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ADVANCED ENGINE DESIGN

CON-ROD ACCELERATION, FORCES AND

DISPLACEMENTS

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1 Introduction

This report shall investigate the acceleration, forces and displacements of a connecting rod (con-rod) from a Ford 1.6 litre GDTI EcoBoost engine. A datasheet of cylinder pressures and component masses were provided, and from this the author researched further data and carried out various calculations to analyse how different engine speeds effect the con-rod characteristics.

For ECXEL calculations, please see appendix 5.

1.1 Data Provided

Table 1 - Data provided

Data	Unit	Value
Piston Cross-Sectional Area	mm ²	139.65
Total Piston Reciprocating Mass	kg	0.3504
Total Con-rod Mass	kg	0.4064

1.2 Data Researched

Table 2 - Data researched

Data	Unit	Value	Source
Ultimate Tensile Stress - Steel	MPa	750	(AZO Materials, 2016)
Ultimate Tensile Stress - Titanium	Mpa	950	
Young's Modulus - Steel	kg	200	
Young's Modulus - Titanium	m	133.8	
Bore	m	0.0790	(Ford, 2009)
Crank Radius (R)	m	0.0407	
Con-rod Length (L)	m	1.3400	

2 Engine Modification

To understand the effects of engine speed on the conrod, the author theoretically modified the engine by increasing the RPM limit from 6000rpm to 9000rpm to see how this effected stresses and performance; this proved to be an inefficient way to modify the engine as the turbo could not provide enough air to see substantial performance gain.

To increase RPM, the author gathered data for the standard engine, then used second order polynomial data extrapolation to analyse effects (figure 1). This is only an assumption and will give an indication of expected trends but may be inaccurate. Second order extrapolation was used to keep the mathematics relatively simplistic.

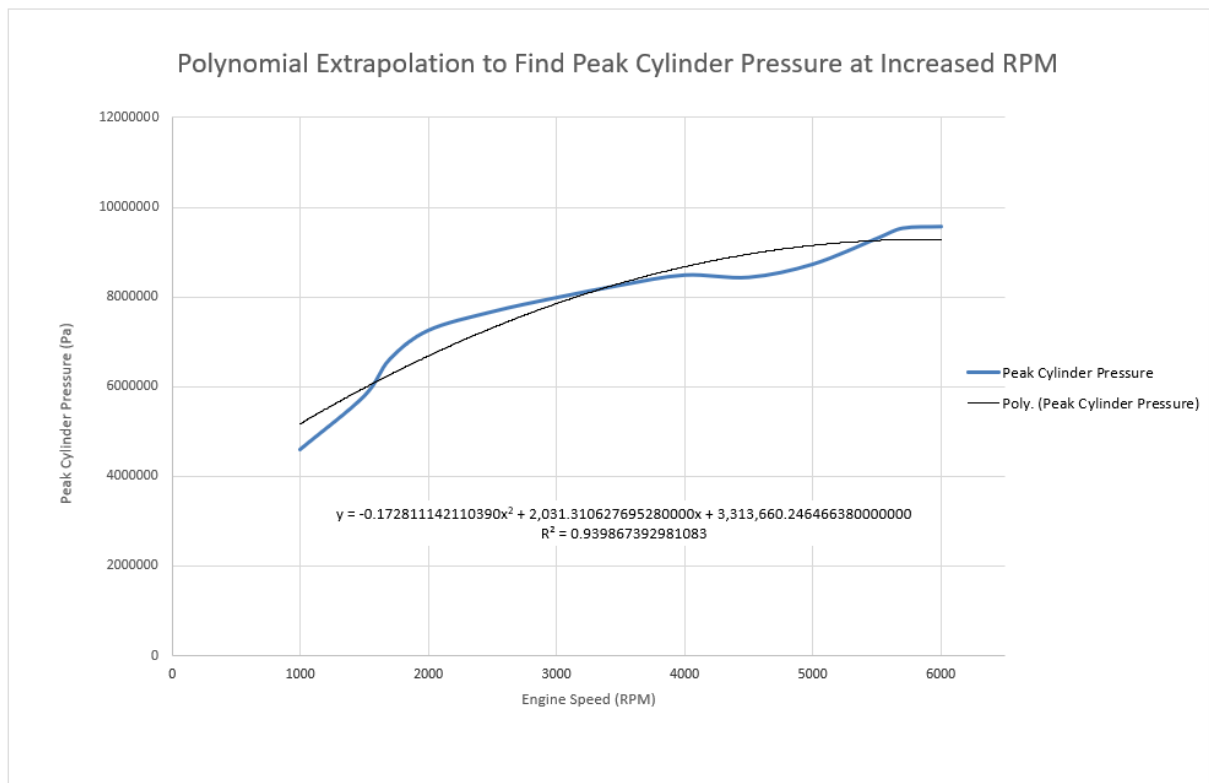


Figure 1 - Example of data extrapolation - peak cylinder pressure

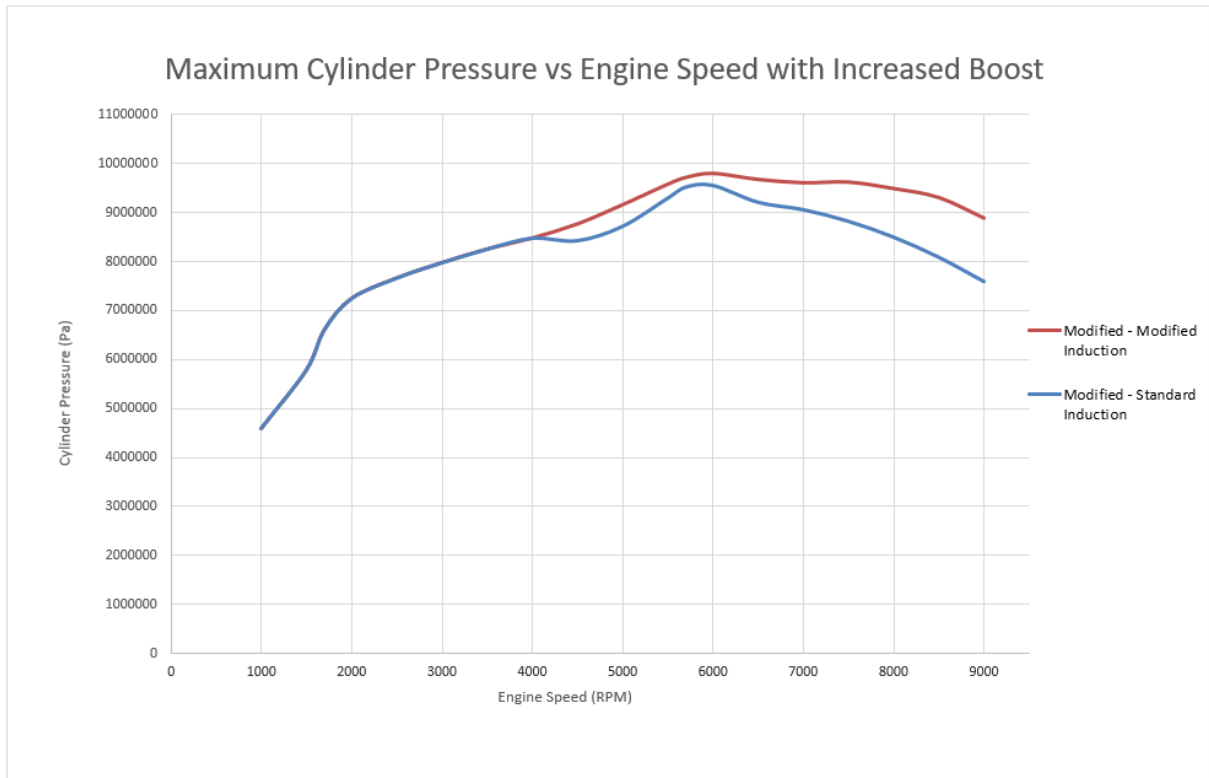


Figure 2 - Maximum cylinder pressure with increased boost

Figure 2 represents how increasing engine speed without modifying the induction system is inefficient. The red line represents how cylinder pressure may stay more constant with an uprated turbo; for example, a hybrid or twin turbo setup. Added boost may reduce the drops in pressure around 4500rpm and 6000rpm. This in turn would increase torque drastically and also slightly increase power, ensuring the engine runs more efficiently overall.

The author created this graph by making an informed assumption as to how much extra pressure an uprated turbo could bring. Research shows that it is common to upgrade this engine's standard Borg Warner turbo to a Borg Warner EFR series high performance turbo (DS Sport, 2018).

Increased pressure was only analysed for some graphs, to illustrate explanations more clearly. It should be noted this modification is purely theoretical and would, in practice, not be viable. For example, the engine may run too hot, introducing thermodynamic losses and high octane fuel would be required to supplement the added air to create sufficiently strong combustion.

3 Engine Gas Forces

The author took an average value across each cylinder and converted to SI units, Pascal, then found the highest average pressure per degree recorded in the engine. From this, the peak gas force can be found:

$$Force = Pressure \times Area$$

$$\therefore Gas Force = Cylinder Pressure \times \frac{\pi \times bore^2}{4}$$

3.1 Gas forces per cycle

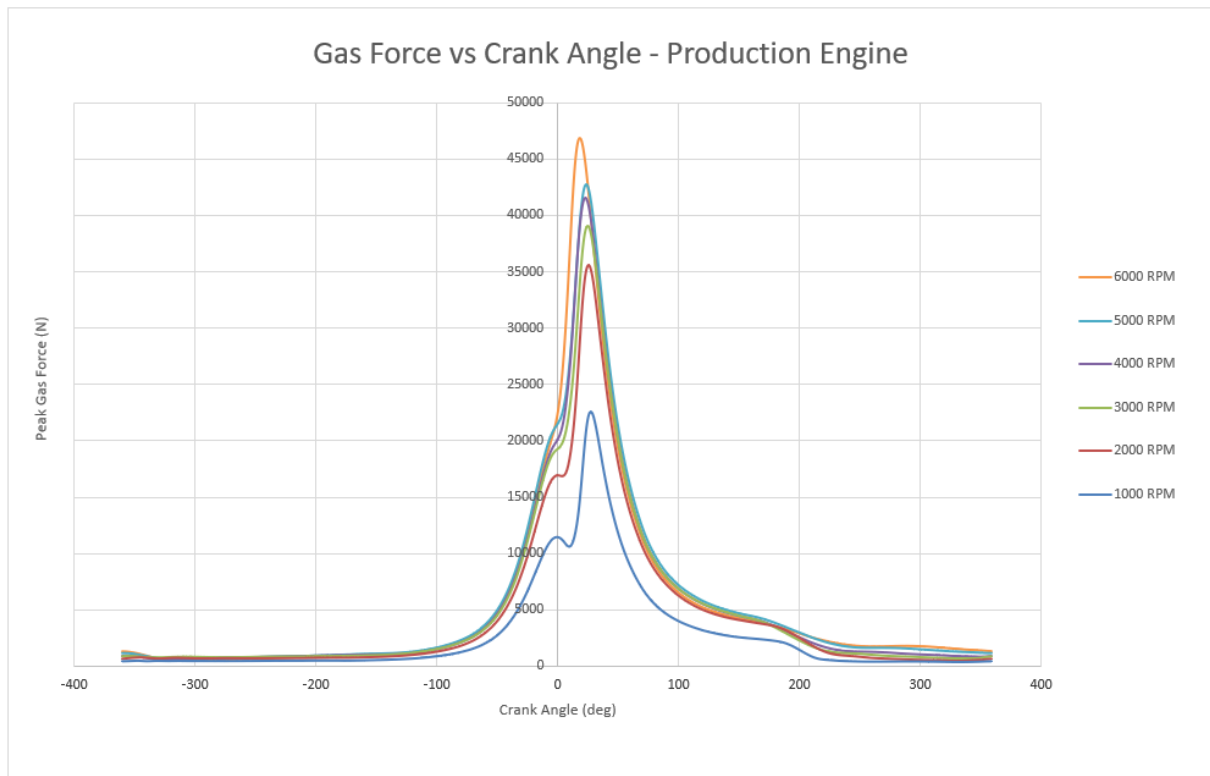


Figure 3 - Gas force vs crank angle

- The highest gas force is seen at highest engine speed. As this engine uses forced induction, higher rpm introduces higher boost pressure. This means more air in the cylinder and thus a stronger combustion (Olta, et al., 2014).
- The peak force for each rpm is just after TDC. The camshaft profile ensures combustion occurs here, as the piston starts to travel downwards, ensuring the most energy can be used to drive the engine.
- From BDC to TDC pressure steadily increases until a drop exactly at TDC. This is as the piston travels back down and increases the volume as the spark ignites, thus reducing pressure.
- As engine speed increases the peak gas force advances as combustion has to start earlier to ensure the process can take place in a shorter time (Caton, 2018).

3.2 Peak Gas Force for Each RPM

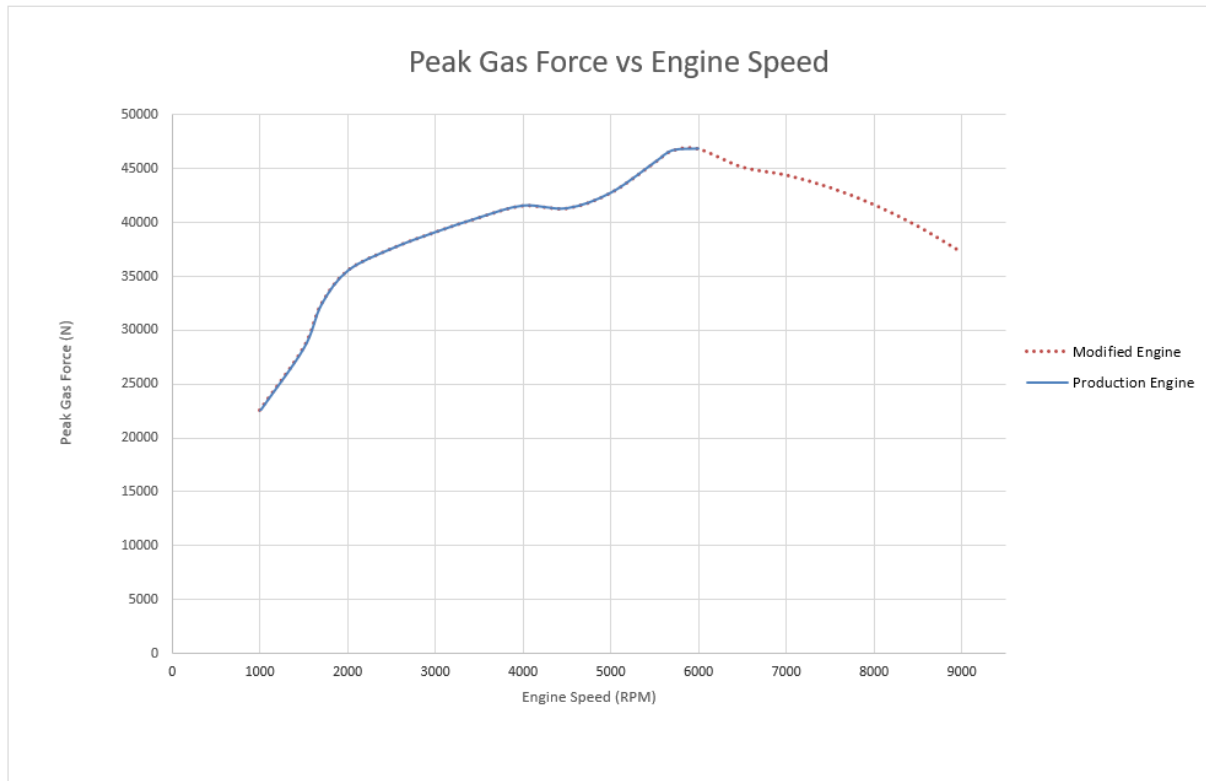


Figure 4 - Peak gas force vs engine speed

- Figure 4 shows an overall positive correlation between engine speed and peak force until 6000rpm. This then declines due to lack of induction capacity, forming the trend for further graphs in this report.

4 Inertia Loads

From the known engine speed, angular velocity can be calculated. This can then be used to calculate piston acceleration for first and second orders:

$$\begin{array}{ll} \text{First Order:} & \text{Second Order:} \\ R \times \omega^2 \times \cos \theta & + \frac{R}{L} \times L \times \omega^2 \times 2 \cos \theta \end{array}$$

From this, the inertia force can be calculated:

$$F = m \times a$$

$$\therefore \text{Inertia Force} = \text{Piston Mass} \times \text{Piston Acceleration}$$

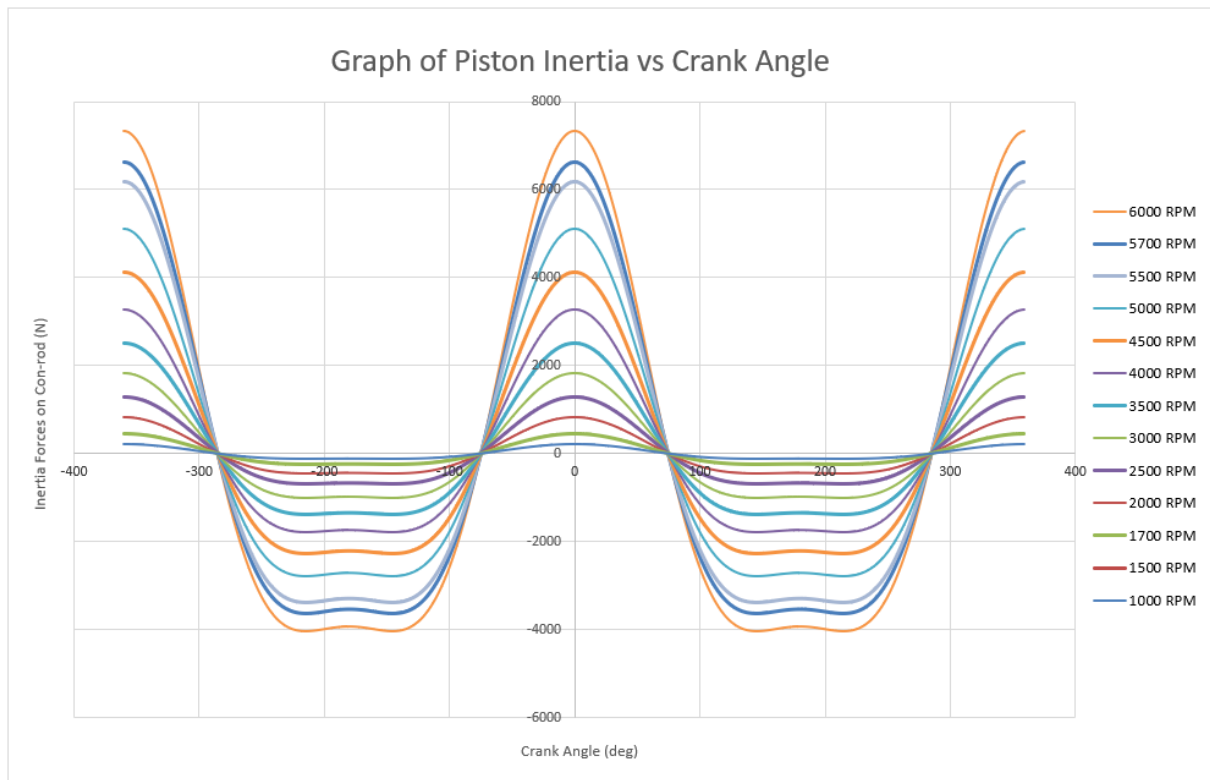


Figure 5 - Inertia force per crank angle - production engine

- Figure 5 shows the highest values at TDC as piston acceleration is at a maximum because of a change of direction. Here, the piston will have most inertia after travelling the full length of the cylinder, opposing the crankshaft force changing its direction.
- The shape of the graph is dictated mainly by the first order of acceleration, the first derivative of the piston's velocity curve. This was added to the second order of acceleration, the second derivative of the position curve. Further orders have been considered negligible.
- Inertia forces at BDC are less and a different shape because the second order element is out of phase by 360° , cancelling out and reducing the amplitude. This is not the case at TDC and thus the first and second orders combine and amplify the peaks (EPI Inc., 2014).

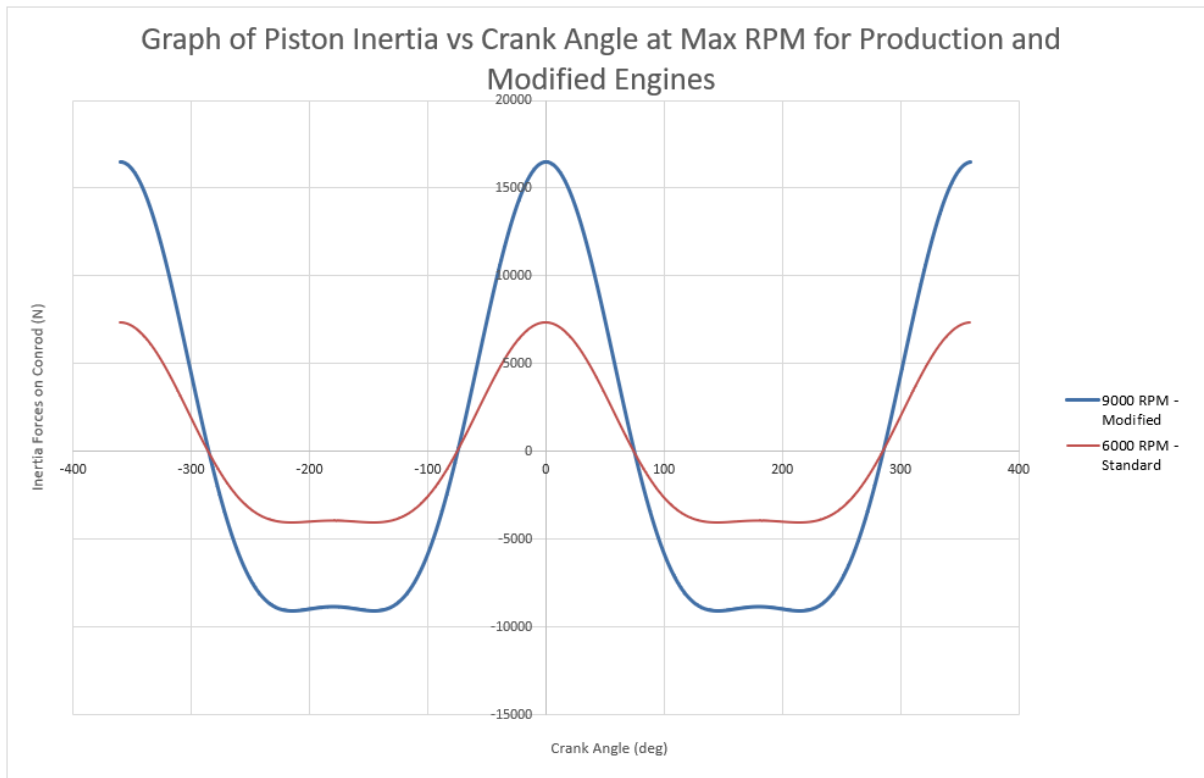


Figure 6 - Inertia forces for modified and production engines

- Because of increased acceleration, a higher engine speed produces higher inertia forces.
- From 6000rpm to 9000rpm inertia forces increase by over 50%. Tensile force is a product of inertia force; showing a potential strain on the con-rod, possibly presenting safety issues.

5 Maximum Net Compressive and Tensile Forces

During each four stroke cycle, the con-rod experiences both tensile and compressive forces. Tensile and Compressive forces are found by calculating the gas force resolved with respect to the con-rod angle and finding maximum and minimum values. Negative values show magnitude of tensile loading.

$$rod\ angle = \sin^{-1}\left(\frac{R}{L} \times \sin(crank\ angle)\right)$$

$$\therefore resolved\ rod\ force = \frac{(gas\ force - inertia\ force)}{\cos(rod\ angle)}$$

5.1 Con-rod Tensile Forces

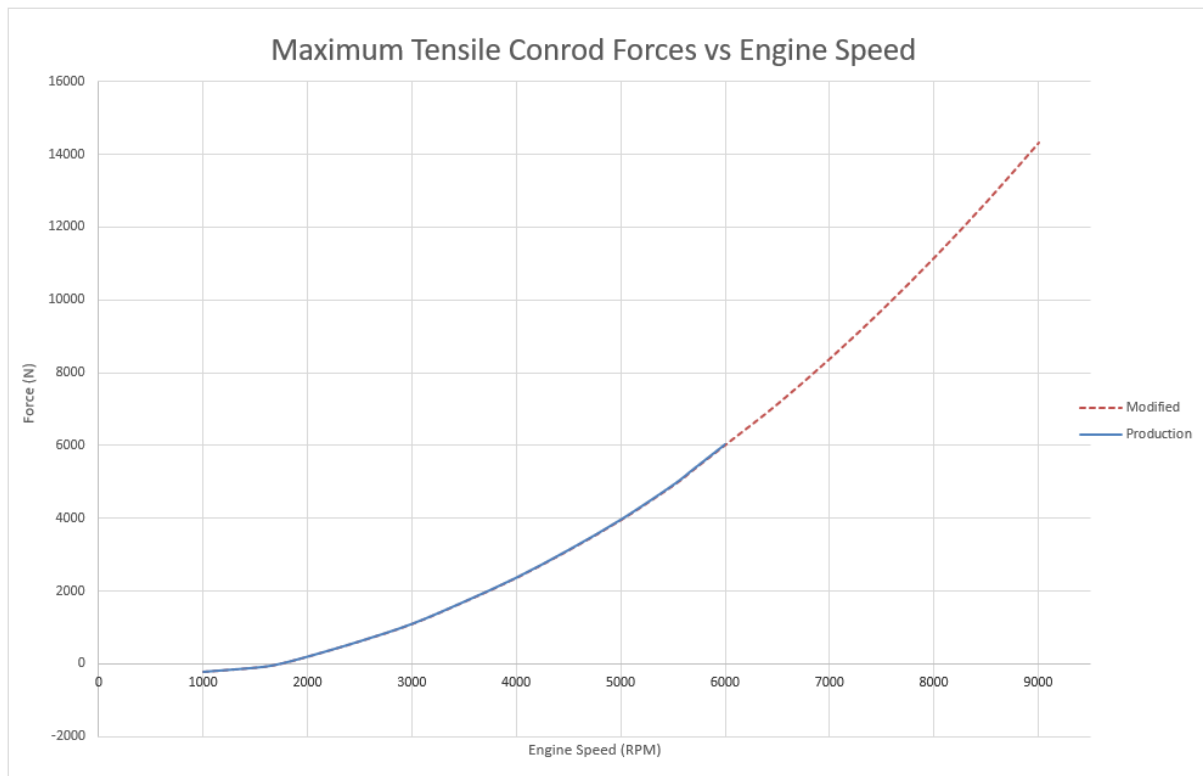


Figure 7 - Con-rod tensile forces

- As the crankshaft pulls the piston down the cylinder, the con-rod experiences a tensile force, stretching it. Tensile force therefore is directly proportional to inertia force.
- Tensile forces on the con-rod will always increase with RPM regardless of changes to induction. This may present a safety issue for the con-rod.
- Figure 7 shows a negative tensile force at low rpm. The nature of a turbocharged engine means initially gas force overrides the tensile load, compressing the con-rod. As engine speed increases, inertia forces increase, thus creating a net torsional force (Taylor, 1985).

5.2 Con-rod Compressive Forces

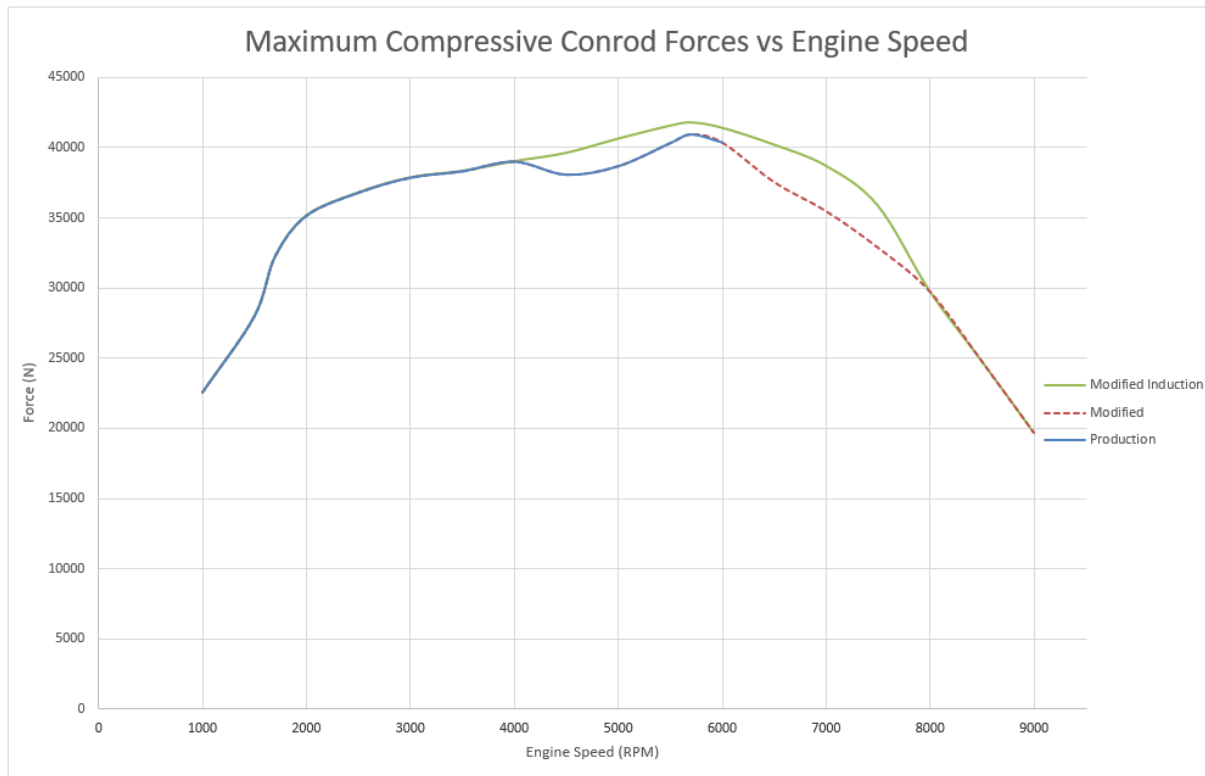


Figure 8 - Con-rod compressive forces

- The force compressing the con-rod is the gas force on the piston, pushing it down as it travels up the cylinder, therefore, without an uprated induction system, the compressive force decreases at high rpm.
- The green line shows an estimate of compressive force with uprated boost, using data from figure 2. The extra pressure overcomes inertia force and increases the compressive force from 4000rpm onwards. The force stays higher until 8000rpm where it drops and converges with the standard turbo, then drops lower than 1000rpm.
- These later trends are seen as the inertia force overcomes the compressive force and reduces it as inertia force increases exponentially with rpm. This shows that the compressive force on the con-rod is not a danger to the modified engine (see section 7).
- Cyclic variation is a common phenomenon within engines. Maximum cylinder pressure on a cycle can occasionally be considerably less, or more than the average value. This is due to inconsistencies within the flame development from the spark plug. This must be considered as a random spike in pressure could produce stress higher than a con-rod's ultimate tensile strength. It is argued that this does not matter as a car isn't driven at full throttle often, but it should be considered if researching this topic further (Smith & Ruprecht, 2018).

6 Maximum Stresses

Stress can be defined as $\frac{force}{area}$. Using the minimum con-rod cross sectional area, stresses can be calculated.

6.1 Maximum Tensile Stresses

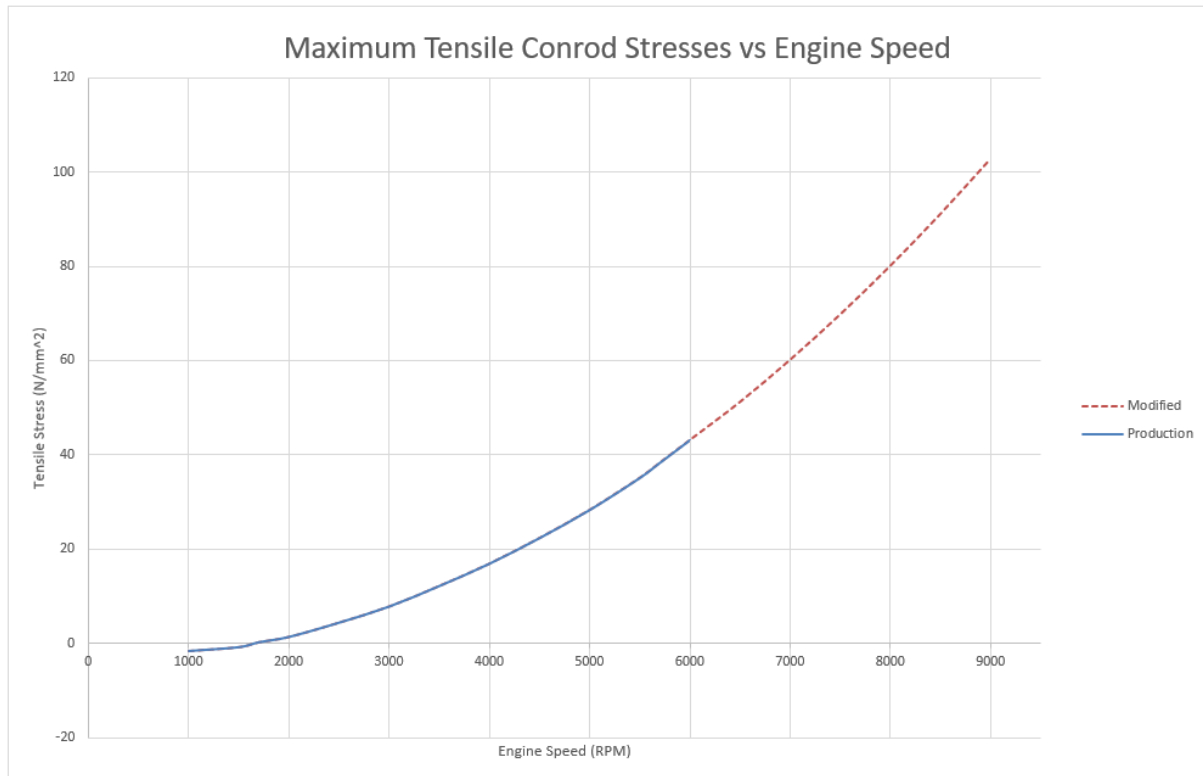


Figure 9 - Con-rod tensile stresses

- As per figure 7, tensile stress should be considered when modifying an engine as it will increase with engine speed.

6.2 Maximum Compressive Stresses

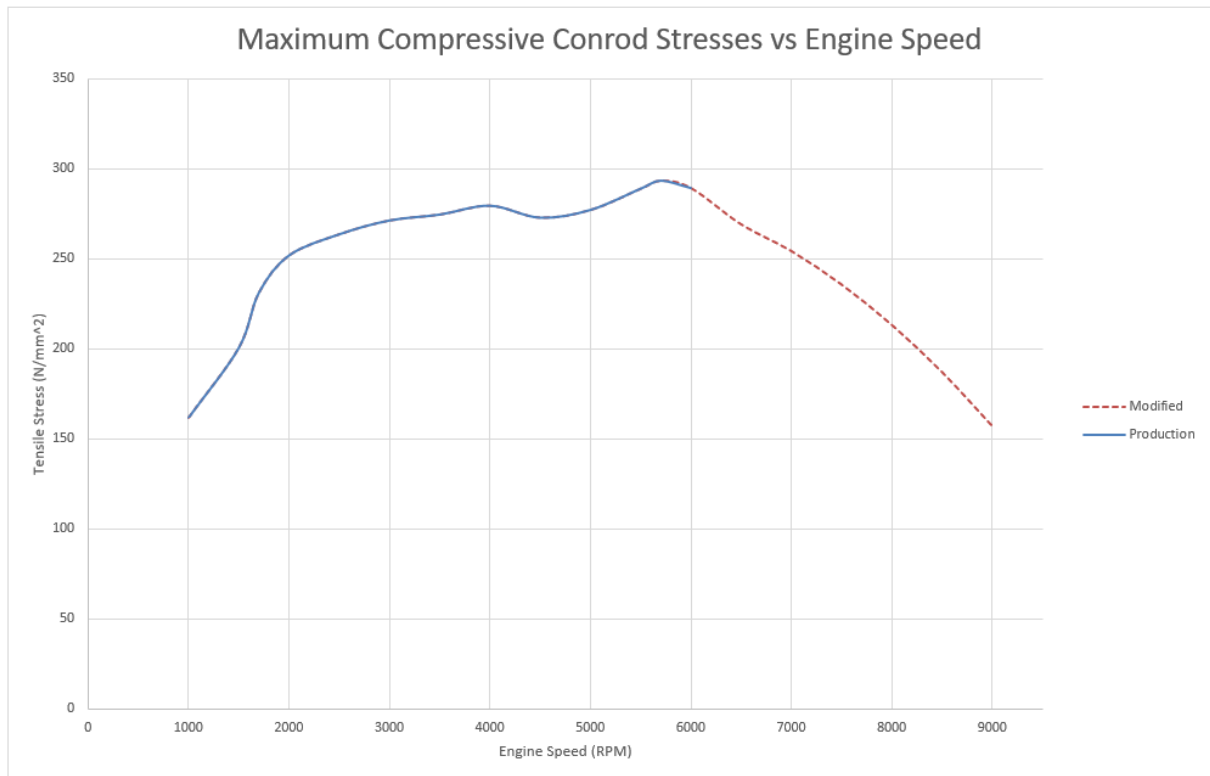


Figure 10 - Con-rod compressive stresses

- Figure 10 follows the trends of figure 8, therefore even with increased boost, stresses do not reach a dangerous level, confirmed below.

7 Nominal Static Safety Factors

The Nominal static safety factor of a con-rod is defined as: $\frac{UTS}{Stress}$. UTS (ultimate tensile strength) dictates how much force is required to shear a section of cross area 1mm² (Anderson, 1990). From this, compressive and tensile stress acting on the con-rod is used to calculate how close to failure it is.

$$Nominal\ Static\ Safety\ Factor = \frac{UTS}{Stress}$$

It was chosen to only calculate this for the RPM at which the highest compressive and tensile forces were seen, as this would produce the lowest values.

The author then investigated theoretically changing the con-rod to titanium to investigate how this material changes deformation and stresses experienced.

Table 3 - Nominal static safety factors

Engine	Material	Nominal Safety Factors
Production	Steel	Compressive = 2.557 / Tensile = 17.398
Modified	Steel	Compressive = 2.557 / Tensile = 7.3032
Modified	Titanium	Compressive = 3.239 / Tensile = 9.2508

Table 1 shows that the con-rod is under no danger within the standard engine as a safe value for steel is considered to be 2-2.5 (Engineering ToolBox, 2010).

The con-rod is still safe in the modified engine, with considerably higher values when a titanium unit is used.

Continuing from section 5.2, the altered compressive nominal safety factor with modified induction was also analysed:

Table 4 - Nominal static safety factors with increased boost

Safety factor steel - no added boost	Safety factor steel - added boost
2.56	2.50

The compressive safety factor is not compromised by increased boost. The ratio is still 2.50, which is safe.

8 Stretch and Compression of Con-rod

The magnitude of con-rod deformation was calculated using:

$$\Delta L = \frac{F \times L}{E \times CSA}$$

Where F = compressive/tensile force, L = con-rod length, E = Young's Modulus and
 CSA = cross-sectional area.

8.1 Con-rod Stretch

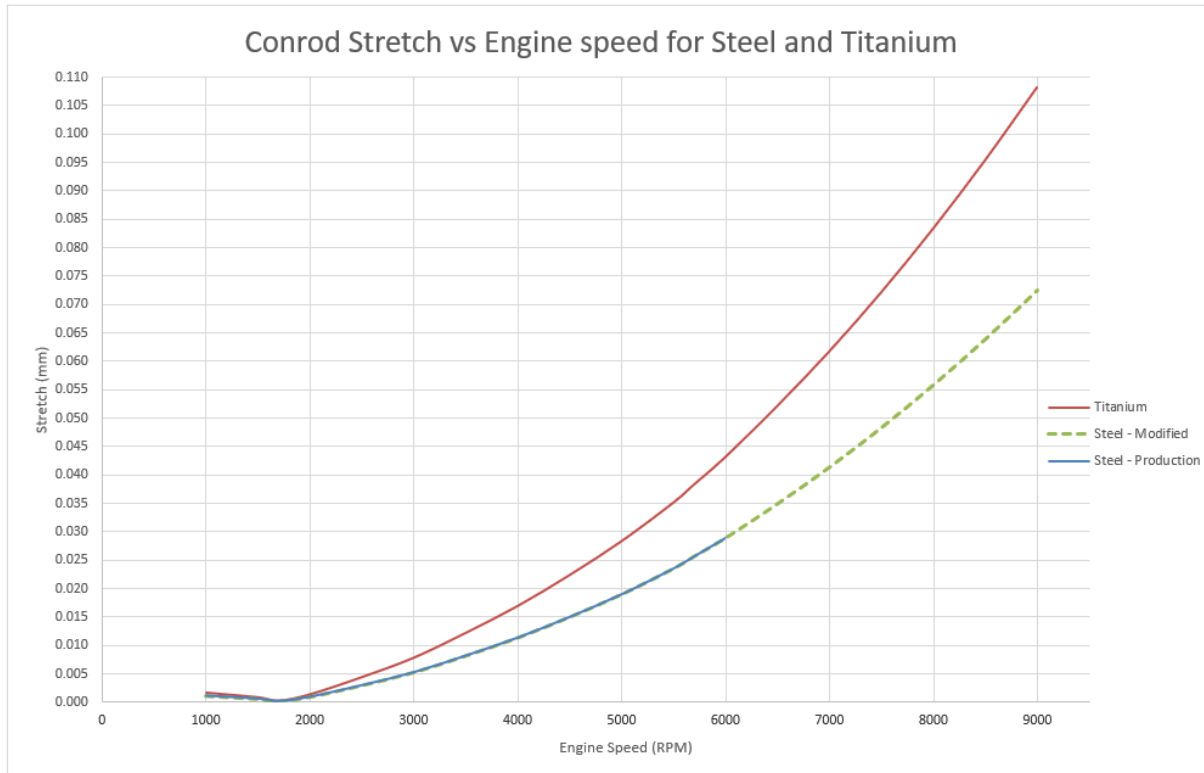


Figure 11 - Con-rod stretch

- When a tensile load is applied to the con-rod, it gets stretched. As per section 5.1, engine speed is proportional to con-rod stretch.
- It should be noted this calculation takes the con-rod to be a simple beam of constant minimum cross sectional area. For this reason, real life deformation would be considerably smaller.

8.2 Con-rod Compression

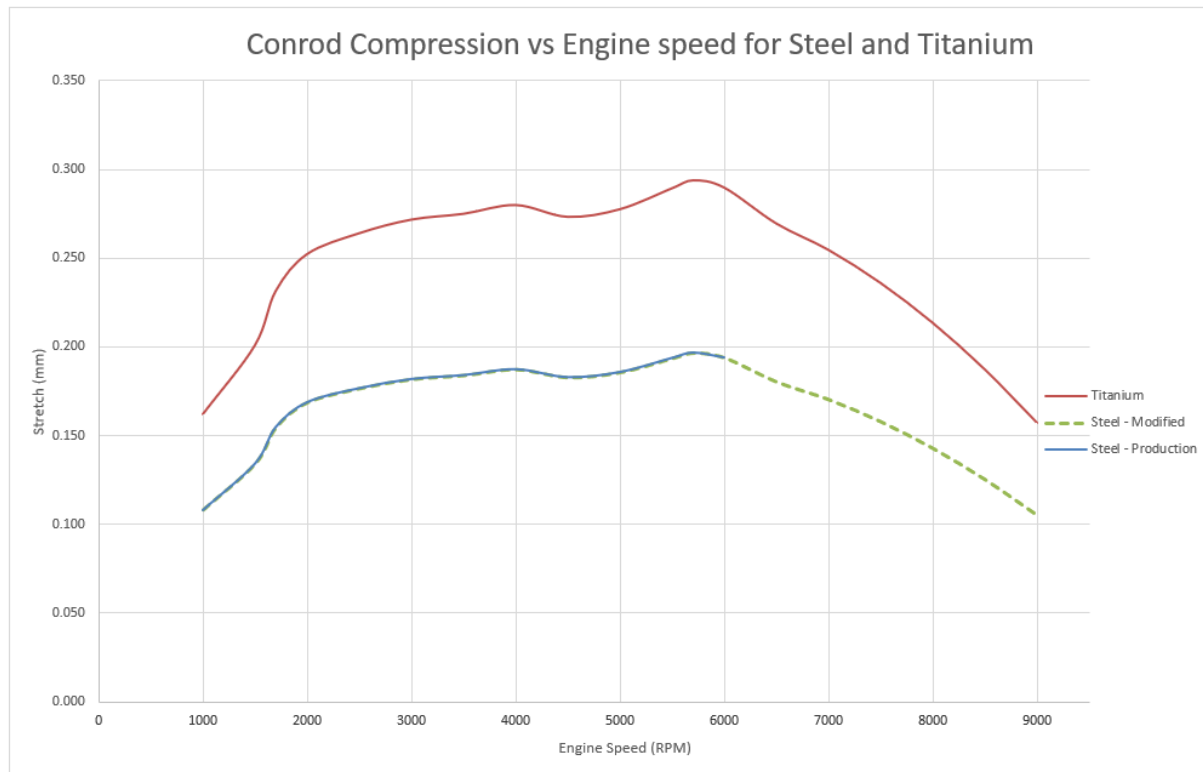


Figure 12 - Con-rod compression

- When a compressive load is applied to the con-rod, it gets compressed. As per section 5.2, compression decreases with rpm with insufficient induction.
- Titanium deforms more than steel. This is because the Young's modulus of steel is higher than titanium showing that steel is more likely to shear, whereas titanium is more elastic and can withstand more force before permanent deformation (Anderson, 1990).
- Although this means more force can be withstood, the increased deformation could be problematic. Increased stretch could affect compression ratio and change the clearance volume, meaning the engine would run less efficiently. The deformation seen is still small, and in a mass produced engine would be unlikely to cause a large issue. Moreover the compressive gas force does counteract this somewhat. In a modified racing engine this could be dangerous, potentially even causing knock, proving fatal for the engine (Carley, 2017).
- By rearranging the formula in section 8.0, it can be calculated that to deform no more than a steel con-rod, the minimum cross sectional area of a titanium unit would have to be 208.73mm^2 . This is a 33% increase in size, which could severely impact the engine clearance tolerances and negate any weight savings.

9 Analysis and Conclusion

It is evident that this report's calculated data is not entirely accurate. The data manipulation proved unrealistic in some areas and could be improved by further researching frictional, thermodynamic and mechanical losses, and creating a more detailed combustion model.

The engine modification clearly shows that when increasing engine speed, the induction system must be correctly altered to gain any substantial benefit. Without doing so, frictional losses outweigh any benefits.

This report did find expected trends and was within an acceptable tolerance to real data. This proves that internal engine components manufactured by large, mass-producing manufacturers are over-engineered and very unlikely to fail. This explains why after-market performance upgrades are so popular with Ecoboost engines.

The con-rod has been referred to as "the Achilles heel of a tuned engine" (DS Sport, 2018). This report shows this is a viable statement, due to the excessive loading of a con-rod throughout its life. If it is considered that the maximum gas force seen was 40955N, nearly 4.2 tonnes, the con-rod has to withstand this loading 50 times per second at maximum production rpm. This report did not however see the con-rod in any substantial danger. This leads the author to believe that material selection and design are considered to be very important, and for this engine materials should be chosen to reduce weight and increase efficiency, whilst maintaining strength and minimising deformation. To take this report further, finite element analysis (FEA) calculations should be carried out and more materials more thoroughly tested.

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11 Appendices - Extra Calculations and Excel Data

11.1 Appendix 1 - Loss of Work Done

To find work done lost to friction the author first calculated the piston displacement per degree:

$$S = R + L - R \cos \theta - L \left(1 - \frac{R^2}{L^2} \sin \theta \right)$$

Where R = crank throw, L = con-rod length and θ = crank angle

- From this, the author could work out frictional force between the side of the piston and the cylinder wall:

$$F_{side} = F_{net} \times \tan \phi$$

Where F_{net} = gas force - inertia force and ϕ = rod angle.

- Now the work done frictional losses to the side wall can be calculated:

$$side \text{ friction } WD \text{ per degree} = F_{side} \times \mu \times (S_2 - S_1)$$

Where μ is taken to be 0.1 and $(S_2 - S_1)$ = cylinder displacement

- Furthermore, the author calculated the frictional force exerted on the piston rings:

$$F_{ring} = radial \text{ force} \times \mu$$

- From this the work done frictional losses to the piston rings can be calculated:

$$ring \text{ friction } WD \text{ per degree} = \frac{F_{ring_1} + F_{ring_2}}{2} \times (S_2 - S_1)$$

- Work done due to inertia can also be calculated:

$$\text{inertia WD per degree} = \frac{Finertia_1 + Finertia_2}{2} \times (S_2 - S_1)$$

- From this the net work done per degree can be calculated by subtracting these losses from the work done from gas force:

$$\text{gas WD per degree} = \left(\frac{Fgas_1 + Fgas_2}{2} \right) \times \left(\frac{(S_2 \times \pi \times Bore^2)}{4} - \frac{(S_1 \times \pi \times Bore^2)}{4} \right)$$

$\therefore$ net WD per degree

$$= \text{gas WD} - \text{side friction WD} - \text{ring friction WD} - \text{inertia WD}$$

11.2 Appendix 2 - Total Work Done

From the losses calculated in section 9, net work done per cycle can be calculated.

$$\begin{aligned} \text{total WD per cycle} = \\ \sum_{-360 \rightarrow +360} (\text{gas WD per degree}) - \sum_{-360 \rightarrow +360} (\text{inertia WD per degree}) \end{aligned}$$

$$\begin{aligned} \text{frictional loss WD per cycle} = \\ \sum_{-360 \rightarrow +360} (\text{gas WD per degree}) + \sum_{-360 \rightarrow +360} (\text{inertia WD per degree}) \end{aligned}$$

$$\therefore \text{net WD per cycle} = \text{total WD} - \text{frictional loss WD}$$

11.3 Appendix 3 - Engine Torque

The author calculated torque produced per cycle for each engine speed. This can be achieved by adding gas torque, produced by the combustion of the air-fuel mixture and inertia torque, produced by the rotational inertia of the crankshaft and piston assembly.

$$\text{Gas torque per degree} = \text{gas force} \times R \times \sin(\theta + \phi)$$

$$\text{Inertia torque per degree} = \text{inertia force} \times R \times \sin(\theta + \phi)$$

The inertia torque acts both with and against the gas torque as at different parts of the cycle, the inertia of the crankshaft can act in the same or different directions as the piston. For this reason the values of inertia torque per degree can be either positive or negative. By adding both torques, opposing values are subtracted and assisting values are added, but overall because of the nature of the cycle, they cancel out.

To find total torque per cycle, the author found the sums of torques above, divided by 720 to account for each degree of the cycle then multiplied by 4 for each cylinder.

$$\therefore \text{total torque per cycle} = \left(\frac{\sum_{-360 \rightarrow +360} (\text{gas torque per degree}) + \sum_{-360 \rightarrow +360} (\text{inertia torque per degree})}{720} \right) \times 4$$

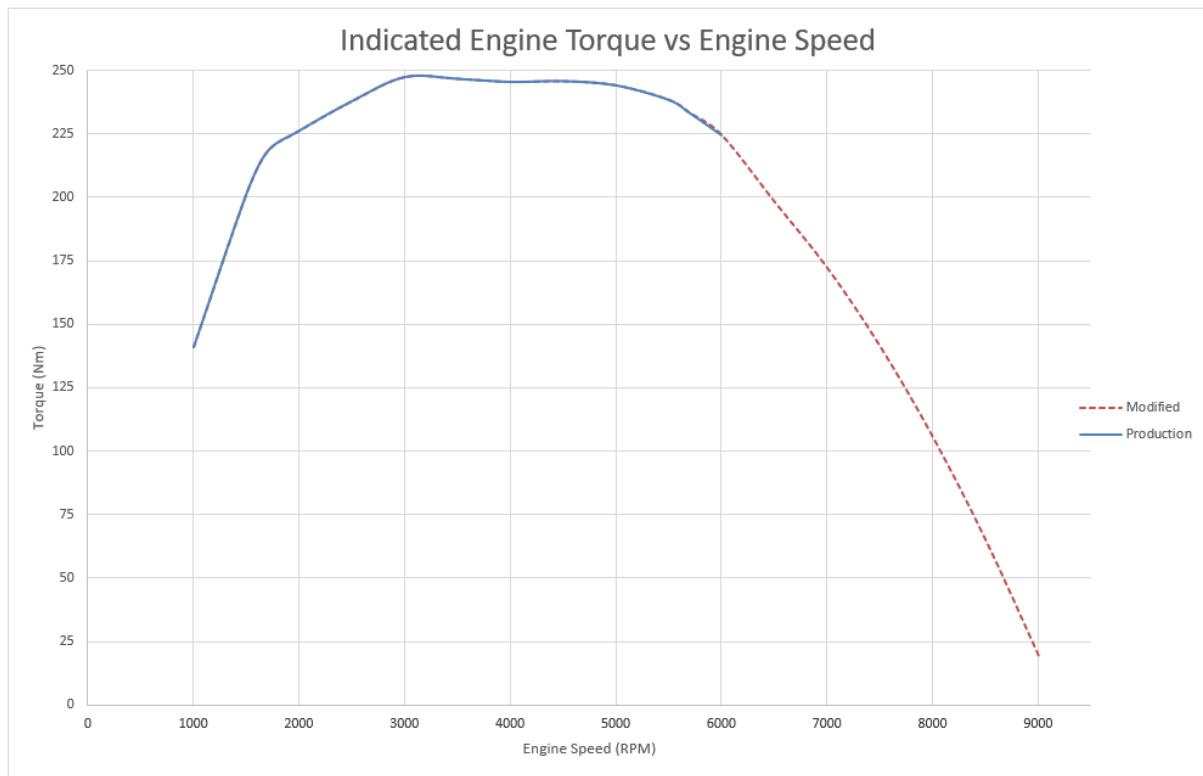


Figure 13 - Engine indicated torque

Figure 13 shows that the peak torque is around 3000rpm, which agrees with Ford's published spec sheet for this engine. This follows the expected trend as at high rpm volumetric efficiency decreases as not enough air is brought into the system. As with compressive force, the torque is calculated as a product of the gas force, which decreases at high RPM for the same reasons. Torque is also affected at high rpm due to increased frictional resistance. Frictional losses

calculated in section 9 are considerably higher at higher engine speeds, this reduces mechanical efficiency, again reducing torque output. Similarly the torque is lower at lower engine speeds as this is how the engine is tuned. Torque and fast acceleration are less commonly demanded at low rpm, thus meaning the engine runs less efficiently with possible valve overlap and inefficient combustion. The engine will run more efficiently at mid rpm (Simpson, 2008).

This value is taken as the indicated torque value as frictional, and other, losses are not removed from the calculated value.

11.4 Appendix 4a - Engine Power

The indicated power of an engine is a figure that does not include frictional losses through the engine. The author calculated the indicated power per cycle with the equation:

$$2\pi \times \text{torque per cycle} \times \frac{RPM}{60}$$

To factor in frictional losses the author took the WD frictional losses value from section 10, which is in joules. To convert this to kW to relate to power, the same equation as above was used. From here this value was subtracted from indicated power to get break power. This was then converted to PS by multiplying by 1.36.

$$\text{Power per cycle} = (\text{indicated power} - \text{frictional power loss}) \times 1.36$$

This is not an entirely accurate representation of break power, as there are other losses within the engine such thermal losses and losses from lubricant friction that are not considered, however it gives a more accurate indication of the engine's actual output. Because of this, the author only applied this to power and not for torque as an example of the process, however it was decided it is not valid enough to warrant doing so for torque also.

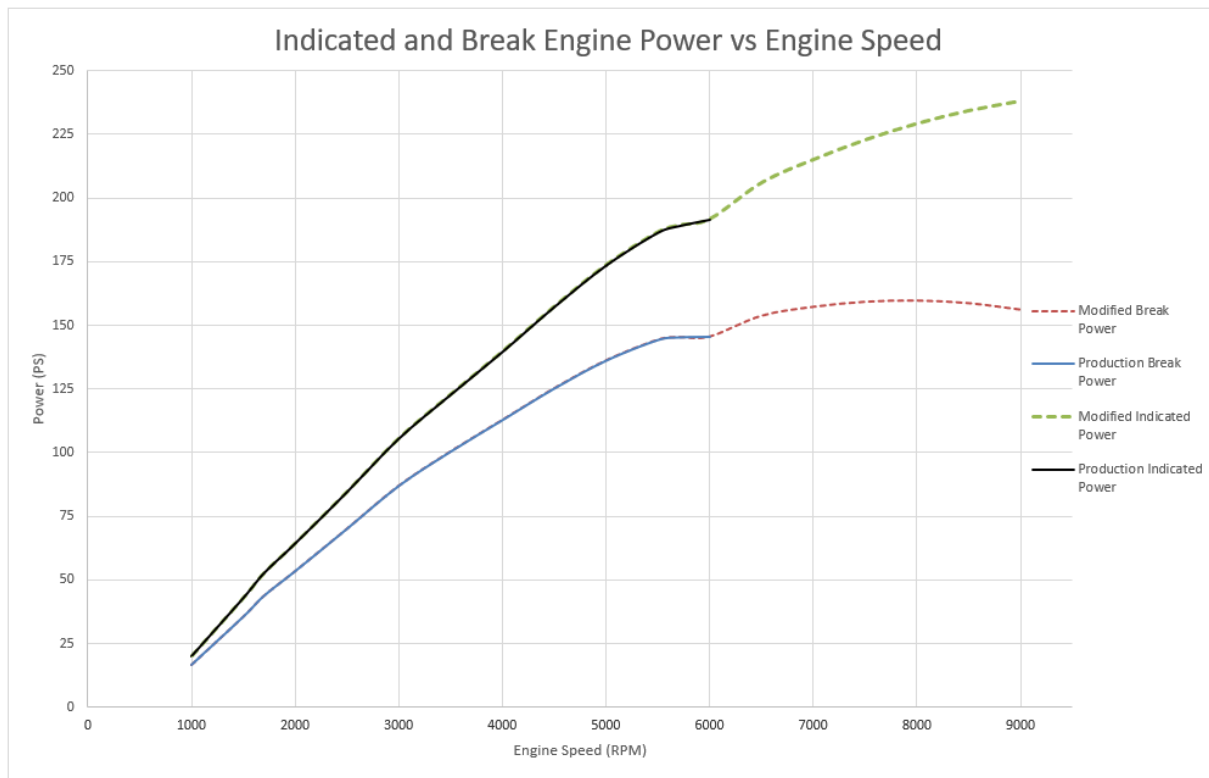


Figure 14 - Indicated and break power

It is clear that just by subtracting frictional losses within the cylinder the power figure reduces significantly. The engines power increases with engine speed, and it is clear that even without added boost a higher rpm will increase power. The power values do reduce towards the highest engine speed as mechanical efficiency again starts to decrease due to high frictional losses. Moreover, lack of air will still factor into this. As with torque, the higher the engine speed, the less burn duration available and the less air and fuel can be introduced to the burn.

11.4.1 Appendix 4b - Engine Torque and Power Curves

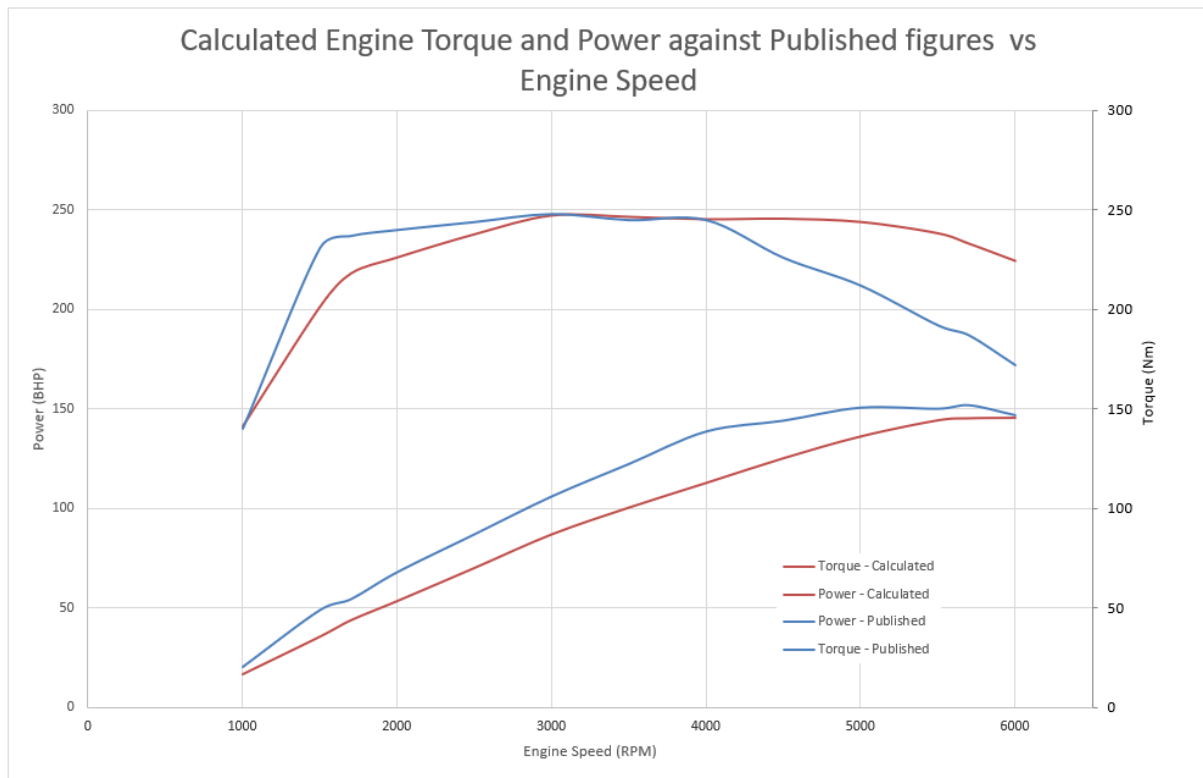


Figure 15 - Engine power and torque - calculated vs published

Figure 16 shows a clear correlation between the author's calculated values and the values published by Ford. This shows validation within the calculations and shows the findings of this report are somewhat trustworthy (Ford, 2009).

The difference in values is expected as this report is based around studying con-rod dynamics not engine output, therefore the methods used are not entirely accurate. The measured figures from Ford may be from a dyno and therefore do not include any minor inaccuracies from calculations but do introduce other inaccuracies from the dyno's margin of error, and the engine speeds provided by Ford do not correlate to the author's data provided perfectly. Moreover, as explained above in section 12.1, the frictional and thermodynamic losses are not correctly calculated, undoubtedly accounting for some inaccuracy seen. The average difference in values for torque is 8.2% and 12.9%, which considering the nature of this report is considered acceptable by the author.

11.5 Appendix 5a - EXCEL Calculations

PRODUCTION							MASSES (kg)									
No.	BORE (m)	STROKE (m)	AREA (m²)	CAPACITY (cc)	CRANK THROW R (m)	ROD LENGTH L (m)	ROD CSA (mm²)	CONROD	CONROD CAP	CONROD	CONROD TOTAL	GAUGEON	PISTON	PISTON RINGS	CIRCLIPS	PISTON TOTAL
4	0.0790	0.0814	0.0049	1595.9837	0.0407	0.1340	139.65	0.2674	0.1038	0.0352	0.4064	0.0802	0.2577	0.0110	0.0015	0.3504
PRODUCTION ENGINE																
RPM	Max Pressure (Pa)	Peak Gas Force (N)	Max Compressive Force (N)	Max Tensile Force (N)	Max Compressive Stress (N/mm²)	Max Tensile Stress (N/mm²)	Comp Safety Factor	Compression Dist. (mm)	Stretch Dist. (mm)	Total Friction VD / Cycle	Total VD / Cycle	TORQUE (Nm)	INDICATED POWER (kW)	BREAK POWER (PS)	ACTUAL TORQUE (Nm)	
1000	4595700.0000	22526.6045	22592.8234	-228.9770	161.7818	-163.96	2.55735	0.1084	0.0011	24.3274	430.5662	140.9534	20.0744	16.5243	140.0000	
1500	5786400.0000	28363.0229	28011.2242	-114.0311	200.5816	-0.8165		0.1344	0.0005	35.2598	615.7204	201.1986	42.9817	35.4492	231.0000	
1700	6609525.0000	32397.7100	32281.5583	-312.355	231.805	0.2237		0.1549	0.0001	37.5514	666.8130	217.9111	52.7589	43.6673	237.0000	
2000	7248850.0000	35531.4701	35165.3348	189.6378	251.8105	1.3580		0.1687	0.0009	38.7287	691.1149	226.0029	64.3742	53.3428	240.0000	
2500	7665850.0000	37575.4665	36803.2218	612.2017	263.5390	4.3838		0.1766	0.0029	41.0641	726.1622	237.6541	84.6161	69.9953	244.0000	
3000	7979125.0000	39111.0371	37873.8993	1089.3616	271.2059	7.8007		0.1817	0.0052	43.7679	753.9469	247.1280	105.5871	86.8870	248.0000	
3500	8256150.0000	40468.9223	38329.3843	1698.9608	274.4675	12.1658		0.1839	0.0082	45.0715	750.0414	246.4290	122.8365	100.3698	245.0000	
4000	8481425.0000	41573.1460	39017.5733	2359.1446	279.3954	16.8933		0.1872	0.0113	47.2532	743.7270	245.2162	139.6937	112.7747	245.0000	
4500	8430625.0000	41324.1411	38089.3216	3119.4182	272.7485	22.3374		0.1827	0.0150	50.1537	741.9958	245.5045	157.3401	125.1974	226.0000	
5000	8723500.0000	42759.7177	38689.6860	3951.3326	277.0475	28.2945		0.1856	0.0190	52.6486	733.8496	243.8553	173.6480	136.1572	212.0000	
5500	9238825.0000	45579.7710	40334.9391	4901.2596	288.8288	35.0967		0.1935	0.0235	53.9582	713.3561	238.1376	186.5341	144.2684	192.0000	
5700	9525500.0000	46690.8570	40955.4359	5347.9300	293.2720	38.2952		0.1965	0.0257	53.9827	696.2366	232.9432	189.1004	145.2780	187.0000	
6000	9560600.0000	46862.9056	40386.7361	6020.1271	289.1997	43.1087		0.1938	0.0289	53.9699	667.9517	224.2592	191.6325	145.5145	172.0000	
MODIFIED ENGINE																
RPM	Max Pressure (Pa)	Peak Gas Force (N)	Max Compressive Force (N)	Max Tensile Force (N)	Max Compressive Stress (N/mm²)	Max Tensile Stress (N/mm²)	Comp Safety Factor	Compression Dist. (mm)	Stretch Dist. (mm)	Total Friction VD / Cycle	Total VD / Cycle	TORQUE (Nm)	INDICATED POWER (kW)	BREAK POWER (PS)		
1000	4595700.0000	22526.6045	22592.8234	-228.9770	161.7818	-163.96	2.55735	0.1084	0.0011	24.3274	430.5662	140.9534	20.0744	16.5243		
1500	5786400.0000	28363.0229	28011.2242	-114.0311	200.5816	-0.8165		0.1344	0.0005	35.2598	615.7204	201.1986	42.9817	35.4492		
1700	6609525.0000	32397.7100	32281.5583	-312.355	231.805	0.2237		0.1549	0.0001	37.5514	666.8130	217.9111	52.7589	43.6673		
2000	7248850.0000	35531.4701	35165.3348	189.6378	251.8105	1.3580		0.1687	0.0009	38.7287	691.1149	226.0029	64.3742	53.3428		
2500	7665850.0000	37575.4665	36803.2218	612.2017	263.5390	4.3838		0.1766	0.0029	41.0641	726.1622	237.6541	84.6161	69.9953		
3000	7979125.0000	39111.0371	37873.8993	1089.3616	271.2059	7.8007		0.1817	0.0052	43.7679	753.9469	247.1280	105.5871	86.8870		
3500	8256150.0000	40468.9223	38329.3843	1698.9608	274.4675	12.1658		0.1839	0.0082	45.0715	750.0414	246.4290	122.8365	100.3698		
4000	8481425.0000	41573.1460	39017.5733	2359.1446	279.3954	16.8933		0.1872	0.0113	47.2532	743.7270	245.2162	139.6937	112.7747		
4500	8430625.0000	41324.1411	38089.3216	3119.4182	272.7485	22.3374		0.1827	0.0150	50.1537	741.9958	245.5045	157.3401	125.1974		
5000	8723500.0000	42759.7177	38689.6860	3951.3326	277.0475	28.2945		0.1856	0.0190	52.6486	733.8496	243.8553	173.6480	136.1572		
5500	9238825.0000	45579.7710	40334.9391	4901.2596	288.8288	35.0967		0.1935	0.0235	53.9582	713.3561	238.1376	186.5341	144.2684		
5700	9525500.0000	46690.8570	40955.4359	5347.9300	293.2720	38.2952		0.1965	0.0257	53.9827	696.2366	232.9432	189.1004	145.2780		
6000	9560600.0000	46862.9056	40386.7361	6020.1271	289.1997	43.1087		0.1938	0.0289	53.9699	667.9517	224.2592	191.6325	145.5145		
6500	9215908.5723	45173.3420	37566.4838	7145.9406	269.0045	51.1680		0.1802	0.0349	54.1526	582.8298	198.0225	205.8810	153.6658		
7000	9065088.6769	44434.0727	35496.3462	8393.0198	254.1808	60.1035		0.1703	0.0413	53.9539	498.5167	171.9794	214.9179	157.1691		
7500	8827963.2105	43271.2717	32896.2195	9735.3681	235.5618	68.7238		0.1678	0.0483	53.3393	398.9975	141.1049	222.6342	159.1624		
8000	8504232.1730	41684.9392	29766.0798	11172.9855	213.1477	80.0291		0.1428	0.0558	52.3087	284.2721	105.3991	229.0299	159.6459		
8500	8094195.5644	39675.0751	24800.6536	12705.8720	186.9384	91.0191		0.1252	0.0638	50.8623	154.3406	64.8619	234.1050	158.6196		
9000	7597753.3848	37241.6794	19724.2430	14334.0276	156.9339	102.6940		0.1051	0.0724	48.9999	9.2030	19.4934	237.8695	156.0833		
Max Pressure - Up-rated Turbo (Pa)								TITANIUM								
	4595700.0000							compression Dist. (mm)Stretch Dist. (mm)								
	5786400.0000							0.16200.0016								
	6609525.0000							0.20090.0008								
	7248850.0000							0.231950.0002								
	7665850.0000							0.252220.0014								
	8256150.0000							0.26390.0044								
	8481425.0000							0.27160.0078								
	8767850.0000							0.27490.0122								
	9159675.0000							0.27980.0169								
	9577789.7500							0.27320.0224								
	9716010.0000							0.27750.0283								
	9739615.0000							0.28930.0361								
	9676704.0009							0.28370.0384								
	9608993.9975							0.28960.0432								
	9622370.8994							0.26940.0522								
								0.25460.0618								

11.5.1 Appendix 5b - Calculations for 4000rpm

Crank Angle deg	CYLINDER PRESSURES								FORCE N	PISTON ACCELERATION m/s^2	INTERIA FORCE N	NET FORCE N	ROD ANGLE rads	ROD FORCE N	SIDE FORCE N	RADIAL FORCE N	RING FRICTION FORCE N	ANGULAR VELOCITY W Rads/Sec
	1 bar	2 bar	3 bar	4 bar	AVG. bar	AVG. Pa	MAX. bar	MAX. Pa										
-360	1.552	2.133	2.095	1.823	1.90075	190075	84.81425	8481425	931.6849134	9310.215519	3262.299518	-2330.614605	7.44232E-17	-2330.614605	-1.73452E-13	55.98170847	5.598170847	418.8790205
-359	1.578	2.146	2.095	1.835	1.9135	191350			937.9345426	9307.806578	3261.455425	-2323.520882	0.005300868	-2323.553527	-12.3167921	56.35722696	5.635722696	
-358	1.591	2.146	2.108	1.835	1.92	192000			941.1206281	9300.581693	3258.923825	-2317.803197	0.01060027	-2317.933424	-24.5702589	56.54866776	5.654866776	
-357	1.604	2.146	2.12	1.848	1.9295	192950			945.7772145	9288.546688	3254.70676	-2308.929545	0.01589674	-2309.221316	-36.70754436	56.82846586	5.682846586	
-356	1.604	2.146	2.12	1.848	1.9295	192950			945.7772145	9271.711257	3248.807624	-2303.03041	0.021188813	-2303.547498	-48.80578483	56.82846586	5.682846586	
-355	1.604	2.133	2.12	1.848	1.92625	192625			944.1841718	9250.088959	3241.231171	-2297.046999	0.026475024	-2297.852266	-60.82858621	56.73274546	5.673274546	
-354	1.604	2.12	2.108	1.848	1.92	192000			941.1206281	9223.697202	3231.983499	-2290.862871	0.031753907	-2292.018307	-72.76830496	56.54866776	5.654866776	
-353	1.604	2.108	2.069	1.835	1.904	190400			933.2779562	9192.557225	3221.072052	-2287.794095	0.037023997	-2289.363019	-84.74200696	56.07742887	5.607742887	
-352	1.578	2.095	2.031	1.81	1.8785	187850			920.7786978	9156.694075	3208.505604	-2287.726906	0.042283832	-2289.77357	-96.79155187	55.32639187	5.532639187	
-351	1.578	2.082	2.018	1.797	1.86875	186875			915.9995696	9116.136581	3194.294258	-2278.294689	0.047531946	-2280.870773	-108.3734084	55.03923067	5.503923067	
-350	1.565	2.056	1.992	1.772	1.84625	184625			904.9708123	9070.917324	3178.44943	-2273.478618	0.052766878	-2276.647367	-120.075833	54.37655097	5.437655097	
-349	1.54	2.031	1.966	1.746	1.82075	182075			892.4715539	9021.072599	3160.983839	-2268.512285	0.057987164	-2272.331584	-131.6922327	53.62551398	5.362551398	
-348	1.514	2.005	1.941	1.72	1.795	179500			879.8497538	8966.64238	3141.91149	-2262.061736	0.063191344	-2266.585634	-143.1332897	52.86711387	5.286711387	
-347	1.501	1.979	1.902	1.695	1.76925	176925			867.2279537	8907.670278	3121.247665	-2254.019712	0.068377957	-2259.299382	-154.3659207	52.0871377	5.20871377	
-346	1.462	1.954	1.877	1.656	1.73725	173725			851.5426099	8844.203492	3099.008904	-2247.466294	0.073545545	-2253.558236	-165.5897968	51.16623598	5.116623598	
-345	1.437	1.928	1.838	1.618	1.70525	170525			835.8572661	8776.29276	3075.212983	-2239.355717	0.078692649	-2246.307295	-176.5854876	50.22375818	5.022375818	
-344	1.411	1.889	1.8	1.592	1.673	167300			820.0493806	8703.992308	3049.878905	-2229.829524	0.083817813	-2237.685269	-187.3383491	49.27391728	4.927391728	
-343	1.372	1.864	1.774	1.554	1.641	164100			804.3640368	8627.359787	3023.026869	-2218.662833	0.088919581	-2227.462964	-197.8041698	48.33143948	4.833143948	
-342	1.347	1.825	1.735	1.516	1.60575	160575			787.0856503	8546.456218	2994.678259	-2207.592609	0.093996501	-2217.381059	-208.1192769	47.29324128	4.729324128	
-341	1.321	1.8	1.71	1.477	1.577	157700			772.9933492	8461.345924	2964.855612	-2191.862262	0.099047121	-2202.657835	-217.810377	46.44648389	4.644648389	
-340	1.282	1.761	1.671	1.452	1.5415	154150			755.5924209	8372.096461	2933.5826	-2177.990179	0.104069992	-2189.83807	-227.4852786	45.40092258	4.540092258	
-339	1.257	1.723	1.633	1.413	1.5065	150650			738.4365761	8278.778553	2900.884005	-2162.447429	0.109063667	-2175.37251	-236.7840305	44.37008749	4.437008749	
-338	1.231	1.684	1.607	1.375	1.47425	147425			722.6286906	8181.466008	2866.785689	-2144.156998	0.114026701	-2158.172176	-245.5563205	43.42024659	4.342024659	
-337	1.192	1.658	1.569	1.35	1.44225	144225			706.9433468	8080.235648	2831.314571	-2124.371224	0.118957652	-2139.49127	-253.909027	42.47776879	4.247776879	
-336	1.167	1.633	1.543	1.324	1.41675	141675			694.4440884	7975.167226	2794.498596	-2100.054508	0.123855082	-2116.265612	-261.4406326	41.7267318	4.17267318	
-335	1.154	1.594	1.517	1.298	1.39075	139075			681.6997466	7866.34334	2756.366706	-2074.666696	0.128717555	-2091.97317	-268.5307226	40.96096859	4.096096859	
-334	1.128	1.569	1.492	1.273	1.3655	136550			669.32303	7753.849347	2716.948811	-2047.625781	0.133543638	-2066.021028	-275.0846201	40.2172947	4.02172947	
-333	1.102	1.543	1.466	1.247	1.3395	133950			656.5786882	7637.773276	2676.275756	-2019.697068	0.138331902	-2039.176526	-281.1843846	39.4515315	3.94515315	
-332	1.102	1.53	1.453	1.222	1.32675	132675			650.329059	7518.205733	2634.379289	-1984.05023	0.143080925	-2004.533808	-285.8329472	39.076013	3.9076013	
-331	1.076	1.517	1.427	1.196	1.304	130400			639.1777599	7395.239807	2591.292028	-1952.114268	0.147789284	-1973.628743	-290.6205372	38.40597019	3.840597019	
-330	1.064	1.504	1.415	1.183	1.2915	129150			633.0506725	7268.97097	2547.047428	-1913.996756	0.152455566	-1936.45745	-294.0814113	38.0378148	3.80378148	
-329	1.064	1.491	1.415	1.158	1.282	128200			628.394086	7139.496984	2501.679743	-1873.285657	0.157078358	-1896.636016	-296.6968532	37.75801671	3.775801671	
-328	1.038	1.479	1.402	1.145	1.266	126600			620.5514141	7006.917792	2455.223994	-1834.67258	0.161656258	-1858.908928	-299.1971359	37.28677781	3.728677781	
-327	1.038	1.466	1.389	1.119	1.253	125300			614.1792432	6871.335416	2407.71593	-1793.536686	0.166187864	-1818.59225	-300.8387057	36.9038962	3.69038962	
-326	1.038	1.453	1.389	1.119	1.24975	124975			612.5862005	6732.853852	2359.19199	-1746.605789	0.170671785	-1772.356552	-301.0248559	36.8081758	3.68081758	
-325	1.025	1.453	1.389	1.107	1.2435	124350			609.5226568	6591.578963	2309.689269	-1700.166612	0.175106634	-1726.569367	-300.7910734	36.62409811	3.662409811	
-324	1.025	1.453	1.389	1.094	1.24025	124025			607.929614	6447.618365	2259.245475	-1651.315861	0.179491031	-1678.277923	-299.6209508	36.52837771	3.652837771	

MAX COMPRESSIVE FORCE	MAX TENSILE FORCE	PISTON TRAVEL	SIDE FRICTION WD	RING FRICTION WD	GAS WD	INERTIA WD	NET WD	TOTAL FRICTIONAL WD / Cyl.	TOTAL WD / Cyl.	GAS TORQUE	INERTIA TORQUE	TOTAL TORQUE	TOTAL TORQUE / CYCLE
N	N	m	J/deg	J/deg	J/deg	J/deg	J/deg	Joules	Joules	Nm	Nm	Nm	Nm
39017.57332	-2359.144619	0	1.40174E-19	4.53931E-05	0.007554617	0.026360696	-0.01885	47.2532256	743.7270288	9.29142E-15	3.2534E-14	4.18254E-14	245.2162045
MAX COMPRESSIVE STRESS	MAX TENSILE STRESS	8.08145E-06	2.98563E-05	0.000136844	0.022774453	0.079028052	-0.05642			0.8685409	3.020154713	3.888695613	
		3.23218E-05	9.92322E-05	0.000228949	0.038103195	0.131533425	-0.09376			1.742475237	6.033864199	7.776339435	
N/mm²	N/mm²	7.27089E-05	0.000207448	0.000321159	0.053449496	0.183769265	-0.13085			2.625371331	9.034700442	11.66007177	
279.3954409	-16.89326616	0.000129223	0.000354391	0.000412298	0.068617324	0.235628672	-0.16778			3.498118536	12.01626979	15.51438833	
		0.000201835	0.000539397	0.000502261	0.083589557	0.287005658	-0.20446			4.361473106	14.97223	19.33370311	
STRETCH	COMPRESSION	0.00029051	0.000761834	0.000589559	0.098118359	0.337795401	-0.24103			5.21122208	17.8963071	23.10752918	
		mm	0.000395203	0.001022492	0.000672096	0.111854685	0.387894501	-0.27773		6.021496374	20.78231201	26.80380838	
0.011318488	0.187194945	0.000515863	0.00132184	0.000753608	0.125420398	0.437201225	-0.31386			6.779673518	23.62415695	30.40383047	
		0.000652428	0.001651654	0.00083377	0.138761568	0.485615755	-0.34934			7.57504628	26.4158714	33.99091768	
STRETCH - TITANIUM	COMPRESSION - TITANIUM	0.000804832	0.002019274	0.000908117	0.151134873	0.533040423	-0.38483			8.300073289	29.15161778	37.45169106	
		mm	0.000972999	0.002421104	0.00097891	0.162916783	0.579379948	-0.41986		8.985663722	31.82570658	40.8113703	
0.016918518	0.279813072	0.001156844	0.002854556	0.001046784	0.174212851	0.624541662	-0.45423			9.642386335	34.43261112	44.07499745	
		0.001356278	0.003317667	0.001109804	0.184701006	0.668435725	-0.48816			10.27114901	36.96698167	47.23813069	
		0.0015712	0.003813606	0.001167528	0.194307838	0.710975344	-0.52165			10.83279415	39.42365905	50.2564532	
		0.001801505	0.004336453	0.001221694	0.203322542	0.752076969	-0.55431			11.36080689	41.79768755	53.15849444	
		0.002047077	0.004884264	0.001272378	0.211757596	0.791660494	-0.58606			11.85336414	44.08432722	55.93769136	
		0.002307796	0.005454176	0.001318359	0.219410108	0.829649435	-0.61701			12.31388854	46.27906549	58.59295403	
		0.002583532	0.006048301	0.001362118	0.226692788	0.865971113	-0.64669			12.71500089	48.37762792	61.09262881	
		0.002874149	0.006650934	0.0014023	0.233380138	0.900556811	-0.67523			13.13396302	50.37598837	63.50995139	
		0.003179503	0.007278182	0.00143607	0.23900041	0.933341931	-0.70306			13.46309511	52.27037815	65.73347326	
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		0.003833814	0.008560909	0.001497345	0.249198143	0.993273487	-0.75413			14.048707	55.73350836	69.78221536	
		0.004182447	0.009209924	0.001527155	0.254159379	1.020312546	-0.77689			14.3061023	57.2960706	71.6021729	
		0.004545172	0.009846877	0.001557171	0.259154798	1.045336497	-0.79759			14.59770127	58.74231835	73.34001962	
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		0.005312179	0.011110808	0.001608932	0.267769231	1.089175445	-0.83413			15.09557019	61.27667754	76.37224773	
		0.005716084	0.011732262	0.001638259	0.272650002	1.107920672	-0.84864			15.29919314	62.36093315	77.66012629	
		0.006133329	0.012301669	0.001667334	0.277488766	1.124511375	-0.86099			15.63161223	63.32116786	78.95278009	
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