

CON-ROD, ACCELERATIONS, FORCES AND DISPLACEMENTS

ADVANCED ENGINE DESIGN | M6X00410

Contents

TABLE OF TABLES	2
TABLE OF FIGURES	3
1. INTRODUCTION.....	4
2. METHODOLOGY.....	4
2.1 Data given.....	4
2.1.1 Con-Rod measurements.....	4
2.1.2 Material.....	4
2.2 Formulas used.....	5
3. MODIFIED ENGINE.....	6
4. RESULTS AND ANALYSIS.....	7
4.1 Peak Gas Forces	7
4.2 Inertia Loads.....	8
4.3 Net Compressive Load	9
4.3 Net Tensile Load.....	10
4.4 Compressive Stress.....	11
4.5 Tensile Stress.....	12
4.6 Compressive and Tensile Safety Factors.....	12
4.7 Compressive Displacement.....	13
4.8 Tensile Displacement	14
4.9 Titanium Compressive Displacement	15
4.10 Titanium Tensile Displacement.....	16
5. VALIDATE DATA.....	17
6. CONCLUSION.....	18
References	19
7. APPENDIX.....	20

TABLE OF TABLES

Table 1 Conrod measurements (Ford, 2015)	4
Table 2 Steel: 34CrNiMo6 (Ovako, 2019).....	4
Table 3 Titanium Ti-6Al-4V (Grade 5), Annealed (ASM Aerospace, n.d.)	5
Table 4 Formulas (Mcdonald, 2019)	5
Table 5 Safety Factors.....	12

TABLE OF FIGURES

Figure 1 Production Max Fgas.....	7
Figure 2 Supercharged Max Fgas	7
Figure 3 Inertia loads vs crank angle.....	8
Figure 4 Net Compressive Load Production vs supercharged	9
Figure 5 Net Tensile Force Load Production vs supercharged	10
Figure 6 Rod Compressive Stress	11
Figure 7 Rod Tensile Stress	12
Figure 8 Rod Compressive Displacement.....	13
Figure 9 Rod Stretch Displacement.....	14
Figure 10 Titanium Rod Compressive Displacement	15
Figure 11 Titanium Rod Stretch Displacement	16
Figure 12 Ford Torque Power Graph (Ford, 2015).....	17
Figure 13 Calculated Production Torque and Power	17
Figure 14 Calculated Supercharged Torque and Power.	18

1. INTRODUCTION.

This paper will compare calculations obtained from a production Ford 1.6l GTDI engine, with theoretical calculations from the same engine but with a supercharger, giving an extra 50% power to the engine. From these calculations, it can be determined if the engine will meet the required safety factors by adding on a supercharger or if any additional tuning of the engine will be required.

2. METHODOLOGY.

2.1 Data given.

For the calculations the following data is used:

2.1.1 Con-Rod measurements.

Table 1 Conrod measurements (Ford, 2015)

Description	Value	Unit
Rod Length (L)	134	mm
Crankshaft Throw (R)	40.7	mm
Piston Mass	350.4	g
Rod Cross-Sectional Area	140	mm ²
Bore Diameter (Ford, 2015)	79	mm

2.1.2 Material.

Two different materials have been used in this report and they are the following:

Table 2 Steel: 34CrNiMo6 (Ovako, 2019)

Part	Value	Unit
Youngs Modulus (E)	210	GPa
Poisson Ratio	0.3	-
UTS	750	MPa

Table 3 Titanium Ti-6Al-4V (Grade 5), Annealed (ASM Aerospace, n.d.)

Part	Value	Unit
Youngs Modulus (E)	113.8	GPa
Poisson Ratio	0.342	-
UTS	950	MPa

2.2 Formulas used.

To obtain the required calculated data the following formulas are used, with their respective measured data, from these formulas the tensile and compressive stresses can be calculated:

Table 4 Formulas (Mcdonald, 2019)

Formula	Units	Description
$F_{gas} = \frac{avg\ cyl\ Pressure * \pi * Bore^2}{4}$	N	Force exerted by the gas on the piston.
$Piston\ Acc = R\omega^2 Cos\theta + \frac{R}{L} R\omega^2 Cos2\theta$	m/sec ²	
$Finertia = Piston\ Acc \times Reciprocating\ Mass$	N	The acceleration and deceleration of the reciprocating mass creates inertia forces in the 1 st and 2 nd moment. (Nigus, 2015)
$F_{net} = F_{gas} - Finertia$	N	
$F_{rod} = F_{net} \times Cos(\varphi)$	N	The Net force and the Rod angle is used to calculate the Force on the rod.
$Compressive\ Stress = \frac{Compressive\ F_{rod}}{rod\ cross\ sectional\ area}$	Pa	Produced by the cylinder pressures pushing down on the piston. The compressive force is the max Force on the rod.
$Tensile\ Stress = \frac{Tensile\ F_{rod}}{rod\ cross\ sectional\ area}$	Pa	Produced by the rotational inertia forces acting on the rod. The tensile force is the min force on the rod.

$Tensile SF = \frac{Tensile Stress}{UTS}$ $Compressive SF = \frac{Compressive Stress}{UTS}$		The Safety factor obtained will tell you the margin of error, which is given to the structure.
$Stiffness = \frac{E * rod cross sectional area}{Length of rod}$	N/m	This calculates the stiffness of the material, which will be used in turn to calculate the displacement of the rod.
$Compression Disp. = \frac{Compressive Frod}{Stiffness}$ $Tensile Disp. = \frac{Tensile Frod}{Stiffness}$	m	Displacement of the rod under compression and tensile forces.

3. MODIFIED ENGINE.

There are several reasons for using a supercharger (Taylor, 1985):

- Increase the maximum output of a given engine.
- To maintain sea level power at high altitudes.
- Reduce the size of an engine.
- Improve fuel economy engine used mostly at full load.

If a supercharger is bolted on to the production engine as it stands, normally it will give the engine a power increase between 30% and 50% (Carley, 2019), for this report it is assumed that a 50% increase is achieved.

For achieving this increase in power the cylinder pressures where increased by 50%, because the increase in air going into the engine means there will be an increase in fuel, which in turn means there will be an increase in power (Mcdonald, 2019)

4. RESULTS AND ANALYSIS.

4.1 Peak Gas Forces

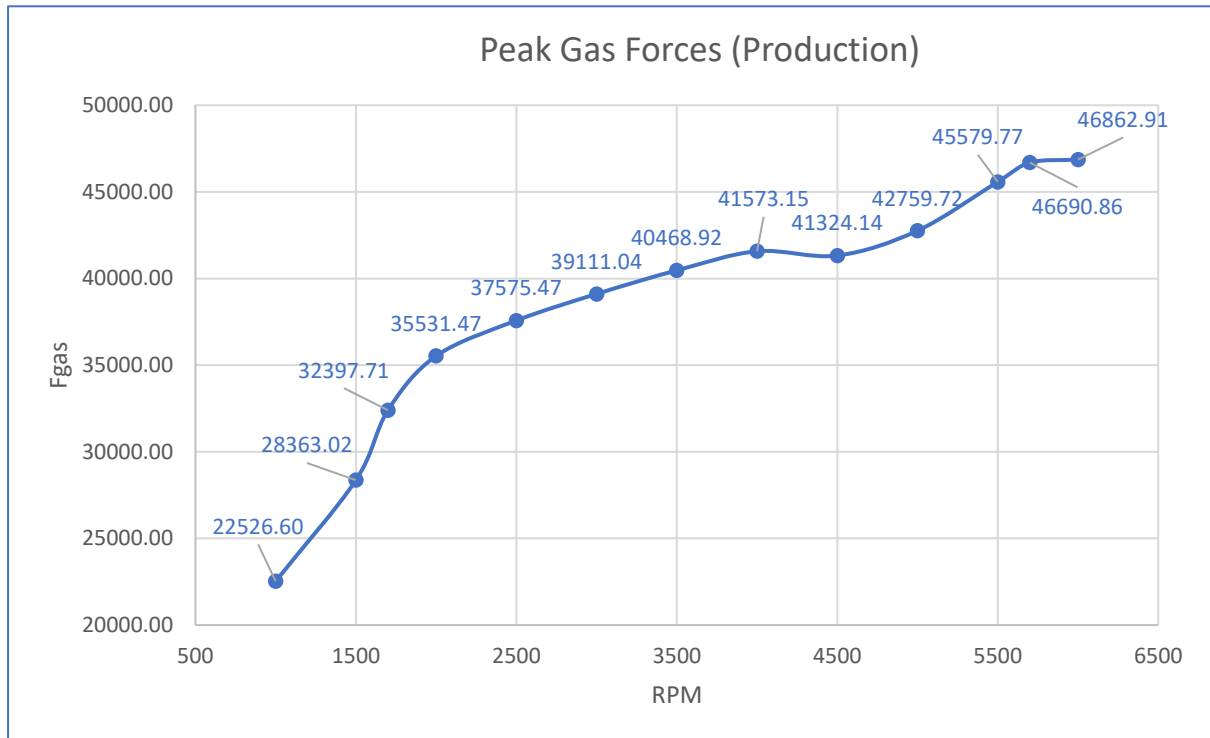


Figure 1 Production Max Fgas

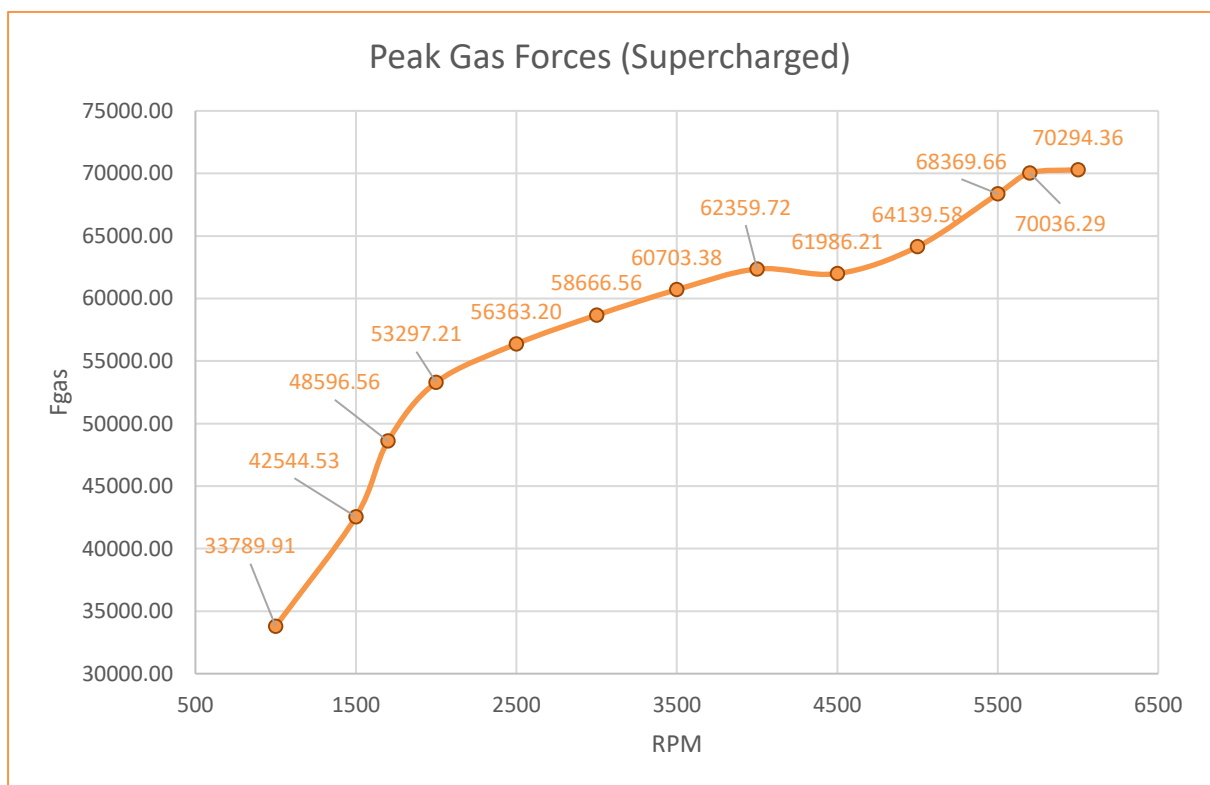


Figure 2 Supercharged Max Fgas

- The max Gas Force as you can see in Figures 1 and 2 happen at 6000RPM

4.2 Inertia Loads.

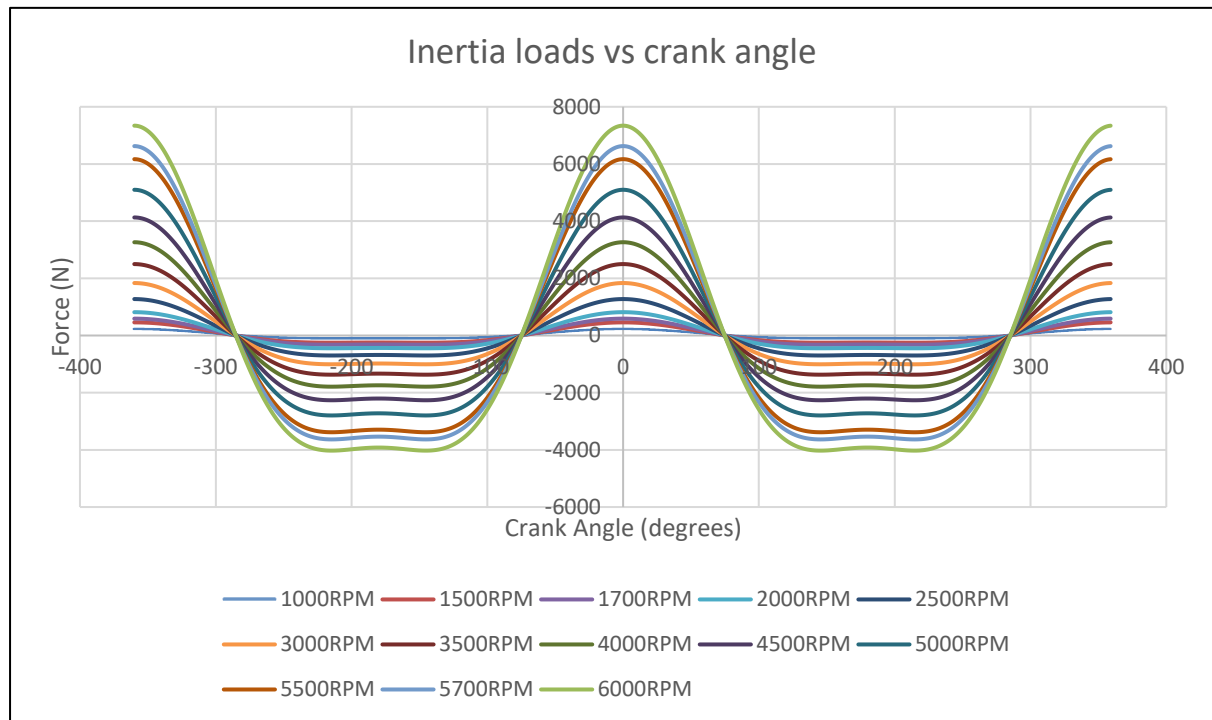


Figure 3 Inertia loads vs crank angle

- The compressive inertia forces are shown on the negative areas of Figure 3, while the tensile inertia forces are shown on the positive areas of Figure 3.
- The inertial forces increase with the RPM, this is due to the increase in Piston acceleration, as shown in Table 4, $Piston\ Acc = R\omega^2\cos\theta + \frac{R}{L}R\omega^2\cos2\theta$ in which the angular velocity (ω) changes with the RPM.
- The sudden compressive dips are due to the second order portion of the Piston Acceleration being double of the first order portion of the Piston Acceleration. Due to this, the sine wave from the second order is double the one from the first order, thus cancelling out when the piston is at BDC.
- The supercharger in this theoretical approach does not affect the inertia loads on the engine.

4.3 Net Compressive Load

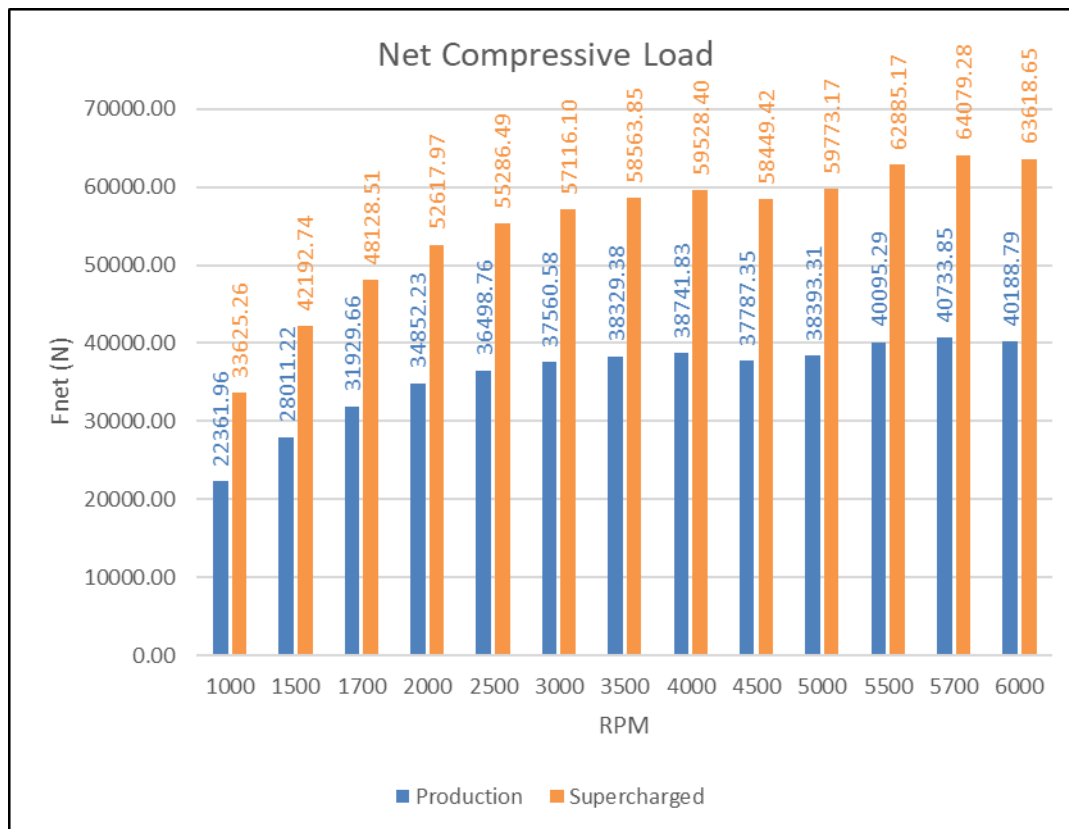


Figure 4 Net Compressive Load Production vs supercharged

- The highest Net compressive load happens at 5700RPM for the production and the Supercharged engine, this is due to the inertial forces applied on the engine.
- To calculate the actual Force on the rod, the rod angle has to be implemented into the equation as seen in Table 4 $F_{rod} = F_{net} \times \cos(\phi)$, this only equates to a slight increase on the load, due to the small rod angles being used.

4.3 Net Tensile Load

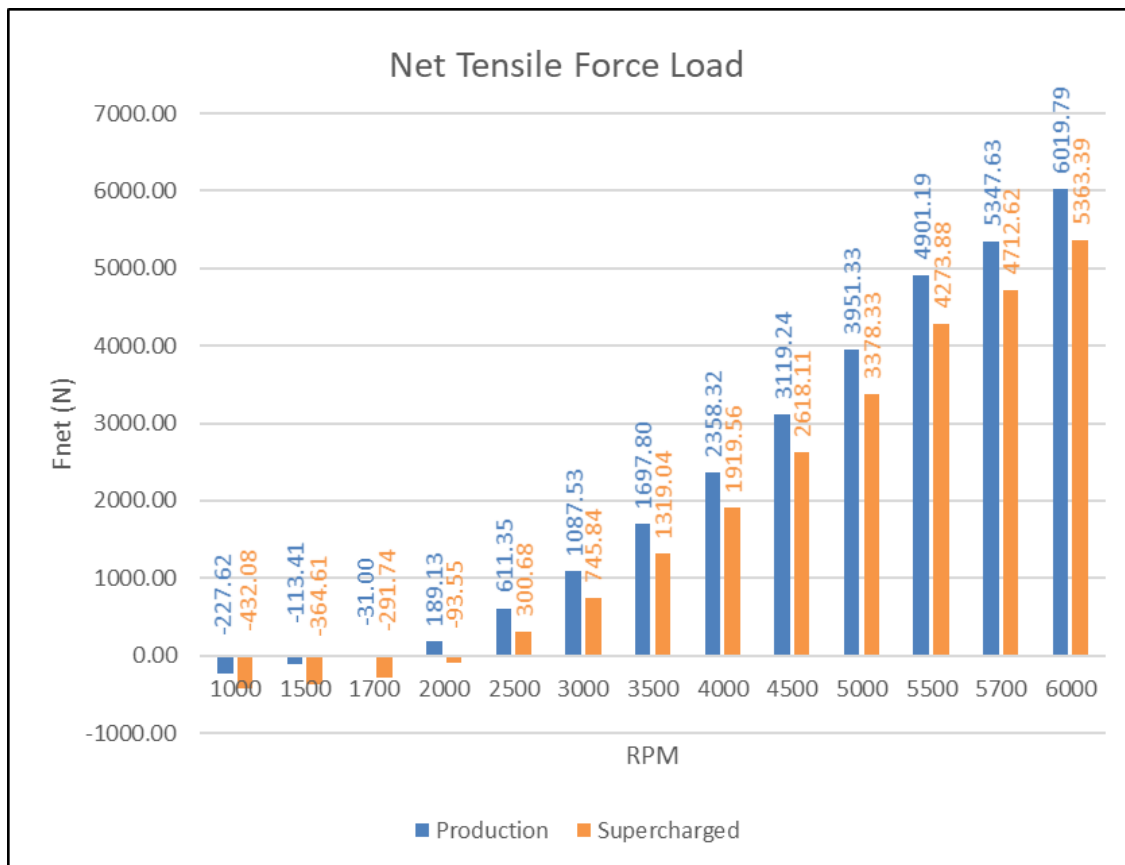


Figure 5 Net Tensile Force Load Production vs supercharged

- The Net tensile force steadily increases with every RPM range.
- The actual Tensile force, like the compressive force has a very slight increase in the load.

4.4 Compressive Stress.

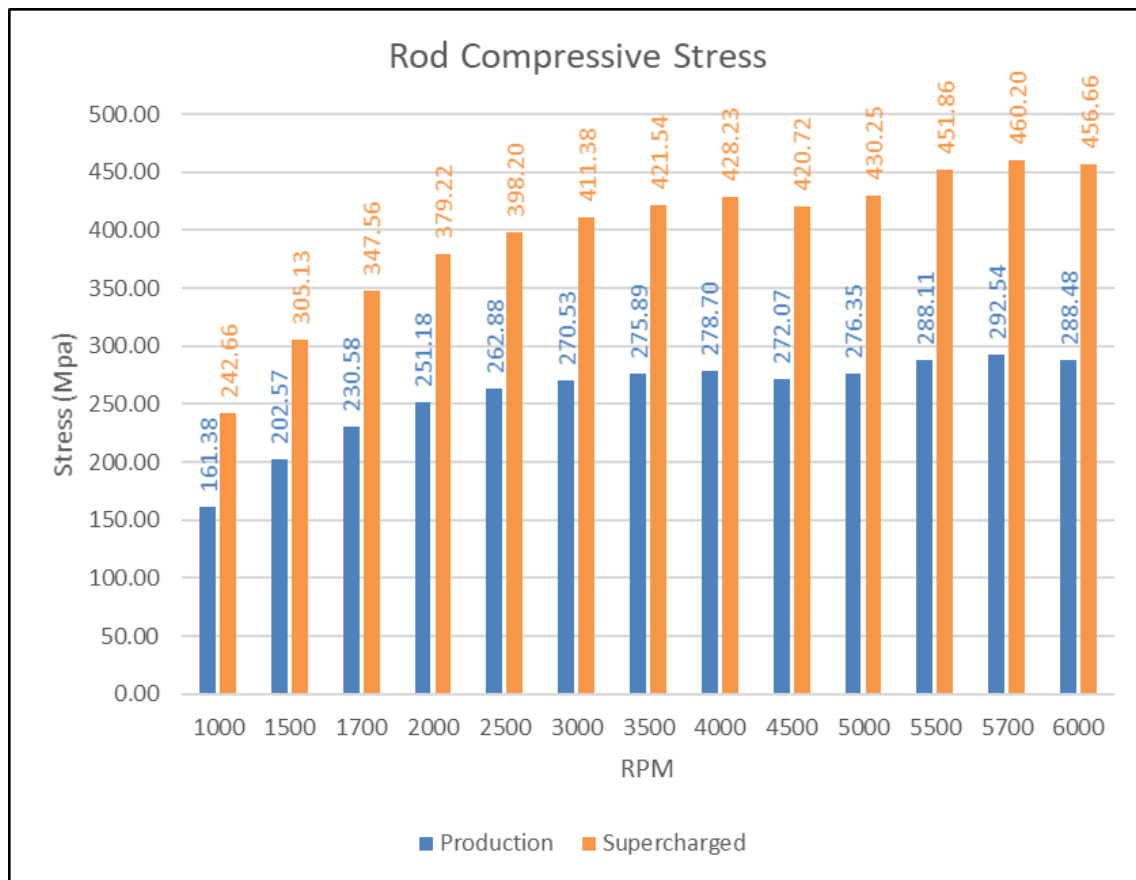


Figure 6 Rod Compressive Stress

- Due to the relatively low Stress compared to the Steel UTS of 750MPa as seen in Table 2, the engine is going to have a relatively high safety factor.

4.5 Tensile Stress

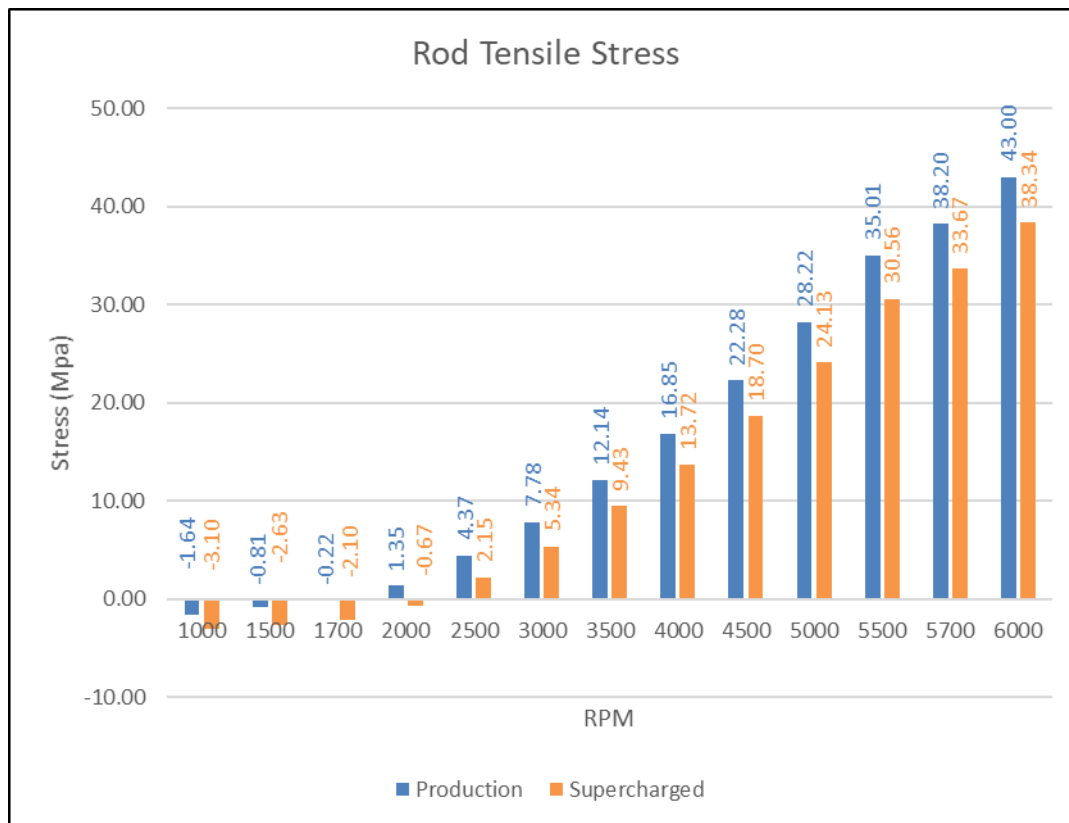


Figure 7 Rod Tensile Stress

4.6 Compressive and Tensile Safety Factors.

Table 5 Safety Factors

RPM	Production engine		Supercharged engine	
	Compressive SF	Tensile SF	Compressive SF	Tensile SF
1000	4.65	-458.56	3.09	-241.57
1500	3.70	-920.80	2.46	-285.04
1700	3.25	-3361.56	2.16	-356.48
2000	2.99	553.69	1.98	-1115.11
2500	2.85	171.51	1.88	348.27
3000	2.77	96.39	1.82	140.45
3500	2.72	61.80	1.78	79.51
4000	2.69	44.51	1.75	54.67
4500	2.76	33.66	1.78	40.10
5000	2.71	26.57	1.74	31.08
5500	2.60	21.42	1.66	24.54
5700	2.56	19.63	1.63	22.28
6000	2.60	17.44	1.64	19.56

- The safety factors on the current production con-rod, are enough to install a supercharger without the need to change the con-rods, as a safety factor of 1.64 is achieved at the highest RPM.

4.7 Compressive Displacement.

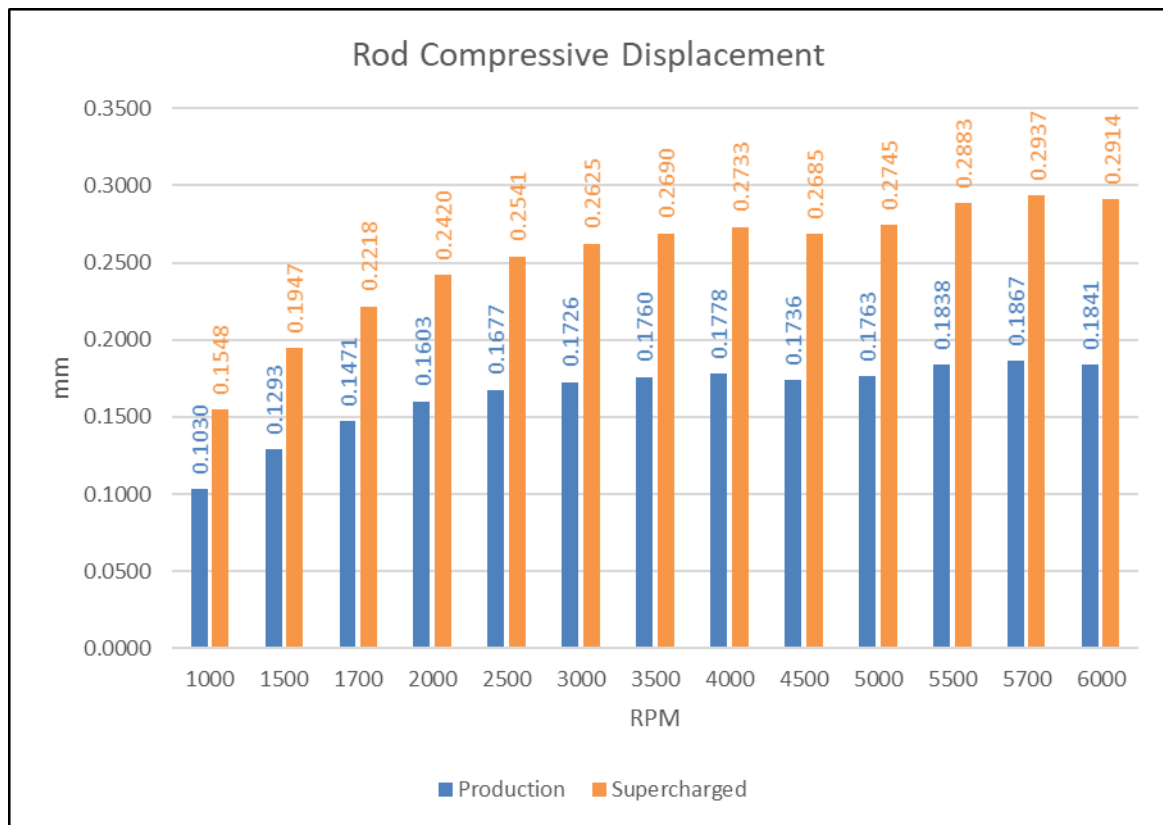


Figure 8 Rod Compressive Displacement

- The highest compressive displacement is at 5700 RPM of 0.1867mm for the production engine.
- The highest compressive displacement is at 5700 RPM of 0.2937mm for the supercharged engine.
- The displacement is higher in the supercharged engine due to increase in cylinder pressures.

4.8 Tensile Displacement

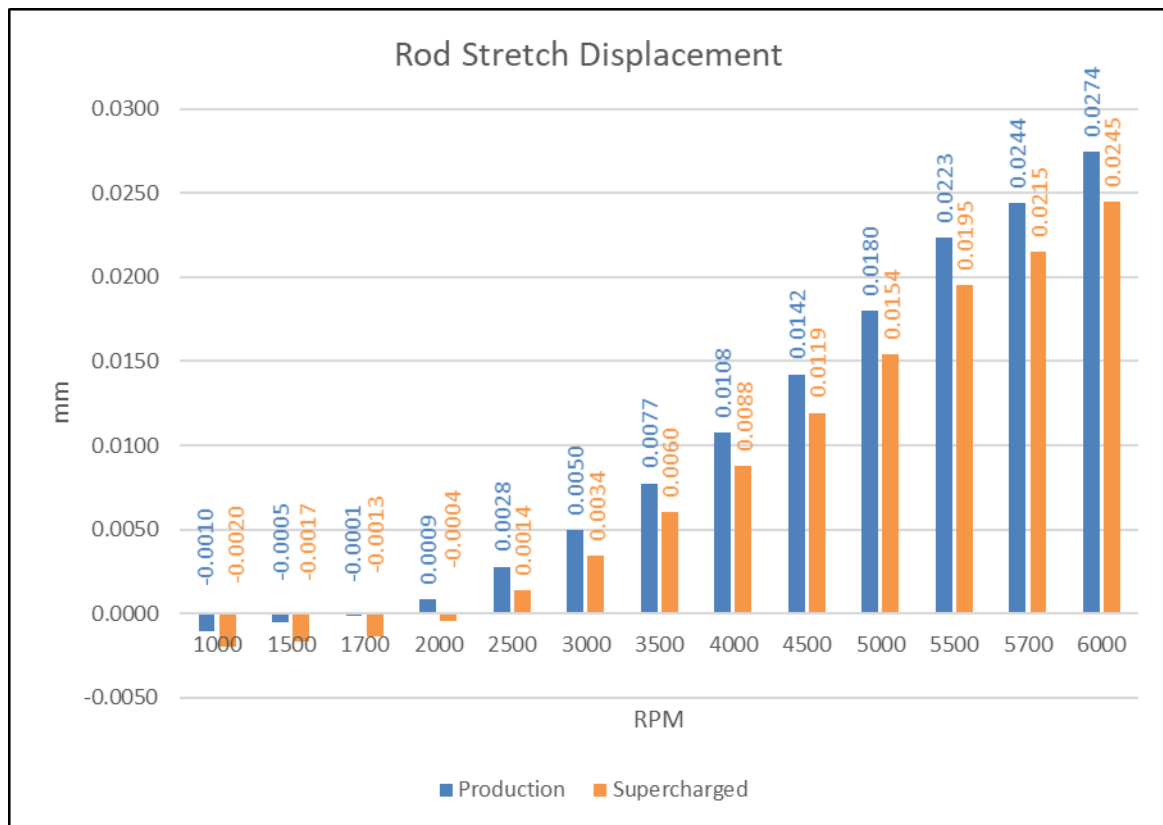


Figure 9 Rod Stretch Displacement

- The highest tensile displacement is at 6000rpm with a displacement of 0.0274mm for the production engine.
- The highest tensile displacement is at 6000rpm with a displacement of 0.0245mm for the supercharged engine.
- The increase in cylinder pressures on the supercharged engine, relieves the conrod from tensile displacements, as the inertial forces in the production engine will act more strongly on the con-rod in a low pressure environment (Taylor, 1985)

4.9 Titanium Compressive Displacement

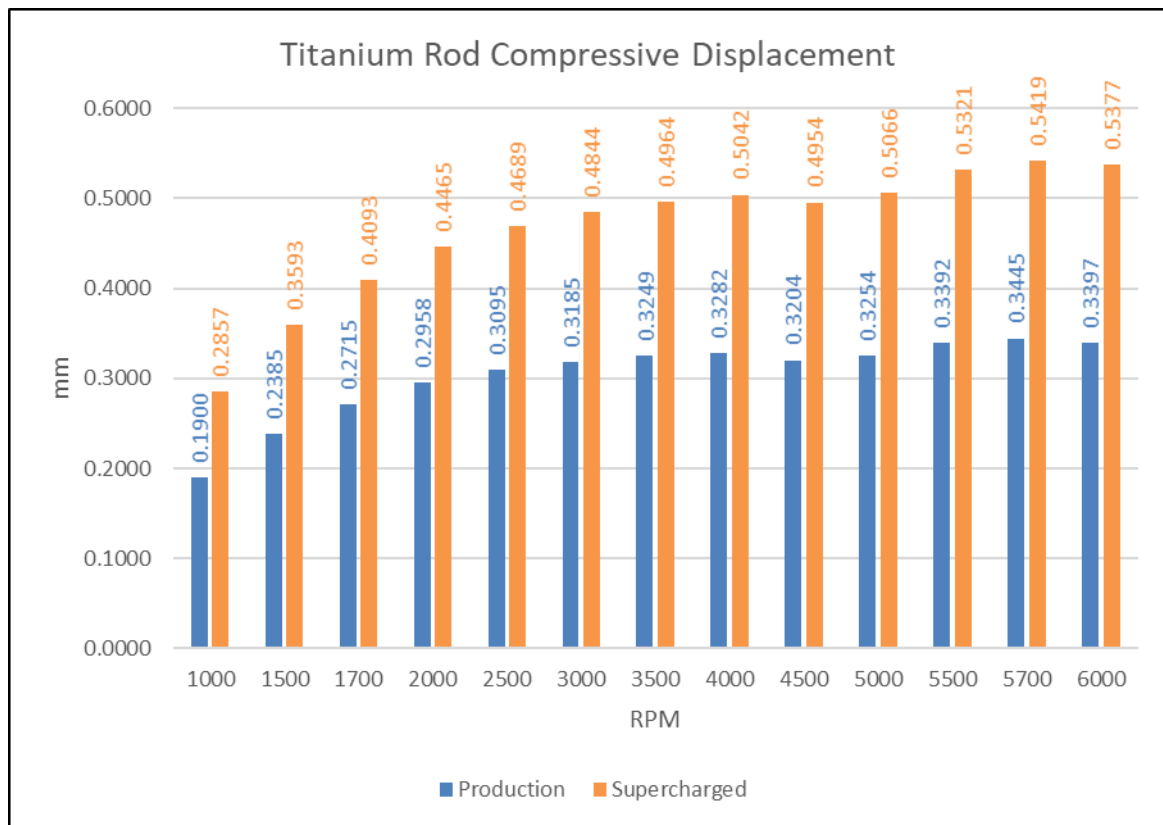


Figure 10 Titanium Rod Compressive Displacement

- The increase in displacement in comparison with the steel rod is due to the lower Young's Modulus of Titanium.
- The highest compressive displacement is at 5700 RPM of 0.3445mm for the production engine.
- The highest compressive displacement is at 5700 RPM of 0.5419mm for the supercharged engine.
- That is a difference in comparison with the steel conrod of 0.1578mm for the production engine, and of 0.2482mm for the supercharged.
- With these differences, clearances within the engine will have to be closely monitored, to avoid any collisions.

4.10 Titanium Tensile Displacement.

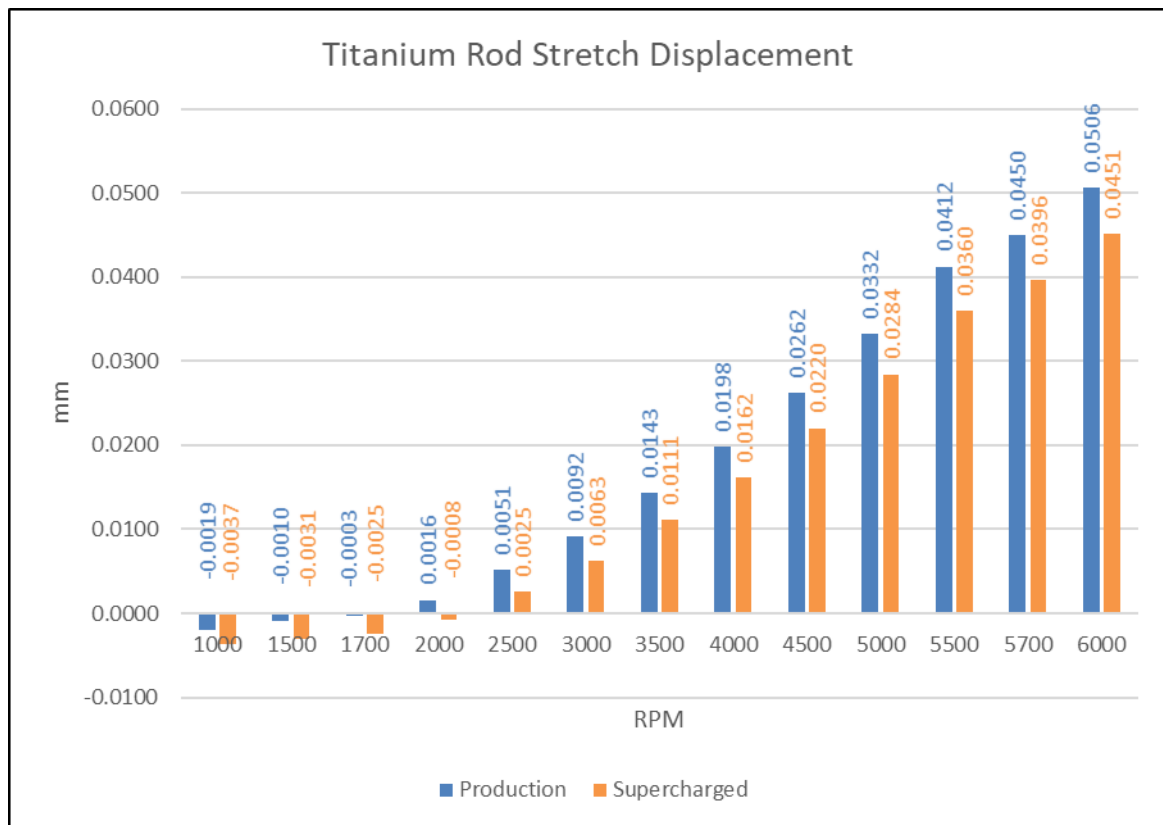


Figure 11 Titanium Rod Stretch Displacement

- The highest tensile displacement is at 5700 RPM of 0.0506mm for the production engine.
- The highest tensile displacement is at 5700 RPM of 0.0451mm for the supercharged engine.
- That is a difference in comparison with the steel conrod of 0.0232mm for the production engine, and of 0.0206mm for the supercharged.

5. VALIDATE DATA.

The calculated data can be validated by comparing it to the torque and power graphs provided by Ford.

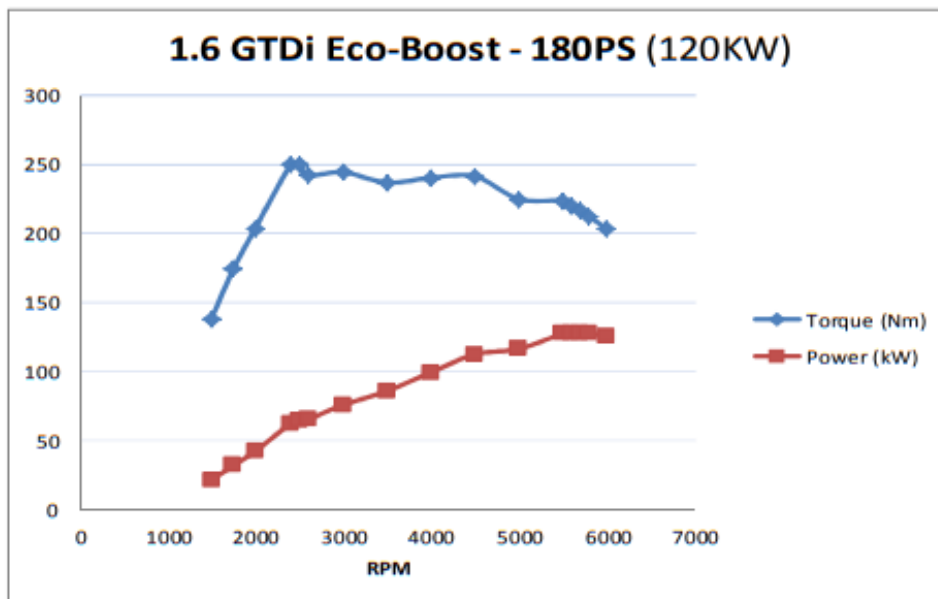


Figure 12 Ford Torque Power Graph (Ford, 2015)

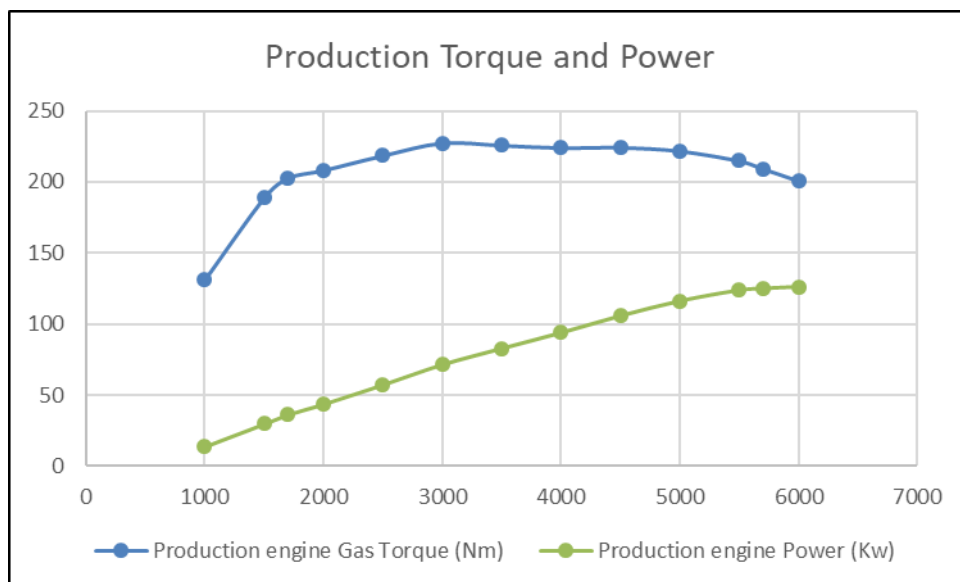


Figure 13 Calculated Production Torque and Power

- Comparing the data given by Ford (Figure 12) and the Calculated data (Figure 13), validates that the calculations have been done in a correct manner.

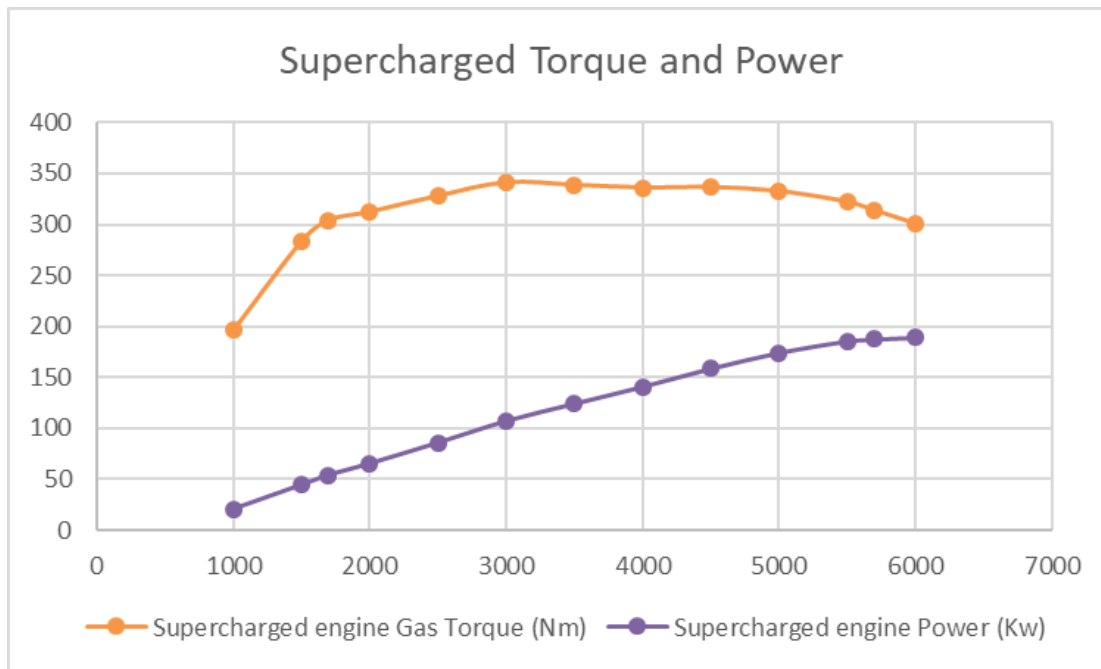


Figure 14 Calculated Supercharged Torque and Power.

- The 50% increase in power (Carley, 2019), shown in Figure 14 validates the calculations done for the modified engine.

6. CONCLUSION

- The use of a supercharger is an easy cost-effective way in increasing the power of the engine.
- When installing one, monitoring carefully the clearances will be of importance due to the increase in conrod displacements.
- The safety factors on the conrod are very significant and open the path for tuning.

References

ASM Aerospace, n.d. *Specification Metals*. [Online]

Available at: <http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=mtp641>

[Accessed 23 October 2019].

Carley, L., 2019. AA1CAR. [Online]

Available at: <https://www.aa1car.com/library/supercharge.htm>

[Accessed 30 October 2019].

Ford, 2015. *Ford Engine Data*. [Online]

Available at: <https://www.ford.co.uk/content/dam/guxeu/uk/documents/home/experience-ford/about-ford/ford-component-sales/specification-details-data-sheets/16-ecoboost-np.pdf>

[Accessed 23 October 2019].

Mcdonald, M., 2019. *Advanced Engine Design*. Swansea: UWTSD.

Nigus, H., 2015. Kinematics and Load Formulation of Engine Crank Mechanism. *Mechanics, Materials Science & Engineering Journal*.

Ovako, 2019. *Steel grades*. [Online]

Available at: <https://steelnavigator.ovako.com/steel-grades/34crnimo6/>

[Accessed 24 October 2019].

Taylor, C. F., 1985. *The Internal Combustion Engine in Theory and Practice Volume 1*. 2nd Edition ed. Massachussets: MIT Press.

7. APPENDIX

Excel Screenshots:

Crank Ang deg	CYLPR1 bar	CYLPR2 bar	CYLPR3 bar	CYLPR4 bar	AVRG P bar	AVRG P N/m^2	Fgas N	Fractal N	Ffriction N	RodAngle radians	Piston Tra m	WD J	TOTAL WD/cyl J	Fmep N/m^2	Fmep bar
-360	0.886	1.053	0.994	0.931	0.966	96600	485.5645605	26.94883311	2.694883311	7.44232E-17	0	2.15608E-05	4.962195706	12405.48926	0.124055
-359	0.886	1.065	0.994	0.944	0.97225	97225	488.7061532	27.1231915	2.71231915	0.005300868	7.97484E-06	6.49802E-05			
-358	0.898	1.065	0.994	0.944	0.97525	97525	490.2141177	27.20688353	2.720688353	0.01060027	3.18954E-05	0.000108973			
-357	0.898	1.065	1.033	0.944	0.985	98500	495.1150022	27.47888262	2.747888262	0.01589674	7.17496E-05	0.00015375			
-356	0.911	1.078	1.033	0.944	0.9915	99150	498.3822586	27.66021535	2.766021535	0.021188813	0.000127518	0.000198796			
-355	0.911	1.078	1.045	0.956	0.9975	99750	501.3981875	27.82759941	2.782759941	0.026475024	0.000199171	0.000244692			
-354	0.924	1.091	1.058	0.956	1.00725	100725	506.2990721	28.0995985	2.80995985	0.031753907	0.000286675	0.000291702			
-353	0.924	1.104	1.071	0.969	1.017	101700	511.1999566	28.37159759	2.837159759	0.037023997	0.000389985	0.000339425			
-352	0.937	1.104	1.084	0.982	1.02675	102675	516.1008411	28.64359668	2.864359668	0.042283832	0.00050905	0.000387833			
-351	0.95	1.117	1.084	0.995	1.0365	103650	521.0017257	28.91559577	2.891559577	0.047531946	0.00064381	0.000436218			
-350	0.963	1.13	1.084	0.995	1.043	104300	524.268982	29.0969285	2.90969285	0.052766878	0.000794198	0.000485092			
-349	0.976	1.13	1.097	1.008	1.05275	105275	529.1698666	29.36892759	2.936892759	0.057987164	0.000960138	0.000534363			
-348	0.989	1.142	1.097	1.008	1.059	105900	532.3114592	29.54328599	2.954328599	0.063191344	0.001141548	0.00058138			
-347	0.989	1.13	1.097	1.02	1.059	105900	532.3114592	29.54328599	2.954328599	0.068377957	0.001338337	0.000625638			
-346	0.989	1.13	1.097	1.008	1.056	105600	530.8034948	29.45959396	2.945959396	0.073545545	0.001550407	0.000666366			
-345	0.976	1.117	1.084	1.008	1.04625	104625	525.9026102	29.18759487	2.918759487	0.078692649	0.001777653	0.000702844			
-344	0.963	1.104	1.071	0.995	1.03325	103325	519.3680975	28.82492941	2.882492941	0.083817813	0.00201996	0.000735687			
-343	0.95	1.091	1.045	0.982	1.017	101700	511.1999566	28.37159759	2.837159759	0.088919581	0.002277209	0.000767046			
-342	0.937	1.078	1.033	0.969	1.00425	100425	504.7911076	28.01590647	2.801590647	0.093996501	0.002549272	0.00079943			
-341	0.924	1.078	1.02	0.956	0.9945	99450	499.890223	27.74390738	2.774390738	0.099047121	0.002836012	0.000831865			
-340	0.911	1.078	1.007	0.944	0.985	98500	495.1150022	27.47888262	2.747888262	0.104069992	0.003137288	0.000867405			
-339	0.911	1.078	1.007	0.944	0.985	98500	495.1150022	27.47888262	2.747888262	0.109063667	0.00345295	0.000909497			
-338	0.911	1.091	1.02	0.944	0.9915	99150	498.3822586	27.66021535	2.766021535	0.114026701	0.003782842	0.000952954			
-337	0.911	1.104	1.02	0.944	0.99475	99475	500.0158867	27.75088171	2.775088171	0.118957652	0.0041268	0.00099944			
-336	0.924	1.117	1.033	0.956	1.0075	100750	506.4247358	28.10657283	2.810657283	0.123855082	0.004484654	0.001049287			
-335	0.937	1.13	1.045	0.956	1.017	101700	511.1999566	28.37159759	2.837159759	0.128717555	0.004856227	0.001097851			
-334	0.95	1.13	1.058	0.969	1.02675	102675	516.1008411	28.64359668	2.864359668	0.133543638	0.005241335	0.001146595			
-333	0.963	1.142	1.058	0.982	1.03625	103625	520.876062	28.90862144	2.890862144	0.138331902	0.005639789	0.001191754			
-332	0.976	1.142	1.058	0.982	1.0395	103950	522.5096901	28.9992878	2.89992878	0.143080925	0.006051392	0.00123309			
-331	0.976	1.142	1.058	0.995	1.04275	104275	524.1433183	29.08995417	2.908995417	0.147789284	0.006475942	0.001270241			
-330	0.976	1.13	1.058	0.995	1.03975	103975	522.6353539	29.00626214	2.900626214	0.152455566	0.006913231	0.001304739			
-329	0.976	1.13	1.058	0.995	1.03975	103975	522.6353539	29.00626214	2.900626214	0.157078358	0.007363044	0.001336238			
-328	0.976	1.13	1.045	0.982	1.03325	103325	519.3680975	28.82492941	2.882492941	0.161656258	0.00782516	0.001366864			
-327	0.976	1.13	1.045	0.982	1.03325	103325	519.3680975	28.82492941	2.882492941	0.166187864	0.008299356	0.001396606			
-326	0.963	1.13	1.045	0.969	1.02675	102675	516.1008411	28.64359668	2.864359668	0.170671785	0.008785398	0.001423201			
-325	0.95	1.13	1.045	0.969	1.0235	102350	514.467213	28.55293032	2.855293032	0.175106634	0.009283051	0.001448791			
-324	0.95	1.117	1.045	0.956	1.017	101700	511.1999566	28.37159759	2.837159759	0.179491031	0.009792072	0.001475732			
-323	0.95	1.117	1.045	0.956	1.017	101700	511.1999566	28.37159759	2.837159759	0.183823605	0.010312216	0.001501945			
-322	0.937	1.117	1.045	0.944	1.01075	101075	508.0583639	28.1972392	2.81972392	0.188102993	0.010843231	0.001527247			
-321	0.937	1.117	1.045	0.944	1.01075	101075	508.0583639	28.1972392	2.81972392	0.192327838	0.011384861	0.001558946			
-320	0.937	1.117	1.058	0.944	1.014	101400	509.6919921	28.28790556	2.828790556	0.196496795	0.011936846	0.001597438			

Bore m	Fgas N	Fgas Tonnes	Revs rpm	Crank Throw m	Length Conrod m	Angular Velocity rad/s	Piston Acceleration m/sec^2	Reciprocating mass Kg	Inertia Force N	Fnet N	Frod N	Fside N
0.079	473.501	0.048	1000	0.0407	0.134	104.720	581.8885	0.3504	203.8937199	269.608	269.6076	2.01E-14
	476.565	0.049					581.7379		203.840964	272.724	272.7277	1.445687
	478.035	0.049					581.2864		203.6827391	274.353	274.368	2.908321
	482.814	0.049					580.5342		203.4191725	279.395	279.4306	4.441849
	486.001	0.050					579.482		203.0504765	282.950	283.0136	5.996274
	488.942	0.050	Max Fgas	22526.605	N		578.1306		202.5769482	286.365	286.465	7.583282
	493.721	0.050					576.4811		201.9989687	291.722	291.8689	9.266419
	498.500	0.051					574.5348		201.3170032	297.183	297.3866	11.00793
	503.279	0.051					572.2934		200.5316002	302.747	303.0182	12.80895
	508.058	0.052					569.7585		199.6433911	308.415	308.7634	14.6706
	511.244	0.052					566.9323		198.6530894	312.591	313.0268	16.50978
	516.023	0.053					563.817		197.5614899	318.462	318.998	18.48742
	519.087	0.053					560.4151		196.3694681	322.717	323.3628	20.42013
	519.087	0.053					556.7294		195.0779791	324.009	324.7678	22.18966
	517.616	0.053					552.7627		193.6880565	323.928	324.8063	23.86653
	512.837	0.052					548.5183		192.2008115	320.636	321.6317	25.28394
	506.465	0.052					543.9995		190.6174315	315.848	316.9604	26.53583
	498.500	0.051					539.21		188.9391793	309.561	310.7885	27.59878
	492.250	0.050					534.1535		187.1673912	305.083	306.4355	28.76147
	487.471	0.050					528.8341		185.3034757	302.168	303.6559	30.02709
	482.814	0.049					523.256		183.3489125	299.466	301.0946	31.27838
	482.814	0.049					517.4237		181.3052503	301.509	303.3114	33.01471
	486.001	0.050					511.3416		179.1741056	306.826	308.832	35.13883
	487.594	0.050					505.0147		176.9571607	310.636	312.8474	37.12788
	493.843	0.050					498.448		174.6561623	319.187	321.651	39.73634
	498.500	0.051					491.6465		172.2729191	326.227	328.9482	42.22458
	503.279	0.051					484.6156		169.8093007	333.470	336.4655	44.79938
	507.936	0.052					477.3608		167.2672348	340.668	343.954	47.42821
	509.529	0.052					469.8879		164.6487056	344.880	348.4405	49.68525
	511.122	0.052					462.2025		161.9557518	349.166	353.0141	51.98199
	509.651	0.052					454.3107		159.1904643	350.461	354.5733	53.84751
	509.651	0.052					446.2186		156.354984	353.296	357.7	55.95615
	506.465	0.052					437.9324		153.4514996	353.014	357.6769	57.56921
	506.465	0.052					429.4585		150.4822456	355.983	360.9559	59.71074
	503.279	0.051					420.8034		147.4494994	355.829	361.0756	61.32667
	501.686	0.051					411.9737		144.3555793	357.330	362.8795	63.21838
	498.500	0.051					402.9761		141.2028422	357.297	363.1308	64.82931
	498.500	0.051					393.8176		137.9936809	360.506	366.6841	67.02621
	495.436	0.051					384.5049		134.7305217	360.706	367.1826	68.66156
	495.436	0.051					375.0452		131.4158219	364.020	370.8584	70.88747

			Min cross m²	Stress rod Pa	Strain Rod Pa				UTS Pa	E youngs Pa	k Stiffness N/m
Max net tensile	227.617 N		0.00014	1925768.544		Max Tensile Stress	1635550.304 Pa		7.5E+08	2.1E+11	219402985.1
Max net compressive	22361.956 N			1948055.195		Max Compressive Stress	161377310.1 Pa				
				1959771.687							34CrNiMo6
Max tensile rod	228.977 N			1995933.019							
Max compressive rod	22592.823 N			2021525.908		Max Tensile SF	458.5612551				
				2046178.698		Max Compression SF	4.647493503				
				2084777.647							
				2124190.225							
				2164415.763		Compression Displacement	0.000102974 m				
				2205453.033			0.102974093 mm				
				2235905.507							
				2278556.998							
				2309734.149		Tensile Displacement	1.04364E-06 m				
				2319770.034			0.001043637 mm				
				2320045.166							
				2297369.64							
				2264002.527							
				2219917.846							
				2188825.338							
				2168970.462							
				2150675.839							
				2166509.842							
				2205943.036							
				2234624.192							
				2297507.201							
				2349629.96							
				2403324.643							
				2456814.076							
				2488860.477							
				2521529.129							
				2532666.521							
				2554999.69							
				2554835.127							
				2578256.085							
				2579111.2							
				2591996.457							
				2593791.435							
				2619171.843							

UTS Pa	E youngs Pa	k Stiffness N/m		Gas Torque Nm				
950000000	1.14E+11	1.19E+08		4.72209E-15				
				0.340304402				
Ti-6Al-4V				0.682603325				
				1.033874851				
				1.387095733				
				1.743552603				
				2.111515377				
				2.485612469				
Compression Displacement	0.00019 m			2.865714506	Sum Gas Torque	23554.91		
	0.190022 mm			3.251688171		32.71515		
				3.632078654	Mean Gas Torque	130.8606 Nm		
				4.02826184				
Tensile Displacement	1.93E-06 m			4.415304784				
	0.001926 mm			4.777067324				
				5.122799378				
				5.429879279				
				5.710728567				
				5.962017122				
				6.222277408				
				6.491715132				
				6.754412746				
				7.077035201				
				7.446286399				
				7.791993012				
				8.214843711				
				8.615765764				
				9.022241199				
				9.429779349				
				9.781508708				
				10.13222229				
				10.41916275				
				10.73203674				
				10.97257103				
				11.2768097				
				11.50473545				
				11.76270037				
				11.9769036				
				12.26211392				

Production Engine		Modified engine	
RPM	Max Fgas	RPM	Max Fgas
1000	22526.60	1000	33789.91
1500	28363.02	1500	42544.53
1700	32397.71	1700	48596.56
2000	35531.47	2000	53297.21
2500	37575.47	2500	56363.20
3000	39111.04	3000	58666.56
3500	40468.92	3500	60703.38
4000	41573.15	4000	62359.72
4500	41324.14	4500	61986.21
5000	42759.72	5000	64139.58
5500	45579.77	5500	68369.66
5700	46690.86	5700	70036.29
6000	46862.91	6000	70294.36

Production engine				Supercharged engine			
RPM	Net Compressive	Net Tensile		RPM	Net Compressive	Net Tensile	
1000	22361.96	227.62	-227.62	1000	33625.26	432.08	-432.08
1500	28011.22	113.41	-113.41	1500	42192.74	364.61	-364.61
1700	31929.66	31.00	-31.00	1700	48128.51	291.74	-291.74
2000	34852.23	-189.13	189.13	2000	52617.97	93.55	-93.55
2500	36498.76	-611.35	611.35	2500	55286.49	-300.68	300.68
3000	37560.58	-1087.53	1087.53	3000	57116.10	-745.84	745.84
3500	38329.38	-1697.80	1697.80	3500	58563.85	-1319.04	1319.04
4000	38741.83	-2358.32	2358.32	4000	59528.40	-1919.56	1919.56
4500	37787.35	-3119.24	3119.24	4500	58449.42	-2618.11	2618.11
5000	38393.31	-3951.33	3951.33	5000	59773.17	-3378.33	3378.33
5500	40095.29	-4901.19	4901.19	5500	62885.17	-4273.88	4273.88
5700	40733.85	-5347.63	5347.63	5700	64079.28	-4712.62	4712.62
6000	40188.79	-6019.79	6019.79	6000	63618.65	-5363.39	5363.39

Production engine				Supercharged engine			
RPM	Compressive Stress (Mpa)	Tensile Stress (Mpa)		RPM	Compressive Stress (Mpa)	Tensile Stress (Mpa)	
1000	161.38	1.64	-1.64	1000	242.66	3.10	-3.10
1500	202.57	0.81	-0.81	1500	305.13	2.63	-2.63
1700	230.58	0.22	-0.22	1700	347.56	2.10	-2.10
2000	251.18	-1.35	1.35	2000	379.22	0.67	-0.67
2500	262.88	-4.37	4.37	2500	398.20	-2.15	2.15
3000	270.53	-7.78	7.78	3000	411.38	-5.34	5.34
3500	275.89	-12.14	12.14	3500	421.54	-9.43	9.43
4000	278.70	-16.85	16.85	4000	428.23	-13.72	13.72
4500	272.07	-22.28	22.28	4500	420.72	-18.70	18.70
5000	276.35	-28.22	28.22	5000	430.25	-24.13	24.13
5500	288.11	-35.01	35.01	5500	451.86	-30.56	30.56
5700	292.54	-38.20	38.20	5700	460.20	-33.67	33.67
6000	288.48	-43.00	43.00	6000	456.66	-38.34	38.34

Production engine				Supercharged engine			
RPM	Compressive SF	Tensile SF		RPM	Compressive SF	Tensile SF	
1000	4.65	458.56	-458.56	1000	3.09	241.57	-241.57
1500	3.70	920.80	-920.80	1500	2.46	285.04	-285.04
1700	3.25	3361.56	-3361.56	1700	2.16	356.48	-356.48
2000	2.99	-553.69	553.69	2000	1.98	1115.11	-1115.11
2500	2.85	-171.51	171.51	2500	1.88	-348.27	348.27
3000	2.77	-96.39	96.39	3000	1.82	-140.45	140.45
3500	2.72	-61.80	61.80	3500	1.78	-79.51	79.51
4000	2.69	-44.51	44.51	4000	1.75	-54.67	54.67
4500	2.76	-33.66	33.66	4500	1.78	-40.10	40.10
5000	2.71	-26.57	26.57	5000	1.74	-31.08	31.08
5500	2.60	-21.42	21.42	5500	1.66	-24.54	24.54
5700	2.56	-19.63	19.63	5700	1.63	-22.28	22.28
6000	2.60	-17.44	17.44	6000	1.64	-19.56	19.56

Production engine				Supercharged engine			
RPM	Compressive Displacement	Tensile Displacement		RPM	Compressive Displacement	Tensile Displacement	
1000	0.1030	0.0010	-0.0010	1000	0.1548	0.0020	-0.0020
1500	0.1293	0.0005	-0.0005	1500	0.1947	0.0017	-0.0017
1700	0.1471	0.0001	-0.0001	1700	0.2218	0.0013	-0.0013
2000	0.1603	-0.0009	0.0009	2000	0.2420	0.0004	-0.0004
2500	0.1677	-0.0028	0.0028	2500	0.2541	-0.0014	0.0014
3000	0.1726	-0.0050	0.0050	3000	0.2625	-0.0034	0.0034
3500	0.1760	-0.0077	0.0077	3500	0.2690	-0.0060	0.0060
4000	0.1778	-0.0108	0.0108	4000	0.2733	-0.0088	0.0088
4500	0.1736	-0.0142	0.0142	4500	0.2685	-0.0119	0.0119
5000	0.1763	-0.0180	0.0180	5000	0.2745	-0.0154	0.0154
5500	0.1838	-0.0223	0.0223	5500	0.2883	-0.0195	0.0195
5700	0.1867	-0.0244	0.0244	5700	0.2937	-0.0215	0.0215
6000	0.1841	-0.0274	0.0274	6000	0.2914	-0.0245	0.0245

Production engine				Supercharged engine			
RPM	Compressive Displacement	Tensile Displacement		RPM	Compressive Displacement	Tensile Displacement	
1000	0.1900	0.0019	-0.0019	1000	0.2857	0.0037	-0.0037
1500	0.2385	0.0010	-0.0010	1500	0.3593	0.0031	-0.0031
1700	0.2715	0.0003	-0.0003	1700	0.4093	0.0025	-0.0025
2000	0.2958	-0.0016	0.0016	2000	0.4465	0.0008	-0.0008
2500	0.3095	-0.0051	0.0051	2500	0.4689	-0.0025	0.0025
3000	0.3185	-0.0092	0.0092	3000	0.4844	-0.0063	0.0063
3500	0.3249	-0.0143	0.0143	3500	0.4964	-0.0111	0.0111
4000	0.3282	-0.0198	0.0198	4000	0.5042	-0.0162	0.0162
4500	0.3204	-0.0262	0.0262	4500	0.4954	-0.0220	0.0220
5000	0.3254	-0.0332	0.0332	5000	0.5066	-0.0284	0.0284
5500	0.3392	-0.0412	0.0412	5500	0.5321	-0.0360	0.0360
5700	0.3445	-0.0450	0.0450	5700	0.5419	-0.0396	0.0396
6000	0.3397	-0.0506	0.0506	6000	0.5377	-0.0451	0.0451

Production engine			Supercharged engine		
RPM	Gas Torque (Nm)	Power (Kw)	RPM	Gas Torque (Nm)	Power (Kw)
1000	131	14	1000	196	21
1500	189	30	1500	283	44
1700	203	36	1700	304	54
2000	208	44	2000	312	65
2500	219	57	2500	328	86
3000	227	71	3000	341	107
3500	226	83	3500	339	124
4000	224	94	4000	336	141
4500	224	106	4500	337	159
5000	222	116	5000	333	174
5500	215	124	5500	322	186
5700	209	125	5700	314	187
6000	201	126	6000	301	189