

Exploration of Energy Losses through the Exhaust system of a Turbo-Charged Engine

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P143397

BEng Advanced Engine Design

2018

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Declaration of Authenticity

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

Signed:

Date:

Acknowledgements

This project was completed with accountability checks, emotional support, patience, late-night car rides, sarcastic remarks, and guidance from Beth Downing, Timothy Tudor, Natasha Williams, Sarah Cronin, and Anisah 'Noreen' Haque.

Manufacturing/fabricating assistance and advice appreciated during the project is given by Paul Davies, who offers not just fantastic practical support no matter how busy, but also impressively horrendous puns.

Finally, immeasurable thanks are given to the project supervisor, Malcolm McDonald, who has continuously provided invaluable wisdom, guidance, random engine components, stories, and support.

Contents

Declaration of Authenticity	2
Acknowledgements.....	3
Abstract.....	6
Aims and Objectives	7
Initial Project.....	7
Turbo-charger Losses	7
Timing Plan.....	Error! Bookmark not defined.
Research / Literature Review	9
Final Project	9
Thermodynamic Principles.....	9
Ford Fox 1.0L EcoBoost Engine	9
Methodology	11
Initial Work	11
Final Project	13
Fuel Products Calculator.....	13
Data Maps	13
Enthalpies and polynomials	14
Transfer Efficiencies	15
Flowbenching the Turbocharger wastegate.....	15
Flowbenching a Turbo-charger.....	16
Combining Flowbench Data and Ford Data	17
Results & Analysis	18
Initial Project.....	18
PV Diagrams.....	18
MEPs	18
Work Done.....	21
Logarithmic PV diagrams	21
Polytropic Index & Mass Fraction Burned.....	22
Ignition Delay	Error! Bookmark not defined.
Turbo-charger Project.....	22
Polynomial Equations for Enthalpy.....	22
Power Losses	23
Flowbench Test.....	24

Combining Flowbench Data	25
Mass Percentage through Wastegate	25
Discussion and Conclusions	31
Recommended further work	32
References	Error! Bookmark not defined.
Bibliography	33
Appendix.....	34
Equations, Derivations, Basic Knowledge.....	34
P-V Diagrams	34
Work Done.....	35
Mean Effective Pressures	35
Engine Knock & Detonation	36
Polytropic Index Values & Pressure rise due to Combustion.....	36
Final Project.....	36
INITIAL PROJECT DIAGRAMS.....	41

Abstract

My final year project changed direction in December from creating a 2-zone combustion model using Ford Sigma and Ford Fox data, to only using Ford Fox dynamometer data to analyse the energy losses pre-turbocharger to post-turbocharger, and then to atmosphere.

This was done using a calculator created for a previous assignment that calculates the amount of each primary emission created for whichever fuel the user wants – gasoline is used for this engine. The calculator calculates the number of reactant molecules and product molecules for a fuel at either stoichiometric mix, or at varying fuel equivalence ratios for both rich and lean mixtures, and it also provides the enthalpy of formation.

The amount of each product for each fuel equivalence ratio (calculated using LAMBDA map in Ford data) allows the calculation of the enthalpy lost across the map for each area (across turbo and out to the atmosphere).

The same maps were used for the compressor, and as a result, compressor efficiencies can be mapped out, revealing what's happening at different loads and RPMs.

These maps have also been created for the intercooler to see how much energy must be removed because of the compressor energy gains.

The kW of energy out of the intercooler reveal the potential to recoup energy to potentially power a supercharger, however, this was not the focus of the project due to time constraints but would be fascinating for further work.

Aims and Objectives

Initial Project

The project started with an aim to explore the effects and benefits of a variable compression ratio (CR), and possible ways to implement it.

The objectives involved gaining a broad knowledge of combustion to form the basis for the analysis of the aim. This would be achieved through literature, lecturers, and data manipulation using Microsoft Excel.

The engine data used for this analysis was provided by Malcolm McDonald and was attained from Ford Motor Company. The dynamometer data was for the Ford Sigma 1.6, 4 cylinder, naturally aspirated engine, and later the Ford Fox 1.0, inline-3, turbocharged engine was introduced for a comparison of the results.

This began with:

- Creating Pressure-Volume (PV) diagrams & understanding what they represent and why they change across the RPM range
- ...Log PV diagrams
- Exploring “Work Done” in a cycle & understanding the thermodynamic principles behind it
- Understanding problems surrounding varying CRs, particularly “Engine knock” & “Detonation”
- Calculating and understanding the Mean Effective Pressures (MEPs)
- ...Polytropic index values
- ...Mass fraction burn
- ...Burn duration & Ignition Delay
- ...Efficiency

Turbo-charger Losses

The project changed aim as the interest moved to the exhaust, and the idea of energy recovery.

The Ford Fox data was taken forward with an aim to analyse the power losses through and exhaust with a turbo-charger, and consider how the system could be more efficient.

The objectives to achieve this:

- Calculate power lost through exhaust system including turbo-charger

- ...power recovered by the turbo-charger via compressor
- ...the power wasted through the intercooler
- Understand the thermodynamic principles behind the calculations
- Discover why and where the losses occur
- Gain data required to finish calculations by flowbenching Fox turbo and recording results
- Design and manufacture flowbench adaptor rig in required timescale to proceed with test

Research / Literature Review

Final Project

Thermodynamic Principles

The first law of thermodynamics provides the concept that the change of the internal energy of a system is equal to the sum of the inputs (heat) and outputs (work done) of that system expressed as:

$$\frac{\Delta(me)}{\Delta t} = \dot{W} + q$$

(Gary L. Borman, 1998)

Where

me = internal energy of the mass t = time $\dot{W}$ = power q = rate of heat into system

This law assumes an adiabatic system where no losses occur when energy is transferred, however, energy losses can occur through heat lost through the boundary, sound energy through waves via vibrations, and mechanical losses due to friction.

Therefore, the energy into a system cannot equal the energy out, however, the efficiency of a system is considered higher when the energy in and out are closer in value.

Hot exhaust gases contain a large amount of energy, as it passes through the turbine of a turbo-charger, this energy is transferred to the compressor kinetically via a shaft. It is possible to find the heat transfer from the mass flowing through, and the enthalpy difference of the mass, which is the specific enthalpy:

$$\dot{W} = \dot{m}(h_{in} - h_{out})$$

The temperature of the exhaust gas is important as it governs the amount of power that can be recovered through the turbine (Heywood, 1988).

This efficiency is important, as internal combustion engines only make use of approximately 30% of the fuel power effectively, therefore minimizing losses elsewhere can increase efficiency.

Ford Fox 1.0L EcoBoost Engine

The Fox engine is an inline, 3-cylinder, turbo-petrol engine which uses direct fuel injection, and has a displacement of 999cm³. It has a maximum power of 92kW at 6000RPM (Ford, 2018).

It was designed for economical road-use, using less fuel but producing equivalent torque and power than a naturally aspirated engine of the same specifications. This is down to the turbo-charger, as a smaller, low speed car -especially when in use in cities and areas with low speeds and traffic- could use assistance in dragging more air into the engine.

The turbo-charger is likely to become most useful at 2750 RPM, judging from the Fox data (2), page 46, AIRMASS kg/h and AIRMASS UEGO kg/h maps, the latter of which is the airmass calculated from the Universal Exhaust Gas Oxygen sensor, as opposed to the air/fuel ratio as was done in this thesis. The latter map can be considered 'real' and the first map can be considered as the ideal airmass that might neglect factors that affect it.

The calculated airmass coming into the engine can be seen to be more than that of the real airmass until 2750RPM when it surpasses it until 4500RPM where it fluctuates and resumes remaining at a vaguely smaller airmass. This implies that the turbocharger is bringing more air into the engine between these RPMs, which is a reasonable driving RPM.

A small turbo has been used in the Fox for packaging reasons, and because it is adequate to achieve the desired effect. A small turbo has the benefit of delivering quicker boost response, even at lower loads and RPMs, but at the expense of high back-pressure at higher RPMs.

This is ideal for a car that is not expected to be driven at high speeds and is likely to be driven through urban or semi-urban areas. (Bell, 1997)

Methodology

Initial Work

The first project aim was to create a 2-zone combustion model using 1.6 Ford Sigma data and 1.0 Ford Fox data as a comparison.

Initially, the data was opened in excel and 'cleaned' up to create a spreadsheet that was easy to work with. The individual cylinder pressures were compiled into a 'mean' pressure column in bar, and volume was left in cc for the purpose of observing the patterns in pressure/volume (PV) diagrams.

Crank Angle θ	Stroke	Piston Position	Work Done
degrees			
-360	Intake	TDC	+
...			+
-180	Compression	BDC	-
...			-
0	Power	TDC	+
...			+
180	Exhaust	BDC	-
...			-
360		TDC	

Figure 1 - Table of work trends across Crank Angle

PV diagrams give a vague overview of the losses in the power loop and pumping loop due to heat losses, pumping losses, and friction losses. This is observed by calculating the 'work done' for every degree of crank and using the sum of the work done within certain strokes to calculate Mean Effective Pressure (MEP), Gross Mean

Effective Pressure (GMEP), Pumping Mean Effective Pressure (PMEP), and Indicated Mean Effective Pressure (IMEP).

The positive and negative work strokes and the crank angles they occur at are seen in Figure 2 - Table of work trends across Crank Angle. GMEP is the gross, the sum of the work done in the power loop divided by cylinder displacement, PMEP is the sum of the pumping loop work done divided by displacement, IMEP is the sum of the entire cycle divided by the displacement, which represents the actual work, positive minus the negative.

The trend of positive and negative work done can be seen in Logarithmic PV diagrams were created to see the rate of change between the pressure and volume clearly, and therefore reveal where the start (SOC) and end of combustion (EOC) is from locating where the rate of change in the pressure and volume ceases or begins to be linear.

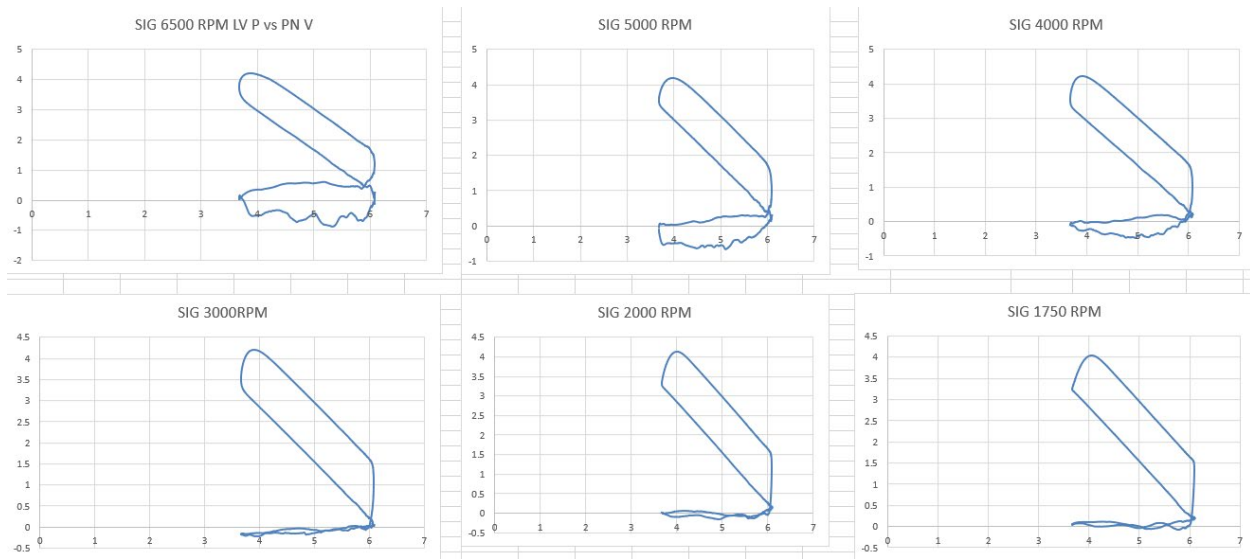


Figure 2 - Overview of Log PV diagrams

The logarithmic PV diagrams also highlight larger power and pumping loops across the RPM ranges, displaying them more clearly to the naked eye.

Larger pumping loops mean increased negative work done in the system, whereas larger power loop indicates less energy losses, and therefore more efficiency, and more positive work in the system. The changes and trend of the logarithmic PV diagrams can be seen in Figure 1 - Overview of Log PV diagrams.

With a clearer view of the SOC, the $n_{compression}$ value can be found within the n data as pictured in Figure 3 - Excel example of equations & process in column 'J'. This sheet is an example of the first steps to calculate mass fraction burned (MFB) and the work done, and this is done for each RPM provided in the data.

Locating the last few angles of crank before the line of compression stops being linear on the log PV diagrams, these angles can be found in column 'E', and then an average can be taken for these points in column 'J' to attain the n value for the compression, which is just the gradient of the line and is a constant.

	A	B	C	D	E	F	G	H	I	J	K	L
1	CYL_1	CYL_2	CYL_3	CYL_4	Crank Angle degrees	Mean Pressure	Volume	LOG V	LOG P	n	P2n	ΔP
2	bar	bar	bar	bar		bar	cc				bar	bar
3	0.97	1.075	0.993	1.042	-360	1.02	39.27	3.670461	0.019803	2.893227173	1.02	-0.003
4	0.971	1.074	0.994	1.031	-359	1.017	39.31	3.671479	0.016857	0.645833042	1.017	-0.002
5						$\frac{\Sigma A1, A2, A3, A4}{4 \text{ cylinders}}$		log G3	log F3	$\frac{(I4 - I3)}{(H3 - H4)}$	$F3 \times \left(\frac{G3}{G4}\right)^{n_{compression}}$	$F4 - K3$

Figure 3 - Excel example of equations & process

P2n represents the pressure -in bar- which would have been reached had the increase only been due to the change in volume. Therefore, the 'change in pressure' in column 'L' is the change in pressure due to only the combustion. This value can be used to find the MFB using

$$MFB = \frac{\sum_{\theta}^{SOC} \Delta P}{\sum_{EOC}^{SOC} \Delta P} 1$$

Final Project

Fuel Products Calculator

A calculator created for a previous assignment was adjusted and used to provide the number of molecules of each primary product of combustion at varying fuel equivalence ratios.

Data Maps

The Ford Fox data had to be converted to excel format to be useable, and the maps for

- Temperature for Pre-Turbocharger, Post-Turbocharger, Pre-Compressor, Post-Compressor, Pre-Intercooler, Post-intercooler (°Celsius to Kelvin)
- LAMBDA
- Fuel mass (kg/g converted to kg/s)
- Air/Fuel Ratio

Were collected and from these

- Air mass (kg/s)
- Total mass (kg/s)
- Fuel Equivalence Ratio
- Atmospheric temperature (assumed 298k)

Could be calculated and mapped out at the same load sites.

Enthalpies and polynomials

The enthalpy of each product at each map site are calculated in Excel using the temperature of the environment and polynomial for the product, and the products must be calculated based on the fuel equivalence ratio as stoichiometric, rich, and lean mixtures output different products to each other.

Polynomial equations for each product were calculated from Microsoft Excel using a polynomial trendline tool, creating an equation to the maximum order Excel allows – 7 – for greater accuracy. The enthalpy (h) data was provided in lectures, and the tables were photocopied from books which reference the JANAF tables.

$$h = IF((TEMPERATURE) > 0, (POLYNOMIAL EQN. \times TEMP), 0)$$

Using the polynomial equations for N_2 , H_2O , CO_2 , O_2 , and CO molecules, an enthalpy map for each element is created, referencing the temperature map. This is repeated for each region – pre and post-turbo, etc.

$$\Delta h \text{ at FER} = IF(AND((h \text{ Region}_1) > 0, (h \text{ Region}_2) > 0), ((h \text{ Region}_1) - (h \text{ Region}_2)) * IF((LAMBDA \text{ VALUE}) > 1, VLOOKUP((LAMBDA \text{ VALUE}), RICH, 4, TRUE), VLOOKUP((LAMBDA \text{ VALUE}), LEAN, 4, TRUE)), 0)$$

Another sheet calculates the difference in the enthalpy values between each region, in essence, the enthalpy loss or gain between each region for each product molecule.

Microsoft Excel “IF” statements provide a method to quickly decide what value to multiply the molecule enthalpy difference by, which is affected by the fuel equivalence ratio (FER). The “VLOOKUP” function can call the required number of molecule values from tables created for either a lean, rich, or stoichiometric mixtures, and “IF” statements reference the LAMBDA table for each corresponding load points to decide which VLOOKUP table to use.

$$h_{total} \left(\frac{kJ}{kmol} \right) = SUM(CO_2, H_2O, N_2, O_2, CO)$$

Summing the enthalpy differences at each load point provides the total enthalpy loss.

$$h \text{ loss per second (kW)} = \left(\frac{h_{total}}{\text{molar mass}} \right) * \text{mass}_{total} \text{ kg/s}$$

A separate row of tables calculates the enthalpy lost/gained per second for each region change, including the loss from pre-turbo all the way through to the atmosphere. The weight of the

molecules for air and fuel can be calculated using atomic masses available in a periodic table saved within the sheet, and the calculated value is also saved within the sheet for ease of cell referencing.

The total mass per second map is calculated using the fuel mass map and the air/fuel ratio map to attain air mass and summing these values to create a new map.

This results in the kilo-watts of energy being lost for each RPM, at each load point, across the turbo-charger and out of the intercooler, and also for the kilo-watts of energy gained from the turbo-charger across the compressor.

Transfer Efficiencies

$$\text{Transfer efficiency} = ((\text{Compressor kW gain})/(\text{Turbo kW lost})) * 100$$

The final map to reveal the transfer efficiency at each point is created by dividing the enthalpy gain per second of the compressor by the enthalpy per second lost from the turbo, and multiplying by 100 to create a percentage.

The efficiencies are affected by the wastegate opening, and an over-efficiency (above 100%) was seen in the first data file, so another data file has been analysed in the same format for comparison, and the turbocharger was physically tested on a flowbench to record the air mass coming through the turbocharger with the wastegate opening at small increments from closed.

Flowbenching the Turbocharger wastegate

The turbocharger must be fitted to the flowbench via a rig that fits both mouths, in the case of this project, the jig had to be manufactured to fit both the flowbench mouth and the turbo entrance from the exhaust manifold.

The port must be blocked from the wastegate port onward to prevent air escaping to the turbine, this was done using blu-tac, however ideally a cork would be used so as not to leave residue in the port once testing is complete.

The flowbench blows air through the turbocharger as it would in an exhaust system – from the exhaust manifold, through the wastegate, and down the exhaust.

A device to both measure the distance that the wastegate has traveled, and open and close it securely was also manufactured using welded bolts, a spring, and a modified nut with 'tip-ex indicators' to crudely, but reasonably accurately allow the wastegate to be opened and closed with a spanner at 0.5mm increments.

Using Excel, the flowscale is recorded at every 0.5mm lift increment from wastegate closed to fully open, and as the flowscale nears 100% for the range in use, the next range is used, and this provides a conversion to find the flow in both litres per second and cubic feet per minute.

The test was conducted twice on two separate days to provide a comparison and potentially relieve any obvious anomalies – ideally the test would be carried out more than twice to provide a better reliability of results.

The test is concluded when maximum opening has been reached, although the results stop fluctuating earlier as the effective area of the port prevents increased wastegate opening from having more of an effect once this limit is reached.

Data is graphed to provide an easy observation of the relationship between the air coming through each second and the amount of which the wastegate is open, effortlessly presenting the significance of effective area, and where the lift becomes useless.

Flowbenching a Turbo-charger

A rig that fits both the flowbench mouth and the exhaust port on the turbo-charger was manufactured. This was done using scrap metal and welding, and the rig was fastened to the flowbench using bolts, however an air-tight seal is created between all components using blu-tac.

Should an air-leak occur, it can be located using a liquid such as WD-40 to make the leak visible. It is important that a leak does not occur during testing, as this can invalidate results, however, if there is a leak that cannot be resolved from the start, a corrected flow can be calculated by subtracting the first reading from the values attained there-on after. This is not ideal as there is no way of knowing if the leak becomes bigger.

A welded bolt provides a method to open and close the wastegate whilst measuring the lift distance, and keeping it in place firmly. A nut with a welded metal tube pushes against a metal plate whilst being free to be screwed up and down the bolt, completing the mechanism to open and close the wastegate. This bolt is turned with a spanner.

Once the turbo-charger has been attached and the wastegate valve is fully closed, the flowbench range should be set to range '1', the flow direction set to 'exhaust', and the CFM value at '150 CFM' as recommended by the handbook to prevent overheating.

The flowscale should be calibrated to start at '0', and the flowbench then turned on to take the first reading. The exhaust tap should be opened until the pitot tube reads 25" of water, and this

sets the test pressure for the rest of the test. The flowscale can be read once the test pressure is reached.

The wastegate valve is opened to 0.5mm by a half turn of the nut, as the thread pitch of the bolt is 1mm, so a full rotation of the nut forces the bolt to pull the wastegate valve open 1mm.

Once the flowscale is nearing 100%, the range is increased to '2', and the process continues as usual until the wastegate is fully open.

All readings are recorded in Excel and can be converted into flow and graphed to observe the flowrate at various wastegate openings.

[Combining Flowbench Data and Ford Data](#)

The data obtained from the flowbench can provide a method to attain flowrate at the wastegate lift openings provided in the Fox data.

A polynomial equation for the lift and flowrate can be created to find the flow at any given amount of lift in the Fox data.

Results & Analysis

Initial Project

PV Diagrams

Fox and Sigma PV diagrams reveal that the Fox engine is turbo-charged as the ignition delay is increased dramatically in lower RPMs where there are low flame speeds and a high risk of knock. Pumping losses are not large until the higher RPMs. The Sigma looks more like an ideal cycle, indicating maybe more efficiency and close to TDC (high pressure).

There is less chance of knock at higher RPMs, therefore less ignition delay, but bigger pumping losses. However, area of power loop increases too, compensating for larger pumping losses. The Sigma remains consistent, pumping loop isn't dramatically large, but the power loop isn't obviously enlarging either

Combustion occurs after TDC but the sigma maximum pressure occurs closer to TDC higher RPM. This affects MFB too.

MEPs

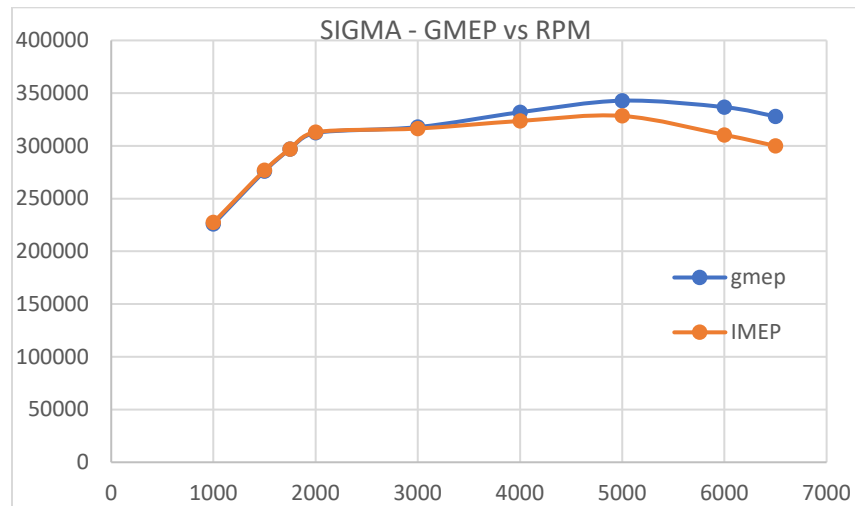


Figure 4 - Sigma GMEP v RPM

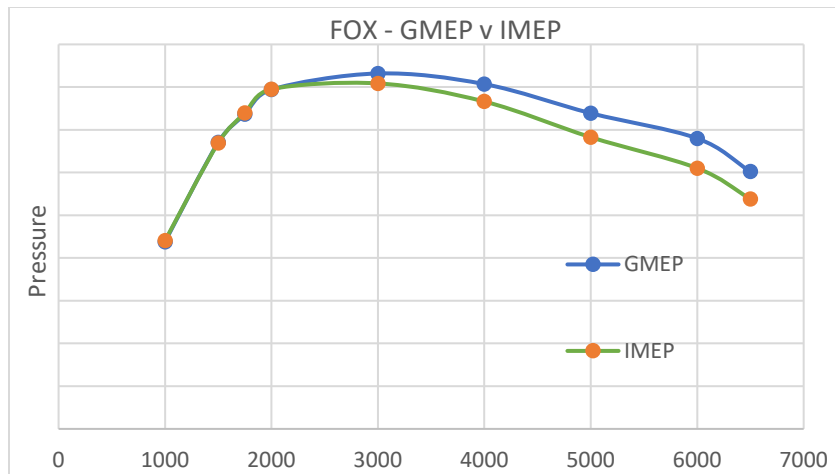


Figure 5 - Fox GMEP v RPM

The PV diagrams may hint to the combustion behavior, however, analysing the data reveals the reality, and it is seen that the Sigma engine GMEP does not compensate the PMEP past 3000 RPM.

RPM	GMEP	IMEP net	PMEP	WD In & Ex J	VD Com & Pov J	Total +ve WD J	Total -ve WD J	NET WD J
1000	225831.4899	227404.2703	1672.780443	2.510132	360.423384	549.753543	-186.820027	362.933516
1500	275938.6554	276838.1777	899.5223269	1.435623	440.393605	652.5824105	-210.7531825	441.829228
1750	296875.2529	297063.9707	188.7177758	0.3011905	473.808074	692.530895	-218.4216305	474.1092645
2000	312288.7643	312980.3848	691.6204583	1.103815	498.4077875	714.2234045	-214.711802	499.5116025
3000	317806.7307	316416.156	-1390.574638	-2.2193345	507.214372	724.9255045	-219.930467	504.9950375
4000	331860.7972	323611.803	-8248.994171	-13.1652605	529.6444335	756.455388	-239.976215	516.479173
5000	342871.4176	328397.6228	-14473.79478	-23.099941	547.2172045	786.275801	-262.1585375	524.1172635
6000	336712.4503	310435.9513	-26276.49904	-41.936865	537.387593	766.579374	-271.128646	495.450728
6500	328006.3234	299984.0271	-28022.29629	-44.723129	523.492756	749.3642875	-270.5946605	478.769627

1.6 SIGMA

Figure 6 - Sigma table of MEP

RPM	GMEP	IMEP net	PMEP
1000	43805635.8	44057329	251693.5
1500	67064126	66935025	-129101
1750	73635388.5	73955334	319945.7
2000	79427899.4	79520071	92172.1
3000	83192745	80869416	-2323329
4000	80710208.2	76625536	-4084673
5000	73890480.4	68267562	-5622918
6000	67996888.6	61019139	-6977750
6500	60241457.3	53819885	-6421572

1.0 FOX

Figure 7 - Fox table of MEP

Tables reveal that for the Sigma, the maximum GMEP achieved is at 5000 RPM, however, the PMEP continues to increase, and does so exponentially until 6000RPM where it increases less aggressively.

The Fox reaches maximum GMEP and IMEP at 3000RPM and is then overcome by the pumping losses. This may be due to the parameters of the throttle, as a choke effect may start to take place if it's not large enough to effectively use all of the air that the turbo-charger is capable of bringing in.

The engine is, after all, designed for road use and economy - the addition of a turbo-charger is to compensate for the power that the engine is lacking due to its small size whilst re-cycling exhaust gases. The choking that may occur may not be an issue for a car that is not designed for performance and speed, however pumping losses do decrease efficiency.

As the values in the table represent full load, throttle can be assumed to be jammed open – looking at the official Ford data, the full-load after-compressor pressure ceases to rise after 2500RPM and drops considerably after 5500RPM as a reflection of the pre-turbo pressures.

The transfer efficiency graphs created show that there is no loss occurring due to this efficiency, it only improves, therefore the pressure drop couldn't have occurred through the compressor not having the ability to draw in air or the turbo-charger not efficiently giving it the energy to do so – there must not be enough air coming through the turbine as the RPM increases.

Looking at the maps for wastegate opening, this may seem invalid as the wastegate opens more through the RPM at full load, but the map showing the massflow that bypasses the turbine does imply that this could be the cause for the dropping power.

Considering a simple power equation $Power = P \times L \times A \times N$ Stroke and Area are constant, N increases linearly with RPM ($Number\ of\ cyls \times \frac{RPM}{2}$), and Pressure is expected to increase as fuel and air is added with throttle demand.

Looking at the Ford data map for manifold pressure (pg 44 recorded in inches of Mercury), at full load, the pressure stops increasing at 2500RPM, which may be low, but for a small, efficient car, could be a practical RPM range for everyday driving.

If this pressure stops increasing, naturally, the simple power equation can show that even the increasing RPM can't counteract this.

For example, taking the engine specifications and using the equation, converting inHg to Pascal (3386.39inHg), Bore and Stroke to metres, Bore diameter to Area ($\pi \frac{D^2}{4}$), the power can be seen to peak at 2500RPM and fluctuate a little before dropping at 6000RPM.

Stroke – 82mm

Bore – 71.9mm

N – 3

RPM	1000	1500	2000	2500	3000	4000	5000	6000	6500
POWER	123	169	225	228	228	219	227	213	184
PRESSURE	36.4	50	66.4	67.4	67.3	64.8	67.2	62.9	54.3

This simple calculation shows the effect pressure can have on output power, even if the RPM value is increasing. Knowing that manifold pressure stops increasing, the volume of the

manifold may not be efficient at allowing more air into the cylinder, though disproved by the airmass map, the airmass does

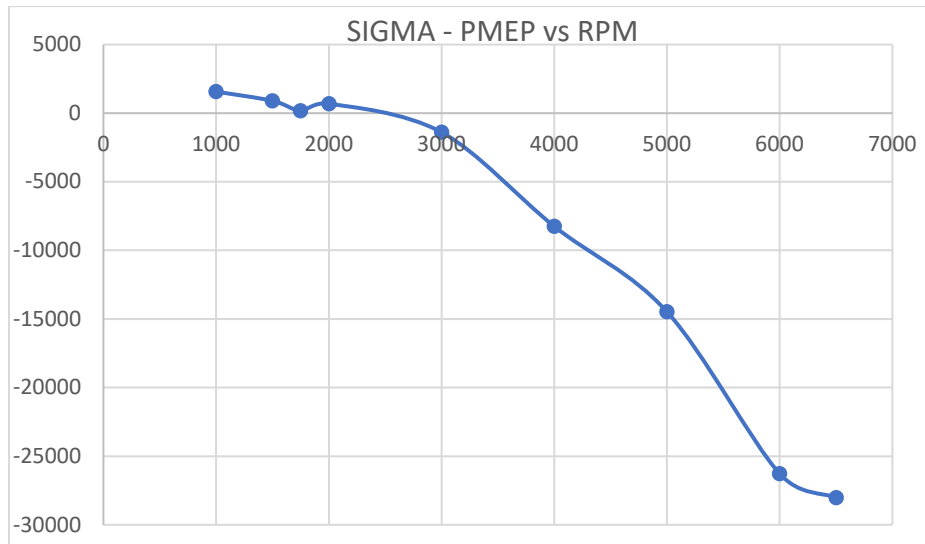


Figure 8 - Sigma PMEP v RPM

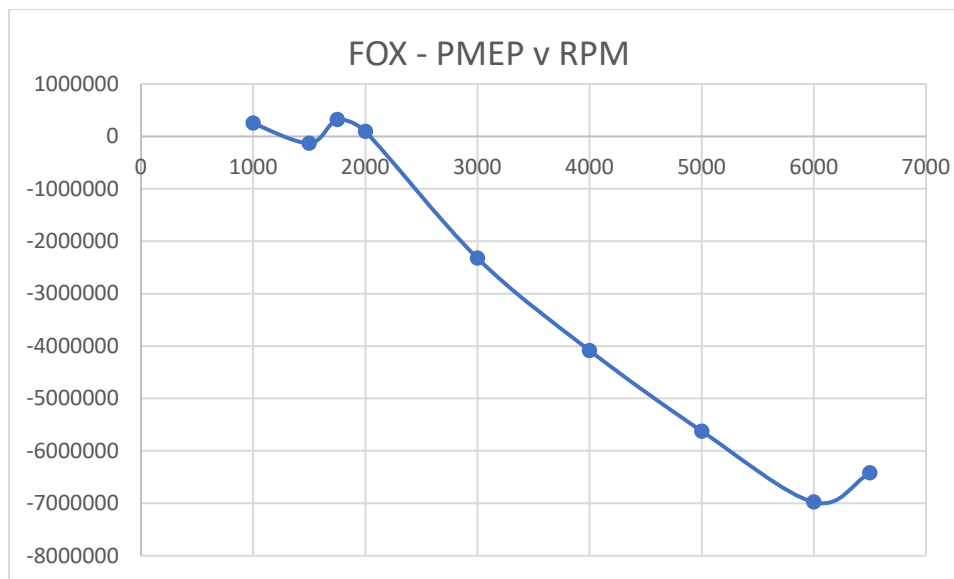


Figure 9 - Sigma PMEP v RPM

Work Done

There is a higher work produced by the Fox engine, however unlike Sigma, it doesn't suffer excessive pumping losses. Compression ratio 10, sigma CR is 11.16. Higher CR gives greater fuel efficiency and non-boosted response (Bell, 1997).

Logarithmic PV diagrams

Logarithmic PV diagrams show where the pressure and volume change exponentially, and therefore can indicate where combustion occurs.

The fluctuations in the pumping loop is likely due to the intake pressure variance resulting from the compressor, and a varying exhaust back pressure resulting from resistance from turbine in exhaust, so they cross over when one of these pressures become higher or lower than the another.

These fluctuations don't exist so prominently in the Fox engine as the air is forced in via a compressor, and any pulses from variance in atmospheric pressure on intake are over-ridden by the compressor.

The higher RPM graphs reveal the ignition delay on the Fox engine, which decreases with increasing RPM to prevent danger of knock. The Sigma, being naturally aspirated, does not have this danger, and this is evident from the lack of ignition delay on the map.

The pumping loop on the Fox engine shows the exhaust pressure becoming higher than the intake pressure at 3500RPM. This is an indicator of which RPM the back-pressure becomes higher than the intake pressure at full load. The Sigma engine has the same trend at higher RPMs, likely because the speed creates a more effective intake pump at higher speeds.

Polytropic Index & Mass Fraction Burned

The polytropic index was calculated from a guess at where the log PV compression and expansion lines stopped being linear, and therefore may not be completely accurate.

The MFB was calculated using two methods, one assumed to be more accurate - $MFB = \frac{\Sigma \Delta \rho}{\Sigma \Delta \rho} = \frac{\Sigma SOC \rightarrow \theta}{\Sigma SOC \rightarrow EOC}$ which calculates it using the change in pressure from combustion alone, and $MFB = \frac{\Sigma V_2 \Delta \rho}{\Sigma V_2 \Delta \rho} = \frac{\Sigma SOC \rightarrow \theta}{\Sigma SOC \rightarrow EOC}$ which accounts for the changing volume, as it seemed obvious that the moving piston, hence changing volume, would interfere with the pressure.

There is a change in the results, particularly mid-combustion where the MFB in the Fox engine becomes slower with increasing RPM. The Sigma engine has fluctuations but can be seen to be generally larger at high RPM than low RPM but not by a significant amount.

The burn duration is longer on the Fox engine than it is for the Sigma engine likely due to the additional mass to burn in the engine and different CR.

Turbo-charger Project

Polynomial Equations for Enthalpy

The enthalpy values at the temperatures in the map were required, but a polynomial equation had to be used to find the desired temperature value for the enthalpy of each product as the data does not have all the temperature values.

When the tables to find the kW's of power down the exhaust were created, the higher RPM values were excessively high considering that, on average, 33% of the fuel power ends up as losses down the exhaust.

As well as this, fellow student, J. Creswell, conducted a similar study using the same Ford Fox data and the comparison between the results was noticeably different, with the smaller order polynomials resulting in much smaller energy losses.

Re-evaluating the process, the only obvious issue was that the polynomial equations were created to a lesser order than Excel offers. Although it seemed insignificant, once changed, the values corrected themselves and proved that the decimal places and the order of a polynomial equation can increase accuracy vastly.

This influenced the creation of the polynomials for the flowbench testing later in the project, where flow values at different lift openings were required, and these were also created with higher accuracy.

Power Losses

The amount of fuel power wasted down the exhaust is evident considering the output power of the engine and the losses calculated.

Incorrect total mass - Pre-turbo to atmosphere																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL	8.47	15.74			38.82		56.00	62.91	76.59	84.18	100.82	105.59	117.86		120.95	106.57
200								66.22	77.15							
190							54.16	61.08	74.76	84.64						
180					37.18		49.46	55.89	68.40	77.64	98.25					
170				27.77	34.67		45.47	51.27	65.02	77.93	94.63	99.68				
160				25.86	31.48		41.10	46.09	58.44	69.76	85.47	98.60	109.46			
150				23.20	28.33	32.10	37.17	41.82	51.83	62.92	77.23	87.17	100.27	112.27		
140				20.85	25.23	28.88	33.49	37.94	46.09	55.91	67.08	77.58	89.72	100.52	114.32	
130				18.32	22.06	25.56	29.56	33.25	40.83	49.32	59.01	68.67	79.65	89.83	104.45	
120			13.13	16.12	19.29	22.79	26.14	29.28	36.01	43.79	52.93	60.58	69.44	80.22	91.01	105.20
110			11.75	14.53	17.13	20.03	23.23	25.77	31.88	38.68	46.20	53.51	61.54	71.56	81.65	94.07
100		7.54	10.33	12.65	15.09	17.64	20.28		28.24	34.05	40.74	47.47	54.89	63.99	73.42	83.96
90		6.71	8.90	11.03	13.00	14.97	17.44	19.38	24.55	29.79	35.48	42.01	48.44	56.41	65.09	75.82
80		5.79	7.72	9.46	11.26	13.14	15.41	17.32	21.44	26.12	31.81	37.03	43.17	50.23	57.30	66.35
70		4.77	6.65	8.18	10.00	11.50	13.15	14.94	18.55	22.81	27.88	32.51	37.98	43.76	50.01	58.35
60		3.77	5.54	6.44	7.65	8.93	10.65	12.54	16.01	19.62	24.01	28.42	33.24	38.43	44.02	50.72
50		2.87	3.95	5.07	6.20	7.30	8.77	10.26	13.31	16.48	20.15	24.39	28.53	33.02	38.04	43.58
40	1.93	2.23	3.12	4.07	5.03	5.97	7.13	8.29	10.63	13.66	16.76	20.35	23.65	27.70	31.86	36.87
30	1.60	1.83	2.54	3.30	4.18	4.93	5.82	6.69	8.64	11.01	13.50	16.32	19.45	22.67	25.97	30.47
20	1.04	1.31	1.93	2.41	3.10	3.77	4.42	5.11	6.57	8.55	10.52	12.81	15.59	18.02	20.81	24.02
10	0.72	0.85	1.30	1.72	2.25	2.72	3.19	3.55	4.93	5.96	7.79	9.36	11.21	13.07		18.52
5	0.41									5.11	6.57	8.00				15.38
2			0.57			1.73										

Figure 10 - Data (2) kW lost through exhaust

The power lost down the exhaust improves dramatically when calculated using the real total mass through the turbine.

PRE-TURBO THROUGH TO ATMOSPHERE ENERGY LOSS																	
energy lost per second (kw)		800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
	FL		8.45	15.68		37.16		51.46	56.93	68.17	74.04	87.90	88.21	98.28		96.76	85.78
	200								59.40	68.56							
	190							49.29	54.88	65.63	72.27						
	180					35.61		45.45	50.41	60.27	67.56	83.10					
	170				27.19	33.25		42.01	46.78	57.99	67.44	78.60	83.32				
	160				25.31	30.19		38.09	42.09	52.60	61.28	72.92	79.84	90.56			
	150				22.62	27.27	30.55	34.51	38.37	46.92	56.02	66.32	73.13	84.25	95.08		
	140				20.33	24.25	27.43	31.08	34.88	42.27	50.60	58.88	66.88	76.76	84.69	93.73	
	130				17.86	21.24	24.22	27.63	30.98	37.93	45.29	52.99	59.98	69.37	76.77	87.45	
	120			12.91	15.72	18.65	21.86	24.95	27.73	34.04	41.03	48.30	54.04	61.66	70.13	78.14	88.06
	110			11.59	14.21	16.79	19.54	22.39	24.83	30.63	36.76	42.92	48.94	55.16	63.29	71.32	80.61
	100		7.46	10.25	12.48	14.84	17.25	19.81		27.42	32.76	38.24	46.75	50.25	58.02	65.71	73.25
	90		6.65	8.85	10.94	12.86	14.79	17.13	19.08	24.09	29.08	34.16	39.85	45.35	52.53	59.70	66.81
	80		5.77	7.68	9.41	11.13	12.96	15.18	17.10	21.13	25.63	30.86	35.42	40.96	47.37	53.58	61.36
	70		4.75	6.60	8.14	9.89	11.35	13.01	14.79	18.20	22.35	27.20	31.32	36.27	41.60	47.05	54.52
	60		3.73	5.52	6.41	7.58	8.84	10.58	12.44	15.72	19.15	23.48	27.52	31.89	36.22	40.91	47.06
	50		2.84	3.89	5.05	6.13	7.23	8.72	10.13	13.12	16.16	19.79	23.72	27.66	31.50	35.81	40.60
	40	1.93	2.23	3.12	4.05	4.99	5.93	7.08	8.21	10.54	13.45	16.53	19.91	23.00	26.65	30.35	34.78
	30	1.60	1.83	2.54	3.30	4.17	4.90	5.79	6.66	8.61	10.88	13.35	16.06	19.03	22.10	25.07	29.07
	20	1.04	1.31	1.93	2.41	3.10	3.76	4.42	5.10	6.56	8.50	10.42	12.66	15.38	17.75	20.44	23.42
	10	0.72	0.85	1.30	1.72	2.25	2.72				5.94	7.72	9.26	11.05	12.96		18.32
	5	0.41									5.10	6.52	7.93				15.28
	2			0.57				1.73									

Figure 11 - Correct total mass - kW lost through exhaust

Knowing that the engine has 92kW output power, and approximately a third of the fuel power is wasted down the exhaust, the fuel power can be assumed to be 276kW. The real total mass passing through the turbine sees the greatest difference from the incorrect mass at higher load and RPM, which is intuitive as the largest amount bypassing the turbine occurs at these values, and when less by-passes the turbine, the total masses are similar.

Incorrect Total Mass - Total Exhaust Loss percentage of Fuel Power																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		3.07	5.70		14.06		20.29	22.79	27.75	30.50	36.53	38.26	42.70		43.82	38.61
Real Total Mass - Total Exhaust Loss percentage of Fuel Power																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		3.06	5.68		13.46		18.65	20.63	24.70	26.83	31.85	31.96	35.61		35.06	31.08

Flowbench Test

When using the Wastegate Position map from the data sheets, the first batch of data had to be used only as the data contained in the second file contained negative values. Of the maps within the first batch of data, the first map for waste gate position (WG_POS mm) was used as it was not rounded up, and is therefore more accurate. A polynomial equation created from the flowbench testing is used to locate the flow at these values.

Combining Flowbench Data

The validity of the data must be questioned as, although the test was completed twice, though not ideal, both tests produced maximum lift values of over 16mm. The Ford data does not show lift values above 12mm, which raises the question of whether the flowbench data is correct.

Possible scenarios are that the mechanical method used to open the wastegate valve opened further than the turbocharger sees in use, and therefore the values are correct, but data recorded above 12mm lift is not applicable to this study.

Additionally, it is not known how Ford measured the lift – whether it be from the actuators linear movement, or if it was somehow taken from a point between the wage gate valve and the port opening.

When determining the flow at each load point on the map, the values on the wastegate position map were used, and therefore, flowrates above 12mm opening were neglected.

Mass Percentage through Wastegate

		RPM															
		800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
WASTEGATE POSITION (OPENING) (mm)	FL		0.15	0.18	0.44	0.78	1.09	2.02	2.59	3.31	4.16	5.88	6.54	6.53	6.73	7.23	8.39
	200						1.09	2.05	2.6	3.43	5						
	190						1.17	2.08	2.77	3.84	5.35						
	180					0.83	1.29	2.18	3.03	4.29	5.66	6.16					
	170				0.45	0.98	1.44	2.57	3.77	4.84	5.87	6.51	6.77				
	160				0.52	1.11	1.6	3.04	4.5	5.32	6.4	6.87	7.22	6.94			
	150				0.63	1.26	1.93	3.9	5.36	6.03	6.77	7.35	7.67	7.57	7.21		
	140				0.21	0.78	1.54	2.66	5.04	6.14	6.52	7.24	7.91	8.15	8.1	7.94	7.74
	130				0.39	1.06	2.17	4.33	5.96	6.69	7.24	8.27	8.61	9.02	8.71	8.59	8.41
	120				0.63	1.51	3.33	4.13	5.43	6.98	7.71	8.93	9.43	10.07	9.62	9.27	9.27
	110				0.18	1	2.06	2.95	5.16	6.19	7.74	8.7	9.66	10.06	10.61	10.5	10.01
	100				0.83	0.9	2.39	4.74	6.91	8.02	9.1	11.99	11.99	11.99	11.64	11.34	10.93
	90				2.13	1.41	7.15	7.93	9.37	11.38	11.99	11.99	11.99	11.99	11.99	11.99	11.82
	80				6.97	5.35	10.56	10.35	11.98	12	11.99	11.99	11.99	11.99	11.99	11.99	12
	70				12	12	12	11.9	12	12	11.99	11.99	11.99	11.99	11.99	11.99	12
	60				12	12	12	12	12	12	11.99	11.99	11.99	11.99	11.99	11.99	12
	50				12	12	12	12	12	12	11.99	11.99	11.99	11.99	11.99	11.99	12
	40				12	12	12	12	12	12	11.99	11.99	11.99	11.99	11.99	11.99	12
	30				12	12	12	12	12	12	11.99	11.99	11.99	11.99	11.99	11.99	12
	20				12	12	12	12	12	12	11.99	11.99	11.99	11.99	11.99	11.99	12
	10				12	12	12	12	12	12	11.99	11.99	11.99	11.99	11.99	11.99	12
	5				8.19	12	9.98	9.05	9.14	9.7	5.93	3.2	4.04	6.17	7.37	8.61	11.54
	2				0.03	0.05	0.09	0.09	0.16	1.62	0.07	0.35	3.89	2.2	0.24	0.48	

Figure 12 - Data (2) wastegate position

Looking at the Ford Data (2) map for wastegate position, the red region shows where the highest lift occurs, and hence where the largest percentage of exhaust gases dispelled through the wastegate would be expected to occur.

Flowrate through wastegate (l/s)	FLOW	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
	FL		0.456711	0.456711	1.475257	2.310019	3.034556	4.776905	5.479648	6.227971	7.003327	8.407399	9.031164	9.031164	9.21165	9.781085	11.11632
	200						3.034556	4.776905	5.479648	6.338529	7.685708						
	190						3.296866	4.862885	5.683307	6.705293	7.93606						
	180					2.463252	3.544814	5.02845	5.996549	7.100899	8.24683	8.683778					
	170				1.475257	2.897737	3.779259	5.479648	6.654449	7.538227	8.407399	9.031164	9.272841				
	160				1.651781	3.167561	4.107413	5.996549	7.246541	7.93606	8.913385	9.396781	9.781085	9.459531			
	150				1.990213	3.422581	4.598135	6.755736	7.986988	8.571855	9.272841	9.913327	10.25281	10.11551	9.715736		
	140			0.717302	2.310019	4.00103	5.616859	7.685708	8.683778	9.031164	9.781085	10.53327	10.82124	10.74857	10.60457	10.3222	
	130			1.293683	3.034556	4.946706	7.100899	8.516588	9.21165	9.781085	10.96792	11.418	11.96018	11.49439	11.34199	11.11632	
	120			1.990213	3.891678	6.283635	6.954299	8.038242	9.522802	10.3222	11.80357	12.4372	13.33327	12.76033	12.27708	12.27708	11.72575
	110		0.456711	2.897737	4.862885	5.874801	7.785065	8.683778	10.3222	11.49439	12.76033	13.33327	14.07842	13.91238	13.25095	13.00487	12.84165
	100		2.463252	2.612203	5.262009	7.440679	9.396781	10.67634	12.03896	15.972	15.972	15.972	15.48435	15.0734	14.49372	14.07842	14.16148
	90		4.946706	3.779259	9.650905	10.53327	12.35701	15.15585	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.72905	15.32039
	80		9.459531	7.93606	13.99538	13.74652	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972
	70		15.972	15.972	15.972	15.89122	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972
	60		15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972
	50		15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972
	40	4.00103	0.029738	0.456711	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972
	30	0.029738	0.029738	0.456711	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972
	20	0.029738	0.029738	0.029738	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972	15.972
	10	0.029738	0.029738	0.029738	15.972	15.972	15.972	15.972	15.972	15.972	11.96018	11.88171	14.07842	15.972	15.972	15.972	15.972
	5	0.029738	0.029738	0.029738	10.89437	15.972	13.25095	11.96018	12.11805	12.84165	8.461772	6.171484	6.905063	8.683778	9.913327	11.418	15.40244
	2	0.029738	0.029738	0.029738	0.456711	4.107413	0.029738	1.106925	6.755736	5.02845	0.717302	1.475257					

Figure 13 - Data (2) flowrate (l/s)

The flowrate calculated for the lift values reflects this – the highest flowrate through the wastegate occurs at the highest lift regions, as expected, and it would seem appropriate for the percentage of mass through the turbine to follow this pattern.

% Exhaust Gas Bypassing Turbine	RPM																
		900	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
	FL		0.27	0.39		4.26		8.10	9.51	11.00	12.05	12.82	16.46	16.61		20.00	19.51
	200								10.29	11.13							
	190							9.00	10.16	12.22	14.61						
	180					4.23		8.10	9.80	11.88	12.98	15.42					
	170				2.08	4.11		7.62	8.77	10.81	13.46	16.94	16.41				
	160				2.16	4.08		7.31	8.68	9.98	12.17	14.69	19.03	17.27			
	150				2.46	3.73	4.80	7.14	8.24	9.47	10.97	14.13	16.10	15.98	15.31		
	140				2.48	3.89	5.05	7.17	8.08	8.29	9.50	12.22	13.80	14.44	15.74	18.01	
	130				2.53	3.71	5.27	6.54	6.81	7.10	8.18	10.20	12.64	12.90	14.54	16.28	
	120			1.63	2.46	3.32	4.05	4.57	5.31	5.48	6.29	8.74	10.79	11.20	12.57	14.14	16.29
	110			1.42	2.18	1.99	2.48	3.58	3.67	3.93	4.96	7.09	8.53	10.37	11.56	12.65	14.31
	100		1.09	0.83	1.30	1.70	2.18	2.32	2.28	2.91	3.78	6.13	1.51	8.47	9.33	10.50	12.75
	90		0.81	0.49	0.85	1.02	1.24	1.77	1.56	1.87	2.39	3.74	5.14	6.39	6.88	8.29	11.88
	80		0.45	0.43	0.55	1.17	1.36	1.53	1.26	1.45	1.89	3.01	4.36	5.12	5.69	6.50	7.52
	70		0.49	0.69	0.54	1.11	1.28	1.05	1.03	1.85	2.05	2.43	3.64	4.50	4.94	5.92	6.57
	60		1.08	0.47	0.40	1.00	1.02	0.67	0.80	1.81	2.41	2.19	3.15	4.06	5.75	7.05	7.22
	50		1.08	1.46	0.44	1.08	0.95	0.55	1.31	1.46	1.98	1.78	2.76	3.04	4.61	5.86	6.83
	40	0.18	0.00	0.04	0.34	0.76	0.67	0.67	0.96	0.86	1.52	1.39	2.14	2.76	3.80	4.74	5.65
	30	0.00	0.00	0.03	0.12	0.43	0.52	0.48	0.55	0.38	1.13	1.05	1.58	2.16	2.53	3.46	4.62
	20	0.00	0.00	0.00	0.01	0.17	0.24	0.18	0.14	0.07	0.57	0.96	1.16	1.35	1.52	1.77	2.51
	10	0.00	0.00	0.00	0.01	0.10		#NUM!	#NUM!	#NUM!	0.27	0.97	1.13	1.39	0.85		1.11
	5	0.00									0.25	0.76	0.87				0.69
	2			0.00			0.17										

Figure 14 - Data (2) Percentage Gas bypassing turbine

This is not the case when looking at the calculated map showing the percentage of mass bypassing the turbine. The most gas bypasses the turbine at higher load and RPM, mimicking the transfer efficiency map.

This might actually be due to the size of the turbo-charger. Knowing that it is an especially small turbo-charger with the benefit of packaging and having a quicker response at the expected region of use, it is hence known that a smaller turbo has a more restrictive port entry to the

turbine, forcing the exhaust gases through it and spinning the turbine at higher speeds. This smaller area also means that there is a potential for 'choke', and an increase in back-pressure.

This concept can be imagined using the conservation of energy principle, as Bernoulli's equations states that a fluid flowing through a pipe has the energy $P + \frac{1}{2}\rho v^2 + \rho gh$ and this is equal to the fluid flowing out if there is nothing to impart energy onto (like a turbine). The pressure decreases and is compensated by an increase in velocity, so energy is not lost, it just transfers from pressure energy to kinetic energy.

Hitting a turbine wheel after gaining velocity imparts this energy onto the wheel, however, the blockage slows the fluid down and prevents it from leaving the system at the rate it would have without the blockage.

This fluid still contains energy but must stay in the system longer than it normally would – the energy in the system is converted back into pressure, and the energy (pressure) in the system increases as a result of not leaving at the rate that it is entering.

As molecules like to move from an area of high concentration to a higher one, the exhaust gases being expelled from the cylinder are less likely to be inclined to leave as rapidly with this increase of fluid in the system. Left over exhaust gases in the system waste space for fresh air and fuel mixture, and so power and efficiency are affected.

This choke is known to affect the power in the upper third of RPM range, or in the case of the Fox engine – the top half as seen in the GMEP data. This can be altered with a different A/R ratio, A being the area of a point along the scroll, and R being the distance from the centre of this area to the centre of the turbine shaft – this ratio is constant for any point along the scroll. The smaller the ratio, the smaller the area which will be hit by the exhaust gases, and the greater pressure is applied to the turbine. (Bell, 1997).

This can be imagined easier considering pressure is $\frac{N}{m^2}$ and the area is the denominator, therefore, a smaller area yields a higher number (pressure), and the force remains the same as Bernoulli's equation shows that the force does not change, it simply transforms its energy type.

Due to the consideration of choking occurring down the turbo scroll, and higher pressures and speeds, it might be possible that the percentage of flow bypassing the turbine is just the result of the backed-up gases desperately fighting to move to the area of lower concentration, and escaping through the wastegate effectively.

There is always a possibility of calculation errors or human errors.

	Transfer Efficiency																
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500	
FL		32.0936	39.6133		64.6837		62.5246	61.0228		61.6335	62.1199	61.9464	64.798		62.8467	57.7905	
200								66.2086									
190							66.4237	66.0678	64.5967	64.0276							
180					62.9832		63.401	63.5895	61.9384	60.5485	64.2105						
170				58.5847	59.8801		62.3601	61.8074	66.704	67.2057	70.5109	61.7803					
160				56.3343	57.2504		58.6705	58.2799	63.5207	65.881	69.4418	69.0404	62.451				
150				52.8293	53.2879	51.6717	54.3996	55.5519	61.1628	64.2014	68.1755	67.8175	58.3588	54.9217			
140				47.4629	48.3516	46.1983	49.5737	53.2927	58.5568	61.5465	65.7191	68.2802	58.3782	55.9184	57.9024		
130				41.2236	35.4363	38.962	45.2086	48.4414	52.6573	56.5402	61.719	66.5442	56.2249	55.0506	53.4414		
120			34.1077	34.2825	28.3001	35.9337	39.5143	43.367	44.1555	51.2698	57.2983	61.9711	53.2339	53.9108	51.1198	50.7282	
110			27.0173	27.216	25.7435	29.4159	30.905	31.5715	38.8949	45.8035	48.3109	56.7254	64.4208	51.4266	48.4138	48.7147	
100		28.9702	22.5783	24.873	18.9438	20.0528	23.1232		31.9666	38.5715	40.9804	48.3737	57.1351	45.2623	42.5931	44.6727	
90		25.3993	21.0489	24.0682	18.8481	18.939	18.8034	25.1854	28.269	32.079	36.1444	41.8783	47.5146	36.8942	34.3863	38.1789	
80		24.51	22.7915	22.9172	14.4565	16.7201	16.39	22.7629	25.3642	27.3881	31.8709	34.7211	38.1267	33.4696	27.1593	29.1628	
70		18.002	20.3742	19.8831	11.5165	12.7191	15.7375	22.0576	24.6321	24.0168	26.5399	30.6522	33.3216	31.5645	27.5504	26.4469	
60		15.0818	16.1844	17.9153	9.6444	12.403	14.3828	21.3389	21.5535	22.594	24.0295	27.3254	30.2161	30.4677	27.2041	27.2814	
50		15.2037	16.4093	16.3366	7.84673	10.4166	14.5918	17.4727	15.5476	51.6671	20.5156	23.1194	25.9858	27.4191	24.5143	25.5413	
40	10.7666	14.7135	15.3839	14.3275	6.99045	9.07036	11.9881	12.3493	9.91007	14.6148	15.9385	17.807	22.7411	24.5809	21.996	22.4009	
30	8.54435	10.4859	12.1524	10.1526	4.73484	6.21027	8.40694	9.00683	7.617	11.312	12.5177	13.8512	15.8564	18.3929	17.7979	18.4357	
20	6.8286	10.0226	9.40902	9.26507	4.14418	5.23839	6.19982	6.01538	7.15447	8.03087	9.36748	10.3645	9.45868	11.4421	10.5721	9.95514	
10	5.22997	9.17532	7.70232	12.6706	3.868	4.74747	9.90994	10.7636	11.3193	7.86891	8.91196	9.05269	13.2003	12.7889		5.58883	
5	8.43048									10.1274	12.4849	12.5119				5.68458	
2			20.4743			8.37008											

Figure 15 - Transfer Efficiency (Data (2))

Transfer efficiencies increase at higher load and RPM, represented on the map by red colour-fill. Theoretically, this can be affected by the efficiency of the compressor, as mathematically, the compressor power is the numerator in transfer efficiency, the better the power gain, the better the efficiency.

Compressor Efficiency																	
		800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL			60.7905	68.2231	70.3374	69.5183	69.3694	72.024	73.0069		75.7866	76.5714	76.5008	75.0817	73.8688	72.2179	70.8526
200							69.4152	71.5646	72.873		76.3294						
190							69.8643	72.0979	73.2129	75.2498	76.9097						
180						69.7928	70.3919	72.516	73.9402	75.5549	77.1075	76.8494					
170					70.4447	71.6825	70.9053	72.9318	74.3115	75.895	77.066	77.3265	76.7679				
160					70.9246	71.8575	71.149	73.1434	74.4302	76.2996	77.4338	77.4809	76.8939	76.0407			
150					71.1426	71.9486	71.6626	73.4581	74.8755	76.237	77.1544	77.4366	76.7611	76.3296	74.8735		
140				68.4175	71.3518	71.7213	71.8435	73.4927	74.8088	75.9419	76.8339	76.9046	76.2593	75.925	74.9116	73.2335	
130				67.7892	70.2891	71.7537	71.2651	72.5191	73.5883	75.334	76.1627	75.943	75.2112	75.3237	74.2927	73.3047	
120				66.5393	68.3202	69.3658	70.1222	70.9749	71.956	73.5956	74.6932	74.4182	72.9849	73.1956	72.8615	71.282	70.1571
110			61.6723	64.6175	65.7246	67.3067	67.4776	68.7835	69.1223	70.966	72.5588	72.7296	71.3256	70.2355	69.2066	68.5547	67.3903
100			54.9903	60.3717	61.36	63.1445	62.6884	63.2506	63.5665	56.5781	62.2083	63.2277	67.3387	67.3427	66.7223	66.6116	64.8074
90			44.8145	54.0157	46.9664	51.4843	52.3469	51.0562	47.3963	53.3562	56.8166	60.7759	60.4044	60.5756	59.2114	63.4663	62.8966
80			27.8561	40.0434	32.8371	41.2186	40.8722	40.8187	42.7977	50.3183	54.8201	61.2946	59.8915	60.6458	58.9429	57.2426	55.4525
70			7.98061	12.8367	20.9532	31.4864	34.5193	36.4385	35.044	46.1446	51.8384	58.6665	57.8745	60.1436	59.5429	58.5037	56.9214
60			3.85682	8.89642	15.4356	23.4855	26.2163	14.9882	18.61	23.0945	26.0578	30.6238	31.6058	34.193	33.937	38.6277	56.4932
50			0	2.52597	6.0719	13.0359	9.91484	10.531	13.6151	18.6126	22.4689	26.85	27.9265	31.4305	31.4598	32.342	33.0409
40		5.4722	8.64738	14.4173	17.7506	5.85888	5.16715	6.42569	9.66648	14.132	16.9917	21.7751	23.4471	27.1392	27.7919	29.8844	30.1796
30		4.21726	4.48378	8.98972	0	1.74723	0	2.79177	4.64658	8.242	10.7982	16.4475	14.5671	20.3722	22.0876	23.9356	25.9641
20		-2.3977	0	2.7216	-2.7635	-2.771	-2.8335	-1.9567	0	0	3.00528	8.17041	6.87361	10.5597	11.3671	14.4789	18.9879
10		-3.2805	-0.6596	-0.7067	-3.7021	-3.8807	-3.7957	-3.8923	-3.8743	-3.1557	0	7.17354	2.82127	2.14902	2.15184	3.29391	7.85651
5		-3.2072	-0.6035	-0.6744	-2.4186	-4.6647	-3.3277	-2.6334	-3.3902	-1.8039	3.116	13.4375	11.8366	12.7265	12.8347	12.0434	7.9744
2		-2.5289	-0.5787	-1.2799	0.65403	1.94017	0	4.50321	6.25683	3.70978	7.51091	21.0629	22.475				

Figure 16 - Compressor Efficiency (Data (2))

As seen in the compressor efficiency map Figure 16 - Compressor Efficiency (Data (2)), although containing obvious anomalies caused by incorrect excel formulas, the performance of the

compressor does not fluctuate, it simply rises with throttle demand, and as such is not likely to influence the efficiency outside of this.

When the power (kW) passing through the turbine increases at a rate above that of the compressor, the denominator increases, decreasing the transfer efficiency.

The turbine power is affected by the total mass, which was not incorporated until a later date when it could be attained using the flowbench testing.

	Transfer Efficiency TRUE MASS															
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		32.1792	39.7676		67.5615		68.0365	67.4374		70.0756	71.2548	74.1515	77.7074		78.5609	71.7951
200								73.8024			70.0756	71.2548	74.1515	77.7074		
190							72.9922	73.5428	73.5885	74.9847						
180					65.7625		68.9888	70.4972	70.2926	69.5825	75.9152					
170				59.8296	62.4472		67.506	67.7474	74.7907	77.6599	84.89	73.9122				
160				57.5762	59.6832		63.3004	63.8182	70.5659	75.0065	81.3989	85.265	75.4848			
150				54.1618	55.3523	54.2793	58.5819	60.5404	67.5624	72.112	79.3973	80.8336	69.4558	64.84723		
140				48.6687	50.3105	48.6542	53.4025	57.9773	63.8499	68.01	74.8653	79.2089	68.2327	66.36731	70.621	
130				42.2954	36.8016	41.1289	48.3715	51.9812	56.6824	61.5785	68.7288	76.175	64.5545	64.41381	63.8315	
120			34.6744	35.146	29.2711	37.4504	41.4087	45.8003	46.7161	54.7119	62.7857	69.4682	59.9488	61.66242	59.5395	60.6002
110			27.4065	27.8237	26.2651	30.1634	32.0515	32.7749	40.4859	48.1933	52.0001	62.0179	71.8723	58.14699	55.4254	56.8504
100		29.2898	22.7681	25.1995	19.2713	20.4988	23.6732		32.924	40.0854	43.6579	49.1172	62.4216	49.91989	47.5894	51.1997
90		25.6072	21.1532	24.2737	19.0418	19.1768	19.1429	25.5842	28.8082	32.8633	37.5479	44.1473	50.756	39.61802	37.4936	43.3266
80		24.6218	22.8889	23.0432	14.6272	16.9501	16.6439	23.0527	25.7362	27.9163	32.8599	36.3053	40.1847	35.49035	29.0474	31.534
70		18.0901	20.515	19.9905	11.646	12.8844	15.9051	22.2861	25.0969	24.5195	27.2011	31.8115	34.891	33.20372	29.2833	28.3067
60		15.2464	16.2606	17.9865	9.74213	12.5306	14.4804	21.5108	21.9498	23.1511	24.5684	28.2151	31.4957	32.32496	29.2661	29.403
50		15.3694	16.6524	16.4094	7.9326	10.5169	14.6718	17.704	15.7778	52.7108	20.8876	23.776	26.8003	28.74504	26.0415	27.4137
40	10.786	14.7137	15.3894	14.3768	7.044	9.13147	12.0692	12.4694	9.99579	14.84	16.1636	18.1964	23.386	25.55216	23.0911	23.7429
30	8.54439	10.4859	12.1559	10.1646	4.75519	6.243	8.44782	9.05686	7.64643	11.4417	12.6509	14.0735	16.206	18.87057	18.4365	19.328
20	6.82861	10.0226	9.40905	9.26598	4.15109	5.25114	6.21093	6.02391	7.15982	8.07671	9.45808	10.486	9.58841	11.61833	10.7625	10.2113
10	5.22997	9.17533	7.70233	12.6724	3.87193	4.74747				7.89014	8.99953	9.15642	13.3865	12.89796		5.65169
5	8.43049									10.1523	12.5808	12.6223				5.72425
2			20.4743			8.38397										

Figure 17 - Transfer Efficiency Correct total mass (Data (2))

Re-calculating the transfer efficiency using the true mass, the efficiencies are seen to increase, however, the trend of the efficiencies does not change vastly.

It is understood that a turbo-charger can increase the pressure in the inlet manifold by re-cycling the energy in the exhaust and using this energy to spin the compressor, which draws in the atmospheric air, and increases the pressure, and inevitably the temperature.

This larger quantity of air drawn in allows more fuel to be burned, and hence allows more power at the expense of a higher fuel consumption. This may explain why the wastegate is at its maximum opening surrounding the drive-cycle region, as the engine was designed with a view to being economical and eco-friendly.

Lower load points are also likely to see pumping losses, which increase with the presence of a turbine blocking the path of the gases.

Discussion and Conclusions

The project, although insightful and vast, would have benefitted from time management and scheduling to allow all work to be completed and analysed thoroughly.

What can be seen is that the engine, although turbo-charged, does not have a noticeable performance advantage compared to other vehicles, but has been designed to offer a responsive car that is economical and intended for city driving and low speeds.

The results have to be considered lightly due to human errors and errors that occurred during the extensive calculations throughout the spreadsheets they were created on, but do provide an overview of characteristics they portray.

Recommended further work

Further work would include testing the effect of wastegate valve by using values above 12mm, making the flowbench minimum and maximum lifts proportional to the values in the Ford data.

Conducting the same experiment for a performance vehicle and analysing the wastegate lift mapping with a view to comparing it to the Fox.

Mapping IMEP to compare it to the wastegate opening/flow maps and percentage of flow bypassing the turbine maps to see if there is an obvious correlation perhaps relating to choke.

Studying available energy recovery mechanisms and deciding what would be suitable for the Fox engine.

Completing unfinished work to gain a thorough overview of the engine, its performance, and how the various results interact with each other.

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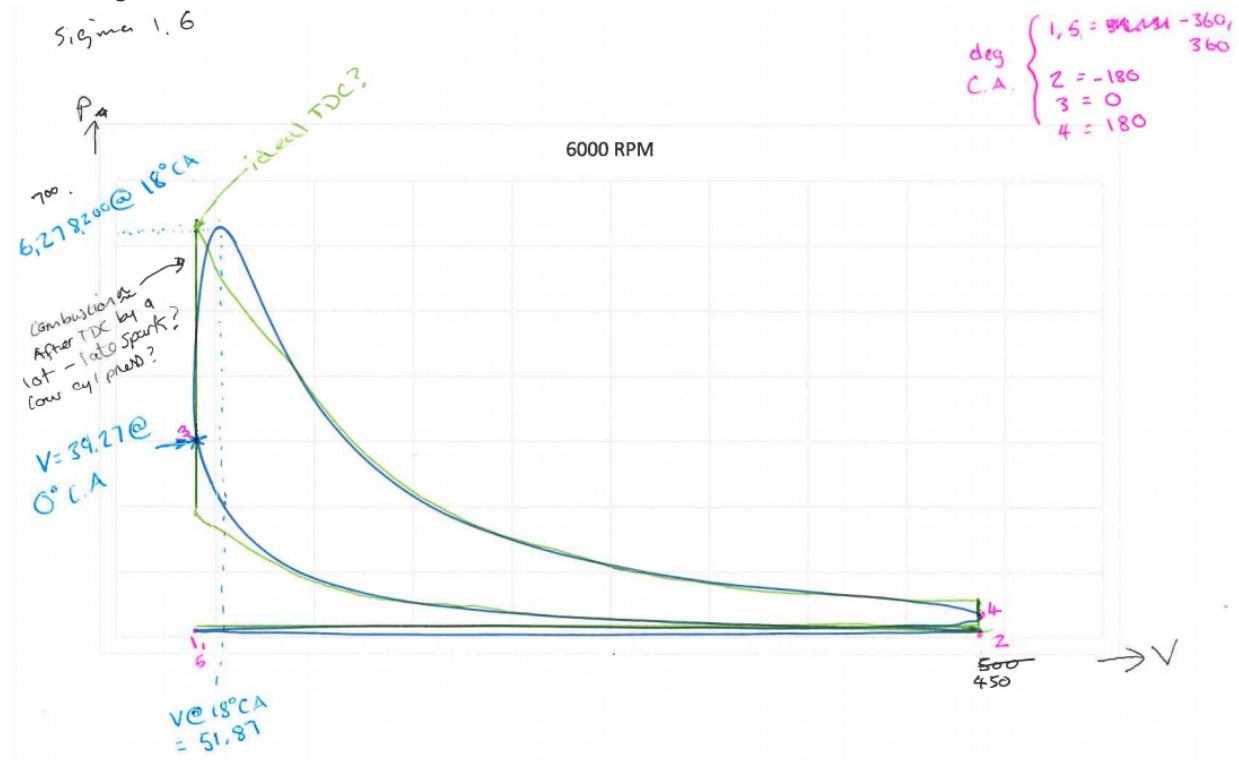
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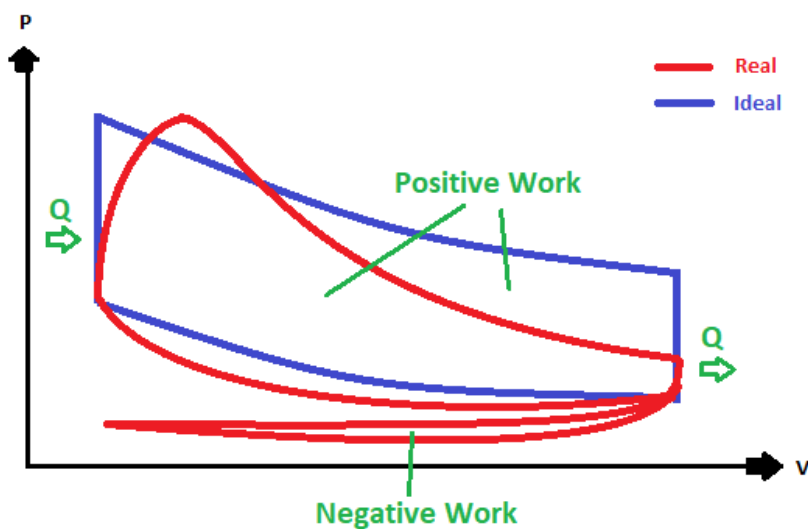
Appendix

Equations, Derivations, Basic Knowledge

P-V Diagrams



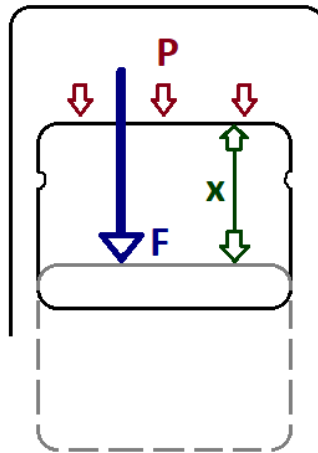
PV diagrams are used to view the efficiency of an engine, however 'Ideal' diagrams are impossible to achieve as they represent an adiabatic cycle with no heat losses, instantaneous combustion and expelling of the exhaust gases, and no pumping losses.



They provide insight on where prominent losses occur, as the area of the ideal diagram (power loop) is the maximum (theoretical) work done, and the area between this and the real engine power loop (GMEP) represents where losses are occurring. The pumping loop losses (PMEP) are additional to the total losses (NMEP) as the 'ideal' cycle is a closed system, neglecting this loop.

Work Done

To find the instantaneous work done (WD) at a certain point, the following equation can be manipulated, and by multiplying by a change in volume, and summing up the values, the WD over a cycle can be found.



$$\begin{aligned}
 WD &= J & (Nm) \\
 WD &= F \times x & (Nm) \\
 F &= P \times A & (Pa)(m^2) \\
 & & \left(\frac{N}{m^2} \times \frac{m^2}{1} \right) \\
 WD &= P \times \textcircled{A \times x} & (N)(m) \\
 WD &= P \times V & \left(\frac{N}{m^2} \times \frac{m^3}{1} \right)
 \end{aligned}$$

Mean Effective Pressures

$$MEP = N \times \frac{\Delta W_{NET}}{V_d}$$

$$PMEP = N \times \frac{\Delta W_{1+4}}{V_d}$$

$$GMEP = N \times \frac{\Delta W_{2+3}}{V_d}$$

Engine Knock & Detonation

Unburned fuel causes danger of detonation due to slow flame propagation and high temperatures and pressures, this is especially an issue in turbo due to higher pressures.

Retarding ignition in earlier RPMs, where flame speed is slower, allows for safety limits. Flame speed increases with longer compression strokes and turbulence in air velocity, which encourages flame movement, hence increases with RPM.

Increasing ignition advance before maximum torque time increases negative work, reducing efficiency. Retarding ignition reduces negative work, but burns after TDC - losing useful pressure.

Fuel chemistry allowing quicker burning -shorter MFB- less burn volume, allows less negative work before TDC, which creates highest achievable useful pressure on downstroke IF ignition is near TDC (Gasson).

Polytropic Index Values & Pressure rise due to Combustion

$$n = \frac{\rho_2 - \rho_1}{V_1 - V_2}$$

$$n_{SOC/EOC} = AVG \ n_{SOC/EOC}$$

Pressure achieved through ONLY the piston motion (per degree):

$$\rho_2 n = \rho_1 \left(\frac{V_1}{V_2} \right)^n$$

Pressure from combustion alone. Will rise and fall during start and end of combustion:

$$\Delta p = P_2 - P_2 n$$

Final Project

Conversions & Units

Data provides fuel mass in kg/hr and the Air/Fuel ratio.

To attain air mass and total mass:

$$Fuel \ mass \left(\frac{kg}{s} \right) = Fuel \ mass \left(\frac{kg}{hr} \right) \div 3600$$

$$Air \ mass \left(\frac{kg}{s} \right) = Fuel \ mass \left(\frac{kg}{s} \right) \times A/F \ ratio$$

$$Total\ mass = Fuel\ mass\ \left(\frac{kg}{s}\right) + Air\ mass\ \left(\frac{kg}{s}\right)$$

Temperatures must be converted into Kelvin from °C:

$$1^{\circ}C = 274\ K$$

LAMBDA (λ) maps can be used to calculate a Fuel Equivalence Ratio (FER) map:

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

The energy difference (gain or loss) is a subtraction of the two regions:

$$\Delta h_{exhaust\ gas}\left(\frac{kJ}{kmol}\right) = h_1 - h_2\left(\frac{kJ}{kmol}\right)$$

To find the amount of energy lost every second:

$$Energy\ lost\ per\ second\ kW = \left(\frac{\Delta h_{exhaust\ gas}}{molar\ mass_{exhaust}}\right) \cdot Total\ mass$$

$$kW = \left(\frac{kJ}{kmol} \div \frac{g}{mol}\right) \cdot \frac{kg}{s}$$

$$kW = \left(\frac{kJ}{\cancel{kmol}} \times \frac{\cancel{mol}}{g}\right) \cdot \frac{kg}{s}$$

$$\frac{mol}{g} \times 10^{-3} = \frac{kmol}{kg}$$

$$kW = \frac{kJ}{s}$$

The transfer efficiency from the turbocharger to the compressor is simply:

$$Transfer\ Efficiency = \frac{kW_{Compressor}}{kW_{Turbo-charger}} \times 100$$

Which originates from the efficiency equation used in thermodynamics:

$$\eta = \frac{w}{JQ'}$$

The flowbench data was converted into l/s of flow, and Cubic Feet per Minute of flow, range conversions can be found in the appendix:

$$Flow (l/s) = Flowscale(\%) \times Range Conversion$$

$$CFM = Flow (l/s) \div 0.472857$$

$$7 (CFM) \div 3.31 (l/s) = 0.472857$$

$$CFM/sq.inch = \frac{CFM}{Valve Area (in)}$$

$$C_f = \frac{CFM}{Perfect flow}$$

$$Perfect Flow = P + \frac{1}{2} \cdot \rho \cdot v^2$$

Polynomials & Enthalpies

The enthalpy values were typed into Excel from JANAF tables provided in lectures, and therefore may contain human errors. This data was used to create the trendline and polynomial equations for each product to fit their corresponding lines.

These polynomial equations are multiplied by the temperature at each point to create maps for every product at every region. In the case of O_2 and CO and the stoichiometric points in the map, O_2 is only created at lean points where there is excess air (LAMBDA over 1), and CO will only be created at rich points where over-fueling occurs (LAMBDA less than 1). Stoichiometric points, LAMBDA 1, do not create CO or O_2 .

The enthalpy at a given temperature, for each molecule must be multiplied by the number of molecules it will form at the given LAMBDA value. These values are calculated by knowing how many atoms of each element of a fuel and air are available as reactants, and allocating these numbers to form the known products – CO₂, H₂O, N₂, and possibly O₂ and CO dependent on LAMBDA.

Energy Lost through exhaust

The formulas used to find the energy in Watts down the exhaust originate from the first laws of thermodynamics where:

$$E_2 - E_1 = Q - W$$

Dividing by a unit of time provides a rate, and multiplying the unit of mass by the change in internal energy provides a specific internal energy per unit mass:

$$\dot{m} = \frac{\Delta(me)}{\Delta t} = \dot{W} + \dot{Q}$$

$$\dot{Q} = (H_2 - H_1)$$

$$h \text{ (specific)} = \frac{H}{mass}$$

$$\dot{W} = \dot{m}(h_{in} - h_{out})$$

Flowbench conversions

To convert the pressure difference across the turbocharger from 25" of water as when tested to pascals, it is known that

$$\text{Weight of Water (N)} = hA\rho g = \frac{m^3}{1} \times \frac{kg}{m^3} \times \frac{m}{s^2}$$

h – height of water A – area of water ρ – density of water g – gravity (m/s²)

As the weight is the volume multiplied by the mass, the pressure at the bottom of the water can be attained through dividing by the cross-sectional area:

$$\text{Pressure at bottom of water (Pa)} = \frac{hA\rho g}{A} = h\rho g = \frac{kg}{1} \times \frac{m}{s^2} \times \frac{1}{m^2} = \frac{kg}{m \cdot s^2}$$

Which cancels out to leave the pressure in pascal.

To calculate the pressure at a difference of 25 inches of water, simultaneously converting inches to metres, finally:

$$1 \text{ Inch} = 25.4mm$$

$$P @ 25" H_2O \text{ (Pa)} = \frac{25 \times 25.4}{1000} \cdot 1000 \cdot 9.81 = 6229$$

The pressure difference affects the flowrate, therefore the flowrate at the pressure difference recorded in the Ford data has to equate to the flowrate recorded at 25" of water using:

$$\text{Flowrate at } \Delta P \text{ Ford Data (l/s)} = \text{Flowrate@ 25"} \times \sqrt{\frac{P_1 - P_2}{6229}}$$

Mass per Second through Wastegate

Assume that the lift and the flowrate coming through the wastegate are known across the map, as are the pressures and temperatures before and after the turbine, and the total mass through the exhaust.

To find the mass going through the wastegate at each load point, the density in and out of the turbine must be calculated. First, considering the ideal gas law which relates pressure, temperature, and the volume of a gas, the specific gas constant R can be found using:

$$PV = mRT$$

$$\text{Universal Gas Constant } R_U \text{ (J/kmol} \cdot \text{K)} = 8314$$

$$\text{Specific Gas Constant } R \text{ (J/(kg} \cdot \text{K))} = \frac{R_U}{\text{molar mass}}$$

$$R = \frac{\text{J}}{\text{kmol} \cdot \text{K}} \times \frac{\text{kmol}}{\text{kg}}$$

$$\text{Weight of 1 molecule} = \frac{\text{molar mass}}{\text{number of molecules}}$$

$$\text{Wt 1 molecule} = \frac{\text{kg}}{\text{kmol}} \times \frac{\text{kmol}}{1}$$

$$R \text{ for 1kg (J/(kg} \cdot \text{K))} = \frac{R_U}{\text{Weight of 1 molecule}}$$

Density can then be attained as rearranging the ideal gas law produces the definition of density:

$$\text{Density } \rho \text{ (kg/m}^3\text{)} = \frac{m}{v} = \frac{P}{RT}$$

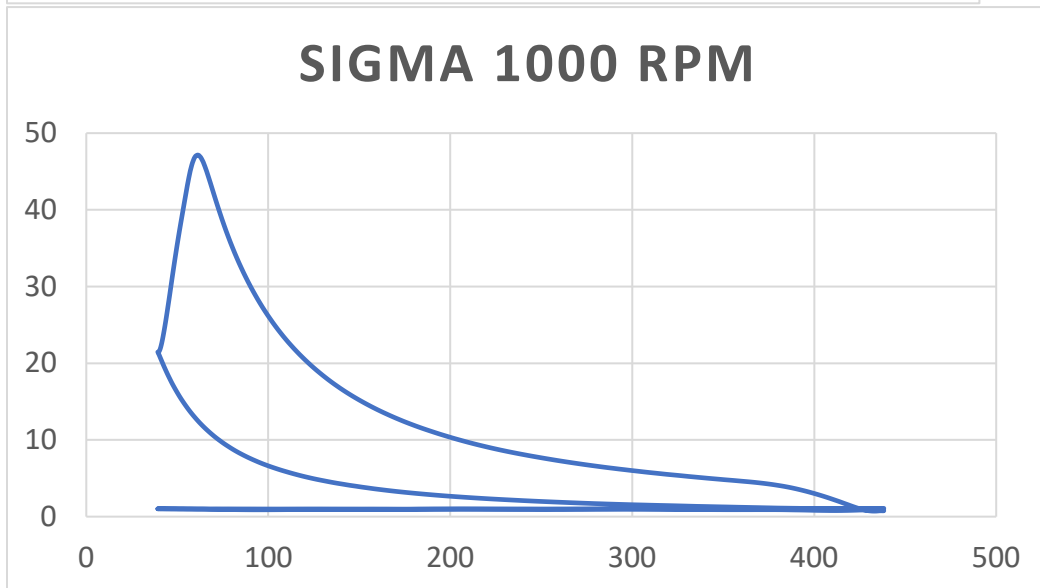
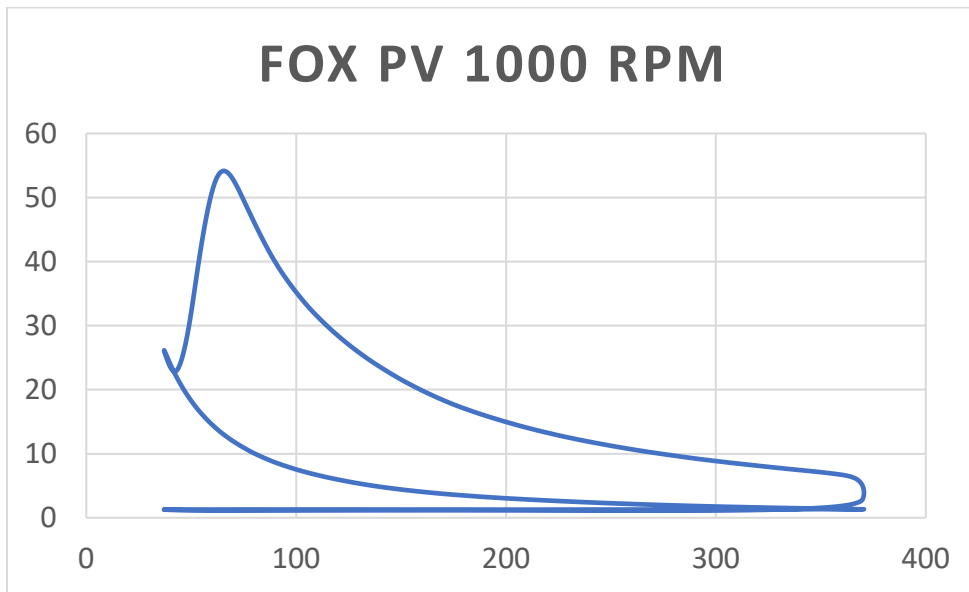
Finally, to convert the litres per second of flow through the wastegate into mass per second (kg/s), the flowrate is converted to m³ per second and multiplied by the average density through the turbo:

$$\text{mass through WG(kg/s)} = \frac{\text{flowrate}}{1000} \times \text{Average Density}$$

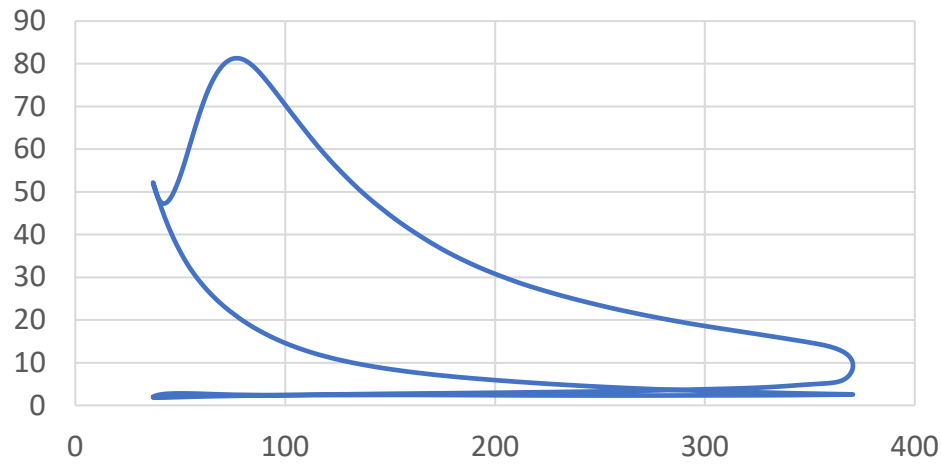
Naturally, the percentage is:

$$\text{Percentage through WG} = \frac{\text{WG mass per sec}}{\text{Total mass per sec}} \times 100$$

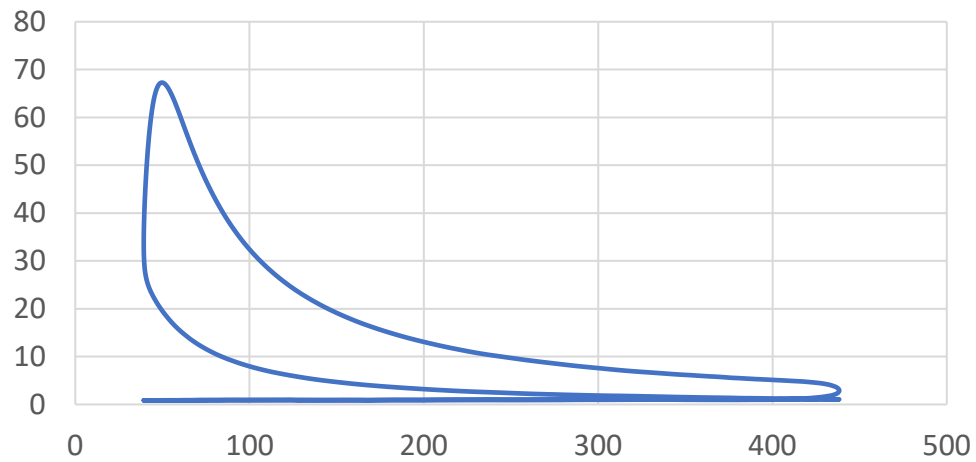
INITIAL PROJECT DIAGRAMS



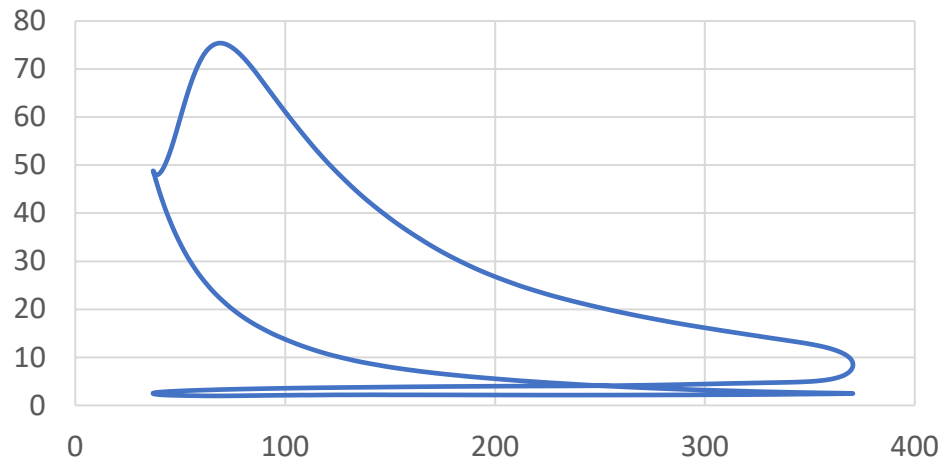
FOX 3000 RPM



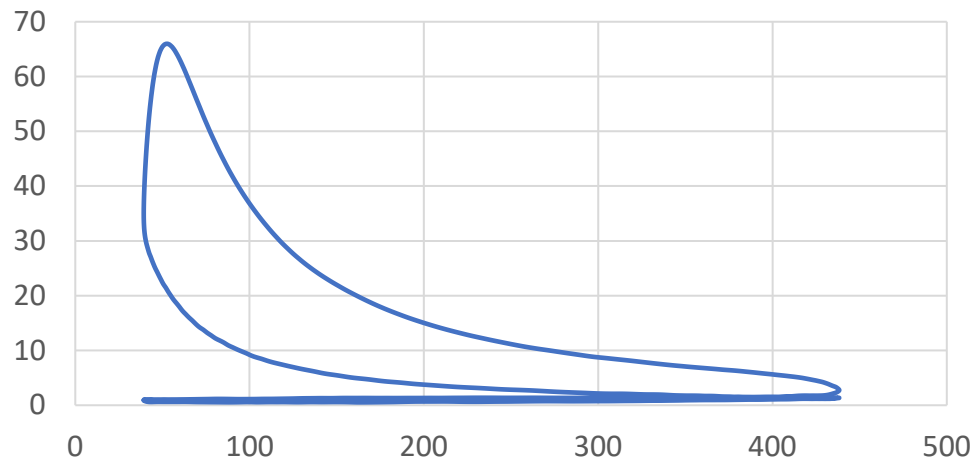
SIGMA 3000 RPM



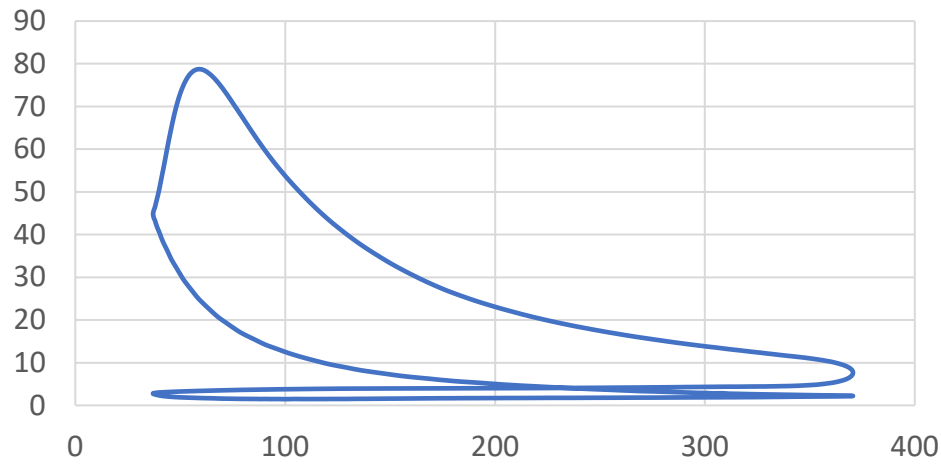
FOX 5000 RPM



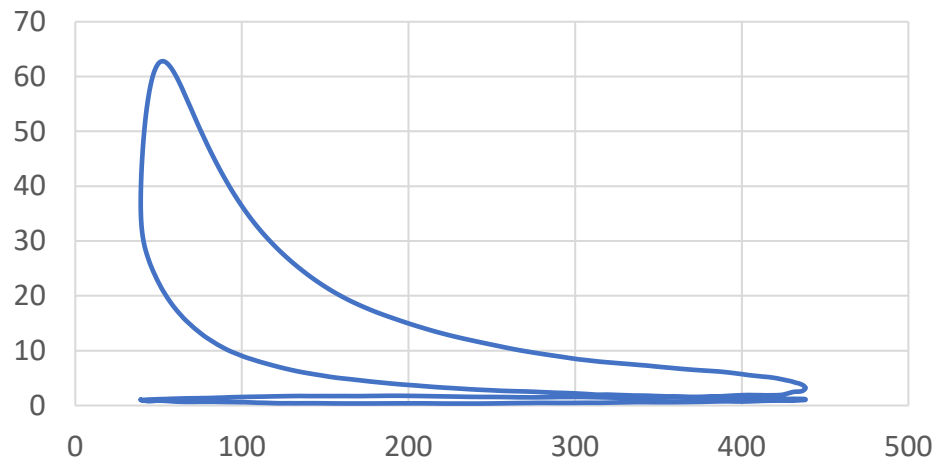
SIGMA 5000 RPM



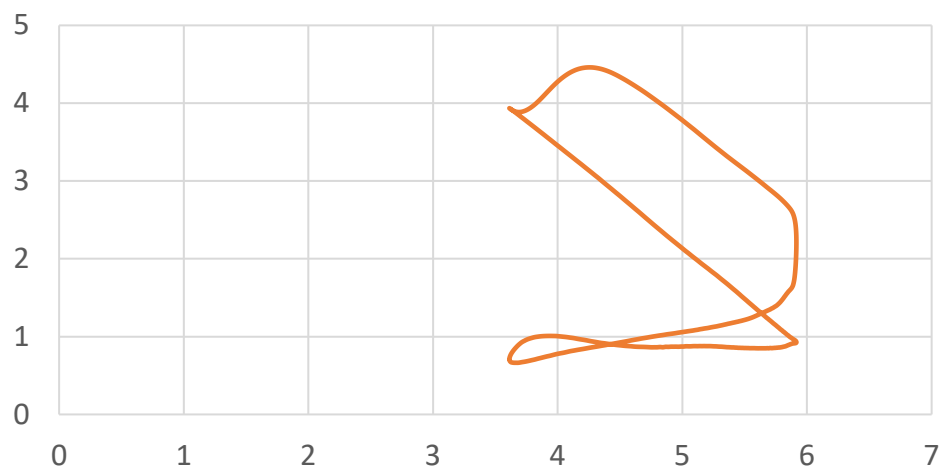
FOX 6000 RPM



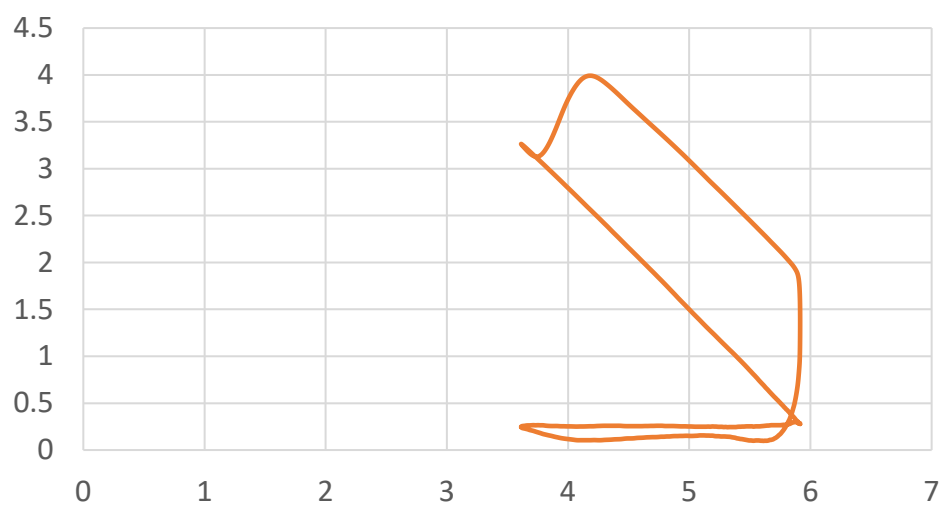
SIGMA 6000 RPM



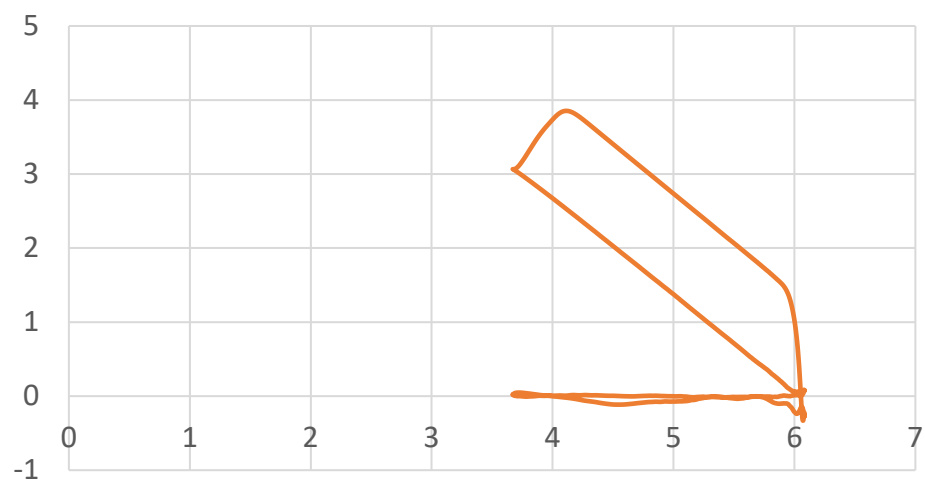
FOX LOG PV 3500 RPM



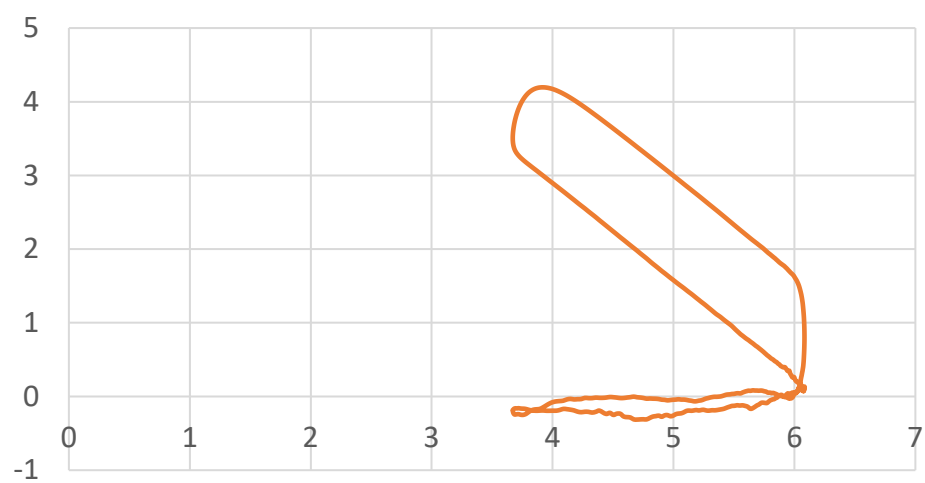
FOX LOG PV 1000 RPM



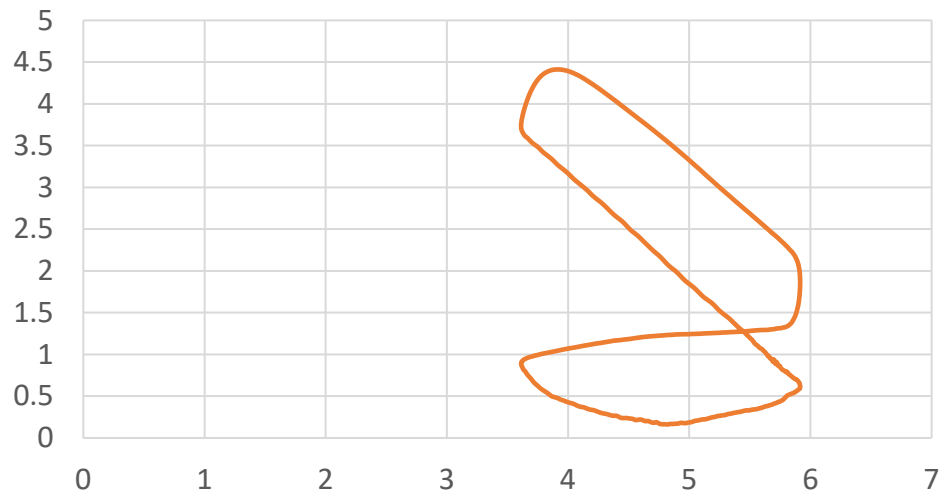
SIG 1000 RPM LN V (CC) VS MEAN P (BAR)



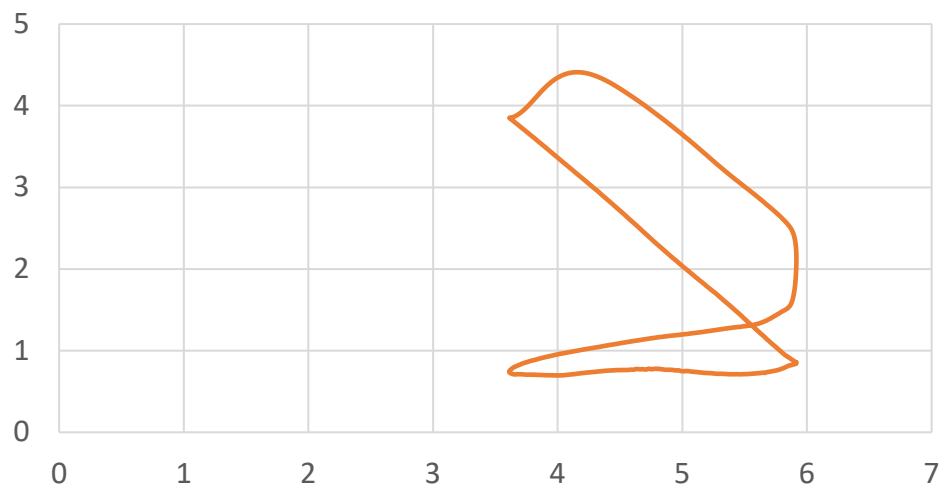
SIG 3500 RPM LN V VS. LN P



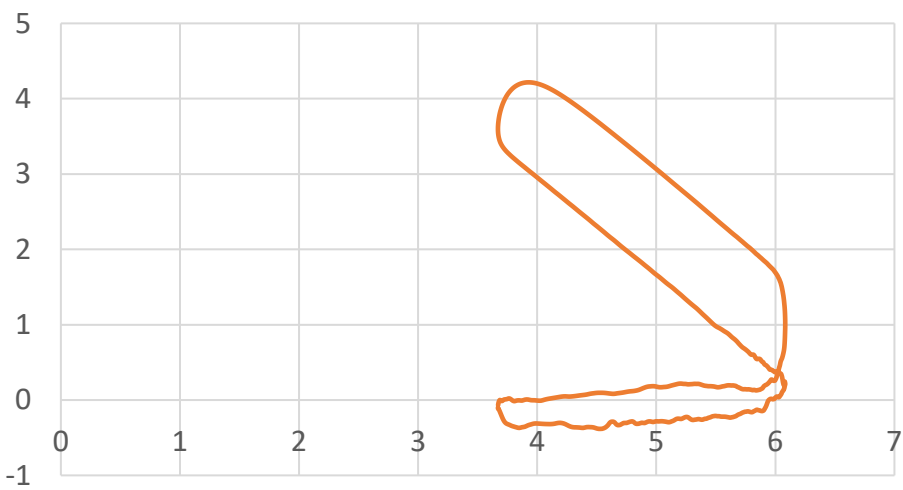
FOX LOG PV 6500 RPM



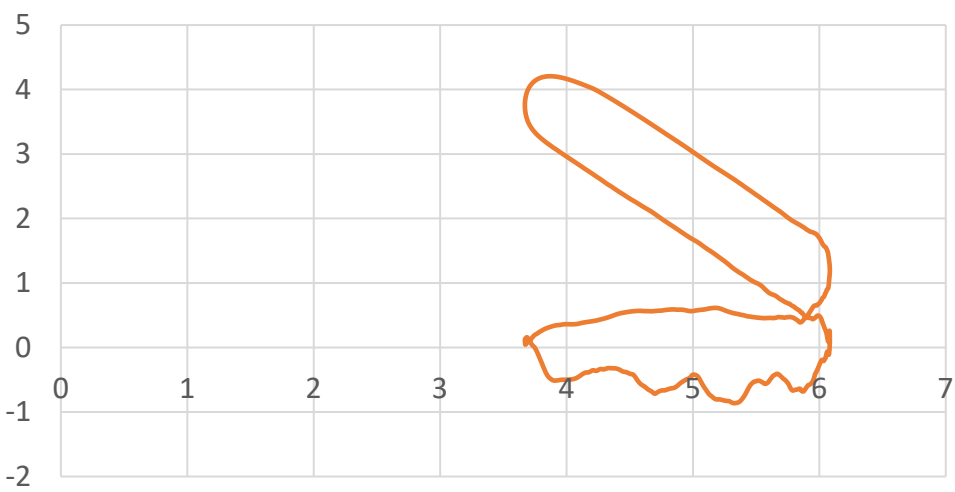
FOX LOG PV 4500 RPM



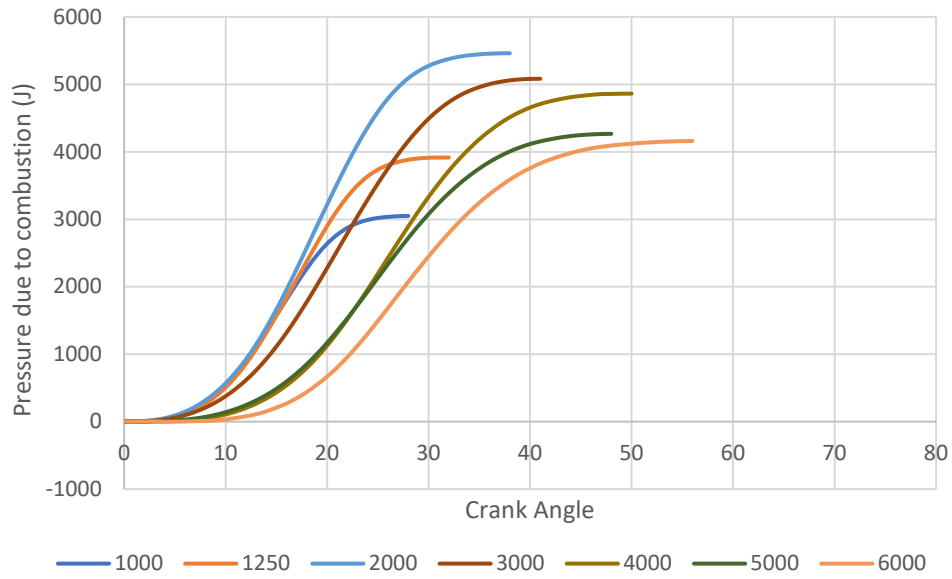
SIG 4500 RPMLN P VS PN V



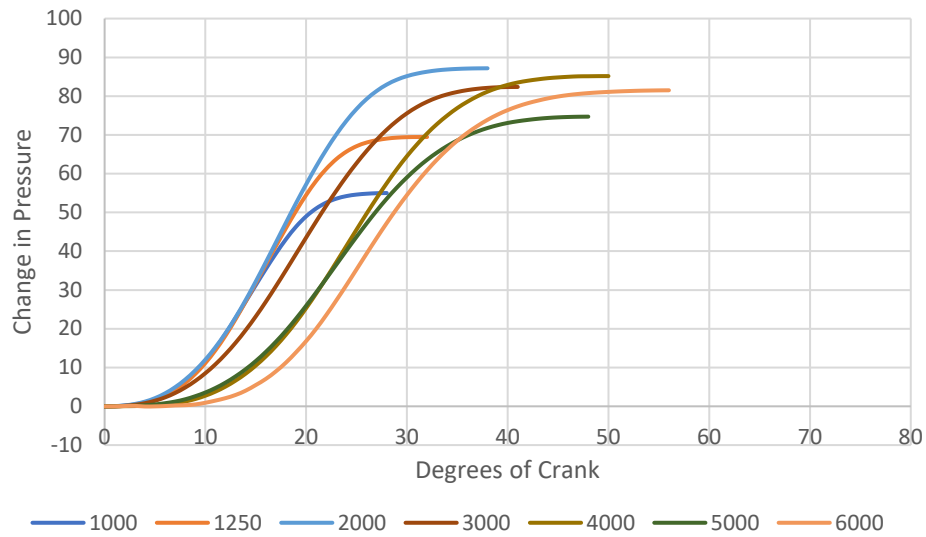
SIG 6500 RPM LV P VS PN V



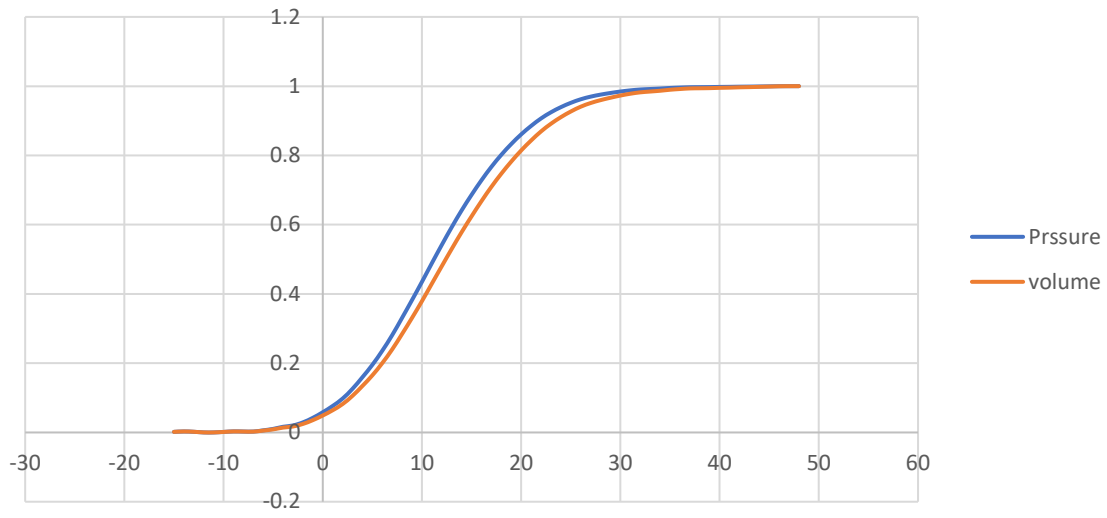
V2*Change in Pressure - Combustion



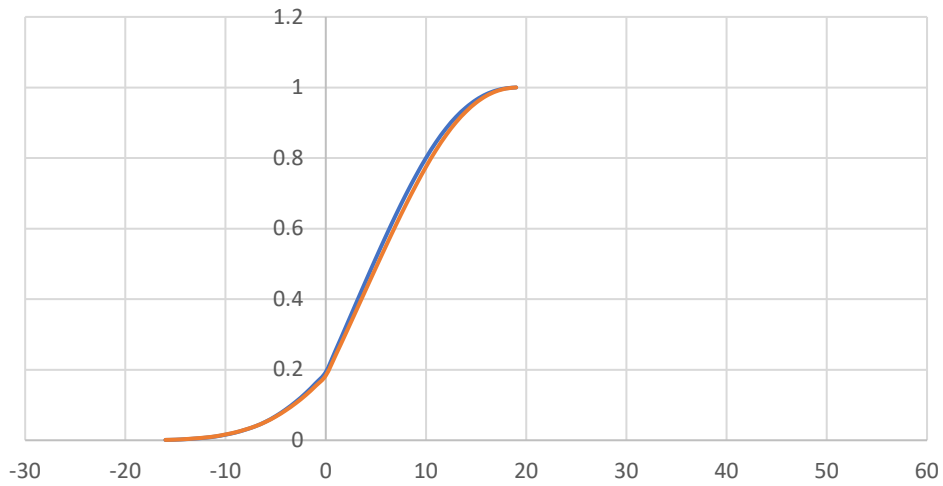
Change in Pressure during combustion



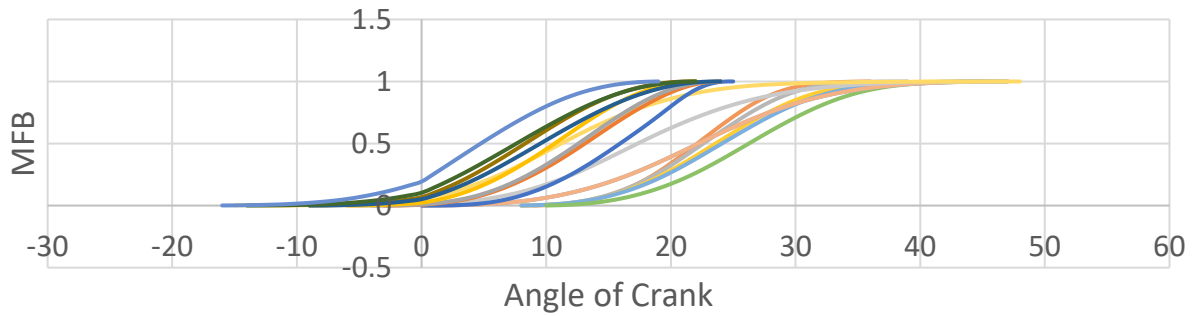
FOX MFB (Volume) 6500 RPM



SIGMA 6500 RPM MFB (VOLUME)



SIGMA - C.A vs MFB vs RPM



- 1000 FOX 1250 RPM 1500 RPM 1750 RPM 2000 RPM
- 5000 RPM 5500 RPM 6000 RPM 6500 FOX 1000
- 1500 1750 2000 5000 5500
- 6000 6500

SPARK ADV °CA (taken from Cyl 1 (TR104))

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

-12	41.79	42.344	44.055	43.124	-33.1816					43.16766667	3.765092	3.732657	1.228862698	44.17575		
-11	41.03	43.369	45.007	44.081	-30.7926					44.15233333	3.787646	3.714304	1.25433123	45.10428		
-10	40.34	44.307	45.96	45.038	-28.2539					45.10166667	3.808919	3.697344	1.329446109	45.9889602	0.001234	
-9	39.72	45.236	46.899	45.985	-26.0117					46.04	3.829511	3.681855	1.24181544	46.8696099	-0.01061	
-8	39.15	46.082	47.693	46.802	-23.1394					46.859	3.847143	3.667656	1.224895125	47.60702787	-0.01969	
-7	38.57	46.809	48.415	47.538	-20.6104					47.58733333	3.862567	3.655064	1.283060862	48.2613421	0.013658	
-6	38.24	47.501	49.098	48.226	-17.4786					48.275	3.875914	3.642882	1.204988426	49.26275218	-0.02442	
-5	37.88	48.069	49.647	48.769	-14.7144					48.82833333	3.888311	3.634423	1.126520291	49.31910389	-0.05144	
-4	37.58	48.512	50.089	49.202	-11.3739					49.26766667	3.897268	3.626472	1.213269196	49.64955786	0.01356	
-3	37.35	48.896	50.45	49.562	-7.95976					49.636	3.904716	3.620333		49.75701	-0.04374	
-2	37.19	49.142	50.667	49.774	-4.99235					49.861	3.909239	3.61604			-0.0444	
-1	37.09	49.272	50.787	49.899	-2.00101					49.986	3.911743	3.613347	1.457348436	50.05388549	0.010781	
0	37.05	49.349	50.879	49.966	2.00178					50.06466667	3.913316	3.612268	0.746913548	49.99676655	0.027567	0.038348
1	37.09	49.315	50.835	49.923	4.996667					50.02433333	3.91251	3.613347	0.857267374	49.88608704	0.022913	0.061261
2	37.19	49.100	50.725	49.803	7.974693					49.909	3.910201	3.61604	0.627810809	49.68926615	0.085401	0.146661
3	37.35		50.6	49.659	11.42379					49.77466667	3.907506	3.620333	0.695265301	49.46158545	0.101081	0.247743
4	37.58		50.388	49.437	14.83995					49.56266667	3.903238	3.626472	0.488998115	49.15926971	0.211064	0.458806

Combustion

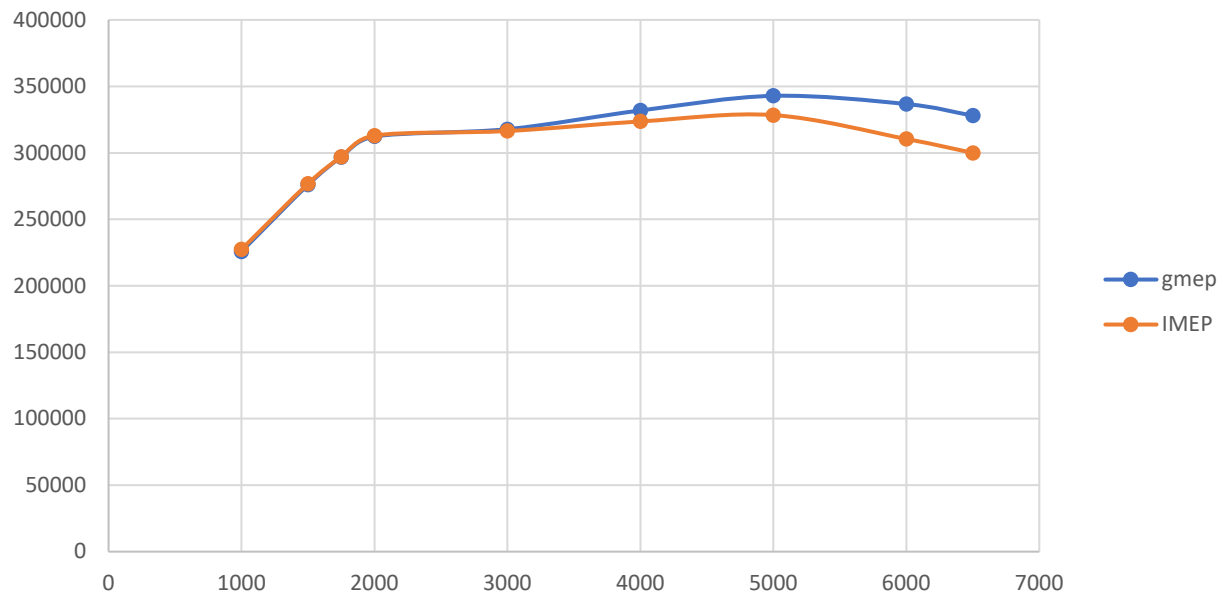
4.3 degrees

			FUEL & AIR MASS IN				TEMPERATURES IN, OUT, DIFFERENCE, & ATMOSPHERIC				PRE TURBO GASES ENTHALPY CALCULATOR			POST TURBO GASES ENTHALPY CALCULATOR		
RPM	Ignition Delay	Burn Duration	Fuel Mass	Fuel Mass	Air Mass	Total Mass	Pre Turbo Temp	Post Turbo Temp	Temp Difference	Atmospheric Temp	N ₂ h _f	H ₂ O h _f	CO ₂ h _f	N ₂ h _f	H ₂ O h _f	CO ₂ h _f
	Crank		kg/hour		kg/sec				K		(kJ/kmol)	(kJ/kmol)	(kJ/kmol)	(kJ/kmol)	(kJ/kmol)	(kJ/kmol)
											PRE TURBO			POST TURBO		
1000	4	28	3.24	0.0009	0.012384	0.013284	847	787.3	59.7	293	16569.09286	19848.2901	25247.49282	14677.05317	17500.79932	22198.28419
1250	3	32	5.22	0.00145	0.019865	0.021315	916.5	856.9	59.6	293	18796.36562	22637.6192	28870.51575	16884.76082	20241.92844	25758.89985
1500	4	38	7.52	0.0020889	0.02878489	0.030873778	973.8	914.7	59.1	293	20651.89268	24982.2717	31912.43121	18738.3545	22564.61931	28775.73877
1750	4.5	40	9.39	0.0026083	0.03625583	0.038864167	1053	975	78	293	23244.00357	28288.5635	36191.71664	20690.93284	25031.80332	31976.6382
2000	5	38	11.35	0.0031528	0.04445417	0.047606944	1126.6	1018.8	107.8	293	25680.03015	31427.6083	40239.26068	22120.86858	26851.62431	34333.6734
2250	6	38	12.92	0.0035889	0.05053156	0.054120444	1152.2	1045.1	107.1	293	26533.23038	32534.1403	41661.83174	22984.05924	27955.4042	35761.18979
2500	6	38	14.34	0.0039833	0.05708117	0.0610645	1190.4	1081.4	109	293	27811.82465	34199.1319	43797.8172	24180.36517	29492.33095	37745.84695
3000	6	41	18.08	0.0050222	0.06739822	0.072420444	1201.8	1091.6	110.2	293	28194.63714	34699.1907	44438.22054	24518.41571	29926.97885	38306.41839
3500	6	44	18.92	0.0052556	0.07147556	0.076731111	1222.6	1105.9	116.7	293	28894.5469	35615.3031	45610.06588	24992.33073	30538.379	39094.39983
4000	3	50	21.54	0.0059833	0.08412567	0.090109	1248.3	1139.7	108.6	293	29761.87786	36753.818	47063.84895	26116.25717	31992.90514	40966.30548
4500	6	50	22.34	0.0062056	0.08631928	0.092524833	1240.7	1135.7	105	293	29505.10172	36416.3827	46633.27291	25982.37515	31820.0861	40744.10286
5000	4	48	25.55	0.0070972	0.09481889	0.101916111	1268.1	1149.1	119	293	30431.97367	37635.8779	48188.1704	26429.75528	32399.74787	41483.18076
5500	5.5	50	36.61	0.0101694	0.13576208	0.145931528	1268.5	1148.4	120.1	293	30445.52761	37653.741	48210.92152	26406.39592	32369.41633	41450.20964
6000	1.5	54	27.62	0.0076722	0.09989233	0.107564556	1253.7	1135.6	118.1	293	29944.47039	36993.9575	47370.1179	25979.64403	31815.7687	40738.55009
6500	-0.5	64	25.11	0.006375	0.0913725	0.0983475	1219	1118.5	100.5	293	28773.2761	35456.4023	45406.93748	25410.69491	31079.06009	39790.68514

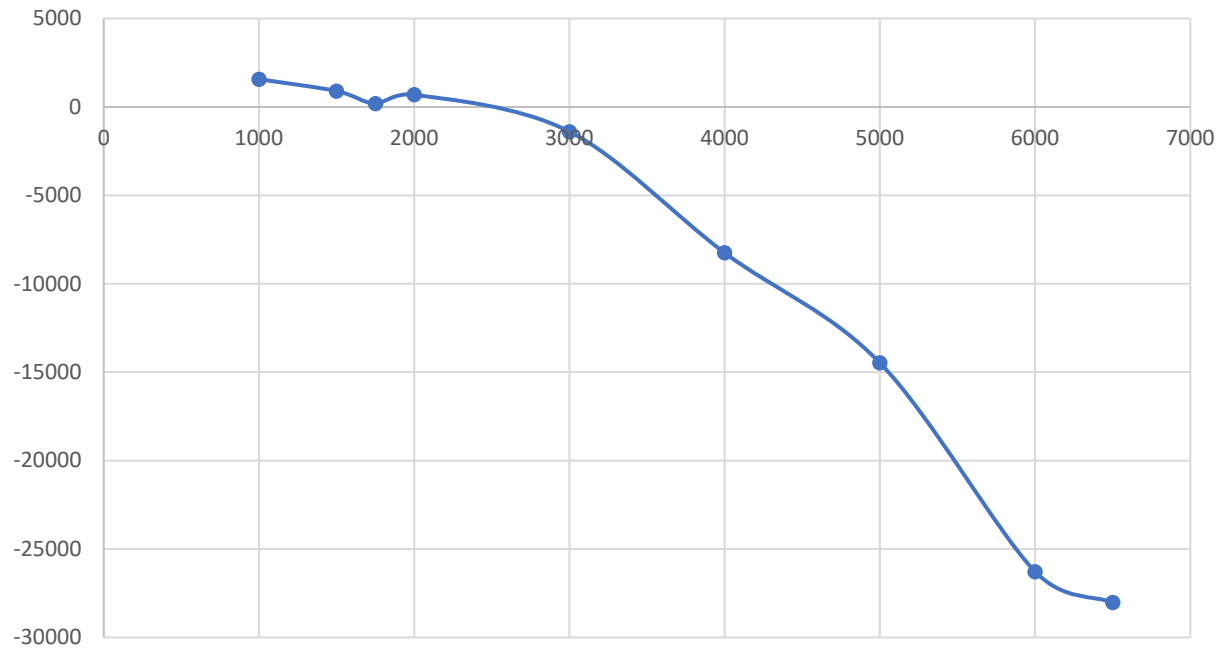
ATMOSPHERIC GASES ENTHALPY CALCULATOR			PRE-TO-POST TURBO ENTHALPY DROP OF GASES			POST-TURBO-TO-ATMOSPHERIC ENTHALPY CALCULATOR			PRE-TO-POST TOTAL KW LOST FROM TOTAL MASS PER SECOND		POST-TO-ATMOSPHERIC KW LOST / S OF MASS		PRE TURBO TO ATMOSPHERIC
N ₂ h _f	H ₂ O h _f	CO ₂ h _f	N ₂ in substance	H ₂ O in substance	CO ₂ in substance	N ₂ in substance	H ₂ O in substance	CO ₂ in substance	SUM substance loss	Energy lost per Second	SUM substance loss	Energy lost per second	Energy lost / sec
(kJ/kmol)	(kJ/kmol)	(kJ/kmol)	h _f (kJ/kmol)	h _f (kJ/kmol)	h _f (kJ/kmol)	h _f (kJ/kmol)	h _f (kJ/kmol)	h _f (kJ/kmol)	h _f (kJ/kmol)	kJ/s OR kW	h _f (kJ/kmol)	kJ/s OR kW	kW
ATMOSPHERIC			ENTHALPY LOSS PER ELEMENT			ENTHALPY LOSS PER ELEMENT			LOSS PRE-TO-POST TURBO		LOSS POST-TO-ATMOSPHERIC		TOTAL LOSS
-157.52532	-158.554305	-187.434303	88925.86546	21127.41741	24393.66905	697225.1892	158934.1826	179085.748	134446.9519	1.406563074	1035245.12	10.830573	12.2371363
-157.52532	-158.554305	-187.434303	89845.42576	21561.2172	24892.9272	800987.4486	183604.3447	207570.6732	136299.5701	2.288016792	1192162.467	12.472218	14.76023487
-157.52532	-158.554305	-187.434303	89936.29461	21758.87107	25093.53955	888106.3516	204508.5625	231705.3846	136788.7052	3.325978189	1324320.299	13.854833	17.18081092
-157.52532	-158.554305	-187.434303	119994.3245	29310.842	33720.62753	979877.5334	226713.2186	257312.58	183025.7941	5.601973421	1463903.332	15.315129	20.91710211
-157.52532	-158.554305	-187.434303	167280.5941	41183.85618	47244.69827	1047084.513	243091.6075	276168.8616	255709.1485	9.587292079	1566344.982	16.386857	25.97414936
-157.52532	-158.554305	-187.434303	166811.0436	41208.62491	47205.13559	1067654.474	253025.6265	287588.9928	255224.8041	10.87836478	1628269.093	17.034698	27.91306248
-157.52532	-158.554305	-187.434303	170650.3952	42361.20833	48415.76202	1143909.053	266857.9673	303466.25	261427.3656	12.57243029	1714233.27	17.934042	30.50647181
-157.52532	-158.554305	-187.434303	172782.4073	42943.90706	49054.41715	1159769.228	270769.7984	307950.8216	264786.7315	15.10208078	1738489.848	18.18781	33.28989084
-157.52532	-158.554305	-187.434303	183404.16	45692.31659	52125.32836	1182043.234	276272.3997	314254.6731	281221.805	16.99416626	1772570.307	18.544355	35.53852077
-157.52532	-158.554305	-187.434303	171344.1726	42848.21573	48780.34775	1234867.777	289363.135	329229.9182	262972.7361	18.66200405	1853460.83	19.390619	38.05262262
-157.52532	-158.554305	-187.434303	169539.9486	41366.66309	47113.36035	1228603.522	287807.7701	327452.2973	254019.9721	18.50996339	1843863.589	19.290214	37.80017712
-157.52532	-158.554305	-187.434303	188104.2646	47125.16989	53591.91711	1249602.188	293024.7195	330412.9205	288821.3516	23.18203322	1876039.828	19.626837	42.80886975
-157.52532	-158.554305	-187.434303	189839.1894	47558.92221	54086.69503	1248504.298	292751.7357	333101.1515	291483.8066	33.49985645	1874357.186	19.609233	53.10908943
-157.52532	-158.554305	-187.434303	186346.8391	46603.69917	53052.54255	1228446.959	287768.9071	327407.8751	286003.0808	24.22809583	1843623.742	19.287704	43.51580031
-157.52532	-158.554305	-187.434303	158041.3161	39396.08004	44930.01866	1201706.351	281138.5296	318824.9556	242367.4148	18.77227637	1802669.836	18.899251	37.63152747

univer gas cons	8.31446															
Air						Fuel										
c	h	c	h	c	h	c	h									
no at	16	19	25	47	8			N2	-10u ⁸ + 1E-07u ⁸ + 0.0025u ⁸ + 24.384u	hi LOST kJ/kg Lost/kg/s						
mol wt	12.01	1.008	15.999	14.01	12.01			H2O	-10u ⁸ + 1E-06u ⁸ + 0.0057u ⁸ + 25.922u	7288.73915	96.82361081					
tot wt	192.16	19.152	399.975	658.47	96.08			CO2	-10u ⁸ + 5E-06u ⁸ + 0.0193u ⁸ + 29.042u	7418.9115	158.1040987					
total	1269.757				114.224			O2	39u ⁸ + 4E-06u ⁸ + 0.0009u ⁸ + 24.741u	7487.88297	230.5617592					
										10024.3094	389.6097497					
										14040.7329	668.4363902					

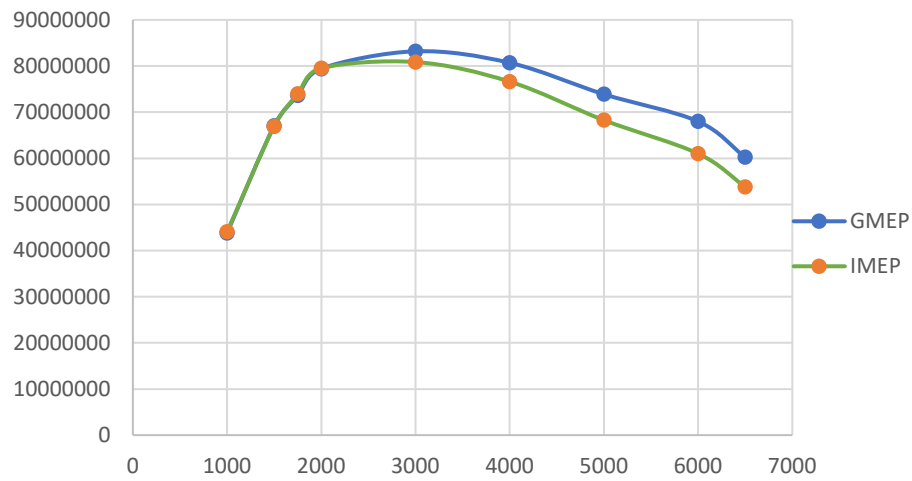
SIGMA GMEP vs RPM



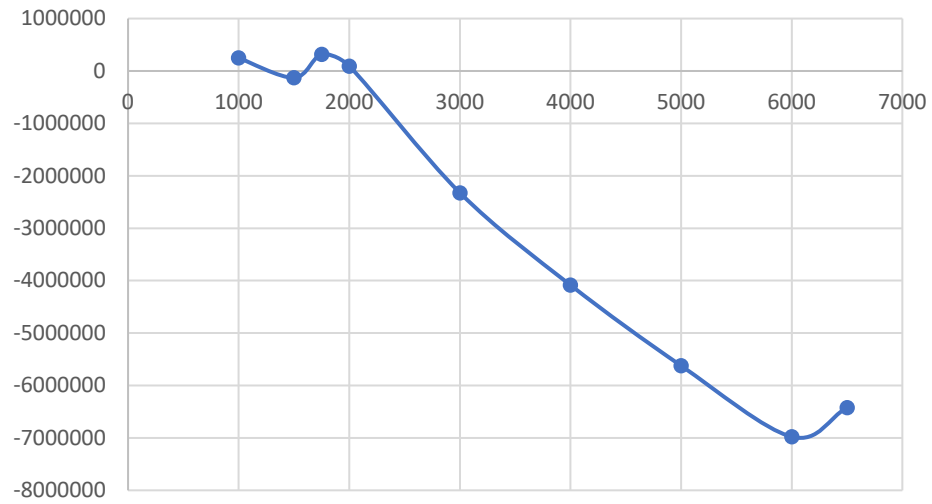
SIGMA PMEP vs RPM



FOX - GMEP v IMEP



FOX - PMEP v RPM

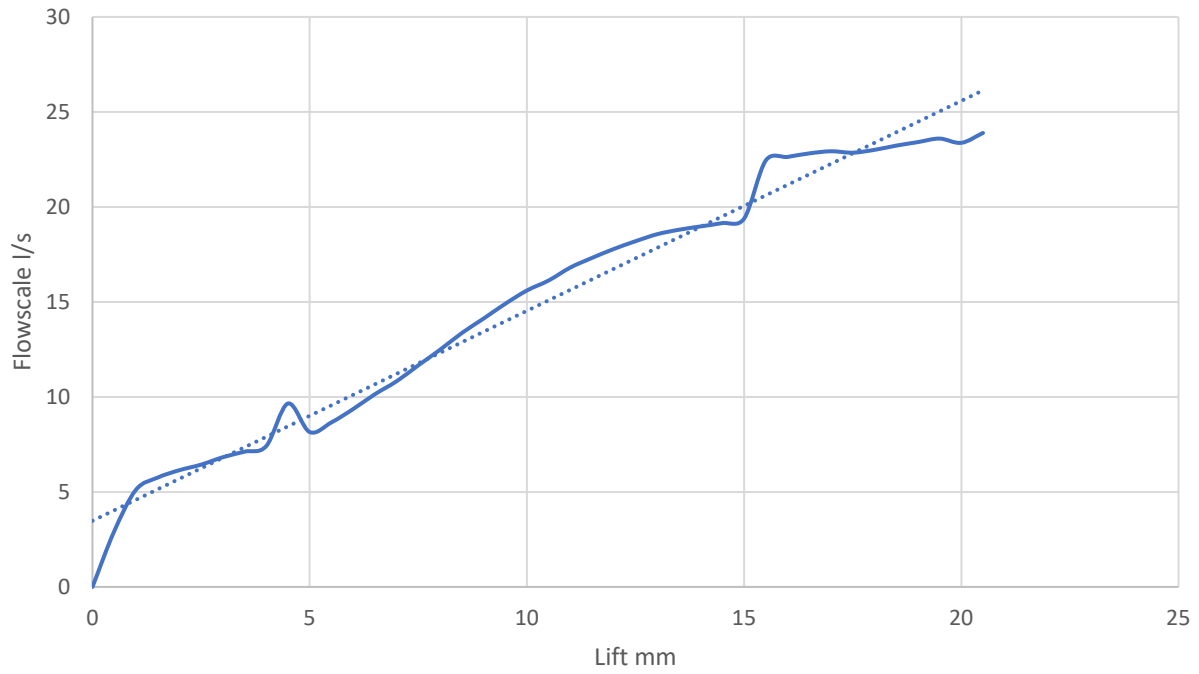


F	G	H	I
WD/deg	Total +ve WD	Total -ve WD	Mean Pressure
J	J	J	bar
0.109813	10906.3807	-4134.546205	2.754
0.271817			2.736666667
0.428853			2.699666667
0.605053	NET WORK DONE		2.661
0.77675	J		2.600333333
0.91848	6771.834492		2.578
1.0479			2.524666667
1.196253			2.465333333
1.337187	WD intake & exhaust	WD Compres & Expa.	2.417333333
1.44026	J	J	2.358333333
1.537027	-774.3826933	7546.217185	2.287666667
1.6585			2.233
1.754055			2.189666667
1.84498	NMEP	PMEP	2.141333333
1.954417	Pa	Pa	2.1
2.038833	61019139	-6977749.569	2.058333333
2.120353			2.019333333
2.181335			1.981333333
2.279367	GMEP	IMEP	1.949
2.35476	Pa	Pa	1.914333333
2.432083	67996888.57	61019139	1.883666667
2.493			1.858

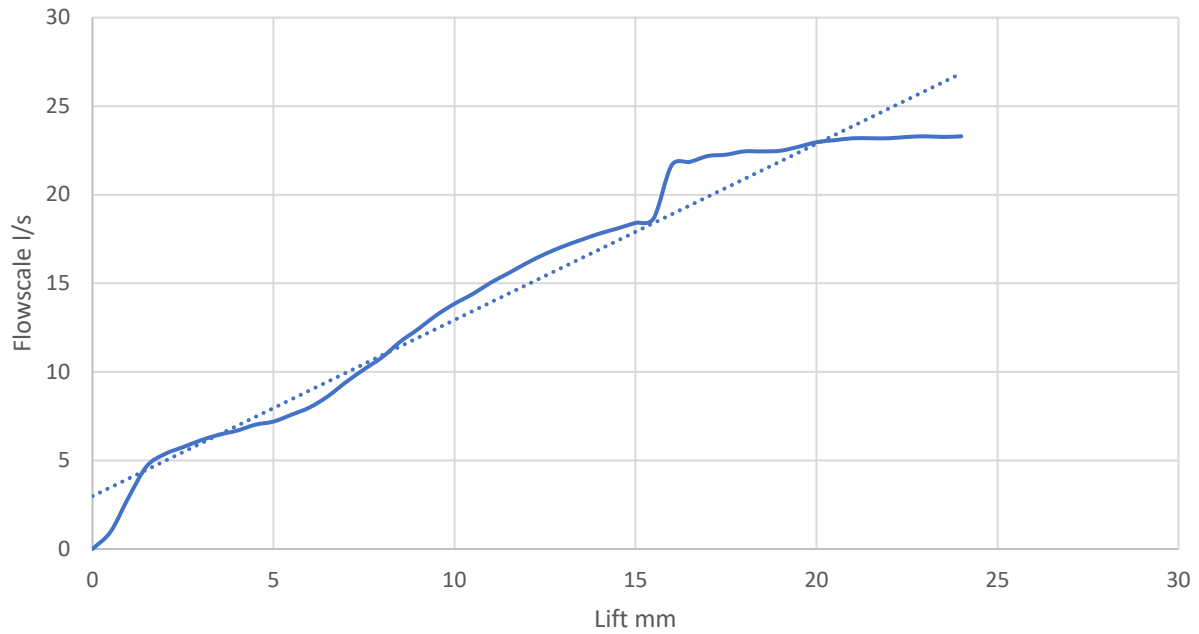
TURBOCHARGER PROJECT DIAGRAMS

Litres per Second		Cubic Feet per Minute		Wastegate x-section Area			Pressure Difference		
Range	Exhaust	CFM	l/s	Diameter	18	mm	Inches H2O	25	
1	19.5	7	3.31	Area	0.000254	m^2	Pascal	6229.35	
2	37.1	RATIO	0.472857						
3	75						Gas K Air	287.05	J/kg.K
4	148.5								
5	219.6								
6	284.6								

TEST 1 - Lift vs Flow



Test 2 - Lift vs Flow



	DATA (2)															
	Transfer Efficiency															
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		32.0936	39.6133		64.6837		62.5246	61.0228		61.6335	62.1199	61.9464	64.798		62.8467	57.7905
200								66.2086								
190							66.4237	66.0678	64.5967	64.0276						
180					62.9832		63.401	63.5895	61.9384	60.5485	64.2105					
170				58.5847	59.8801		62.3601	61.8074	66.704	67.2057	70.5109	61.7803				
160				56.3343	57.2504		58.6705	58.2799	63.5207	65.881	69.4418	69.0404	62.451			
150				52.8293	53.2879	51.6717	54.3996	55.5519	61.1628	64.2014	68.1755	67.8175	58.3588	54.92166		
140				47.4629	48.3516	46.1983	49.5737	53.2927	58.5568	61.5465	65.7191	68.2802	58.3782	55.91838	57.9024	
130				41.2236	35.4363	38.962	45.2086	48.4414	52.6573	56.5402	61.719	66.5442	56.2249	55.05062	53.4414	
120			34.1077	34.2825	28.3001	35.9337	39.5143	43.367	44.1555	51.2698	57.2983	61.9711	53.2339	53.91079	51.1198	50.7282
110			27.0173	27.216	25.7435	29.4159	30.905	31.5715	38.8949	45.8035	48.3109	56.7254	64.4208	51.42662	48.4138	48.7147
100		28.9702	22.5783	24.873	18.9438	20.0528	23.1232		31.9666	38.5715	40.9804	48.3737	57.1351	45.2623	42.5931	44.6727
90		25.3993	21.0489	24.0682	18.8481	18.939	18.8034	25.1854	28.269	32.079	36.1444	41.8783	47.5146	36.8942	34.3863	38.1789
80		24.51	22.7915	22.9172	14.4565	16.7201	16.39	22.7629	25.3642	27.3881	31.8709	34.7211	38.1267	33.46962	27.1593	29.1628
70		18.002	20.3742	19.8831	11.5165	12.7191	15.7375	22.0576	24.6321	24.0168	26.5399	30.6522	33.3216	31.56451	27.5504	26.4469
60		15.0818	16.1844	17.9153	9.6444	12.403	14.3828	21.3389	21.5535	22.594	24.0295	27.3254	30.2161	30.46766	27.2041	27.2814
50		15.2037	16.4093	16.3366	7.84673	10.4166	14.5918	17.4727	15.5476	51.6671	20.5156	23.1194	25.9858	27.41913	24.5143	25.5413
40	10.7666	14.7135	15.3839	14.3275	6.99045	9.07036	11.9881	12.3493	9.91007	14.6148	15.9385	17.807	22.7411	24.58085	21.996	22.4009
30	8.54435	10.4859	12.1524	10.1526	4.73484	6.21027	8.40694	9.00683	7.617	11.312	12.5177	13.8512	15.8564	18.39288	17.7979	18.4357
20	6.8286	10.0226	9.40902	9.26507	4.14418	5.23839	6.19982	6.01538	7.15447	8.03087	9.36748	10.3645	9.45868	11.44211	10.5721	9.95514
10	5.22997	9.17532	7.70232	12.6706	3.868	4.74747	9.90994	10.7636	11.3193	7.86891	8.91196	9.05269	13.2003	12.78889		5.58883
5	8.43048									10.1274	12.4849	12.5119				5.68458
2			20.4743			8.37008										

	DATA (1)															
	Transfer Efficiency															
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL		44.8973	80.0353	108.456	93.3271	78.4465	75.9432	77.4439		72.722	75.8634	72.7879	69.9784	68.7028	65.3559	59.9177
200						78.1572	79.1375	77.2773		75.1341						
190						76.2615	77.6135	76.1973	71.9304	70.5944						
180					92.5288	74.1401	75.4548	72.9068	73.0486	70.4292	74.3474					
170				107.763	117.782	72.2914	73.6522	72.1089	74.1245	73.9733	75.4779	72.438				
160				103.885	110.473	68.8995	70.4024	69.9754	72.251	73.5612	77.1866	71.8888	68.6076			
150				99.4822	100.801	68.3365	70.3498	71.4687	73.9275	73.3082	77.3676	72.756	69.5442	67.5212		
140			79.3716	90.4777	92.1989	70.3507	72.6456	70.7871	71.6955	71.0032	77.1121	77.6607	75.3481	69.0834	63.8856	
130			71.5516	74.4928	80.2113	71.0927	66.8274	66.108	66.5143	70.6507	76.6419	77.6753	80.5577	70.1043	62.1386	
120			60.1455	54.7146	66.073	62.177	58.6424	53.5415	58.4075	65.6613	74.6875	78.2004	81.9749	78.6046	64.2216	61.3464
110		41.2463	43.9154	44.2015	50.9681	48.6732	45.1876	42.6076	48.9338	58.6328	68.6889	78.0315	80.8324	83.7275	63.3729	62.0798
100		29.672	29.8825	32.1152	37.3727	35.1903	32.1727	35.0616	41.7677	51.1894	71.8024	72.7762	76.4369	85.0287	79.466	60.3935
90		24.0393	22.3667	25.737	26.4348	27.1451	25.9218	26.5516	36.1257	40.8311	51.6692	60.045	68.2798	86.5619	82.9612	79.0332
80		22.8131	19.5109	25.3606	28.1994	28.8614	22.4937	24.1386	30.5269	34.0809	41.3117	46.7027	58.0225	76.1122	76.1695	79.9903
70		18.33	17.7141	23.9224	31.1434	28.5509	20.7774	23.5262	27.1271	27.8677	34.0603	37.0574	44.4807	54.0435	62.5876	69.2233
60		13.4512	14.0459	20.7237	26.6637	22.2442	18.9842	21.728	23.4101	22.9355	26.8462	28.2059	32.6506	37.6393	44.4246	49.2614
50		11.6829	13.3703	17.3897	20.3811	19.0161	15.8816	18.1641	18.5395	17.7304	20.123	21.0187	23.7152	26.3144	29.9713	33.0219
40	9.20676	10.9265	14.2916	12.8622	15.881	14.3664	12.0449	13.8984	13.6228	14.0371	15.4114	15.0061	16.8209	18.8108	21.0008	23.3989
30	7.99817	8.69728	10.2367	8.80049	10.4183	9.27266	8.61636	9.08459	9.1132	9.98877	10.6044	10.4043	11.1761	12.3331	14.002	16.0554
20	6.90203	7.61025	7.63765	5.73399	6.1465	5.80781	5.76201	6.17009	5.59364	6.46545	7.26337	6.79444	6.96954	7.83544	8.98486	10.6969
10	6.26802	7.32121	5.86114	5.17768	5.38212	5.68203	5.58231	5.74813	5.14555	5.78396	6.66803	5.99497	5.35304	6.22832	6.6226	7.93431
5	10.2557	10.2448	6.88306	5.40948	4.96973	4.64244	4.65433	5.07744	4.9726	6.08441	8.05931	8.00551	6.84437	9.31177	8.24608	10.4361
2	30.1169	11.8002	9.50571	9.99966	8.89815	5.67634	7.24962	6.88622	5.5221	6.19617	11.0597	11.7464				

[illegible]

PRE- TURBO TO ATMOSPHERE ENERGY LOSS (1)																	
energy lost per second (kW)		800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
	FL		8.3724598	15.2702	24.3396	34.6905	47.1529	55.4212	65.6074		86.0255	103.893	105.892	120.64	125.614	125.508	110.182
	200						47.13	55.6087	65.0833		95.6957						
	190						43.8118	50.7082	59.79	72.1542	85.6033						
	180					33.2366	40.0055	46.8343	54.7329	67.1796	78.289	97.8086					
	170				24.2635	29.6039	36.597	42.9625	50.0261	63.02	70.9343	88.8521	99.8103				
	160				22.6694	26.9768	33.3974	38.8197	44.9706	56.9851	67.6375	81.1756	90.3579	110.421			
	150				20.4607	24.7733	30.132	34.9535	40.4221	50.3777	61.2116	73.2106	82.0465	97.6061	115.979		
	140			15.3193	18.8076	22.3937	27.0131	31.1555	35.9851	44.7398	54.8962	65.3179	74.9588	87.5996	99.6089	116.395	
	130			13.806	16.7624	19.9844	23.6044	27.1049	31.0669	39.2587	48.7961	59.091	67.1459	78.04	88.1192	103.976	
	120			12.7824	14.9759	17.4837	21.0367	23.9909	27.1136	34.3123	43.7943	53.8983	60.8647	68.6914	79.691	89.2374	104.361
	110		8.2952189	11.363	13.7226	15.5717	18.4663	21.4434	24.3041	30.9383	38.881	47.5648	54.5837	61.1894	70.8619	80.773	92.7875
	100		7.0632433	9.85091	11.748	13.94	16.5537	19.1346	21.8504	27.6475	34.6009	41.5744	48.5597	55.4521	64.3476	73.7592	83.499
	90		6.3031959	8.54369	10.3071	12.4212	14.6621	17.0745	19.4171	24.6745	30.3136	36.3949	43.0522	49.3107	57.0437	65.9517	77.1047
	80		5.3290103	7.29079	9.05041	10.9015	12.6906	14.9161	17.2644	21.891	26.6293	32.5759	37.9475	44.0529	51.5087	58.1718	67.5667
	70		4.4359978	6.18306	7.81617	9.48213	10.978	12.9921	14.9915	18.7246	23.093	28.5144	33.102	38.7418	44.5398	51.2368	59.5729
	60		3.6573329	5.09283	6.51428	7.812	9.16855	10.8987	12.8448	16.1958	19.791	24.4823	28.5958	33.6432	38.7191	44.6088	51.3315
	50		2.9628086	4.12655	5.3305	6.3698	7.54342	8.85091	10.4238	13.4862	16.7748	20.6144	24.3216	28.6922	32.8253	38.1571	43.6856
	40	1.92292	2.3806343	3.30952	4.27793	5.07624	5.96967	7.17348	8.39979	11.0944	13.9498	17.0403	20.3258	24.2549	28.079	32.2476	37.1028
	30	1.55285	1.8140691	2.53951	3.28312	4.05925	4.71876	5.72673	6.67333	8.78993	11.2322	13.6863	16.5318	19.7888	23.3484	26.5716	30.9519
	20	0.91111	1.256228	1.81245	2.42814	3.06464	3.66447	4.31233	5.06305	6.59472	8.56199	10.6423	13.1	15.6558	18.2622	20.8767	24.3956
	10	0.62064	0.8267726	1.27991	1.64014	2.09357	2.46236	2.85847	3.29088	4.67592	5.94807	7.97813	9.56595	11.632	13.4615	15.6955	18.5856
	5	0.3884	0.5809741	0.97964	1.30173	1.81886	2.26327	2.59131	2.93914	3.95436	5.02875	6.64762	8.0228	9.7909	11.2813	12.8642	15.3956
	2	0.32891	0.5211678	0.81611	1.01967	1.39473	1.98447	2.15676	2.62738	3.79532	4.72357	6.11616	7.15267				

Compressor Efficiency DATA (1)																	
	800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500	
FL		60.7905	68.2231	70.3374	69.5183	69.3694	72.024	73.0069		75.7866	76.5714	76.5008	75.0817	73.8688	72.2179	70.8526	
200						69.4152	71.5646	72.873		76.3294							
190						69.8643	72.0979	73.2129	75.2498	76.9097							
180					69.7928	70.3919	72.516	73.9402	75.5549	77.1075	76.8494						
170				70.4447	71.6825	70.9053	72.9318	74.3115	75.895	77.066	77.3265	76.7679					
160				70.9246	71.8575	71.149	73.1434	74.4302	76.2996	77.4338	77.4809	76.8939	76.0407				
150				71.1426	71.9486	71.6626	73.4581	74.8755	76.237	77.1544	77.4366	76.7611	76.3296	74.8735			
140			68.4175	71.3518	71.7213	71.8435	73.4927	74.8088	75.9419	76.8339	76.9046	76.2593	75.925	74.9116	73.2335		
130			67.7892	70.2891	71.7537	71.2651	72.5191	73.5883	75.334	76.1627	75.943	75.2112	75.3237	74.2927	73.3047		
120			66.5393	68.3202	69.3658	70.1222	70.9749	71.956	73.5956	74.6932	74.4182	72.9849	73.1956	72.8615	71.282	70.1571	
110		61.6723	64.6175	65.7246	67.3067	67.4776	68.7835	69.1223	70.966	72.5588	72.7296	71.3256	70.2355	69.2066	68.5547	67.3903	
100		54.9903	60.3717	61.36	63.1445	62.6884	63.2506	63.5665	56.5781	62.2083	63.2277	67.3387	67.3427	66.7223	66.6116	64.8074	
90		44.8145	54.0157	46.9664	51.4843	52.3469	51.0562	47.3963	53.3562	56.8166	60.7759	60.4044	60.5756	59.2114	63.4663	62.8966	
80		27.8561	40.0434	32.8371	41.2186	40.8722	40.8187	42.7977	50.3183	54.8201	61.2946	59.8915	60.6458	58.9429	57.2426	55.4525	
70		7.98061	12.8367	20.9532	31.4864	34.5193	36.4385	35.044	46.1446	51.8384	58.6665	57.8745	60.1436	59.5429	58.5037	56.9214	
60		3.85682	8.89642	15.4356	23.4855	26.2163	14.9882	18.61	23.0945	26.0578	30.6238	31.6058	34.193	33.937	38.6277	56.4932	
50		0	2.52597	6.0719	13.0359	9.91484	10.531	13.6151	18.6126	22.4689	26.85	27.9265	31.4305	31.4598	32.342	33.0409	
40	5.4722	8.64738	14.4173	1.77506	5.85888	5.16715	6.42569	9.66648	14.132	16.9917	21.7751	23.4471	27.1392	27.7919	29.8844	30.1796	
30	4.21726	4.48378	8.98972	0	1.74723	0	2.79177	4.64658	8.242	10.7982	16.4475	14.5671	20.3722	22.0876	23.9356	25.9641	
20	-2.39766	0	2.7216	-2.76353	-2.77097	-2.8335	-1.9567	0	0	3.00528	8.17041	6.87361	10.5597	11.3671	14.4789	18.9879	
10	-3.28049	-0.65962	-0.70668	-3.70207	-3.8807	-3.79572	-3.89231	-3.87429	-3.15568	0	7.17354	2.82127	2.14902	2.15184	3.29391	7.85651	
5	-3.2072	-0.60349	-0.67438	-2.41863	-4.66475	-3.32767	-2.63345	-3.39021	-1.80387	3.116	13.4375	11.8366	12.7265	12.8347	12.0434	7.9744	
2	-2.52886	-0.57869	-1.27994	0.65403	1.94017	0	4.50321	6.25683	3.70978	7.51091	21.0629	22.475					

Compressor Efficiency DATA (2)																	
		800	1000	1250	1500	1750	2000	2250	2500	3000	3500	4000	4500	5000	5500	6000	6500
FL			60.7905	68.2231	70.3374	69.5183	69.3694	72.024	73.0069		75.7866	76.5714	76.5008	75.0817	73.8688	72.2179	70.8526
	200						69.4152	71.5646	72.873		76.3294						
	190						69.8643	72.0979	73.2129	75.2498	76.9097						
	180					69.7928	70.3919	72.516	73.9402	75.549	77.1075	76.8494					
	170				70.4447	71.6825	70.9053	72.9318	74.3115	75.895	77.066	77.3265	76.7679				
	160				70.9246	71.8575	71.149	73.1434	74.4302	76.2996	77.4338	77.4809	76.8939	76.0407			
	150				71.1426	71.9486	71.6626	73.4581	74.8755	76.237	77.1544	77.4366	76.7611	76.3296	74.8735		
	140			68.4175	71.3518	71.7213	71.8435	73.4927	74.8088	75.9419	76.8339	76.9046	76.2593	75.925	74.9116	73.2335	
	130			67.7892	70.2891	71.7537	71.2651	72.5191	73.5883	75.334	76.1627	75.943	75.2112	75.3237	74.2927	73.3047	
	120			66.5393	68.3202	69.3658	70.1222	70.9749	71.956	73.5956	74.6932	74.4182	72.9849	73.1956	72.8615	71.282	70.1571
	110		61.6723	64.6175	65.7246	67.3067	67.4776	68.7835	69.1223	70.966	72.5588	72.7296	71.3256	70.2355	69.2066	68.5547	67.3903
	100		54.9903	60.3717	61.36	63.1445	62.6884	63.2506	63.5665	56.5781	62.2083	63.2277	67.3387	67.3427	66.7223	66.6116	64.8074
	90		44.8145	54.0157	46.9664	51.4843	52.3469	51.0562	47.3963	53.3562	56.8166	60.7759	60.4044	60.5756	59.2114	63.4663	62.8966
	80		27.8561	40.0434	32.8371	41.2186	40.8722	40.8187	42.7977	50.3183	54.8201	61.2946	59.8915	60.6458	58.9429	57.2426	55.4525
	70		7.98061	12.8367	20.9532	31.4864	34.5193	36.4385	35.044	46.1446	51.8384	58.6665	57.8745	60.1436	59.5429	58.5037	56.9214
	60		3.85682	8.89642	15.4356	23.4855	26.2163	14.9882	18.61	23.0945	26.0578	30.6238	31.6058	34.193	33.937	38.6277	56.4932
	50		0	2.52597	6.0719	13.0359	9.91484	10.531	13.6151	18.6126	22.4689	26.85	27.9265	31.4305	31.4598	32.342	33.0409
	40	5.4722	8.64738	14.4173	1.77506	5.85888	5.16715	6.42569	9.66648	14.132	16.9917	21.7751	23.4471	27.1392	27.7919	29.8844	30.1796
	30	4.21726	4.48378	9.89872	0	1.74723	0	2.79177	4.64658	8.242	10.7982	16.4475	14.5671	20.3722	22.0876	23.9356	25.9641
	20	-2.39766	0	2.7216	-2.76353	-2.77097	-2.8335	-1.9567	0	0	3.00528	8.17041	6.87361	10.5597	11.3671	14.4789	18.9879
	10	-3.28049	-0.65962	-0.70668	-3.70207	-3.8807	-3.79572	-3.89231	-3.87429	-3.15568	0	7.17354	2.82127	2.14902	2.15184	3.29391	7.85651
	5	-3.2072	-0.60349	-0.67438	-2.41863	-4.66475	-3.32767	-2.63345	-3.39021	-1.80387	3.116	13.4375	11.8366	12.7265	12.8347	12.0434	7.9744
	2	-2.52886	-0.57869	-1.27994	0.65403	1.94017	0	4.50321	6.25683	3.70978	7.51091	21.0629	22.475				

