



University of Wales Trinity Saint David

School of Engineering

Optimization of a High Speed 3 Cylinder Using the
Ricardo Wave Engine Development Software

Advanced Computational Methods

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Figure 1 Ricardo Wave (Ricardo)

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1 Acronyms

ICE – Internal Combustion Engine

RPM – Revolutions Per Minute

TDC – Top Dead Centre

BDC – Bottom Dead Centre

CC – Cubic Centimetres

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6 Introduction

This report consists of a study where real cylinder pressure data from a Triumph Daytona 675cc at RPM sites; 10,250, 13,000 & 14,400 was reverse engineered with the use of Microsoft Excel and MATLAB, specifically by a method of determining the combustion characteristics for an engine of this type. A baseline model of the engine was provided within the Ricardo WAVE software package, the reverse engineered data was then used as a validation tool to ensure that the model was logical and a realistic representation of the real-life data and to demonstrate a correlation between the two.

7 Interpretation of Data Provided

The data provided by Dr Williams was attained during a Dynamometer session undertaken on the Triumph Daytona 675cc engine. It consisted of the following;

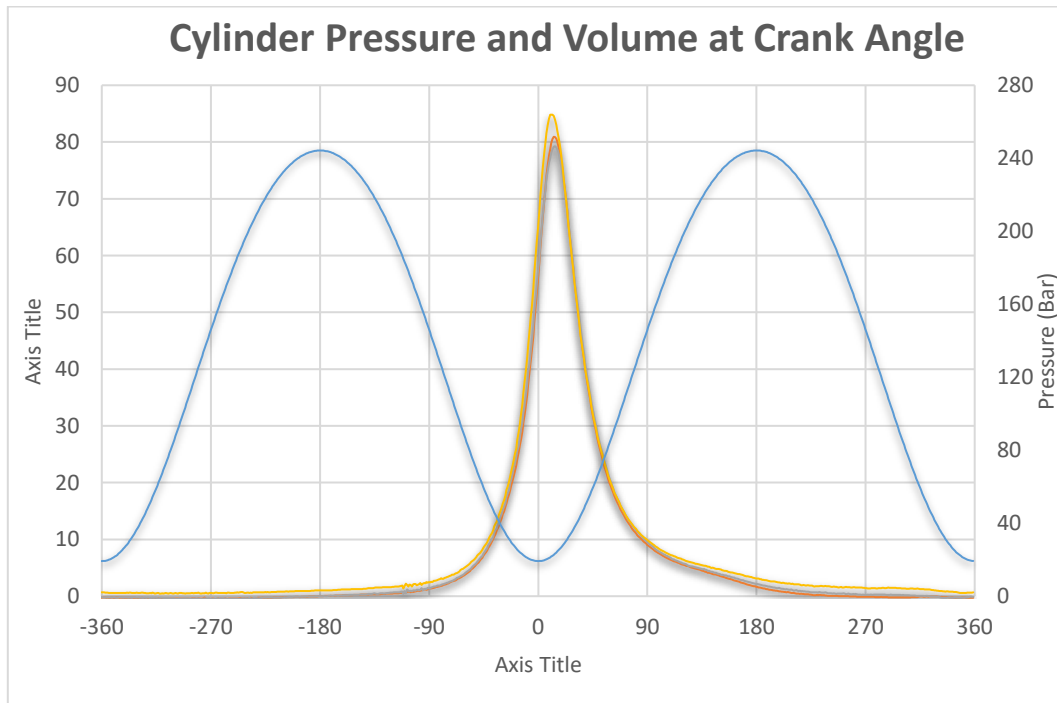
- Crank Angle°
- Cylinder Pressure (Bar)
- Volume (%)
- Burn Rate (%)
- Time (μs)

7.1 Cylinder Pressure and Volume

The cylinder pressures acquired from the triumph data were gauge pressures, meaning they were equal to absolute pressure minus atmospheric pressure. Therefore, negative values are seen “*Gauge Pressure is positive for pressures above atmospheric pressure, and negative for pressures below it*”. (Hinrichs, 2019). To ensure all the values were positive, atmospheric pressure (1 bar) was added to the gauge pressure making it absolute.

$$\text{Absolute Pressure} = \text{Gauge Pressure} + \text{Atmospheric Pressure}$$

Equation 1 Absolute Pressure



Graph 1 Cylinder Pressure & Volume Against Crank Angle

Graph 1 displays the cylinder pressure and volume on the y axis plotted against crank angle on the x axis. Initially, the volume within the cylinder from the provided data was given as a percentage

where 0% represented the piston being located at TDC, and 100% being when the piston was at BDC. The volume needed to be re-calculated to cubic centimetres (cc) in respect to each degree of crank angle, this was done using equation 2.

$$Volume = \left(\frac{Volume\ Percentage}{100} \times Swept\ Volume \right) + clearance\ Volume$$

Equation 2 Volume

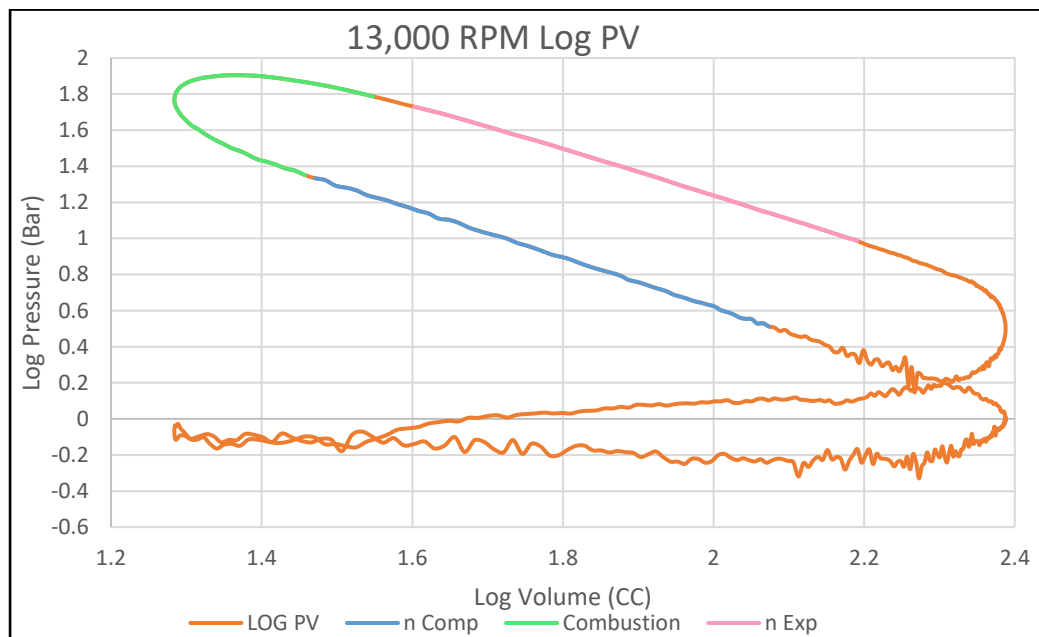
The values for the swept and clearance volumes were found within the technical information PDF that was provided. Swept volume being the volume displaced by the piston during its reciprocating motion and clearance volume representing the remaining volume between the piston head and cylinder head at TDC.

Finally, Logarithmic values of both pressure and volume were taken, by plotting these against one another as shown in graph 2 crucial information such as the polytropic index “n” of compression and expansion strokes can be seen. Furthermore, a polytropic process is a thermodynamic process expressed by the following equation;

$$PV^n = constant$$

Equation 3 Polytropic Index (Connor, 2019)

Therefore, because of the polytropic being a process where volume and pressure increase are constant combustion can be seen when the increase in pressure and volume are no longer linear, which can be seen in graph 2.



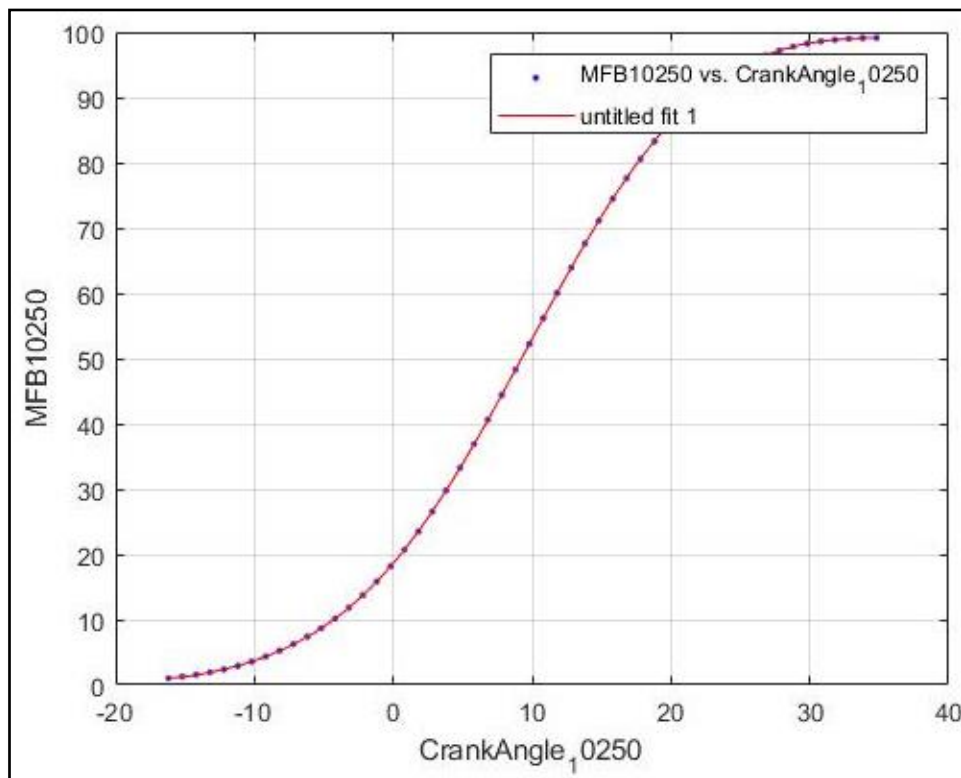
Graph 2 13000 RPM Log PV

8 MFB

The Mass Fraction Burned of fuel within an engines cylinder is “a normalized quantity with a scale of 0 to 1, describing the process of chemical energy release as a function of crank angle” (Mendera, 2002) and is one of the most decisive factors of simulating and predicting combustion as it is the governing factor of the rate of fuel burned.

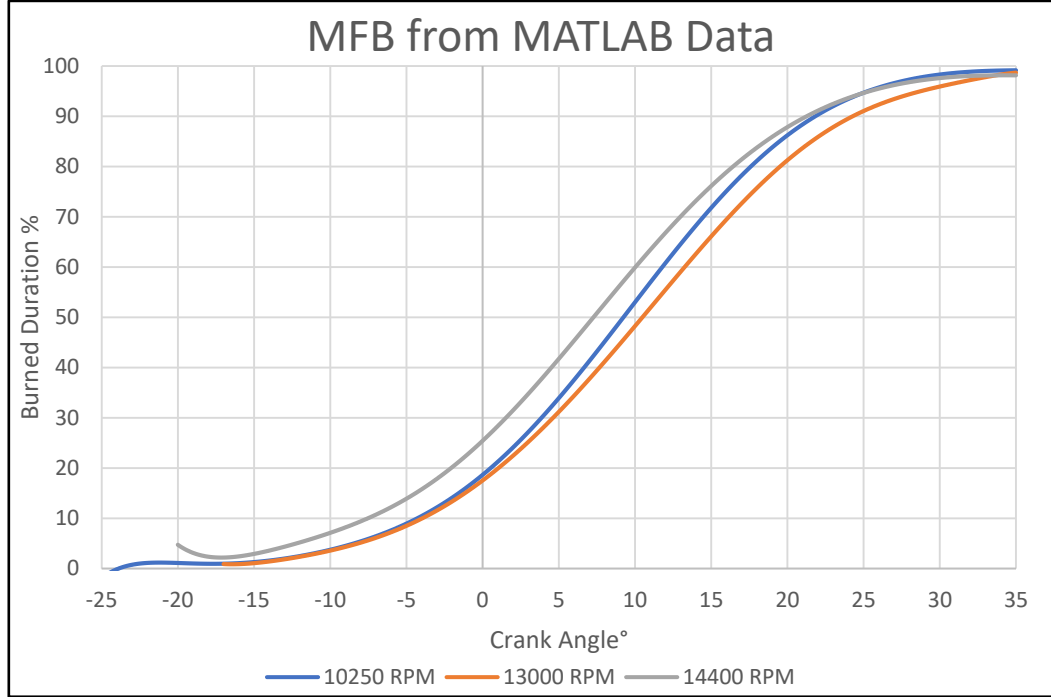
8.1 Timing & Duration of burn

The crank angle and burned data was inputted into MATLAB (Appendix 7.1). Next, with the use of the “*cftool*” curve fitting tool a polynomial trend was applied to the 9th order to increase the accuracy of the results.



Graph 3 10250RPM MATLAB 9th Order Polynomial

Graph 3 shows that only crank angles between -20° and 40° have been plotted as because the values either side of this are considered constant (0% and 100%). Next, a code was then generated and run, and the data exported into an Excel spreadsheet. This gave more accuracy as exported data's crank angle moved in iterations of 0.01° as opposed to the 1° of the provided Triumph data.



Graph 4 MFB

Graph 4 shows the values of MFB from the exported data for all three engine speeds. A further benefit of this method is when certain points of burned rates need to be pin pointed to be later on inputted into WAVE, 50% burn, 10-90% burn duration etc. An interpolation equation can be used for the below and above values to more accurately identify the exact position of the crank angle at each specific burn rate.

$$CA1 + (CA2 - CA1) \times \left(\frac{\text{Burned \%} - BD1}{(BD2 - BD1)} \right)$$

Equation 4 Interpolation Equation

- Where CA_1 & BD_1 are the below values
- And CA_2 & BD_2 are the above values
- And “Burned %” is the burn rate percentage at the crank angle being searched for.

8.2 Use of Wiebe Function to fit MFB Curve

There are multiple mathematical functions, most of which are based on the law of normal distribution of a continuous random variable. The most commonly known being the Wiebe Function “Which is used to predict the burn fraction and burn rate in internal combustion engines operating with different combustion systems and fuels” (Ghojel).

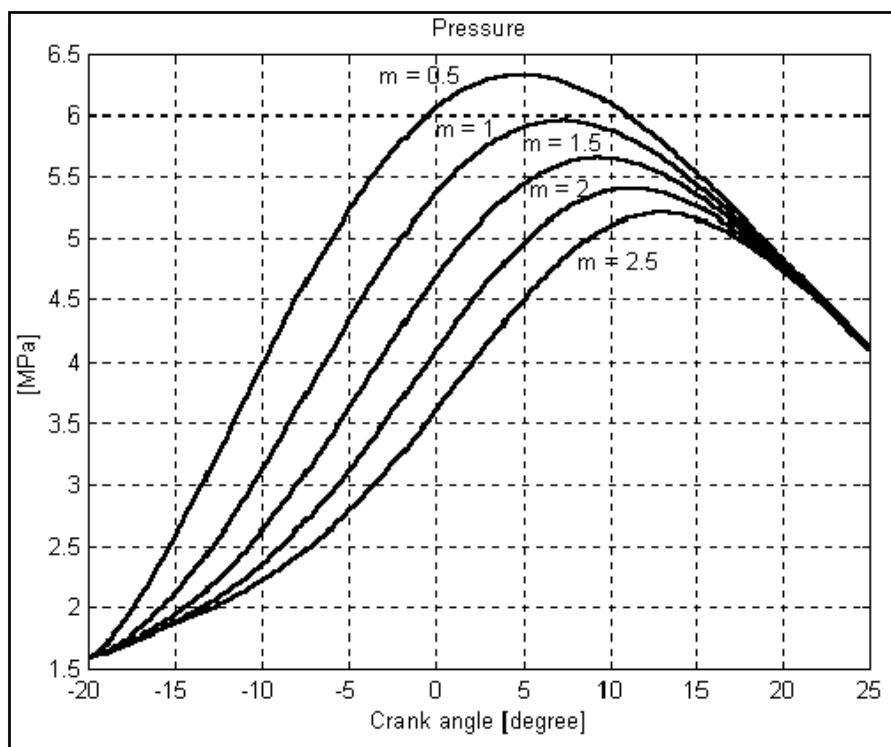
$$x_b = \left\{ 1 - \exp \left[-a \left(\frac{\theta - \theta_o}{\Delta\theta} \right)^{m+1} \right] \right\}$$

Equation 5 Wiebe Function (Yeliana, 2008)

Equation 5 displays the Wiebe Function where;

- a is the “function efficiency parameter” (Giakoumis, 2008)
- m is the form factor
- θ is the current crank angle°
- θ_o is the degree of crank angle at the start of combustion.
- $\Delta\theta$ is the combustion duration in degrees of crank rotation.

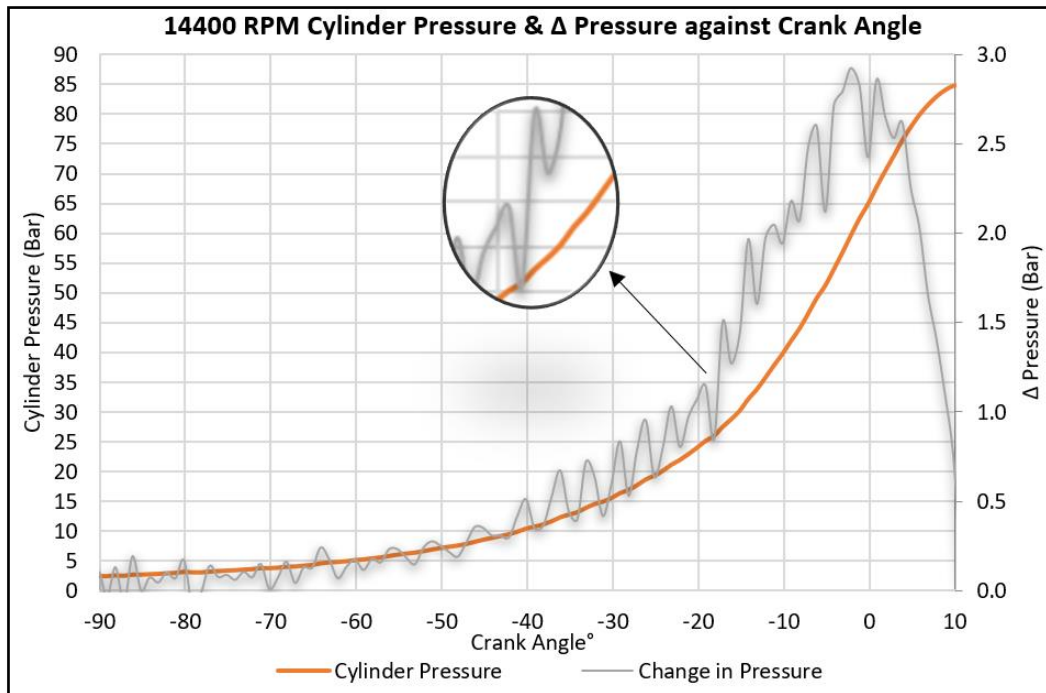
The a and m exponents were provided within the technical information sheet as 5 & 2. These exponents are the values that characterize the curve as proven in graph 6.



Graph 5 Wiebe Function (Romero, 2003)

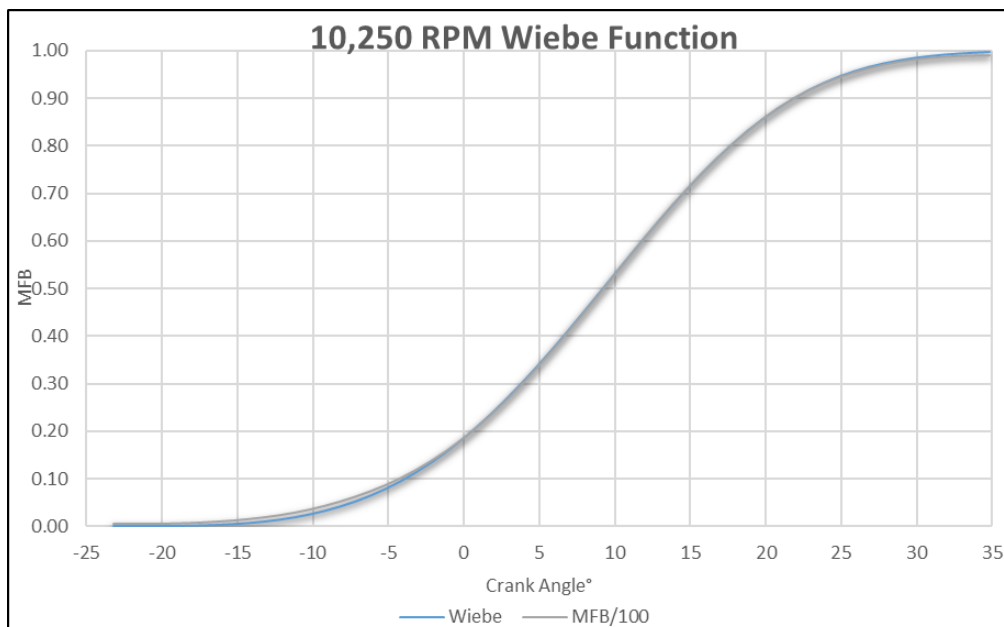
8.2.1 Excel Curve Fit

With the use of Microsoft Excel the Wiebe function was utilised in order to find the most accurate values to later be inputted in to the WAVE model. Assumptions were made for the start & end of combustion and the combustion duration. The start of combustion was chosen by overlaying the difference in pressure and cylinder pressure over one another and looking for the greatest rate of change and assuming this was where combustion begins as shown in graph 7. Also, the combustion duration was chosen from the straying curve within the Log PV graph as previously stated.



Graph 7 14,400 RPM Difference in Pressure & Cylinder Pressure against crank angle

Once all of the values required for the Wiebe function were known and calculated the values were then plotted against MFB in respect to crank angle. The variables within the equation were then altered until both trends showed complete correlation as shown in graph 8.



Graph 8 10,250 RPM Wiebe Function

Max Burn Rate	
99.1339	398
Duration Complete Comb	
55.8	
C.A start of combustion	
-23.25	
C.A @ Full Combustion	
34.81	
Wiebe	
a	-5
m	2.65

C.A	Wiebe	MFB	MFB/100
-23	(\$T\$14+1))	0.532327	0.005323
-22	0.000003	0.534244	0.005342
-21	0.000029	0.538939	0.005389
-20	0.000125	0.557631	0.005576
-19	0.000351	0.605782	0.006058
-18	0.000783	0.700512	0.007005
-17	0.001512	0.838683	0.008387
-16	0.002638	1.023828	0.010238
-15	0.004275	1.262816	0.012628
-14	0.006544	1.560980	0.015610

Figure 2 10,250 Spreadsheet for Wiebe Function

8.2.2 MATLAB Curve Fit

Furthermore, following the same method the calculations were re-done in MATLAB predominantly for comparative reasons, but also as the software is able to calculate to a considerably superior level of accuracy.

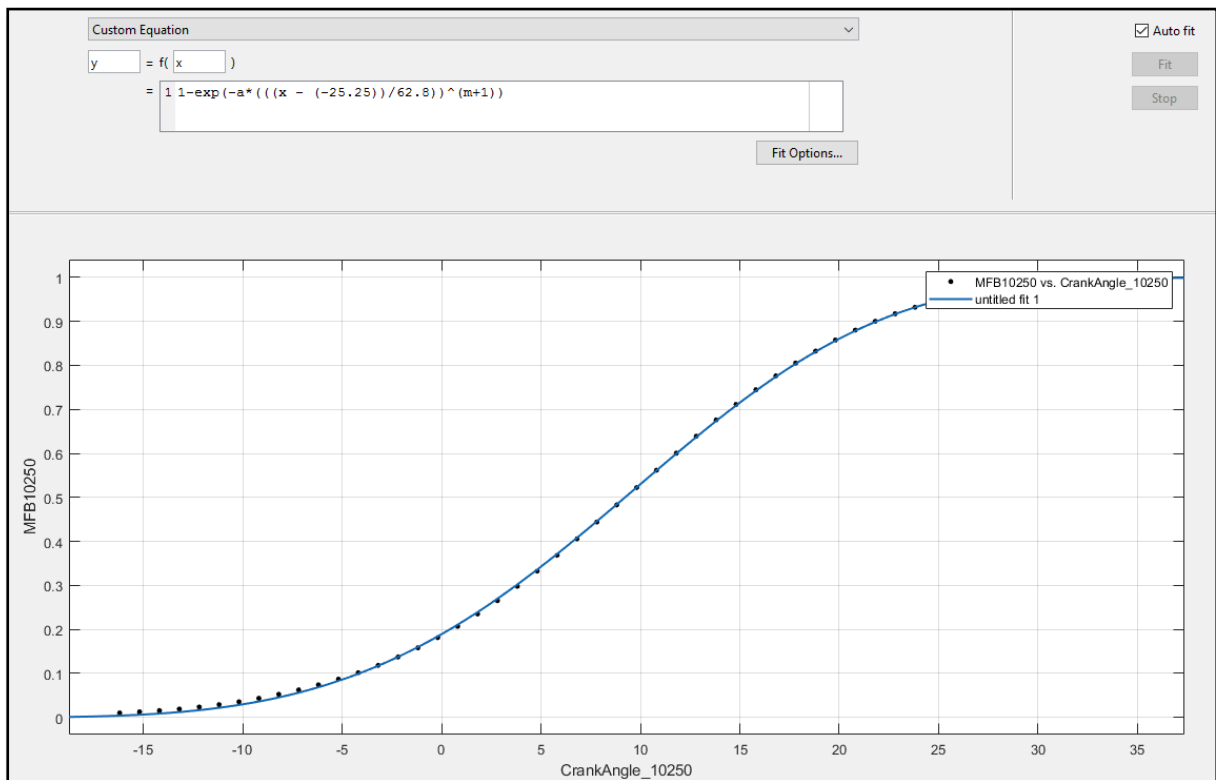


Figure 3 MATLAB Wiebe Function

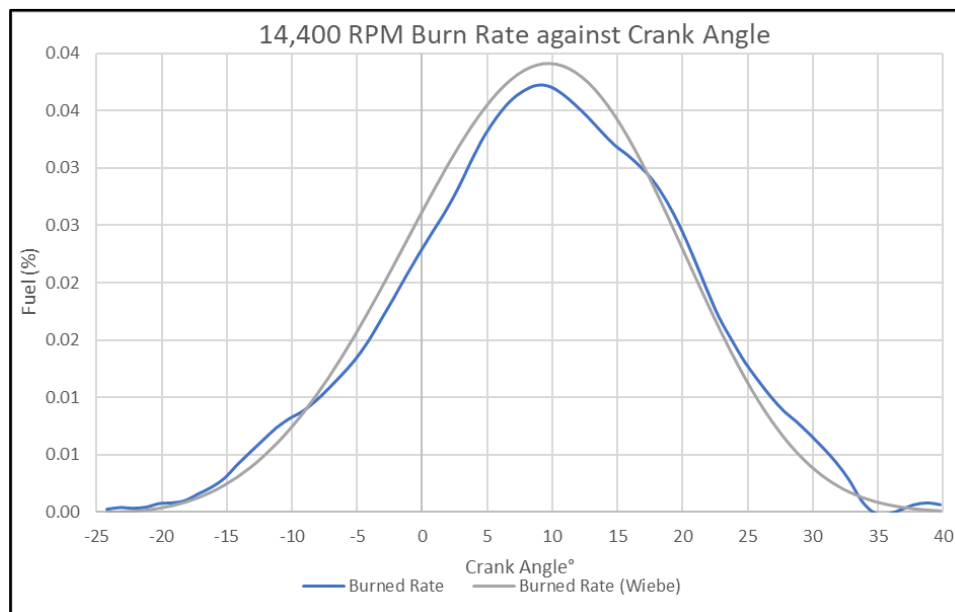
Table 1 shows the values used within the Wiebe function for all three engine speeds in both Excel and MATLAB.

	θ_o	$\Delta\theta$	a	m
10,250 RPM				
Excel	-23.25°	55.80°	5	2.65
MATLAB	-25.25°	62.80°	6.96	2.84
13,000 RPM				
Excel	-26.40°	67.40°	5	2.85
MATLAB	-26.40°	67.40°	6.757	2.78
14,400 RPM				
Excel	-27.05°	57.49°	5	2.9
MATLAB	-27.05°	57.49°	4.18	2.48

Table 1 Wiebe Function Values

8.3 Burn Rate and Unburned Fuel

To calculate the burn rate during combustion, it's simply the rate of change of the Mass Fraction Burnt, predicted via the Wiebe Function. The following graph shows the burn rate through combustion for both the real data provided and that from the prediction. As can be seen, there is an indefinite trend with respect to start and end of the burn, but the Wiebe function has the limitation of creating a linear pattern. Also, as seen from the real data, the burn rate most certainly isn't linear when operating in real conditions, but the maximum difference is only 0.0019% and therefore shows the function has the ability to predict the MFB to a high enough degree of accuracy for modelling.



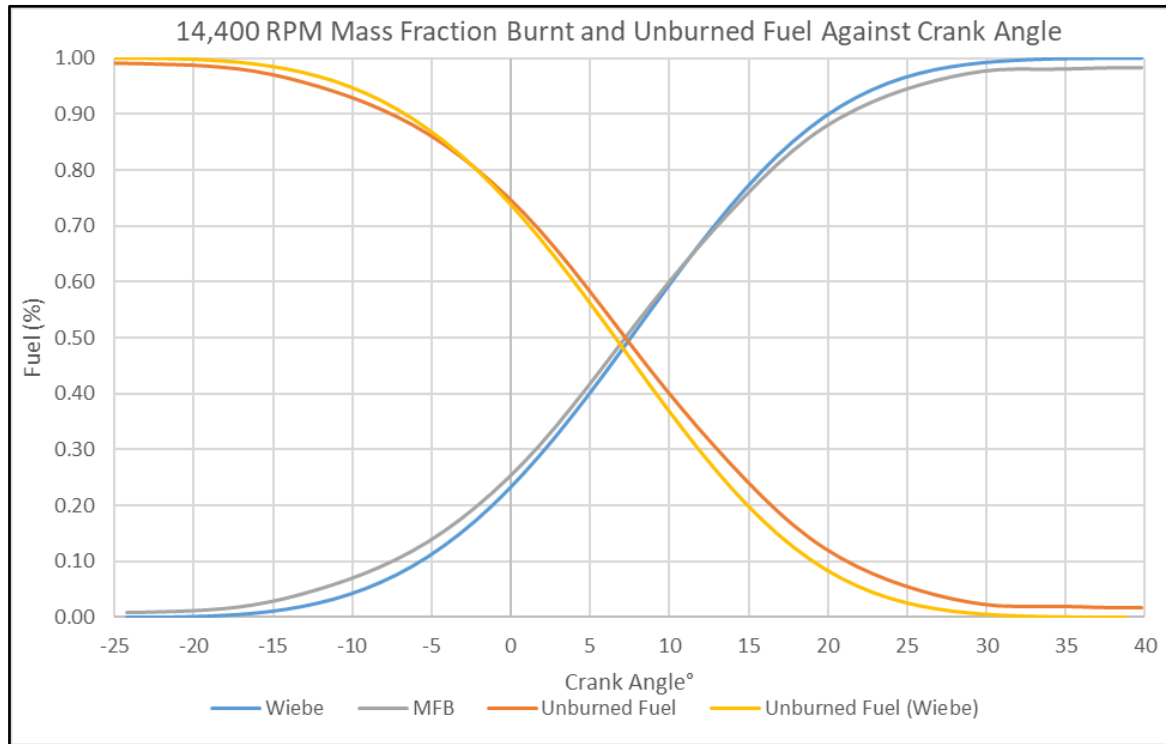
Graph 9 14,400 RPM Burn Rate Against Crank Angle

With having calculated the MFB, the unburnt fraction can be found by;

$$\text{Unburnt Fuel} = 1 - \text{MFB}$$

Equation 6 Unburnt Fuel

This is shown in graph 10 below by having the unburnt proportion, it aids in developing a two-zone combustion model within a cylinder.



Graph 10 14,400 RPM Mass Fraction Burn & Unburnt Fuel Against Crank Angle

9 WAVE Model

As previously stated, a Baseline WAVE Model of the three-cylinder Triumph Daytona 675cc was provided, camshaft and flow bench data that was given was inputted into the model allowing it to run correctly. Figures 4 and 5 show the Baseline models interface and the table of constants. Numerous alterations were then made to the model in the aim of correlating the data it produces with that of the actual dynamometer data.

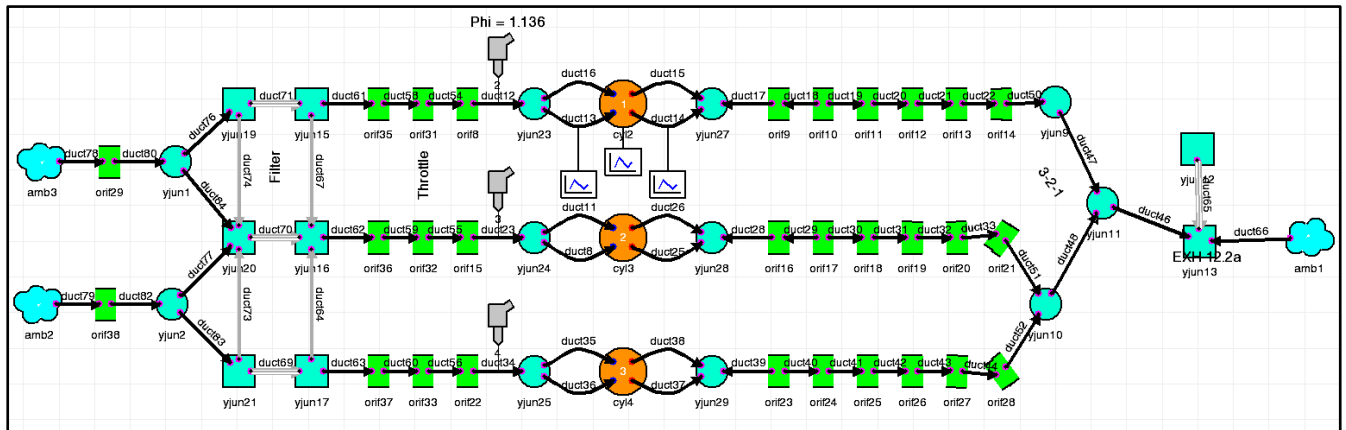


Figure 4 Baseline WAVE Model Interface

Constants Table		Sweep Constants	Dependent Constants		External Constants					
	Name	Units	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Status			Skip	Run	Run	Skip	Run	Skip	Skip	Skip
Title			Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
1	BDUR	deg	20	32	28	28	26	26	26	26
2	eop	deg	85	85	85	85	85	85	85	85
3	exh		180	180	180	180	180	180	180	180
4	FARD		0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
5	iop	deg	250	250	250	250	250	250	250	250
6	NCYC		20	20	20	20	20	20	20	20
7	PREF		1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325
8	SPEED	rpm	15000	14400	13000	11750	10250	9500	8750	7500
9	TCYL		575	575	575	575	575	575	575	575
10	THB50	deg	8	7.23	10.52	10.52	9.25	9.25	9.25	9.25
11	THEAD		600	600	600	600	600	600	600	600
12	thrt	mm	40	40	40	40	40	40	40	40
13	TPIS		550	550	550	550	550	550	550	550
14	TREF		298.15	298.15	298.15	298.15	298.15	298.15	298.15	298.15

Figure 5 Constants Table

9.1 Benchmark Run

Initially, a benchmark run was done without making any changes to the model apart from adding in the valve lift data for both intake and exhaust, and their flow coefficient profiles. Subsequently, a combustion model needed to be added, the Wiebe model within the software was used, and also the Woschni model was used for the heat transfer model.

Benchmark Run			
Maximum Cylinder Pressure (Bar)			
RPM	10,250	13,000	14,400
WAVE	98.89	90.72	76.67
Excel	81.93	80.25	84.82
Δ	16.96	10.47	-8.15

Table 2 Benchmark Run

9.2 Modifications to Model

The only modification made to the geometry of the engine was the length of the Connecting Rod which was altered from 98mm to 104.6 mm for each cylinder.

The screenshot shows the 'Case #1: Cylinder Panel' window. The 'Template Name' is 'Default Engine Cylinder'. The 'Name' field contains 'cyl2'. The 'Cylinder Number' is '1' and the 'Number of Valves' is '4'. The 'Edit Engine General Properties' section is active, with tabs for 'Geometry', 'Initial Conditions', 'Valves', 'Sub-Models', and 'Initial Fluid Composition'. Under the 'Geometry' tab, there are sub-tabs for 'Liner', 'Head', and 'Piston'. The 'Surface Area Multiplier' is '1.0', 'Surface Area' is '4536.46' mm², 'Connecting Rod Length' is '104.6' mm, 'Wrist Pin Offset' is '0' mm, and 'Compression Ratio' is '12.65'.

Figure 6 Connecting Rod Length

Next, in order to make the model more realistic, the use of the methods previously stated in regards to situating the crank angle at a certain burnt percentage, using MATLAB and the interpolation equation, the 50% burn rate and the burn duration (10-90%) were calculated and inputted into the model.

$M_{ass} F_{raction} B_{urned}$			
MFB	RPM		
%	10250	13000	14400
5%	-8.4443	-8.1737	-12.2200
10%	-4.2884	-3.9548	-7.5281
50%	9.2418	10.4869	7.2748
90%	21.8346	24.2877	21.2674
Burn Duration			
C.A°			
	26.1230	28.2425	28.7955

Table 3 10, 50 & 90 Burn Rates

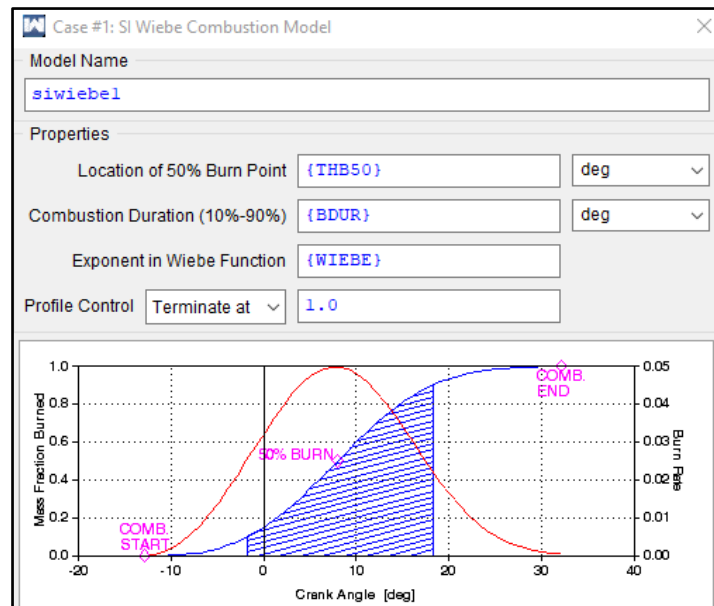


Figure 7 50% Burn and Burn Duration

Next, the Inlet Valve Diameter was changed from 29mm to 31mm, which is stated within the Triumph technical information sheet, the diameter of the intake port duct was also changed from 28.3mm to 30.3mm. This value was chosen, to maintain a difference of 0.7mm between the valve and the duct. Furthermore, the exhaust valve diameter was not on the technical information sheet, but was attained online as 25.5mm (Ape Race Parts, 2009).

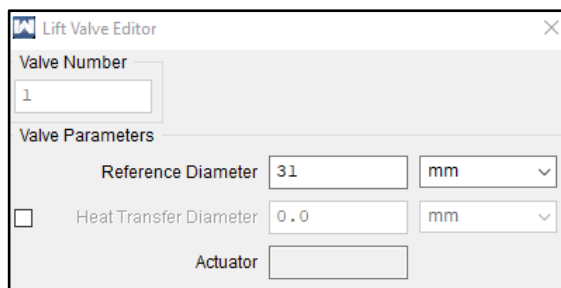


Figure 8 Intake Valve Lift

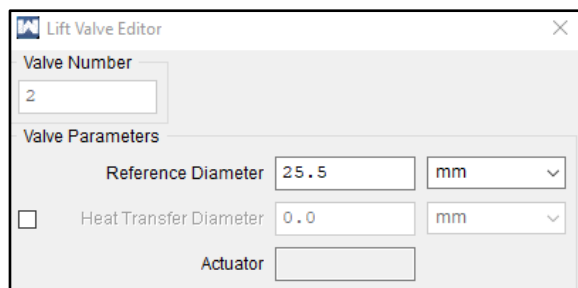


Figure 9 Exhaust Valve Lift

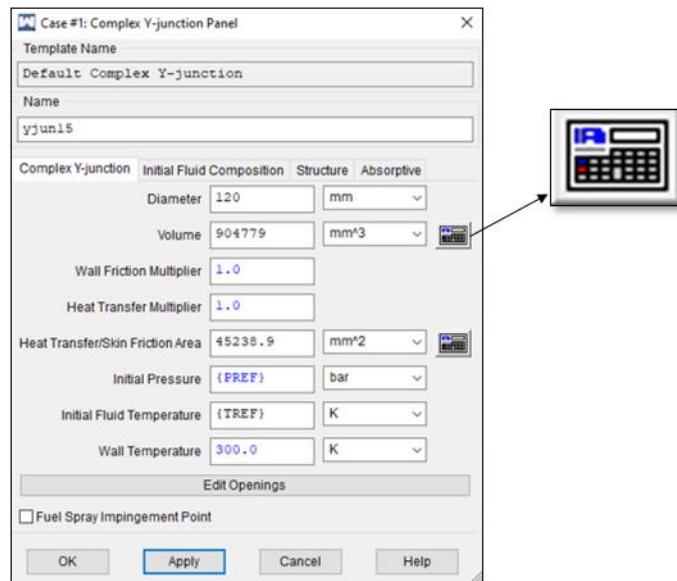


Figure 10 Re-calculating Volume and Heat Transfer & Skin Friction Area

Every Y-Junction within the model had incorrect Heat Transfer/Skin Friction Area values, therefore in order to replicate realistic results these values were re-calculated as displayed in figure 10. Subsequently, the same method was carried out to calculate the coolant-side area values. Originally, they were at 0 but by using the re-calculation function, WAVE accurately calculated the correct numbers affiliated with Conduction.

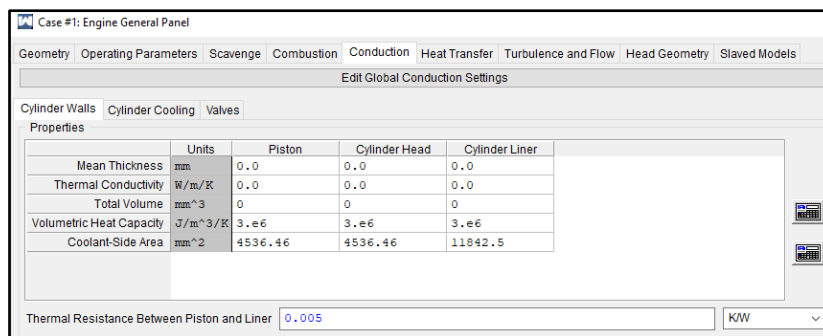


Figure 11 Re-Calculating Coolant-Side Area

As previously discussed with the use of the Wiebe Function, a more accurate value for the Wiebe m exponent could be calculated, this was done within Excel and MATLAB, the MATLAB values seemed to yield better results within the WAVE model.

10,250 RPM	13,000 RPM	14,400 RPM
2.84	2.78	2.48

Table 4 Wiebe m Values

Within the constants table as previously shown in figure 5 “*TREF*” referred to the ambient temperature and was set at 298.15 Kelvin, this was then changed to 293 Kelvin assuming an ambient air temperature of 20°C. Furthermore, a constant consisting of the ambient pressure (1 Bar) was added and denoted as “*PREF*” and applied to each duct and junction before reaching the cylinders (Induction).

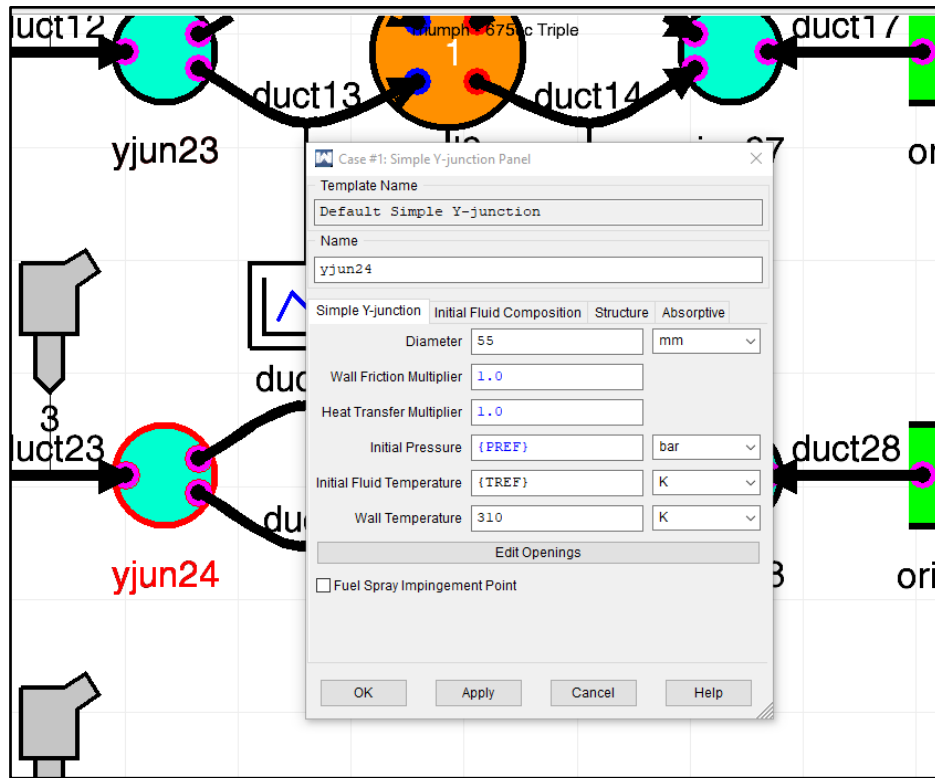


Figure 12 Pressure Reference

Also, it is worth noting that for each default ambient the temperatures were changed to *PREF* & *TREF* (was previously 300K and 1.065Bar).

The baseline WAVE Model did not provide a clearance height, therefore using the following equation one was calculated and then added in;

$$V = \pi r^2 h$$

$$\therefore h = \frac{V}{\pi r^2}$$

Equation 7 Clearance Height

Where;

- Radius is half of bore in metres.
- V is Clearance Volume.

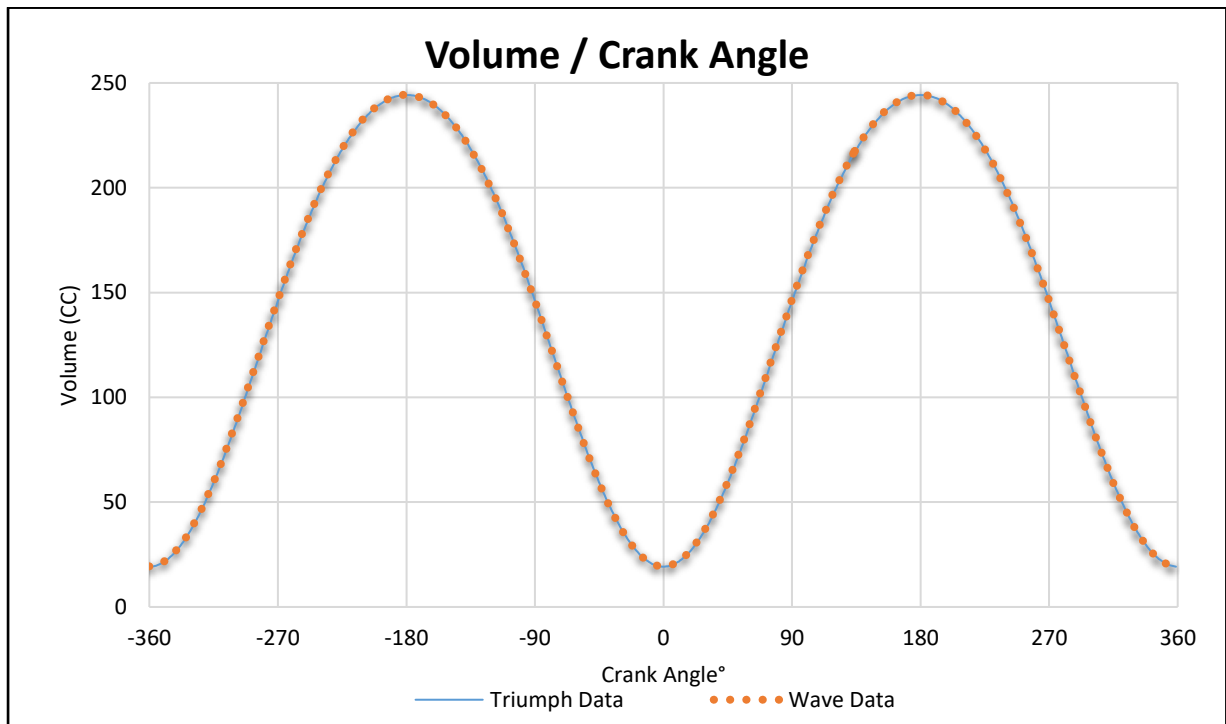
	Swept Volume	Clearance Volume
m ³	0.0002250	1.9314E-05
CC	225.0084	19.3140

Clearance Height	
0.0043	M
4.2575	mm

Equation 8 Clearance Height

Comparison & Analysis

9.3 Volume

*Graph 11 Volume Against Crank Angle*

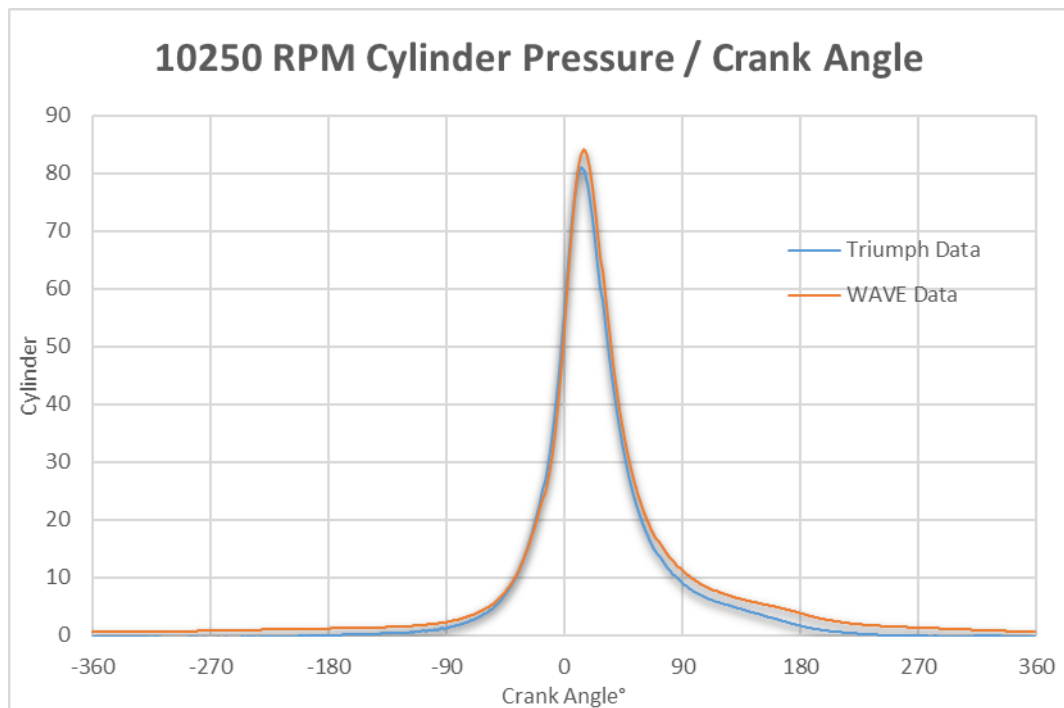
The WAVE data for Volume was only exported out for one RPM as engine speed has no effect on volume, Graph 11 clearly demonstrates that the volume calculated within WAVE completely correlates with the real-life data.

9.4 Cylinder Pressure

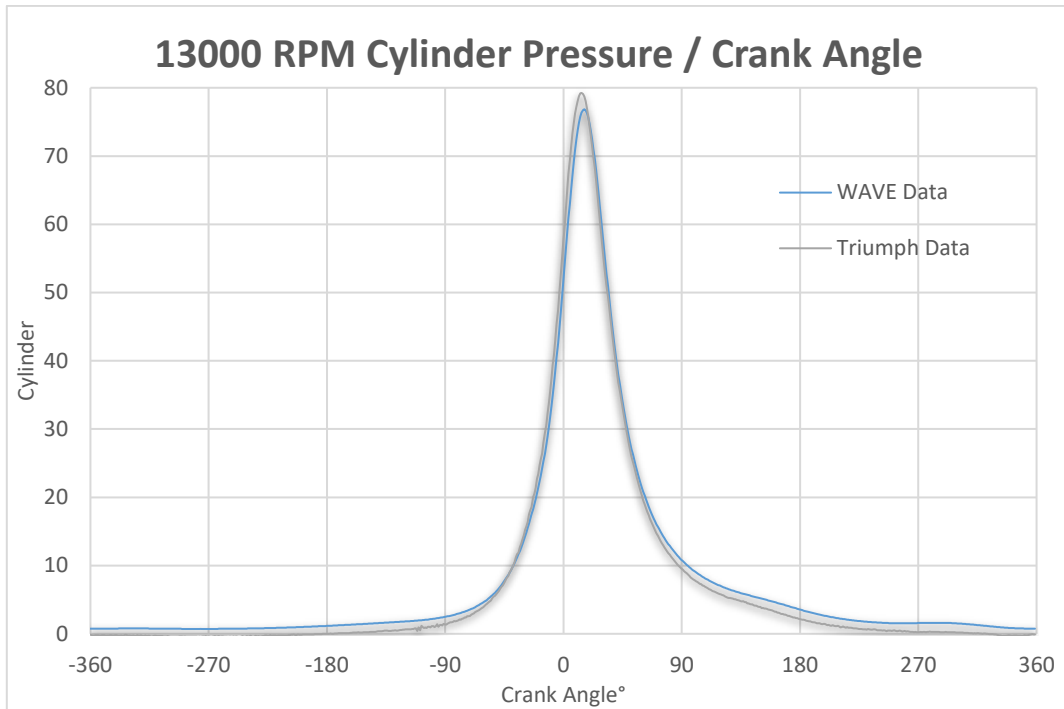
Final Run			
<i>Maximum Cylinder Pressure (Bar)</i>			
RPM	10,250	13,000	14,400
WAVE	85.19	79.51	84.46
Excel	81.93	80.25	84.82
Δ	3.26	0.74	0.36
Δ From Bench Mark WAVE Model.	13.85 %	12.36 %	10.16 %

Table 5 Final Run Pressure Differences

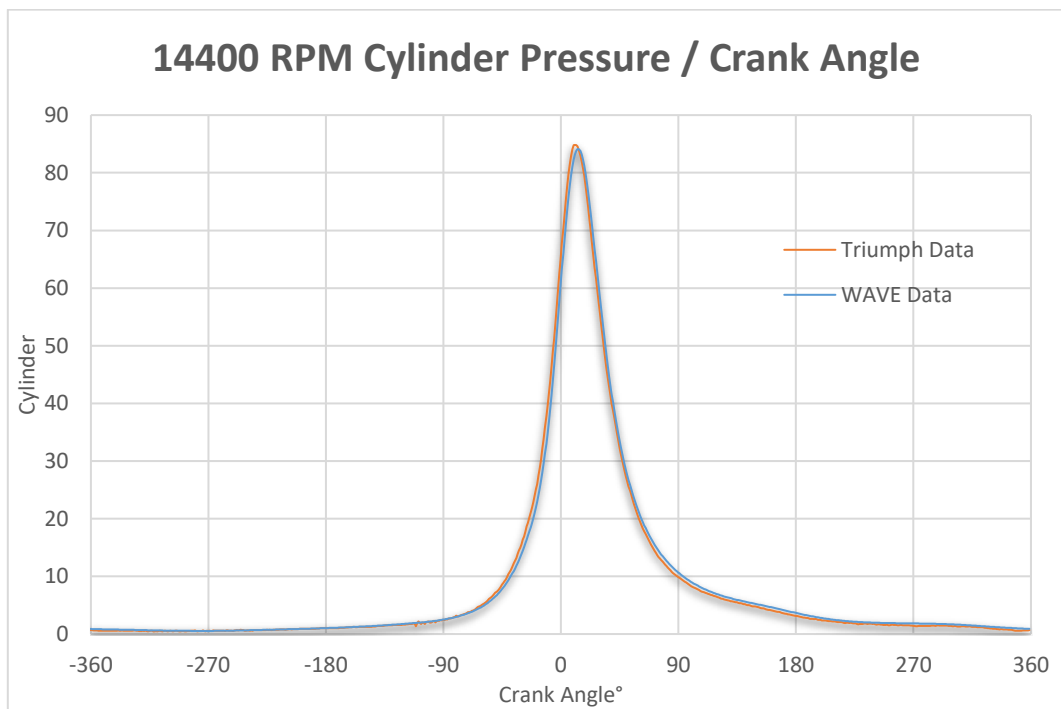
Table 5 displays the final pressure values after all of the modifications that were implicated into to the WAVE model. The WAVE data for every RPM stint was exported out into an Excel spreadsheet and plotted against crank angle alongside the real-life data. The following three graphs demonstrates that even though the pressures were not able to be completely corelated, the trends and gradients have been.



Graph 12 10,250 RPM Cylinder Pressure Against Crank Angle



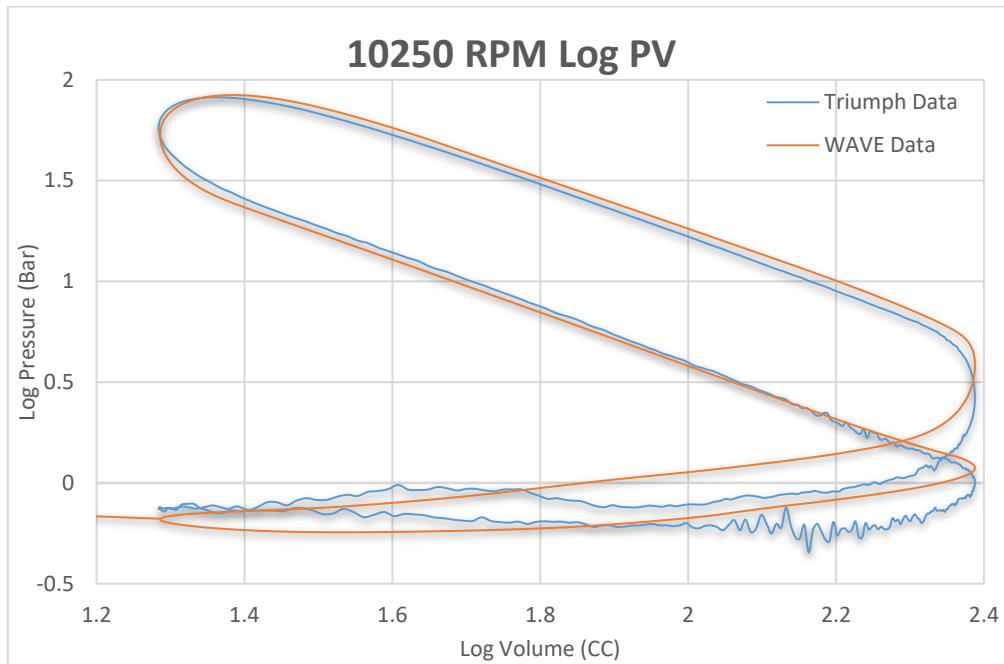
Graph 13 13,000 RPM Cylinder Pressure against Crank Angle



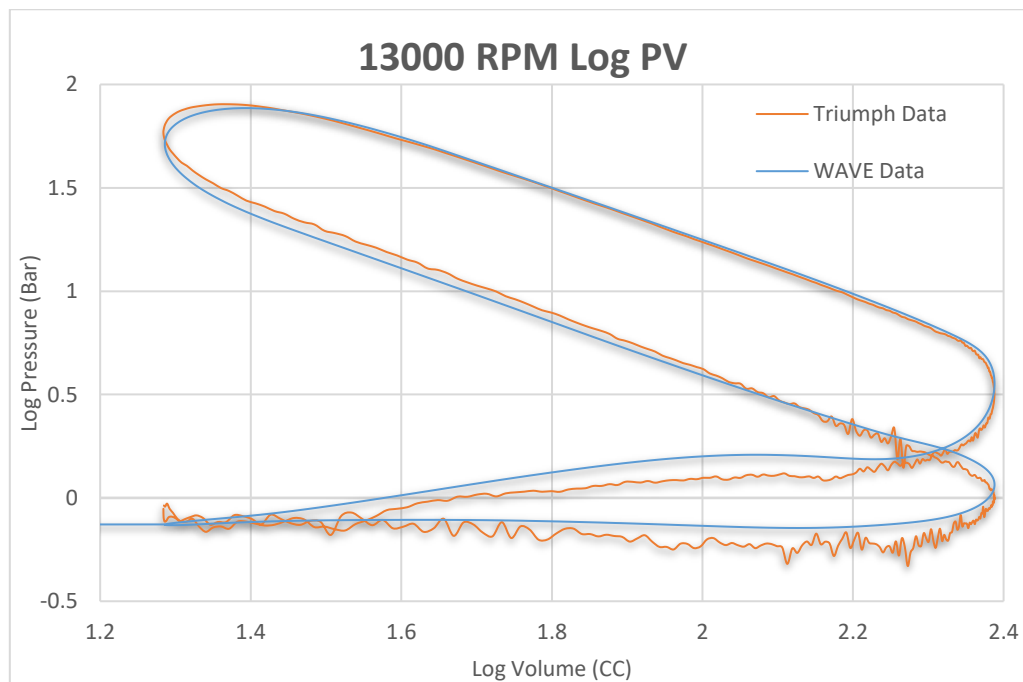
Graph 14 14,400 RPM Cylinder Pressure Against Crank Angle

9.5 Log PV

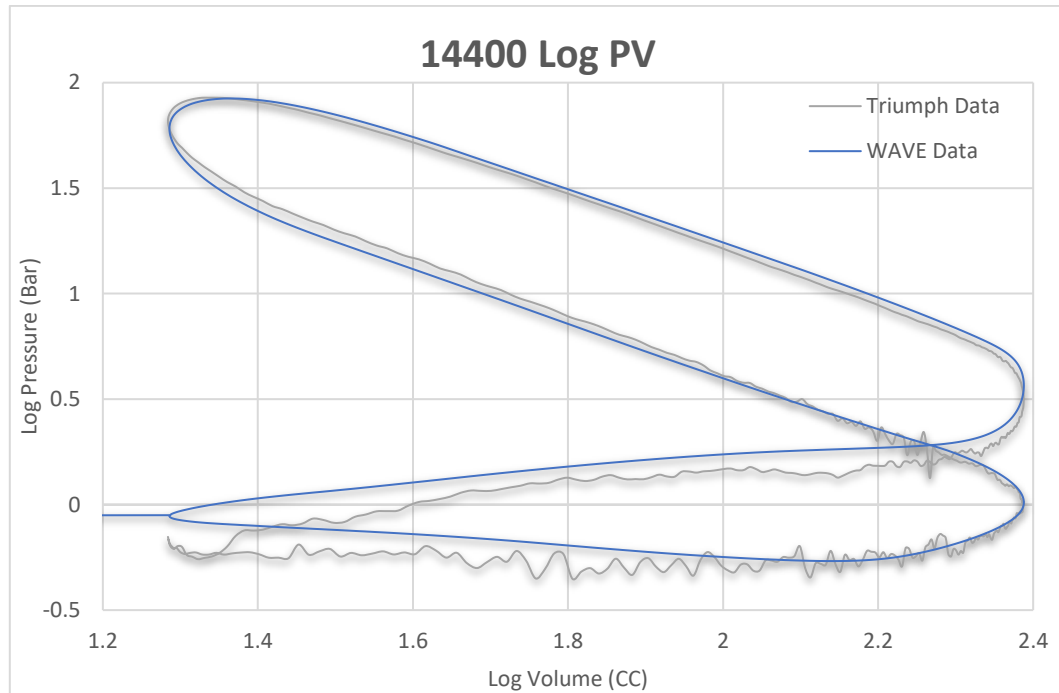
By taking Logarithmic values of the pressure and volume values and plotting them against one another the characteristics of the combustion cycle can be analysed. From reviewing the following three graphs for each RPM it is clear that there is correlation. On the other hand, at each engine speed the WAVE data does not show the same linear increase during n compression.



Graph 5 10,250 RPM LOG PV



Graph 6 13,000 RPM



Graph 7 14,400 RPM

9.6 Power

The brief for this study stated that at 12,600 RPM the engine was putting out 94 Kw of power. Therefore, a run was added into the WAVE model at this engine speed to see how close the model was to this value.

Power @ 12,600 RPM		
	Actual	WAVE
	94	95.05
Difference	-1.05	

Figure 13 Power @ 12,600 RPM

10 Conclusion

To conclude, WAVE has proven to be a useful software package in regards to engine modelling and simulation. It has the complexity to calculate the changes of crucial characteristics such as power, emissions, and efficiency.

The WAVE model could be seen as a relatively realistic interpretation of the Triumph Daytona 675cc. On the other hand, attempting to model combustion in a virtual engine with the limited amounts of data that was provided showed numerous limitations, and proved almost impossible to exactly correlate the model with real life data.

11 References

- Ape Race Parts. (2009). *2009 Triumph Daytona 675cc*. Retrieved from Ace Race Parts:
<http://aperaceparts.com/tech/2009%20Triumph%20Daytona%20675.html>
- Connor, N. (2019, May 22). *What is Polytrropic Process - Definition*. Retrieved from Thermal Engineering: <https://www.thermal-engineering.org/what-is-polytropic-process-definition/>
- Ghojel, J. (n.d.). *Review of the Development and applications of the Wiebe function: A tribute to the contribution of Ivan Wiebe to engine Research*.
- Giakoumis, E. (2008). *Availability analysis of a syngas fueled spark ignition engine using a multi-zone combustion model*. Research Gate.
- Hinrichs, P. P. (2019, August 1). *Gauge Pressure, Absolute Pressure, and Pressure Measurement*. Retrieved from Physics Libre Texts:
[https://phys.libretexts.org/Bookshelves/College_Physics/Book%3A_College_Physics_\(Open Stax\)/11%3A_Fluid_Statics/11.07%3A_Gauge_Pressure%2C_Absolute_Pressure%2C_and_Pressure_Measurement](https://phys.libretexts.org/Bookshelves/College_Physics/Book%3A_College_Physics_(Open_Stax)/11%3A_Fluid_Statics/11.07%3A_Gauge_Pressure%2C_Absolute_Pressure%2C_and_Pressure_Measurement)
- Mendera, K. Z. (2002). *Mass Fraction Burned Analysis*. Technical University of Czestochowa.
- Ricardo. (n.d.). *WAVE*. Retrieved from <https://software.ricardo.com/products/wave>
- Romero, C. A. (2003). *Prediction of In-Cylinder Pressure, Temperature, & Loads Related To the Crank Slider Mechanism of I.C. Engines: A Computational Model*. Universidad Technologica de pereira.
- Yeliana, C. J. (2008). *Wiebe Function Parameter Determination for Mass Fraction Burn Calculation in an Ethanol-Gasoline Fuelled SI Engine*. Michigan: Mechanical Engineering-Engineering Mechanics.

12 Appendix

12.1 MFB MATLAB Script

```
BDSet = xlsread('Burned Duration.xlsx')

MFB10250 = BDSet(345:396,2);
MFB13000 = BDSet(345:397,3);
MFB14400 = BDSet(345:400,4);
CrankAngle_10250 = BDSet(345:396,1);
CrankAngle_13000 = BDSet(345:397,1);
CrankAngle_14400 = BDSet(345:400,1);

NewCrank_10250 = (-25:0.01:35)';
MFB10 = MFB10250(NewCrank_10250);
MFB10(:,2) = NewCrank_10250;

NewCrank_13000 = (-17:0.01:35)';
MFB13 = MFB_13000(NewCrank_13000);
MFB13(:,2) = NewCrank_13000;

NewCrank_14400 = (-20:0.01:35)';
MFB14 = MFB_14400(NewCrank_14400);
MFB14(:,2) = NewCrank_14400;
```