



University of Wales Trinity Saint David

School of Engineering

**Optimisation of a High Speed 3 Cylinder Using
the Ricardo WAVE Engine Development Software**

Advanced Computational Methods (M6X00408)

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1. Introduction

I. Aims

Ricardo WAVE will be used to validate a 3 cylinder (IC) engine model against real cylinder pressure data. Individual studies will be carried out for a variety of parameters within the 1D program to investigate the effects they have through a cycle. The results will be analysed and used to produce a final validation model at a single engine speed.

II. Objectives

- Extract relevant information from the Triumph 675 cylinder data to include into WAVE
- Verify base WAVE model settings against engine specification sheet, making changes where necessary.
- Gather results from base model to compare with real data and design an experiment to validate the model.
- Analyse the results produced from the changes made and discuss limitations to WAVE, real data and processes used.

2. Real Cylinder Data Extraction

I. Presented Data

Cylinder data for the Triumph 675 engine will be used to validate the WAVE model. The provided data is recorded over one complete engine cycle. All measurements are listed in *table 1* (per degree crank angle).

Table 1 - Recorded Variables from Real Engine Data

Variable	Measurement Unit
Crankshaft Angle	Degrees
Cylinder Pressure	Bar
Cylinder Volume	% of Total Volume
Burn Rate	% of Mass Fraction Burned
Time	Micro Seconds

II. Data Interpretation

MATLAB will be used to extract relevant information in the form of 3D plots. The results of which can be implemented to drive and validate the model. The measured engine speeds are 10,250, 13,000 and 14400 RPM. It is not clear whether the provided cylinder pressures are for an individual cylinder or averaged across all three.

a) Cylinder Volume

The volume as a percentage is calculated with the following conversion. The swept and clearance volumes are extracted from the engine specification sheet.

Equation 1 - Volume Conversion Equation

$$Volume (CC) = \left(Swept Volume (CC) \times \frac{Volume(\%)}{100} + Clearance Volume(CC) \right) \times 10^6$$

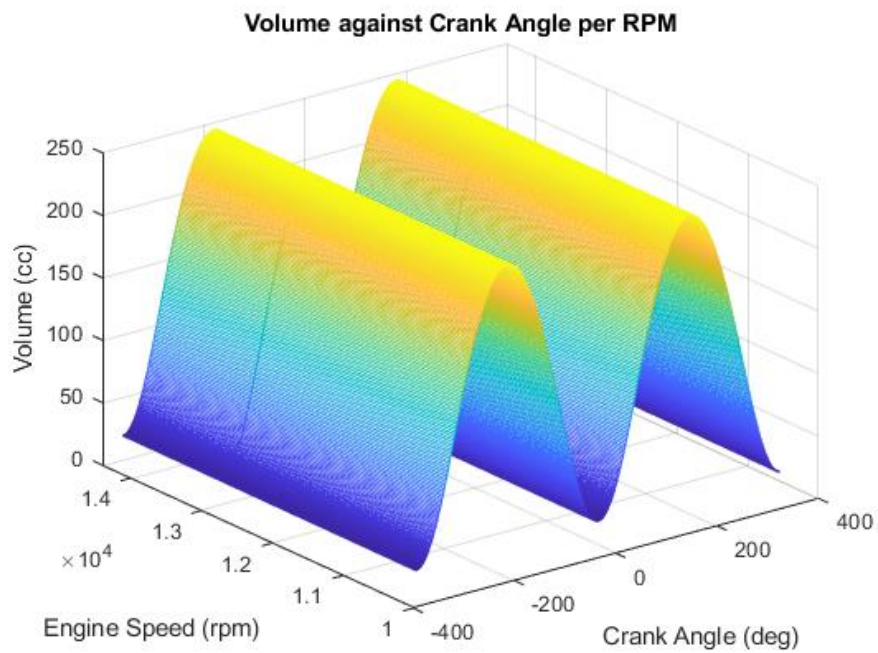


Figure 1- Volume against Crank Angle per Engine Speed (Real Data)

b) Cylinder Pressure

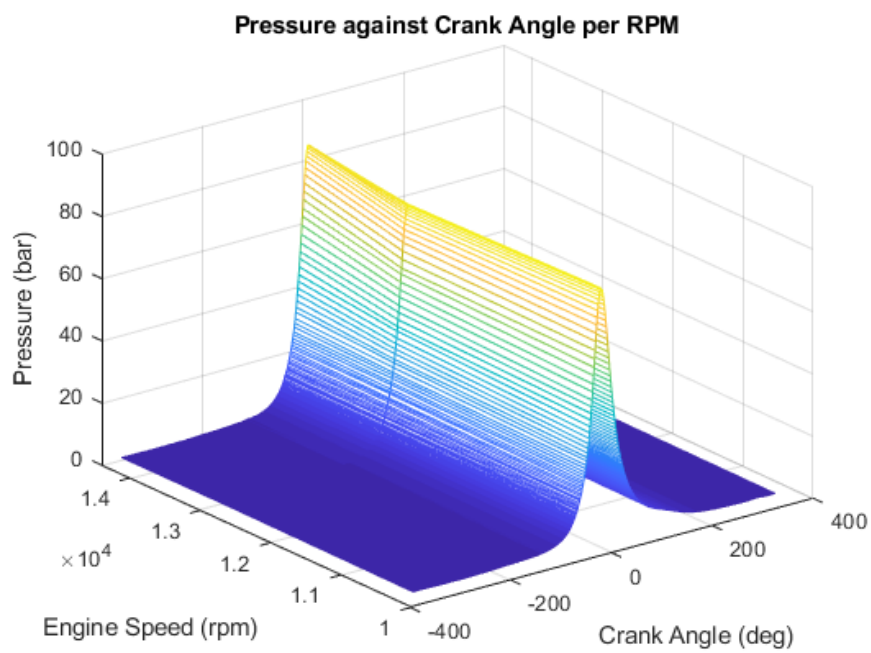


Figure 2 - Pressure against Crank Angle per Engine Speed (Real Data)

c) Pressure Volume (PV)

The engine loading conditions are not provided with the real data. However, a reasonable assumption for full throttle/load can be made based on the peak pressures shown in the PV plot for each engine speed.

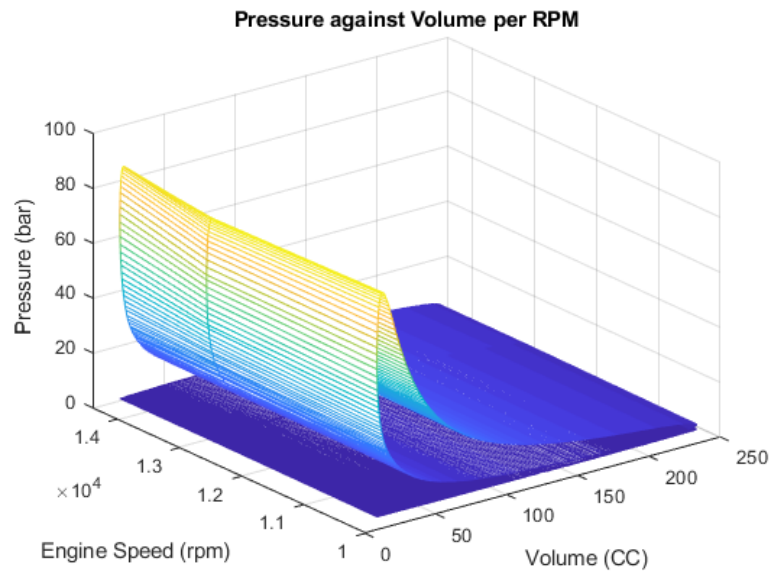


Figure 3 - Pressure against Volume per Engine Speed (Real Data)

d) Log PV

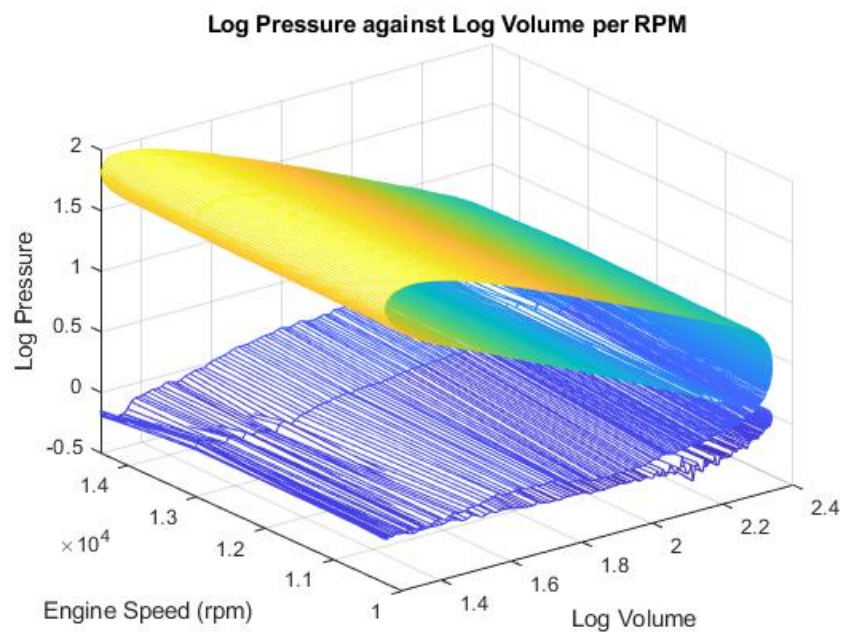


Figure 4 - Log Pressure against Log Volume per Engine Speed (Real Data)

Mass Fraction Burned (MFB)

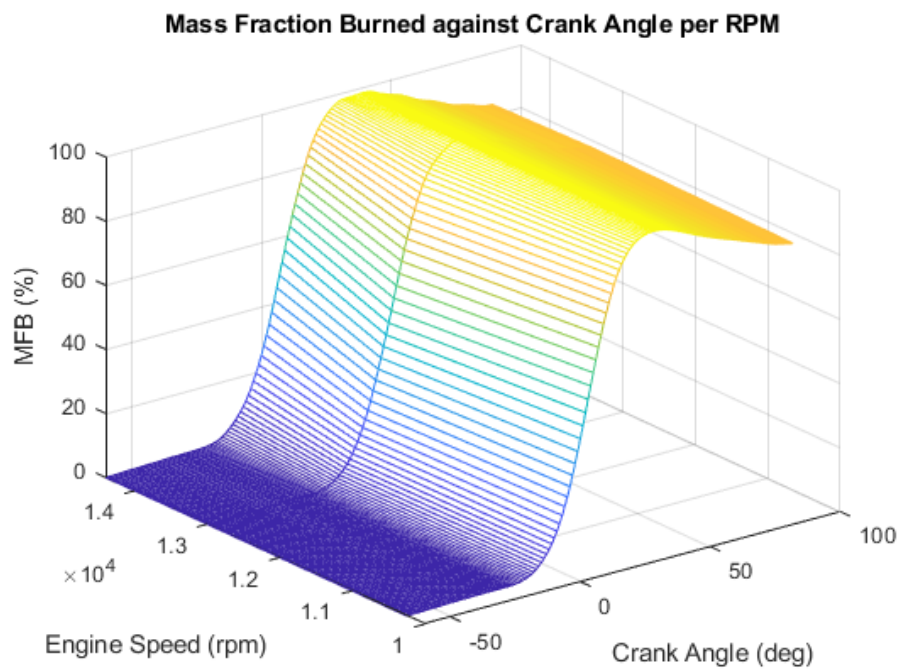


Figure 5 - Mass Fraction Burned against Crank Angle per Engine Speed (Real Data)

The Wiebe function will be included to the Ricardo WAVE combustion model. This changes for each engine speed.

3. Design of Experimental Procedure

The primary method for validation is through comparison of cylinder pressures between the real engine data and WAVE model. This section will highlight the methodology used to complete the experiment.

I. Model Manipulation

The first iterations will include changes to the “Base Model” to match those indicated by the real data and specification sheet. The “Modified Model” will be referred to where additional changes are made. The correlations produced from the “Base Model” will provide the criteria to determine a sensible range of variables to test, based on thermodynamic principles.

II. WAVE Case Studies & Constant Table

The original WAVE model constants can be seen in *figure 6*. The Unassigned variables are highlighted with an (!) inside a yellow triangle. These can be removed from the constants table.

One variable will be changed at a time through 5 increments, for each engine speed. *Figure 7* shows an example of the sweep function that will be used for this.

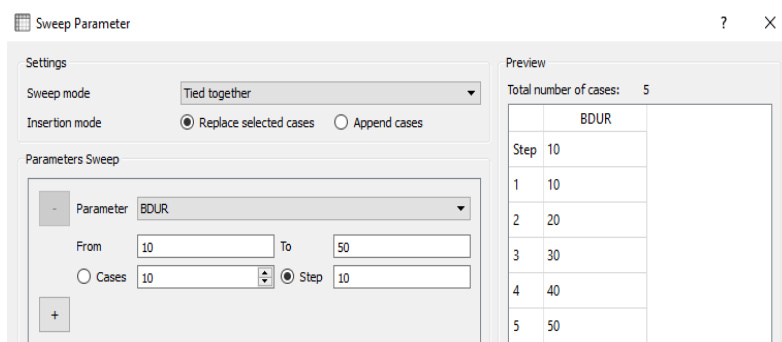


Figure 7 - Sweep Function in WAVE

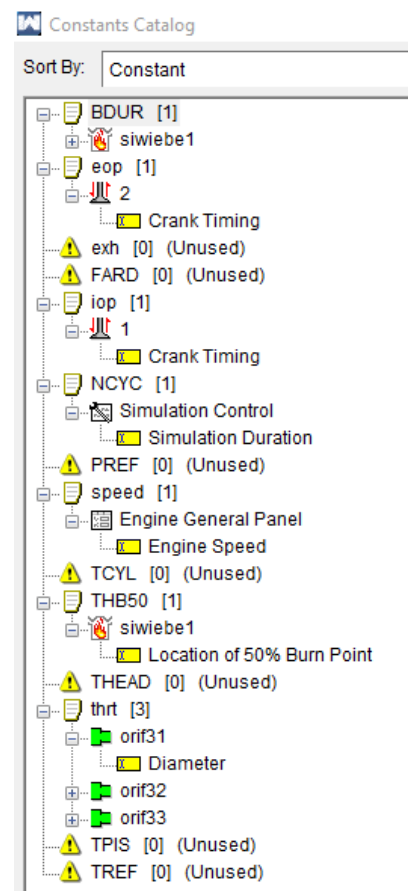


Figure 6 - Original Wave Constants Tree

III. Ricardo WAVE Post Processing

The following table outlines primary WAVE outputs for all iterations.

Table 2 - Engine Outputs for Post Processing

Iteration Type	WAVE Output
Base Model	Pressure, Volume
Modified Model	Pressure

The Post Processing tool is used to export the combined results from each iteration as an “.xls” file. The primary outputs are selected to plot against crank angle in steps of 1 degree to match the real data.

A “roll back” feature will be incorporated by saving the model at various stages through the modification process.

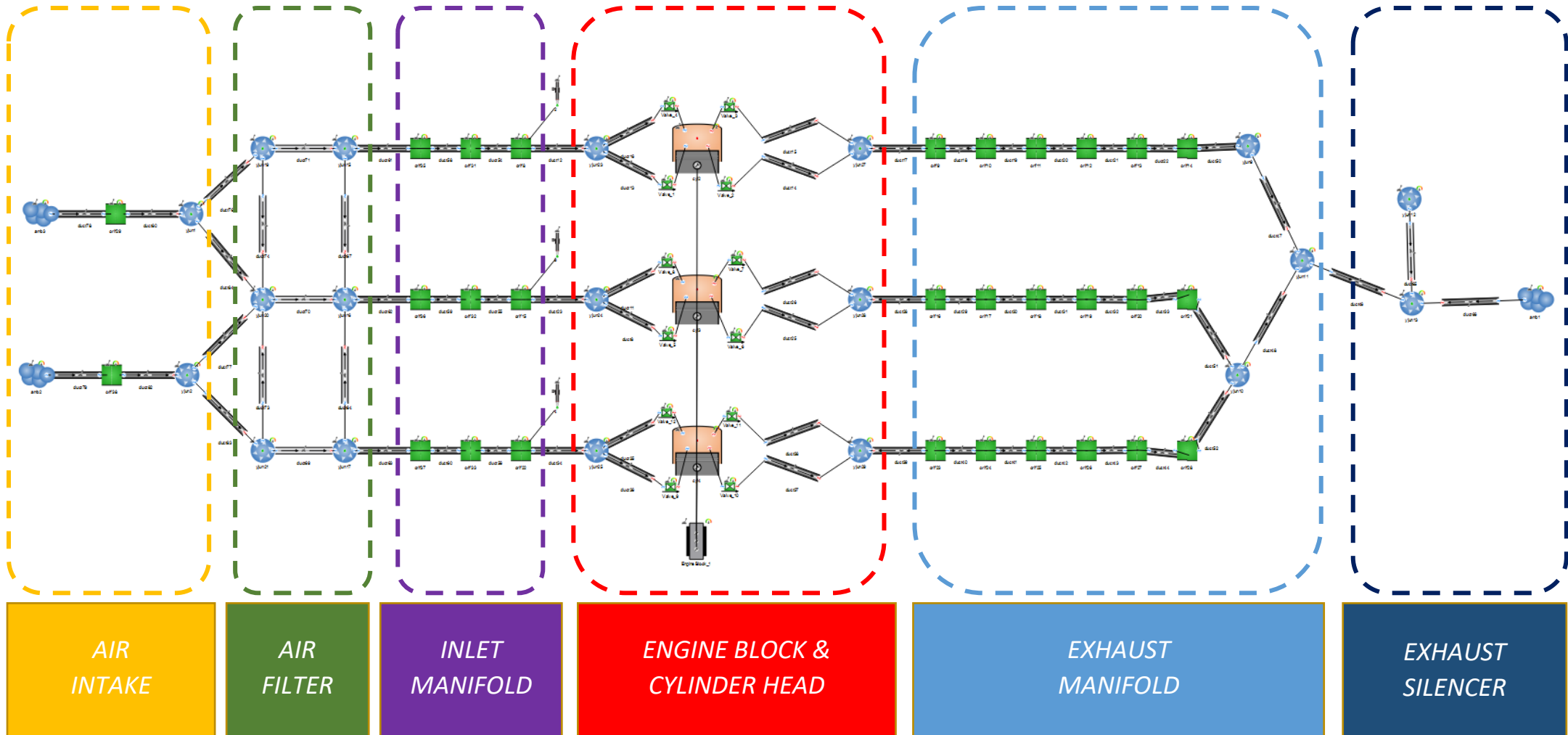
IV. MATLAB Data Processing

A MATLAB script will be used to import and process the results.

- The first section of the script will include an image pop-up function for the WAVE constants table and any variables changed.
- The next section will index the relevant data from the Excel file and arrange them as MATLAB variables. This includes shifting all of the results to match the crank angle alignment of the real data.
- Finally, the corresponding real data variables are loaded into the script and a range of over 12 plots are created for comparing between each cylinder in WAVE (including average) and the real data. The primary comparison method is to plot the percentage difference of peak pressure and also the area of the pressure curves, between the real and WAVE data. A log PV diagram will then be used to further examine the trends.

A new script is created for each simulation so all previous settings can be accessed.

4. Triumph 675 Model Tree



5. Baseline Model

The model was run with the settings from the engine specification sheet and information extracted from the real cylinder pressure data. These settings are detailed below and form the initial baseline model.

The first step in the validation process is to compare the WAVE calculated cylinder volume with the real data.

Table 3 - Connecting Rod Change

Variable Name	Adjustment
Connecting Rod Length	From 98mm to 106.4mm

I. Volume Correlation

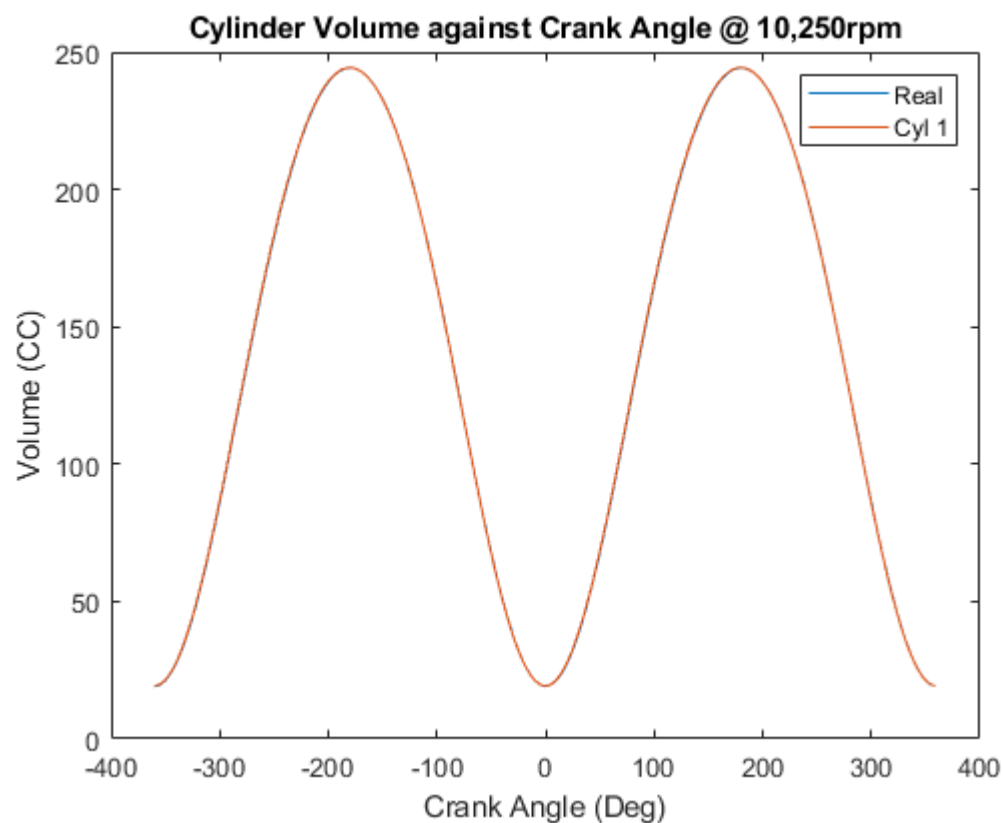


Figure 8 - Volume Comparison between Real Data and WAVE (Base Model)

Figure 8 shows an acceptable volume correlation.

II. Changes due to Triumph Engine Specifications

Table 4 - Base Model Variables (Engine Spec Sheet)

Variable Name	Adjustment
Ambient Air Pressure	From 1.06bar to 1.01bar (sea level)
Compression Ratio	From 12.65 to 12.7
Inlet Valve Diameter	From 28mm to 31mm (plus port adjustment)

III. Burn Duration from Real Data

The “PCHIP” interpolation method was used in MATLAB to find the crank angle relative to 10%, 50% and 90% burned, from the real cylinder data. WAVE uses these values to characterise the burn profile. (Heywood, 2002) states 10% is a reasonable estimate for ignition delay. However, alternative values such as 1 and 5 percent have been used. The end of flame propagation is estimated to occur at approximately 90% (Bonatesta, Waters and Shayler, 2010). These values are included in the WAVE model as seen in *table 5*.

Table 5 - Burn Duration (Real Data) Table

Engine Speed	Crank Angle			
	10% Burned	50% Burned	90% Burned	Burn Duration
10,250 rpm	-4.2936°	9.2444°	21.8027°	26.0963°
13,000 rpm	-4.0006°	10.5204°	24.2067°	28.2037°
14,400 rpm	-7.5234°	7.2309°	21.2181°	28.7415°

WAVE considers the total burn duration to be the difference in crank angle from 10 to 90 percent, where the bulk of the mass has burned. The real data shows an increase in burn duration with engine speed as expected.

(Eriksson and Andersson, 2002) suggests A 50% burn point of around 8° crank angle tends to give the best efficiency and lowest exhaust temperatures in an Otto cycle.

IV. Cylinder Pressure against Volume

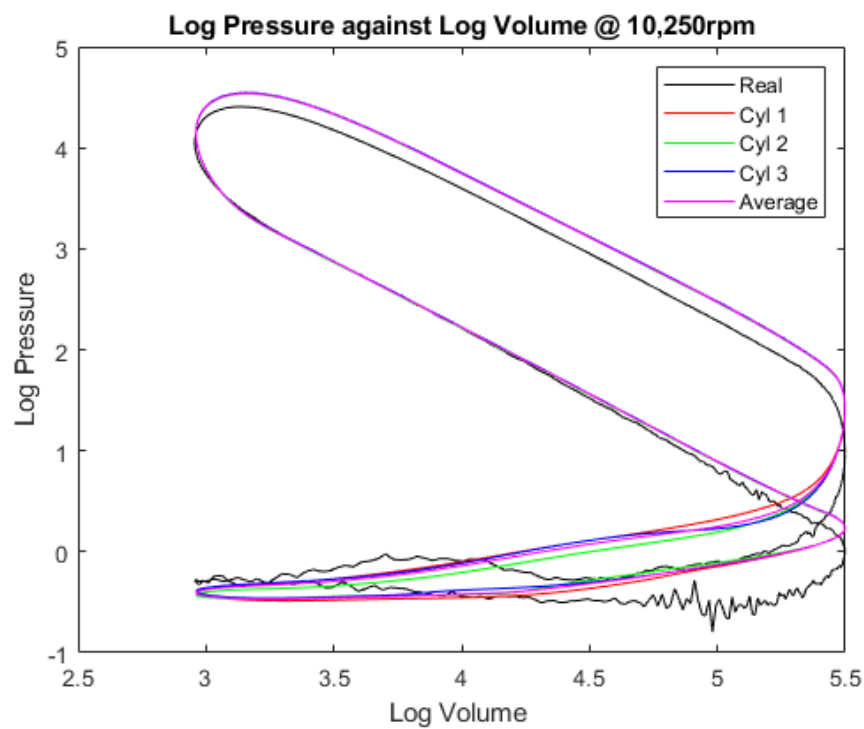


Figure 9 - Log PV Diagram for Base Model @ 10,250rpm

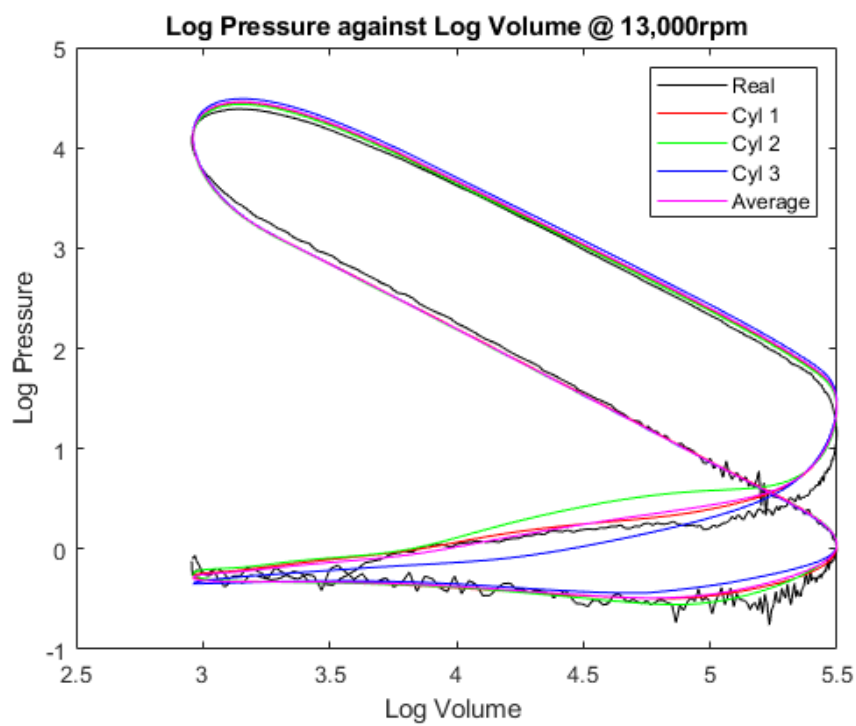


Figure 10 - Log PV Diagram for Base Model @ 13,000rpm

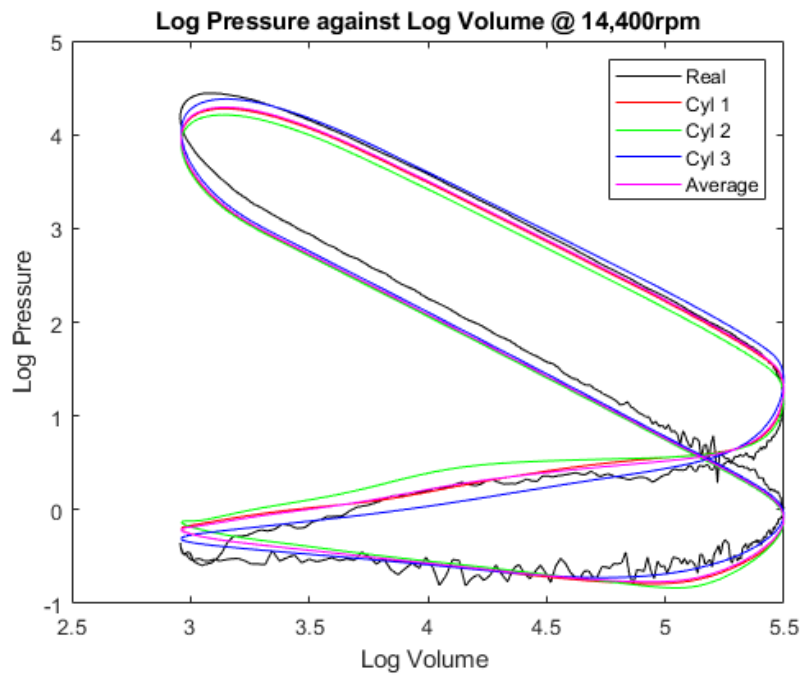


Figure 11 - Log PV Diagram for Base Model @ 14,400rpm

- The plots suggest there is a variation of peak pressure across each cylinder in the WAVE model, increasing past 10,250rpm.
- Compression and expansion trends are different to the real data for each engine speed.
- The pumping loop increases in line with the real data through each engine speed. However, at 10,250rpm the pressure through intake and exhaust is predicting too high.

The average cylinder pressures will be compared from this point due to the cross cylinder variation in the model.

6. Investigation of Changing Variables in Ricardo WAVE

This section will detail the effects of changing fundamental engine parameters in areas such as combustion, geometry and heat transfer. The baseline model will be interrogated by changing one variable at a time, through a sweep of values relative to the real data, as explained in *Section 3*.

I. Wiebe Sub Model Study

a) Burn Duration @13,000rpm

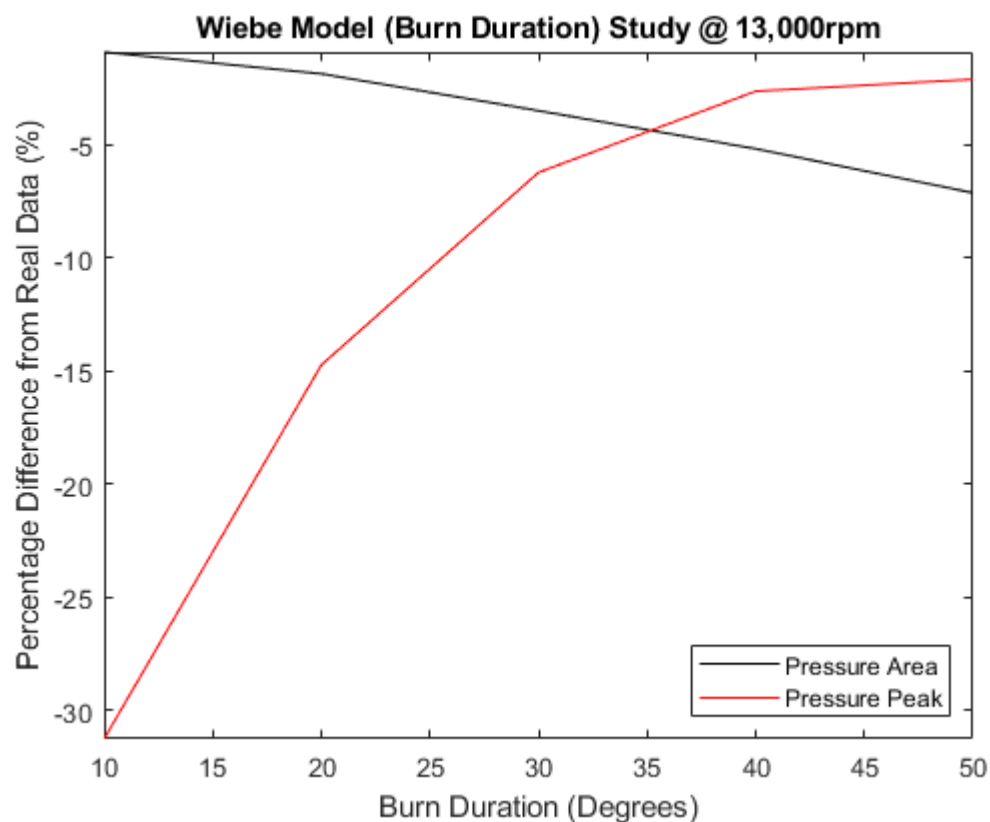


Figure 12 - Wiebe Model (Burn Duration) Peak Pressure & Pressure Area Comparison

Relationships shown in figure 12 are linked to figure 13.

- Peak Pressure decreases as burn duration increases.
- Intersection occurs at around 35 degrees burn duration (within 5% of real pressure data).

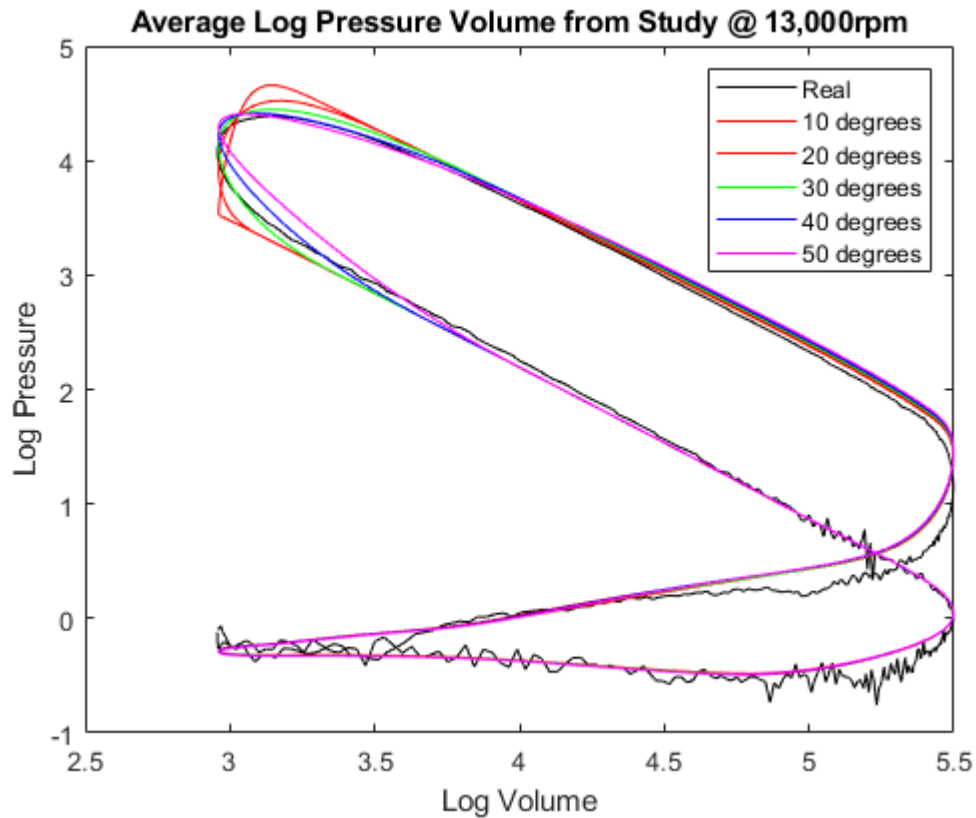


Figure 13 - Wiebe Model (Burn Duration) Peak Pressure & Pressure Log PV plot

- The ideal Otto cycle assumes an isochoric process through combustion. The plot at 10° implies that WAVE is modelling the burn duration consistent with first principles (Eriksson and Andersson, 2002).
- The overall trend is sensible through the sweep.
- Curves between 30 and 40 degrees are consistent with *figure 12*.

The burn duration for the base model is proven to be a reasonable prediction at 13,000rpm.

b) 50% Burned Location @ 10,250rpm

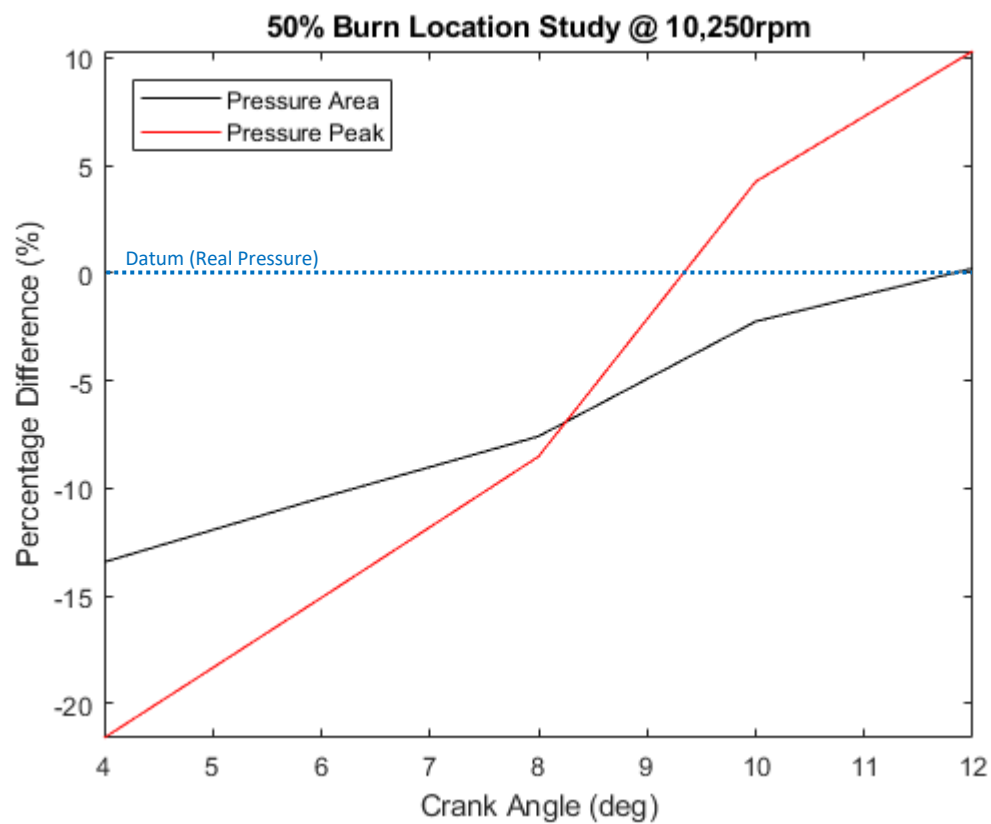


Figure 14 - Wiebe Model (50% Burned) Peak Pressure & Pressure Area Comparison

Relationships shown in figure 14 are linked to figure 15.

WAVE predicts the highest accuracy for the 50% point to fall around 9° ATDC. This is a good correlation to the interpolated method from the real data that was used to find the 50% burn location of 9.2 ° @ 10,250rpm.

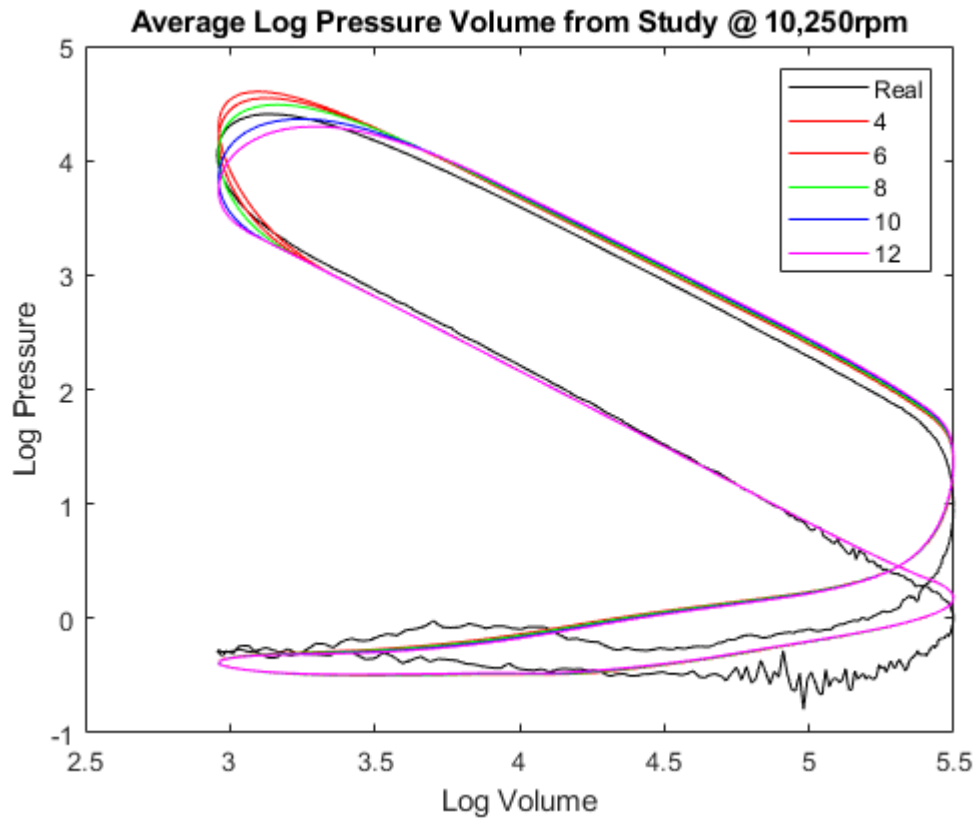


Figure 15 - Wiebe Model (50% Burned) Log PV Plot

WAVE drives the selected burn duration through the specified 50% burn point as shown in *figure 15*. This alters the shape of the combustion profile, moving peak pressure and the rate of rise and fall. Moving the 50% marker closer to TDC increases peak pressure as the baseline settings are selected for this sweep.

c) Exponent in Wiebe Function @13,000rpm

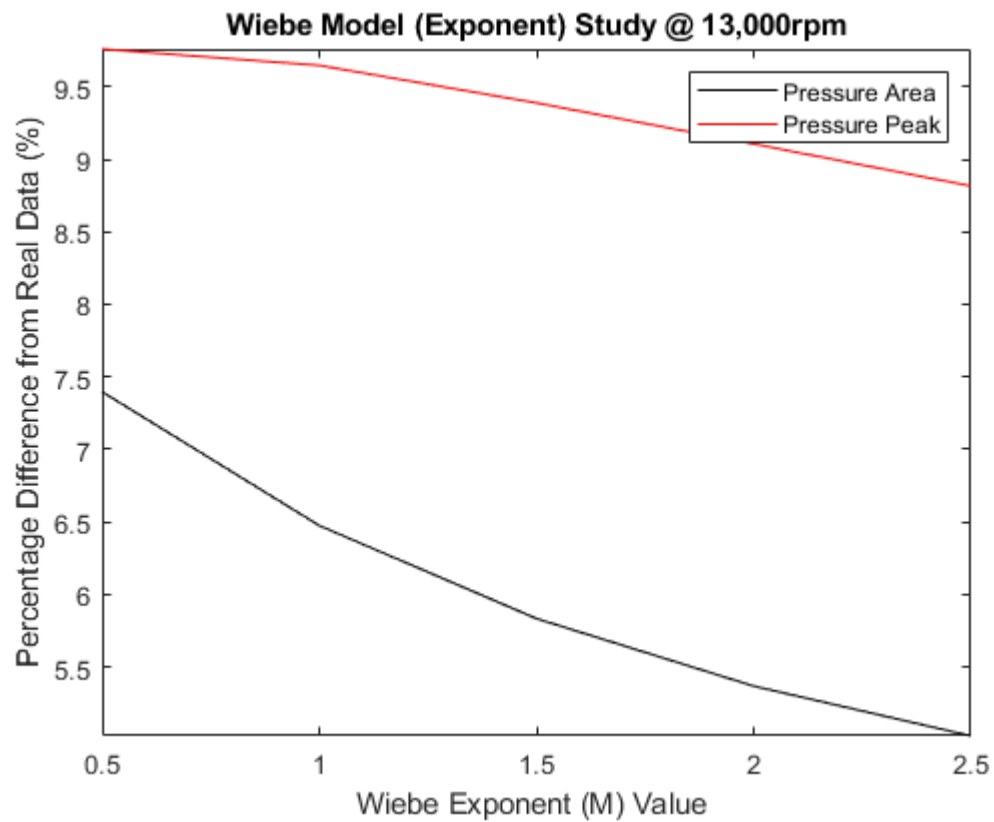


Figure 16 - Wiebe Model (Exponent) Peak Pressure & Pressure Area Comparison

Relationships shown in figure 16 are linked to figure 17.

- Highest accuracy when “m” is at 2.5 (with base settings applied through the sweep).

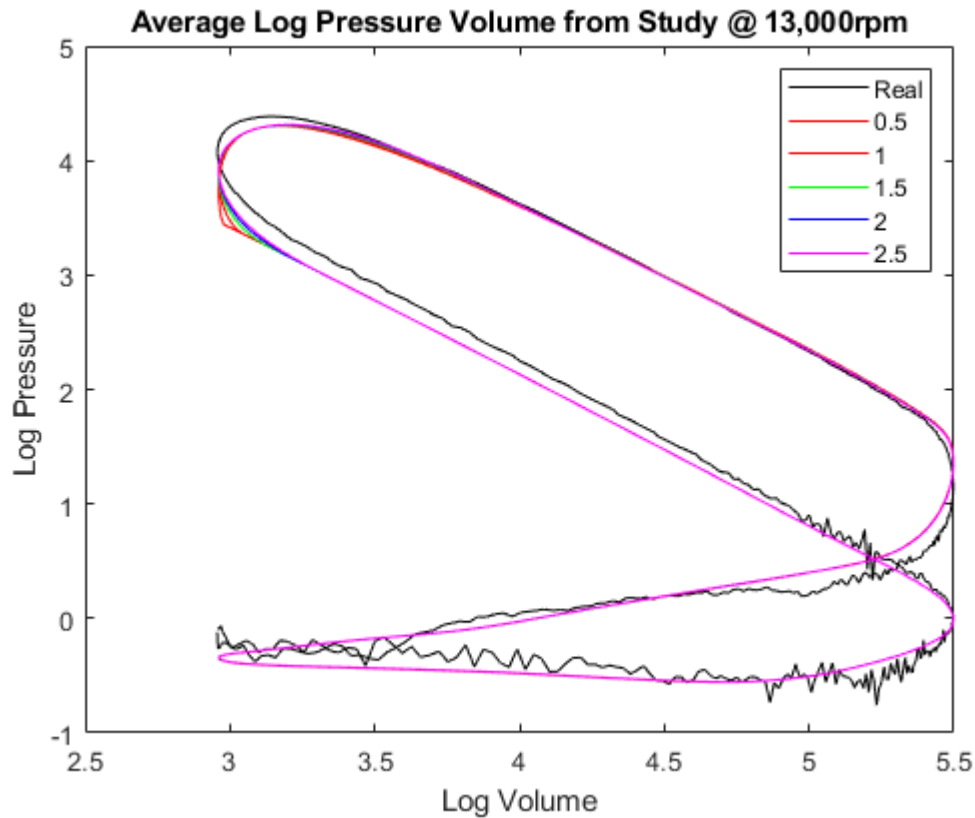


Figure 17 - Wiebe Model (Exponent) Log PV Plot

- Exponent “ m ” is referred to as a form factor and controls the shape of the Wiebe curve. Changing this coefficient influences the shape through start of combustion.
- Figure 17 proves that the typical “ m ” value of 2 preserves the trend produced from the real data. A smaller “ m ” value is shown to delay the pressure rise in WAVE.

This study demonstrates how WAVE uses the Wiebe function to predict combustion characteristics. The isolated conditions prove sensible estimations are being made for each parameter. WAVE provides the user with an option to change the exponent “ m ” but not “ a ”. (Heywood, 2002) mentions that both “ a ” and “ m ” are adjustable to change the shape of the Wiebe function. Conversely, (Cooney *et al.*, 2008) determines “ a ” as a fully dependant variable. This would mean that WAVE automatically changes the “ a ” coefficient based on the user specified crank angles for start and end of combustion.

II. Heat Transfer Study @ 10,250rpm - Original Woschni Model (Intake Valves Closed)

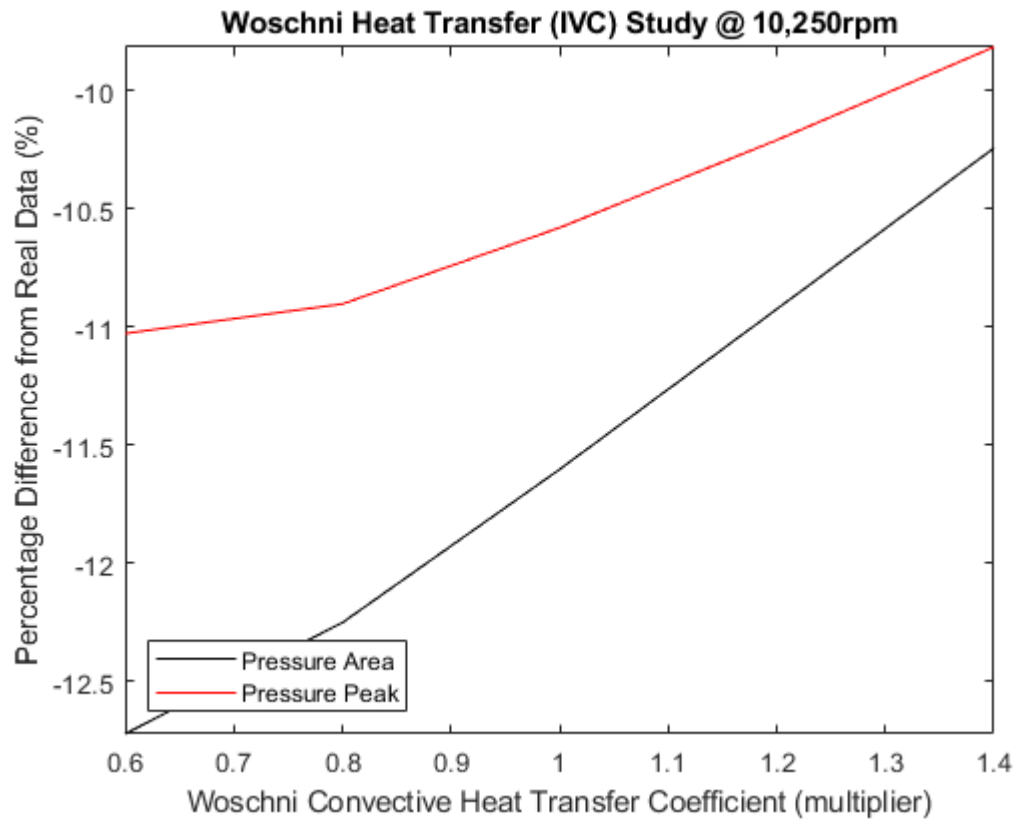


Figure 18 - Woschni Model (Coefficient) Peak Pressure & Pressure Area Comparison

Relationships shown in figure 18 are linked to figure 19.

- Increasing the Convective Heat Transfer Coefficient within the Woschni Original Model improves the accuracy of the predicted pressure curve whilst not reaching a close correlation to the real data. This implies there are thermal inaccuracies in the Triumph WAVE model.

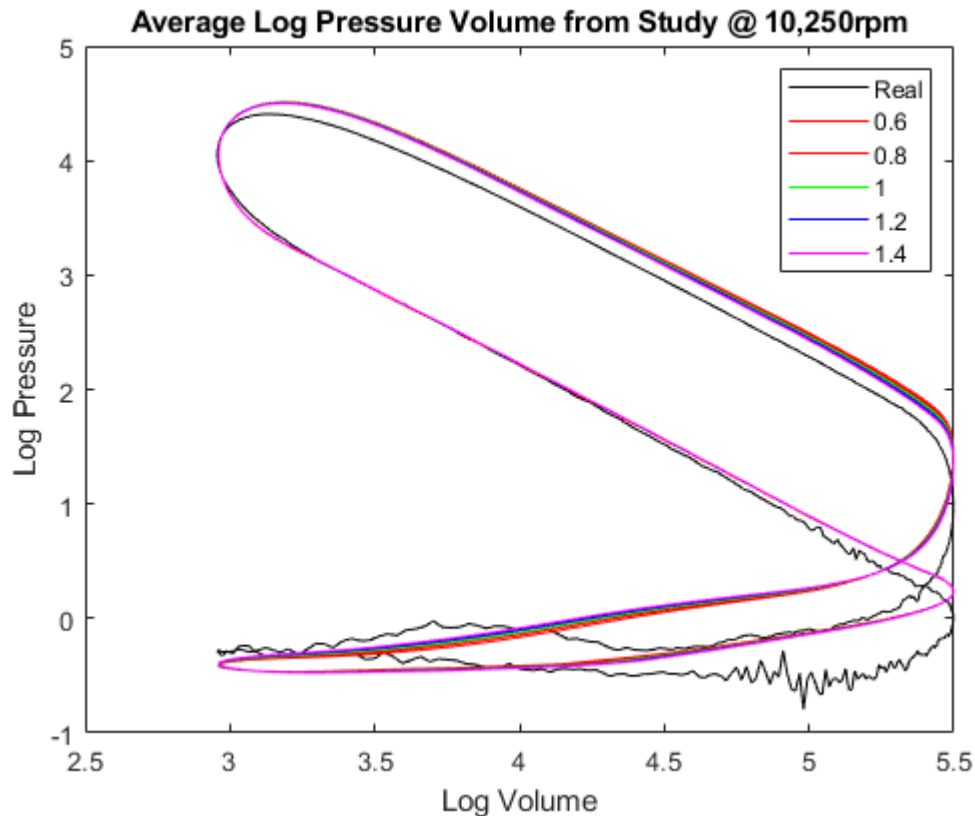


Figure 19 - Woschni Model (Coefficient) Log PV Plot

- The pumping loop area is increased with this multiplier whilst giving a reduction in pressure through the expansion cycle.

The Woschni model accounts for the increase in gas velocity through combustion and is active whilst inlet valves are closed (Guo, Qin and Schmitz, 2010). A negligible effect can be seen through compression. This is due to the lower difference in temperatures between the charge, piston and cylinder walls through this phase.

The increase in heat energy through expansion results in a higher rate of heat transfer to the surroundings through convection. This function sweep was isolated by maintaining the base settings for referenced temperatures in the engine, inlet and exhaust. However, these variables are likely to play a part in how this heat transfer model is driven and the magnitude of change it can produce (Shayler, May and Ma, 1993).

There are several other heat transfer models in WAVE to account for diesel, a simplified Annand model and variations of the Woschni model. The original model was selected based on the information available for the engine.

III. Valve Timing Study @ 10,250rpm

This section investigates the effect of offsetting the valve timing from original values by an equal amount of both advance and retard for inlet and exhaust. **TABLE** provides the information for each case in the sweep.

Case Number	1	2	3	4	5
Inlet Opens (ATDC)	270°	260°	250°	240°	230°
Exhaust opens (ATDC)	65°	75°	85°	95°	105°

Base Settings

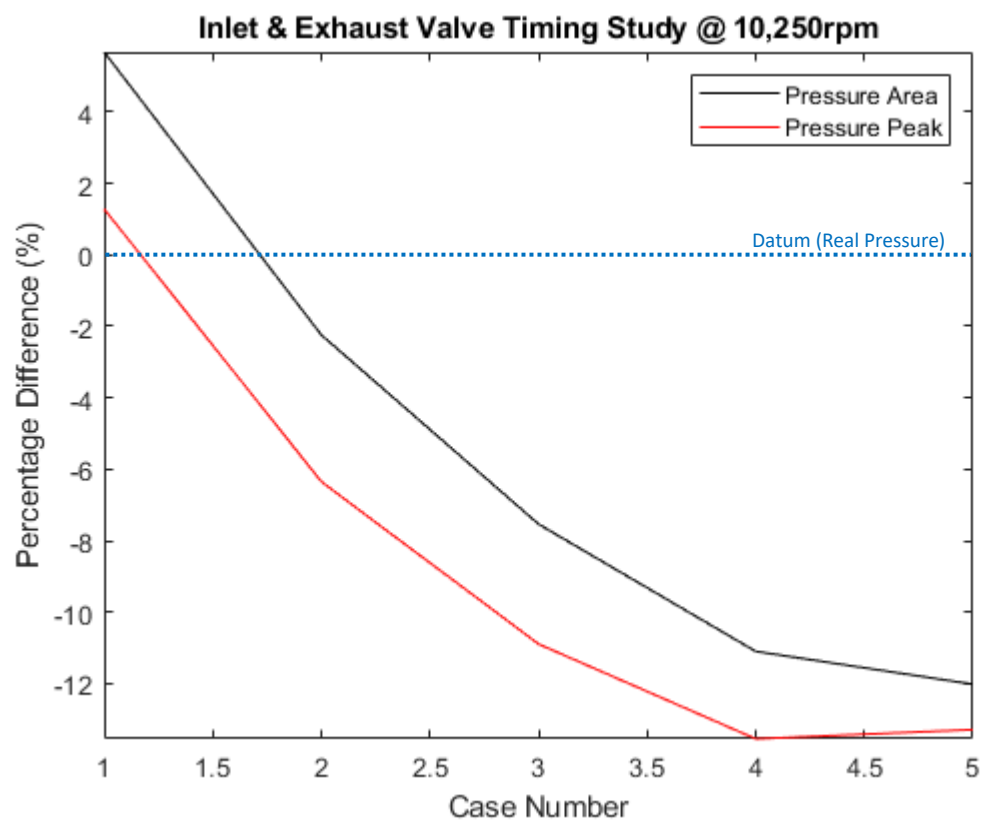


Figure 20 - Valve Timing Study (Opening Points) Peak Pressure & Pressure Area Comparison

Relationships shown in figure 20 are linked to figure 21.

Figure 20 indicates the valve timing in the WAVE model is inconsistent with the real pressure data.

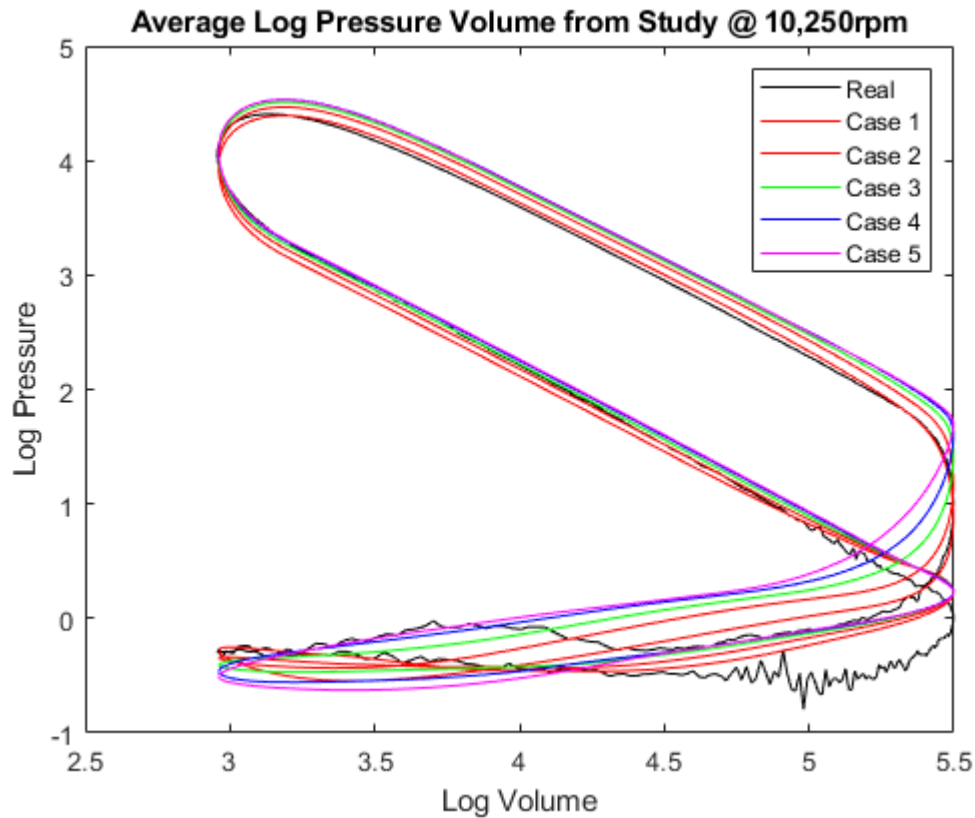


Figure 21 - Valve Timing Study (Opening Points) Log PV Plot

- Case 1 and 2 provide the best match through expansion and initial period after exhaust valves open at 10,250rpm.
- This parameter has a significant effect on pressure through the whole cycle which is in line with the sensitivity to valve timing in real engines as discussed by (Mechadyne, 2006) and (Shiga *et al.*, 1996).

Although the pumping loop is altered by valve timing, the induction pressure is not closely matched to that of the real data. (Silvestri, Morel and Costello, 1994) implies further errors could exist within the model such as inlet geometries and conditions. The valve timing should be further studied with respect to the actual opening times for the engine, to assess the scavenging effects from the WAVE model.

IV. Fuel / Air Ratio Study @ 14,400rpm

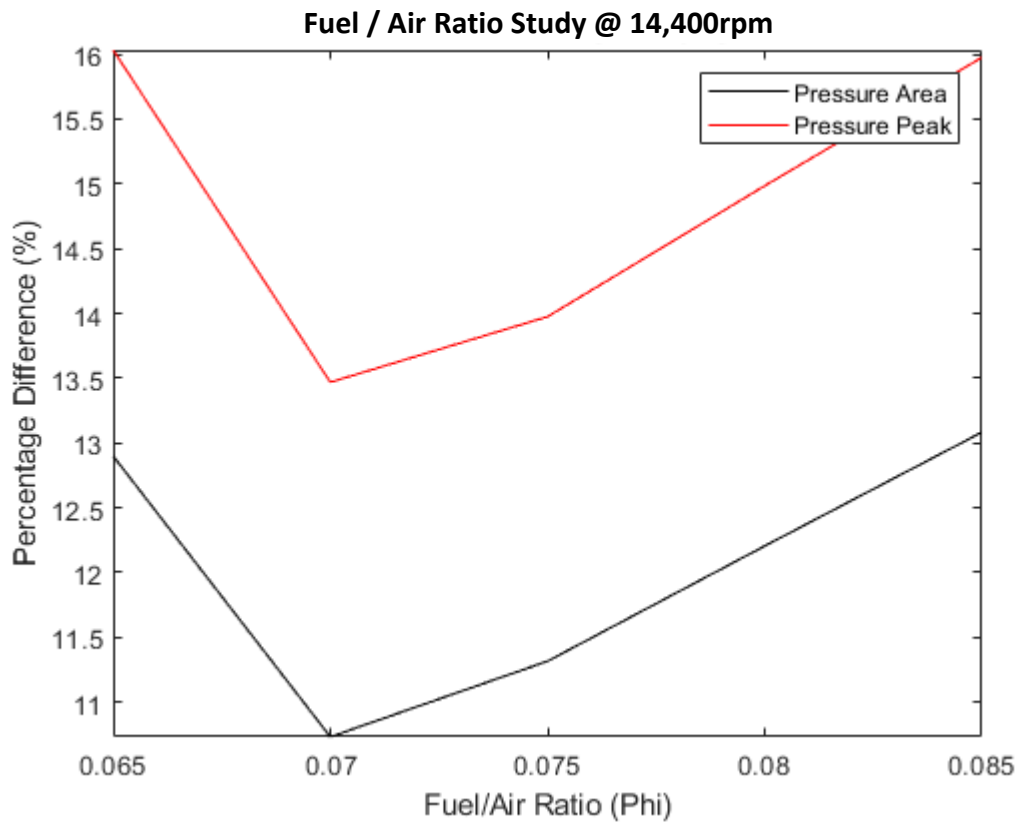


Figure 22 - Fuel/Air Ratio Study Peak Pressure & Pressure Area Comparison

Relationships shown in figure 22 are linked to figure 23.

- WAVE tracks a constant combustion Air/fuel ratio based on the assumption that the fuel and air are fully premixed and calculates the total injected mass per event by referencing the total airflow through the engine from the previous cycle (Ricardo, n.d.).
- The trend in figure 22 highlights the sensitivity of this parameter.

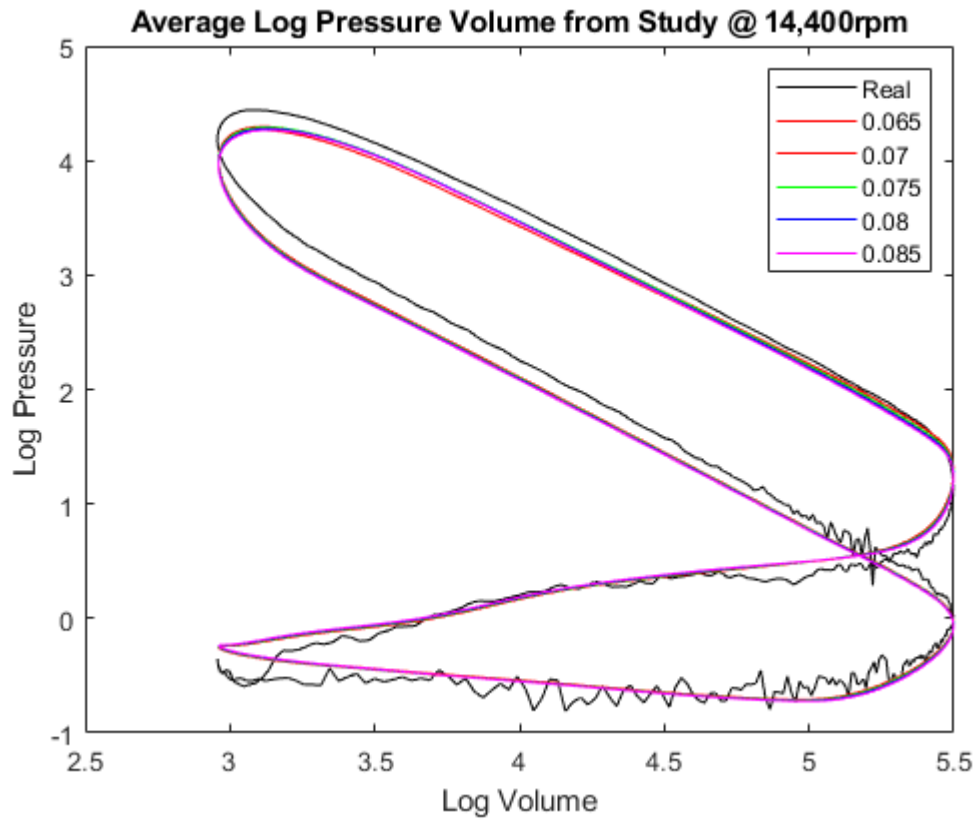


Figure 23 - Fuel/Air Ratio Study Log PV Plot

The fuel/air ratio is proven to make a small change through combustion and expansion in the model over the range that has been tested.

7. WAVE Model Correlation @ 10,250rpm

This section will demonstrate how using the information gathered through *section 6* can be used to further improve the correlation of the WAVE model against real data. The settings in *table 6* reflect those applied to *figure 24*.

Table 6 - Final Correlation Settings for 10,250rpm

Parameter	Base Setting	Correlation Setting	Percentage Difference
Burn Duration	26.0963	30.5	16.87 %
Exhaust Opening Point	85	72	15.29 %
Inlet opening Point	250	238	4.8 %
50% Burned Point	9.244	9.2	0.48 %
Woschni Coefficient (IVC)	0.8	2.4	199.99 %

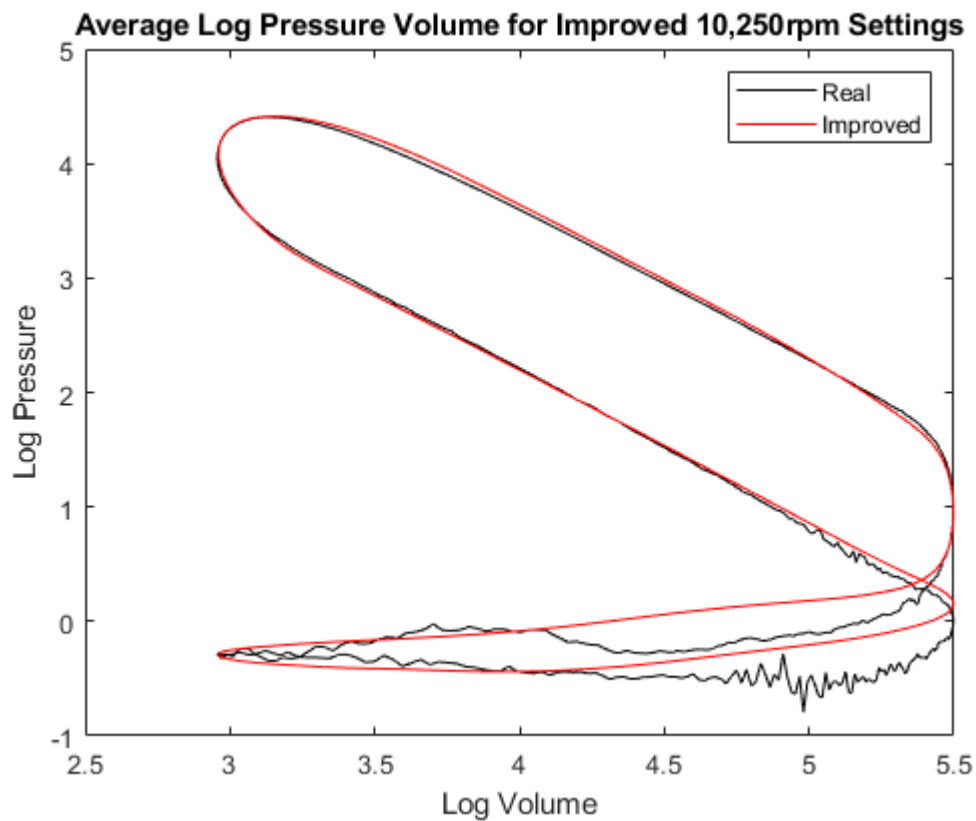


Figure 24 - Final Correlation Log PV Plot (10,250rpm)

The pumping loop has been neglected from the correlation process as none of the previous settings were found to alter the pressures experienced through the inlet and exhaust strokes by any significant amount. However, a small correction in pressure magnitude can be observed through the second half of the induction stroke as well as a more consistent trend through the transition from expansion to exhaust.

The provided WAVE model inlet and exhaust parameters/geometries cannot be verified against those of the real engine, meaning this should be considered as a possible further improvement.

Comparing the base model (*figure 9*) with the correlated model (*figure 24*) reveals significant improvements through compression, combustion and expansion phases from sensible changes to the settings.

The values found through interpolating the burn profile for the real engine are nearly 17% off the final correlation. This could be due to compensating for the pumping loop pressures or a combination of accumulating small faults through the model.

I. Power Comparison

As a final comparison, the power output was verified against a generic Triumph 675 dynamometer run. The results of the real engine (*page 19*) suggest a power of 93 BHP @ 10,250rpm. Ricardo WAVE calculates the power to be 68kW @ 10,250rpm, meaning just a 2% difference.

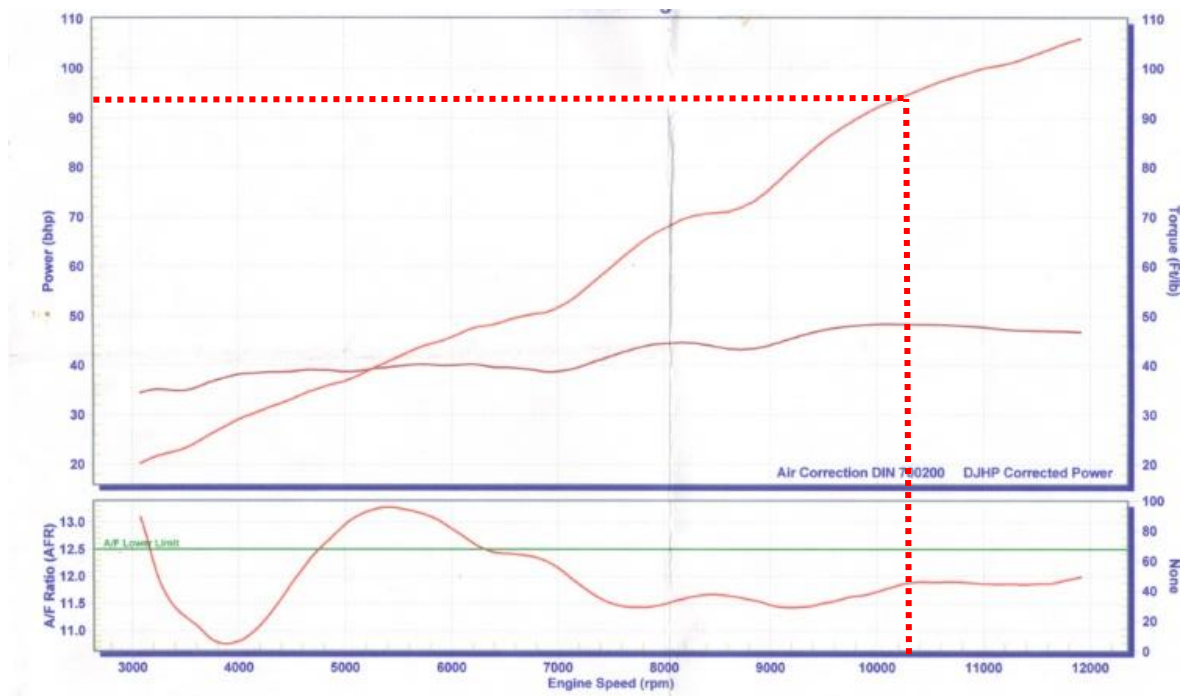


Figure 25 - Triumph Daytona 675 Dynamometer Graph

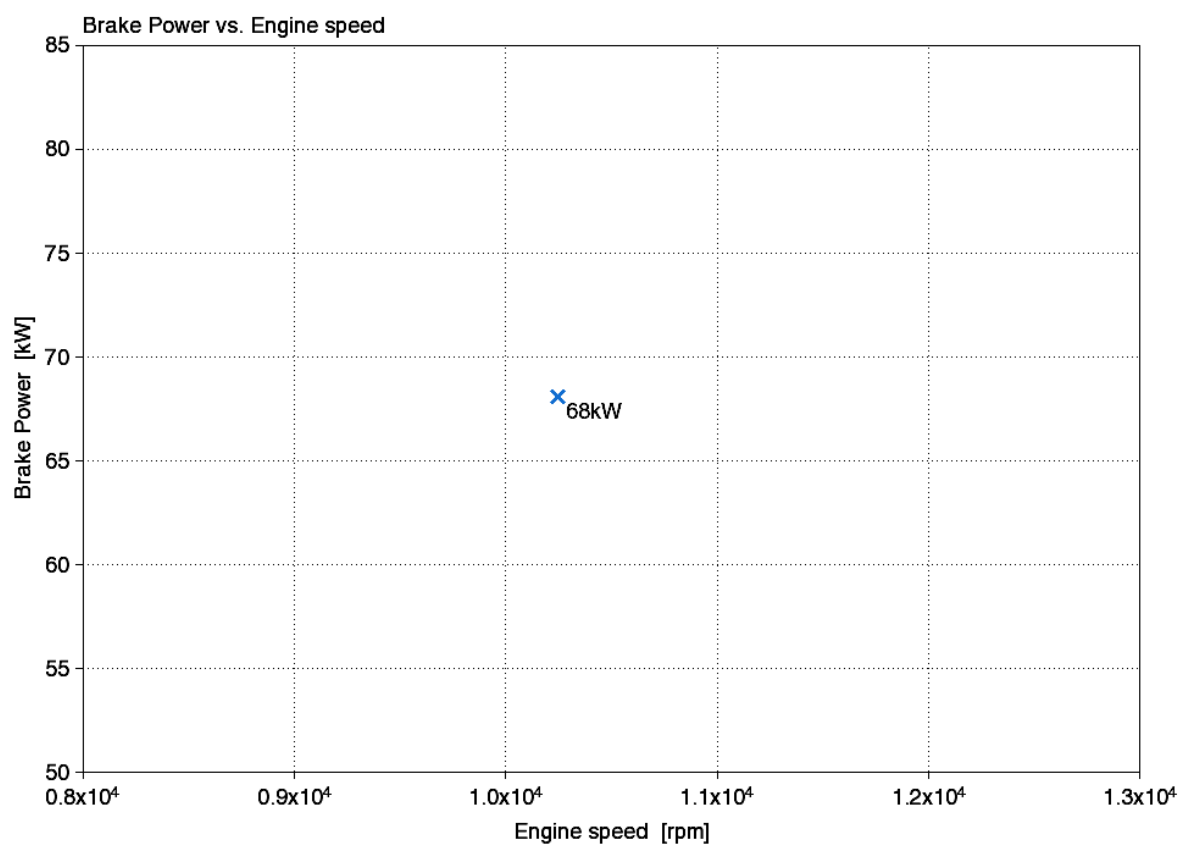


Figure 26 - Ricardo WAVE Power Output (10,250rpm)

8. Conclusion

Ricardo WAVE provides a suitable alternative to physical engine testing. It has been proven through this investigation that the calculations and assumptions being made can be accurate in isolated conditions, as the background equations include real thermodynamic principles. However, there are several areas within the program where multipliers are used and this can cause some issues with reflecting the reality of the changes being made when compared to those with quantifiable measuring units.

In addition, there is no certainty to the accuracy of the geometries and boundary conditions being applied to the WAVE model outside of the combustion chamber. This investigation has focused on the known engine specifications (*provided in the data sheet*) and has not explored extensively through the remaining aspects of the model.

As mentioned in *section 6*, a more in depth study should be carried out to the effects on changing inlet and exhaust variables and these should be validated through physical measurements of the real engine. The provided cylinder data has limited information to drive the model accurately, with no known engine loads, temperatures or fuel / air metering being logged. This additional information is instrumental in accurately correlating the WAVE model through an engine cycle.

Finally, all of the mentioned considerations should be included when choosing variables to correct errors in Ricardo WAVE. The final WAVE model should be compared against the real engine through multiple outputs, not just cylinder pressure.

9. Appendix

Example of MATLAB Data Processing Script

```
%% BASELINE RUN

% VARIED SETTINGS

% Burn Duration changed to match real data through interpolation
% for all rpm [26.0963 deg 10250, 28.2073 deg 13000, 28.7415 deg 14400]
% 50% burn [9.2444 deg 10250, 10.5204 deg 13000, 7.2309 deg 14400]

% ADDITIONAL VARIABLES

% N/A

imshow('Base_4.PNG'); % Pulls Image of Constants Table from Run

%% XLS READ RESULTS

% File in Results Folder
% Base_4 = xlsread('Base_4','A3:BY722'); %*****CHANGE*****

%% RESULTS PROCESSING

% load RealData
load Base_4 %*****CHANGE*****

load realcompare

% 1st = case 2nd = cylinder

% PRESSURE
b4p1(:,1) = Base_4(:,2); %*****CHANGE then [Shift+Ent]*****
b4p1(:,2) = Base_4(:,4);
b4p1(:,3) = Base_4(:,6);
b4p1(:,1) = circshift(b4p1(:,1)), [180,0]);
b4p1(:,2) = circshift(b4p1(:,2)), [-60,0]);
b4p1(:,3) = circshift(b4p1(:,3)), [-300,0]);
b4p1(:,4) = mean(b4p1,2);

b4p2(:,1) = Base_4(:,31); %*****CHANGE then [Shift+Ent]*****
b4p2(:,2) = Base_4(:,33);
b4p2(:,3) = Base_4(:,35);
b4p2(:,1) = circshift(b4p2(:,1)), [180,0]);
b4p2(:,2) = circshift(b4p2(:,2)), [-60,0]);
b4p2(:,3) = circshift(b4p2(:,3)), [-300,0]);
b4p2(:,4) = mean(b4p2,2);

b4p3(:,1) = Base_4(:,60); %*****CHANGE then [Shift+Ent]*****
b4p3(:,2) = Base_4(:,62);
b4p3(:,3) = Base_4(:,64);
b4p3(:,1) = circshift(b4p3(:,1)), [180,0]);
b4p3(:,2) = circshift(b4p3(:,2)), [-60,0]);
```

```

b4p3(:,3) = circshift((b4p3(:,3)), [-300,0]);
b4p3(:,4) = mean(b4p3,2);

```

```
%% GRAPHS
```

```
***CHECK VARIABLES ARE CORRECT***
```

```
% PRESSURE
```

```

figure(1)
% COMPARE PRESSURES 10,250
plot(CA,realp(1,:), 'color','k') %REAL PRESSURE DATA
hold on
plot(CA,b4p1(:,1), 'color','r') %CYLINDER 1
plot(CA,b4p1(:,2), 'color','g') %CYLINDER 2
plot(CA,b4p1(:,3), 'color','b') %CYLINDER 3
plot(CA,b4p1(:,4), 'color','m') %AVERAGE
hold off
title ('Cylinder Pressure against Crank Angle @ 10250rpm')
xlabel ('Crank Angle (Deg)')
ylabel ('Pressure (Bar)')
legend ('Real','Cyl 1','Cyl 2','Cyl 3','Average')
axis tight

```

```

figure(2)
% COMPARE PRESSURES 13,000
plot(CA,realp(1,:), 'color','k') %REAL PRESSURE DATA
hold on
plot(CA,b4p2(:,1), 'color','r') %CYLINDER 1
plot(CA,b4p2(:,2), 'color','g') %CYLINDER 2
plot(CA,b4p2(:,3), 'color','b') %CYLINDER 3
plot(CA,b4p2(:,4), 'color','m') %AVERAGE
hold off
title ('Cylinder Pressure against Crank Angle @ 13,000rpm')
xlabel ('Crank Angle (Deg)')
ylabel ('Pressure (Bar)')
legend ('Real','Cyl 1','Cyl 2','Cyl 3','Average')
axis tight

```

```

figure(3)
% COMPARE PRESSURES 14,400
plot(CA,realp(1,:), 'color','k') %REAL PRESSURE DATA
hold on
plot(CA,b4p3(:,1), 'color','r') %CYLINDER 1
plot(CA,b4p3(:,2), 'color','g') %CYLINDER 2
plot(CA,b4p3(:,3), 'color','b') %CYLINDER 3
plot(CA,b4p3(:,4), 'color','m') %AVERAGE
hold off
title ('Cylinder Pressure against Crank Angle @ 14,400rpm')
xlabel ('Crank Angle (Deg)')
ylabel ('Pressure (Bar)')
legend ('Real','Cyl 1','Cyl 2','Cyl 3','Average')
axis tight

```

```
%% PV
```

```

figure(5)
% COMPARE PV 10,250
plot(realv(1,:),realp(1,:), 'color','k') %REAL PRESSURE DATA
hold on
plot(bv1(:,1),b4p1(:,1), 'color','r') %CYLINDER 1

```

```

plot(bv1(:,1),b4p1(:,2),'color','g') %CYLINDER 2
plot(bv1(:,1),b4p1(:,3),'color','b') %CYLINDER 3
plot(bv1(:,1),b4p1(:,4),'color','m') %AVERAGE
hold off
title ('Cylinder Pressure against Crank Angle @ 10,250rpm')
xlabel ('Crank Angle (Deg)')
ylabel ('Pressure (Bar)')
legend ('Real','Cyl 1','Cyl 2','Cyl 3','Average')

figure(6)
% COMPARE PV 13,000
plot(realv(1,:),realp(1:),'color','k') %REAL PRESSURE DATA
hold on
plot(bv1(:,1),b4p2(:,1),'color','r') %CYLINDER 1
plot(bv1(:,1),b4p2(:,2),'color','g') %CYLINDER 2
plot(bv1(:,1),b4p2(:,3),'color','b') %CYLINDER 3
plot(bv1(:,1),b4p2(:,4),'color','m') %AVERAGE
hold off
title ('Cylinder Pressure against Crank Angle @ 13,000rpm')
xlabel ('Crank Angle (Deg)')
ylabel ('Pressure (Bar)')
legend ('Real','Cyl 1','Cyl 2','Cyl 3','Average')

figure(7)
% COMPARE PV 14,400
plot(realv(1,:),realp(3:),'color','k') %REAL PRESSURE DATA
hold on
plot(bv1(:,1),b4p3(:,1),'color','r') %CYLINDER 1
plot(bv1(:,1),b4p3(:,2),'color','g') %CYLINDER 2
plot(bv1(:,1),b4p3(:,3),'color','b') %CYLINDER 3
plot(bv1(:,1),b4p3(:,4),'color','m') %AVERAGE
hold off
title ('Cylinder Pressure against Crank Angle @ 14,400rpm')
xlabel ('Crank Angle (Deg)')
ylabel ('Pressure (Bar)')
legend ('Real','Cyl 1','Cyl 2','Cyl 3','Average')

%% LOG PV

% COMPARE LOG PV 10,250
figure(8)
plot(log(realv(1:)),log(realp(1:)), 'k') %REAL PRESSURE DATA
hold on
plot(log(bv1(:,1)),log(b4p1(:,1)), 'r') %CYLINDER 1
plot(log(bv1(:,1)),log(b4p1(:,2)), 'g') %CYLINDER 2
plot(log(bv1(:,1)),log(b4p1(:,3)), 'b') %CYLINDER 3
plot(log(bv1(:,1)),log(b4p1(:,4)), 'm') %AVERAGE

title ('Log Pressure against Log Volume @ 10,250rpm')
xlabel ('Log Volume ')
ylabel ('Log Pressure')
legend ('Real','Cyl 1','Cyl 2','Cyl 3','Average')
hold off
% COMPARE LOG PV 13,000
figure(9)
plot(log(realv(1:)),log(realp(2:)), 'k') %REAL PRESSURE DATA
hold on
plot(log(bv1(:,1)),log(b4p2(:,1)), 'r') %CYLINDER 1
plot(log(bv1(:,1)),log(b4p2(:,2)), 'g') %CYLINDER 2
plot(log(bv1(:,1)),log(b4p2(:,3)), 'b') %CYLINDER 3

```

```

plot(log(bv1(:,1)),log(b4p2(:,4)),'m') %AVERAGE

title ('Log Pressure against Log Volume @ 13,000rpm')
xlabel ('Log Volume ')
ylabel ('Log Pressure')
legend ('Real','Cyl 1','Cyl 2','Cyl 3','Average')
hold off
% COMPARE LOG PV 14,400
figure(10)
plot(log(realv(1,:)),log(realp(3,:)),'color','k') %REAL PRESSURE DATA
hold on
plot(log(bv1(:,1)),log(b4p3(:,1)),'r') %CYLINDER 1
plot(log(bv1(:,1)),log(b4p3(:,2)),'g') %CYLINDER 2
plot(log(bv1(:,1)),log(b4p3(:,3)),'b') %CYLINDER 3
plot(log(bv1(:,1)),log(b4p3(:,4)),'m') %AVERAGE

title ('Log Pressure against Log Volume @ 14,400rpm')
xlabel ('Log Volume ')
ylabel ('Log Pressure')
legend ('Real','Cyl 1','Cyl 2','Cyl 3','Average')
hold off

```

10. References

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