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Engine Performance Characteristics

Motorcycle Technology – ACHA4003

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1 Introduction

Measuring performance can provide valuable insight into the running conditions of an internal combustion engine. Data collected from a 2000-2001 Honda 1.6 Litre VTEC (D16V3) engine on a Schenck W230 Dynamometer is used to assess performance parameters through a range of running conditions.

Corrected power, torque, brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC) and overall thermal efficiency are calculated, plotted and evaluated.

2 Method

2.1 Equipment

- Honda D16V3 engine
- Schenck W230 Dynamometer & control room
- W230 calibration arm and weights

2.2 Experimental Method

The Honda D16V3 crankshaft is connected directly to the Schenck W230 Dynamometer via a drive shaft (Figure 1).

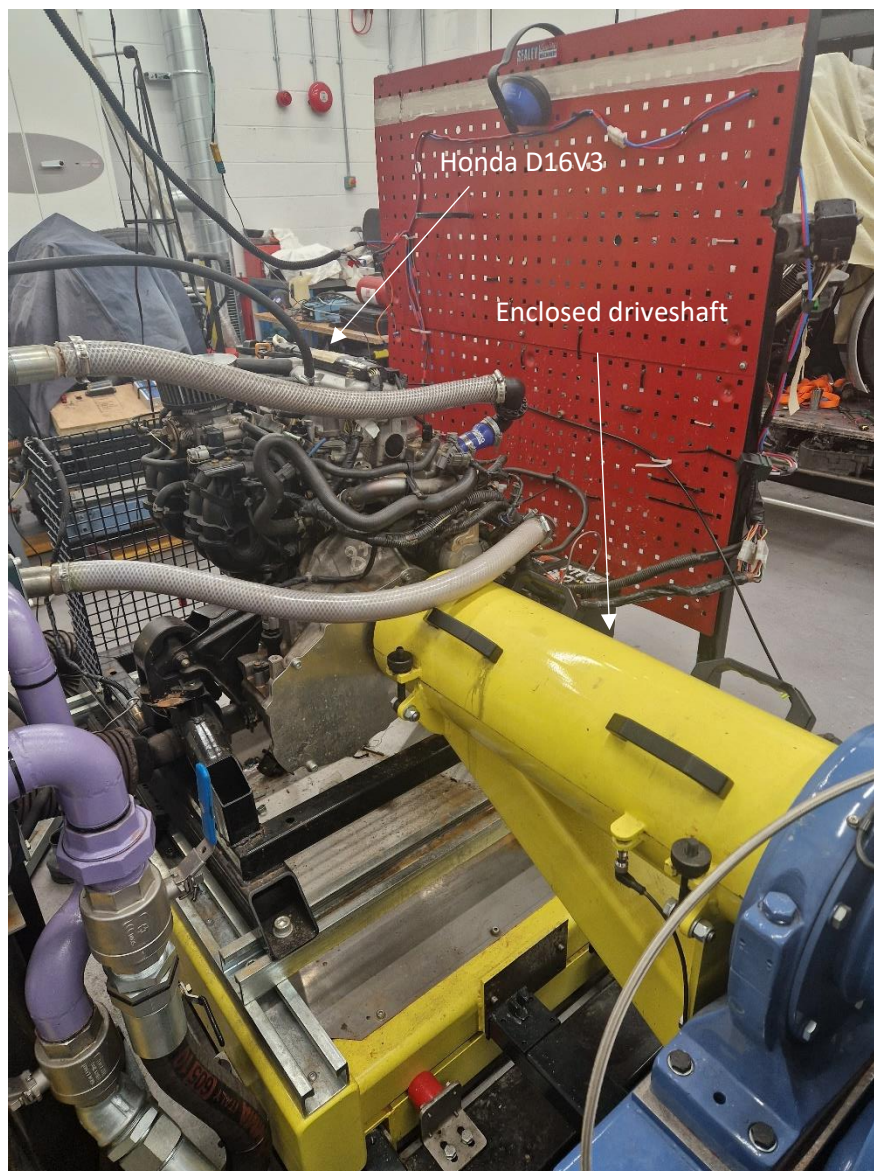


Figure 1: Engine and driveshaft setup.

The dynamometer uses a strain gauge (Figure 2) to send a voltage signal to the test cell control room, this data alongside data collected from various engine mounted sensors allow for the calculation of engine performance values.



Figure 2: Dynamometer strain gauge.

The dynamometer is first calibrated using two calibration arms of known length (815.776mm). Hanging a known mass from the calibration arm (Figure 3) provides a torque applied around the central axis of the dynamometer. Hanging multiple known weights allows the dynamometer to build an accurate picture of the torque applied and the corresponding voltage recorded by the strain gauge.

Engine speed and dynamometer load are controlled via individual knobs found in the test cell (figure 4). Test sequences can also be programmed and allow tests to run a specific course of pre-defined parameters.

Data is exported for calculation. Atmospheric conditions are recorded (figure 7) as these affect engine efficiencies.



Figure 3: Calibration arm with loop for hanging weights.

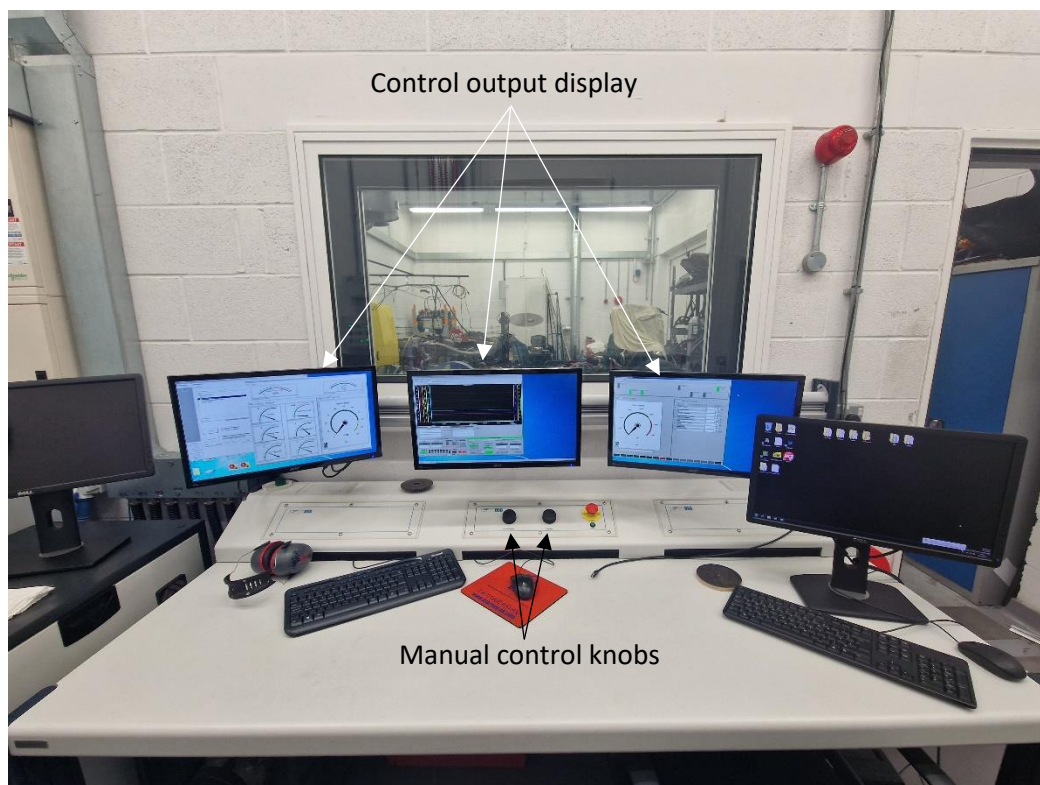


Figure 4: Dyno control room.

3 Raw Data

Calculated Data							
Fuel Flow Rate (kg/min)	Fuel Rate (kg/sec)	Brake Power (Watts)	Corrected Power (kW/h)	Torque (Nm)	SFC (kg/kWh)	Overall Thermal Efficiency (%)	BMEP (Pa)
0.053	0.00088	8737.13	8.79	83.43	0.36	23.07%	659227.58
0.054	0.00091	9217.14	9.27	83.83	0.35	23.67%	662327.93
0.055	0.00092	9743.72	9.80	84.59	0.34	24.58%	668341.71
0.055	0.00091	10237.70	10.30	85.01	0.32	26.14%	671693.44
0.056	0.00093	10847.05	10.91	86.32	0.31	27.11%	682019.35
0.059	0.00099	11480.44	11.55	87.70	0.31	27.03%	692970.49
0.059	0.00099	12159.32	12.24	89.32	0.29	28.62%	705719.96
0.060	0.00100	12893.28	12.97	91.20	0.28	30.11%	720602.94
0.063	0.00104	13666.34	13.75	93.22	0.27	30.43%	736530.11
0.064	0.00106	14342.09	14.43	94.45	0.26	31.48%	746295.25
0.066	0.00111	14990.67	15.08	95.43	0.26	31.44%	754042.91
0.070	0.00117	15596.68	15.69	96.09	0.27	31.11%	759218.75
0.072	0.00120	16193.16	16.29	96.65	0.26	31.39%	763621.12
0.074	0.00123	16741.62	16.85	96.89	0.26	31.52%	765561.26
0.075	0.00125	17232.10	17.34	96.80	0.26	32.02%	764813.57
0.077	0.00129	17769.57	17.88	96.96	0.26	32.06%	766134.92
0.082	0.00137	18388.45	18.50	97.55	0.27	31.28%	770795.12
0.086	0.00143	18954.55	19.07	97.84	0.27	30.87%	773051.09
0.088	0.00147	19506.12	19.63	98.04	0.27	30.88%	774610.94
0.090	0.00151	20148.04	20.27	98.67	0.27	31.07%	779586.97
0.094	0.00157	20871.22	21.00	99.65	0.27	30.91%	787379.74
0.096	0.00160	21513.49	21.65	100.21	0.27	31.28%	791814.34
0.098	0.00164	22208.82	22.35	100.99	0.26	31.54%	797944.14
0.101	0.00168	22920.90	23.06	101.80	0.26	31.72%	804376.89
0.103	0.00172	23518.41	23.67	102.08	0.26	31.75%	806587.74
0.106	0.00176	24224.18	24.38	102.81	0.26	31.93%	812330.81
0.109	0.00181	24886.67	25.04	103.33	0.26	31.92%	816404.45
0.112	0.00187	25460.21	25.62	103.46	0.26	31.59%	817448.64
0.115	0.00192	25974.85	26.14	103.35	0.26	31.42%	816597.82
0.117	0.00195	26487.11	26.65	103.24	0.26	31.64%	815708.32
0.120	0.00200	27003.32	27.17	103.15	0.26	31.46%	814973.52
0.122	0.00203	27500.04	27.67	102.98	0.26	31.44%	813690.84
0.126	0.00210	28021.93	28.20	102.92	0.27	31.00%	813188.08
0.129	0.00214	28489.73	28.67	102.66	0.27	30.89%	811164.15
0.131	0.00218	28811.38	28.99	101.90	0.27	30.67%	805131.03
0.134	0.00223	29113.75	29.30	101.10	0.27	30.34%	798788.52
0.135	0.00225	29586.16	29.77	100.90	0.27	30.55%	797254.46
0.137	0.00229	30041.45	30.23	100.66	0.27	30.50%	795320.77
0.141	0.00235	30352.96	30.54	99.95	0.28	30.03%	789713.06
0.144	0.00241	30704.41	30.90	99.39	0.28	29.65%	785317.14
0.149	0.00249	31192.02	31.39	99.29	0.29	29.14%	784492.10
0.155	0.00258	31559.20	31.76	98.81	0.29	28.48%	780714.95
0.158	0.00263	32076.83	32.28	98.81	0.29	28.39%	780721.40
0.162	0.00270	32520.73	32.72	98.59	0.30	27.98%	778961.74
0.163	0.00272	32967.23	33.17	98.38	0.30	28.12%	777318.10
0.167	0.00279	33550.08	33.76	98.58	0.30	27.96%	778890.84
0.169	0.00282	34289.80	34.50	99.23	0.29	28.27%	784002.23
0.171	0.00286	34966.17	35.19	99.67	0.29	28.45%	787534.44
0.176	0.00293	35706.47	35.93	100.29	0.29	28.34%	792381.56
0.177	0.00295	36391.31	36.62	100.73	0.29	28.66%	795875.09
0.181	0.00302	36904.67	37.14	100.69	0.29	28.36%	795572.15
0.184	0.00307	37667.52	37.90	101.32	0.29	28.53%	800580.41
0.191	0.00319	38155.30	38.39	101.21	0.30	27.81%	799684.47
0.193	0.00322	38654.36	38.90	101.13	0.30	27.90%	799046.35
0.198	0.00331	39135.83	39.38	101.01	0.30	27.51%	798066.61
0.199	0.00331	39649.31	39.90	100.97	0.30	27.81%	797757.22
0.202	0.00337	40094.22	40.35	100.76	0.30	27.68%	796094.25
0.205	0.00342	40346.49	40.60	100.07	0.30	27.40%	790699.25
0.207	0.00345	40698.88	40.95	99.65	0.30	27.42%	787379.74
0.212	0.00354	40892.34	41.15	98.86	0.31	26.88%	781108.14
0.213	0.00356	41006.74	41.26	97.90	0.31	26.79%	773502.29
0.215	0.00359	41079.93	41.34	96.86	0.31	26.60%	765316.33
0.217	0.00361	41134.56	41.39	95.81	0.31	26.47%	756988.56
0.220	0.00366	41302.24	41.56	95.04	0.32	26.20%	750916.77
0.221	0.00369	41595.70	41.86	94.57	0.32	26.22%	747249.20
0.223	0.00371	41765.21	42.03	93.84	0.32	26.13%	741467.47
0.227	0.00378	42020.37	42.28	93.32	0.32	25.85%	737322.92
0.230	0.00383	42369.62	42.64	93.01	0.32	25.74%	734905.81
0.232	0.00387	42802.13	43.07	92.89	0.32	25.74%	733971.19
0.232	0.00387	43331.85	43.60	92.99	0.32	26.00%	734705.99
0.236	0.00393	43557.70	43.83	92.43	0.32	25.75%	730329.41
0.238	0.00396	43951.50	44.23	92.24	0.32	25.77%	728834.02
0.240	0.00399	44089.06	44.37	91.53	0.32	25.66%	723168.30
0.240	0.00401	44117.82	44.39	90.60	0.32	25.59%	715858.95
0.241	0.00401	44155.36	44.43	89.71	0.32	25.60%	708846.10
0.244	0.00406	44089.88	44.37	88.64	0.33	25.23%	700344.30
0.243	0.00406	43906.91	44.18	87.35	0.33	25.15%	690173.08
0.244	0.00407	43603.58	43.88	85.85	0.33	24.89%	678338.89
0.246	0.00410	43380.00	43.65	84.54	0.34	24.61%	667974.31
0.246	0.00411	43274.19	43.55	83.48	0.34	24.49%	659614.32
0.247	0.00411	43186.35	43.46	82.48	0.34	24.43%	651692.63
0.247	0.00412	42845.51	43.11	81.02	0.34	24.15%	640147.85
0.247	0.00412	42514.51	42.78	79.60	0.35	23.97%	628974.98
0.248	0.00414	42168.93	42.43	78.19	0.35	23.69%	617805.33
0.250	0.00417	42113.99	42.38	77.34	0.35	23.46%	611067.71
0.248	0.00414	41753.93	42.02	75.95	0.35	23.43%	600073.38
0.249	0.00416	41558.91	41.82	74.88	0.36	23.24%	591636.05
0.248	0.00414	41404.91	41.66	73.90	0.36	23.27%	583934.80
0.254	0.00424	41350.67	41.61	73.12	0.37	22.69%	577770.19
0.258	0.00430	41402.15	41.66	72.54	0.37	22.39%	573182.18
0.262	0.00436	41651.27	41.91	72.32	0.37	22.20%	571389.01

Figure 5: Calculated data.

Dyno Results			
Load (N)	Dyno Speed (RPM)	Fuel Flow Rate (L/min)	Lambda (A)
102.275	1000	0.0704	1.2658
102.756	1050	0.0724	1.26783
103.689	1100	0.0737	1.27344
104.209	1150	0.0728	1.28476
105.811	1200	0.0744	1.29181
107.51	1250	0.07895	1.29729
109.488	1300	0.079	1.29895
111.797	1350	0.0796	1.29469
114.268	1400	0.0835	1.2855
115.783	1450	0.0847	1.27818
116.985	1500	0.08865	1.2795
117.788	1550	0.0932	1.27766
118.471	1600	0.0959	1.28235
118.772	1650	0.09875	1.29028
118.656	1700	0.10005	1.29942
118.861	1750	0.10305	1.31053
119.584	1800	0.1093	1.3149
119.934	1850	0.11415	1.31849
120.176	1900	0.11745	1.31892
120.948	1950	0.12055	1.31484
122.157	2000	0.12555	1.31653
122.845	2050	0.12785	1.32098
123.796	2100	0.1309	1.32287
124.794	2150	0.13435	1.32164
125.137	2200	0.1377	1.31652
126.028	2250	0.14105	1.30465
126.66	2300	0.14495	1.29646
126.822	2350	0.14985	1.28229
126.69	2400	0.1537	1.27304
126.552	2450	0.15565	1.26984
126.438	2500	0.1596	1.27446
126.239	2550	0.1626	1.27876
126.161	2600	0.16805	1.27634
125.847	2650	0.17145	1.28027
124.911	2700	0.17465	1.28371
123.927	2750	0.1784	1.2812
123.689	2800	0.18005	1.27448
123.389	2850	0.1831	1.26036
122.519	2900	0.1879	1.2531
121.837	2950	0.19255	1.23943
121.709	3000	0.199	1.22735
121.123	3050	0.20605	1.2193
121.124	3100	0.21005	1.20692
120.851	3150	0.21605	1.19274
120.596	3200	0.21795	1.18481
120.84	3250	0.22305	1.17378
121.633	3300	0.2255	1.16118
122.181	3350	0.2285	1.15104
122.933	3400	0.2342	1.14117
123.475	3450	0.23605	1.12669
123.428	3500	0.24195	1.11975
124.205	3550	0.24545	1.10622
124.066	3600	0.25505	1.09697
123.967	3650	0.25755	1.09401
123.815	3700	0.26445	1.09659
123.767	3750	0.2651	1.09808
123.509	3800	0.2693	1.09907
122.672	3850	0.27375	1.10533
122.157	3900	0.2759	1.11704
121.184	3950	0.28285	1.12259
120.004	4000	0.28455	1.12461
118.734	4050	0.2871	1.1222
117.442	4100	0.28895	1.12394
116.5	4150	0.29305	1.12233
115.931	4200	0.2949	1.12179
115.034	4250	0.29715	1.12456
114.391	4300	0.3022	1.12278
114.016	4350	0.30605	1.11943
113.871	4400	0.3092	1.11986
113.985	4450	0.3099	1.11873
113.306	4500	0.31445	1.11563
113.074	4550	0.3171	1.10953
112.195	4600	0.3194	1.10569
111.061	4650	0.32055	1.09782
109.973	4700	0.3207	1.09558
108.654	4750	0.32485	1.08827
107.076	4800	0.32455	1.08396
105.24	4850	0.3257	1.08221
103.632	4900	0.3277	1.0846
102.335	4950	0.32845	1.08823
101.106	5000	0.3287	1.08687
99.3149	5050	0.32985	1.0891
97.5815	5100	0.3297	1.09185
95.8486	5150	0.33095	1.09407
94.8033	5200	0.3338	1.09346
93.0976	5250	0.3313	1.08804
91.7886	5300	0.3324	1.08339
90.5938	5350	0.3308	1.08007
89.6374	5400	0.3388	1.07895
88.9256	5450	0.3438	1.07923
88.6474	5500	0.3488	1.08366

Figure 6: Data extracted from dyno session.

Key			
Baro (mBar)	Humidity (%)	Ambient Temp (°C)	Ambient Temp (K)
1018.9	46	27	300
Crank Shaft Radius (mm)	Bore (mm)	Stroke (mm)	Engine Displacement (cc)
22.50	75	90	1590
Dyno Torque Arm Radius (mm)	Specific Gravity of Fuel	Calorific Value (E5) (kJ/kg)	Calorific Value (Gasoline) (kJ/kg)
815.776	0.75	43300	44000
Calorific Value (Ethanol) (kJ/kg)	Engine Displacement (m ³)		
30000	0.0016		

Figure 7: Further data needed for calculations.

4 Graphs

4.1 BSFC/Engine Speed

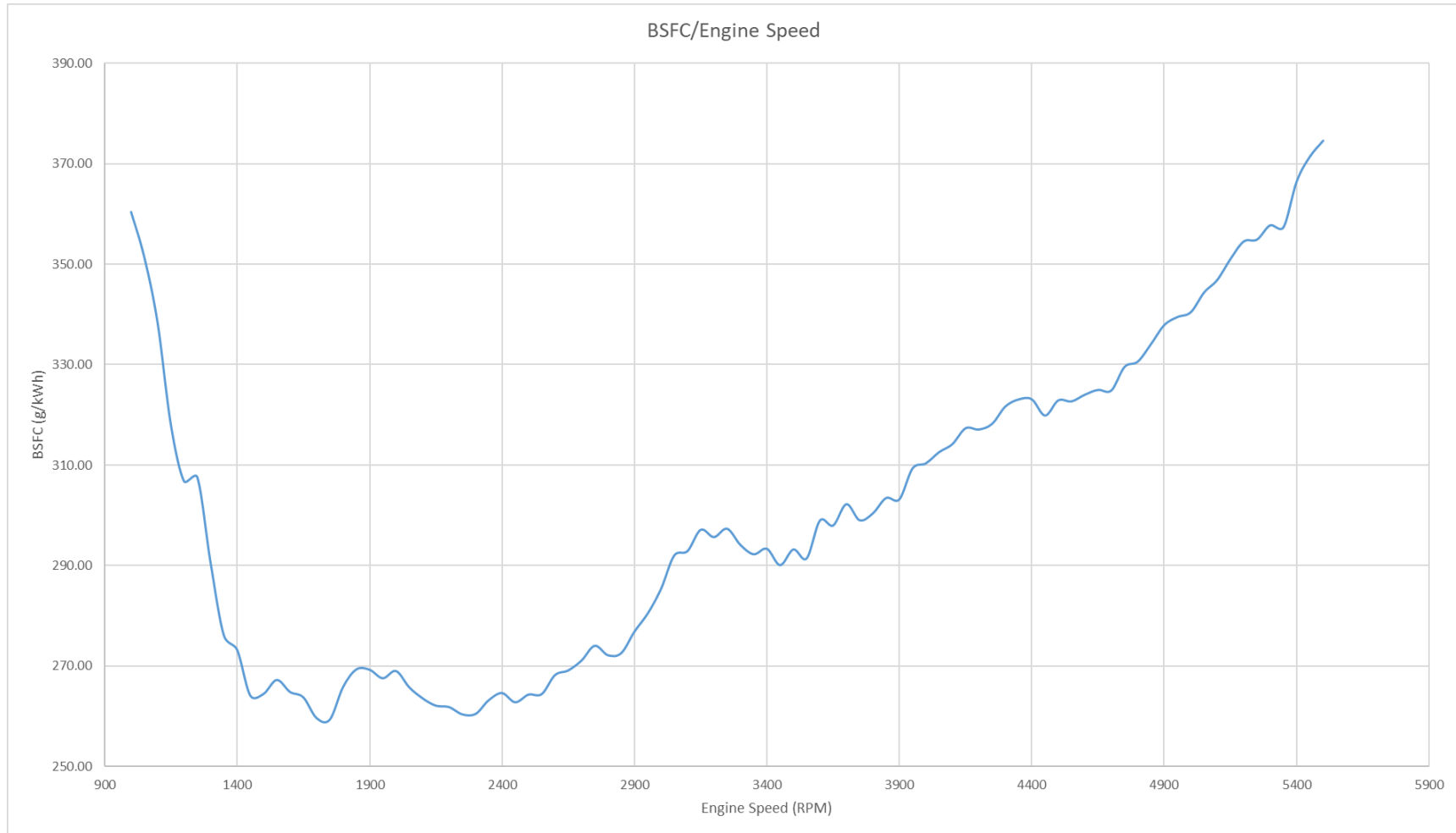


Figure 8: BSFC against engine speed.

4.2 Torque/Engine Speed

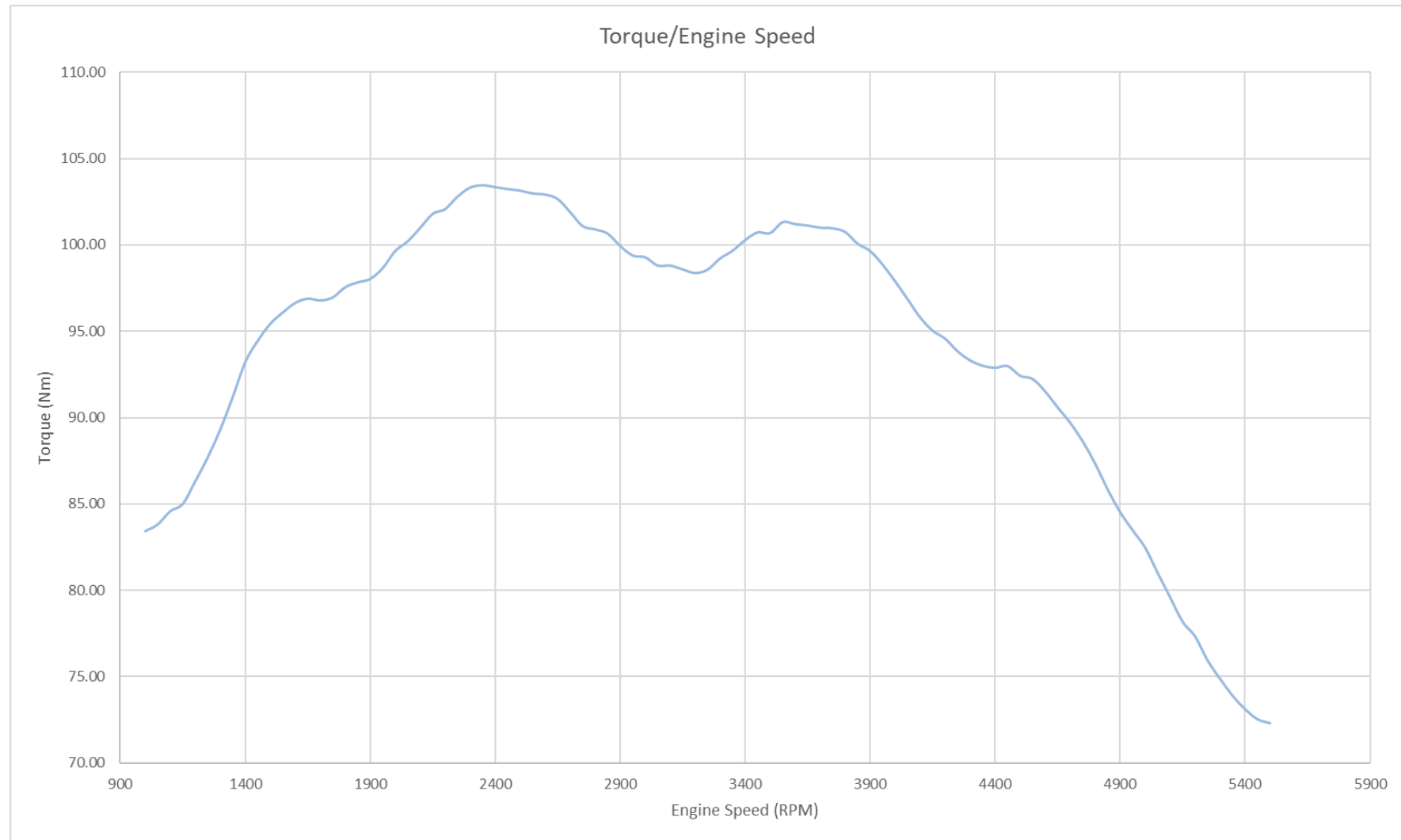


Figure 9: Torque against engine speed.

4.3 Brake Power/Engine Speed

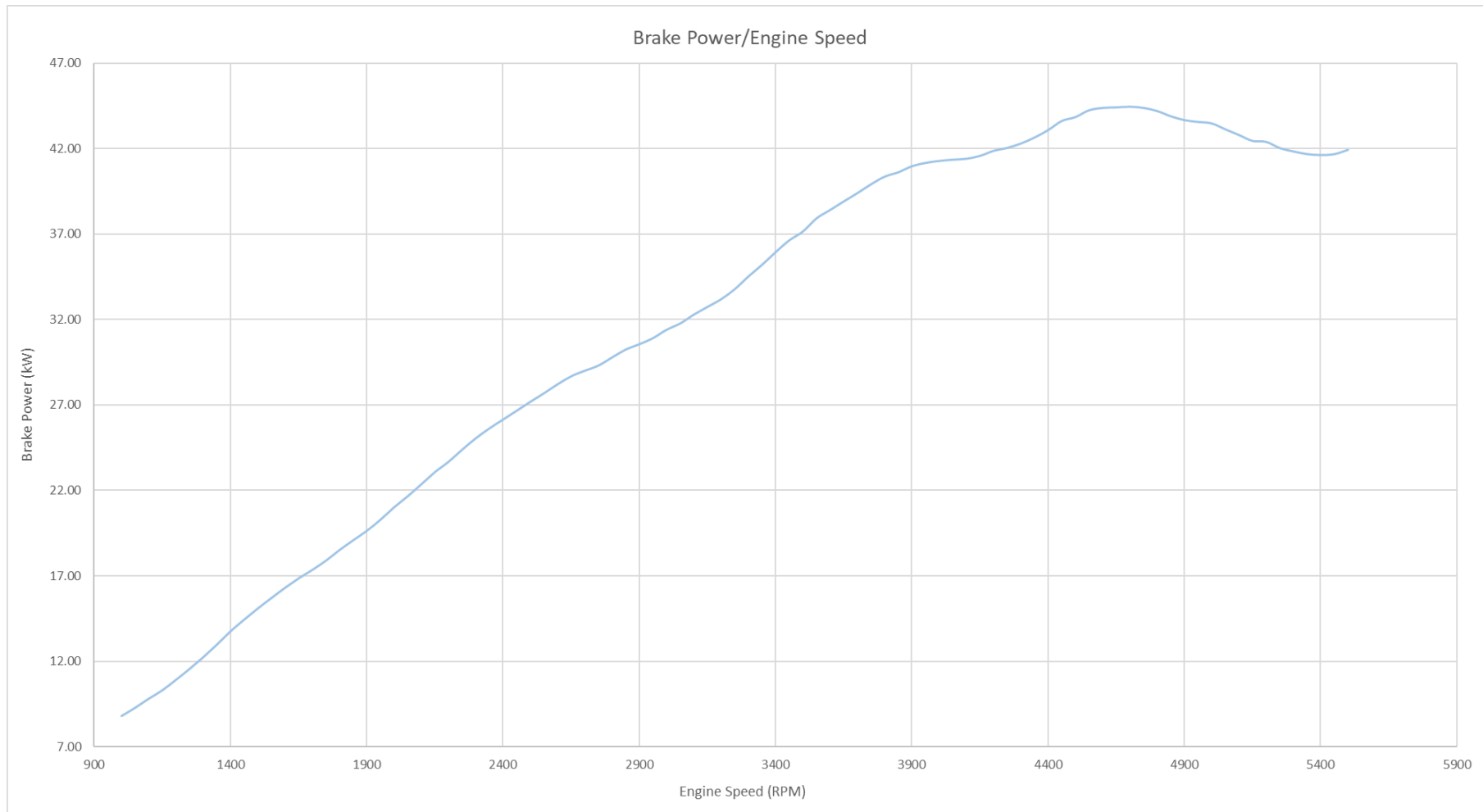


Figure 10: Brake power against engine speed.

4.4 Thermal Efficiency/Engine Speed

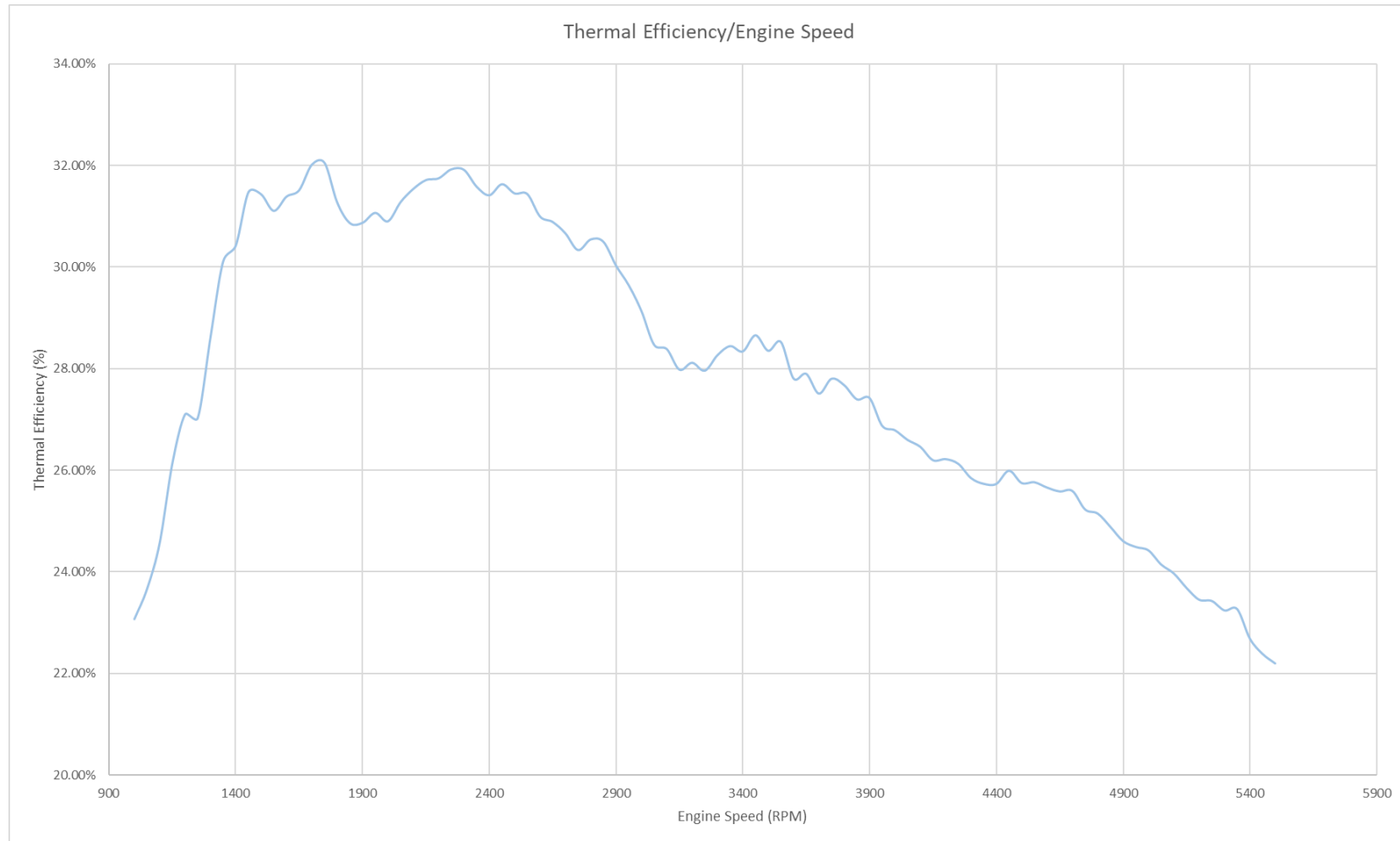


Figure 11: Thermal efficiency against engine speed.

5 Results

5.1 BSFC/Engine Speed

BSFC is the measure of efficiency when converting fuel energy into work energy and can be calculated by dividing the fuel flow rate $\dot{m}_f$ by the brake power $\dot{W}_b$. BSFC varies from engine to engine but is mainly affected by engine load and speed (Kirkpatrick A. 2021 p. 15).

$$BSFC = \frac{\dot{m}_f}{\dot{W}_b} \quad \dots(1)$$

Figure 8 plots BSFC against engine speed and is seen to drop (become more efficient) with an increase in engine speed. The lowest BSFC values are recorded at 259.34g/kWh at an engine speed of 1750 rpm. Heywood (2019 p. 66) suggests that a BSFC value of around 235g/kWh is considered an efficient value for a spark ignition engine.

The Honda is at its most efficient within the ranges of 1450-2500rpm aligning with data gathered on torque values and further discussed in chapter 5.3.

Higher fuel consumption values seen at idle can be explained by combustion efficiency, rich operating conditions produces less fully complete combustion processes due to the lack of oxygen, as engine load increases as does combustion efficiency and so the BSFC lowers (Heywood J. 2018 p. 101).

As engine speeds further increase the efficiency of heat transfer to coolant (cooling systems as well as engine oil) surpasses optimal, this in turn increases temperatures within the combustion chamber and surrounding areas, increasing friction and decreasing efficiency (Kirkpatrick A. 2021 p 502). BSFC and overall thermal efficiency are plotted in figure 12 showing they are inversely proportional. Overall thermal efficiency can be found by dividing fuel flow rate by brake power and the fuels calorific value Q multiplied.

$$Overall\ Thermal\ Efficiency = \frac{\dot{m}_f}{(\dot{W}_b)(Q)} \quad \dots(2)$$

The thermal efficiency of an engine is greatly dependant on the compression ratio, the higher the compression ratio the more efficient. Petrol engines are often limited to a compression ratio of 10:1 to negate the possibility of detonation, a phenomenon where atomised fuel-air mixture spontaneously ignites. Detonation results in a loss of power but can also cause engine damage (Zammit 1987 p. 273). The Honda workshop manual states the compression ratio of the engine (without a catalytic converter) is 9:1.

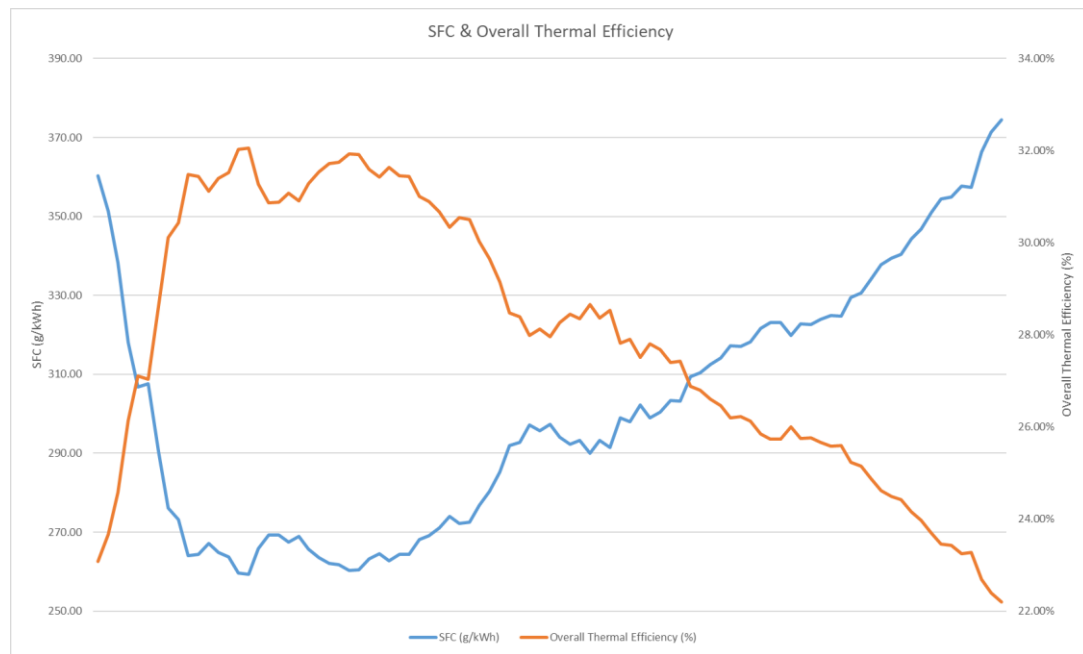


Figure 12: SFC against overall thermal efficiency.

5.2 Lambda

Optimising air-fuel ratio should be considered from an efficiency and temperature control perspective. Lambda is used to measure the efficiency of air-fuel burn in a combustion engine. Lambda 1 is considered stoichiometric (chemically correct), anything lower is considered a rich mixture (excess fuel) and anything higher is considered a lean mixture (too little fuel). A lean mixture will provide a slower burn and so will have a lower temperature (Stone 2012 p. 109).

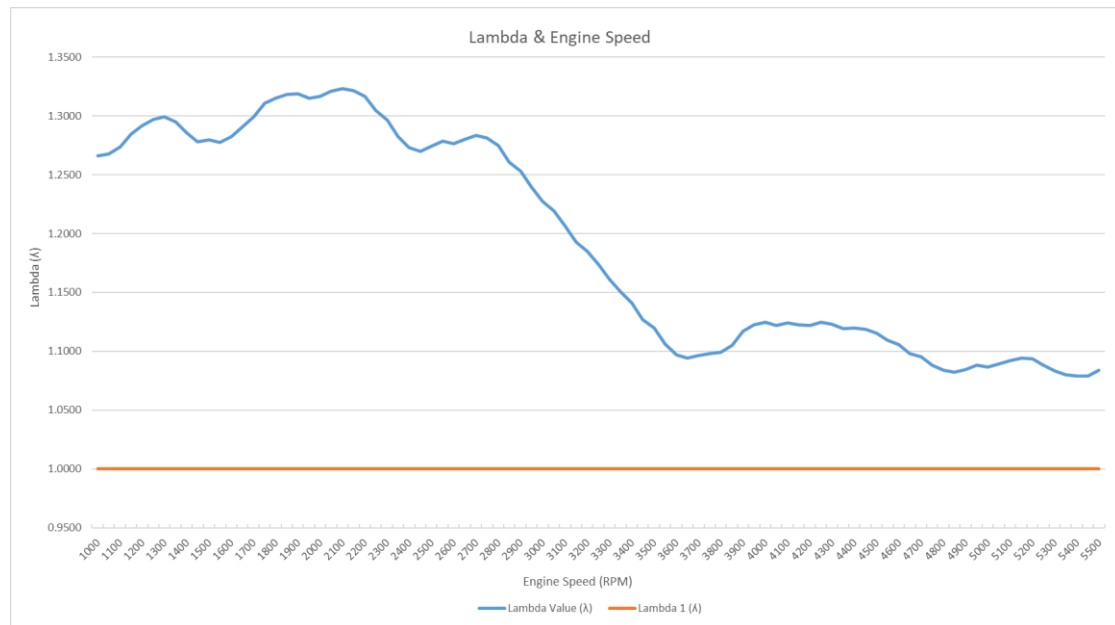


Figure 13: Lambda readings through engine speed.

Figure 9 plots the lambda readings collected through the dyno run and suggests the engine is running a slightly lean mixture throughout the entire rev range. The air-fuel ratio never reaching stoichiometric could be caused by the aftermarket air filter installed on the Honda engine. It's unlikely the Honda has been tuned for the change in air flow and air pressure produced by the aftermarket air filter.

5.3 Torque/Engine Speed

Figure 9 shows calculated torque against engine speed. As engine speed increases as does torque, with a maximum torque of 103.46Nm achieved at 2350rpm, however torque starts to decrease as the engine rpm is further increased and shows a substantial drop as the engine reaches maximum rpm.

Kirkpatrick A. (2021 p. 12, 394) suggests that the correlation between engine speed increase and torque decrease is the cause of increasing mechanical friction, defined as fluid and component friction alongside pumping, and auxiliary losses.

Frictional losses contribute to a large percentage of indicated power produced by an engine with losses varying depending on engine load (table 1).

Table 1: Varying losses over engine load (Heywood J. 2018 p. 648).

Friction Losses ($\pm$)	Engine Load
10%	Full load/lower speed
50%	Light load
100%	No load/Idle

Alongside frictional losses the drop in torque at increased speeds is due to the decrease in the engine volumetric efficiency. Volumetric efficiency is the measure of the completeness of the cylinder filling with fresh fuel-air mixture (Zammit 1987 p. 273).

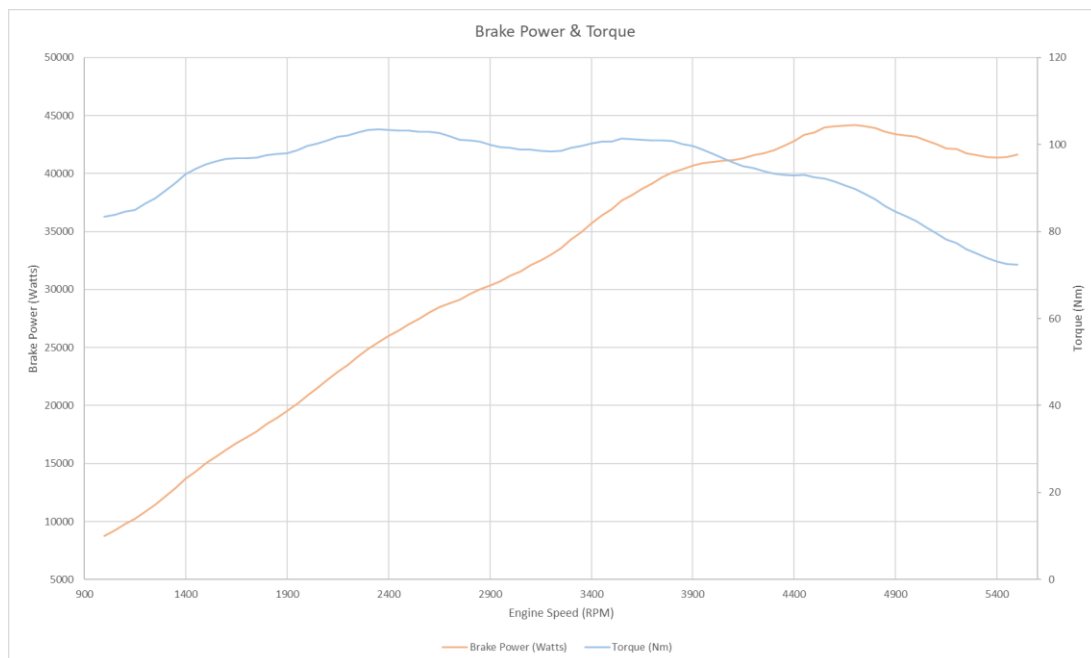


Figure 14: Brake Power & Torque

On the intake cycle of a 4 stroke engine the pressure drops inside the cylinder and a fresh charge (air-fuel mixture) is sucked in, ready for compression and ignition. At higher speeds the intake cycle is shortened and so the volume of charge that is successfully drawn into the cylinder decreases. Alternatively at lower engine speeds the flow of intake and exhaust gases is correspondingly slower and so the cylinder may not draw in the optimal amount of charge. Medium engine speeds are ideal in respect to the amount of time a fresh charge has to enter the cylinder alongside the amount of gas flow through the system (Hillier, Coombes 2004 p. 43), this corresponds with data gathered in figure 4 where the maximum torque is produced at roughly half of the maximum engine rpm.

The Honda engine is fitted with valve timing electronically controlled (VTEC) technology, a set of low speed and high-speed cams residing in the valve train are switched depending on engine load and speed. VTEC provides a steady increase in torque throughout the rev range and an improvement in fuel efficiency and emissions (Honda 1989). Hardalupas et al (1995) showed the benefits of VTEC operation by reducing the number of fluctuations in indicated mean effective pressure (IMEP) at given air-fuel ratios.

5.4 Brake Power/Engine Speed

Similarly with torque in chapter 5.2, brake power increases with engine speed and can be seen to drop as the engine reaches maximum load (figure 6). Maximum power occurs at higher engine loads as power is the product of torque and speed as seen in equation 3.

$$P = T\omega \quad \dots(3)$$

The drop off in brake power at higher engine speeds can be explained by the drop in BMEP (brake mean effective pressure), the average pressure acting on the piston over its stroke, seen in figure 15 it follows a similar path to torque as it is a product of torque and engine displacement (equation 4). BMEP can be affected by a range of engine conditions including air-fuel ratio, compression ratio and cylinder bore diameter (Zammit S. 1997 p. 282).

$$BMEP = 2\pi(2) \left(\frac{T}{V_d} \right) \quad \dots(4)$$

Many of the factors discussed in chapter 5.3 also affect brake power values, this can be seen in figure 14 where torque and brake power tend to reduce at higher engine speeds.

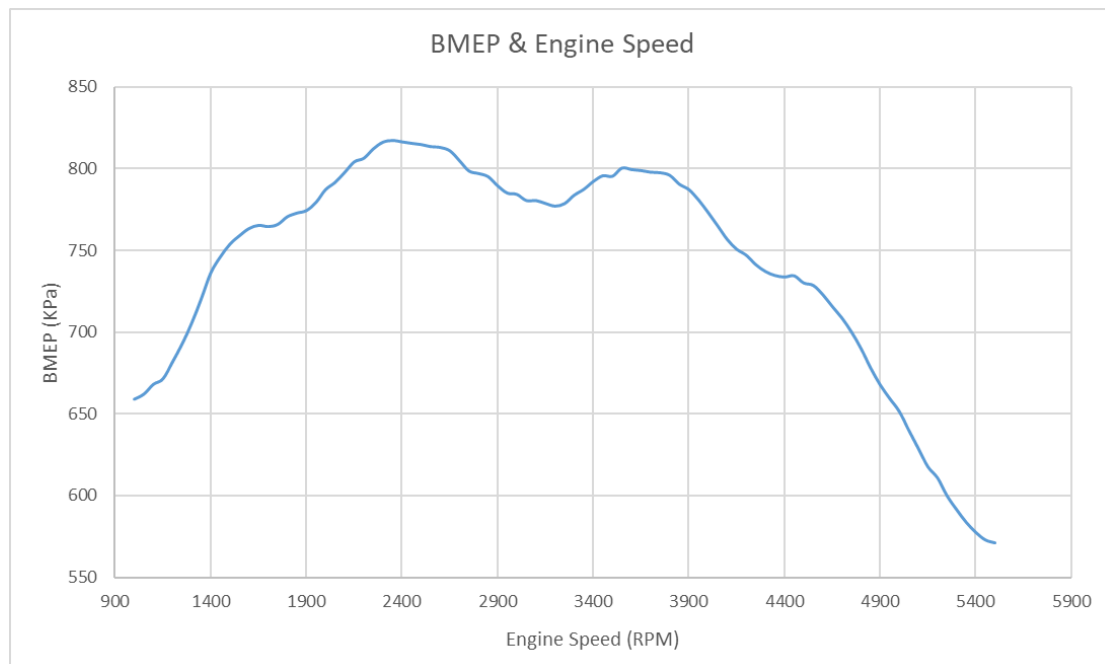


Figure 15: BMEP & Engine Speed.

6 Conclusion

From data gathered it is clear the Honda engine is most efficient at lower engine speeds where values BSFC, thermal efficiency and BMEP are at their highest. Lambda values show there may be a fuelling issue as the engine runs lean throughout the test, never reaching stoichiometric. The aftermarket air filter is a potential cause of the lack in efficiency.

Other factors should be considered, milage, service history and general engine health is not known and could play a massive role in the efficiency of running. Fouled or old spark plugs may not be igniting completely, piston rings may be worn and allowing blow-by, resulting in a loss of compression and BMEP effectiveness, parts can be worn further increasing internal resistances.

The VTEC system can be seen producing a smooth increase in torque throughout the test and no doubt assists with efficiencies and emissions.

Any changes to the engine to seek improved performance should be made individually. Tests should be re-run to distinguish whether the change has a positive or negative effect on performance.

7 Further Work

A morse test is used to measure the indicated power of an internal combustion engine. The engine is run on a dynamometer to a set rpm where the brake horsepower is measured for all cylinders, following this each cylinder is cut-out (ignition stopped by removing spark) one by one. The loss of one cylinder will cause the power value to drop and hence the load produced by the dynamometer lowered, to return the engine to its original rpm value. The brake horsepower is once again measured with each cylinder cut-out and the difference between the two powers is equivalent to the indicated power of the cut-out cylinder (Penny A, p. 11-12). The morse test allows for the accurate gathering of engine BMEP and mechanical efficiencies and will allow for a broader picture of the overall performance of the engine.

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9 Appendices

Table 2: Table of equations

Measurement	Equation	Unit
Brake Power	$BP = \frac{2\pi(N)(T)}{60}$ $N = \text{engine speed}$ $T = \text{torque}$	Watts
Corrected Power	$P_s = \left(\frac{1.01325}{P_a}\right) \left(\sqrt{\frac{T_a}{293}}\right) (P)$ $P_a = \text{atmospheric pressure}$ $T_a = \text{ambient temperature}$	Watts
Torque	$T = Fs$ $F = \text{force (engine load)}$ $s = \text{Distance (length of dyno calibration arm)}$	Nm
BSFC	$BSFC = \frac{\dot{m}_f}{\dot{W}_b}$ $\dot{m}_f = \text{fuel flow rate}$ $\dot{W}_b = \text{brake power}$	Kg/kWh
Thermal efficiency	$\eta_t = \frac{\dot{W}_b}{(\dot{m}_f)(Q)}$ $\dot{W}_b = \text{brake power}$ $\dot{m}_f = \text{fuel flow rate}$ $CV = \text{fuel calorific value}$	%
BMEP	$P_{bme} = \frac{2\pi(2) \left(\frac{T}{\theta_e}\right)}{1000}$ $T = \text{torque}$ $\theta_e = \text{engine displacement}$	Pascals

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