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School of Engineering
The Total Friction Created by an Engine
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MOUNT PLEASANT
SWANSEA

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Deduction

This report is dedicated to the memory of Raymond Bedford

Statement

This report is the result of my own investigations, except where otherwise stated. This report was under the supervision of Mr Malcolm McDonald, in the faculty of Motorsport engineering of the University of Wales Trinity Saint David of Higher Education.

Signature

Candidate

Certificate

This report has not previous been submitted for any degree and is not currently being submitted for any other degree.

Signature

Candidate

Acknowledgement

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Abstract

In recent years due to government regulations, the demand for the automotive industry to produce a small engine, high efficiency vehicle has increased. This is to help reduce emissions, a big part of the study and research in the field of internal combustion engines is the friction created by the engine. Without the correct lubrication and coatings, parts run against each other at high speed, creating friction which then leads to heat. This heat can wear the parts, leading to a loss in the engine efficiency and performance. Therefore any effort to minimize friction losses will have an immediate impact on engine efficiency and the vehicles fuel economy. This paper provides a detailed review of the friction created by an internal combustion engine, presents all major findings and discusses trials and errors.

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Introduction

Government regulations on the internal combustion engine have changed over the recent years, currently with the emissions produced by an engine constantly being criticised. Automotive companies are being forced to reduce the emissions as well as meeting customer's performance expectations. For this reason friction is a critical factor for the automotive industry as friction creates heat and heat can wear the parts, leading to a loss in efficiency and performance.

This paper investigates the theoretical friction created by the piston skirt, piston ring, exhaust valve train and inlet valve train. For this investigation the complete friction model was carried out on a Ford's 1.6 litre SGDI VP engine.

All the relative friction models were created through excel, allowing the models to be easily modified for different engines. The information and equations required to calculate the desired friction a component creates, will all be shown at the maximum engines RPM.

The paper will discuss how friction is created and what boundaries effect friction. Along with techniques to reduce friction through lubricating oils, coatings and crank offsets. During this investigation the three types of lubrication regimes including boundary, mixed and hydrodynamic will be covered through the Stribeck Curve.

Piston Friction

Introduction into piston friction

Over recent years, research has found that friction between the piston and cylinder accounts for around 20% of the losses in an engine.[1] This section of the paper investigates the piston skirt friction created by three different types of unleaded internal combustion engines. These include an old ford 1.6 litre naturally aspirated engine, a ford 1.6 litre turbo engine and finally the modern ford 1.0 litre eco boost engine. It also looks into the piston ring friction created by the ford 1.6 litre turbo engine.

The friction created by these engines were calculated using the excel program, through the IMEP method which is based on the concept of force balance. This method uses the forces on the piston such as combustion gas pressure, side thrust and inertial forces to determine the friction force between the piston and the cylinder.

Any effort to minimize friction losses will have an immediate impact on engine efficiency and vehicle fuel economy, therefore ways to reduce the friction through coatings, lubrications and even crank offsets will be discussed. The process involved to produce the friction models will be explained in a step by step process along with all the information and calculations needed, all the results and findings during the investigation will be discussed and evaluated.

How Piston Friction is created

The pistons gudgeon pin is offset slightly (around 0.5mm) this offset forces the piston to the left hand side, this side is known as the thrust side and the opposite side is known as the anti-thrust side. This is purposely implemented by engineers. This is so they are aware of what the piston is doing within the engine at all times. [7,8]

As the piston goes up the offset forces it into the thrust side, this forces the piston rings and skirt on the one side into the cylinder wall creating the friction force. As the piston is forced into the wall of the cylinder there is an opposing force acting on it this is shown as F_{side} in figure 1. As the combustion pressures push the piston back down it will again be forced to the left hand side and the same friction force will be created.

Forcing the piston to the one side also helps to reduce engine noise, this is due to the fact the offset fixes the piston to the one side stopping it from being able to move freely. Without the offset the piston would be able to move freely in the cylinder constantly moving side to side. This would increase the engines noise, result in wasted fuel and causes severe engine damage. [7]

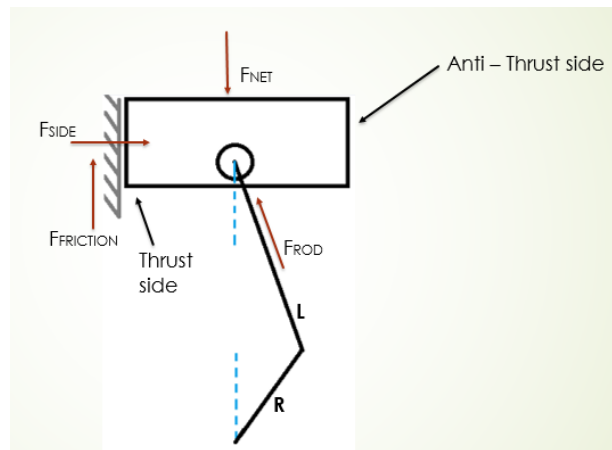


Figure 1

Ways to reduce piston friction

There are many things that affect friction such as surface finish, temperature, operational load, relative speed, lubricant characteristics and even the nature of the relative motion between the surfaces. Over many years, engine designers and suppliers have been tackling piston friction through many various methods. [11]

Some of the ways engineers have been decreasing friction is through reducing the size of the piston skirt and by coating it with ceramic or polymer. The coatings allow the piston to slide easier up and down the bore. Coatings used by Mahle and other piston suppliers include graphite, carbon fiber and molybdenum disulfide.

The piston skirt can also be machined with small grooves which holds and transports oil to the cylinder walls providing extra lubrication. The combination of piston skirt grooves and coatings aid the lubrication and prevents scuffs from occurring on the cylinder wall. Helping to reduce friction. [11, 13]

Designers have also been pushing the boundaries of piston rings, especially the shape of the outside face which makes contact with the cylinder wall. Low friction piston rings are typically thinner and have less tension pushing them out onto the cylinder wall. Mahle's latest piston rings exert about 50 percent less pressure against the cylinder bore, than rings from just a few years ago. Smoother, coated cylinder bore surfaces are also reducing piston friction.

Another way to reduce friction is through crankshaft offset, this has a great effect on engine friction and just offsetting the crank by a few degrees reduces the friction created by the piston. It also has the potential to increase thermodynamic efficiency.

The friction created by an engine's piston can also be influenced by the length of the connecting rod. The geometric relationship of the connecting rod length to the stroke of the crankshaft impacts its ability to move and also increase or decrease friction through changes in angularity. The greater the rod length the less friction is created.

Piston Skirt Friction Model's

Friction Mean Effective Pressure (FMEP) model's

- Theoretical mean effective pressure required to overcome engine friction

Ford 1.6 litre turbo engine model

Critical measurements for the engine had to be obtained before any calculations could be carried out, these can be seen in table 1.

Once the measurements were obtained, ω (rads/sec) was calculated for every RPM range by using the equation:

$$2\pi \times \frac{RPM}{60} \text{ (rads/sec)}$$

Note: Coefficient of Friction (μ_e) was taken to be 0.1.

Mass of Piston & $\frac{1}{3}$ of the Rod Mass (Kg)	0.488
R(half the stroke) (M)	0.0407
L (connecting rod length)(M)	0.134
R/L	0.3037313
RPM	6000
ω (rads/sec)	628.3185307
BORE (M)	0.079
Coefficient of Friction	0.1

Table 1

After all the information in table 1 was gathered, the friction model in excel could be created. The crank angle in degrees went from -360 to +360, this was then converted into radians using the function in excel (this can be seen in table 3).

The pressure data for each cylinder was provided by Malcolm McDonald and also went from -360 to +360, from this data the average pressures were taken for each degree in bar (this can be seen in table 2).

Engine Speed:6000					
Crank Ang deg	CYLPR1 bar	CYLPR2 bar	CYLPR3 bar	CYLPR4 bar	Average Pressure bar
-360	3.158	3.235	3.253	3.253	3.22475
-359	3.119	3.222	3.24	3.227	3.202
-358	3.093	3.209	3.202	3.202	3.1765
-357	3.068	3.209	3.215	3.176	3.167
-356	3.029	3.209	3.202	3.137	3.14425
-355	2.991	3.183	3.189	3.112	3.11875
-354	2.965	3.145	3.163	3.086	3.08975
-353	2.939	3.106	3.138	3.06	3.06075
-352	2.901	3.055	3.112	3.009	3.01925
-351	2.863	3.004	3.061	2.97	2.9745
-350	2.837	2.965	3.022	2.958	2.9455

Table 2

After the average cylinder pressure in bar was obtained through the data provided, this was then input into the friction model. The average pressure was then converted into Pascal's using the equation:

$$\text{Average Pressure (Bar)} \times 10^5 (\text{N/m}^2)$$

Crank Angle (Degrees)	Crank Angle (Radians)	Average Pressure (Bar)	Average Pressure (N/m²)
-360	-6.283185307	3.22475	322475
-359	-6.265732015	3.202	320200
-358	-6.248278722	3.1765	317650
-357	-6.23082543	3.167	316700
-356	-6.213372137	3.14425	314425
-355	-6.195918845	3.11875	311875
-354	-6.178465552	3.08975	308975
-353	-6.16101226	3.06075	306075
-352	-6.143558967	3.01925	301925
-351	-6.126105675	2.9745	297450
-350	-6.108652382	2.9455	294550

Table 3

Once the crank angle and the average pressure were converted, all the forces required to calculate the theoretical mean effective pressure required to overcome engine friction were calculated (these can be seen in table 4).

Firstly the Gas Force was calculated for every degree, using the equation:

$$\frac{\text{Average Pressure (N/m}^2\text{)} \times \pi \times \text{Bore}^2}{\text{Number of Pistons}} \text{N}$$

After this the Inertia Force was calculated for every degree, using the equation:

$$\text{Mass} \times R \times \omega^2 \times \cos(\text{crank angle Radians}) + \frac{R}{L} \times \cos(\text{crank angle Radians}) \text{N}$$

Mass = Piston Mass & $\frac{1}{3}$ of the Rod Mass

R = Half the Stroke

L = Connecting Rod Length

With both the Gas Force and Inertia Force calculated, the Net Force can be calculated for every degree using the equation:

$$\text{Gas Force} - \text{Inertia Force N}$$

The Side Force was calculated for every degree, using the equation:

$$\text{Net Force} \times \tan(\text{Rod Angle}) \text{ N}$$

Finally, the Friction Force was then calculated for every degree using the equation:

$$\text{Coefficient of Friction} \times \text{Side Force N}$$

Fgas (N)	Inertia Force (N)	Fnet (N)	Fside (N)	Ffriction (N)
1580.666013	10222.6163	-8641.95	-6.4E-13	-6.4E-14
1569.514714	10221.05935	-8651.54	-45.8611	-4.58611
1557.015456	10216.38896	-8659.37	-91.7951	-9.17951
1552.358869	10208.60656	-8656.25	-137.618	-13.7618
1541.20757	10197.71452	-8656.51	-183.449	-18.3449
1528.708312	10183.71616	-8655.01	-229.195	-22.9195
1514.493469	10166.61574	-8652.12	-274.831	-27.4831
1500.278626	10146.41847	-8646.14	-320.261	-32.0261
1479.936696	10123.1305	-8643.19	-365.685	-36.5685
1458.001723	10096.75893	-8638.76	-410.926	-41.0926
1443.78688	10067.31179	-8623.52	-455.459	-45.5459

Table 4

The Rod Angle was calculated for every degree using the equation:

$$\sin^{-1} \frac{R}{L} \times \sin(\text{Crank Angle Radians})$$

After the Rod Angle was calculated, the Piston Travel was then calculated for every degree using the equation:

$$(R + L) - (R \times \cos(\text{Crank Angle Radians})) + (L \times \cos(\text{Rod Angle Radians})) \text{ M}$$

The work done was calculated for every degree, using the equation:

$$\Delta W = \sqrt{(\Delta W)^2} \text{ J}$$

With the work done; calculated the total work per cycle could be found by adding all the work done at every degree together.

The FMEP was calculated, using the equation:

$$\frac{\text{Total work done per cycle}}{400 \times 10^{-6}} \text{ N/m}^2$$

The FMEP was then converted in to bar, using the equation:

$$\text{FMEP (N/m}^2\text{)} \times 10^5 \text{ Bar}$$

RodAngle (Radians)	Piston Travle (m)	WD (J)	TOTAL WD/cycle (J)	Fmep (N/m^2)	Fmep (Bar)
7.44E-17	0	1.85E-05	47.5780608	118945.2	1.189452
0.005301	8.08145E-06	0.000167			
0.0106	3.23218E-05	0.000463			
0.015897	7.27089E-05	0.000907			
0.021189	0.000129223	0.001498			
0.026475	0.000201835	0.002235			
0.031754	0.00029051	0.003115			
0.037024	0.000395203	0.004138			
0.042284	0.000515863	0.005303			
0.047532	0.000652428	0.006602			
0.052767	0.000804832	0.008032			

Table 5

FMEP Ford 1.6 naturally aspirated engine model

The process and method used to create the previous friction model for the Ford 1.6 litre turbo engine, is the same for the Ford 1.6 naturally aspirated engine.

All the critical measurements for the engine that had to be obtained before any calculations could be carried out, can be seen in table 6. The average pressures were taken from the data provided by Malcolm McDonald and can be seen in table 7 in the (mean B) column.

Tables 8, 9 and 10 show the complete friction model for the Ford 1.6 naturally aspirated engine. All the equations used in the previous friction model, were used whilst creating this friction model.

Note: Whilst the equations used are the same, the measurements and data gathered are different for the two engines.

Mass of Piston (Kg)	0.4014
R(half the stroke) (M)	0.0407
L (connecting rod length)(M)	0.134
R/L	0.297080292
RPM	6000
ω (rads/sec)	628.3185307
BORE (M)	0.079
Coefficient of Friction	0.1

Table 6

LUCID	MEAN	CYCLE	PRESSURE	DATA	FILE			
D:\4mlc509\0084.014								
06/02/2003	13:53							
Leistungsmessung	Lambda	0.9	FKI4=2	EBP=	35 kpa	6000 rpm		
4mlc509								
BORE(m)	STROKE(m)	CONROD(m)	COM.RATIO	NCYCLES	NCYLS	VOLUME		
0.079	0.0814	0.137	11.16	300	4	1		
I-FILE	DATA							
NUMBER	OF	READINGS	720					
C.A.(DEG)	VOL(CC)	MEAN(B)	CYL_1	CYL_2	CYL_3	CYL_4		
-360	39.27	1.079	0.942	1.026	0.981	1.367		
-359	39.31	1.06	0.938	1.015	0.973	1.313		
-358	39.43	1.025	0.929	1	0.948	1.223		
-357	39.63	0.977	0.916	0.985	0.938	1.068		
-356	39.9	0.936	0.911	0.972	0.927	0.933		
-355	40.26	0.92	0.9	0.96	0.903	0.917		
-354	40.69	0.924	0.888	0.952	0.894	0.964		
-353	41.2	0.91	0.869	0.932	0.886	0.952		
-352	41.79	0.874	0.856	0.916	0.864	0.86		
-351	42.45	0.837	0.842	0.902	0.851	0.752		
-350	43.2	0.811	0.827	0.894	0.842	0.679		

Table 7

Crank Angle (Degrees)	Crank Angle (Radians)	Average Pressure (Bar)	Average Pressure (N/m²)
-360	-6.283185307	1.079	107900
-359	-6.265732015	1.06	106000
-358	-6.248278722	1.025	102500
-357	-6.23082543	0.977	97700
-356	-6.213372137	0.936	93600
-355	-6.195918845	0.92	92000
-354	-6.178465552	0.924	92400
-353	-6.16101226	0.91	91000
-352	-6.143558967	0.874	87400
-351	-6.126105675	0.837	83700
-350	-6.108652382	0.811	81100

Table 8

Fgas (N)	Inertia Force (N)	Fnet (N)	Fside (N)	Ffriction (N)
528.8901863	8365.624651	-7836.73	-5.7E-13	-5.7E-14
519.5770134	8364.350526	-7844.77	-40.6739	-4.06739
502.4211686	8360.528539	-7858.11	-81.4769	-8.14769
478.8931529	8354.159853	-7875.27	-122.459	-12.2459
458.7963062	8345.24641	-7886.45	-163.468	-16.3468
450.9536343	8333.790924	-7882.84	-204.173	-20.4173
452.9143022	8319.796884	-7866.88	-244.411	-24.4411
446.0519643	8303.268553	-7857.22	-284.657	-28.4657
428.4059526	8284.210967	-7855.81	-325.081	-32.5081
410.2697738	8262.62993	-7852.36	-365.322	-36.5322
397.525432	8238.532015	-7841.01	-405.037	-40.5037

Table 9

RodAngle (Radians)	Piston Travle (m)	WD (J)	TOTAL WD/cycle (J)	Fmep (N/m²)	Fmep (Bar)
7.28E-17	0	1.64E-05	32.80918005	82022.95	0.82023
0.005185	8.04022E-06	0.000147			
0.010368	3.21569E-05	0.00041			
0.015549	7.23381E-05	0.000804			
0.020725	0.000128564	0.001328			
0.025895	0.000200806	0.001979			
0.031058	0.00028903	0.002755			
0.036213	0.000393191	0.00366			
0.041357	0.000513238	0.00469			
0.04649	0.00064911	0.005841			
0.05161	0.000800743	0.007104			

Table 10

FMEP Ford 1.0 litre eco boost engine model

The Ford 1.0 litre eco boost engine was chosen as it is slightly different compared to the other two engines, due to its crank offset of 8mm. As a result of the crank offset, the process of finding the FMEP is slightly different.

The critical measurements for the engine still had to be obtained before any calculations could be carried out, the offsets also had to be taken into consideration. These can be seen in table 11.

Once the measurements were obtained, ω (rads/sec) was calculated for every RPM range by using the equation:

$$2\pi \times \frac{RPM}{60} \text{ (rads/sec)}$$

Note: Coefficient of Friction (μ_e) was taken to be 0.1.

Due to the 8mm crank offset, Top Dead Centre (TDC) isn't at 360°. Therefore the offset Crank Correction in the FOX engine at TDC had to be calculated using the calculations shown below.

$$X1 = 0.5mm \quad \& \quad X2 = 8mm$$

$$AB = (X2 - X1)$$

$$\sin \theta \text{ at TDC} = \frac{(X2 - X1)}{(R + L)}$$

$$\sin \theta \text{ at TDC} = \frac{(8 - 0.5)}{(41 + 136)}$$

$$\sin \theta \text{ at TDC} = \frac{(8 - 0.5)}{(41 + 136)}$$

$$\sin \theta \text{ at TDC} = \frac{(7.5)}{(177)} = 0.04237 \text{ Rads}$$

$$\sin \theta \text{ at TDC} = 0.04237 \times \frac{(360)}{(2\pi)}$$

$$\sin \theta \text{ at TDC} = 2.4^\circ$$

The piston on the left represents an engine with a 8mm crank offset, where the piston on the right represents an engine with a 0mm offset. As seen in figure 1, the piston with an 8mm offset does not technically reach TDC. Therefore the crank data had to be corrected.

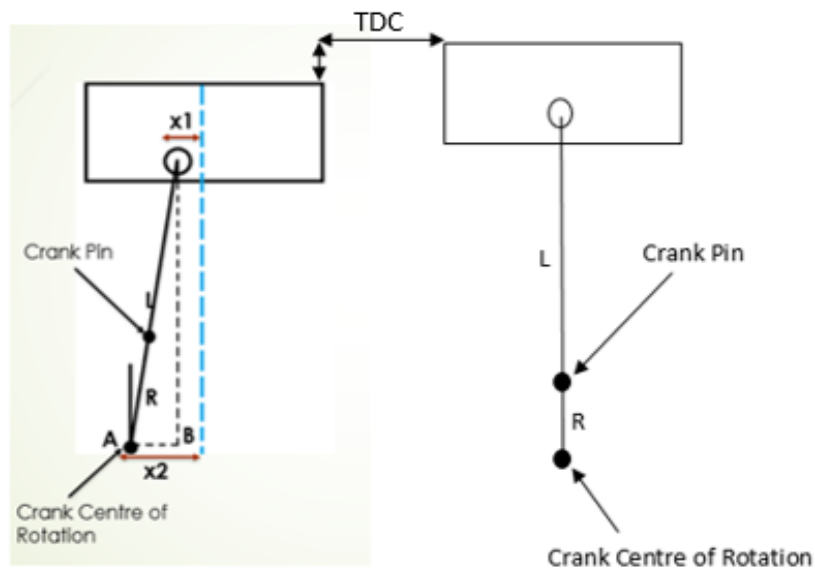
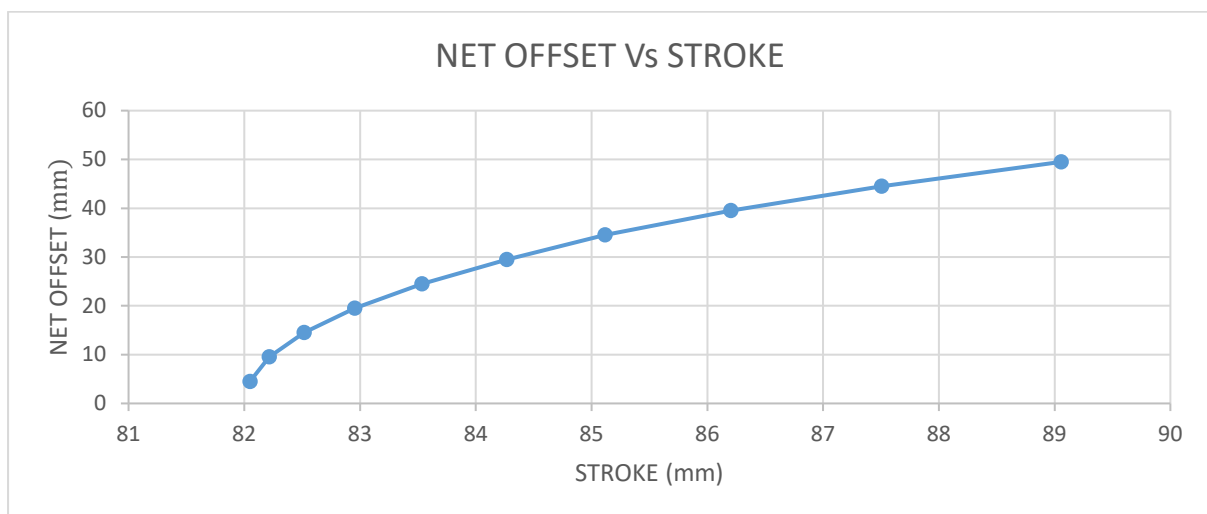


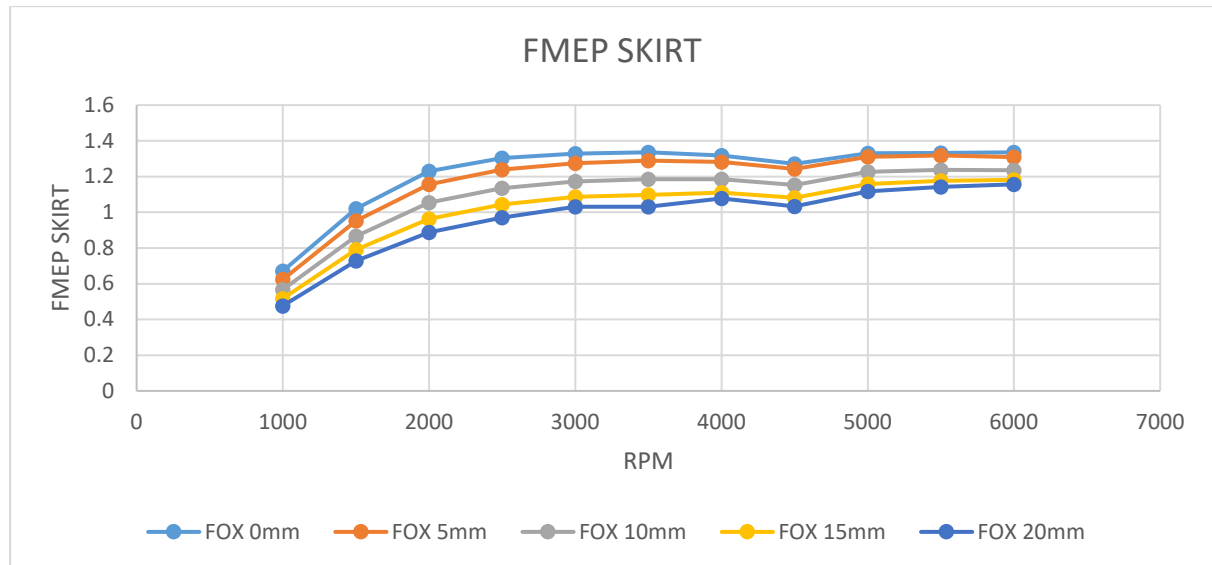
Figure 2

When introducing a crank offset to reduce friction it is very important to consider, how much offset you would like to apply and the implication of how that would affect the stroke. As seen in graph 1 as the offset is increased the stroke increases, therefore technically with enough offset a 1.0 litre engine could be classed as a 1.3 litre engine. In motorsport this could have severe consequences, as the class the vehicle could be entered in may only allow 1.0 litre engines and with enough offset making the engine a 1.3 litre may be classed as cheating and result in disqualification. [4, 6]



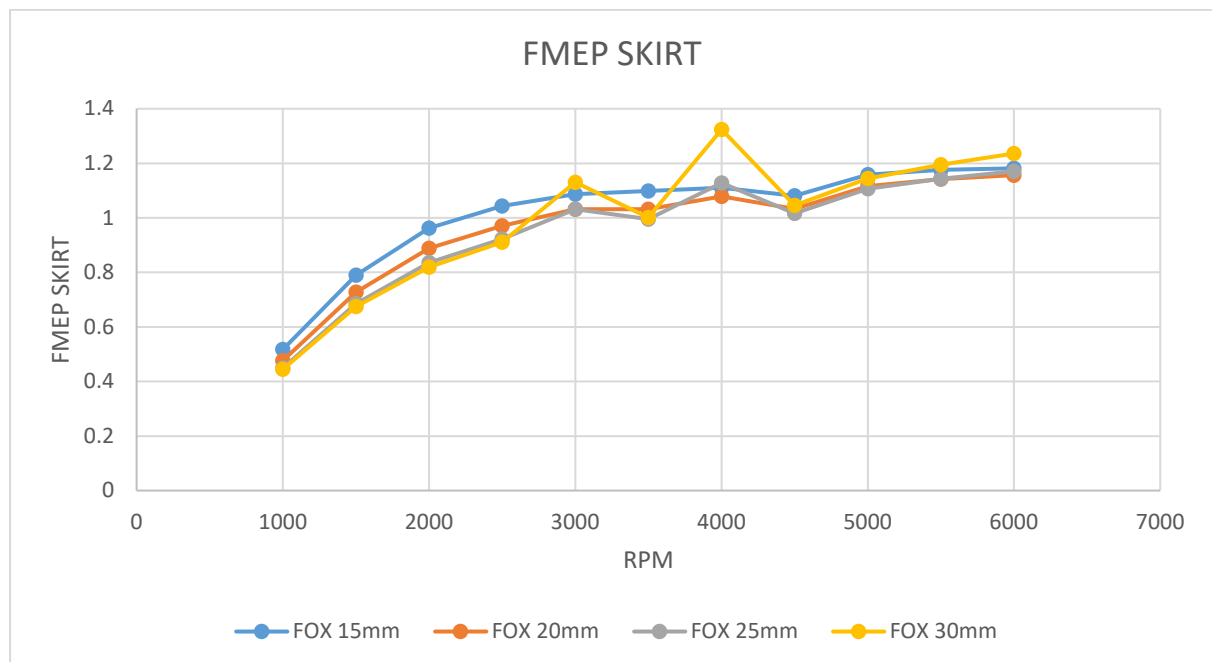
Graph 1

Graph 2 shows the crank offset increasing from 0mm up to 20mm, it can be seen by the graph as the offset is increased the piston friction created by the engine is reduced. This is due to the fact the more the offset is increases the force being applied to the thrust side of the piston decreases, this results in less friction being created.



Graph 2

Graph 3 however show the crank offset being increased from 15mm up to 30mm, it can be seen by the graph as the offset is increased to 25mm and 30mm the piston friction created by the engine is actually increased. This is due to the fact the offset is so great the piston has no force applying it to the thrust side, resulting in the piston having no guidance and causing it to shift from side to side. This not only results in an increase in friction, it also makes the engine sound loud and rough because of the piston slap and it also creates uneven wear on the bore.



Graph 4

Mass of Piston (Kg)	0.414
R(half the stroke) (M)	0.041
L (connecting rod length)(M)	0.136
R/L	0.30147059
RPM	6000
w (rads/sec)	628.3185307
BORE (M)	0.072
Coefficient of Friction	0.1
X1 offset (Gudgeon Pin) (mm)	0.5
X2 offset (Crank) (mm)	8
Corrected Crank Angle	2.4

Table 11

After the information in table 11 was gathered, the friction model in excel was created. The crank angle in degrees went from -360 to +360. Due to the 8mm crank offset the crank angle had to be corrected, this involved creating another column in excel and subtracting the corrected crank angle calculated at TDC.

Therefore the corrected crank angle = $-360 - 2.4 = -357.6^\circ$ this was carried out for each degree.

The corrected crank angle was then converted into radians using the function in excel (this can be seen in table 13).

The pressure data for each cylinder was provided by Malcolm McDonald, from this data the average pressures were taken for each degree in bar (this can be seen in table 12).

Crank Ang deg	V_ABS cm ³	CYLPR1 bar	CYLPR2 bar	CYLPR3 bar	Average Pressure bar
-360	37.05	2.619	2.825	2.818	2.754
-359	37.09	2.59	2.821	2.799	2.736666667
-358	37.19	2.552	2.787	2.76	2.699666667
-357	37.35	2.508	2.729	2.746	2.661
-356	37.58	2.475	2.686	2.64	2.600333333
-355	37.88	2.446	2.662	2.626	2.578
-354	38.24	2.388	2.604	2.582	2.524666667
-353	38.66	2.335	2.541	2.52	2.465333333
-352	39.15	2.292	2.493	2.467	2.417333333
-351	39.71	2.244	2.431	2.4	2.358333333
-350	40.33	2.186	2.359	2.318	2.287666667

Table 12

After the average cylinder pressure in bar was obtained through the data provided, this was then input into the friction model. The average pressure was then converted into Pascal's using the equation:

$$\text{Average Pressure (Bar)} \times 10^5 (\text{N/m}^2)$$

Crank Angle (Degrees)	Corrected Crank Angle (Degrees)	Crank Angle (Radians)	Average Pressure (Bar)	Average Pressure (N/m ²)
-360	-357.6	-6.241297405	2.754	275400
-359	-356.6	-6.223844113	2.736666667	273666.6667
-358	-355.6	-6.20639082	2.699666667	269966.6667
-357	-354.6	-6.188937528	2.661	266100
-356	-353.6	-6.171484235	2.600333333	260033.3333
-355	-352.6	-6.154030943	2.578	257800
-354	-351.6	-6.13657765	2.524666667	252466.6667
-353	-350.6	-6.119124357	2.465333333	246533.3333
-352	-349.6	-6.101671065	2.417333333	241733.3333
-351	-348.6	-6.084217772	2.358333333	235833.3333
-350	-347.6	-6.06676448	2.287666667	228766.6667

Table 13

The Piston Travel was then calculated for every degree using the equation:

$$(R + L) \times \cos(\text{Radians } (2.4) - (R \times \cos(\text{Crank Angle Radians})) + (L \times \cos(\text{Rod Angle Radians})) \text{ M}$$

The Velocity in m/° was calculated using the equation:

$$\text{piston travel at } (-359^\circ) - \text{piston travel at } (-360^\circ)$$

$$\text{Therefore velocity} = 1.13859\text{E-}05 - 3.71723\text{E-}06 = 7.66868\text{E-}06\text{m/}^\circ$$

The Acceleration in m/°/° was calculated using the equation:

$$\text{Velocity at } (-359^\circ) - \text{Velocity at } (-360^\circ)$$

$$\text{Therefore the Acceleration} = 2.39227\text{E-}05 - 7.66868\text{E-}06 = 1.6254\text{E-}05 \text{ m/}^\circ/\text{ }^\circ$$

The Acceleration in m/s² was calculated using the equation:

$$\text{Acceleration m/}^\circ/\text{ }^\circ \times (6 \times \text{RPM})^2 \text{m/s}^2$$

Piston Travle (m)	Velocity (m/°)	Acceleration (m/°/°)	Acceleration (m/s^2)
3.71723E-06	7.66868E-06	1.6254E-05	21065.22512
1.13859E-05	2.39227E-05	1.62313E-05	21035.75779
3.53086E-05	4.0154E-05	1.62005E-05	20995.89319
7.54626E-05	5.63545E-05	1.61618E-05	20945.66911
0.000131817	7.25163E-05	1.61151E-05	20885.12973
0.000204333	8.86314E-05	1.60604E-05	20814.32551
0.000292965	0.000104692	1.59979E-05	20733.31328
0.000397657	0.00012069	1.59276E-05	20642.15614
0.000518346	0.000136617	1.58495E-05	20540.9235
0.000654964	0.000152467	1.57637E-05	20429.69104
0.000807431	0.00016823	1.56702E-05	20308.54072

Table 14

Once the corrected crank angle, piston travel, velocity and acceleration were calculated and the average pressure was obtained, all the forces required to calculate the theoretical mean effective pressure required to overcome engine friction (FMEP) where calculated (these can be seen in table 15).

The Gas Force was calculated for every degree, using the equation:

$$\frac{\text{Average Pressure (N/m}^2\text{)} \times \pi \times \text{Bore}^2}{\text{Number of Pistons}} \text{N}$$

The Inertia Force was calculated for every degree, using the equation:

$$\text{Mass} \times \text{Acceleration m/°/° N}$$

Mass = Piston Mass & $\frac{1}{3}$ of the Rod Mass

With both the Gas Force and Inertia Force calculated, the Net Force can be calculated for every degree using the equation:

$$\text{Gas Force} - \text{Inertia Force N}$$

The Side Force was calculated for every degree, using the equation:

$$\text{Net Force} \times \text{Tan(Rod Angle) N}$$

The Friction Force was then calculated for every degree using the equation:

$$\text{Coefficient of Friction} \times \text{Side Force } N$$

Fgas (N)	Inertia Force (N)	Fnet (N)	Fside (N)	Ffriction (N)
1495.056298	8721.003201	-7225.946903	307.5455319	30.75455319
1485.6466	8708.803726	-7223.157126	269.3792595	26.93792595
1465.560513	8692.299779	-7226.739266	231.5082546	23.15082546
1444.569647	8671.507013	-7226.937366	193.5791111	19.35791111
1411.635703	8646.443707	-7234.808004	155.8916962	15.58916962
1399.511669	8617.130762	-7217.619094	117.7998274	11.77998274
1370.558751	8583.591698	-7213.032947	80.12242225	8.012242225
1338.34863	8545.852642	-7207.504012	42.59049472	4.259049472
1312.291004	8503.942329	-7191.651325	5.220029836	0.522002984
1280.261838	8457.892092	-7177.630254	-31.874851	-3.1874851
1241.899222	8407.735857	-7165.836635	-68.71870997	-6.871870997

Table 15

The Rod Angle was calculated for every degree using the equation:

$$\sin^{-1} \frac{R}{L} \times \sin(\text{Crank Angle Radians}) - \frac{(X_2 - X_1)}{L} \text{ Radians}$$

The work done was calculated for every degree, using the equation:

$$\Delta W = \sqrt{(\Delta W)^2} J$$

With the work done; calculated the total work per cycle could be found by adding all the work done at every degree together.

The FMEP was calculated, using the equation:

$$\frac{\text{Total work done per cycle}}{400 \times 10^{-6}} \text{ N/m}^2$$

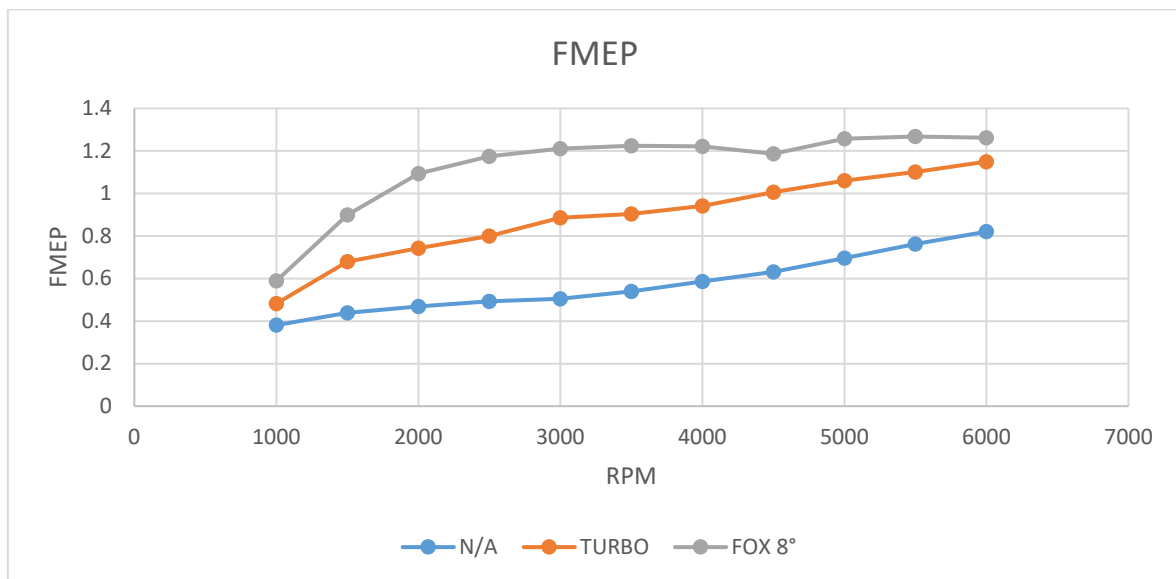
The FMEP was then converted in to bar, using the equation:

$$\text{FMEP (N/m}^2) \times 10^5 \text{ Bar}$$

RodAngle (Radians)	WD (J)	TOTAL WD/cycle (J)	Fmep (N/m^2)	Fmep (Bar)
-0.042535606	0.000221212	50.4923542	126230.8855	1.262308855
-0.037276564	0.000599129			
-0.032024002	0.000853448			
-0.026779371	0.000984713			
-0.021544121	0.000992355			
-0.016319699	0.000877106			
-0.01110755	0.000642352			
-0.005909119	0.000288512			
-0.000725846	0.000182076			
0.004440831	0.000766859			
0.009589474	0.001462229			

Table 16

Once all the FMEP models were created for all three engines at various RPM's they were put into a graph to see which engine creates more friction, as seen in graph 4. The 1.0 litre eco boost engine creates the most friction by a large proportion, this is followed by the 1.6 litre turbo engine and lastly the 1.6 litre naturally aspirated engine created the least amount of friction.



Graph 4

Indicated Mean Effective Pressure (IMEP) model's

- Mean effective pressure calculated from in-cylinder pressure over compression and expansion portion of engine cycle 720° in a four-stroke engine.

Once the FMEP models were created for the three engines, the next step was producing the IMEP models for all three engines. The first step to producing the IMEP models, was to obtain the average cylinder pressures for every degree from -360° to +360°. These pressures were obtained from the FMEP models previously produced.

The volumes in cubic centimetres were obtained from various data provided by Malcolm McDonald. These volumes were then converted into cubic metres using the equation:

$$\text{Volumes in Cubic Centimetres} \times 10^{-6} \text{ (Cubic Metres)}$$

After the pressures and volumes were obtained, the work done per degree by the gas could be calculated using the equation:

$$\frac{\text{Av Pressure (N/m}^2\text{) in first row} + \text{Av Pressure (N/m}^2\text{) in second row}}{2} \times \text{Vol (Cubic meters) in second row} - \text{Vol (Cubic meters) in first row}$$

Therefore the work done per degree by the gas for the Ford 1.6 litre turbo engine at -360° =

$$\frac{(322475 + 320200)}{2} \times (0.00004448 - 0.00004444) \text{ J}$$

Note: this can be seen in table 17.

With the work done; calculated the total work per cycle could be found by adding all the work done at every degree together.

The IMEP was calculated, using the equation:

$$\frac{\text{Total work done by gas}}{400 \times 10^{-6}} \text{ N/m}^2$$

The IMEP was then converted in to bar, using the equation:

$$\text{FMEP (N/m}^2\text{)} \times 10^5 \text{ Bar}$$

Tables 17, 18 and 19 show the complete IMEP model's for all three engines.

Note: Whilst the equations and processes used to create the IMEP models are the same, the pressure and volume data are different for all the engines.

IMEP Ford 1.6 litre turbo engine model

Average Pressure (Bar)	Average Pressure (N/m ²)	Volume (Cubic Centimeters)	Volume (Cubic Metres)	WD/° by gas (J)	TOTAL WD BY GAS (J)	Imep (N/m ²)	Imep (Bar)
3.22475	322475	44.44	0.00004444	0.0128535	726.3140633	1815785.158	18.15785158
3.202	320200	44.48	0.00004448	0.038271			
3.1765	317650	44.6	0.0000446	0.063435			
3.167	316700	44.8	0.0000448	0.085201875			
3.14425	314425	45.07	0.00004507	0.112734			
3.11875	311875	45.43	0.00004543	0.13348275			
3.08975	308975	45.86	0.00004586	0.15683775			
3.06075	306075	46.37	0.00004637	0.17936			

Table 17

IMEP Ford 1.6 naturally aspirated engine model

Average Pressure (Bar)	Average Pressure (N/m ²)	Volume (Cubic Centimetres)	Volume (Cubic Metres)	WD/° by gas (J)	TOTAL WD BY GAS (J)	Imep (N/m ²)	Imep (Bar)
1.079	107900	39.27	0.00003927	0.004278	493.331919	1233329.798	12.33329798
1.06	106000	39.31	0.00003931	0.01251			
1.025	102500	39.43	0.00003943	0.02002			
0.977	97700	39.63	0.00003963	0.0258255			
0.936	93600	39.9	0.0000399	0.033408			
0.92	92000	40.26	0.00004026	0.039646			
0.924	92400	40.69	0.00004069	0.046767			
0.91	91000	41.2	0.0000412	0.052628			

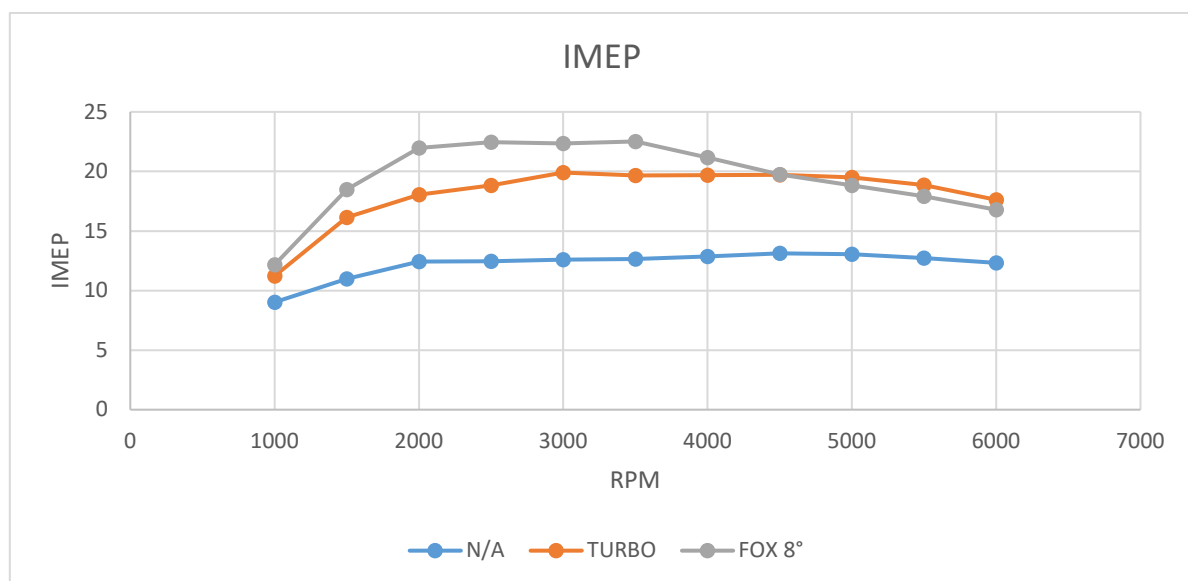
Table 18

IMEP Ford 1.0 litre eco boost engine model

Average Pressure (Bar)	Average Pressure (N/m ²)	Volume (Cubic Centimetres)	Volume (Cubic Metres)	WD/° by gas (J)	TOTAL WD BY GAS (J)	Imep (N/m ²)	Imep (Bar)
2.754	275400	37.05	0.00003705	0.010981333	672.0038592	1680009.648	16.80009648
2.736666667	273666.6667	37.09	0.00003709	0.027181667			
2.699666667	269966.6667	37.19	0.00003719	0.042885333			
2.661	266100	37.35	0.00003735	0.060505333			
2.600333333	260033.3333	37.58	0.00003758	0.077675			
2.578	257800	37.88	0.00003788	0.091848			
2.524666667	252466.6667	38.24	0.00003824	0.10479			
2.465333333	246533.3333	38.66	0.00003866	0.119625333			

Table 19

Once all the IMEP models were created for all three engines at various RPM's they were put into a graph to see which engine performed best, as seen in graph 5. The 1.0 litre eco boost engine slightly starts of worse and constantly gets worse until 3500 RPM where it starts to drop and eventually finishes just below the 1.6 litre turbo engine at maximum RPM. This suggests the 1.0 litre eco boost engine is good on efficiency at high RPM's on motorways but at low RPM's around town it is much worse. The 1.6 litre turbo and naturally aspirated engine, tend to follow the same line at the various RPM ranges with the naturally aspirated engine performing much better.



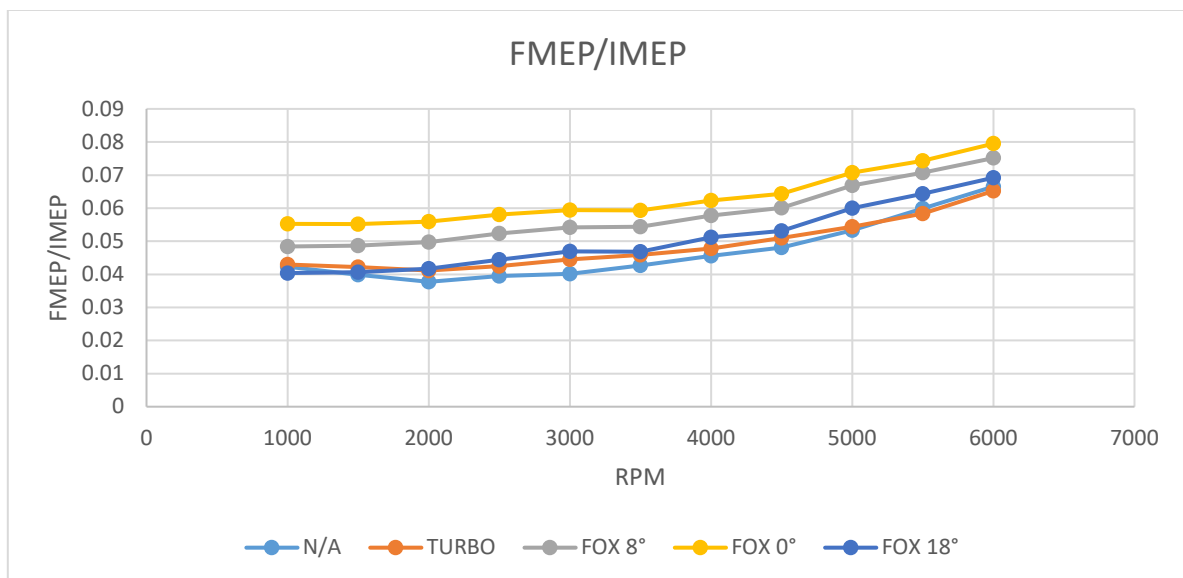
Graph 5

Once all the FMEP and IMEP models were created for all three engines at various RPM's, the FMEP was divided by the IMEP and plotted on a graph (seen on graph 6) to see what engine performs the worst. Firstly, the 1.6 litre naturally aspirated engine, 1.6 litre turbo engine and the 1.0 litre eco boost engine with an 8mm crank offset was plotted.

After seeing how much worse off the 1 litre eco boost engine was with an 8mm crank offset, compared to the 1.6 litre naturally aspirated and turbo engine. The 1 litre eco boost engine was then plotted on the graph with a 0mm and an 18mm crank offset.

From the graph it is clear to see without the crank offset the engines performance is reduced, the 8mm crank offset does help slightly but it is still a far way off the 1.6 litre naturally aspirated and turbo engine. Therefore an 18mm crank offset was introduced to bring the engines performance in par with the 1.6 litre engine, unfortunately it is impractical in the real world to have such a large offset of 18mm. The largest crank offset introduced in production vehicles so far has been 12mm.

The 1.6 litre naturally aspirated and turbo engine were very similar with the 1.6 litre turbo starting off worse at low RPM, but at the higher RPM range the 1.6 turbo engine was the best performing. Therefore from the data gathered so far it seems a larger turbo engine is the future as they offer the performance desired by the customer and are also very efficient.



Graph 6

Piston Ring Friction Model

From this point forward all the information will be referring to the Ford 1.6 litre turbo engine, as many companies use larger turbo engines. Also as seen in the comparison on piston skirt friction, the friction created by this engine was very much in-between that of the 1.6 litre naturally aspirated engine and the smaller 1.0 litre turbo engine.

As many companies are trying to produce very efficient high performance engines, from the piston skirt friction comparisons the larger turbo seems a better option at this moment in time.

Ford 1.6 litre turbo engine model

Certain measurements for the engine had to be obtained before any calculations could be carried out, these can be seen in table 20.

Once the measurements were obtained, ω (rads/sec) was calculated for every RPM range by using the equation:

$$2\pi \times \frac{RPM}{60} \text{ (rads/sec)}$$

Note: Coefficient of Friction (Mue) was taken to be 0.1.

Mass of Piston (Kg)	0.488
R (m)	0.0407
L (m)	0.134
R/L	0.3037313
RPM	6000
ω (rads/sec)	628.3185307
BORE (m)	0.079
Mue	0.1
1st ring thickness (m)	0.00115
1st ring diameter (m)	0.077

Table 20

After all the information in table 20 was gathered, the piston ring friction model in excel could be created. The crank angle in degrees went from -360 to +360, this was then converted into radians using the function in excel. The pressure data was obtained from the Ford 1.6 litre turbo engine piston skirt model (this can be seen in table 21).

Crank Angle (Degrees)	Crank Angle (Radians)	Average Pressure (Bar)	Average Pressure (N/m²)
-360	-6.283185307	3.22475	322475
-359	-6.265732015	3.202	320200
-358	-6.248278722	3.1765	317650
-357	-6.23082543	3.167	316700
-356	-6.213372137	3.14425	314425
-355	-6.195918845	3.11875	311875
-354	-6.178465552	3.08975	308975
-353	-6.16101226	3.06075	306075
-352	-6.143558967	3.01925	301925
-351	-6.126105675	2.9745	297450
-350	-6.108652382	2.9455	294550

Table 21

After the crank angle and the average pressure were gathered, all the forces required to calculate the theoretical mean effective pressure required to overcome engine friction, were calculated (these can be seen in table 22).

Firstly, the Gas Force was calculated for every degree, using the equation:

$$\frac{\text{Average Pressure (N/m}^2\text{)} \times \pi \times \text{Bore}^2}{\text{Number of Pistons}} \text{N}$$

After this the Inertia Force was calculated for every degree, using the equation:

$$\text{Mass} \times R \times \omega^2 \times \cos(\text{crank angle Radians}) + \frac{R}{L} \times \cos(\text{crank angle Radians}) \text{N}$$

Mass = Piston Mass & $\frac{1}{3}$ of the Rod Mass

R = Half the Stroke

L = Connecting Rod Length

With both the Gas Force and Inertia Force calculated, the Net Force can be calculated for every degree using the equation:

$$\text{Gas Force} - \text{Inertia Force N}$$

The Radial Force was calculated for every degree, using the equation:

$$\text{Average Pressure (N/m}^2\text{)} \times \text{Ring thickness} \times \pi \times \text{Ring diameter N}$$

Finally, the Friction Force was then calculated for every degree using the equation:

$$\text{Coefficient of Friction} \times \text{Radial Force N}$$

Fgas (N)	Inertia Force (N)	Fnet (N)	Fradial (N)	Ffriction (N)
1580.666013	10222.6163	-8641.95	89.70868	8.970868481
1569.514714	10221.05935	-8651.54	89.07581	8.907580704
1557.015456	10216.38896	-8659.37	88.36643	8.836642756
1552.358869	10208.60656	-8656.25	88.10215	8.810214893
1541.20757	10197.71452	-8656.51	87.46927	8.746927117
1528.708312	10183.71616	-8655.01	86.75989	8.675989169
1514.493469	10166.61574	-8652.12	85.95315	8.595314641
1500.278626	10146.41847	-8646.14	85.1464	8.514640112
1479.936696	10123.1305	-8643.19	83.99192	8.39919208
1458.001723	10096.75893	-8638.76	82.74703	8.274702937
1443.78688	10067.31179	-8623.52	81.94028	8.194028408

Table 22

The Rod Angle was calculated for every degree using the equation:

$$\sin^{-1} \frac{R}{L} \times \sin(\text{Crank Angle Radians})$$

After the Rod Angle was calculated, the Piston Travel was then calculated for every degree using the equation:

$$(R + L) - (R \times \cos(\text{Crank Angle Radians})) + (L \times \cos(\text{Rod Angle Radians})) \text{ M}$$

The work done was calculated for every degree, using the equation:

$$\Delta W = \sqrt{(\Delta W)^2} \text{ J}$$

With the work done; calculated the total work per cycle could be found by adding all the work done at every degree together.

The FMEP was calculated, using the equation:

$$\frac{\text{Total work done per cycle}}{400 \times 10^{-6}} \text{ N/m}^2$$

The FMEP was then converted in to bar, using the equation:

$$FMEP (N/m^2) \times 10^5 \text{ Bar}$$

RodAngle (Radians)	Piston Travle (m)	WD (J)	TOTAL WD/cycle (J)	Fmep (N/m^2)	Fmep (Bar)
7.44232E-17	0	7.22E-05	9.762955724	24407.39	0.244074
0.005300867	8.08145E-06	0.000215			
0.010600268	3.23218E-05	0.000356			
0.015896738	7.27089E-05	0.000496			
0.02118881	0.000129223	0.000633			
0.02647502	0.000201835	0.000766			
0.031753902	0.00029051	0.000896			
0.037023992	0.000395203	0.00102			
0.042283826	0.000515863	0.001139			
0.047531939	0.000652428	0.001255			
0.05276687	0.000804832	0.001369			

Table 23

Valve Friction

Introduction into valve train friction

Over recent years, research has found that friction from the valve train accounts for around 10% of losses in an engine. This section of the paper investigates the valve train friction created by a ford 1.6 litre turbo engine unleaded internal combustion engine. [2]

The friction created by the ford 1.6 litre turbo engine were calculated using the excel program, any effort to minimize friction losses will have an immediate impact on engine efficiency and vehicle fuel economy, therefore ways to reduce the friction through coatings, lubrications and weight deductions will be discussed. The process involved to produce the friction models will be explained in a step by step process along with all the information and calculations needed, all the results and findings during the investigation will be discussed and evaluated.

Valve Train Friction Model's

Friction Mean Effective Pressure (FMEP) model's

- Theoretical mean effective pressure required to overcome engine friction

Ford 1.6 litre turbo engine model

Critical measurements and for the engine had to be obtained before any calculations could be carried out, these can be seen in table 24 and 25.

Spring Rate (N/mm)	14.35
Engine Capacity (CC)	1600
Coefficient of Friction	0.1
RPM	500
Initial Compression	0.0115
Mass (Kg)	0.06785

Table 24

The valve lift had to be measured before the valve train friction model could be produced. This involved locating a Ford 1.6 litre turbo engine and stripping it down to obtain the cylinder head of the engine. Once the head was obtained the inlet and exhaust cams were taken out along with all the valves, the valve springs, collets, bucket, spring retainer and valves themselves were weighed. The valve spring rate was also measured.

After this one inlet and exhaust valve was placed back into the head without the springs, the head was then clamped to a worktop. With the use of a 360° wheel which was marked every degree, a piece of wire to mark every degree and a dial indicator gauge the valve lift was ready to be measured. (The set up can be seen in figures 3)

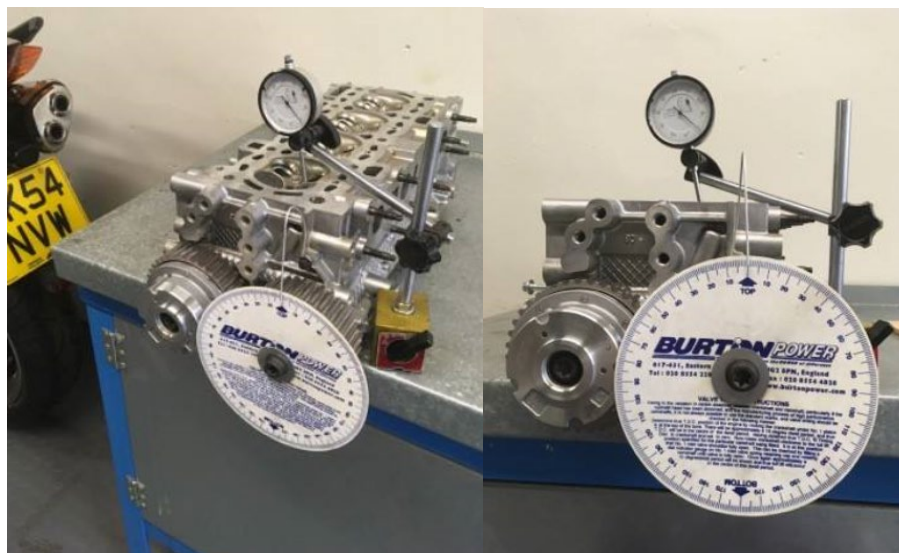


Figure 3

Once everything was set up ready the measurements of lift for every degree from 0 to 360 were taken and put into excel. From this the velocity in mm/° was calculated using the equation:

Lift 2 – Lift 1

From the velocity, the acceleration in mm/°/° was calculated using the equation:

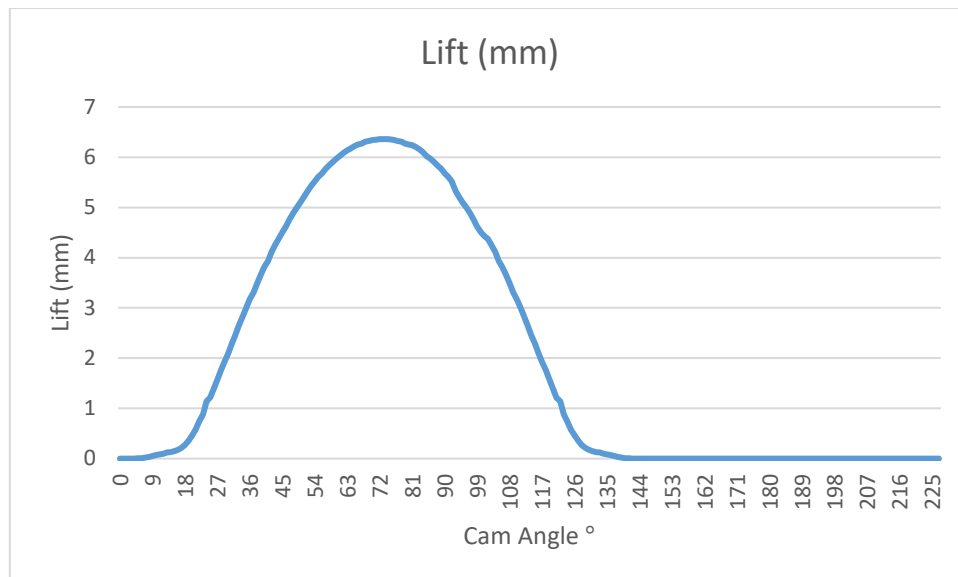
Velocity 2 – Velocity 1

Note: (these can be seen in table 26).

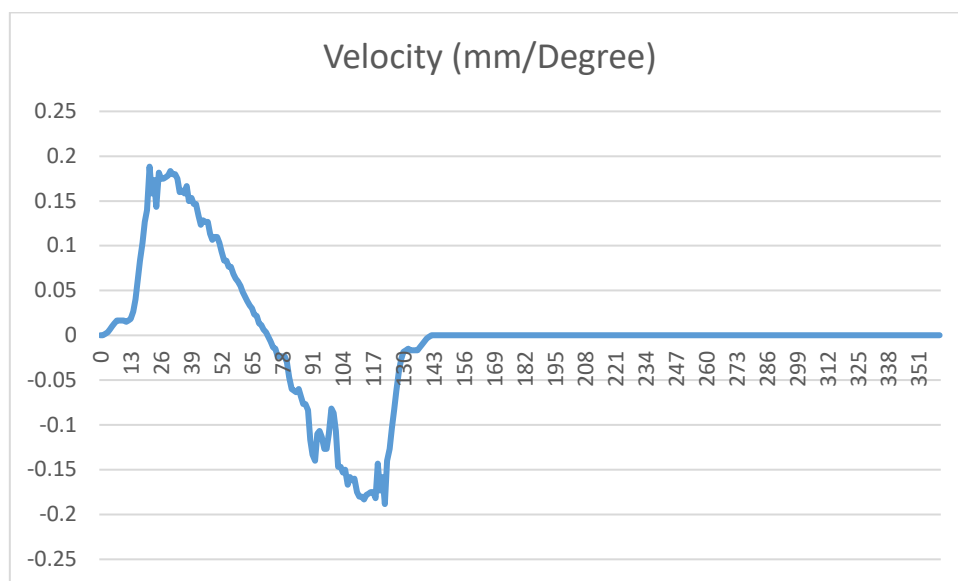
[illegible]

Table 25

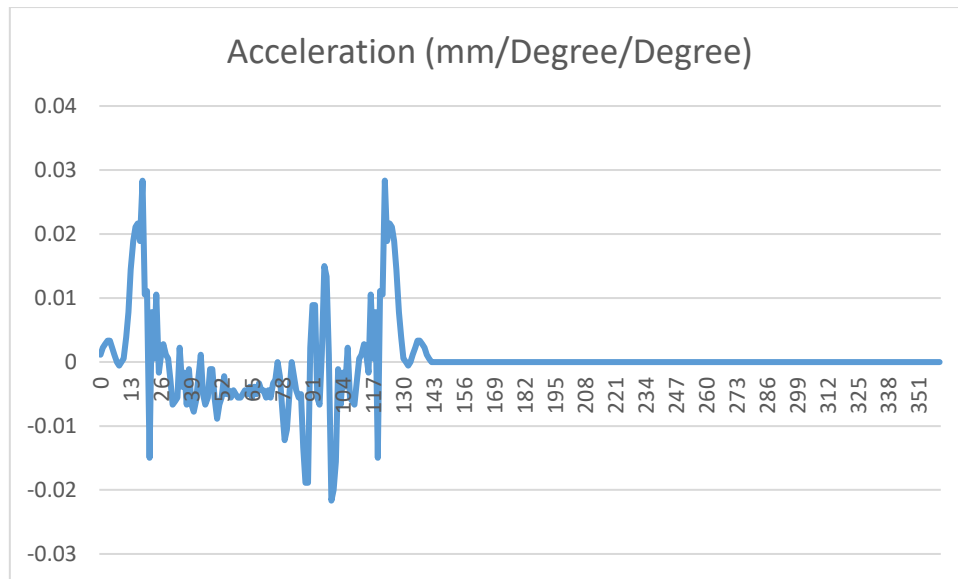
Once the lift, velocity and acceleration was gathered graphs were produced through the excel program to show the behaviour of the valves (as seen in graphs 7, 8 and 9). All the graphs showed the behaviour expected, but unfortunately the velocity and acceleration graphs were too unstable and needed to follow a smoother line.



Graph 7

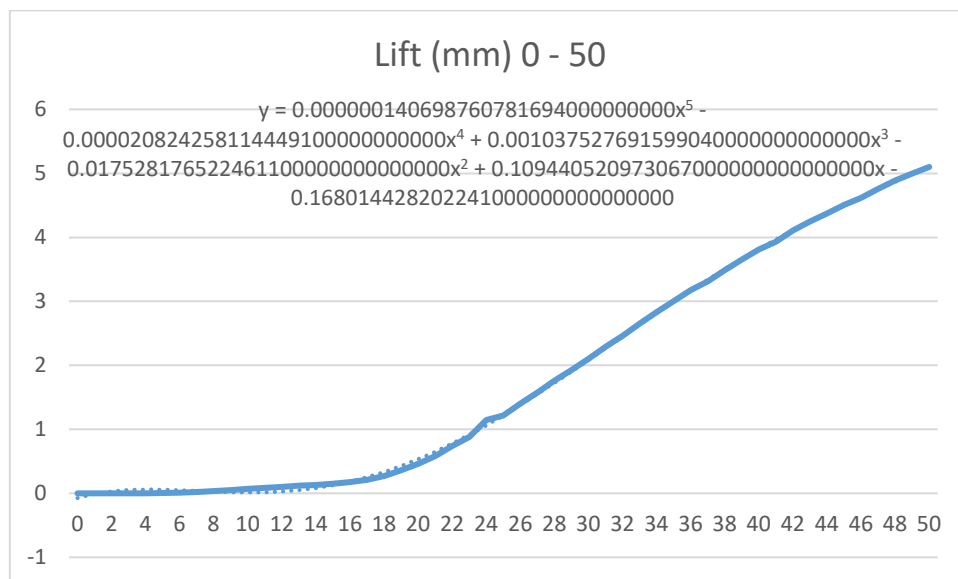


Graph 8



Graph 9

Due to the velocity and acceleration graphs needing to be smoother. A polynomial to 30 decimal places was introduced to try and smooth them out, going from orders one all the way to six still wasn't accurate enough as the polynomial lines took away from the valve lift profile making the results much less accurate.



Graph 10

After the polynomial didn't produce the results and accuracy needed. The previously calculated lift, velocity and acceleration was taken. These were then smoothed, by taking the average of a few measurements.

Therefore, L smooth was calculated using the equation:

$$\frac{Lift\ 1 + Lift\ 2 + Lift\ 3}{3}$$

Therefore, V smooth was calculated using the equation:

$$\frac{Velocity\ 1 + Velocity\ 2 + Velocity\ 3}{3}$$

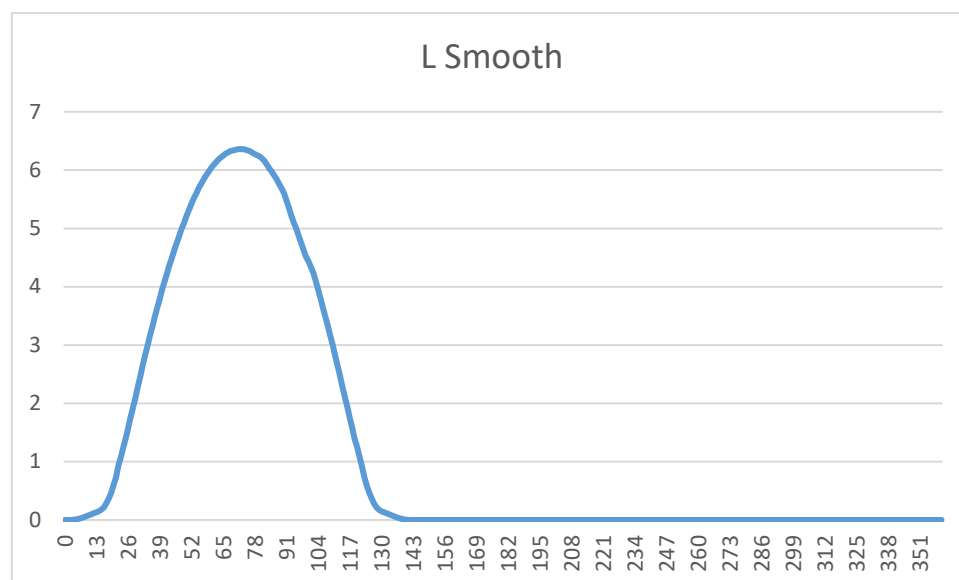
Therefore, A smooth was calculated using the equation:

$$\frac{Acceleration\ 1 + Acceleration\ 2 + Acceleration\ 3}{3}$$

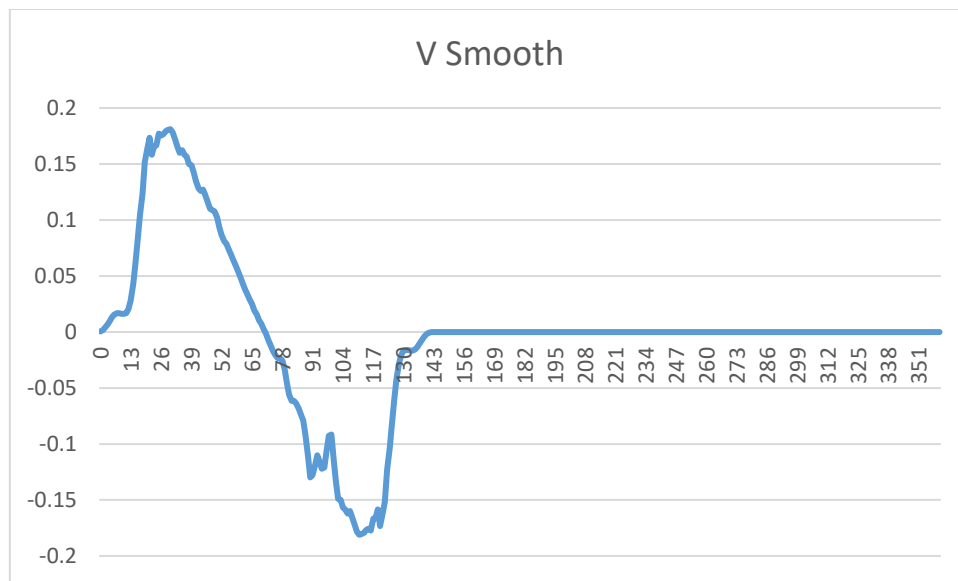
Note: (All the smoothed calculations can be seen plotted in table 26).

Once the calculated lift, velocity and acceleration was smoothed out by taking the average, they were then plotted on graphs to see if this has made any difference. As seen in the smoothed graphs 11, 12 and 13 there is a significant difference compared to the non-smoothed graphs seen in graphs 7, 8 and 9.

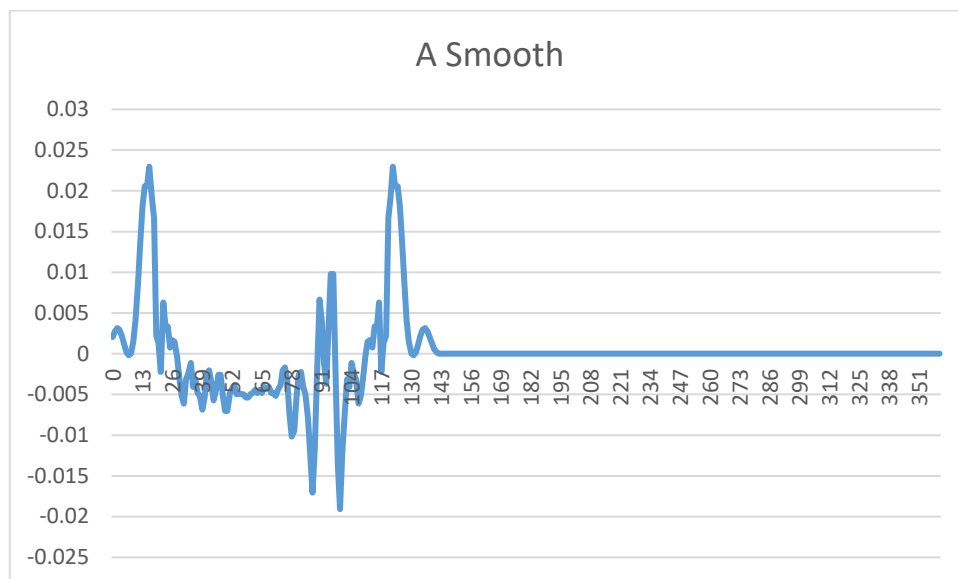
Unfortunately, the smoothed velocity and acceleration graphs are still not as smooth and accurate as required for the friction model.



Graph 11



Graph 12



Graph 13

As smoothing the data and replotting them, did not offer the accuracy required for the friction model. The lift measurements carried out had to be looked at, the conclusion was made that there was too many measurement errors within the first lot of lift measurement

Therefore the valve lift measurements were taken 10 time over, from these measurements an average lift was taken using the equation:

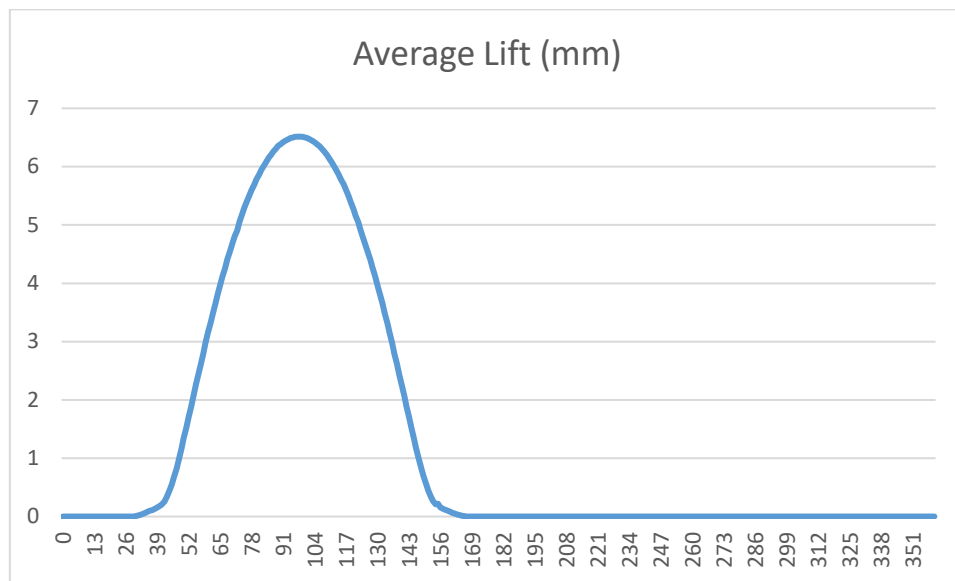
$$\frac{Lift + Lift\ 2 + Lift\ 3 + Lift\ 4 + Lift\ 5 + Lift\ 6 + Lift\ 7 + Lift\ 8 + Lift\ 9 + Lift\ 10}{10} \text{ (mm)}$$

(This can be seen in table 27).

CAM Angle (Degrees)	Lift (mm)	Lift 2 (mm)	Lift 3 (mm)	Lift 4 (mm)	Lift 5 (mm)	Lift 6 (mm)	Lift 7 (mm)	Lift 8 (mm)	Lift 9 (mm)	Lift 10 (mm)	Average Lift (mm)
0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0
30	0.005	0.01	0.005	0.005	0.005	0.005	0.01	0.005	0.01	0.01	0.007
31	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.016
32	0.02	0.035	0.02	0.03	0.04	0.02	0.03	0.03	0.03	0.04	0.0295
33	0.035	0.05	0.04	0.05	0.05	0.03	0.05	0.05	0.06	0.06	0.0475
34	0.05	0.07	0.06	0.07	0.06	0.05	0.07	0.07	0.07	0.07	0.064
35	0.07	0.09	0.08	0.09	0.08	0.07	0.09	0.09	0.09	0.09	0.084
36	0.085	0.11	0.09	0.11	0.1	0.09	0.1	0.1	0.11	0.11	0.1005
37	0.1	0.12	0.11	0.12	0.11	0.1	0.12	0.11	0.12	0.12	0.113
38	0.12	0.14	0.13	0.14	0.13	0.12	0.13	0.13	0.14	0.14	0.132

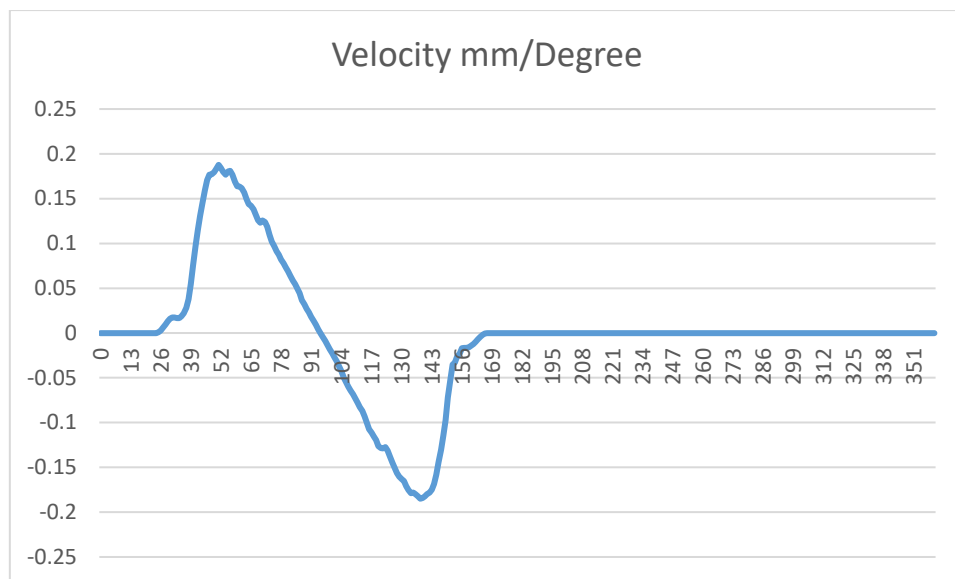
Table 26

Once the lift measurements were taken 10 times and the average was obtained, the velocity and acceleration was calculated again with the new average lift and plotted on graphs. This has made a great difference and can be seen in graphs 14, 15 and 16.



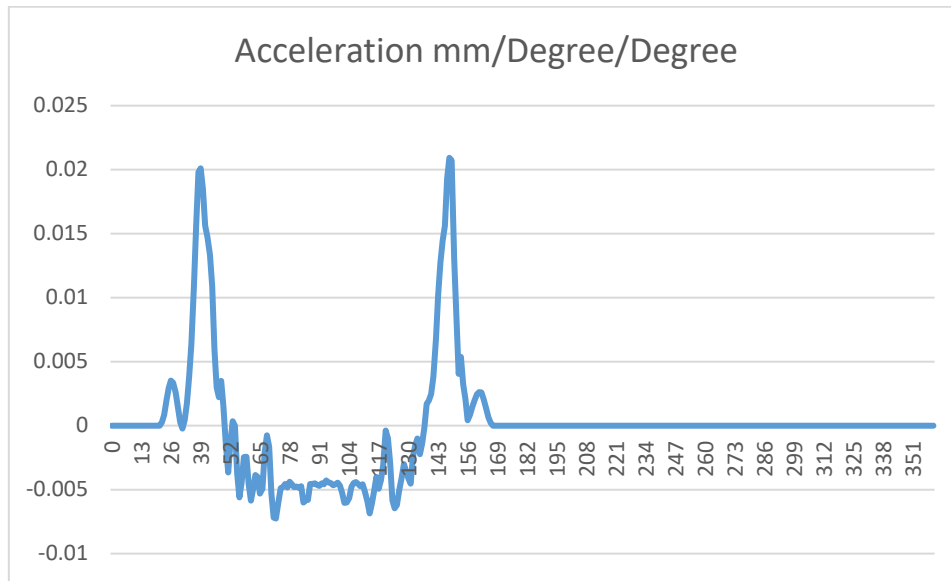
Graph 14

As seen in the velocity graph it has smoothed out a great deal, with a few little bumps in the data. This could be due to minor measurement errors or imperfections in the cam lobe during the machining process.



Graph 15

As for the acceleration graph it is also clear to see it smoothed out not as much as preferred, but it is now clear to read the data. The acceleration peaks around 0.02 and bottoms out around -0.005.



Graph 16

With the lift, velocity and acceleration now meeting expectations, they can be used within the valve train friction model.

Ford 1.6 litre turbo engine valve train exhaust model

After all the information in table 24 was gathered and the valve lift accuracy was acceptable, the friction model in excel could be created. The cam angle in degrees went from 0 to 360 (this can be seen in table 28).

The Average lift was taken from the previous measurements carried out in table 27. Once the cam angle and average lift was put into the excel friction model the velocity could then be calculated for every degree using the equation:

$$Lift\ 2 - Lift\ 1\ (mm/^{\circ})$$

After the velocity was calculated, the acceleration could be calculated for every degree using the equation:

$$Velocity\ 2 - Velocity\ 1\ (mm/^{\circ}/^{\circ})$$

The acceleration in mm/ $^{\circ}/^{\circ}$ was then put into M/S/S for every degree using the equation:

$$Acceleration\ m/^{\circ}/^{\circ} \times (6 \times RPM)^2$$

Note: (These can be seen in table 28)

CAM Angle (Degrees)	Average Lift (mm)	Velocity (mm/Degree)	Acceleration (mm/Degree/Degree)	Acceleration (M/S/S)
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
19	0	0	0	0
20	0	0	0	0
21	0	0	0	0
22	0	0	0	0
23	0	0	0	0
24	0	0	0	0
25	0	0	0	0
26	0	0	0	0
27	0	0	0	0
28	0	0	0.007	2268000
29	0	0.007	0.002	648000
30	0.007	0.009	0.0045	1458000
31	0.016	0.0135	0.0045	1458000
32	0.0295	0.018	-0.0015	-486000
33	0.0475	0.0165	0.0035	1134000
34	0.064	0.02	-0.0035	-1134000

Table 27

Once the crank angle, lift, velocity and acceleration were gathered and calculated, all the forces required to calculate the theoretical mean effective pressure required to overcome engine friction were calculated.

Firstly the Inertia Force was calculated for every degree, using the equation:

$$Mass \times Acceleration \text{ N}$$

After this the Spring Force was calculated for every degree, using the equation:

$$K (y + y_o) \text{ N}$$

K = Spring Rate

y = lift

y_o = Initial compression

Once the spring force was calculated the Contact Force was then calculated for every degree using the equation:

$$Spring \text{ Force} + Inertia \text{ Force}$$

Finally, the Friction Force was then calculated for every degree using the equation:

$$Coefficient \text{ of Friction} \times Contact \text{ Force} \text{ N}$$

Note: (These can be seen in table 29)

[illegible]

Once all the forces were calculated (x) could then be calculated for every degree using the equation:

$$\frac{360 \times \text{Velocity}}{1000 \times 2\pi} (M)$$

After (x) was calculated (x2) was subtracted from (x1).

Note: (x) is the horizontal distance from the tip of the cam lobe to the vertical axis of the base circle.

The work done was then calculated for every degree, using the equation:

$$\Delta W = \sqrt{(\Delta W)^2} J$$

With the work done; calculated the total work could be found by adding all the work done at every degree together.

The FMEP per valve was calculated, using the equation:

$$\frac{\text{Total work done per cycle}}{1600 \times 10^{-6}} N/m^2$$

The FMEP per valve was then converted in to bar, using the equation:

$$FMEP (N/m^2) \times 10^5 \text{ Bar}$$

The FMEP for the all the valves in the engine was then calculated using the equation:

$$FMEP \text{ per valve} \times \text{Number of valves in the engine} (\text{Bar})$$

Note: (These can be seen in table 30)

Ford 1.6 litre turbo engine valve train inlet model

The process and method used to create the previous exhaust friction model, is the same for the inlet friction model.

All the critical measurements for the engine that had to be obtained before any calculations could be carried out, can be seen in table 31. All the measurements will stay the same as the exhaust valve model for the inlet model with the same lift, but the mass will change.

Tables 32, 33 and 34 show the complete friction model for the inlet valve train. All the equations used in the previous friction model, were used whilst creating this friction model.

Note: Whilst the equations, measurements and data gathered used are the same, the masses used are different for the two valves.

Spring Rate (N/mm)	14.35
Engine Capacity (CC)	1600
Coefficient of Friction	0.1
RPM	500
Initial Compression	0.0115
Mass (Kg)	0.0851

Table 31

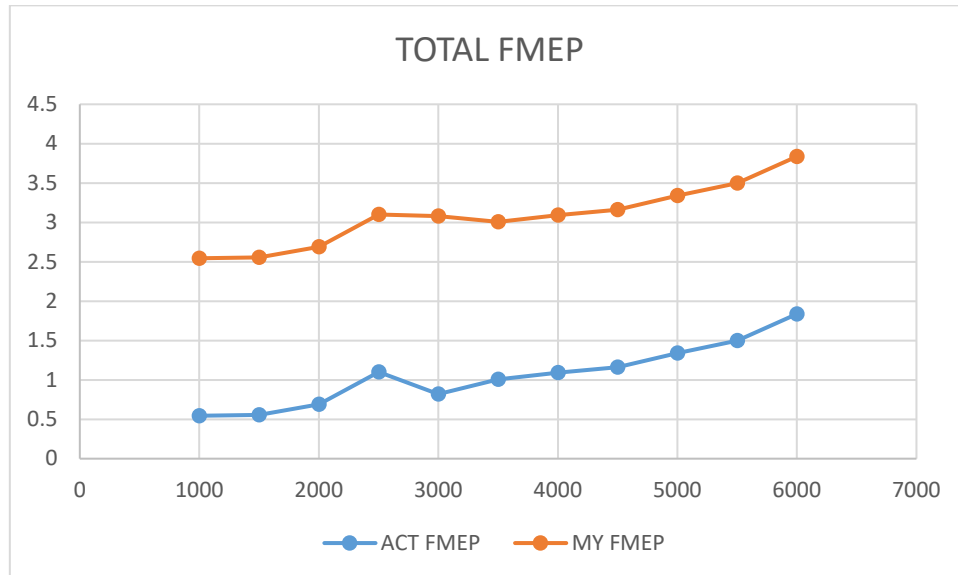
CAM Angle (Degrees)	Average Lift (mm)	Velocity (mm/Degree)	Acceleration (mm/Degree/Degree)	Acceleration (M/S/S)
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
19	0	0	0	0
20	0	0	0	0
21	0	0	0	0
22	0	0	0	0
23	0	0	0	0
24	0	0	0	0
25	0	0	0	0
26	0	0	0	0
27	0	0	0	0
28	0	0	0.007	2268000
29	0	0.007	0.002	648000
30	0.007	0.009	0.0045	1458000
31	0.016	0.0135	0.0045	1458000
32	0.0295	0.018	-0.0015	-486000
33	0.0475	0.0165	0.0035	1134000
34	0.064	0.02	-0.0035	-1134000

Table 30

[illegible]

Once all the FMEP models were created for the Ford 1.6 litre engine, the actual FMEP (Blue) was taken from the data provided and the calculated FMEP (Orange) was the total of all the FMEP models added together.

As seen from graph 17 the calculated FMEP was much higher than the actual FMEP, considering this they still follow a similar line of increase. This could be due to the fact the calculated FMEP did not take into consideration the coefficient of friction varies with RPM (this can be explained through the Stribeck curve).



Graph 17

Stribeck curve

In recent years, studies have revealed that friction in an engine is very difficult to measure due to the presence of all three types of lubrication regimes. These include boundary, mixed, and hydrodynamic. The importance of lubricating oil and various additives increases as it affects the oil film thickness, temperature, and viscosity. These factors affect the amount of friction created by an engine. Lubricating oils and additives play a critical factor in controlling the amount of friction loss in an engine. [14, 15]

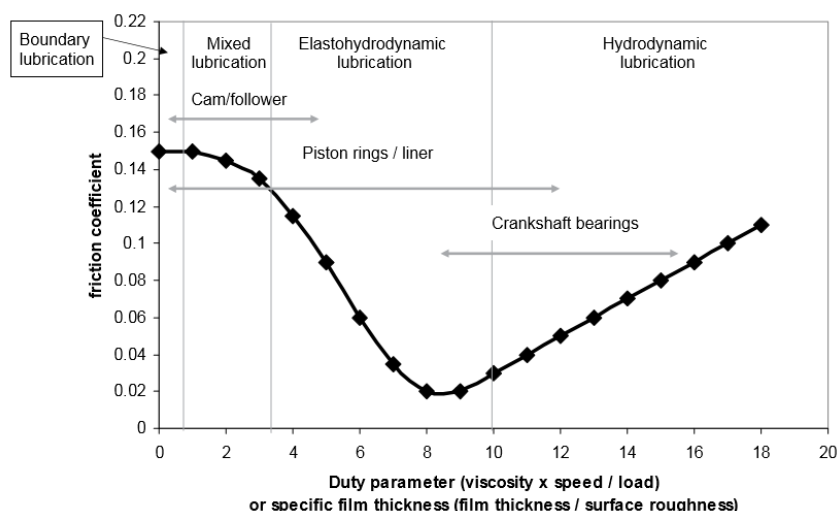


Figure 4

Boundary Lubrication—this is when the speed is very low, resulting in no pressure build up in the lubricant and the loading is 100% carried by the asperities in the contact area, protected by absorbed molecules of the lubricant and a thin oxide layer. Characteristic for boundary lubrication is the absence of hydrodynamic pressure. Dry contact is excluded from boundary lubrication. [15]

Mixed Lubrication—this is when the speed increased and the hydrodynamic pressure has build up in the lubricant. The characteristic for mixed lubrication is when the loading is carried by a combination of the hydrodynamic pressure and the contact pressure between the asperities of both surfaces. It is the intermediate region between boundary lubrication and hydrodynamic lubrication. [15]

(Elasto) Hydrodynamic Lubrication- At high speed the hydrodynamic pressure increases such that the surface asperities are completely separated by a lubricant film. The characteristic for hydrodynamic lubrication is when the load and hydrodynamic pressure are in equilibrium. [15]

Conclusion

This thesis has investigated and explained the friction created by the piston skirt, rings and the valve train. When investigating piston friction it is clear to see introducing a crank off set rapidly reduced the friction created by the engine. As seen in graph 2, introducing a 10mm crank offset has a dramatic effect on reducing the friction. When considering a crank offset it is important to consider how this effects the stroke as seen in graph 1, as the offset increase the stroke also increases.

When observing graph 17, it was clear to see the calculated FMEP followed the same curve as the actual FMEP but was much higher. When investigating this it was found that the coefficient of friction changes with RPM, this was not implemented in the friction models. Therefore the friction would be expected to be higher in the calculated FMEP.

Evaluation

As a whole I believe the thesis was successful in furthering my understanding and knowledge of the friction created by an engine. Most of the data was provided, the most challenging and time consuming part of the thesis was obtaining the smooth valve lift data. This was due to the amount of measurements that had to be repeated, as various attempts to smooth the data failed.

This has increased my understanding of the information and equations needed to create a friction model and calculate the FMEP and IMEP. I feel that the thesis was successful, it is well presented, clear to read and contains all the relevant information.

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Appendix

The FMEP Skirt model for the 1.6 Turbo engine

Piston and Rod Mass friction - Excel

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P21

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Mass of Piston (Kg)	R (m)	L (m)	R/L	RPM	w (rads/sec)	BORE (m)	Mue								
0.488	0.0407	0.134	0.3037313	6000	628.3185307	0.079	0.1								
Crank Angle (Degrees)	Crank Angle (Radians)	Average Pressure (Bar)	Average Pressure (N/m^2)	Fgas (N)	Inertia Force (N)	Fnet (N)	Fside (N)	Friction (N)	RodAngle (Radians)	Piston Travle (m)	WD (J)	TOTAL WD/cykle (J)	Fmep (N/m^2)	Fmep (Bar)	
-360	=RADIANS(A6)	3.22475	322475	1580.666013	10222.6163	-8641.95	-6.4E-13	-6.4E-14	7.44E-17	0	1.85E-05	47.5780608	118945.2	1.189452	
-359	=RADIANS(A7)	3.202	320200	1569.514714	10221.05935	-8651.54	-45.8611	-4.58611	0.005301	8.08145E-06	0.000167				
-358	=RADIANS(A8)	3.1765	317650	1557.015456	10216.38896	-8659.37	-91.7951	-9.17951	0.0106	3.23218E-05	0.000463				
-357	=RADIANS(A9)	3.167	316700	1552.358869	10208.60656	-8656.25	-137.618	-13.7618	0.015897	7.27089E-05	0.000907				
-356	=RADIANS(A10)	3.14425	314425	1541.20757	10197.71452	-8656.51	-183.449	-18.3449	0.021189	0.000129223	0.001498				
-355	=RADIANS(A11)	3.11875	311875	1528.708312	10183.71616	-8655.01	-229.195	-22.9195	0.026475	0.000201835	0.002235				
-354	=RADIANS(A12)	3.08975	308975	1514.493469	10166.61574	-8652.12	-274.831	-27.4831	0.031754	0.00029051	0.003115				
-353	=RADIANS(A13)	3.06075	306075	1500.278626	10146.41847	-8646.14	-320.261	-32.0261	0.037024	0.000395203	0.004138				
-352	=RADIANS(A14)	3.01925	301925	1479.936696	10123.1305	-8643.19	-365.685	-36.5685	0.042284	0.000515863	0.005303				
-351	=RADIANS(A15)	2.9745	297450	1458.001723	10096.75893	-8638.76	-410.926	-41.0926	0.047532	0.000652428	0.006602				
-350	=RADIANS(A16)	2.9455	294550	1443.78688	10067.31179	-8623.52	-455.459	-45.5459	0.052767	0.000804832	0.008032				
-349	=RADIANS(A17)	2.907	290700	1424.915451	10034.79805	-8609.88	-499.823	-49.9823	0.057987	0.000972999	0.009597				
-348	=RADIANS(A18)	2.8525	285250	1398.20135	9999.227608	-8601.03	-544.235	-54.4235	0.063191	0.001156844	0.011298				
-347	=RADIANS(A19)	2.782	278200	1363.644577	9960.611307	-8596.97	-588.761	-58.8761	0.068378	0.001356278	0.013137				
-346	=RADIANS(A20)	2.689	268900	1318.059046	9918.960908	-8600.9	-633.701	-63.3701	0.073546	0.0015712	0.015098				
-345	=RADIANS(A21)	2.61825	261825	1283.379731	9874.289097	-8590.91	-677.44	-67.744	0.078693	0.001801504	0.017163				

Piston and Rod Mass friction - Excel

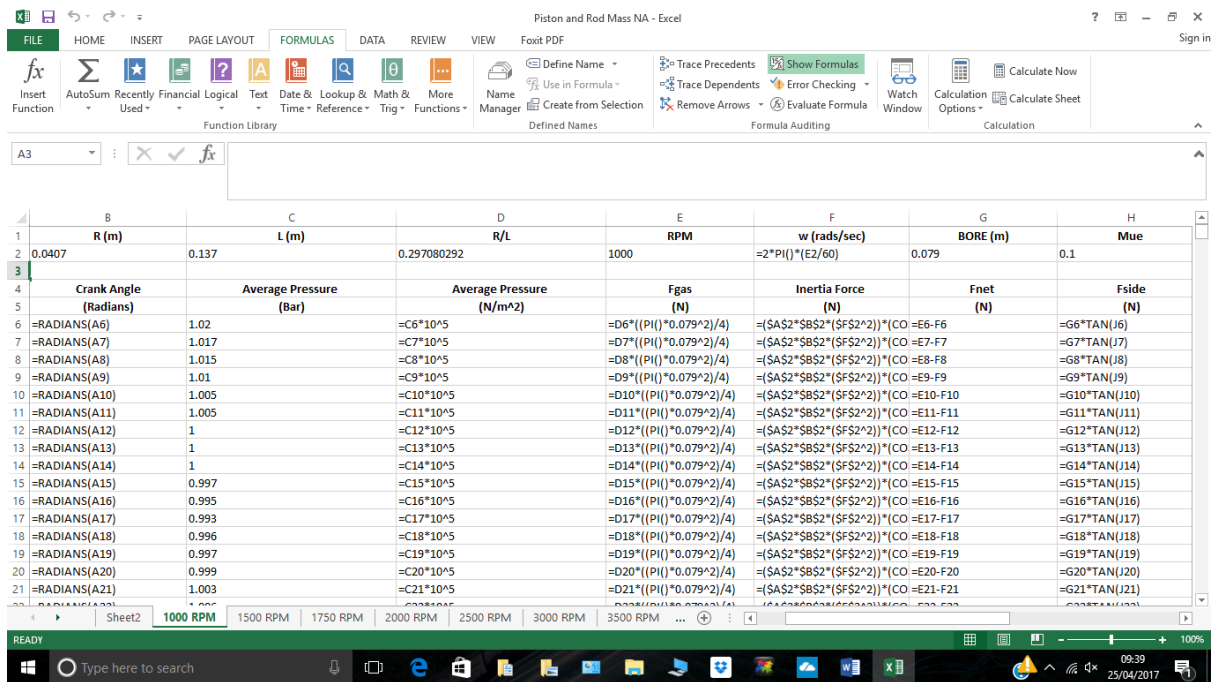
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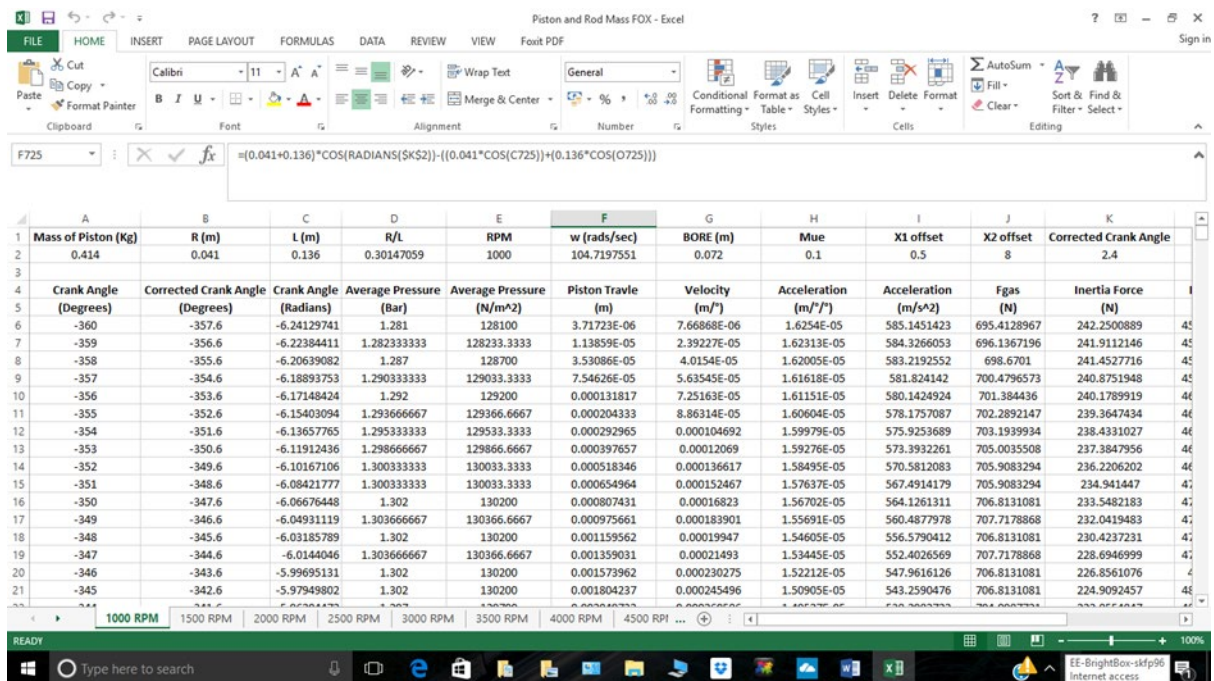
P21

A	B	C	D	E	F	G
Mass of Piston (Kg)	R (m)	L (m)	R/L	RPM	w (rads/sec)	BORE (m)
0.488	0.0407	0.134	0.3037313	6000	=2*PI()*E2/60	0.079
Crank Angle (Degrees)	Crank Angle (Radians)	Average Pressure (Bar)	Average Pressure (N/m^2)	Fgas (N)	Inertia Force (N)	Fnet (N)
-360	=RADIANS(A6)	3.22475	=C6*10^5	=D6*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E6-F6	
-359	=RADIANS(A7)	3.202	=C7*10^5	=D7*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E7-F7	
-358	=RADIANS(A8)	3.1765	=C8*10^5	=D8*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E8-F8	
-357	=RADIANS(A9)	3.167	=C9*10^5	=D9*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E9-F9	
-356	=RADIANS(A10)	3.14425	=C10*10^5	=D10*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E10-F10	
-355	=RADIANS(A11)	3.11875	=C11*10^5	=D11*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E11-F11	
-354	=RADIANS(A12)	3.08975	=C12*10^5	=D12*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E12-F12	
-353	=RADIANS(A13)	3.06075	=C13*10^5	=D13*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E13-F13	
-352	=RADIANS(A14)	3.01925	=C14*10^5	=D14*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E14-F14	
-351	=RADIANS(A15)	2.9745	=C15*10^5	=D15*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E15-F15	
-350	=RADIANS(A16)	2.9455	=C16*10^5	=D16*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E16-F16	
-349	=RADIANS(A17)	2.907	=C17*10^5	=D17*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E17-F17	
-348	=RADIANS(A18)	2.8525	=C18*10^5	=D18*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E18-F18	
-347	=RADIANS(A19)	2.782	=C19*10^5	=D19*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E19-F19	
-346	=RADIANS(A20)	2.689	=C20*10^5	=D20*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E20-F20	
-345	=RADIANS(A21)	2.61825	=C21*10^5	=D21*((PI()*0.079^2)/4)	=(A\$2*\$B\$2*(F\$2^2))*(COI=E21-F21	

[illegible]



The FMEP Skirt model for the 1.0 Turbo engine



The screenshot displays an Excel spreadsheet titled "Piston and Rod Mass FOX - Excel". The spreadsheet is used for calculating the mass of a piston and rod. The columns are labeled as follows:

- Column A:** Mass of Piston (Kg)
- Column B:** R (m)
- Column C:** L (m)
- Column D:** R/L
- Column E:** RPM
- Column F:** Piston Tr (m)

The data is organized into rows, with the first row (Row 1) containing the headers. The subsequent rows (Rows 2-24) contain numerical data and formulas. The formula bar at the top shows the calculation for R/L:

$$=(0.041+0.136)*\cos(\text{RADIANS}(\$K\$2))-((0.041*\cos(C725)))+(0.136*\cos(C725)))$$

The spreadsheet also includes a "Formula Auditing" tab and a "Calculation" section on the right side of the ribbon.

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IMEP - Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Average Pressure (Bar)	Average Pressure (N/m ²)	Volume (Cubic Centimeters)	Volume (Cubic Metres)	WD/* by gas (J)	TOTAL WD BY GAS (J)	Imep (N/m ²)	Imep (Bar)								
3	3.22475	322475	44.44	0.00004444	0.0128535	726.3140633	1815785.158	18.15785158								
4	3.202	320200	44.48	0.00004448	0.038271											
5	3.1765	317650	44.6	0.0000446	0.063435											
6	3.167	316700	44.8	0.0000448	0.085201875											
7	3.14425	314425	45.07	0.00004507	0.112734											
8	3.11875	311875	45.43	0.00004543	0.13348275											
9	3.08975	308975	45.86	0.00004586	0.15683775											
10	3.06075	306075	46.37	0.00004637	0.17936											
11	3.01925	301925	46.96	0.00004696	0.19779375											
12	2.9745	297450	47.62	0.00004762	0.222											
13	2.9455	294550	48.37	0.00004837	0.2399525											
14	2.907	290700	49.19	0.00004919	0.25629775											
15	2.8525	285250	50.08	0.00005008	0.2760905											
16	2.782	278200	51.06	0.00005106	0.284492											
17	2.689	268900	52.1	0.0000521	0.299859625											
18	2.61825	261825	53.23	0.00005323	0.310365											
19	2.5545	255450	54.43	0.00005443	0.320532125											
20	2.49325	249325	55.7	0.0000557	0.33022625											
21	2.4355	243550	57.04	0.00005704	0.34081775											

IMEP - Excel

	A	B	C	D	E	F
	Average Pressure (Bar)	Average Pressure (N/m ²)	Volume (Cubic Centimeters)	Volume (Cubic Metres)	WD/* by gas (J)	TOTAL WD BY GAS (J)
3	3.22475	=A3*10^5	44.44	=C3*10^-6	=(B3+B4)/2*(D4-D3)	=SUM(E:E)
4	3.202	=A4*10^5	44.48	=C4*10^-6	=(B4+B5)/2*(D5-D4)	
5	3.1765	=A5*10^5	44.6	=C5*10^-6	=(B5+B6)/2*(D6-D5)	
6	3.167	=A6*10^5	44.8	=C6*10^-6	=(B6+B7)/2*(D7-D6)	
7	3.14425	=A7*10^5	45.07	=C7*10^-6	=(B7+B8)/2*(D8-D7)	
8	3.11875	=A8*10^5	45.43	=C8*10^-6	=(B8+B9)/2*(D9-D8)	
9	3.08975	=A9*10^5	45.86	=C9*10^-6	=(B9+B10)/2*(D10-D9)	
10	3.06075	=A10*10^5	46.37	=C10*10^-6	=(B10+B11)/2*(D11-D10)	
11	3.01925	=A11*10^5	46.96	=C11*10^-6	=(B11+B12)/2*(D12-D11)	
12	2.9745	=A12*10^5	47.62	=C12*10^-6	=(B12+B13)/2*(D13-D12)	
13	2.9455	=A13*10^5	48.37	=C13*10^-6	=(B13+B14)/2*(D14-D13)	
14	2.907	=A14*10^5	49.19	=C14*10^-6	=(B14+B15)/2*(D15-D14)	
15	2.8525	=A15*10^5	50.08	=C15*10^-6	=(B15+B16)/2*(D16-D15)	
16	2.782	=A16*10^5	51.06	=C16*10^-6	=(B16+B17)/2*(D17-D16)	
17	2.689	=A17*10^5	52.1	=C17*10^-6	=(B17+B18)/2*(D18-D17)	
18	2.61825	=A18*10^5	53.23	=C18*10^-6	=(B18+B19)/2*(D19-D18)	
19	2.5545	=A19*10^5	54.43	=C19*10^-6	=(B19+B20)/2*(D20-D19)	
20	2.49325	=A20*10^5	55.7	=C20*10^-6	=(B20+B21)/2*(D21-D20)	
21	2.4355	=A21*10^5	57.04	=C21*10^-6	=(B21+B22)/2*(D22-D21)	

The IMEP model for the 1.6 naturally aspirated engine

IMEP for NA Engine - Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Average Pressure (Bar)	Average Pressure (N/m ²)	Volume (Cubic Centimetres)	Volume (Cubic Metres)	WD/* by gas (J)	TOTAL WD BY GAS (J)	Imep (N/m ²)	Imep (Bar)								
3	1.079	107900	39.27	0.00003927	0.004278	493.331919	1233329.798	12.33329798								
4	1.06	106000	39.31	0.00003931	0.01251											
5	1.025	102500	39.43	0.00003943	0.02002											
6	0.977	97700	39.63	0.00003963	0.0258255											
7	0.936	93600	39.9	0.0000399	0.033408											
8	0.92	92000	40.26	0.00004026	0.039646											
9	0.924	92400	40.69	0.00004069	0.046767											
10	0.91	91000	41.2	0.0000412	0.052628											
11	0.874	87400	41.79	0.00004179	0.056463											
12	0.837	83700	42.45	0.00004245	0.0618											
13	0.811	81100	43.2	0.0000432	0.065764											
14	0.793	79300	44.02	0.00004402	0.0703545											
15	0.788	78800	44.91	0.00004491	0.078106											
16	0.806	80600	45.89	0.00004589	0.085384											
17	0.836	83600	46.93	0.00004693	0.096163											
18	0.866	86600	48.06	0.00004806	0.10458											
19	0.877	87700	49.26	0.00004926	0.1113155											
20	0.876	87600	50.53	0.00005053	0.117116											
21	0.872	87200	51.87	0.00005187	0.122688											

IMEP for NA Engine - Excel

	A	B	C	D	E	F
	Average Pressure (Bar)	Average Pressure (N/m ²)	Volume (Cubic Centimetres)	Volume (Cubic Metres)	WD/* by gas (J)	TOTAL WD BY GAS (J)
3	1.079	=A3*10^5	39.27	=C3*10^-6	=(B3+B4)/2*(D4-D3)	=SUM(E:E)
4	1.06	=A4*10^5	39.31	=C4*10^-6	=(B4+B5)/2*(D5-D4)	
5	1.025	=A5*10^5	39.43	=C5*10^-6	=(B5+B6)/2*(D6-D5)	
6	0.977	=A6*10^5	39.63	=C6*10^-6	=(B6+B7)/2*(D7-D6)	
7	0.936	=A7*10^5	39.9	=C7*10^-6	=(B7+B8)/2*(D8-D7)	
8	0.92	=A8*10^5	40.26	=C8*10^-6	=(B8+B9)/2*(D9-D8)	
9	0.924	=A9*10^5	40.69	=C9*10^-6	=(B9+B10)/2*(D10-D9)	
10	0.91	=A10*10^5	41.2	=C10*10^-6	=(B10+B11)/2*(D11-D10)	
11	0.874	=A11*10^5	41.79	=C11*10^-6	=(B11+B12)/2*(D12-D11)	
12	0.837	=A12*10^5	42.45	=C12*10^-6	=(B12+B13)/2*(D13-D12)	
13	0.811	=A13*10^5	43.2	=C13*10^-6	=(B13+B14)/2*(D14-D13)	
14	0.793	=A14*10^5	44.02	=C14*10^-6	=(B14+B15)/2*(D15-D14)	
15	0.788	=A15*10^5	44.91	=C15*10^-6	=(B15+B16)/2*(D16-D15)	
16	0.806	=A16*10^5	45.89	=C16*10^-6	=(B16+B17)/2*(D17-D16)	
17	0.836	=A17*10^5	46.93	=C17*10^-6	=(B17+B18)/2*(D18-D17)	
18	0.866	=A18*10^5	48.06	=C18*10^-6	=(B18+B19)/2*(D19-D18)	
19	0.877	=A19*10^5	49.26	=C19*10^-6	=(B19+B20)/2*(D20-D19)	
20	0.876	=A20*10^5	50.53	=C20*10^-6	=(B20+B21)/2*(D21-D20)	
21	0.872	=A21*10^5	51.87	=C21*10^-6	=(B21+B22)/2*(D22-D21)	

The IMEP model for the 1.0 Turbo engine

IMEP for FOX Engine - Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Average Pressure (Bar)	Average Pressure (N/m ²)	Volume (Cubic Centimetres)	Volume (Cubic Metres)	WD/* by gas (J)	TOTAL WD BY GAS (J)	Imep (N/m ²)	Imep (Bar)								
1																
2	2.754	275400	37.05	0.00003705	0.010981333	672.0038592	1680009.648	16.80009648								
3	2.736666667	273666.6667	37.09	0.00003709	0.027181667											
4	2.699666667	269966.6667	37.19	0.00003719	0.042885333											
5	2.661	266100	37.35	0.00003735	0.060505333											
6	2.600333333	260033.3333	37.58	0.00003758	0.077675											
7	2.578	257800	37.88	0.00003788	0.091848											
8	2.524666667	252466.6667	38.24	0.00003824	0.10479											
9	2.465333333	246533.3333	38.66	0.00003866	0.119625333											
10	2.417333333	241733.3333	39.15	0.00003915	0.133718667											
11	2.358333333	235833.3333	39.71	0.00003971	0.144026											
12	2.287666667	228766.6667	40.33	0.00004033	0.153702667											
13	2.233	223300	41.01	0.00004101	0.16585											
14	2.189666667	218966.6667	41.76	0.00004176	0.1754055											
15	2.141333333	214133.3333	42.57	0.00004257	0.184498											
16	2.1	210000	43.44	0.00004344	0.195441667											
17	2.058333333	205833.3333	44.38	0.00004438	0.203883333											
18	2.019333333	201933.3333	45.38	0.00004538	0.212035333											
19	1.981333333	198133.3333	46.44	0.00004644	0.2181335											
20	1.949	194900	47.55	0.00004755	0.227936667											
21																

3000 RPM 3500 RPM 4000 RPM 4500 RPM 5000 RPM 5500 RPM 6000 RPM

IMEP for FOX Engine - Excel

	A	B	C	D	E	F
	Average Pressure (Bar)	Average Pressure (N/m ²)	Volume (Cubic Centimetres)	Volume (Cubic Metres)	WD/* by gas (J)	TOTAL WD BY GAS (J)
1						
2						
3	2.754	=A3*10^5	37.05	=C3*10^-6	=(B3+B4)/2*(D4-D3)	=SUM(E:E)
4	2.736666667	=A4*10^5	37.09	=C4*10^-6	=(B4+B5)/2*(D5-D4)	
5	2.699666667	=A5*10^5	37.19	=C5*10^-6	=(B5+B6)/2*(D6-D5)	
6	2.661	=A6*10^5	37.35	=C6*10^-6	=(B6+B7)/2*(D7-D6)	
7	2.600333333	=A7*10^5	37.58	=C7*10^-6	=(B7+B8)/2*(D8-D7)	
8	2.578	=A8*10^5	37.88	=C8*10^-6	=(B8+B9)/2*(D9-D8)	
9	2.524666667	=A9*10^5	38.24	=C9*10^-6	=(B9+B10)/2*(D10-D9)	
10	2.465333333	=A10*10^5	38.66	=C10*10^-6	=(B10+B11)/2*(D11-D10)	
11	2.417333333	=A11*10^5	39.15	=C11*10^-6	=(B11+B12)/2*(D12-D11)	
12	2.358333333	=A12*10^5	39.71	=C12*10^-6	=(B12+B13)/2*(D13-D12)	
13	2.287666667	=A13*10^5	40.33	=C13*10^-6	=(B13+B14)/2*(D14-D13)	
14	2.233	=A14*10^5	41.01	=C14*10^-6	=(B14+B15)/2*(D15-D14)	
15	2.189666667	=A15*10^5	41.76	=C15*10^-6	=(B15+B16)/2*(D16-D15)	
16	2.141333333	=A16*10^5	42.57	=C16*10^-6	=(B16+B17)/2*(D17-D16)	
17	2.1	=A17*10^5	43.44	=C17*10^-6	=(B17+B18)/2*(D18-D17)	
18	2.058333333	=A18*10^5	44.38	=C18*10^-6	=(B18+B19)/2*(D19-D18)	
19	2.019333333	=A19*10^5	45.38	=C19*10^-6	=(B19+B20)/2*(D20-D19)	
20	1.981333333	=A20*10^5	46.44	=C20*10^-6	=(B20+B21)/2*(D21-D20)	
21	1.949	=A21*10^5	47.55	=C21*10^-6	=(B21+B22)/2*(D22-D21)	

3000 RPM 3500 RPM 4000 RPM 4500 RPM 5000 RPM 5500 RPM 6000 RPM

The FMEP model of the piston ring friction

Piston Ring Friction - Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M
	Mass of Piston (Kg)	R (m)	L (m)	R/L	RPM	w (rads/sec)	BORE (m)	Mue	1st ring thickness (m)	1nd ring diamiter (m)			
1	0.488	0.0407	0.134	0.3037313	6000	628.3185307	0.079	0.1	0.00115	0.077			
4	Crank Angle (Degrees)	Crank Angle (Radians)	Average Pressure (Bar)	Average Pressure (N/m^2)	Fgas (N)	Inertia Force (N)	Fnet (N)	Fradiat (N)	Friction (N)	RodAngle (Radians)	Piston Travle (m)	WD (J)	TOTAL WD/cycle (J)
6	-360	=RADIANS(A6)	3.22475	322475	1580.666013	10222.6163	-8641.95	89.70868	8.970868481	7.44232E-17	0	7.22E-05	9.762955724
7	-359	=RADIANS(A7)	3.202	320200	1569.514714	10221.05935	-8651.54	89.07581	8.907580704	0.005300867	8.08145E-06	0.000215	
8	-358	=RADIANS(A8)	3.1765	317650	1557.015456	10216.38896	-8659.37	88.36643	8.836642756	0.010600268	3.23218E-05	0.000356	
9	-357	=RADIANS(A9)	3.167	316700	1552.358869	10208.60656	-8656.25	88.10215	8.810214893	0.015896738	7.27089E-05	0.000496	
10	-356	=RADIANS(A10)	3.14425	314425	1541.20757	10197.71452	-8656.51	87.46927	8.746927117	0.02118881	0.000129223	0.000633	
11	-355	=RADIANS(A11)	3.11875	311875	1528.708312	10183.71616	-8655.01	86.75989	8.675989169	0.02647502	0.000201835	0.000766	
12	-354	=RADIANS(A12)	3.08975	308975	1514.493469	10166.61574	-8652.12	85.95315	8.595314641	0.031753902	0.00029051	0.000896	
13	-353	=RADIANS(A13)	3.06075	306075	1500.278626	10146.41847	-8646.14	85.1464	8.514640112	0.037023992	0.000395203	0.00102	
14	-352	=RADIANS(A14)	3.01925	301925	1479.936696	10123.1305	-8643.19	83.99192	8.39919208	0.042283826	0.000515863	0.001139	
15	-351	=RADIANS(A15)	2.9745	297450	1458.001723	10096.75893	-8638.76	82.74703	8.274702937	0.047531939	0.000652428	0.001255	
16	-350	=RADIANS(A16)	2.9455	294550	1443.78688	10067.31179	-8623.52	81.94028	8.194028408	0.05276687	0.000804832	0.001369	
17	-349	=RADIANS(A17)	2.907	290700	1424.915451	10034.79805	-8609.88	80.86926	8.086926017	0.057987156	0.000972999	0.001473	
18	-348	=RADIANS(A18)	2.8525	285250	1398.20135	9999.227608	-8601.03	79.35314	7.935313541	0.063191335	0.001156844	0.001563	
19	-347	=RADIANS(A19)	2.782	278200	1363.644577	9960.611307	-8596.97	77.39191	7.73919098	0.068377948	0.001356278	0.001636	
20	-346	=RADIANS(A20)	2.689	268900	1318.059046	9918.960908	-8600.9	74.80476	7.480476113	0.073545535	0.0015712	0.0017	
21	-345	=RADIANS(A21)	2.61825	261825	1283.379731	9874.289097	-8590.91	72.83658	7.283658082	0.078692638	0.001801504	0.001767	

Piston Ring Friction - Excel

	A	B	C	D	E	F	G
	Mass of Piston (Kg)	R (m)	L (m)	R/L	RPM	w (rads/sec)	BORE (m)
1	0.488	0.0407	0.134	0.3037313	6000	=2*PI()/E2/60	0.079
4	Crank Angle (Degrees)	Crank Angle (Radians)	Average Pressure (Bar)	Average Pressure (N/m^2)	Fgas (N)	Inertia Force (N)	Fnet (N)
6	-360	=RADIANS(A6)	3.22475	=C6*10^5	=D6*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E6-F6	
7	-359	=RADIANS(A7)	3.202	=C7*10^5	=D7*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E7-F7	
8	-358	=RADIANS(A8)	3.1765	=C8*10^5	=D8*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E8-F8	
9	-357	=RADIANS(A9)	3.167	=C9*10^5	=D9*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E9-F9	
10	-356	=RADIANS(A10)	3.14425	=C10*10^5	=D10*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E10-F10	
11	-355	=RADIANS(A11)	3.11875	=C11*10^5	=D11*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E11-F11	
12	-354	=RADIANS(A12)	3.08975	=C12*10^5	=D12*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E12-F12	
13	-353	=RADIANS(A13)	3.06075	=C13*10^5	=D13*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E13-F13	
14	-352	=RADIANS(A14)	3.01925	=C14*10^5	=D14*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E14-F14	
15	-351	=RADIANS(A15)	2.9745	=C15*10^5	=D15*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E15-F15	
16	-350	=RADIANS(A16)	2.9455	=C16*10^5	=D16*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E16-F16	
17	-349	=RADIANS(A17)	2.907	=C17*10^5	=D17*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E17-F17	
18	-348	=RADIANS(A18)	2.8525	=C18*10^5	=D18*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E18-F18	
19	-347	=RADIANS(A19)	2.782	=C19*10^5	=D19*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E19-F19	
20	-346	=RADIANS(A20)	2.689	=C20*10^5	=D20*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E20-F20	
21	-345	=RADIANS(A21)	2.61825	=C21*10^5	=D21*((PI()*0.079^2)/4)	=(\$A\$2*\$B\$2*(SF\$2^2))*(COI=E21-F21	

The FMEP model of the exhaust valve

Valve Lift Exhaust - Excel

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M11

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1		Spring Rate (N/mm)	Engine Capacity	Mue	RPM		Initial Compression (mm)	Mass (Kg)						
2		14.36	1600	0.1	3000		5	0.06785						
4	CAM Angle (Degrees)	Average Lift (mm)	Velocity (mm/Degree)	Acceleration (mm/Degree/Degree)	Acceleration (M/S/S)	Inertia Force (N)	Spring Force (N)	FC (N)	FF (N)	x (m)	x2-x1 (m)	Work Done/D (J)	Total Work Done (J)	FMEI (N/m²)
6	0	0	0	0	0	0	71.8	71.8	71.8	0	0	0	19.78233312	12363.
7	1	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
8	2	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
9	3	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
10	4	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
11	5	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
12	6	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
13	7	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
14	8	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
15	9	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
16	10	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
17	11	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
18	12	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
19	13	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
20	14	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
21	15	0	0	0	0	0	71.8	71.8	71.8	0	0	0		

3,000 RPM 3,500 RPM 4,000 RPM 4,500 RPM 5,000 RPM 5,500 RPM 6,000 RPM FF ...

Valve Lift Exhaust - Excel

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M11

	A	B	C	D	E	F	
1		Spring Rate (N/mm)	Engine Capacity	Mue	RPM		
2		14.36	1600	0.1	3000		5
4	CAM Angle (Degrees)	Average Lift (mm)	Velocity (mm/Degree)	Acceleration (mm/Degree/Degree)	Acceleration (M/S/S)	Inertia Force (N)	
6	0	0	=B7-B6	=C7-C6	=(D6)*((6*\$E\$2)^2)	=\$A\$2*E6	=\$B\$2
7	1	0	=B8-B7	=C8-C7	=(D7)*((6*\$E\$2)^2)	=\$A\$2*E7	=\$B\$2
8	2	0	=B9-B8	=C9-C8	=(D8)*((6*\$E\$2)^2)	=\$A\$2*E8	=\$B\$2
9	3	0	=B10-B9	=C10-C9	=(D9)*((6*\$E\$2)^2)	=\$A\$2*E9	=\$B\$2
10	4	0	=B11-B10	=C11-C10	=(D10)*((6*\$E\$2)^2)	=\$A\$2*E10	=\$B\$2
11	5	0	=B12-B11	=C12-C11	=(D11)*((6*\$E\$2)^2)	=\$A\$2*E11	=\$B\$2
12	6	0	=B13-B12	=C13-C12	=(D12)*((6*\$E\$2)^2)	=\$A\$2*E12	=\$B\$2
13	7	0	=B14-B13	=C14-C13	=(D13)*((6*\$E\$2)^2)	=\$A\$2*E13	=\$B\$2
14	8	0	=B15-B14	=C15-C14	=(D14)*((6*\$E\$2)^2)	=\$A\$2*E14	=\$B\$2
15	9	0	=B16-B15	=C16-C15	=(D15)*((6*\$E\$2)^2)	=\$A\$2*E15	=\$B\$2
16	10	0	=B17-B16	=C17-C16	=(D16)*((6*\$E\$2)^2)	=\$A\$2*E16	=\$B\$2
17	11	0	=B18-B17	=C18-C17	=(D17)*((6*\$E\$2)^2)	=\$A\$2*E17	=\$B\$2
18	12	0	=B19-B18	=C19-C18	=(D18)*((6*\$E\$2)^2)	=\$A\$2*E18	=\$B\$2
19	13	0	=B20-B19	=C20-C19	=(D19)*((6*\$E\$2)^2)	=\$A\$2*E19	=\$B\$2
20	14	0	=B21-B20	=C21-C20	=(D20)*((6*\$E\$2)^2)	=\$A\$2*E20	=\$B\$2
21	15	0	=B22-B21	=C22-C21	=(D21)*((6*\$E\$2)^2)	=\$A\$2*E21	=\$B\$2

3,000 RPM 3,500 RPM 4,000 RPM 4,500 RPM 5,000 RPM 5,500 RPM 6,000 RPM FF ...

The FMEP model of the inlet valve

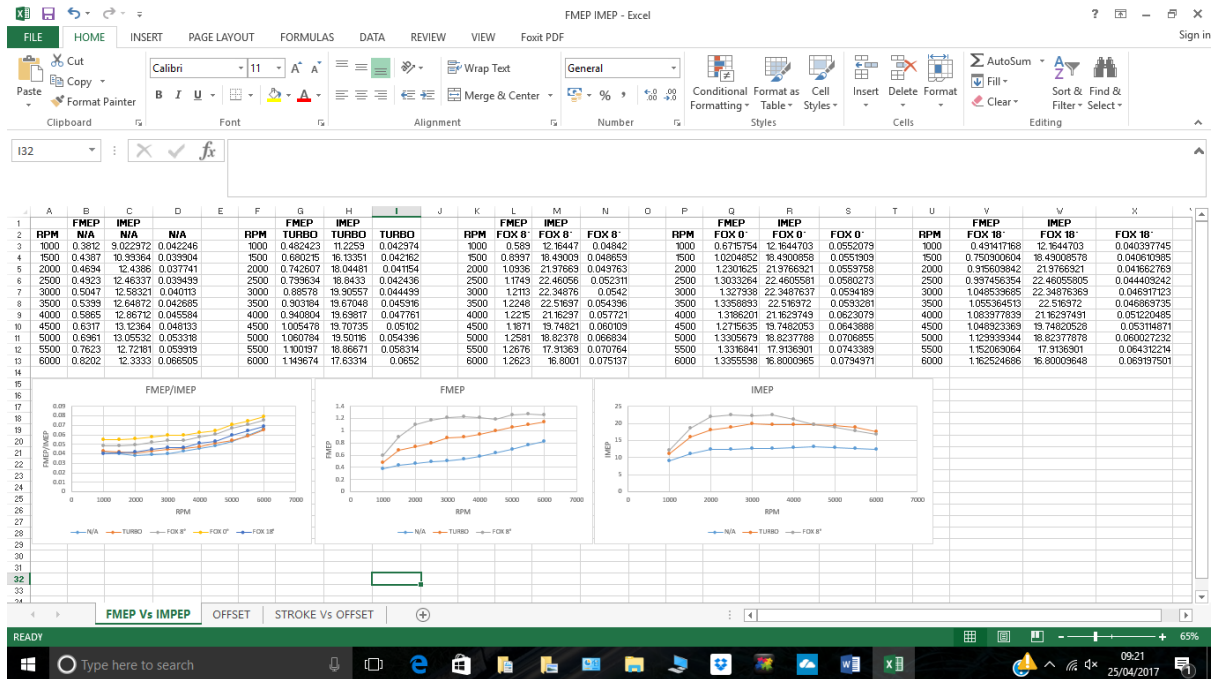
Valve Lift Exhaust - Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Mass (Kg)	Spring Rate (N/mm)	Engine Capacity	Mue	RPM		Initial Compression (mm)	Mass (Kg)						
2	0.0851	14.36	1600	0.1	3000		5	0.06785						
3														
4	CAM Angle	Average Lift	Velocity	Acceleration	Acceleration	Inertia Force	Spring Force	FC	FF	x	x2-x1	Work Done/D	Total Work Done	FMEI
5	(Degrees)	(mm)	(mm/Degree)	(mm/Degree/Degree)	(M/S/S)	(N)	(N)	(N)	(N)	(m)	(m)	(J)	(J)	(N/m)
6	0	0	0	0	0	0	71.8	71.8	71.8	0	0	0	19.78233312	12363.
7	1	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
8	2	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
9	3	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
10	4	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
11	5	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
12	6	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
13	7	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
14	8	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
15	9	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
16	10	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
17	11	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
18	12	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
19	13	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
20	14	0	0	0	0	0	71.8	71.8	71.8	0	0	0		
21	15	0	0	0	0	0	71.8	71.8	71.8	0	0	0		

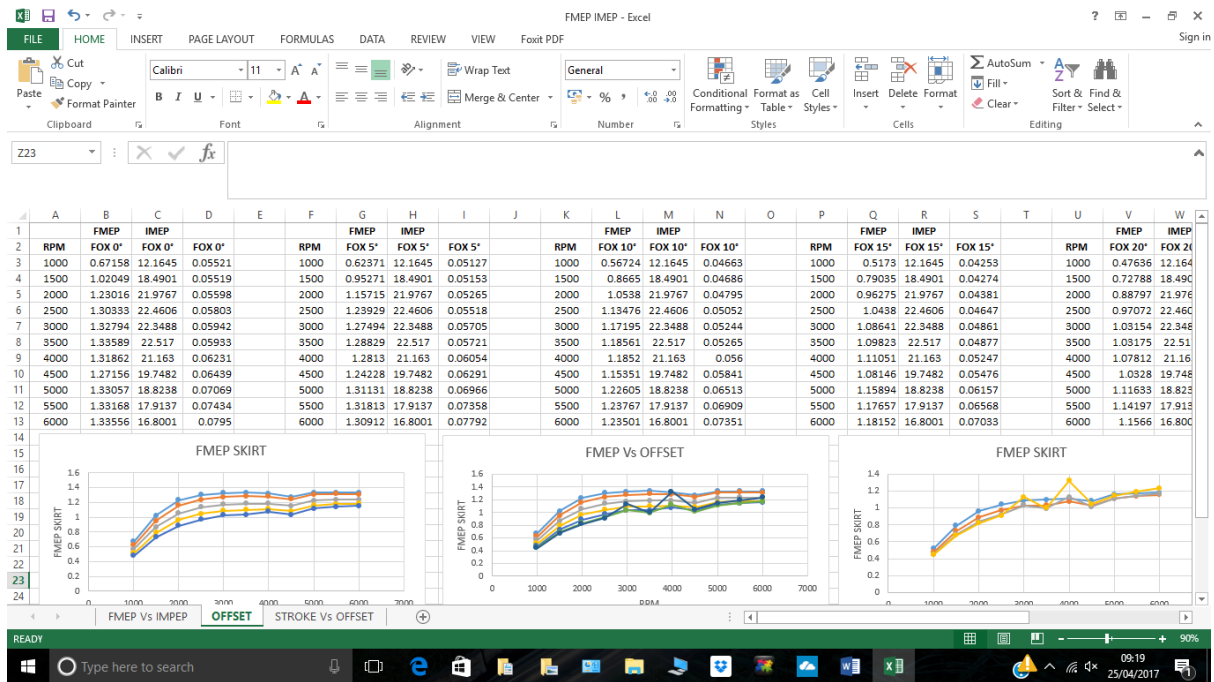
Valve Lift Exhaust - Excel

	A	B	C	D	E	F
1	Mass (Kg)	Spring Rate (N/mm)	Engine Capacity	Mue	RPM	
2	0.0851	14.36	1600	0.1	3000	5
3						
4	CAM Angle	Average Lift	Velocity	Acceleration	Acceleration	Inertia Force
5	(Degrees)	(mm)	(mm/Degree)	(mm/Degree/Degree)	(M/S/S)	(N)
6	0	0	=B7-B6	=C7-C6	=(D6)*((6*\$E\$2)^2)	=\$A\$2*E6
7	1	0	=B8-B7	=C8-C7	=(D7)*((6*\$E\$2)^2)	=\$A\$2*E7
8	2	0	=B9-B8	=C9-C8	=(D8)*((6*\$E\$2)^2)	=\$A\$2*E8
9	3	0	=B10-B9	=C10-C9	=(D9)*((6*\$E\$2)^2)	=\$A\$2*E9
10	4	0	=B11-B10	=C11-C10	=(D10)*((6*\$E\$2)^2)	=\$A\$2*E10
11	5	0	=B12-B11	=C12-C11	=(D11)*((6*\$E\$2)^2)	=\$A\$2*E11
12	6	0	=B13-B12	=C13-C12	=(D12)*((6*\$E\$2)^2)	=\$A\$2*E12
13	7	0	=B14-B13	=C14-C13	=(D13)*((6*\$E\$2)^2)	=\$A\$2*E13
14	8	0	=B15-B14	=C15-C14	=(D14)*((6*\$E\$2)^2)	=\$A\$2*E14
15	9	0	=B16-B15	=C16-C15	=(D15)*((6*\$E\$2)^2)	=\$A\$2*E15
16	10	0	=B17-B16	=C17-C16	=(D16)*((6*\$E\$2)^2)	=\$A\$2*E16
17	11	0	=B18-B17	=C18-C17	=(D17)*((6*\$E\$2)^2)	=\$A\$2*E17
18	12	0	=B19-B18	=C19-C18	=(D18)*((6*\$E\$2)^2)	=\$A\$2*E18
19	13	0	=B20-B19	=C20-C19	=(D19)*((6*\$E\$2)^2)	=\$A\$2*E19
20	14	0	=B21-B20	=C21-C20	=(D20)*((6*\$E\$2)^2)	=\$A\$2*E20
21	15	0	=B22-B21	=C22-C21	=(D21)*((6*\$E\$2)^2)	=\$A\$2*E21

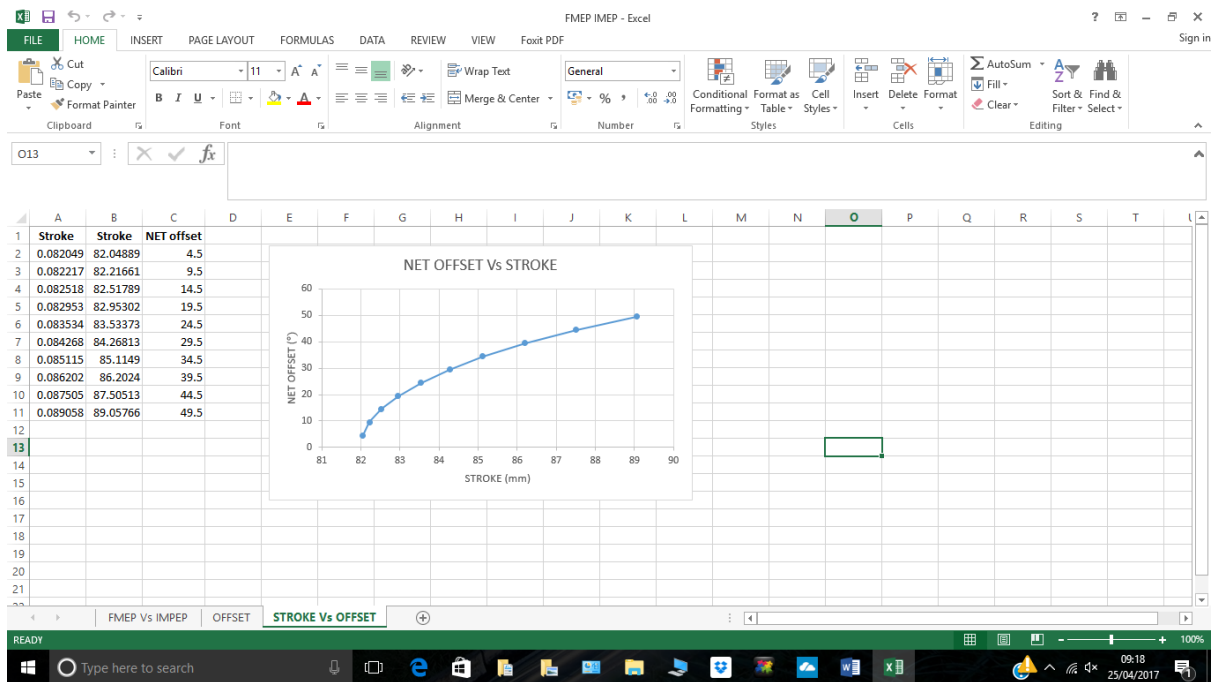
IMEP and FMEP graphs being produced



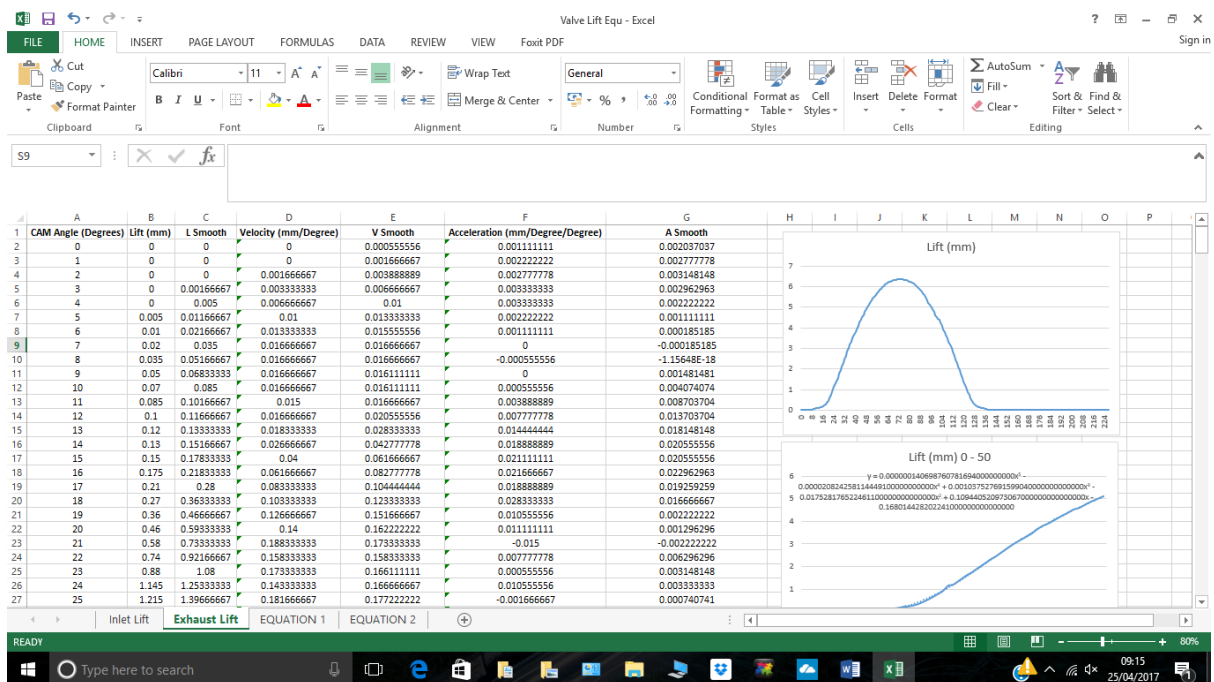
The FMEP against offset graphs

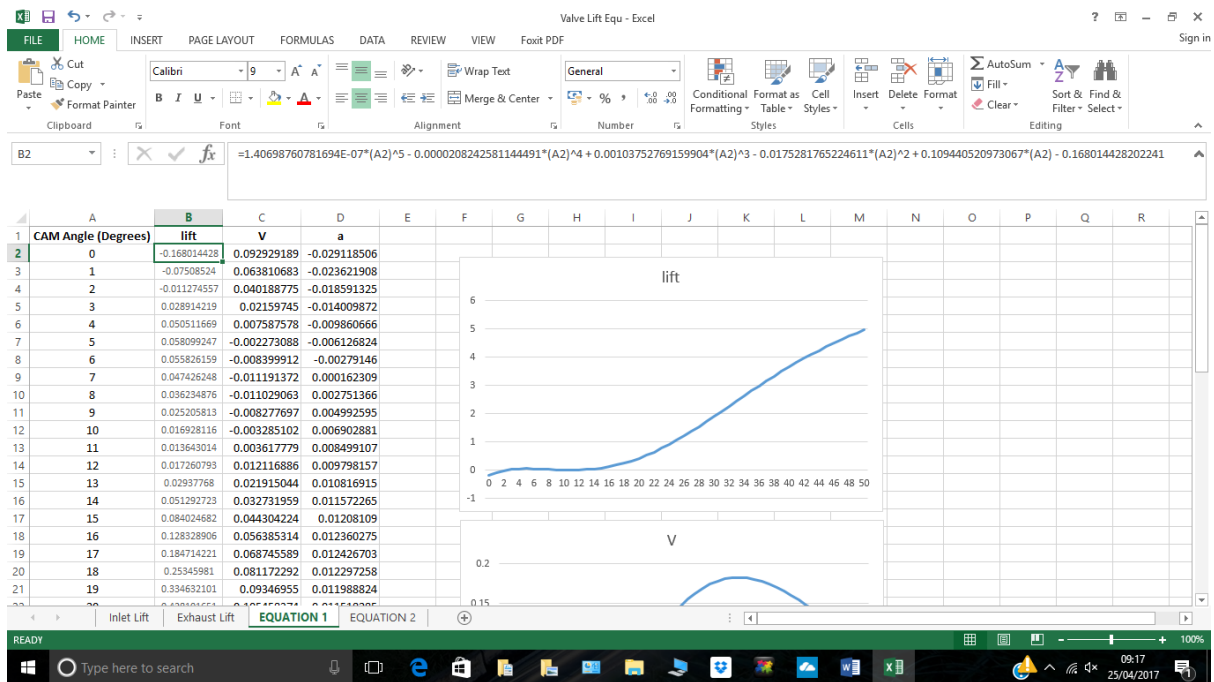


The net offset graph being produced



The polynomial being produced





Total FMEP graph being produced

