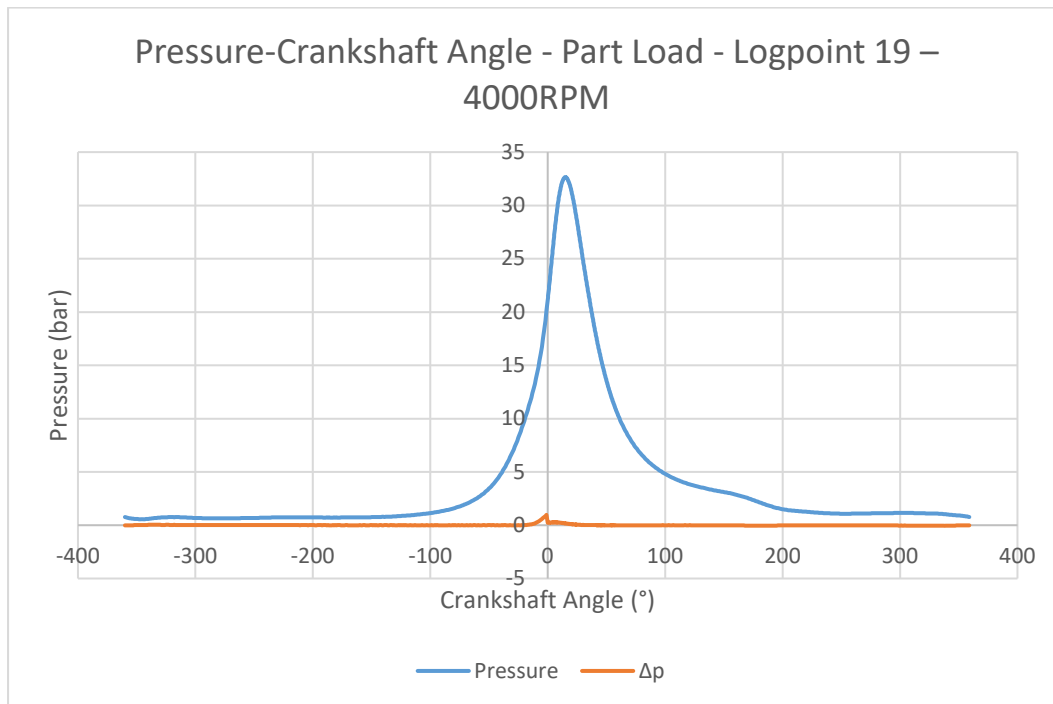


Figure 37: Pressure-Crankshaft Angle - Part Load - Logpoint 19 – 4000RPM

Appendix B: Pressure-Crankshaft Angle Graphs for Full Load Logpoints

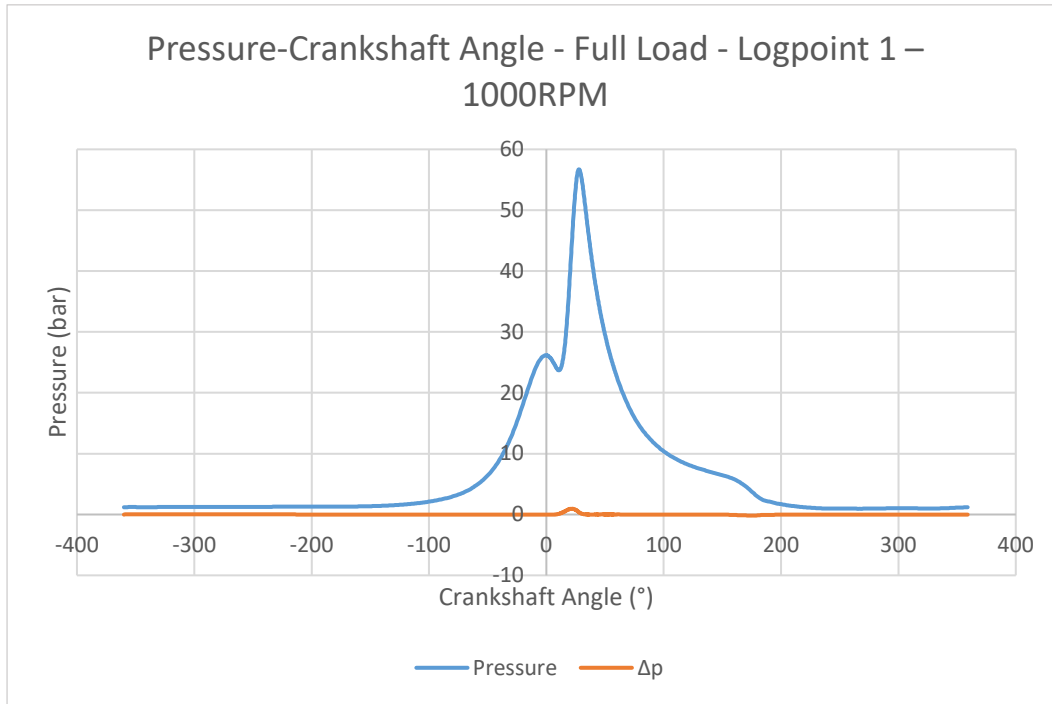


Figure 38: Pressure-Crankshaft Angle - Full Load - Logpoint 1 – 1000RPM

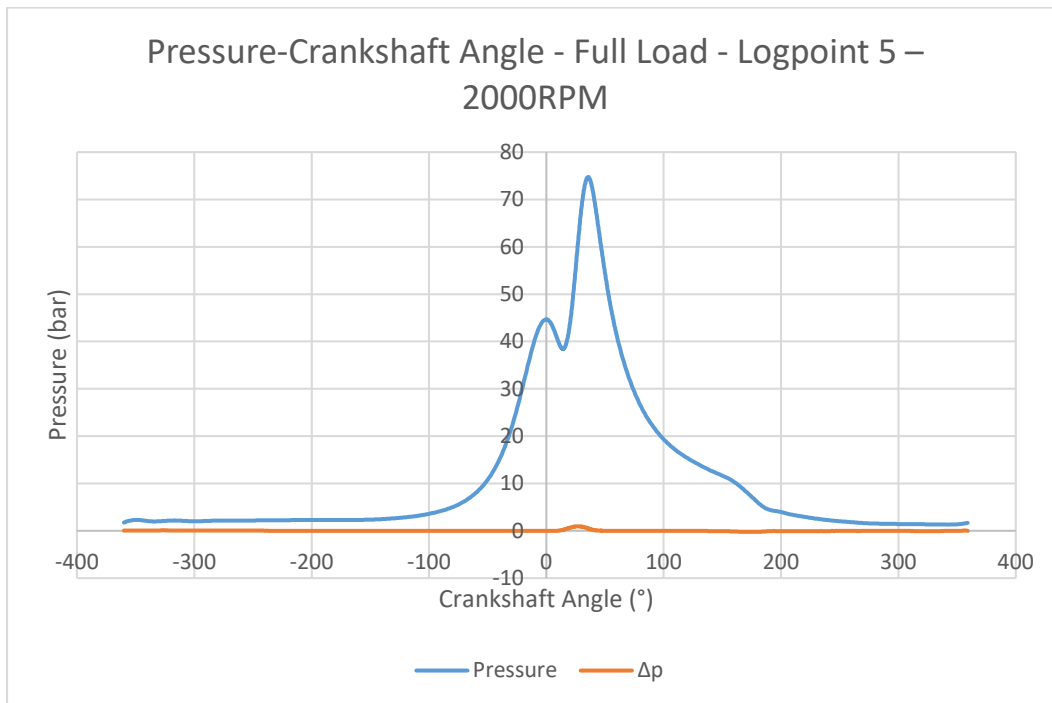


Figure 39: Pressure-Crankshaft Angle - Full Load - Logpoint 5 – 2000RPM

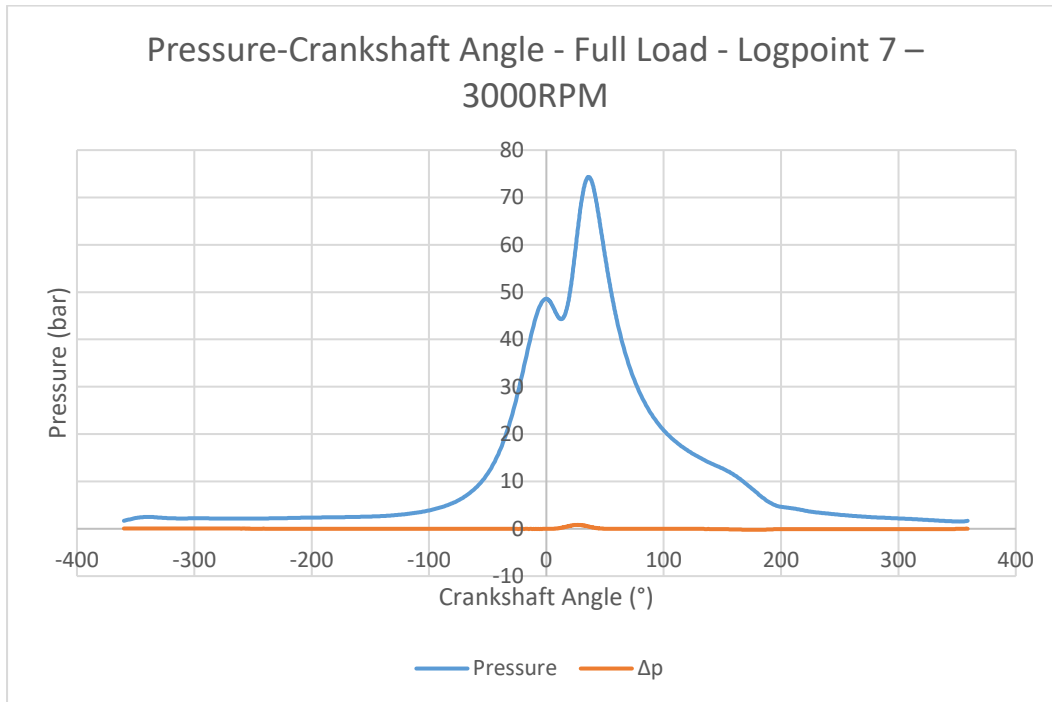


Figure 40: Pressure-Crankshaft Angle - Full Load - Logpoint 7 – 3000RPM

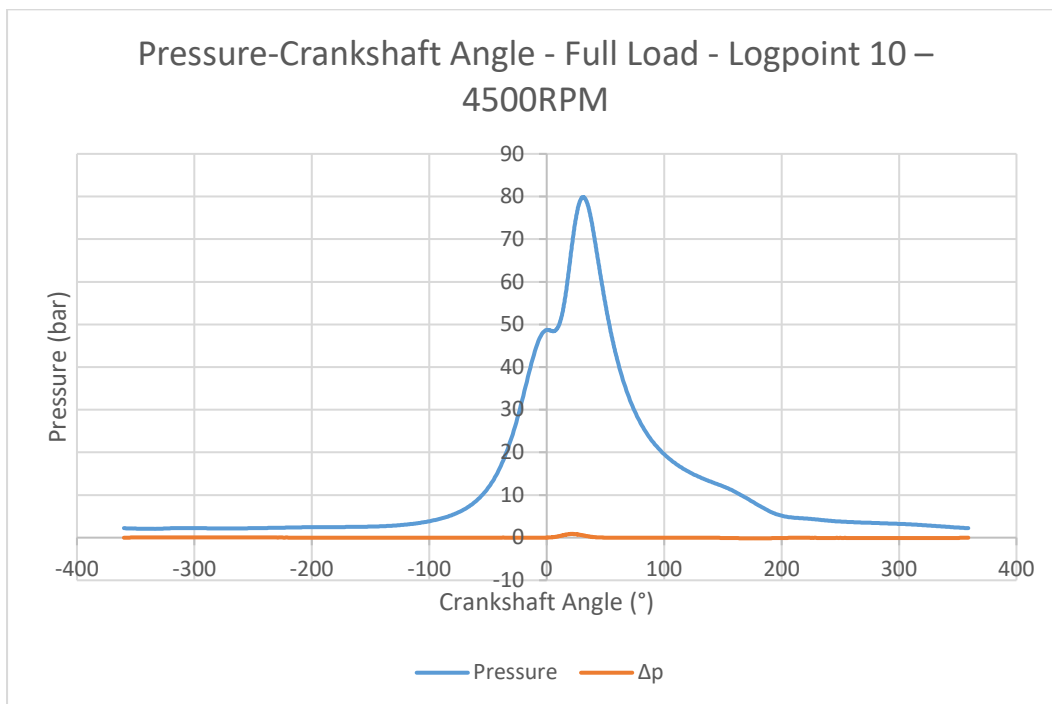


Figure 41: Pressure-Crankshaft Angle - Full Load - Logpoint 10 – 4500RPM

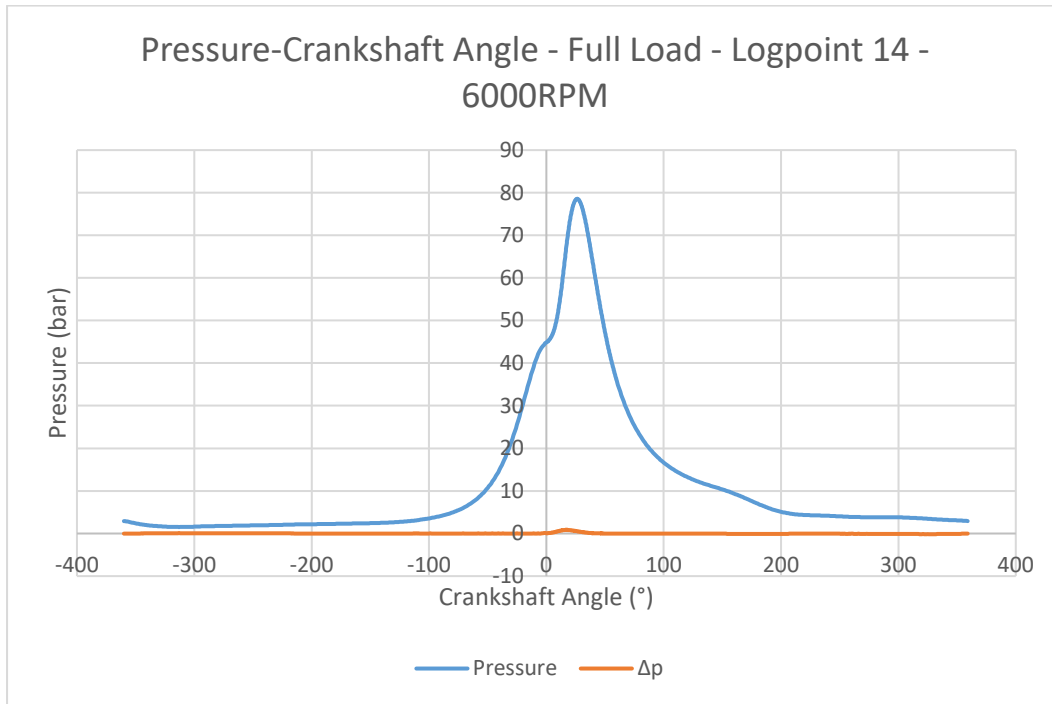


Figure 42: Pressure-Crankshaft Angle - Full Load - Logpoint 14 – 6000RPM

Appendix C: Logp-LogV Graphs for Part Load Logpoints

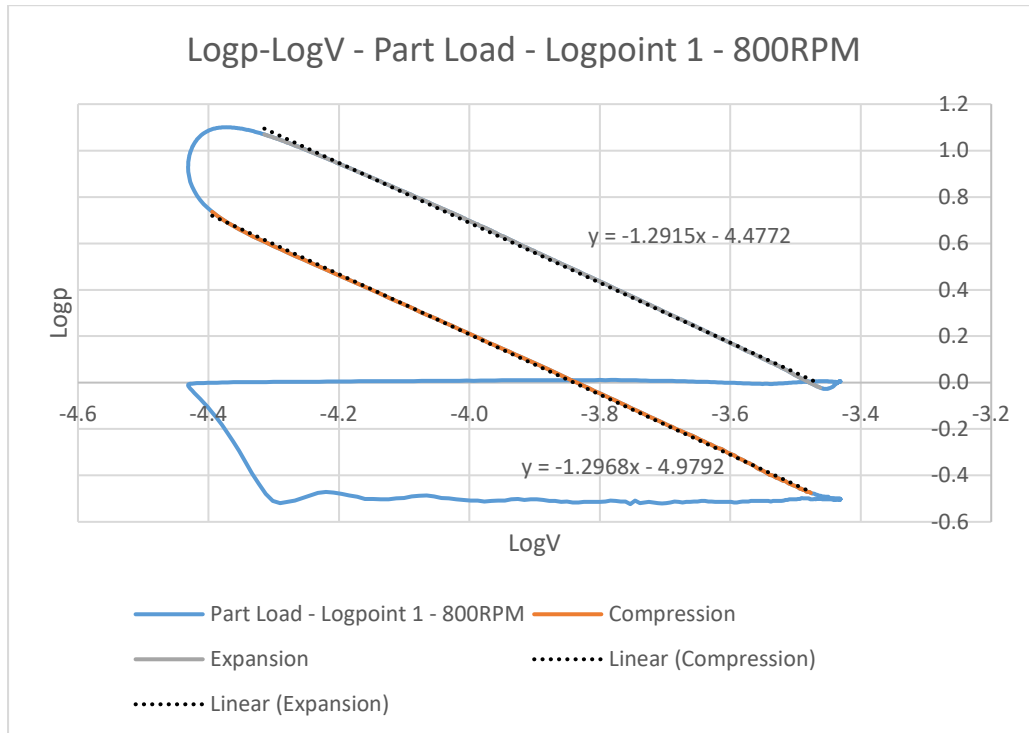


Figure 43: Logp-LogV - Part Load - Logpoint 1 - 800RPM

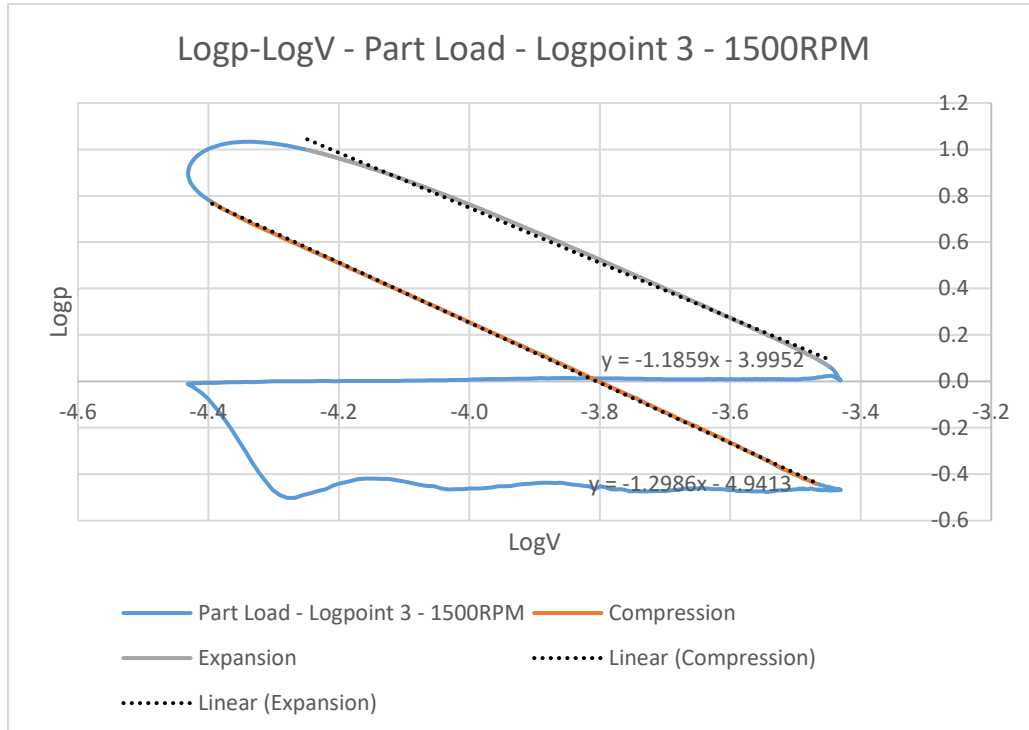


Figure 44: Logp-LogV - Part Load - Logpoint 3 - 1500RPM

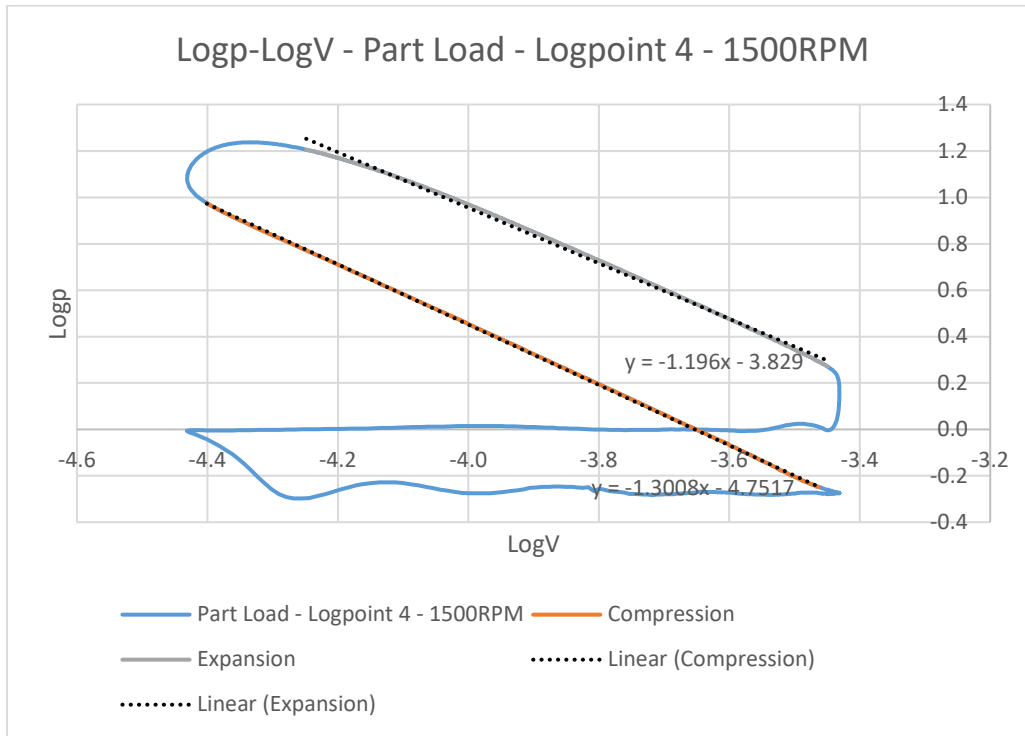


Figure 45: Logp-LogV - Part Load - Logpoint 4 - 1500RPM

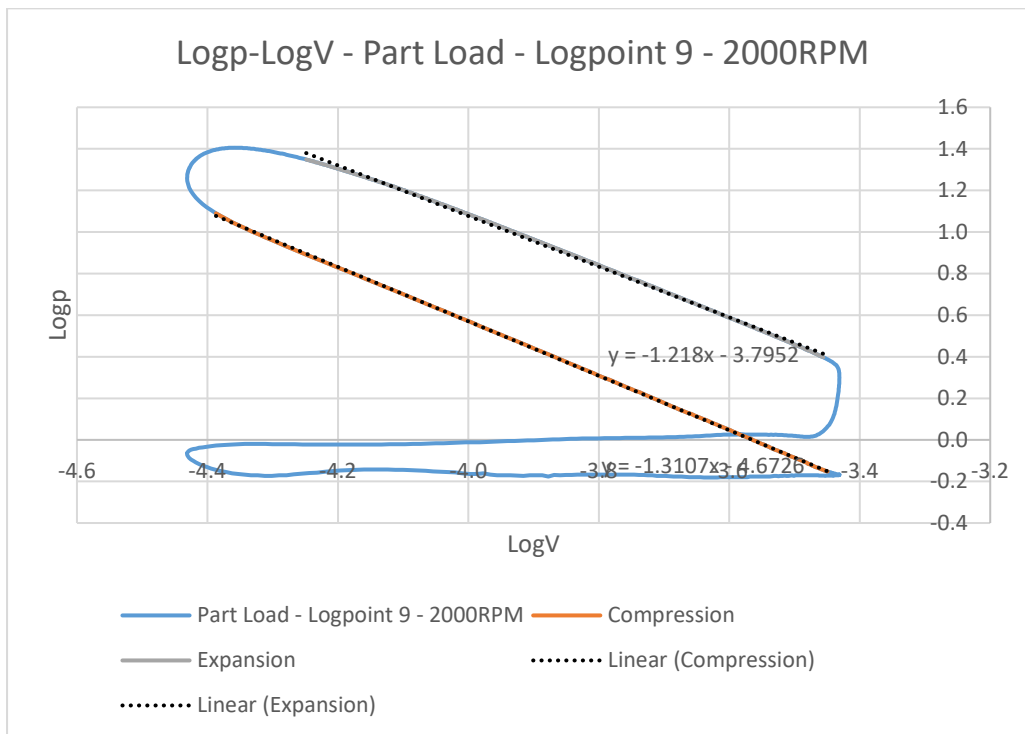


Figure 46: Logp-LogV - Part Load - Logpoint 9 - 2000RPM

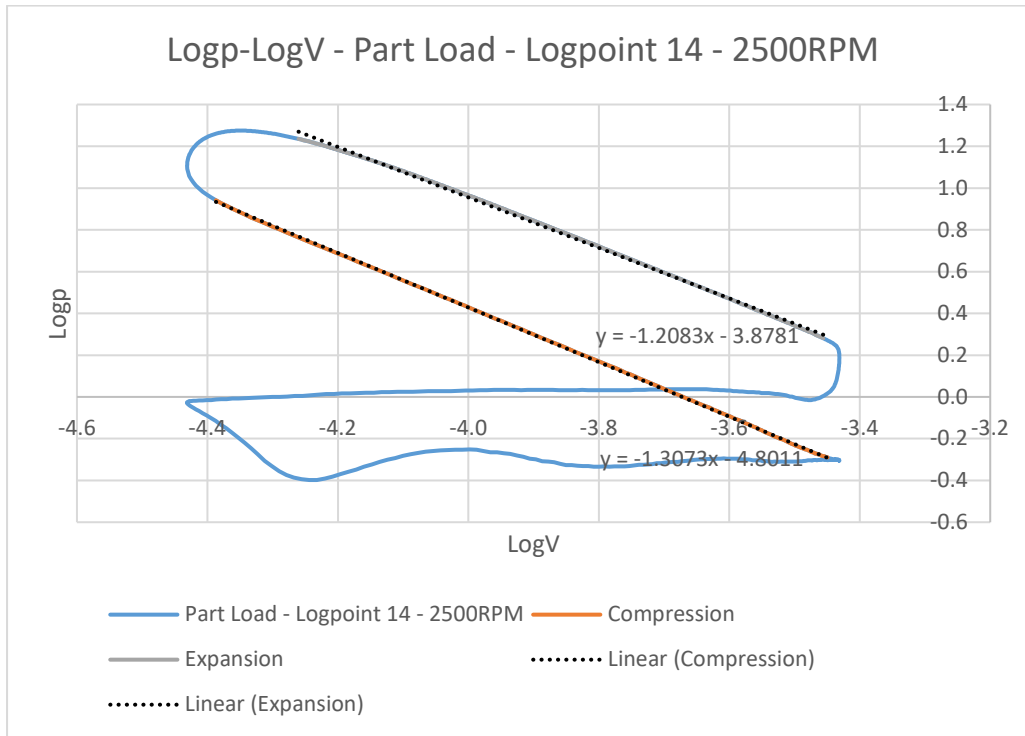


Figure 47: Logp-LogV - Part Load - Logpoint 14 - 2500RPM

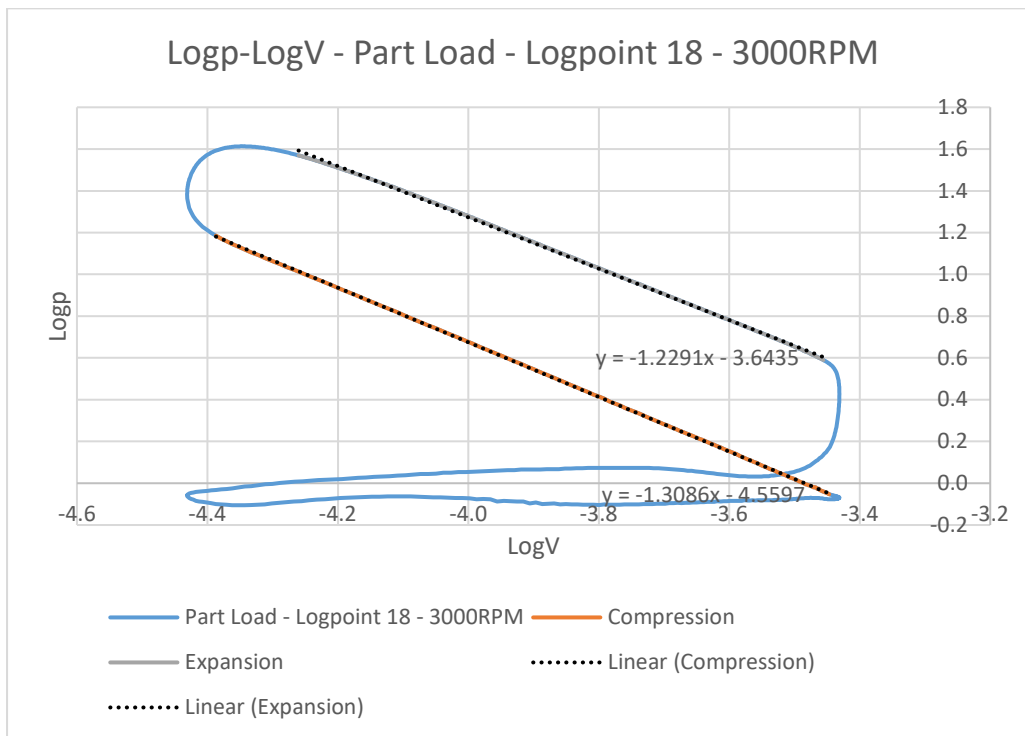


Figure 48: Logp-LogV - Part Load - Logpoint 18 - 3000RPM

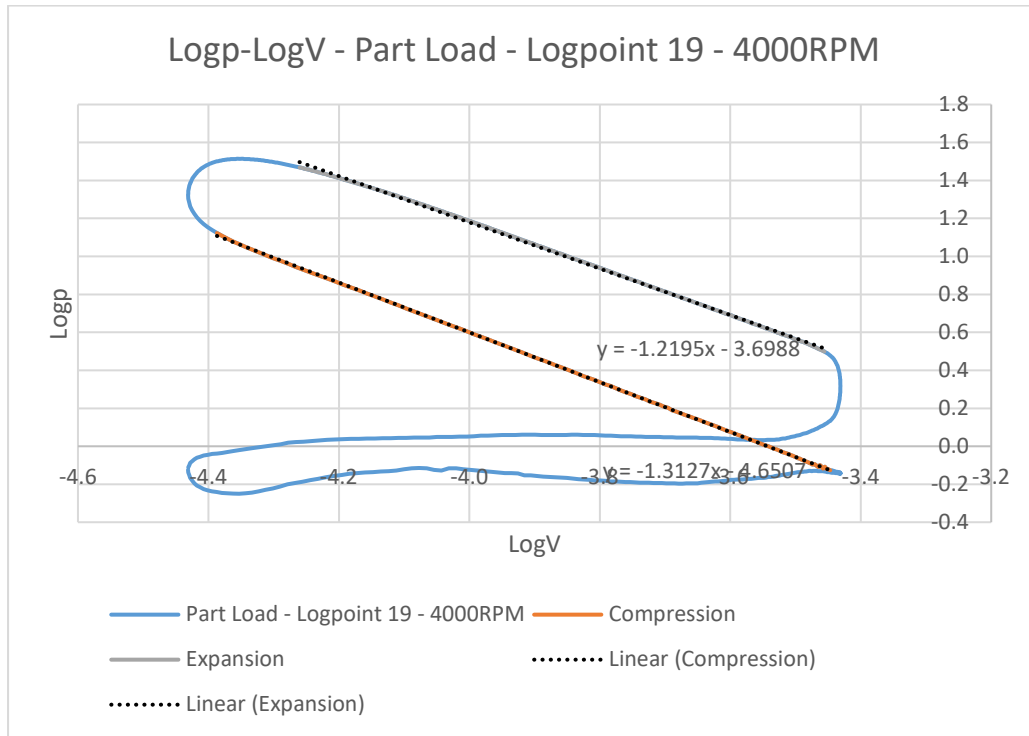


Figure 49: Logp-LogV - Part Load - Logpoint 19 - 4000RPM

Appendix D: Logp-LogV Graphs for Full Load Logpoints

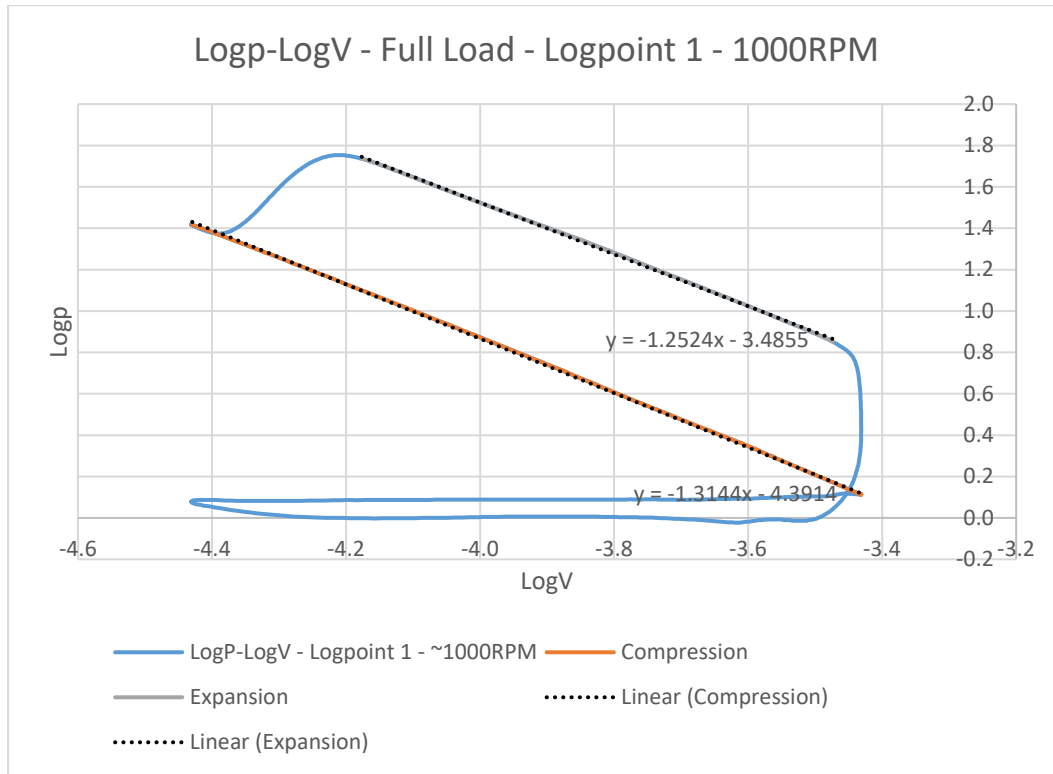


Figure 50: Logp-LogV - Full Load - Logpoint 1 - 1000RPM

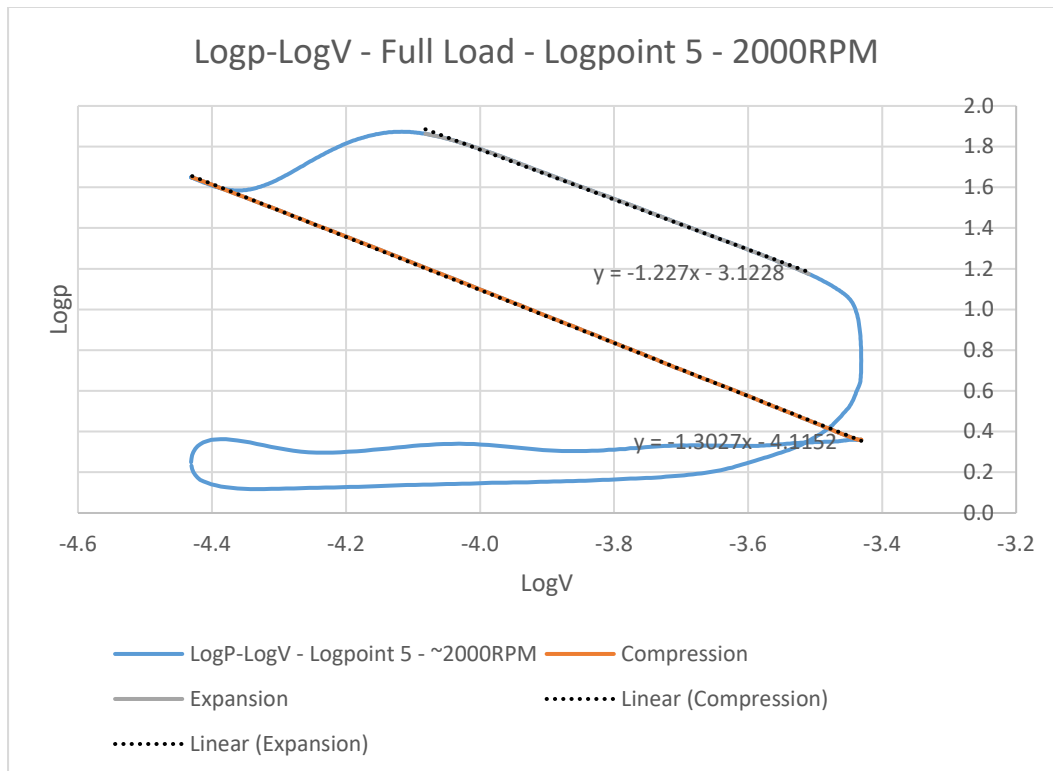


Figure 51: Logp-LogV - Full Load - Logpoint 5 - 2000RPM

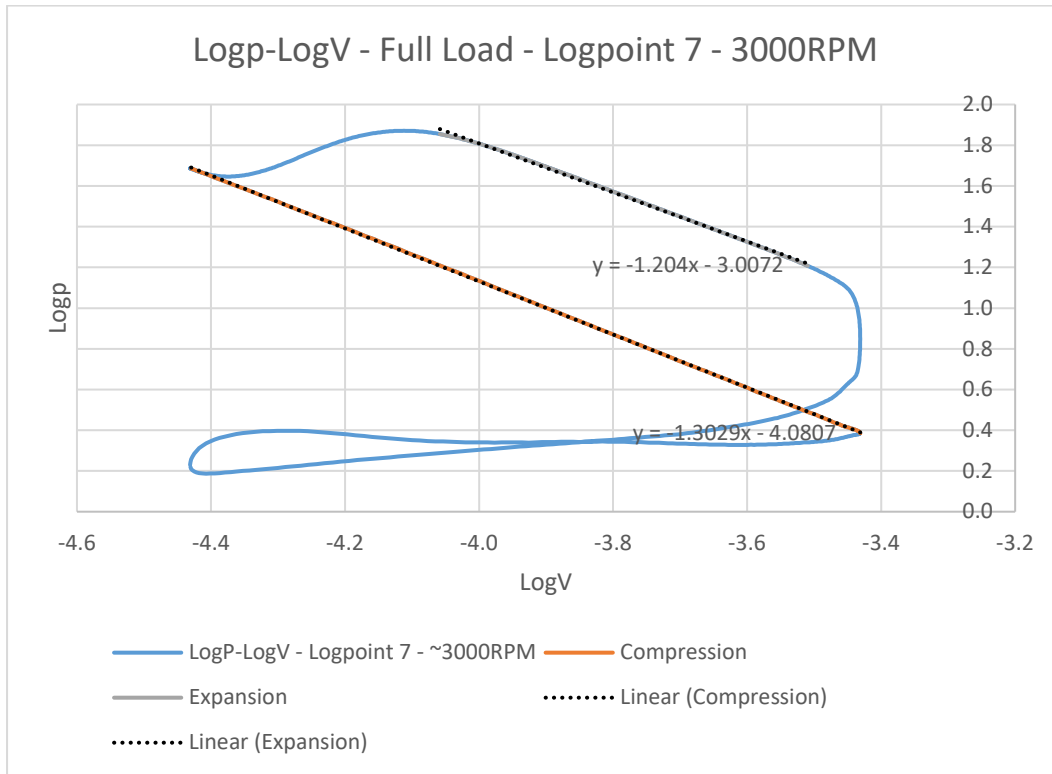


Figure 52: Logp-LogV - Full Load - Logpoint 7 - 3000RPM

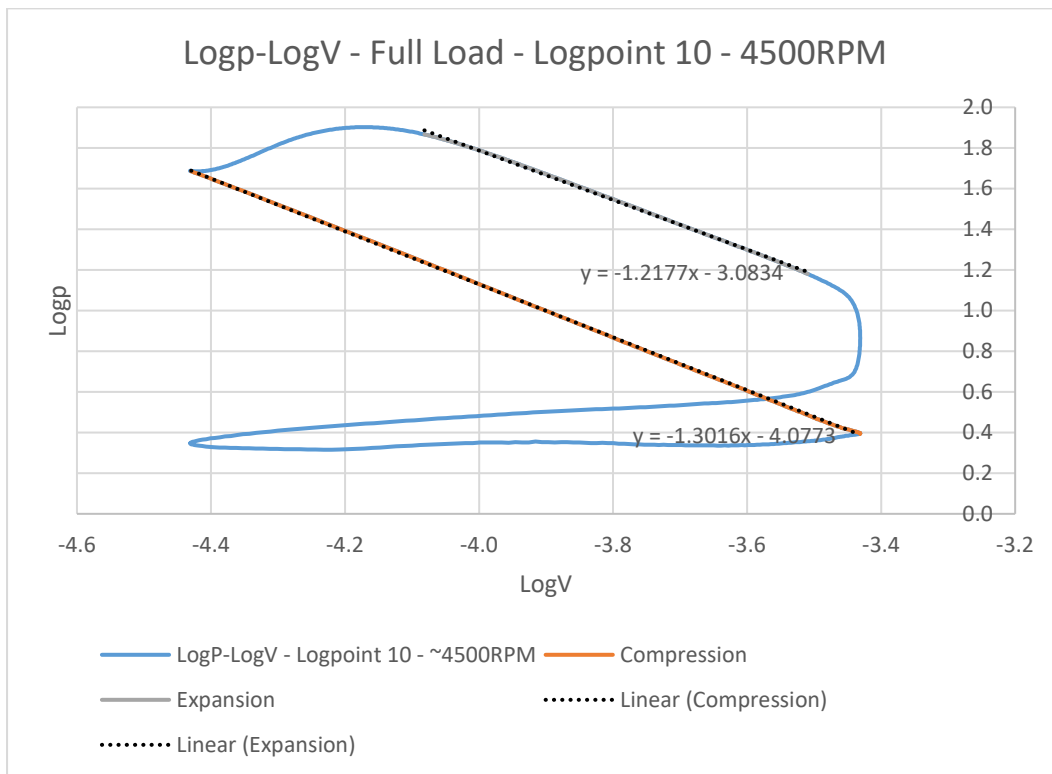


Figure 53: Logp-LogV - Full Load - Logpoint 10 - 4500RPM

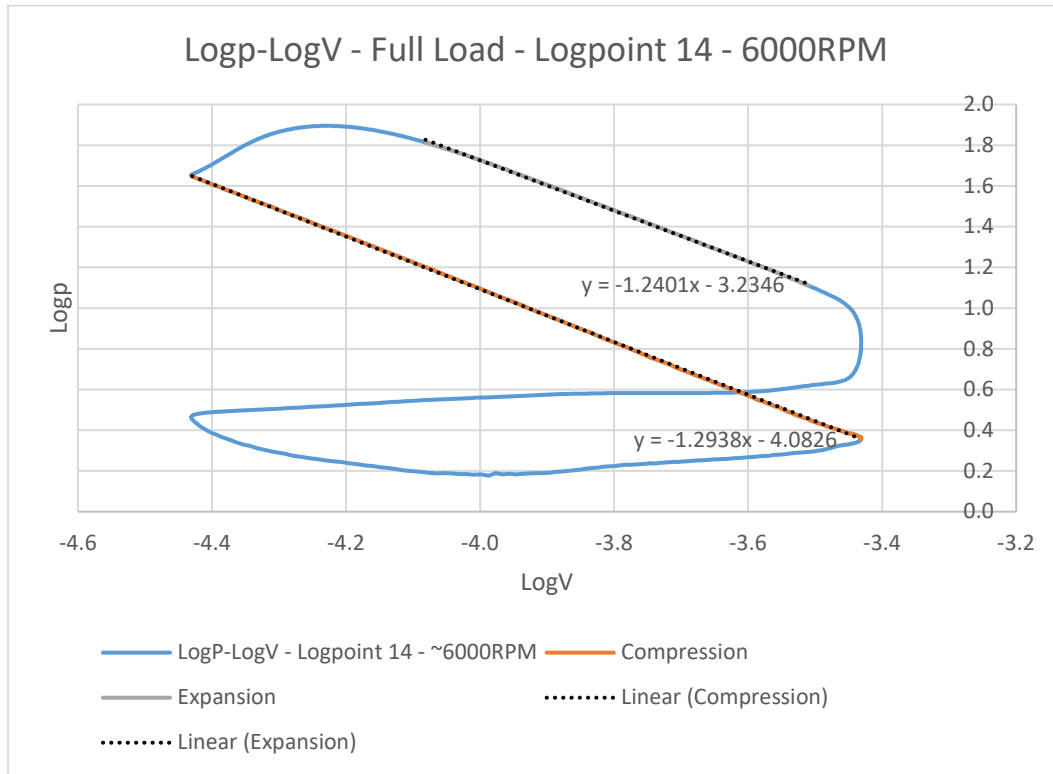


Figure 54: Logp-LogV - Full Load - Logpoint 14 - 6000RPM

Appendix E: Wiebe Function Coefficient Graphs for Part Load Logpoints

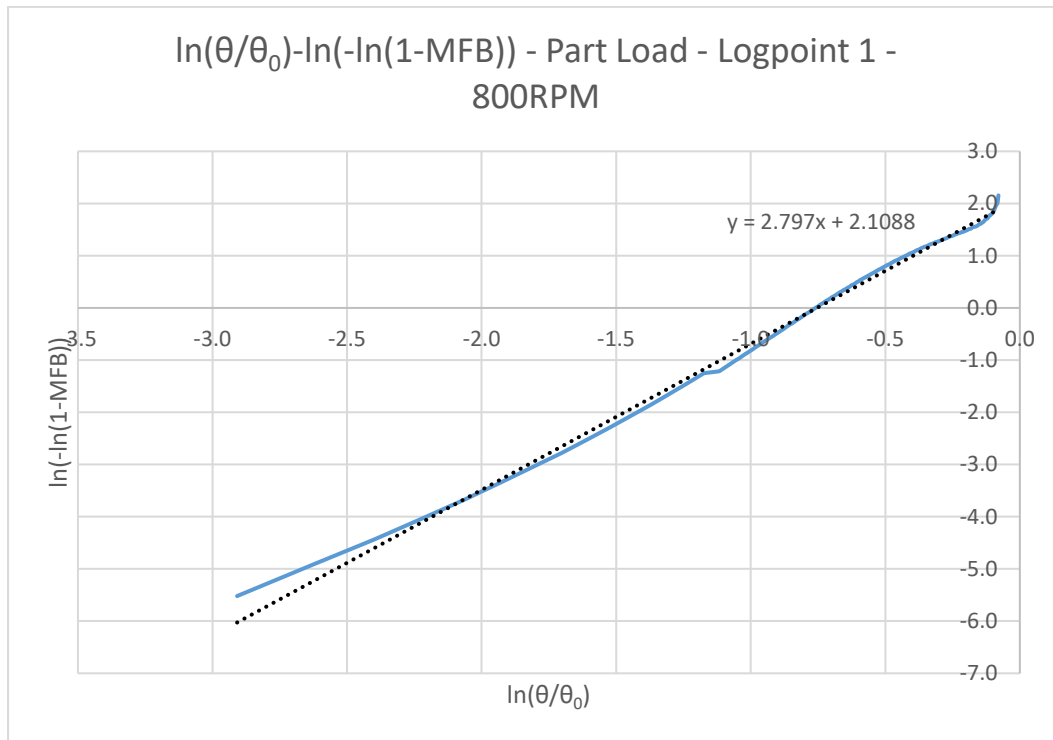


Figure 55: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Part Load - Logpoint 1 - 800RPM

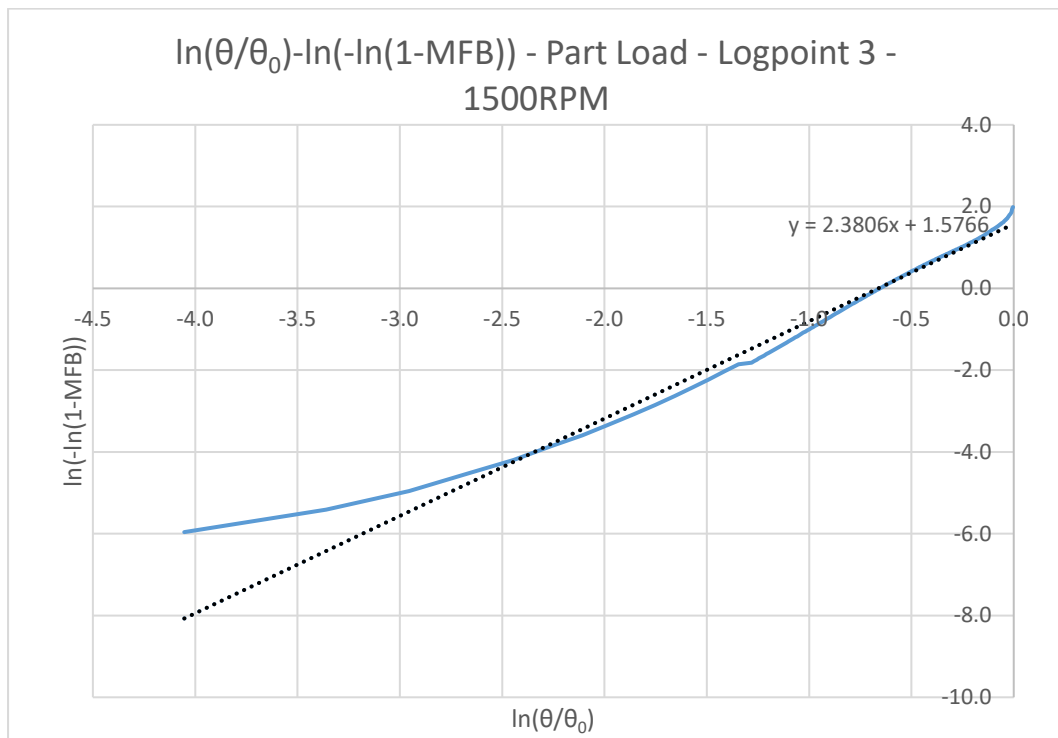


Figure 56: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Part Load - Logpoint 3 - 1500RPM

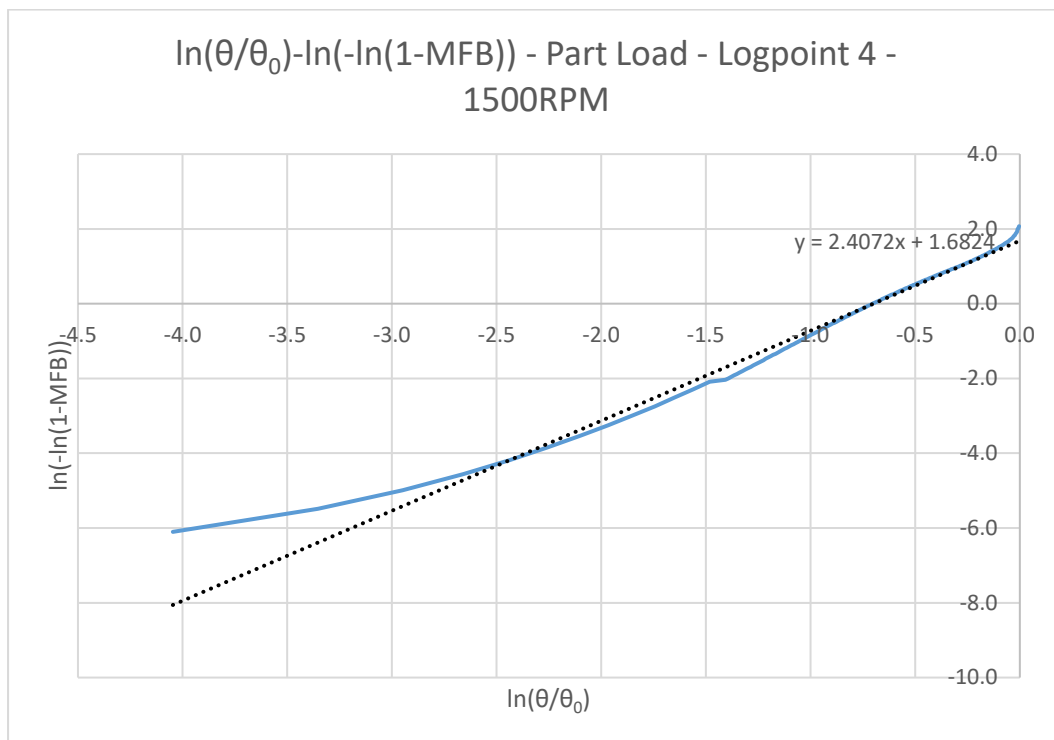


Figure 57: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Part Load - Logpoint 4 - 1500RPM

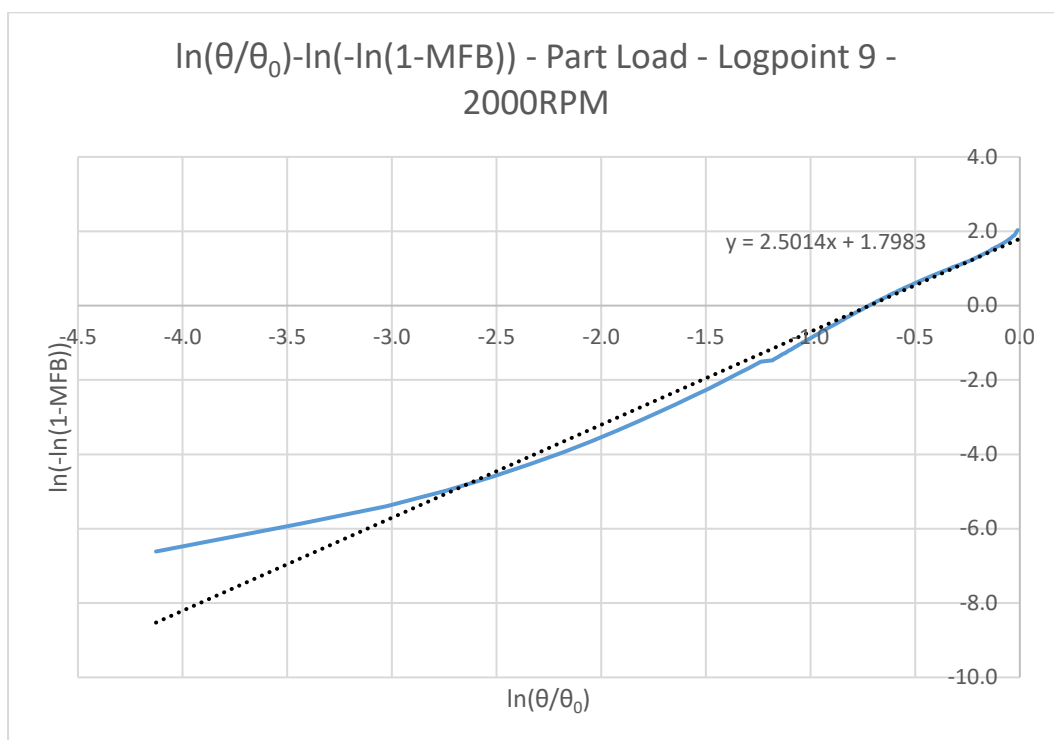


Figure 58: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Part Load - Logpoint 9 - 2000RPM

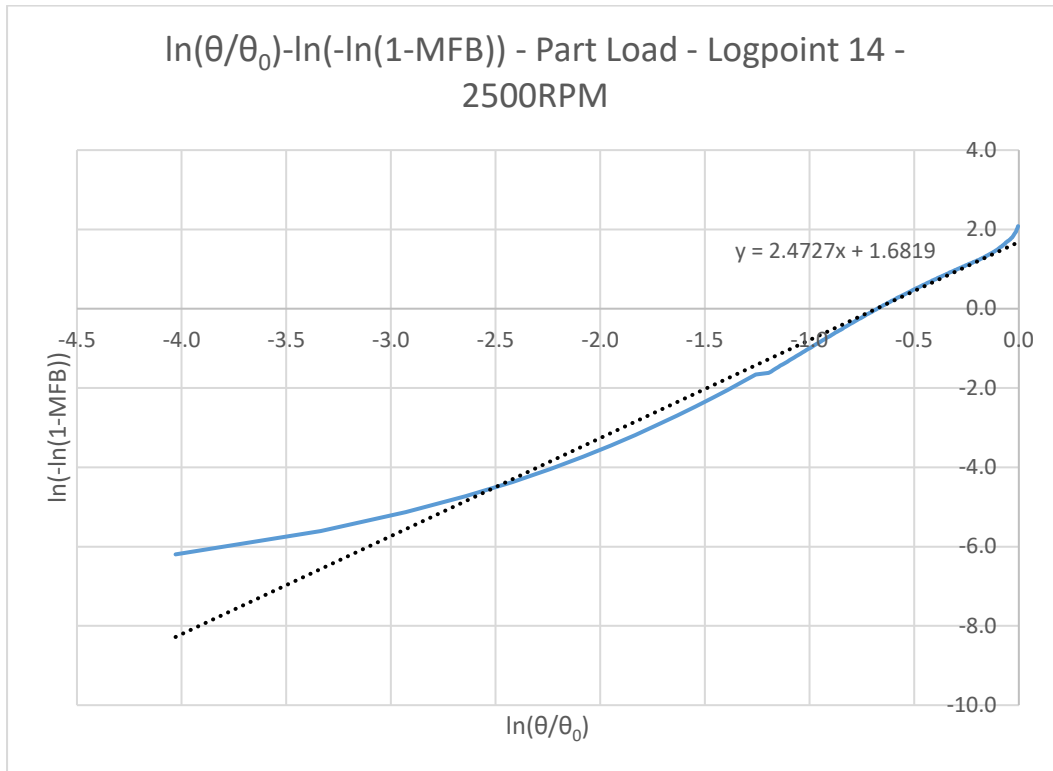


Figure 59: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Part Load - Logpoint 14 - 2500RPM

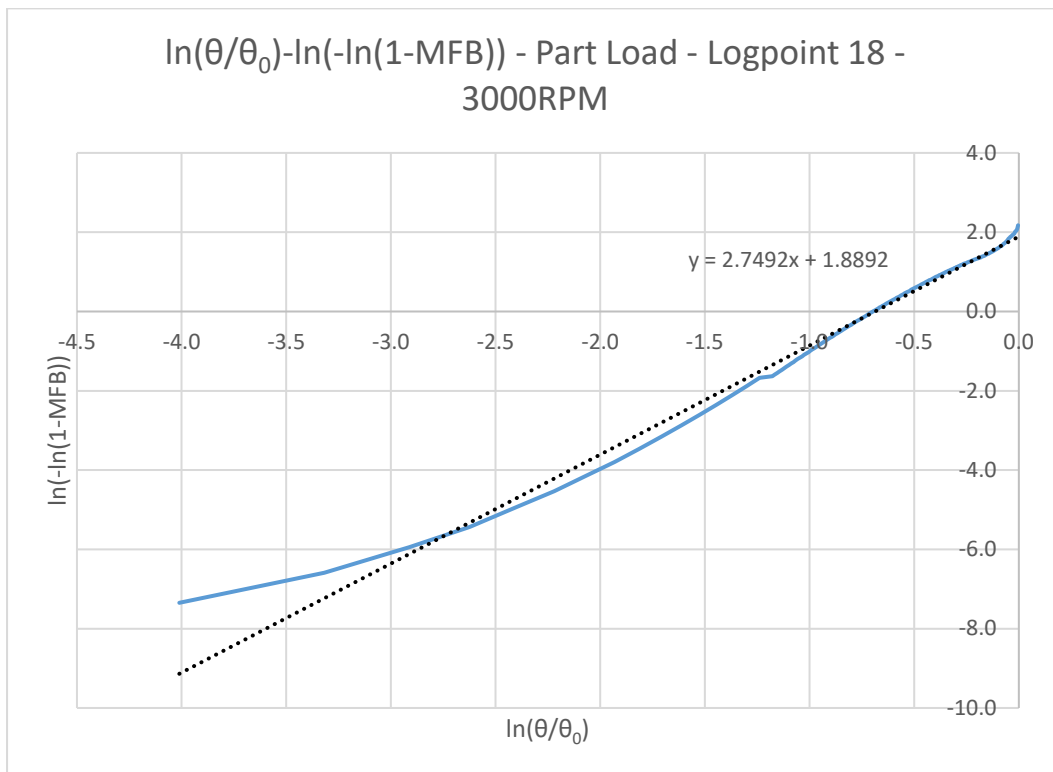


Figure 60: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Part Load - Logpoint 18 - 3000RPM

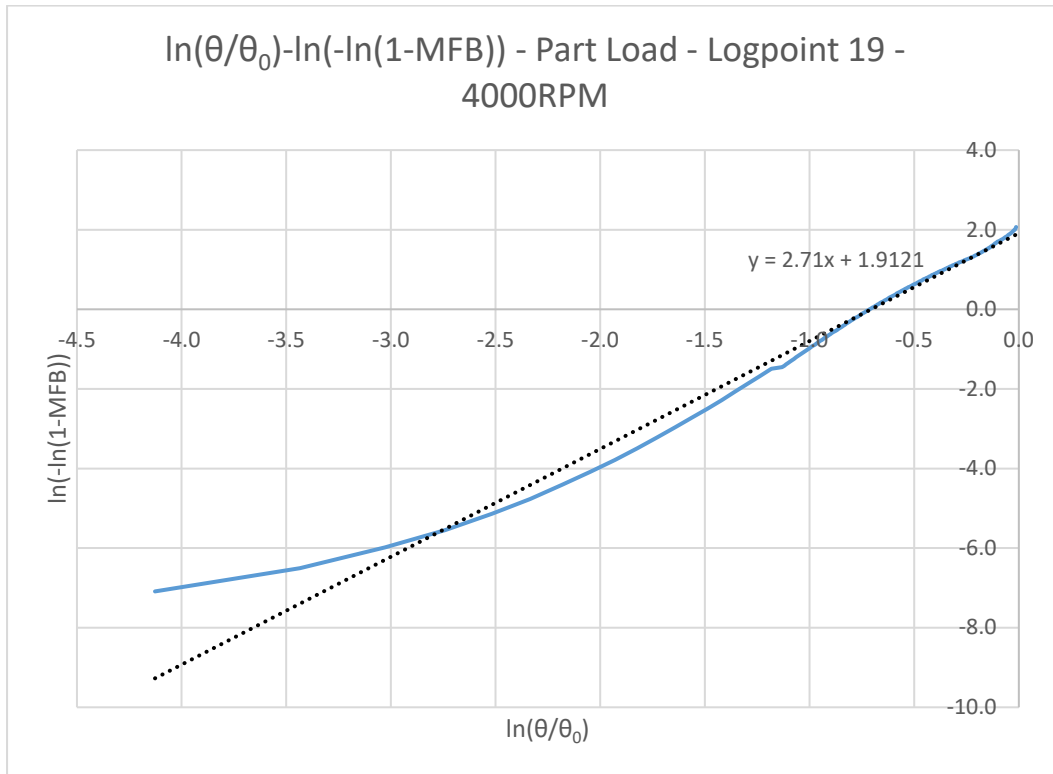


Figure 61: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Part Load - Logpoint 19 - 4000RPM

Appendix F: Wiebe Function Coefficient Graphs for Full Load Logpoints

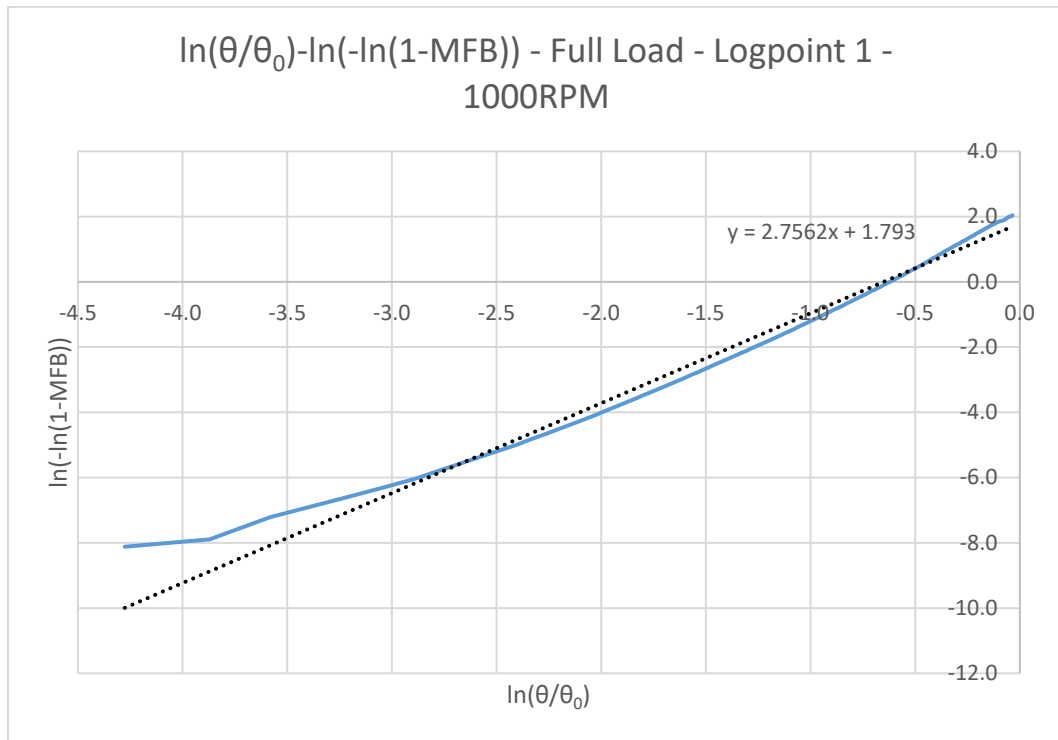


Figure 62: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Full Load - Logpoint 1 - 1000RPM

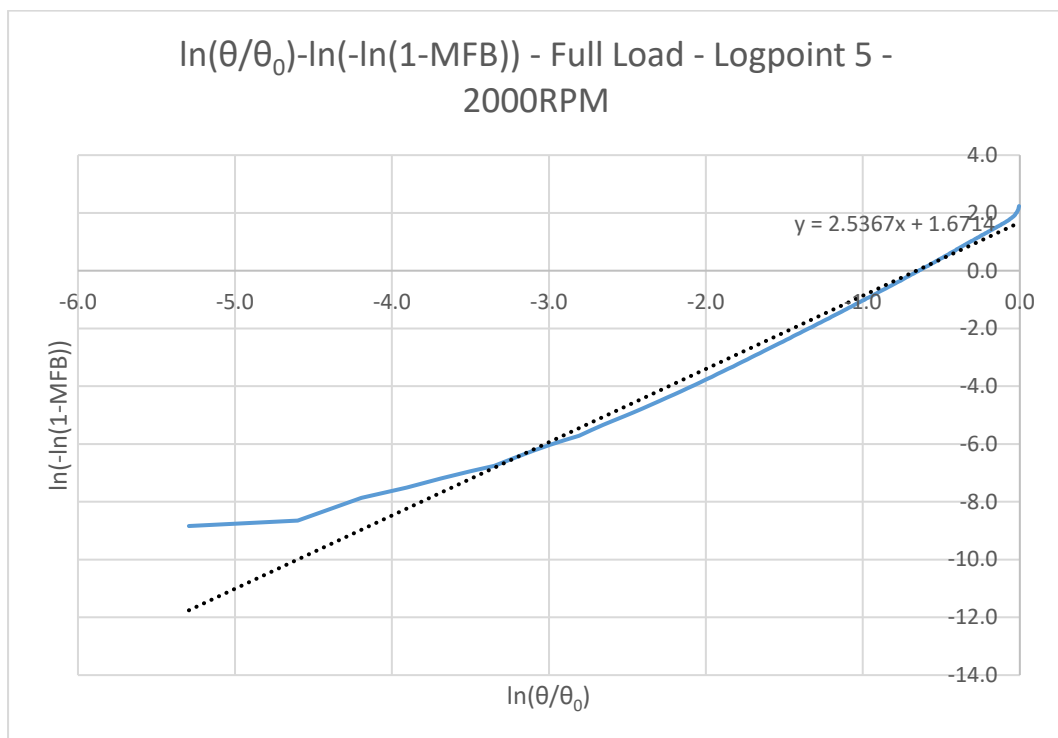


Figure 63: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Full Load - Logpoint 5 - 2000RPM

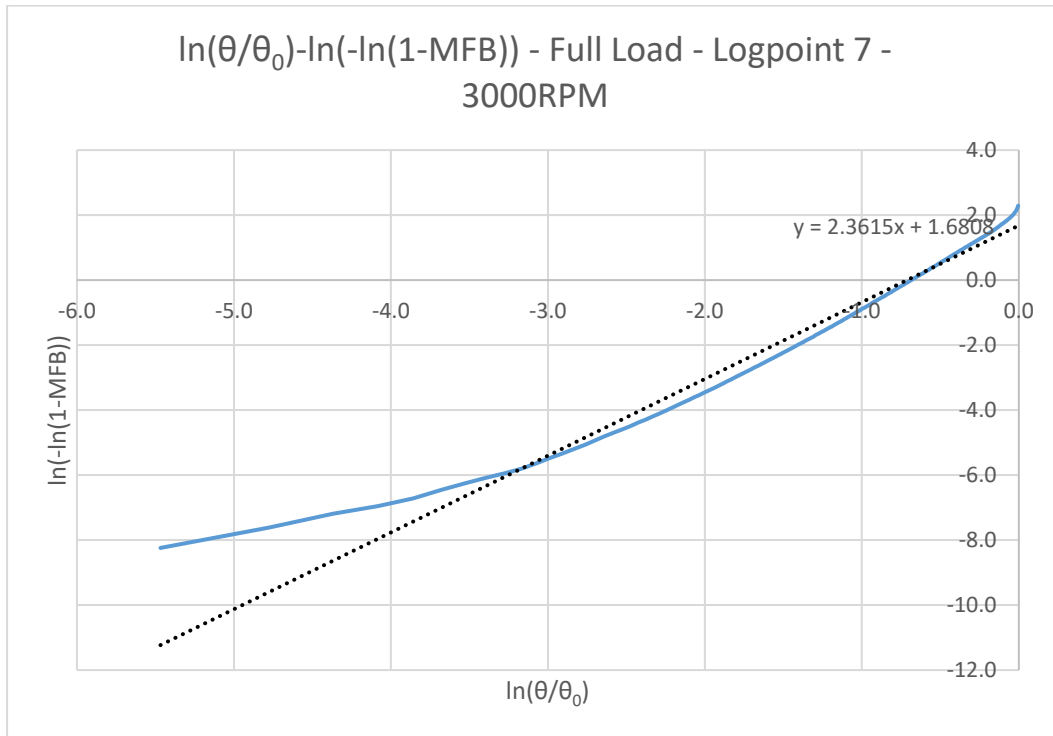


Figure 64: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Full Load - Logpoint 7 - 3000RPM

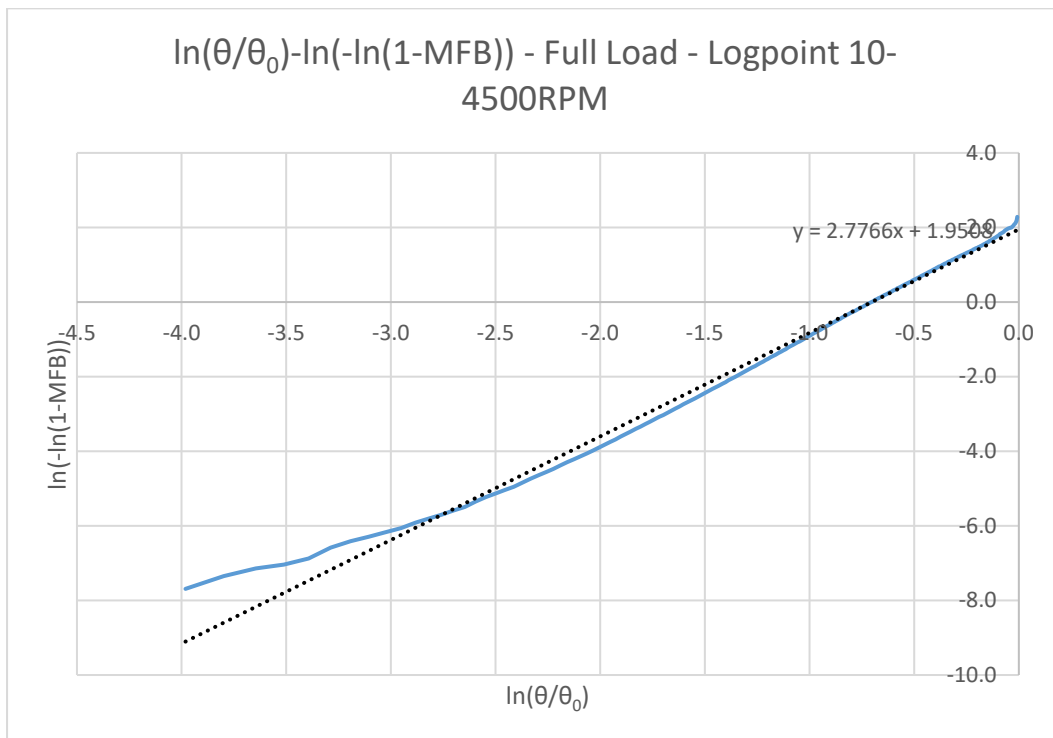


Figure 65: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Full Load - Logpoint 10 - 4500RPM

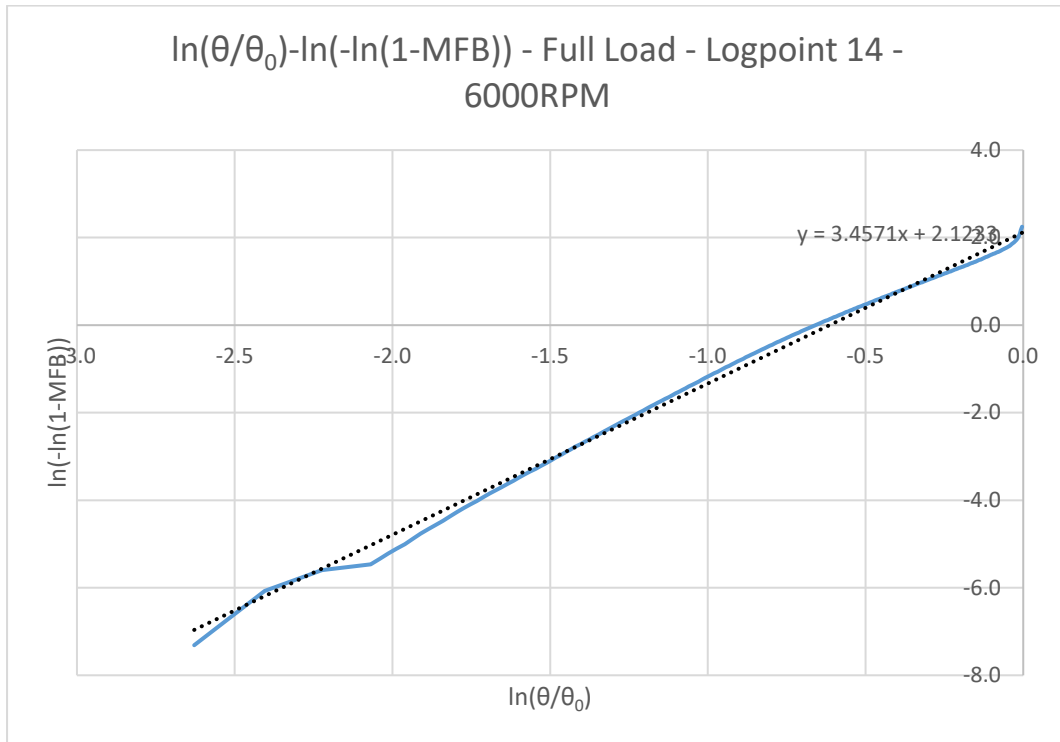


Figure 66: $\ln(\theta/\theta_0) - \ln(-\ln(1-MFB))$ - Full Load - Logpoint 14 - 6000RPM

Appendix G: Theoretical MFB Profiles for Part Load Logpoints

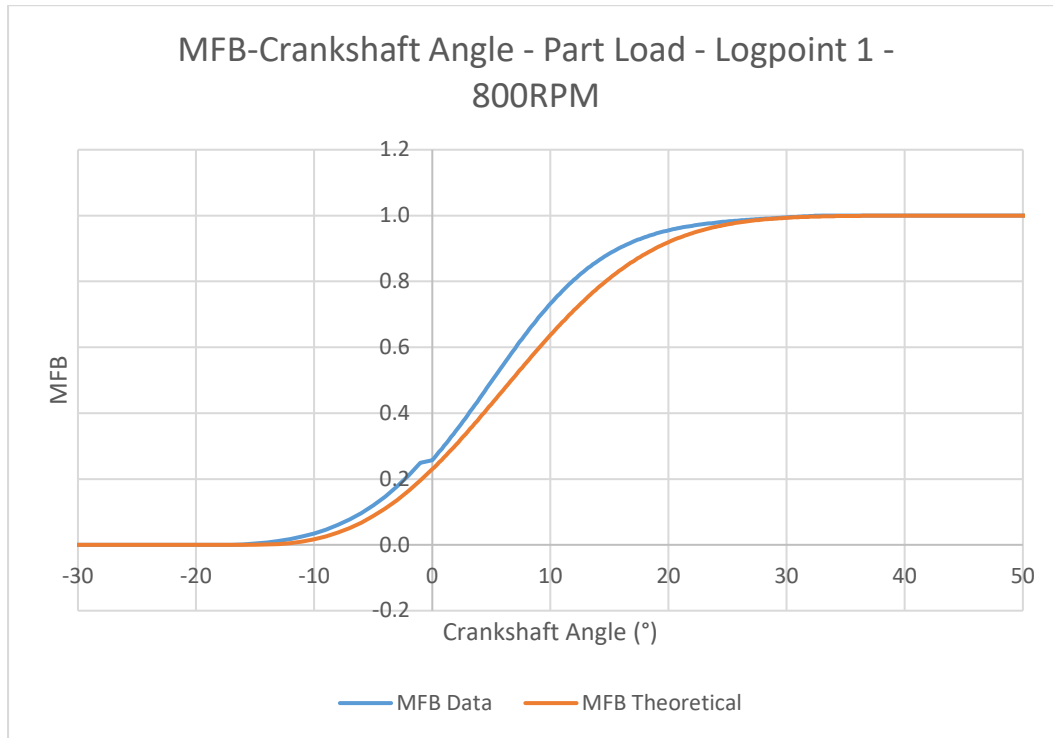


Figure 67: MFB-Crankshaft Angle - Part Load - Logpoint 1 - 800RPM

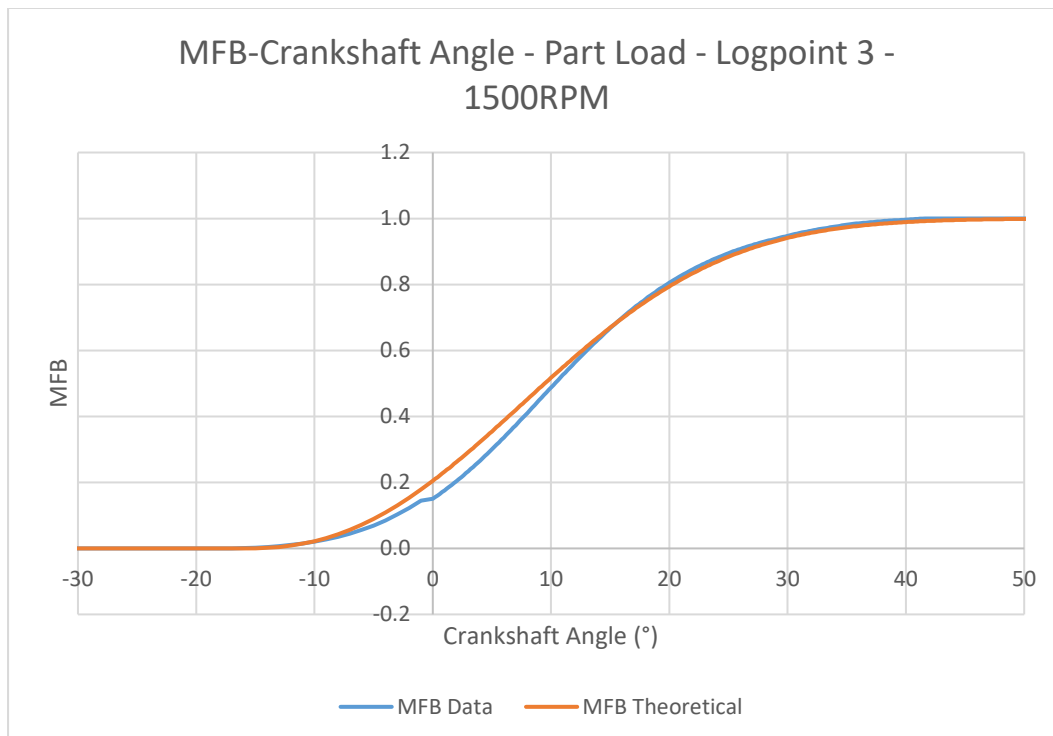


Figure 68: MFB-Crankshaft Angle - Part Load - Logpoint 3 - 1500RPM

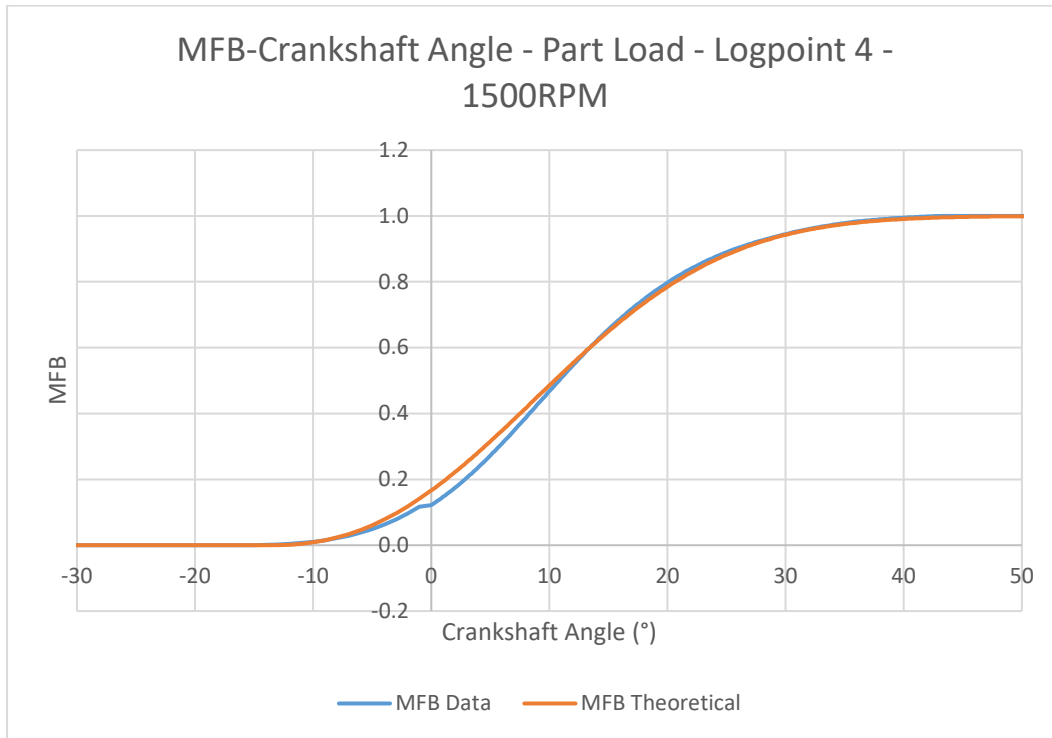


Figure 69: MFB-Crankshaft Angle - Part Load - Logpoint 4 - 1500RPM

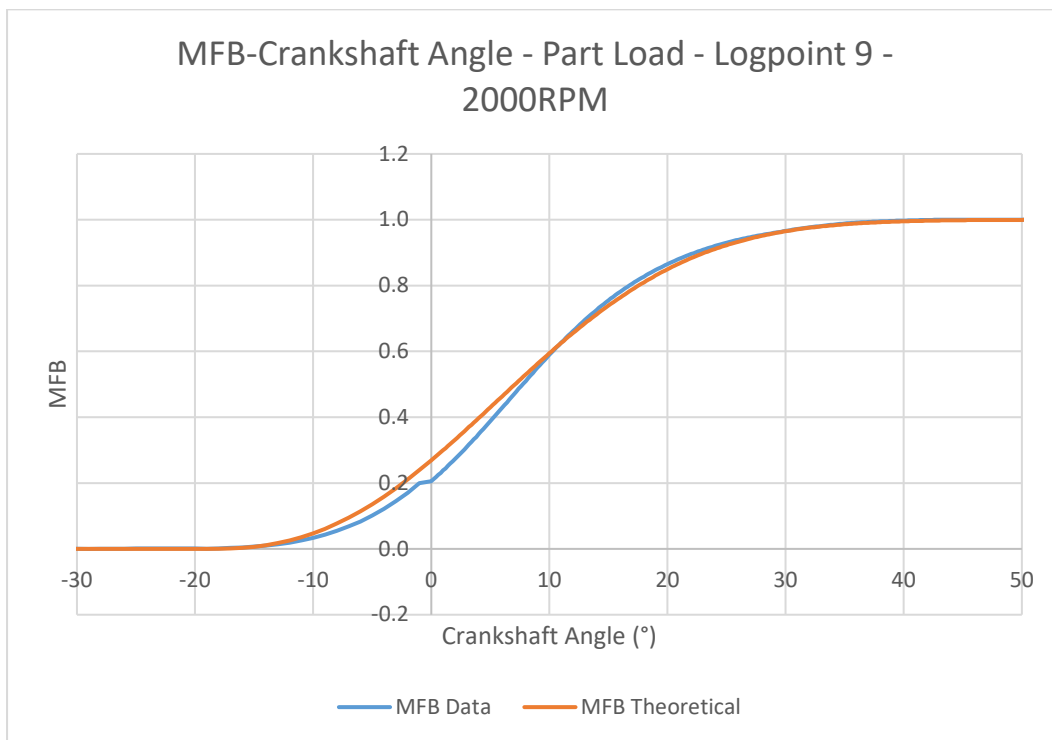


Figure 70: MFB-Crankshaft Angle - Part Load - Logpoint 9 - 2000RPM

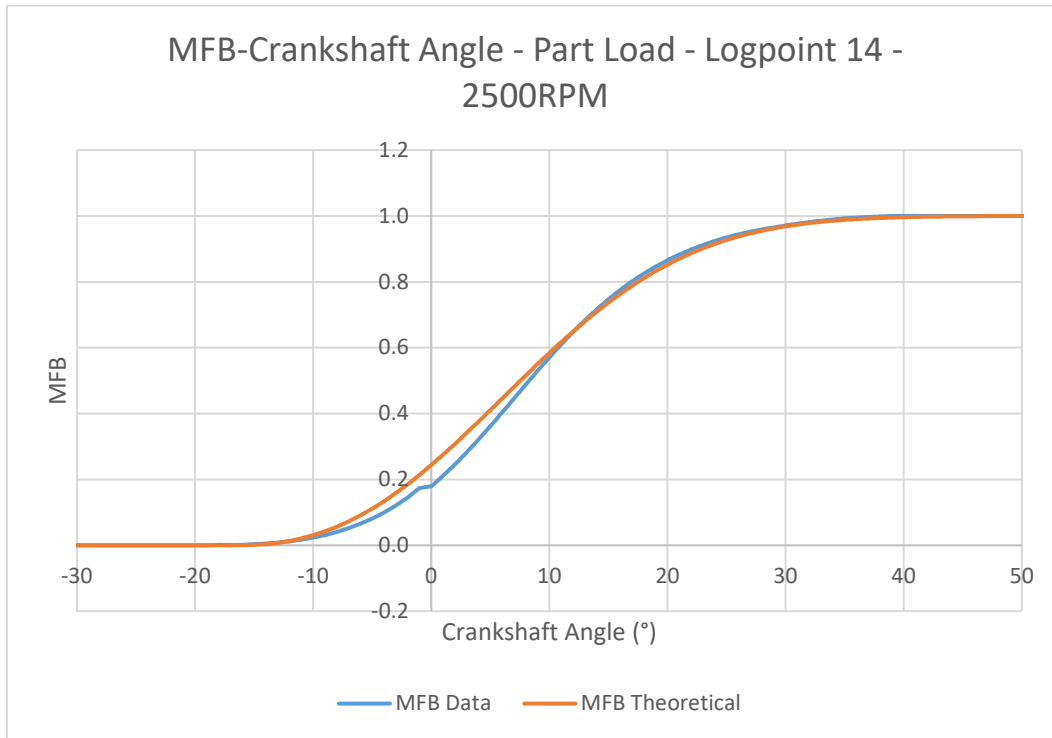


Figure 71: MFB-Crankshaft Angle - Part Load - Logpoint 14 - 2500RPM

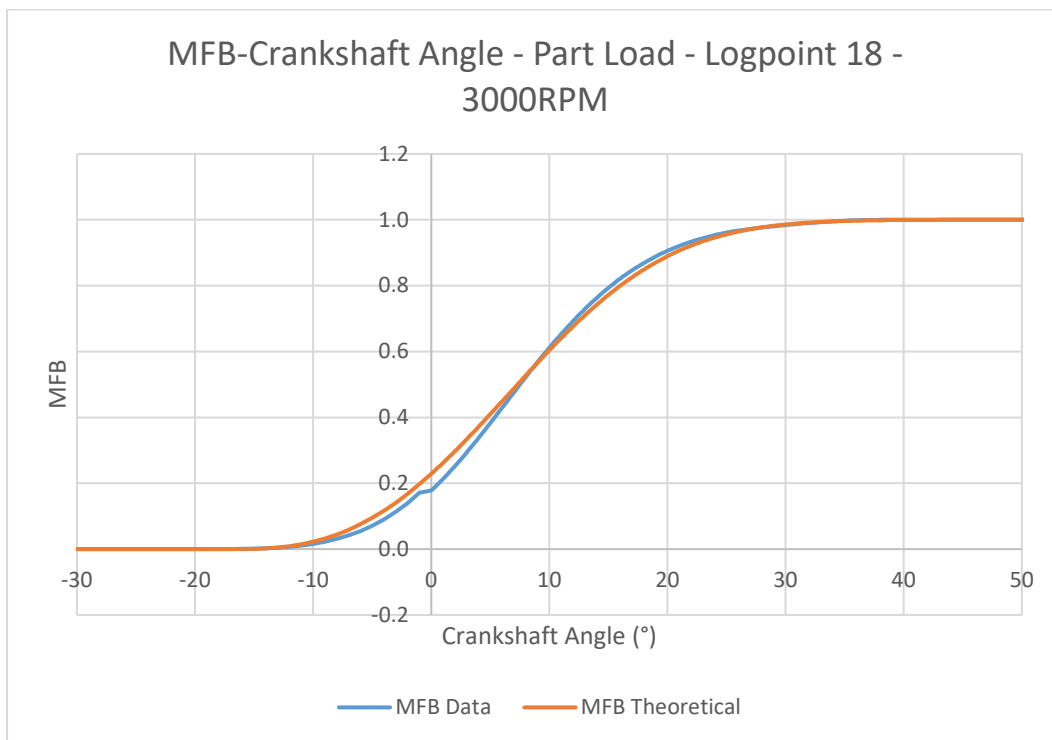


Figure 72: MFB-Crankshaft Angle - Part Load - Logpoint 18 - 3000RPM

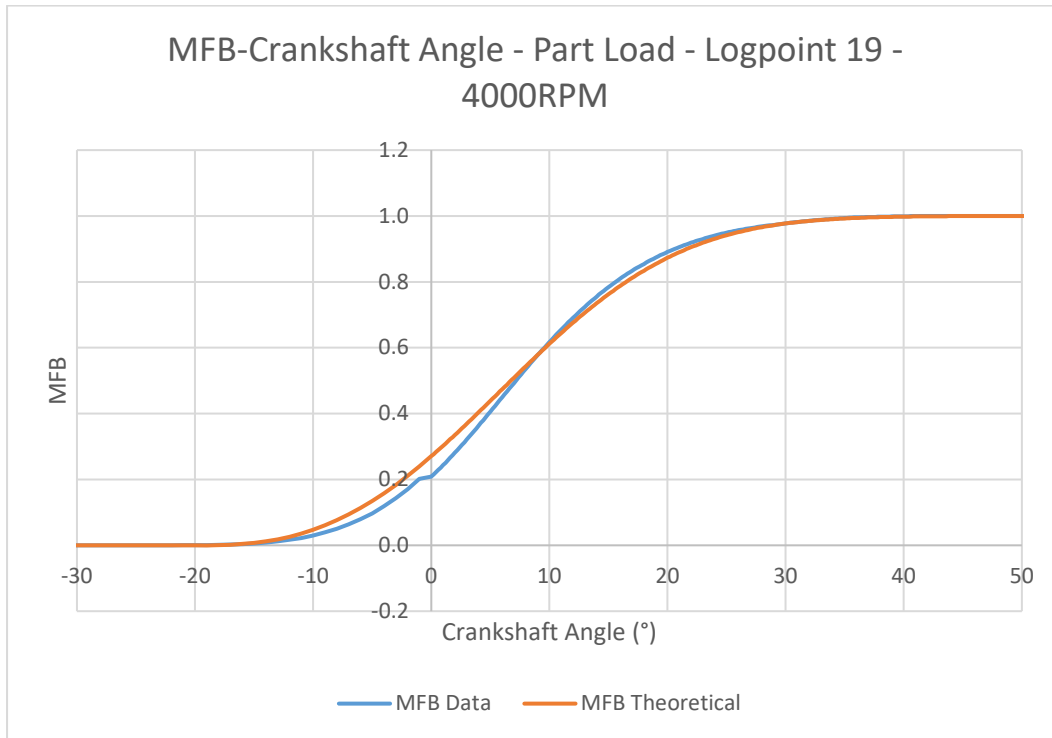


Figure 73: MFB-Crankshaft Angle - Part Load - Logpoint 19 - 4000RPM

Appendix H: Specific Heats & γ -Crankshaft Angle Graphs for Part Load Logpoints

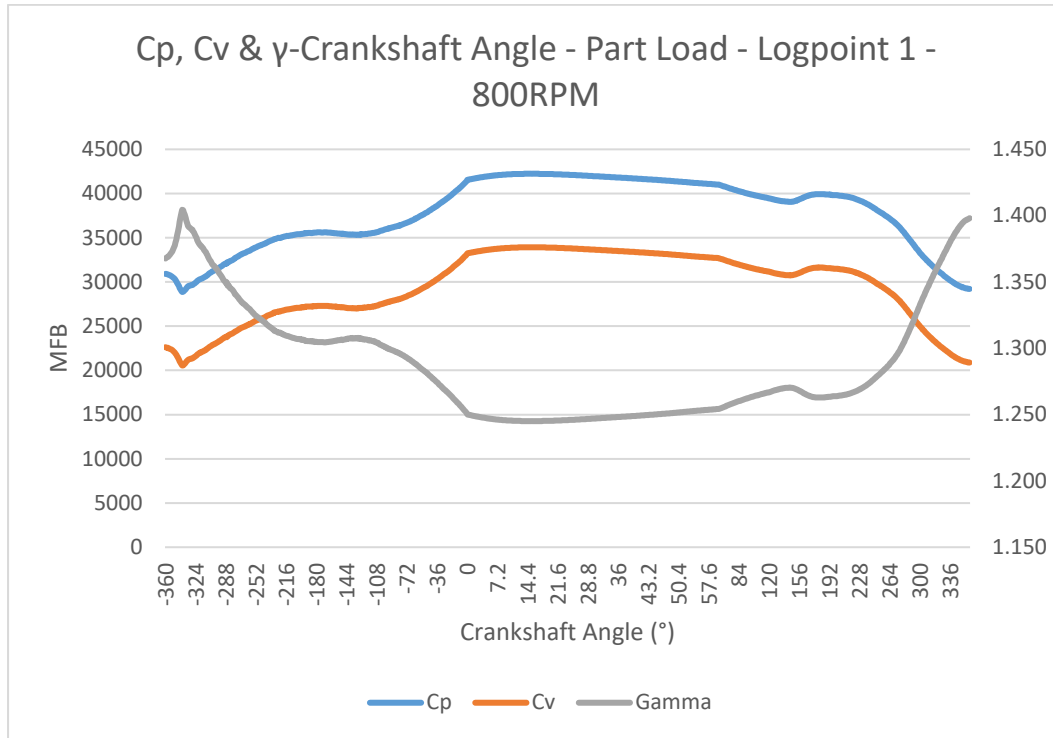


Figure 74: Cp, Cv & γ -Crankshaft Angle – Part Load - Logpoint 1 - 800RPM

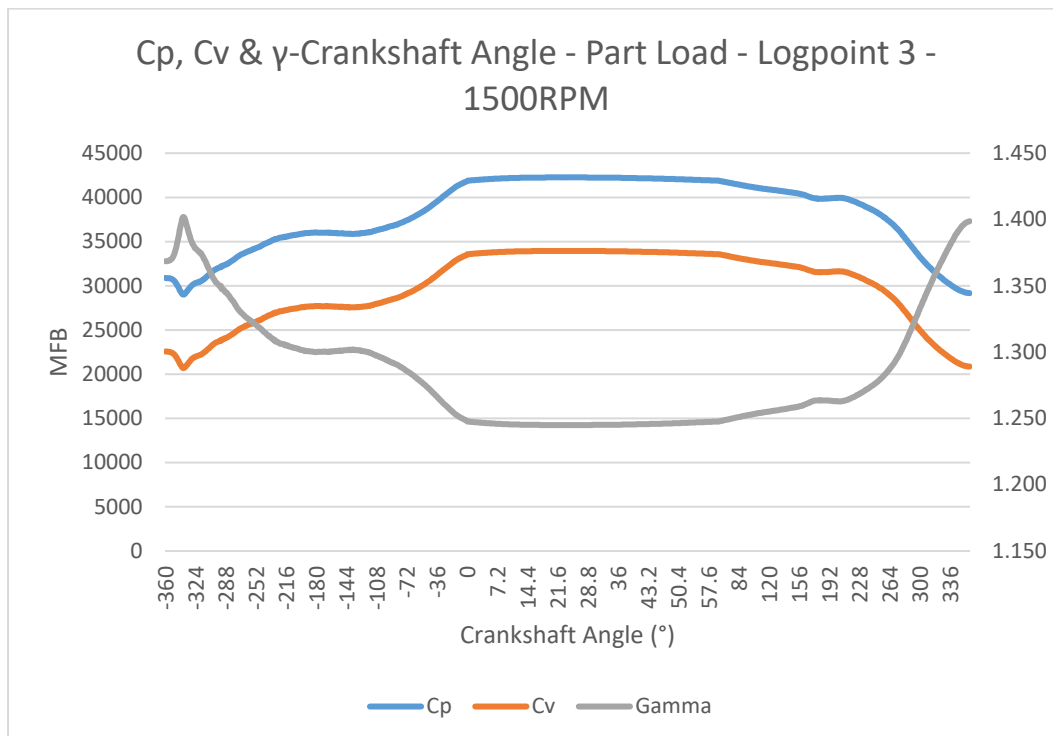


Figure 75: Cp, Cv & γ -Crankshaft Angle - Part Load - Logpoint 3 - 1500RPM

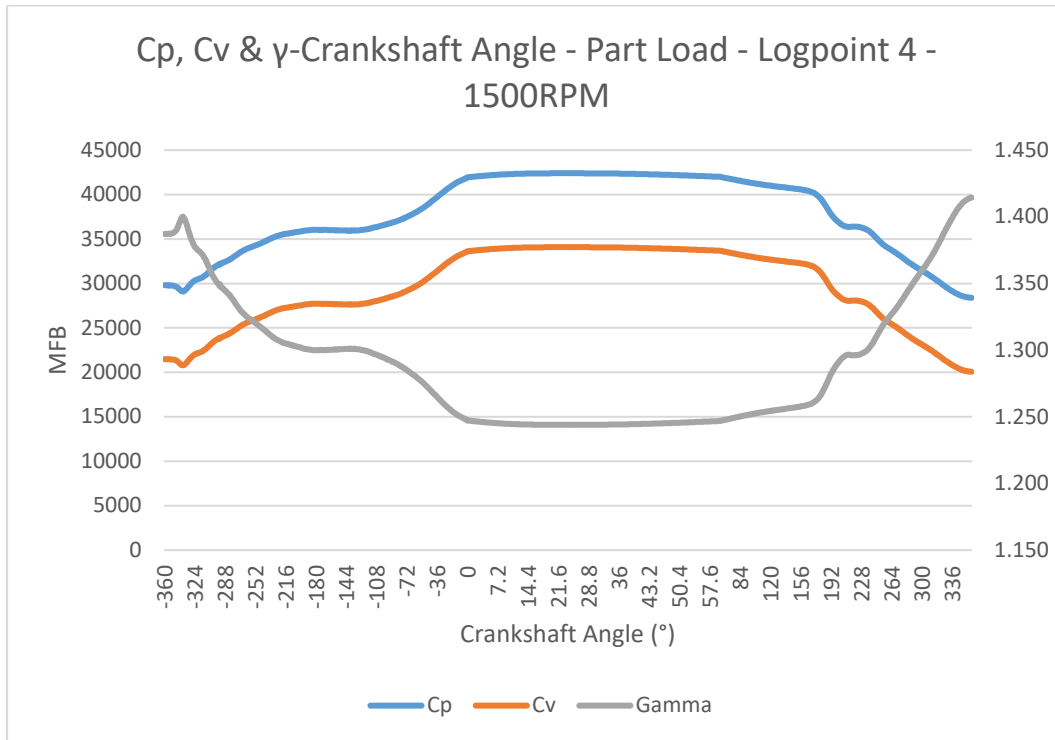


Figure 76: Cp, Cv & γ -Crankshaft Angle - Part Load - Logpoint 4 - 1500RPM

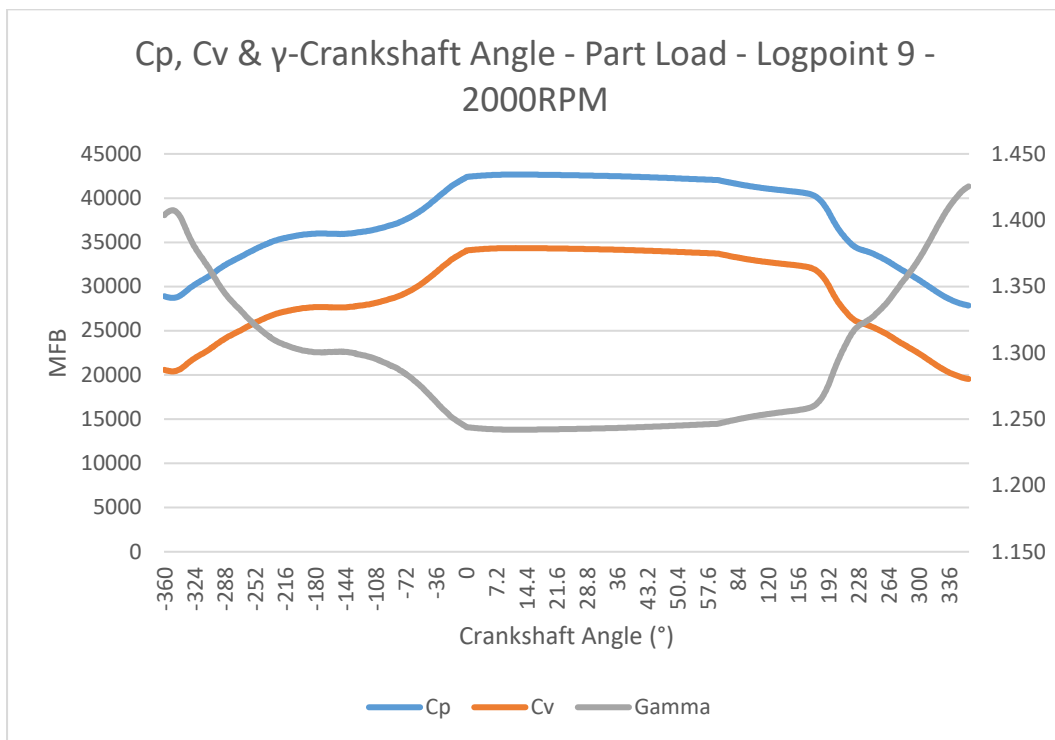


Figure 77: Cp, Cv & γ -Crankshaft Angle - Part Load - Logpoint 9 - 2000RPM

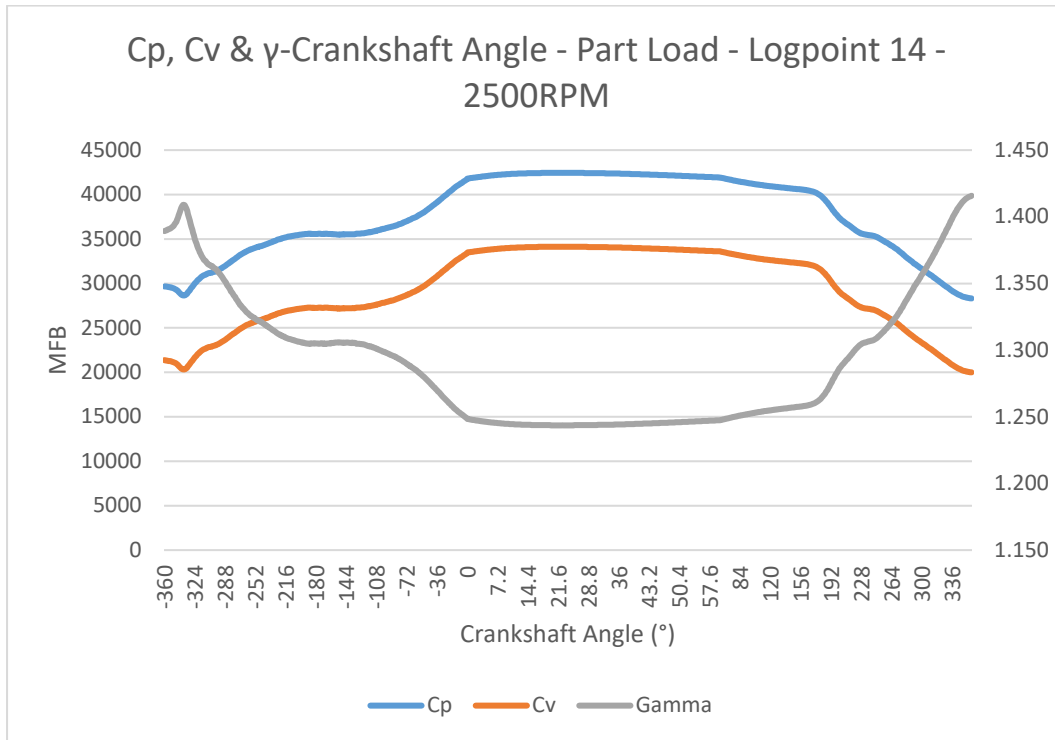


Figure 78: Cp, Cv & γ -Crankshaft Angle - Part Load - Logpoint 14 - 2500RPM

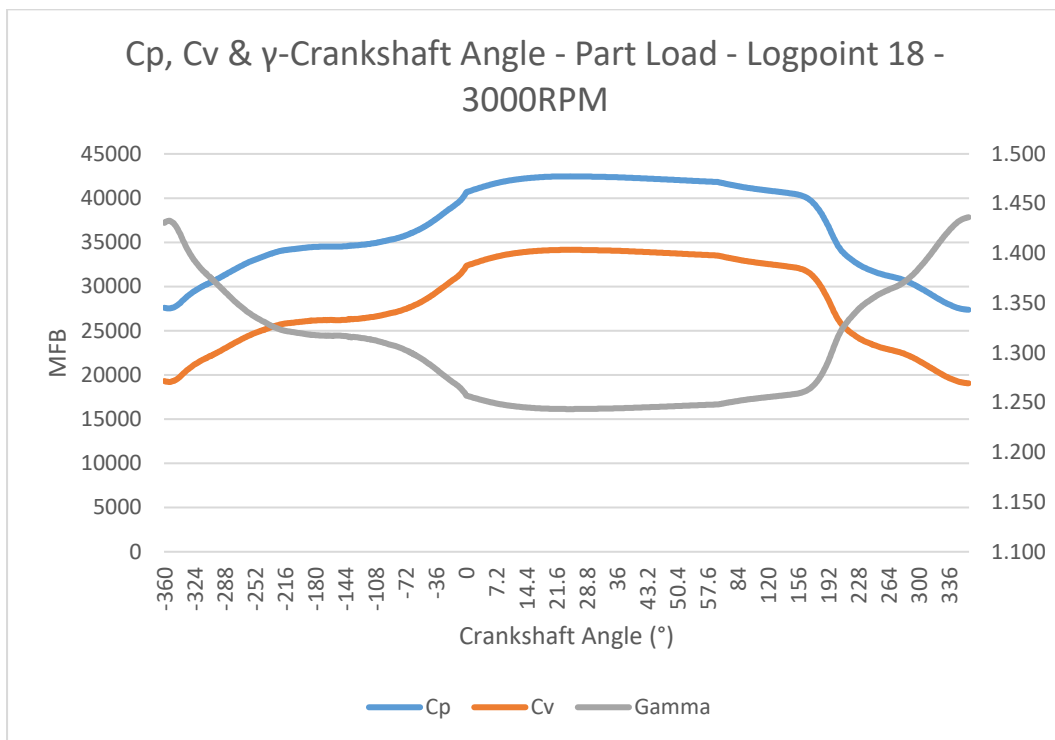


Figure 79: Cp, Cv & γ -Crankshaft Angle - Part Load - Logpoint 18 - 3000RPM

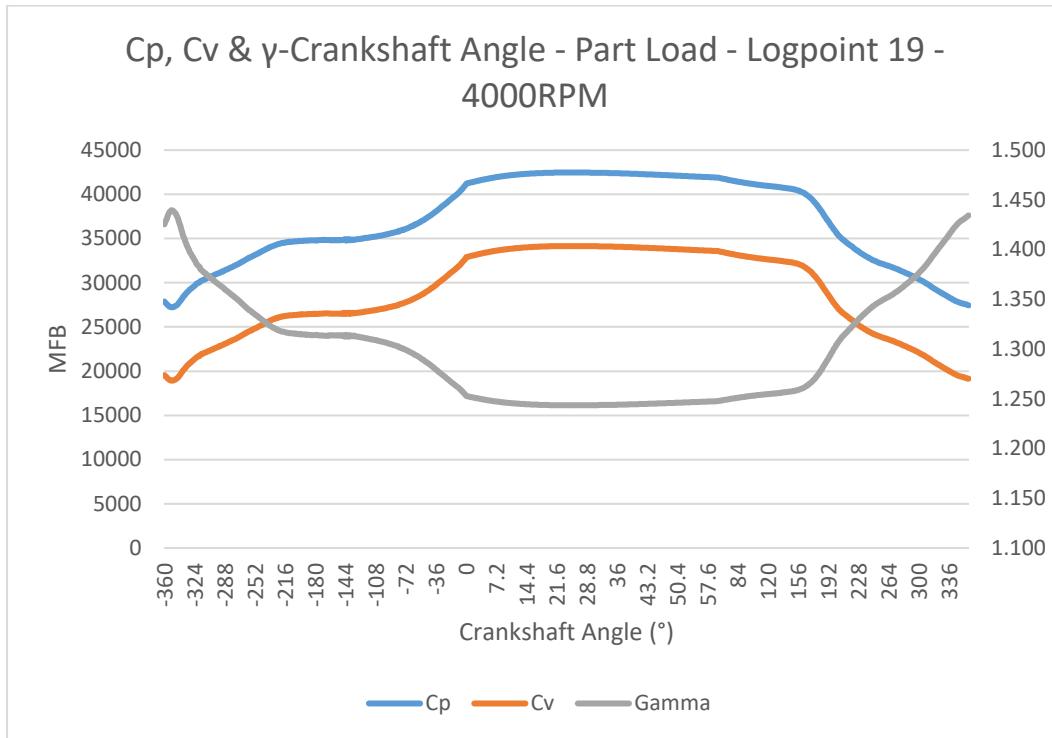


Figure 80: Cp, Cv & γ -Crankshaft Angle - Part Load - Logpoint 19 - 4000RPM

Appendix I: Specific Heats & γ -Crankshaft Angle Graphs for Full Load Logpoints

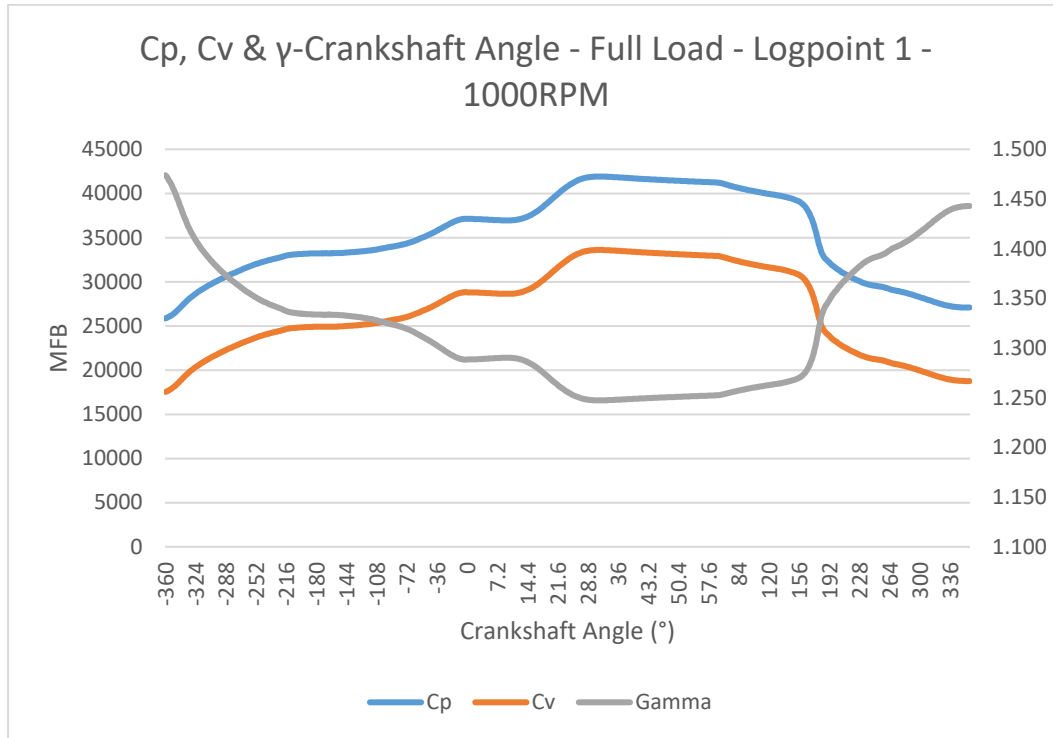


Figure 81: Cp, Cv & γ -Crankshaft Angle - Full Load - Logpoint 1 - 1000RPM

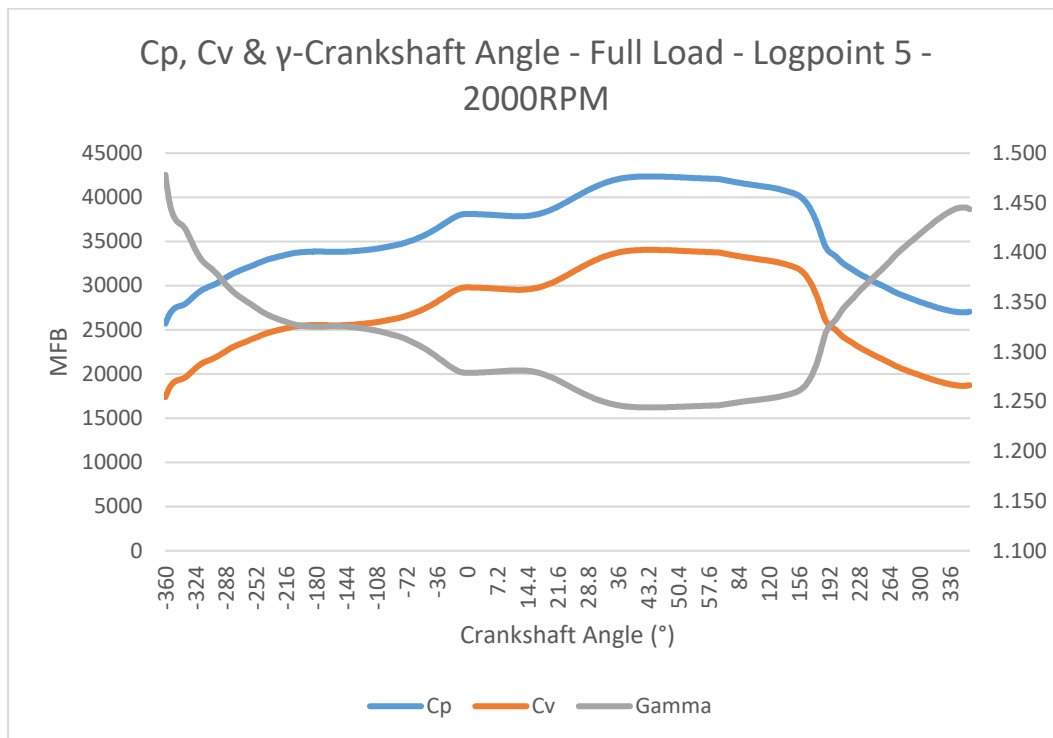


Figure 82: Cp, Cv & γ -Crankshaft Angle - Full Load - Logpoint 5 - 2000RPM

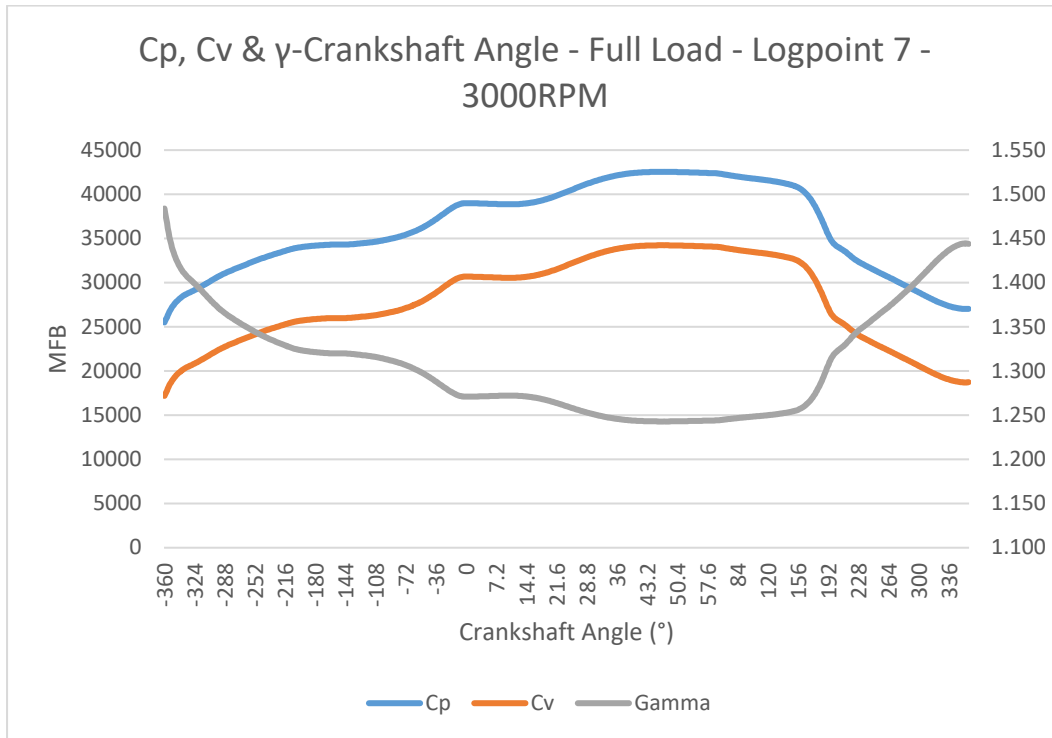


Figure 83: C_p , C_v & γ -Crankshaft Angle - Full Load - Logpoint 7 - 3000RPM

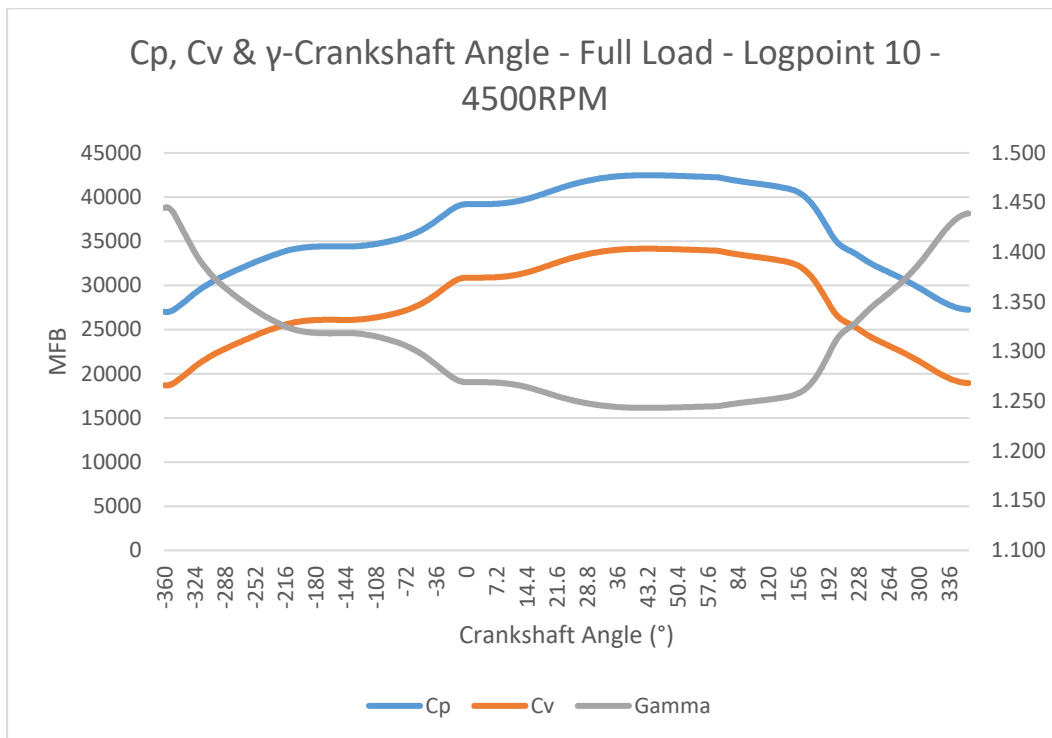


Figure 84: C_p , C_v & γ -Crankshaft Angle - Full Load - Logpoint 10 - 4500RPM

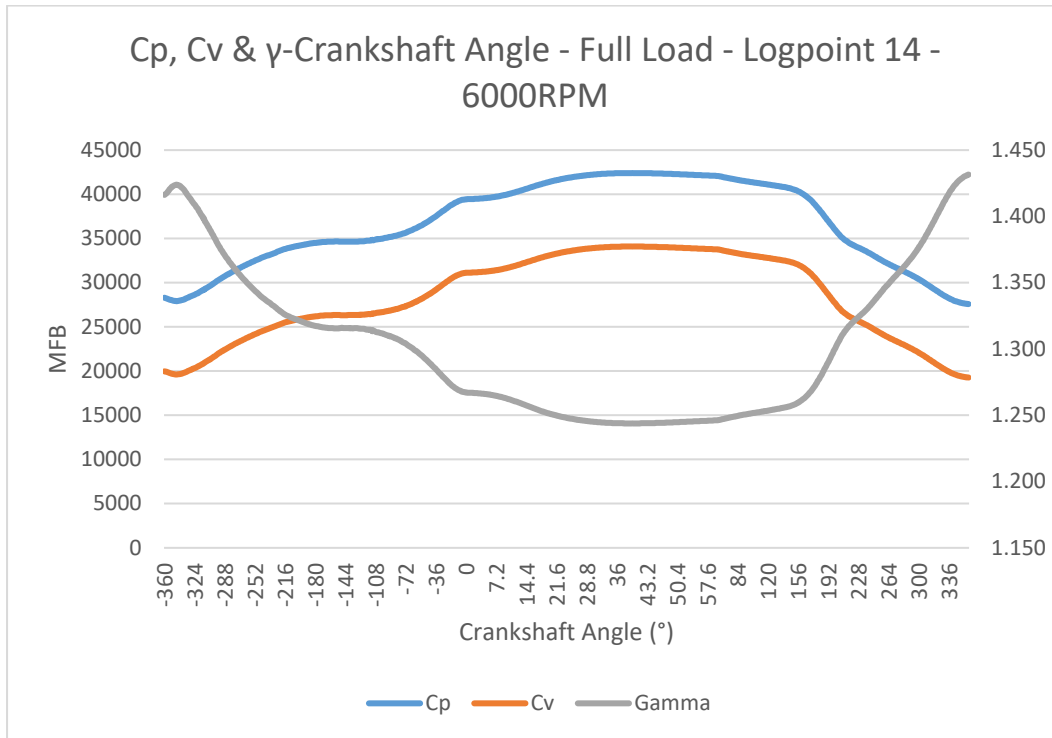


Figure 85: Cp, Cv & γ -Crankshaft Angle - Full Load - Logpoint 14 - 6000RPM

Appendix J: Part Load Engine Parameters and Results

LOGPOINT	DYNO SPD	BMEP	TORQUE	SPARKADV	MANI ABS	AIRMASS	AFR	EBP
	rpm	kN/m ²	Nm	°CA	kPa	kg/h		kPa
1	800.1	71.3	6.30	35.033	30.23	5.59	14.56	-0.0647047
3	1500	99.7	8.80	40.3	32.66	10.62	14.7	-0.0557387
4	1500	261.7	23.11	30.367	52.08	16.56	14.75	0.000832912
9	2000	400.4	35.36	40.7	66.48	28.34	14.72	0.0914085
14	2500	262.2	23.16	36.633	48.14	27.66	14.76	0.277551
18	3000	750.3	66.26	26.633	79.86	69.22	14.71	2.07512
19	4000	550.3	48.60	34.5	67.48	73.65	14.71	2.05444
Bore	71.9 mm		0.0719 m		Offset	6 mm		0.006 m
Stroke	82 mm		0.082 m		θTDC	2.706887221		
CR	10 :1		Cylinders	3				
Crank Radius	41 mm		0.041 m					
Connecting	86 mm		0.086 m					
Swept Volume	0.000332937 m ³		332.937 cc					
Clearance Volume	3.6993E-05 m ³		36.993 cc					
Logpoint 1	ncompression	1.2959		nexpansion	1.2905			
Logpoint 3	ncompression	1.2986		nexpansion	1.1859			
Logpoint 4	ncompression	1.3008		nexpansion	1.196			
Logpoint 9	ncompression	1.3107		nexpansion	1.218			
Logpoint 14	ncompression	1.3073		nexpansion	1.2083			
Logpoint 18	ncompression	1.3086		nexpansion	1.2291			
Logpoint 19	ncompression	1.3127		nexpansion	1.2195			
Logpoint 1	SOC	350 #		EOC	532 #			
Logpoint 3	SOC	351 #		EOC	575 #			
Logpoint 4	SOC	353 #		EOC	583 #			
Logpoint 9	SOC	348 #		EOC	582 #			
Logpoint 14	SOC	350 #		EOC	563 #			
Logpoint 18	SOC	350 #		EOC	558 #			
Logpoint 19	SOC	347 #		EOC	577 #			
Logpoint 1	Burn Duration	55 °						
Logpoint 3	Burn Duration	57.6 °						
Logpoint 4	Burn Duration	57.2 °						
Logpoint 9	Burn Duration	62 °						
Logpoint 14	Burn Duration	56.2 °						
Logpoint 18	Burn Duration	55.2 °						
Logpoint 19	Burn Duration	62 °						
Logpoint 1	Intercept	2.1088 a		8.2383				
	Gradient	2.7970 m		1.7970				
Logpoint 3	Intercept	1.5766 a		4.8385				
	Gradient	2.3806 m		1.3806				
Logpoint 4	Intercept	1.6824 a		5.3784				
	Gradient	2.4072 m		1.4072				
Logpoint 9	Intercept	1.7983 a		6.0394				
	Gradient	2.5014 m		1.5014				
Logpoint 14	Intercept	1.6819 a		5.3758				
	Gradient	2.4727 m		1.4727				
Logpoint 18	Intercept	1.8892 a		6.6141				
	Gradient	2.7492 m		1.7492				
Logpoint 19	Intercept	1.9121 a		6.7673				
	Gradient	2.7100 m		1.7100				
Logpoint 1	Air Mass/cyl	7.76292E-05 kg		Fuel Mass/cyl	5.33167E-06 kg		Total Mass/cyl	8.29609E-05 kg
Logpoint 3	Air Mass/cyl	7.86667E-05 kg		Fuel Mass/cyl	5.35147E-06 kg		Total Mass/cyl	8.40181E-05 kg
Logpoint 4	Air Mass/cyl	0.000122667 kg		Fuel Mass/cyl	8.31638E-06 kg		Total Mass/cyl	0.000130983 kg
Logpoint 9	Air Mass/cyl	0.000157444 kg		Fuel Mass/cyl	1.0696E-05 kg		Total Mass/cyl	0.00016814 kg
Logpoint 14	Air Mass/cyl	0.000122933 kg		Fuel Mass/cyl	8.32882E-06 kg		Total Mass/cyl	0.000131262 kg
Logpoint 18	Air Mass/cyl	0.00025637 kg		Fuel Mass/cyl	1.74283E-05 kg		Total Mass/cyl	0.000273799 kg
Logpoint 19	Air Mass/cyl	0.000204583 kg		Fuel Mass/cyl	1.39078E-05 kg		Total Mass/cyl	0.000218491 kg
Logpoint 1	Comb. Eff.	80.20 %						
Logpoint 3	Comb. Eff.	75.83 %						
Logpoint 4	Comb. Eff.	80.64 %						
Logpoint 9	Comb. Eff.	85.17 %						
Logpoint 14	Comb. Eff.	82.90 %						
Logpoint 18	Comb. Eff.	88.30 %						
Logpoint 19	Comb. Eff.	87.43 %						

Figure 86: Part Load Engine Parameters and Results

Appendix K: Part Load Logpoint 1 Values

CYL VOL	CYL VOL		CYLPR1	CYLPR2	CYLPR3	CYLPRAVE	LOGP	LOGV	n	Δn	p2n	Δp	MFB Actual	ln(-ln(1-MFB)	ln(θ/θ ₀)	MFBvary1	MFBvary2	MFBvary3	MFBvary4	MFB Theoretical	ΔMFB
cc	m3	CA	bar	bar	bar	bar					bar	bar				a=6, m=2	a=12, m=2	a=6, m=0	a=6, m=4		
44.43	0.000044	-15	4.518	4.655	4.554	4.575	0.660	-4.352	1.525	0.441	4.705	0.023	0.004	-5.520	-2.909	0.000	0.000	0.103	0.000	0.000	0.004
43.48	0.000043	-14	4.666	4.818	4.703	4.729	0.675	-4.362	1.656	0.131	4.856	0.036	0.007	-4.907	-2.621	0.000	0.001	0.196	0.000	0.001	0.007
42.60	0.000043	-13	4.820	4.990	4.865	4.892	0.689	-4.371	1.788	0.132	5.015	0.048	0.012	-4.431	-2.398	0.001	0.002	0.279	0.000	0.002	0.009
41.79	0.000042	-12	4.982	5.177	5.028	5.062	0.704	-4.379	1.958	0.169	5.184	0.063	0.018	-4.021	-2.216	0.002	0.005	0.354	0.000	0.005	0.012
41.03	0.000041	-11	5.145	5.383	5.215	5.248	0.720	-4.387	2.166	0.209	5.364	0.080	0.025	-3.665	-2.061	0.004	0.009	0.420	0.000	0.010	0.015
40.34	0.000040	-10	5.323	5.598	5.411	5.444	0.736	-4.394	2.452	0.286	5.554	0.100	0.035	-3.344	-1.928	0.008	0.015	0.480	0.000	0.017	0.018
39.72	0.000040	-9	5.505	5.838	5.622	5.655	0.752	-4.401	2.788	0.335	5.760	0.123	0.046	-3.050	-1.810	0.012	0.024	0.534	0.000	0.025	0.021
39.16	0.000039	-8	5.706	6.096	5.847	5.883	0.770	-4.407	3.231	0.443	5.980	0.148	0.060	-2.781	-1.705	0.018	0.036	0.582	0.000	0.037	0.023
38.67	0.000039	-7	5.917	6.374	6.091	6.127	0.787	-4.413	3.832	0.601	6.217	0.179	0.077	-2.526	-1.609	0.026	0.051	0.625	0.001	0.051	0.026
38.24	0.000038	-6	6.147	6.686	6.355	6.396	0.806	-4.417	4.672	0.841	6.475	0.210	0.097	-2.287	-1.522	0.035	0.070	0.664	0.001	0.068	0.029
37.88	0.000038	-5	6.406	7.016	6.633	6.685	0.825	-4.422	5.754	1.082	6.754	0.244	0.119	-2.062	-1.442	0.047	0.092	0.699	0.002	0.087	0.032
37.58	0.000038	-4	6.688	7.375	6.929	6.998	0.845	-4.425	7.766	2.012	7.054	0.286	0.146	-1.844	-1.368	0.060	0.117	0.730	0.003	0.110	0.036
37.35	0.000037	-3	7.000	7.768	7.250	7.339	0.866	-4.428	11.325	3.559	7.380	0.325	0.177	-1.637	-1.299	0.076	0.147	0.758	0.004	0.136	0.041
37.19	0.000037	-2	7.326	8.194	7.595	7.705	0.887	-4.430	18.393	7.058	7.732	0.364	0.211	-1.440	-1.235	0.094	0.180	0.783	0.006	0.164	0.047
37.09	0.000037	-1	7.685	8.645	7.959	8.096	0.908	-4.431	46.516	28.123	8.108	0.405	0.249	-1.251	-1.174	0.115	0.216	0.805	0.009	0.196	0.053
37.05	0.000037	0	8.063	9.128	8.347	8.513	0.930	-4.431	-45.816	-92.332	8.511	0.087	0.257	-1.213	-1.117	0.137	0.256	0.825	0.012	0.229	0.028
37.06	0.000037	0.2	8.140	9.229	8.424	8.598	0.934	-4.431	-47.932	-2.116	8.595	0.092	0.266	-1.175	-1.106	0.142	0.264	0.829	0.013	0.236	0.029
37.07	0.000037	0.4	8.222	9.330	8.510	8.687	0.939	-4.431	-46.609	1.324	8.685	0.090	0.274	-1.138	-1.095	0.147	0.273	0.833	0.014	0.244	0.031
37.07	0.000037	0.6	8.303	9.430	8.591	8.775	0.943	-4.431	-46.154	0.455	8.772	0.090	0.283	-1.102	-1.084	0.152	0.281	0.836	0.015	0.251	0.032
37.08	0.000037	0.8	8.380	9.535	8.673	8.863	0.948	-4.431	-45.709	0.445	8.860	0.090	0.291	-1.067	-1.073	0.157	0.290	0.840	0.016	0.258	0.033
37.09	0.000037	1	8.461	9.636	8.754	8.950	0.952	-4.431	-18.767	26.942	8.944	0.097	0.300	-1.030	-1.063	0.162	0.298	0.843	0.017	0.266	0.035
37.11	0.000037	1.2	8.543	9.741	8.840	9.041	0.956	-4.431	-17.615	1.152	9.035	0.093	0.309	-0.995	-1.052	0.168	0.307	0.847	0.018	0.273	0.036
37.13	0.000037	1.4	8.619	9.842	8.922	9.128	0.960	-4.430	-18.746	-1.131	9.121	0.099	0.318	-0.959	-1.042	0.173	0.316	0.850	0.019	0.281	0.038
37.15	0.000037	1.6	8.706	9.947	9.008	9.220	0.965	-4.430	-18.250	0.496	9.214	0.097	0.327	-0.925	-1.032	0.178	0.325	0.853	0.020	0.288	0.039
37.17	0.000037	1.8	8.787	10.053	9.094	9.311	0.969	-4.430	-18.082	0.168	9.305	0.097	0.337	-0.891	-1.022	0.184	0.334	0.857	0.021	0.296	0.040
37.19	0.000037	2	8.868	10.158	9.180	9.402	0.973	-4.430	-11.200	6.832	9.392	0.101	0.346	-0.856	-1.012	0.190	0.343	0.860	0.022	0.304	0.042
37.22	0.000037	2.2	8.950	10.264	9.267	9.493	0.977	-4.429	-11.103	0.097	9.483	0.102	0.356	-0.822	-1.002	0.195	0.353	0.863	0.024	0.312	0.044
37.25	0.000037	2.4	9.036	10.369	9.348	9.584	0.982	-4.429	-11.008	0.096	9.574	0.102	0.365	-0.789	-0.992	0.201	0.362	0.866	0.025	0.320	0.045
37.29	0.000037	2.6	9.118	10.474	9.434	9.675	0.986	-4.428	-10.914	0.094	9.665	0.102	0.375	-0.756	-0.982	0.207	0.371	0.869	0.026	0.328	0.047
37.32	0.000037	2.8	9.199	10.580	9.520	9.766	0.990	-4.428	-10.633	0.281	9.756	0.100	0.384	-0.724	-0.972	0.213	0.381	0.871	0.028	0.336	0.048
37.35	0.000037	3	9.281	10.680	9.607	9.856	0.994	-4.428	-7.599	3.034	9.840	0.108	0.394	-0.691	-0.963	0.219	0.390	0.874	0.029	0.344	0.050
37.40	0.000037	3.2	9.367	10.786	9.693	9.948	0.998	-4.427	-7.408	0.191	9.933	0.107	0.404	-0.658	-0.953	0.225	0.400	0.877	0.031	0.352	0.052
37.44	0.000037	3.4	9.448	10.891	9.779	10.039	1.002	-4.427	-7.222	0.186	10.024	0.105	0.414	-0.626	-0.944	0.231	0.409	0.880	0.032	0.360	0.054
37.49	0.000037	3.6	9.530	10.992	9.865	10.129	1.006	-4.426	-7.295	-0.073	10.113	0.107	0.424	-0.594	-0.935	0.238	0.419	0.882	0.034	0.369	0.056
37.53	0.000038	3.8	9.616	11.092	9.951	10.220	1.009	-4.426	-7.239	0.056	10.204	0.107	0.434	-0.563	-0.925	0.244	0.429	0.885	0.036	0.377	0.057
37.58	0.000038	4	9.697	11.198	10.038	10.311	1.013	-4.425	-5.220	2.019	10.290	0.107	0.444	-0.532	-0.916	0.251	0.438	0.887	0.037	0.385	0.059
37.64	0.000038	4.2	9.774	11.298	10.119	10.397	1.017	-4.424	-5.376	-0.156	10.376	0.111	0.455	-0.500	-0.907	0.257	0.448	0.890	0.039	0.394	0.061
37.70	0.000038	4.4	9.860	11.394	10.205	10.486	1.021	-4.424	-5.244	0.132	10.465	0.109	0.465	-0.469	-0.898	0.264	0.458	0.892	0.041	0.402	0.063
37.76	0.000038	4.6	9.942	11.495	10.287	10.574	1.024	-4.423	-5.209	0.035	10.553	0.109	0.475	-0.439	-0.889	0.270	0.468	0.894	0.043	0.410	0.065

Figure 87: Part Load Logpoint 1 Values (From -15° to 4.6° Crankshaft Angle) Part 1

Combustion Modelling Based on the Ford Fox Engine

T _{un}	Cp _{un}	Cv _{un}	γ _{un}	m _{un}	V _{un}	V _b	T _b	Cp _b	Cv _b	γ _b	Cp _{overall}	Cv _{overall}	γ _{overall}	dQr Actual	ΣdQr	dQr Theoretical
K	J/kmol.K	J/kmol.K		kg	m ³	m ³	K	J/kmol.K	J/kmol.K		J/kmol.K	J/kmol.K		J	J	J
871.691	40166	31852	1.261	8.26E-05	0.000044	0.000000	1736.759	40386	32072	1.259	40167	31853	1.261	0.397	0.732	0.938
877.657	40234	31920	1.260	8.23E-05	0.000043	0.000001	1892.026	40876	32562	1.255	40239	31925	1.260	0.599	1.331	1.728
883.820	40304	31990	1.260	8.20E-05	0.000041	0.000001	2004.404	41184	32870	1.253	40315	32001	1.260	0.781	2.112	2.777
890.101	40375	32061	1.259	8.15E-05	0.000040	0.000002	2052.002	41304	32990	1.252	40392	32078	1.259	1.022	3.134	4.172
896.712	40449	32135	1.259	8.09E-05	0.000039	0.000002	2091.960	41400	33086	1.251	40473	32159	1.259	1.266	4.400	5.928
903.509	40524	32210	1.258	8.01E-05	0.000037	0.000003	2112.048	41447	33133	1.251	40556	32242	1.258	1.570	5.970	8.138
910.578	40601	32287	1.258	7.91E-05	0.000036	0.000004	2128.953	41486	33172	1.251	40642	32328	1.257	1.904	7.875	10.852
917.988	40680	32366	1.257	7.80E-05	0.000034	0.000005	2146.072	41524	33210	1.250	40731	32417	1.256	2.252	10.127	14.100
925.653	40761	32447	1.256	7.66E-05	0.000032	0.000006	2153.565	41541	33227	1.250	40821	32507	1.256	2.703	12.831	18.036
933.778	40846	32532	1.256	7.49E-05	0.000031	0.000008	2166.647	41570	33256	1.250	40916	32602	1.255	3.151	15.981	22.662
942.216	40932	32618	1.255	7.30E-05	0.000029	0.000009	2179.953	41598	33284	1.250	41011	32697	1.254	3.631	19.612	28.027
951.014	41019	32705	1.254	7.08E-05	0.000027	0.000011	2188.773	41617	33303	1.250	41107	32793	1.254	4.236	23.848	34.319
960.248	41109	32795	1.254	6.83E-05	0.000025	0.000012	2204.025	41649	33335	1.249	41205	32891	1.253	4.798	28.646	41.467
969.736	41199	32885	1.253	6.55E-05	0.000023	0.000014	2220.533	41684	33370	1.249	41301	32987	1.252	5.375	34.021	49.486
979.476	41289	32975	1.252	6.23E-05	0.000021	0.000016	2237.581	41718	33404	1.249	41396	33082	1.251	5.983	40.004	58.411
989.426	41377	33063	1.251	6.16E-05	0.000020	0.000017	2421.960	42058	33744	1.246	41552	33238	1.250	1.289	41.293	60.326
991.394	41394	33080	1.251	6.09E-05	0.000020	0.000017	2421.984	42058	33744	1.246	41570	33256	1.250	1.361	42.654	62.347
993.457	41412	33098	1.251	6.02E-05	0.000019	0.000018	2425.458	42064	33750	1.246	41591	33277	1.250	1.339	43.993	64.334
995.465	41429	33115	1.251	5.95E-05	0.000019	0.000018	2428.095	42068	33754	1.246	41610	33296	1.250	1.340	45.333	66.321
997.456	41446	33132	1.251	5.88E-05	0.000019	0.000019	2430.746	42072	33758	1.246	41628	33314	1.250	1.342	46.674	68.308
999.431	41462	33148	1.251	5.80E-05	0.000018	0.000019	2430.303	42072	33758	1.246	41645	33331	1.249	1.446	48.120	70.449
1001.461	41479	33165	1.251	5.73E-05	0.000018	0.000019	2435.115	42080	33766	1.246	41665	33351	1.249	1.377	49.497	72.486
1003.368	41495	33181	1.251	5.66E-05	0.000017	0.000020	2434.952	42079	33765	1.246	41681	33367	1.249	1.475	50.972	74.664
1005.399	41512	33198	1.250	5.58E-05	0.000017	0.000020	2438.445	42085	33771	1.246	41700	33386	1.249	1.453	52.425	76.808
1007.379	41529	33215	1.250	5.50E-05	0.000017	0.000020	2441.225	42090	33776	1.246	41717	33403	1.249	1.456	53.881	78.954
1009.343	41545	33231	1.250	5.43E-05	0.000016	0.000021	2442.495	42092	33778	1.246	41734	33420	1.249	1.517	55.397	81.187
1011.290	41561	33247	1.250	5.35E-05	0.000016	0.000021	2445.219	42096	33782	1.246	41751	33437	1.249	1.520	56.917	83.423
1013.222	41577	33263	1.250	5.27E-05	0.000016	0.000022	2447.965	42101	33787	1.246	41768	33454	1.249	1.523	58.441	85.660
1015.139	41593	33279	1.250	5.19E-05	0.000015	0.000022	2450.728	42105	33791	1.246	41785	33471	1.248	1.527	59.967	87.899
1017.041	41608	33294	1.250	5.11E-05	0.000015	0.000022	2454.068	42111	33797	1.246	41801	33487	1.248	1.506	61.474	90.105
1018.894	41623	33309	1.250	5.03E-05	0.000015	0.000023	2454.072	42111	33797	1.246	41815	33501	1.248	1.629	63.103	92.488
1020.800	41639	33325	1.249	4.94E-05	0.000014	0.000023	2457.398	42116	33802	1.246	41832	33518	1.248	1.610	64.713	94.839
1022.657	41654	33340	1.249	4.86E-05	0.000014	0.000024	2460.668	42121	33807	1.246	41848	33534	1.248	1.590	66.303	97.157
1024.469	41669	33355	1.249	4.78E-05	0.000014	0.000024	2462.866	42125	33811	1.246	41862	33548	1.248	1.619	67.922	99.514
1026.299	41684	33370	1.249	4.69E-05	0.000013	0.000024	2465.659	42129	33815	1.246	41877	33563	1.248	1.624	69.546	101.873
1028.116	41698	33384	1.249	4.61E-05	0.000013	0.000025	2468.423	42134	33820	1.246	41892	33578	1.248	1.630	71.176	104.238
1029.824	41712	33398	1.249	4.52E-05	0.000013	0.000025	2470.032	42136	33822	1.246	41905	33591	1.248	1.684	72.861	106.676
1031.583	41726	33412	1.249	4.44E-05	0.000012	0.000025	2473.220	42141	33827	1.246	41919	33605	1.247	1.666	74.527	109.083
1033.299	41740	33426	1.249	4.35E-05	0.000012	0.000026	2475.903	42146	33832	1.246	41933	33619	1.247	1.671	76.198	111.492

Figure 88: Part Load Logpoint 1 Values (From -15° to 4.6° Crankshaft Angle) Part 2

Appendix L: Full Load Engine Parameters and Results

LOGPOINT	DYNO SPD	BMEP	TORQUE	SPARKADV	MANI ABS	AIRMASS	AFR	EBP
	rpm	kN/m2	Nm	°CA	kPa	kg/h		kPa
1	999.8	1269.3	100.91	-5.8333	124.86	46.82	16.15	1.415
5	1999.8	2237.3	177.86	-4.7667	205.86	141.19	14.45	7.553
7	2999.9	2288.1	181.9	1.1	216.68	217.06	13.56	15.651
10	4500.4	2175.2	172.93	5.6333	223.65	307.93	13.89	27.68
14	6000.1	1846.2	146.77	9.5667	212.42	364.92	13.04	36.089
Bore	71.9 mm		0.0719 m					
Stroke	82 mm		0.082 m					
CR	10 : 1							
Crank Radius	41 mm		0.041 m					
Connecting Rod Length	86 mm		0.086 m					
Swept Volume	0.000332937 m ³		332.937 cc					
Clearance Volume	3.6993E-05 m ³		36.993 cc					
Logpoint 1	ncompression	1.3144		nexpansion	1.2524			
Logpoint 5	ncompression	1.3027		nexpansion	1.227			
Logpoint 7	ncompression	1.3029		nexpansion	1.204			
Logpoint 10	ncompression	1.3016		nexpansion	1.2177			
Logpoint 14	ncompression	1.2938		nexpansion	1.2401			
Logpoint 1	SOC	405 #	EOC	547 #				
Logpoint 5	SOC	409 #	EOC	608 #				
Logpoint 7	SOC	396 #	EOC	633 #				
Logpoint 10	SOC	366 #	EOC	629 #				
Logpoint 14	SOC	363 #	EOC	609 #				
Logpoint 1	Burn Duration	28.8 °						
Logpoint 5	Burn Duration	39.8 °						
Logpoint 7	Burn Duration	47.4 °						
Logpoint 10	Burn Duration	53.6 °						
Logpoint 14	Burn Duration	55.4 °						
Logpoint 1	Intercept	1.793 a	6.0074					
	Gradient	2.7562 m	1.7562					
Logpoint 5	Intercept	1.6714 a	5.3196					
	Gradient	2.5367 m	1.5367					
Logpoint 7	Intercept	1.6808 a	5.3699					
	Gradient	2.3615 m	1.3615					
Logpoint 10	Intercept	1.9508 a	7.0343					
	Gradient	2.7766 m	1.7766					
Logpoint 14	Intercept	2.1233 a	8.3587					
	Gradient	3.4571 m	2.4571					
Logpoint 1	Air Mass/cyl	0.000520326 kg	Fuel Mass/cyl	3.22183E-05 kg	Total Mass/cyl	0.000553 kg		
Logpoint 5	Air Mass/cyl	0.000784467 kg	Fuel Mass/cyl	5.42884E-05 kg	Total Mass/cyl	0.000839 kg		
Logpoint 7	Air Mass/cyl	0.000773031 kg	Fuel Mass/cyl	5.70082E-05 kg	Total Mass/cyl	0.00083 kg		
Logpoint 10	Air Mass/cyl	0.000760253 kg	Fuel Mass/cyl	5.47339E-05 kg	Total Mass/cyl	0.000815 kg		
Logpoint 14	Air Mass/cyl	0.000675767 kg	Fuel Mass/cyl	5.18226E-05 kg	Total Mass/cyl	0.000728 kg		
Logpoint 1	Comb. Eff.	82.76 %						
Logpoint 5	Comb. Eff.	86.87 %						
Logpoint 7	Comb. Eff.	86.48 %						
Logpoint 10	Comb. Eff.	87.40 %						
Logpoint 14	Comb. Eff.	81.92 %						

Figure 89: Full Load Engine Parameters and Results

Appendix M: Full Load Logpoint 1 Values

CYLVOL	CYLVOL		CYLPR1	CYLPR2	CYLPR3	CYLPRAVE	LOGP	LOGV	n	Δn	P2n	ΔP	MFB	ln(-ln(1-MFB))	ln(θ/θ ₀)	MFBtheoretical
cc	m3	CA	bar	bar	bar	bar										
44.43	0.000044	-15	20.805	21.229	21.074	21.036	1.323	-4.352	1.237	-0.006	21.642	-0.036	0.000	0.000	0.000	0.000
43.48	0.000043	-14	21.380	21.799	21.640	21.606	1.335	-4.362	1.228	-0.009	22.195	-0.039	0.000	0.000	0.000	0.000
42.60	0.000043	-13	21.931	22.354	22.181	22.155	1.345	-4.371	1.228	0.000	22.722	-0.038	0.000	0.000	0.000	0.000
41.79	0.000042	-12	22.458	22.886	22.708	22.684	1.356	-4.379	1.240	0.012	23.238	-0.032	0.000	0.000	0.000	0.000
41.03	0.000041	-11	22.966	23.418	23.234	23.206	1.366	-4.387	1.236	-0.003	23.729	-0.031	0.000	0.000	0.000	0.000
40.34	0.000040	-10	23.441	23.916	23.737	23.698	1.375	-4.394	1.245	0.009	24.185	-0.026	0.000	0.000	0.000	0.000
39.72	0.000040	-9	23.886	24.385	24.207	24.159	1.383	-4.401	1.214	-0.031	24.614	-0.035	0.000	0.000	0.000	0.000
39.16	0.000039	-8	24.294	24.811	24.633	24.579	1.391	-4.407	1.188	-0.026	24.989	-0.040	0.000	0.000	0.000	0.000
38.67	0.000039	-7	24.658	25.180	25.011	24.950	1.397	-4.413	1.183	-0.005	25.319	-0.037	0.000	0.000	0.000	0.000
38.24	0.000038	-6	24.984	25.515	25.346	25.282	1.403	-4.417	1.188	0.006	25.598	-0.030	0.000	0.000	0.000	0.000
37.88	0.000038	-5	25.276	25.803	25.624	25.568	1.408	-4.422	1.142	-0.047	25.836	-0.035	0.000	0.000	0.000	0.000
37.58	0.000038	-4	25.515	26.038	25.849	25.801	1.412	-4.425	1.105	-0.036	26.010	-0.033	0.000	0.000	0.000	0.000
37.35	0.000037	-3	25.693	26.215	26.022	25.976	1.415	-4.428	1.071	-0.034	26.123	-0.027	0.000	0.000	0.000	0.000
37.19	0.000037	-2	25.813	26.335	26.141	26.096	1.417	-4.430	0.863	-0.209	26.189	-0.032	0.000	0.000	0.000	0.000
37.09	0.000037	-1	25.875	26.397	26.199	26.157	1.418	-4.431	0.057	-0.806	26.194	-0.036	0.000	0.000	0.000	0.000
37.05	0.000037	0	25.875	26.402	26.199	26.158	1.418	-4.431	0.848	0.792	26.151	0.002	0.000	0.000	0.000	0.000
37.06	0.000037	0.2	25.870	26.397	26.194	26.154	1.418	-4.431	1.414	0.566	26.147	-0.001	0.000	0.000	0.000	0.000
37.07	0.000037	0.4	25.860	26.392	26.184	26.146	1.417	-4.431	1.981	0.567	26.139	-0.004	0.000	0.000	0.000	0.000
37.07	0.000037	0.6	25.851	26.378	26.175	26.134	1.417	-4.431	2.266	0.285	26.127	-0.006	0.000	0.000	0.000	0.000
37.08	0.000037	0.8	25.836	26.368	26.160	26.122	1.417	-4.431	2.835	0.569	26.115	-0.009	0.000	0.000	0.000	0.000
37.09	0.000037	1	25.817	26.354	26.146	26.106	1.417	-4.431	1.362	-1.473	26.088	-0.002	0.000	0.000	0.000	0.000
37.11	0.000037	1.2	25.798	26.335	26.127	26.087	1.416	-4.431	1.591	0.229	26.069	-0.005	0.000	0.000	0.000	0.000
37.13	0.000037	1.4	25.774	26.315	26.103	26.064	1.416	-4.430	1.593	0.002	26.047	-0.005	0.000	0.000	0.000	0.000
37.15	0.000037	1.6	25.755	26.291	26.079	26.042	1.416	-4.430	1.824	0.230	26.024	-0.008	0.000	0.000	0.000	0.000
37.17	0.000037	1.8	25.731	26.263	26.055	26.016	1.415	-4.430	1.941	0.117	25.999	-0.010	0.000	0.000	0.000	0.000
37.19	0.000037	2	25.702	26.239	26.026	25.989	1.415	-4.430	1.358	-0.583	25.961	-0.002	0.000	0.000	0.000	0.000
37.22	0.000037	2.2	25.669	26.210	25.998	25.959	1.414	-4.429	1.576	0.218	25.931	-0.007	0.000	0.000	0.000	0.000
37.25	0.000037	2.4	25.635	26.176	25.959	25.924	1.414	-4.429	1.507	-0.068	25.896	-0.006	0.000	0.000	0.000	0.000
37.29	0.000037	2.6	25.602	26.143	25.926	25.890	1.413	-4.428	1.727	0.219	25.862	-0.011	0.000	0.000	0.000	0.000
37.32	0.000037	2.8	25.563	26.105	25.887	25.852	1.412	-4.428	1.803	0.076	25.824	-0.012	0.000	0.000	0.000	0.000
37.35	0.000037	3	25.520	26.066	25.849	25.812	1.412	-4.428	1.308	-0.495	25.772	-0.002	0.000	0.000	0.000	0.000
37.40	0.000037	3.2	25.482	26.023	25.806	25.770	1.411	-4.427	1.463	0.155	25.731	-0.007	0.000	0.000	0.000	0.000
37.44	0.000037	3.4	25.434	25.980	25.758	25.724	1.410	-4.427	1.417	-0.046	25.685	-0.005	0.000	0.000	0.000	0.000
37.49	0.000037	3.6	25.386	25.937	25.715	25.679	1.410	-4.426	1.624	0.207	25.640	-0.012	0.000	0.000	0.000	0.000
37.53	0.000038	3.8	25.338	25.884	25.662	25.628	1.409	-4.426	1.527	-0.097	25.589	-0.009	0.000	0.000	0.000	0.000
37.58	0.000038	4	25.290	25.836	25.615	25.580	1.408	-4.425	1.293	-0.235	25.529	-0.002	0.000	0.000	0.000	0.000
37.64	0.000038	4.2	25.238	25.784	25.562	25.528	1.407	-4.424	1.415	0.123	25.477	-0.007	0.000	0.000	0.000	0.000
37.70	0.000038	4.4	25.175	25.731	25.504	25.470	1.406	-4.424	1.421	0.005	25.420	-0.007	0.000	0.000	0.000	0.000
37.76	0.000038	4.6	25.123	25.669	25.447	25.413	1.405	-4.423	1.387	-0.034	25.362	-0.005	0.000	0.000	0.000	0.000

Figure 90: Full Load Logpoint 1 Values (From -15° to 4.6° Crankshaft Angle) Part 1

Combustion Modelling Based on the Ford Fox Engine

T _{un}	Cp _{un}	Cv _{un}	γ _{un}	m _{un}	V _{un}	V _b	T _b	Cp _b	Cv _b	γ _b	Cp _{overall}	Cv _{overall}	γ _{overall}	dQr Actual	ΔdQr	dQr Theoretical
K	J/kmol.K	J/kmol.K		kg	m ³	m ³	K	J/kmol.K	J/kmol.K		J/kmol.K	J/kmol.K		J	J	J
604.111	36850	28536	1.291	5.53E-04	0.000044	0.000000	0.000	26465	18151	1.458	36850	28536	1.291	-0.551	0.000	0.000
607.214	36889	28575	1.291	5.53E-04	0.000043	0.000000	0.000	26465	18151	1.458	36889	28575	1.291	-0.587	0.000	0.000
610.049	36924	28610	1.291	5.53E-04	0.000043	0.000000	0.000	26465	18151	1.458	36924	28610	1.291	-0.552	0.000	0.000
612.725	36958	28644	1.290	5.53E-04	0.000042	0.000000	0.000	26465	18151	1.458	36958	28644	1.290	-0.457	0.000	0.000
615.429	36991	28677	1.290	5.53E-04	0.000041	0.000000	0.000	26465	18151	1.458	36991	28677	1.290	-0.443	0.000	0.000
617.902	37022	28708	1.290	5.53E-04	0.000040	0.000000	0.000	26465	18151	1.458	37022	28708	1.290	-0.361	0.000	0.000
620.252	37052	28738	1.289	5.53E-04	0.000040	0.000000	0.000	26465	18151	1.458	37052	28738	1.289	-0.483	0.000	0.000
622.137	37075	28761	1.289	5.53E-04	0.000039	0.000000	0.000	26465	18151	1.458	37075	28761	1.289	-0.538	0.000	0.000
623.611	37094	28780	1.289	5.53E-04	0.000039	0.000000	0.000	26465	18151	1.458	37094	28780	1.289	-0.499	0.000	0.000
624.885	37110	28796	1.289	5.53E-04	0.000038	0.000000	0.000	26465	18151	1.458	37110	28796	1.289	-0.404	0.000	0.000
626.000	37124	28810	1.289	5.53E-04	0.000038	0.000000	0.000	26465	18151	1.458	37124	28810	1.289	-0.466	0.000	0.000
626.705	37133	28819	1.288	5.53E-04	0.000038	0.000000	0.000	26465	18151	1.458	37133	28819	1.288	-0.435	0.000	0.000
627.110	37138	28824	1.288	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37138	28824	1.288	-0.353	0.000	0.000
627.302	37140	28826	1.288	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37140	28826	1.288	-0.411	0.000	0.000
627.070	37137	28823	1.288	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37137	28823	1.288	-0.457	0.000	0.000
626.432	37129	28815	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37129	28815	1.289	0.029	0.000	0.000
626.452	37129	28815	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37129	28815	1.289	-0.012	0.000	0.000
626.396	37129	28815	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37129	28815	1.289	-0.053	0.000	0.000
626.264	37127	28813	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37127	28813	1.289	-0.073	0.000	0.000
626.093	37125	28811	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37125	28811	1.289	-0.115	0.000	0.000
625.845	37122	28808	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37122	28808	1.289	-0.020	0.000	0.000
625.723	37120	28806	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37120	28806	1.289	-0.061	0.000	0.000
625.524	37118	28804	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37118	28804	1.289	-0.062	0.000	0.000
625.324	37115	28801	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37115	28801	1.289	-0.103	0.000	0.000
625.047	37112	28798	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37112	28798	1.289	-0.124	0.000	0.000
624.731	37108	28794	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37108	28794	1.289	-0.030	0.000	0.000
624.538	37105	28791	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37105	28791	1.289	-0.093	0.000	0.000
624.229	37102	28788	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37102	28788	1.289	-0.073	0.000	0.000
623.957	37098	28784	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37098	28784	1.289	-0.136	0.000	0.000
623.569	37093	28779	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37093	28779	1.289	-0.157	0.000	0.000
623.140	37088	28774	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37088	28774	1.289	-0.023	0.000	0.000
622.904	37085	28771	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37085	28771	1.289	-0.086	0.000	0.000
622.549	37081	28767	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37081	28767	1.289	-0.067	0.000	0.000
622.231	37077	28763	1.289	5.53E-04	0.000037	0.000000	0.000	26465	18151	1.458	37077	28763	1.289	-0.152	0.000	0.000
621.755	37071	28757	1.289	5.53E-04	0.000038	0.000000	0.000	26465	18151	1.458	37071	28757	1.289	-0.112	0.000	0.000
621.353	37066	28752	1.289	5.53E-04	0.000038	0.000000	0.000	26465	18151	1.458	37066	28752	1.289	-0.021	0.000	0.000
621.063	37062	28748	1.289	5.53E-04	0.000038	0.000000	0.000	26465	18151	1.458	37062	28748	1.289	-0.086	0.000	0.000
620.652	37057	28743	1.289	5.53E-04	0.000038	0.000000	0.000	26465	18151	1.458	37057	28743	1.289	-0.089	0.000	0.000
620.237	37052	28738	1.289	5.53E-04	0.000038	0.000000	0.000	26465	18151	1.458	37052	28738	1.289	-0.071	0.000	0.000

Figure 91: Full Load Logpoint 1 Values (From -15° to 4.6° Crankshaft Angle) Part 2