CRANFIELD UNIVERSITY

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MAF TO MAP BASED ENGINE LOAD ANALOGY CONVERSION

SCHOOL OF APPLIED SCIENCES

MSc THESIS

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MAF to MAP based engine load analogy conversion

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Abstract

In motorsport, high engine power output and engine responsiveness are often desired in order to gain competition advantage. The engine tuner will normally upgrade the standard vehicle with aftermarket components such as a higher rating turbo, a longer duration camshafts, and an exhaust system. As a result of the modifications, some of the standard sensors/actuators are not able to work efficiently.

For example, air reversal flow and venting of excess air pressure caused by the aftermarket tuning devices can affect the reading accuracy of the mass air flow (MAF) sensor. This thesis is to develop an Engine Control Unit (ECU) system, which will replace the MAF sensor with a manifold absolute pressure (MAP) sensor to calculate the air flow into the engine.

Enduring Solution Limited (ESL) seeks to develop the MAP based system into their existing programmable ECU, thus improve their market position. The challenge of the newly developed system is to be economically viable by minimising hardware and software alterations.

The approach is to modify and correlate the load analogy in the system embedded code, while retaining the other comprehensive code designed by the original manufacturer. This will minimise the system coding conflict crash and also reduce engine tuning time consumption.

The end results were tested to ensure the new system functioned and was capable of reproducing the same power output without any major setback.

Acknowledgements

I would like to express my gratitude to Mr. Andrew Steven and Mr. Spence Steven, the directors of Enduring Solutions Limited, for the great thesis opportunity. Through their support, I was able to learn the technical advancement of electronic engine control and the art of product marketing. Furthermore, I would also like to thank my project supervisor Mr. John Nixon, for his support, insight, and guidance during the project.

A sincere thank you must go to all the academic staff of the Motorsport Engineering and Management course, who have always kept their helping hands open for all the students. I have also enjoyed the informative and fascinating knowledge delivered by the lecturers.

Finally but not least, I thank all my family and friends for their unconditional support throughout the course. Their encouragement, advice, and moral support are appreciated whole heartily.

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Notation

Symbol:

D: Engine displacement
F_{ma}: Mass air fraction
M_a: Air mass
n: Number of moles
n_v: Volumetric efficiency
N_c: number of cylinders
P: Pressure
P_{AD}: Pressure in digital value
P_B: Barometric pressure
P_{BC}: Boost control pressure
P_{INT}: Internal pressure

ρ: Density
R: Universal gas constant
R_a: Air volume flow rate
R_{fm}: Fuel mass flow rate
R_m: Air mass flow rate
R_T: Thermistor electrical resistance
T: Temperature
T_{LKP}: Temperature lookup table
V: Volume
V_{in}: Voltage in
V_{out}: Voltage out

Nomenclature:

A/D: Analogue to digital
AFR: Air fuel ratio
ECU: Engine control unit
ESL: Enduring Solution Limited
MAF: Mass air flow
MAP: Manifold absolute pressure
MAT: Manifold air temperature
NTC: Negative temperature coefficient
PTC: Positive temperature coefficient
RPM: Rotation per minute
VE: Volumetric efficiency

1 Introduction

All Subaru Impreza regardless of production year, operates a MAF based system to calculate the amount of air entering the engine. ESL seeks to replace this system with a MAP based speed density system to improve the ESL system tunability and marketing advantage.

ESL has previously developed an electronic daughter board that employs in the Subaru Impreza ECU 92-97 models. It allows the user to run a live mapping system to optimise the ignition timing, fuel injection, and boost control. The ESL daughter board also has the ability to rewrite the embedded code in the factory ECU and to accommodate non-standard sensors/actuators by changing the scaling factor and offsets. This new project will benefit the present ESL system as well as the development of an ESL system board that adapt can be adapted into newer Subaru Impreza models.

Figure 1 - ESL system board (cited from http://www.enduringsolutions.com)

Shortcomings with the factory MAF system configuration (ESL, *personal communication*, 2008), which is designed for road and mild racing application, are identified when modifications for an improved response and higher power output are desired. For example:

(1) The front-mounted intercooler which replaces the standard top mounted intercooler helps to reduce the chances of engine detonation from higher power

configurations. However, it increases the distance between the MAF sensor and the inlet manifold due to an extra air ducting route, as show in Figure 2; hence, it results in a time delay in air flow calculation.

Figure 2 - Standard air duct route (left) and front mounted intercooler air duct route (right). Highlighted in yellow. (Photographed by author)

(2) The "vent to atmospheric" blow off valve is a very common aftermarket device that if installed in a turbocharged car can prevent a compressor surge by venting excess pressure when the throttle plate closes. The MAF sensor is not able to detect the vented air through the blow off valve and this result in over-fuelling.

(3) The air flow reflects off the turbine inlet and back to the MAF sensor, and this affects the reading accuracy, which leads to heavy over-fuelling during part throttle and throttle lift off. The problem worsens as the turbo size increases and the oil cooled ball bearing turbo is used as the oil in the airflow can contaminate the MAF sensor by the reversal flow.

The problems encountered by the MAF system can be improved by running speed density system which eliminates the use of MAF sensor. ESL seeks to maintain competitive in the aftermarket ECU system by being able to offer the customer the choice of a running speed density system in the ESL system board. This offers ESL an advantageous marketing position as the speed density system available in competitors' system boards are at least 3 times the price of ESL system board.

1.1 Objectives and specifications

1. Remove MAF sensor from the system.
2. Operate an alternative method that enables the ECU to calculate cylindrical air charge and load.
3. Allow similar or greater air flow induction for higher engine power output compare to standard MAF
4. Produce similar power output compares to the MAF system.
5. Achieve smoother engine transient state control (drivability) for a vehicle with front mounted intercooler and higher rating turbocharger.
6. Establish system that is free from bugs, errors and system crash
7. Minimise parts changes
8. Minimise wiring loom alterations
9. Ensure minimal cost
10. No physical and electronic circuitry alterations on the ESL board

1.2 Thesis structures

This thesis presents the work done in the 4 months period, in a chronological way it has been performed. A project flow diagram has also developed in chapter 1.3 for the ease of the reader to follow and understand the structures of the thesis.

The author has been approached by ESL to negotiate the possibility of implementing a MAP based system into their existing system board. The key skills among the author and the ESL team were compared and agreed on a delegated task. It was highlighted that author can contribute in theory/mechanical research in the project and the ESL would be responsible in rewriting the embedded code. It was not possible for the author to perform all the task including rewriting the embedded code due to the scale of the project and the limited knowledge of the embedded code in the ESL system board.

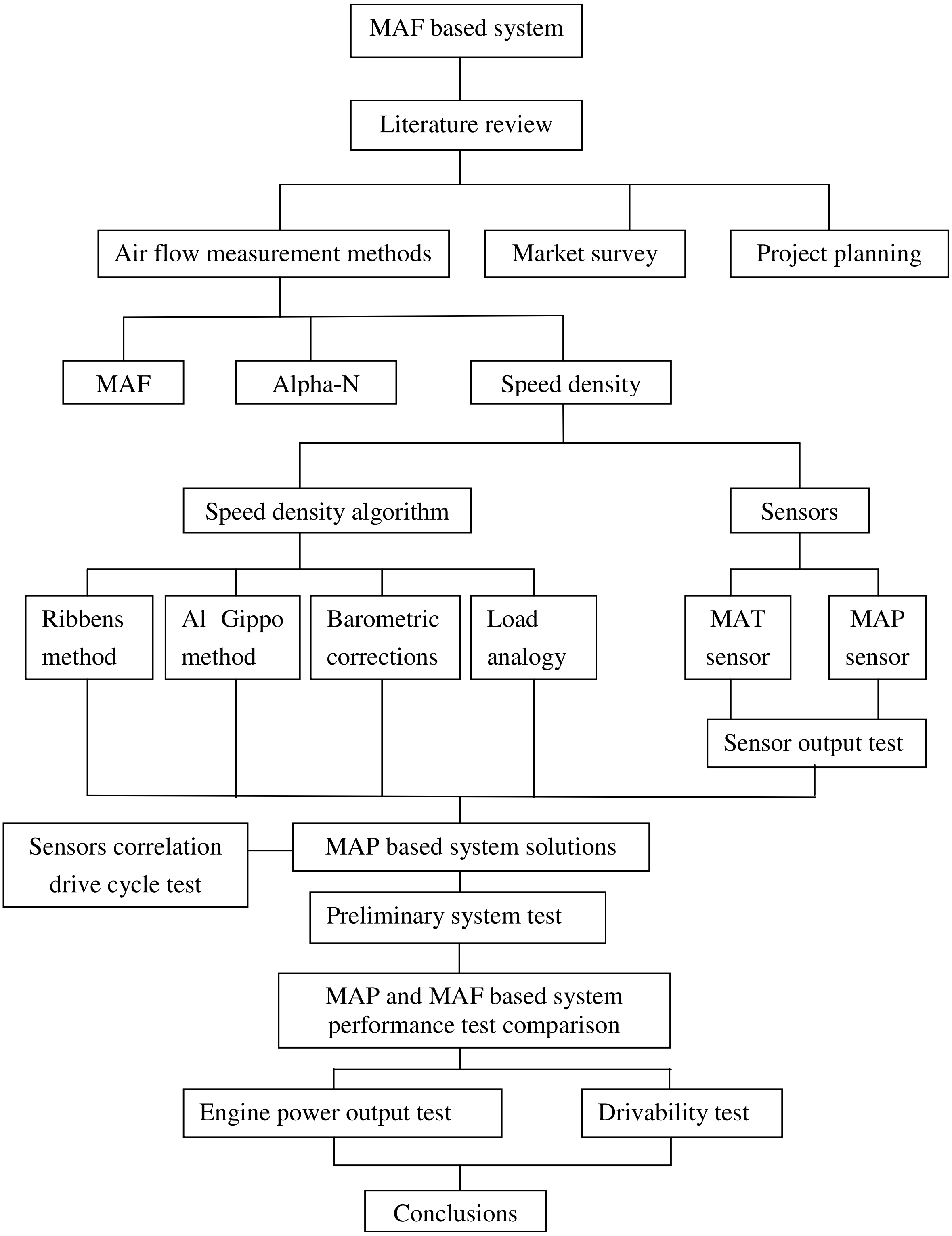
Once the aims and main objectives have been identified, literature review of existing system and possible solutions were considered in chapter 2. It includes the analogy of air flow calculations, sensors options, competitor survey, cost and market justification, challenges, project risk, and etc.

Chapter 4 introduces the methodology and the design of the MAP system; it presents and justifies the analogy of the new system solution. It also shows how the solutions were derived from the physical testing and the analysis of the collected data. The collected data has also highlighted the downfall of MAF sensor, which confirmed the project motivation.

Chapter 5 compares the performance of the MAF and the MAP system to ensure it meets the objectives requirement such as no compromise in power output and system crash. The test involves preliminary test, engine power output test and drivability test.

Chapter 6 presents the overall conclusions of the thesis and recommendations for further research.

1.3 Project flow diagram



2 Literature review

2.1 Air flow measurement methods

In order to maximise performance and reduce emissions on a motor vehicle engine, the amount of air entering the engine needs to be accurately determined. The ECU can then calculate the required fuel injections, spark timing and other secondary controls.

The current ECU technology is much more sophisticated than just monitoring air flow into the engine. Parameters such as the coolant temperature, air temperature, knock sensing, lambda sensing are also important to enhance the optimal engine control. This section focuses on the air flow measurement methods; other parameter monitors will be discussed in later sections.

There are many types of air flow measurement methods used in production car engine and motorsports racing engine.

3 main types of air flow measurement methods is as shown in following table:

Method	Primary input	Secondary input
Mass air flow	Mass air flow (MAF) (Vane meter, hot-wire meter or vortex flow sensor)	Inlet air temperature, coolant temperature, throttle position, lambda.
Alpha-N	Throttle position (TPS)	Barometric pressure, inlet air temperature, coolant temperature, lambda.
Speed density	Manifold absolute pressure (MAP)	Barometric pressure, inlet air temperature, coolant temperature, throttle position, lambda.

Table 1 - Air flow measurement methods

The primary inputs for each method listed in the Table 1 are the basic inputs required for the calculation of air flow into the engine up to certain accuracy. Secondary input enhances the drivability and adapting to the minor external conditions.

2.1.1 Mass Air flow

Hot-wire MAF sensor

The hot-wire MAF sensor operates in the standard Subaru Impreza; the aim of this thesis is to replace it with another method of air flow measurement. Hence, this section offers only the brief account of the types of air flow sensor and how they are measured.

The hot-wire/anemometer MAF sensor is primarily a tube in the inlet duct through which the air flows to enter the engine. A very fine platinum wire mesh is stretched across the tube and heated by a constant current to maintain a temperature above ambient. The air passes into the engine flow over the wire and cools it in direct proportion to mass air flow. The current required to maintain the wire temperature is then signalled to the ECU. (Bell, 1998)

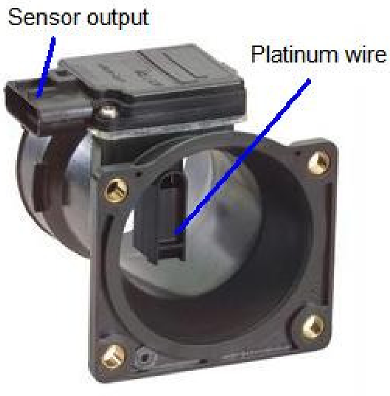


Figure 3- Hot-wire MAF sensor (cited from http://www.probedistributors.co.uk)

Vane MAF sensor

The vane-type air flow sensor is a simple unit that passes air flowing into the engine through a passage blocked by a spring loaded flap. The amount of air passes through the flap can be determined by the angular position of the flap that "blew open" by the air. Flap surface area, spring force and air temperature are also required to calculate the amount of air flow into the engine. (Bell, 1998)

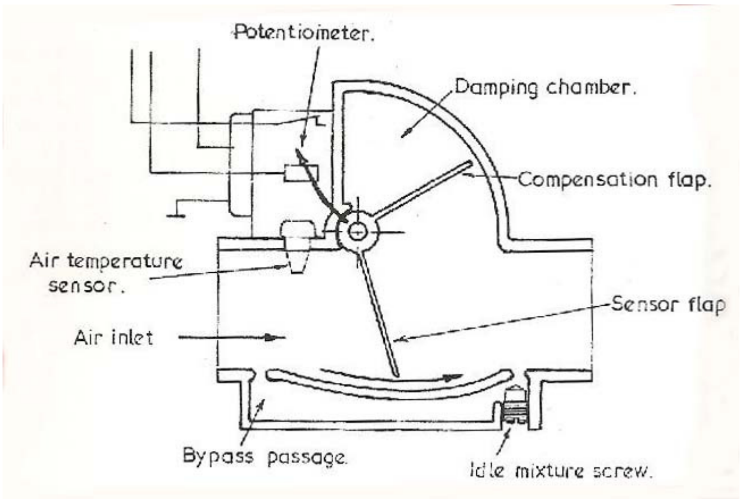


Figure 3 - Vane MAF sensor (cited from Bell, 1998)

2.1.2 Alpha-N

Alpha-N is a simple system originally developed for race competition engine, it has no direct measurement of the actual mass or volume of air entering the engine. (Stroes, 2002)

The ECU determines the inlet air flow by 2 primary inputs of throttle position and engine speed, this serves an advantage of no air flow obstructions from air-flow meter. Alpha-N arrangement is also immune to metering difficulties caused by MAP sensing when either low or wildly fluctuating manifold vacuum levels. (Bell, 1998)

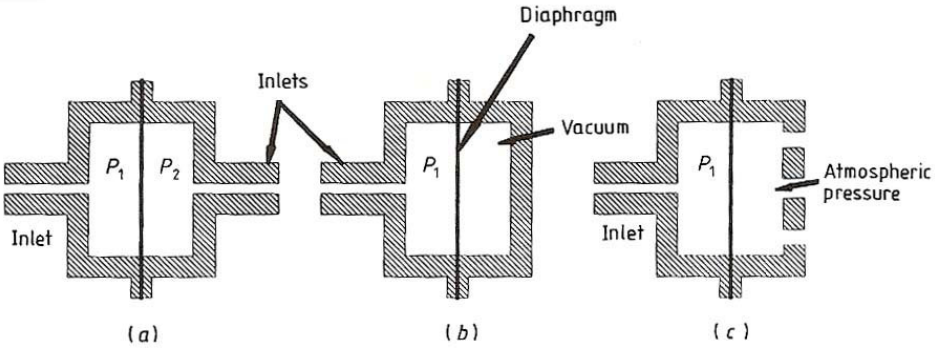
“Alpha-N is useful for long duration camshaft where the resolution of manifold air pressure (MAP) would be small. It is also useful to get smoother idle on engines that have erratic map values.” (Bowling, 2008)

Such system works very well in a competition natural aspirated engine due to the system simplicity. However, Turbocharged engines do not have a linear relationship between throttle position, rpm, and fuel requirements, and thus cannot use alpha-N.
(Bowling, 2008)

2.1.2 Speed density

Pressure sensor

When a fluid comes into contact with a surface it produces a force perpendicular to it; the force per unit area is called the pressure. Pressure measurements divide mainly into 3 categories, namely differential pressure, absolute pressure and gauge pressure. The devices use to for the pressure measurements are shown in the following diagram.



Differential (*a*), absolute (*b*) and gauge (*c*) pressure sensors (diaphragm type).

Figure 4 - Types of pressure sensors (cited from Westbrook, 1994)

- Differential pressure – Refers to the differences between two input pressures, this is rarely used in automotive engine applications.

- Absolute pressure – Refers to the differences between an input pressure and the absolute zero pressure (vacuum). A MAP sensor measures pressure using the vacuum as reference.

- Gauge pressure – Refers to the differences between an input pressure and atmospheric pressure. Gauge pressure is normally applied in turbocharged engine boost pressure; it indicates of how pressure is increased from the atmospheric pressure by the compressor. (Westbrook, 1994)

2.2 Speed density algorithms

2.2.1 Ribbens method

The speed density system estimate air flow into engine with a MAP sensor. This is based upon the concept of mass density as applied to air, where the air mass flow rate, R_m is the product of volume flow rate, R_a and density, ρ. (Ribbens, 1989)

$$R_m = R_a\rho \tag{1.1}$$

Where the density,

$$\rho = \frac{M_a}{V} \tag{1.2}$$

M_a, is the air mass
V, is the volume

This assumes a constant pressure to keep the air in a per unit volume, V, the mass of air M_a in a given volume depends on the temperature; Hence the density of air is depends upon its temperature, the air density values are stored in a lookup table for the corresponding inlet temperature.

Alternative to lookup table for inlet temperature and density, Pohl (2006) suggested the Ideal Gas Law equation:

$$PV = nRT \tag{1.3}$$

Substitute equation (1.3) into equation (1.2)

$$\rho = \frac{Mass}{Volume} = \frac{n}{V} = \frac{P}{R * T_{in}} \tag{1.4}$$

Wherein,
n is number of moles

R is the universal gas constant
P is the pressure from the MAP sensor
T_{in} is the inlet temperature

The volume flow rate during the intake stroke is estimated from the engine displacement, D for every 2 complete crankshaft revolutions (4 strokes engine) with the engine speed per second ($\frac{RPM}{60}$). (Ribbens, 1989).

The volume flow rate of air,

$$R_a = [\left(\frac{RPM}{60}\right)\left(\frac{D}{2}\right)n_v] \tag{1.5}$$

Where in,
RPM is the engine running speed
D is the engine displacement
n_v is the volumetric efficiency

During the intake stroke cycle, air charge might not be completely filled the cylinder due to poor "breathing efficiency" of the engine design. Hence the volumetric efficiency is the ratio between actual air drawn into the cylinder and the maximum volume of air with the cylinder completely filled. (Duffy and Smith, 1992).

Volumetric efficiency varies with the manifold absolute pressure (MAP) and engine speed (RPM). A table of values representing $n_v$for a given speeds and MAP values can be stored in memory as a lookup table. (Ribbens, 1988, p190).

Following on, the required fuel mass flow rate is

$$R_{fm} = \frac{R_{am}}{14.7} \tag{1.6}$$

The 14.7 is the stoichiometric mass fuel flow rate and it varies depends on engine tuner requirements.

2.2.2 Al Grippo method

The Al Grippo method retains the basic speed density calculation, but it is calculated in mass air fraction in pounds per cylinder firing. Hence the engine speed is taken out of the equation; it also uses American/imperial units. However it can be converted to SI unit if required.

$$F_{ma} = \rho \left[\frac{D}{1728}\right]\left[\frac{1}{N_c}\right][n_v] \tag{2.1}$$

Where in,
Fma is the mass air fraction
D is the cubic inch displacement of the engine, (D/1728) converts into cubic feet.
N_c is the number of cylinders.

$$\rho = \frac{0.0391568[P_B - 31.0]}{\left(\frac{T_{in}}{10}\right) + 459.7} \tag{2.2}$$

Where in,
P_B is the barometric pressure in kPa x 10 (from sensor)
T_{in} is the intake manifold air temperature in degrees F x 10 (from sensor)

The 31 = 3.1kPa correction for vapour pressure, assuming a humidity of 75 percent at 85 degrees F temperature. This is arbitrary since it does not sense humidity but this is the nearest prediction of air density. (Al Grippo, 2007)

2.3 Manifold air temperature

The speed density system requires a manifold air temperature (MAT) sensor to calculate the density of air which affects by the air temperature. It is useful to investigate the type of temperature sensors commonly used as a MAT sensor, namely the thermocouple and the thermistor.

2.3.1 Thermocouple

A thermocouple is a thermoelectric temperature sensor; it is a self-generating transducer compromising 2 or more junction between dissimilar metals (Denton, 2000). A voltage will be generated which is dependent on the temperature difference between the ends of the wire. The properties of different types of thermocouple are shown on Table 2 and Table 3 (Westbrook, 1994).

Type	**Conductors (positive conductor first)**	**Accuracy**	**Output (mV) for indicated temperature**	**Service temperature range (°c)**
B	Platinum: 30% rhodium alloy Platinum: 6% rhodium alloy	0~1100 ± 3°c 1100~1550 ± 4°c	1.24 at 500°c	0~1500
E	Nickel: chromium/constantan	0~400 ± 3°c	6.32 at 100°c	-200~850
J	Iron/constantan	0~300 ± 3°c 300~850 °c ± 1%	5.27 at 100°c	-200~850
K	Nickel: chromium/nickel: Aluminium (chromel/alumel)	0~400 ± 3°c 400~1100 °c ± 1%	4.1 at 100°c	-200~1100
R	Platinium: 13% rhodium/ Platinium	0~1100 ± 1°c 1100~1400 ± 2°c 1400~1500 ± 3°c	4.47 at 500°c	0~1500
S	Platinium: 10% rhodium. Platinium	As type R	4.23 at 500°c	0~1500
T	Copper/constantan	0~100 ± 1°c 100~400 °c ± 1%	4.28 at 100°c	-250~400

Table 2 - Thermocouple properties table 1

Type	Properties
B	Best life expectancy at high temperatures.
E	Resistance to oxidising atmospheres.
J	Low-cost, general-purpose.
K	General-purpose, good in oxidising atmospheres.
R	High-temperature, corrosion resistant.
S	As R.
R	High resistance to corrosion by water

Table 3 - Thermocouple properties table 2

A significant problem has highlighted by Nixon (2007), the thermocouple has a low output voltage level. This makes their signal sensitive to external noise and interference, the performance can be optimised by amplifying thermocouple signals as close to the sensor as possible. However, the thermocouple is located in the inlet manifold for this project; where electrical noise and interference can be very high (Hammer, 2008). Moreover, the needs and the critical location of a signal amplifier can impose challenges in the design.

2.3.2 Thermistor

A thermistor is a small semi-conducting transducer commonly used as MAT sensor. The principle of measurement is that the temperature will cause a change in resistance, and hence an electrical signal proportional to the measurement can be obtained. (Denton, 2000)

There are 2 main types of thermistor; Negative temperature Coefficient (NTC) thermistor and Positive Temperature Coefficient (PTC) thermistor. A PTC increases in electrical resistance as the temperature increases. The PTC is usually only used to provide thermal protection for wound equipment such as transformers and motors. It is often connected in series of the power supply of an equipment to be protected, once the temperature becomes too high the resistance rises and power is effectively disconnected from the load. (Westbrook, 1994)

On the other hand, a NTC has the property of falling in electrical resistance as the temperature increases, the Figure 5 as shown below is a typical NTC thermistor used in automotive application. Due to the thermistor does not produce electrical signal like the thermocouple, a simple voltage divider circuit or a bridge circuit is required for it to produce an electrical signal (Denton, 2000).

Figure 5 - NTC MAT sensor (cited from: http://www.bmotorsports.com)

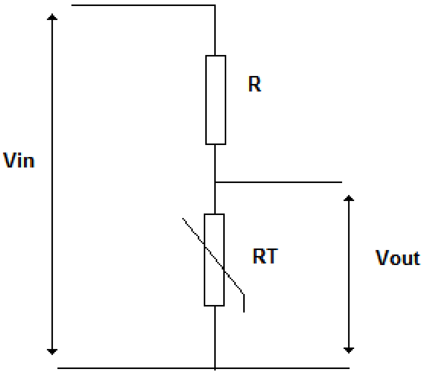


Figure 6 - Voltage divider circuit

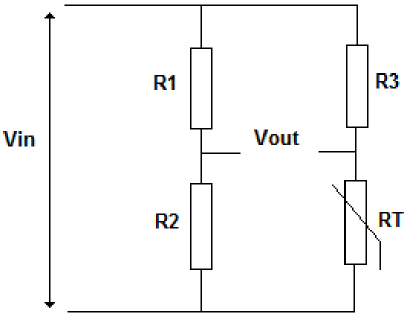


Figure 7 - Bridge circuit

The voltage divider circuit as shown in Figure 6, (Alexander, 2003) the voltage output can be calculated by equation 2.3

$$V_{out} = V_{in}(\frac{R_T}{R_T + R}) \tag{2.3}$$

However, the thermistor resistance/temperature response curve is frequently not linear (Nixon, 2007). It can be improved by implementing a bridge circuit to produce a partially linear output to compensate non-linearity responses from a thermistor. For the bridge configuration as shown in Figure 7, the equation is given by:

$$V_{out} = V_{in}(\frac{R_2}{R_2 + R_1} - \frac{R_T}{R_T + R_3}) \qquad (2.4)$$

By choosing the suitable resistor values, the output of the bridge will be as shown. This is achieved by substituting the known values of R_T at three temperatures and deciding that, for example: If Vout output range required is 0 to 5v and -10ºc to 90ºc, then Vout = 0v at -10ºc, Vout = 2.5v at 40ºc and Vout = 5v at 90ºc. (Denton, 2000)

2.3.3 Sources of error

There are 3 main sources of error to be considered when using a thermistor and voltage divider/bridge circuit.

1. **Self heating error**: According to Zurbuchen (2000), the temperature of a typical thermistor will increase by 1ºc of approximately every 1mW power dissipated. This will cause a reading error, hence it is important to use a high resistance resistor as a current limiter.

2. **Supply voltage instability:** The alternator charging rate and electrical load demand in the car can result in supply voltage instability for the voltage divider/bridge circuit; which can cause a voltage output error from the voltage divider/bridge circuit. There are several methods that could be used to correct for this:
    a. The ECU has an internal measure of battery voltage, this could be used to correct for the error in software.
    b. Ignore the error and assess the consequences of doing so.
    c. Implement a voltage regulator (extra hardware) to ensure the potentiometer is held across a consistent voltage range.

3. **Thermistor accuracy**: The reading accuracy of a thermistor is dependent on the manufacturer specification.

2.4 Speed density load analogy

Most aftermarket and factory ECUs, in order to protect their technology, do not openly review their load analogy. While it is not an easy task to investigate existing load analogy methods, the fundamental method can still be studied from the aftermarket ECU user-tuning software and by gaining advices from experienced engine tuners.

The amount of air entering the engine is shown as load on the lookup table, load can be represented as manifold air pressure against engine speed or load against engine speed.

- **Manifold air pressure versus engine speed –** The load is represented as manifold air pressure in the vertical axis on the table as shown in Figure 9 the air density is then incorporated in a secondary table (as shown in Table 4) to reflect the true load by retarding the ignition timing and reducing fuel pulse width as the manifold air temperature increases. (Vems, 2008)

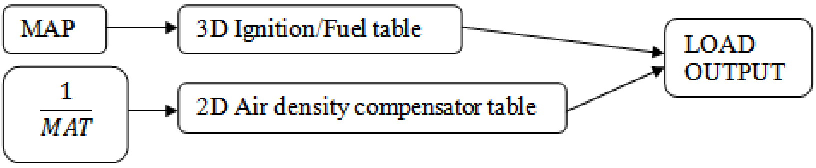
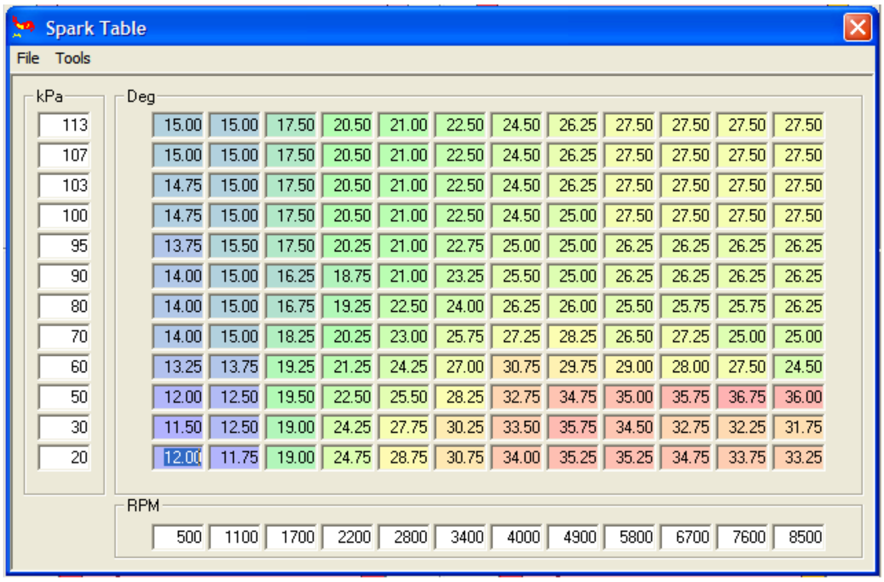


Figure 8 - Load analogy for MAP vs. RPM



kPa	Deg											
113	15.00	15.00	17.50	20.50	21.00	22.50	24.50	26.25	27.50	27.50	27.50	27.50
107	15.00	15.00	17.50	20.50	21.00	22.50	24.50	26.25	27.50	27.50	27.50	27.50
103	14.75	15.00	17.50	20.50	21.00	22.50	24.50	26.25	27.50	27.50	27.50	27.50
100	14.75	15.00	17.50	20.50	21.00	22.50	24.50	25.00	27.50	27.50	27.50	27.50
95	13.75	15.50	17.50	20.25	21.00	22.75	25.00	25.00	26.25	26.25	26.25	26.25
90	14.00	15.00	16.25	18.75	21.00	23.25	25.50	25.00	26.25	26.25	26.25	26.25
80	14.00	15.00	16.75	19.25	22.50	24.00	26.25	26.00	25.50	25.75	25.75	26.25
70	14.00	15.00	18.25	20.25	23.00	25.75	27.25	28.25	26.50	27.25	25.00	25.00
60	13.25	13.75	19.25	21.25	24.25	27.00	30.75	29.75	29.00	28.00	27.50	24.50
50	12.00	12.50	19.50	22.50	25.50	28.25	32.75	34.75	35.00	35.75	36.75	36.00
30	11.50	12.50	19.00	24.25	27.75	30.25	33.50	35.75	34.50	32.75	32.25	31.75
20	12.00	11.75	19.00	24.75	28.75	30.75	34.00	35.25	35.25	34.75	33.75	33.25
RPM	500	1100	1700	2200	2800	3400	4000	4900	5800	6700	7600	8500

Figure 9 - VEMs ignition timing table (MAP vs. RPM)

Manifold air temp. °c	0	30	45	55	65	75	100
Ignition retard. deg	0	0	1	2	3	4	9
Fuel trim %	100	100	95	95	93	90	90

Table 4 - Air density correction table

- **Load percentile versus engine speed –** Such method is normally found in a highly sophisticated aftermarket ECU, where the manifold air temperature and manifold air pressure are taken into account in the load table. An example can be found from Motec engine tuning software as shown in Figure 11

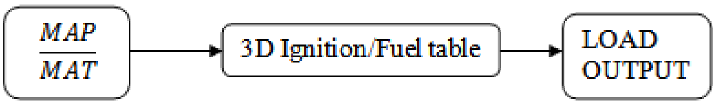
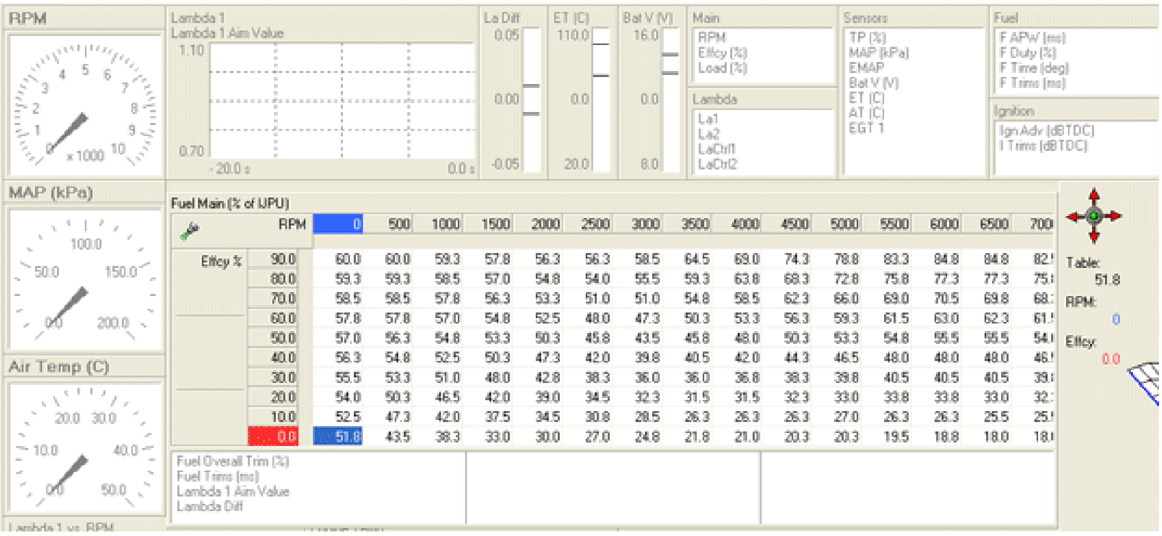


Figure 10 - Load analogy for Load% vs. RPM



Fuel Main (% of IJPU)

Effcy % \ RPM	0	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	700
90.0	60.0	60.0	59.3	57.8	56.3	56.3	58.5	64.5	69.0	74.3	78.8	83.3	84.8	84.8	82.
80.0	59.3	59.3	58.5	57.0	54.8	54.0	55.5	59.3	63.8	68.3	72.8	75.8	77.3	77.3	75.
70.0	58.5	58.5	57.8	56.3	53.3	51.0	51.0	54.8	58.5	62.3	66.0	69.0	70.5	69.8	68.
60.0	57.8	57.8	57.0	54.8	52.5	48.0	47.3	50.3	53.3	56.3	59.3	61.5	63.0	62.3	61.
50.0	57.0	56.3	54.8	53.3	50.3	45.8	43.5	45.8	48.0	50.3	53.3	54.8	55.5	55.5	54.
40.0	56.3	54.8	52.5	50.3	47.3	42.0	39.8	40.5	42.0	44.3	46.5	48.0	48.0	48.0	46.
30.0	55.5	53.3	51.0	48.0	42.8	38.3	36.0	36.0	36.8	38.3	39.8	40.5	40.5	40.5	39.
20.0	54.0	50.3	46.5	42.0	39.0	34.5	32.3	31.5	31.5	32.3	33.0	33.8	33.8	33.0	32.
10.0	52.5	47.3	42.0	37.5	34.5	30.8	28.5	26.3	26.3	26.3	27.0	26.3	26.3	25.5	25.
0.0	51.8	43.5	38.3	33.0	30.0	27.0	24.8	21.8	21.0	20.3	20.3	19.5	18.8	18.0	18.

Figure 11 - Motec engine tuning software (Load% vs. RPM)

An investigation of type of load analogy adopts by different aftermarket ECU has performed, and it is shown as following table:

MAP vs. RPM	**Load % vs. RPM**
Gems	Motec
Vems	Autronic
Links	

Table 5 - Type of load analogy adopt by various ECU

It is very clear that only the high-end aftermarket ECUs are using load% (MAP/MAT) as load axis, it is also the most accurate way to represent load on the fuel and ignition map. It would be a technical and marketing advantage if ESL is operating such load analogy.

2.5 Barometric corrections

Barometric pressure varies with the weather condition and the altitude. As illustrated in section 2.2-Speed density algorithms, conflicting theories on the requirement of a barometric pressure measurement for speed density calculation exist.

Following extensive review of available literatures and consultation with engine experts, it is concluded that by applying Pohl's (2006) Ideal gas law method to calculate air density, manifold absolute pressure is the most valid for turbocharged engine. For a turbocharged engine, the air pressure and density within the manifold is independent from atmospheric pressure. Hence, there is no need of barometric corrections for speed density in this application.

This conclusion is also supported by VEMs ECU programmer Rob Humpris (*private communication*, 2008), and verified by successful outcomes to similar methods applied in the VEMs ECU, HKS Vein Pressure Convertor, and GEMS.

On the other hand, in terms of boost pressure monitor. Gauge pressure measurement is used in calculate the pressure differences across the turbo compressor, this will require a barometric correction.

There are 2 main functions boost pressure monitoring:

- Engine protection – by restricting the amount of air entering the engine to prevent engine failure. This is the pressure within the inlet manifold; therefore, it is completely independent from atmospheric influence.

- Turbocharger protection - by preventing high pressure difference across the turbo compressor, it can cause turbo failure. It will require barometric corrections to accurately determine the pressure difference.

2.5.1 Barometric corrections strategy

On the standard Subaru Impreza, the MAP and MAF sensors both have separate but dedicated task of boost level monitoring and air flow measurement. The MAP sensor measures the barometric correction pressure via pressure exchange solenoid when the turbo charger is not spooling (ie. idling)

On the MAP based operation speed density system, the MAP sensor has a greater task of monitoring the boost pressure as well as the air flow into the engine. ESL suggested the engine will run erratically with the absent of MAP air flow sensing signal while it is sensing the barometric at idling. The potential strategies for overcoming this problem are:

Option 1. Monitor the boost pressure difference at a predefined standard sea level atmospheric pressure (101.3kPa) without sensing the actual barometric pressure. Such method has been widely used in production cars and numbers of aftermarket ECU. It is base on the concept that the atmospheric pressure does not vary much due to minimal weather* and altitude changes**

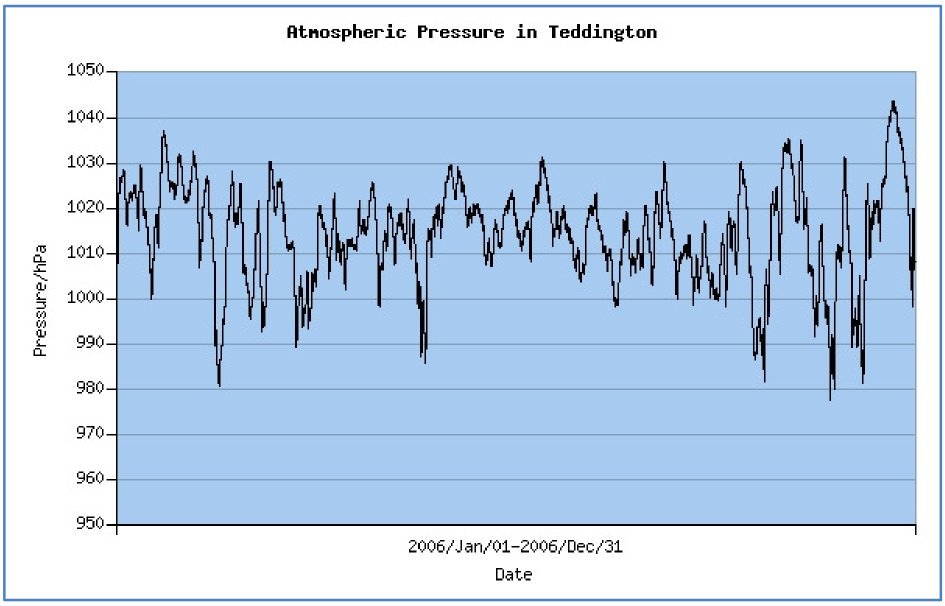


Figure 12 - Atmospheric pressure in Teddington during 2006 (cited from – NPL)

*According to NPL (National Physical Laboratory) research data, the annual atmospheric pressure fluctuation in Teddington (UK) is approximately ±30hPa

(≈3kPa or 0.03bar) as shown in Figure 12 - Atmospheric pressure in Teddington during 2006.

**The UK highest mountain is 1344 metres above sea level, the difference in atmospheric pressure at 1000 metres and sea level is 10kPa. It is very rare for a sport saloon car to go above 500 metres of road altitude. 5kPa (0.05bar) of boost pressure inaccuracy would not yield a risk of turbo compressor failure. (Engineering tool box, 2008)

Option 2. Utilises pressure exchange solenoid to sense barometric pressure when idling and TPS (throttle position sensor) at 0%. The IAC (idle speed actuator control valve) activates when TPS is at 0% and the IAC can give an output reading of airflow into the inlet manifold as suggested by Olin and Maloney (1999). This depends on memory availability in the computer chip and no interference of other functions.

Option 3. Install an independent MAP sensor for full time barometric monitor, this will require extra channel in the ECU and increases the wiring loom/hardware alteration work.

Option 4. Install an independent gauge type MAP sensor for full time compressor pressure difference (boost) monitor. This is the most accurate method but increases wiring loom/hardware alteration as well as software modification.

2.6 Integer arithmetic

Modern ECUs are capable of floating-point arithmetic natively. However, the 92-97 models Impreza are not; the assembly language only supports integer arithmetic. While it is possible to perform floating point arithmetic "long hand" (i.e. performing long multiplication etc. algorithmically), to do so considerably increases development cost and complexity. It is more appropriate that fixed point arithmetic is used.

The Impreza ECU is a 16-bit ECU and can carry out both 16-bit and 8-bit arithmetic operations easily. It would be useful to express all calculations in this format, rather than in floating-point arithmetic. The different types of operation (Schäuffele and Zurawka, 2005, pg277-297) are as follows:

- ***Unsigned 16-bit arithmetic***: minimum value 0, maximum value 65,535. Addition and subtraction between two 16-bit values are supported, giving a 16-bit result. Multiplication between two 16-bit values are supported, giving a 32-bit result, and is fairly efficient. Division is supported but slow and should be avoided. Multiplication by 2 or divide by 2 are trivial bit shift operations and are very easy to do.

- ***Unsigned 8-bit arithmetic***: minimum value 0, maximum 255. Addition and subtraction between two 8-bit values are supported, giving an 8-bit result. Extension to 16-bit is available. Multiplication of two 8-bit values gives a 16-bit result and is efficient. Division is supported but slow and should be avoided. Multiplication by 2 or divide by 2 are trivial bit shift operations and are very easy to do.

- ***Signed arithmetic***: as above, except ranges are –32,768 to +32,767 for signed 16-bit arithmetic; –128 to +127 for signed 8-bit arithmetic.

For the Impreza ECU to read a signal, the voltage is converted using a 10-bit A/D converter. This gives a value between 0 (0 volts) and 1023 (+5 volts).

It would be useful to express the design in terms of integer arithmetic and the potential consequences, in particular, scaling calculations to optimally fit within 8-bit or 16-bit arithmetic. "Optimally fit" here means such that there is no risk of overflow (exceeding the maximum or minimum value in a calculation) and that the quantisation error from the smallest permissible value (1) does not affect the performance. Any calculations which may overflow should be flagged up, ideally tested in the software and the correct action for the ECU to take be specified.

2.7 Market survey

The results of a market survey of aftermarket plug-in ECU specifically made for Subaru Impreza is shown in Table 6. It illustrates that ESL is the cheapest among the competitors. Most competitors offer the MAP based speed density system as an option; as it is an advantage to justify their higher cost differences when comparing to ESL system. Thus, ESL seeks to offer MAP based speed density system as an option to remain competitive in the market.

Product	MAF system capability	MAP based speed density system capability	Retail cost
ESL	Yes	No	£346
Apexi PFC	Yes	No	£528
Gems	Yes	Yes	£1640
Simtek	No	Yes	£1050
Links	Yes	Yes	£1000
Autronic	Yes	Yes	£1404

Table 6 - Aftermarket plug-in ECU survey

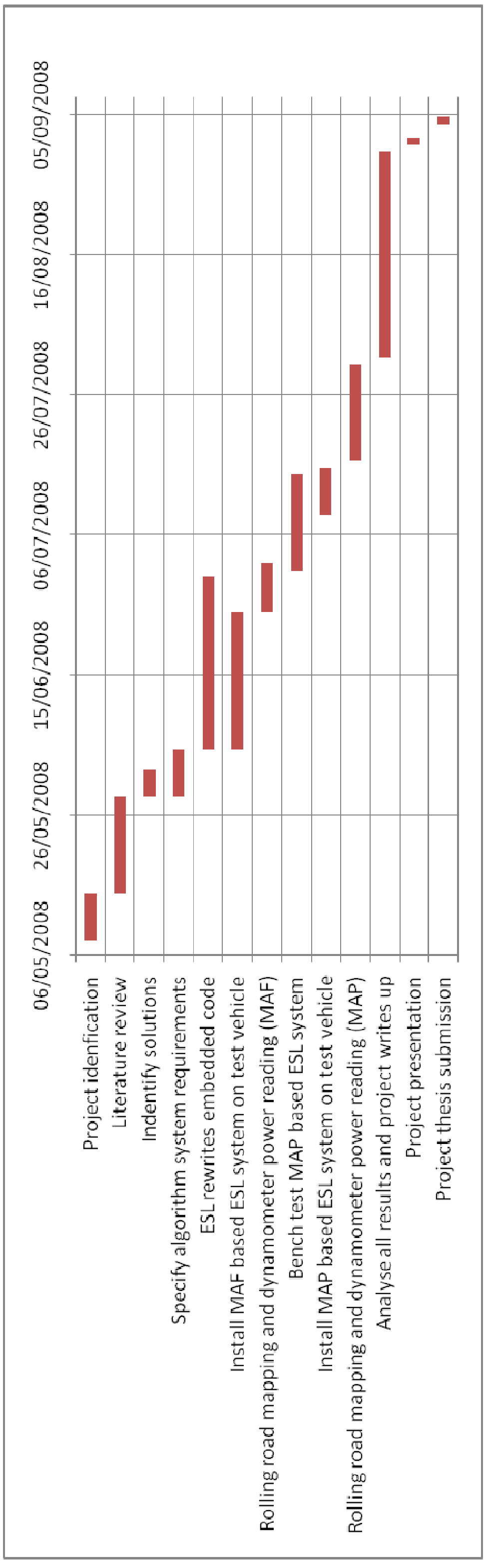
Information sources: http://www.zenperformance.co.uk, http://www.scoobymania.com, http://www.thor-racing.co.uk.

2.8 Project risk

In order to manage a project successfully, it is necessary to examine the potential project risks. Prevention measures need to be implemented once the nature of the risk and the severity of its consequences are identified.

Risk nature	**Reason**	**Consequence**	**Prevention measure**
Test vehicle availability	Engine or mechanical failure.	Unable to test the MAP based ESL system on car.	ESL has a fleet of 4 Subaru Impreza as backup.
Dynamometer/rolling road availability	Machine failure or time slot unavailable.	Unable to test and compare results.	Pre-booked rolling road time slot and over 10 ESL dealers with rolling road facility
Speed density system could not work within project time scale	Unexpected system complexity resulted system errors and crash.	Speed density system failure but would not cause academic study project failure.	Adequate background studies and literature review.

2.9 Project milestone



2.10 Conclusions

The literature review provided a brief account of existing methods and also suggested a number of possible solutions for the new map system.

The theory and derivation of air calculation equations was presented; however, conflicting theories exist on whether or not the barometric pressure is required for the determination of air flow. Hence, a further investigation of barometric pressure was performed, experts were consulted, and options were laid out.

The type of MAT sensors were compared and the potential reading errors of the NTC MAT sensor was also highlighted to ensure the new system design will keep the reading errors to the minimal.

The speed density load analogy among the competitors' are divided into 2 main groups, and the load percentile vs. engine speed is a more accurate way to represent the load; but it increases the complexity in the design. If possible, the design should adopt such load analogy as to gain technical and marketing advantage.

For 92-96 model Impreza ECU, the assembly language only supports integer arithmetic which means the division of signal is slow and should be avoided. The resolutions of 8-bit and 16-bit (signed and unsigned) were presented; it was to raise the awareness of whether the resolution is adequate for the chosen signal.

One of the main objectives of the project is for ESL system board to gain marketing advantage by being able to offer MAP system in their system board. Competitors were shown to offer MAP system at least 3 times the price of ESL system board. This indicated that the newly developed system should cost less than £1000, unless it can be justified that the new system offers much greater advantage than competitors' unit.

Nevertheless, it should be the aim that the cost of the new designed board is at the minimal.

Lastly, the project risk and milestone must be observed to ensure the project is able to deliver on time.

3 Materials and equipments

The test vehicle
1993 Subaru Impreza WRX

Non-standard bolt on parts fitted:
HKS air induction kit (air filter)
Subaru Impreza STI 4 MAF sensor
Subaru Impreza post-97 MAP sensor
Magnex exhaust system
TD05 20G turbocharger
440cc injectors
Autobahn 88 front mounted intercooler
Walbro fuel pump and adjustable fuel pressure regulator

Parts required:
ESL system board
Bosch NTC thermistor
Electrical wiring connectors

Test instruments:
Electrical multimeter
Oscilloscope
Knock sensor and analyser
Wideband lambda sensor and analyser
4 wheels rolling road dynamometer
Personal computer (Laptop)

Software:
ESL live version.5a
MatLab

4 Methodology and MAP based system design

4.1 Load analogy

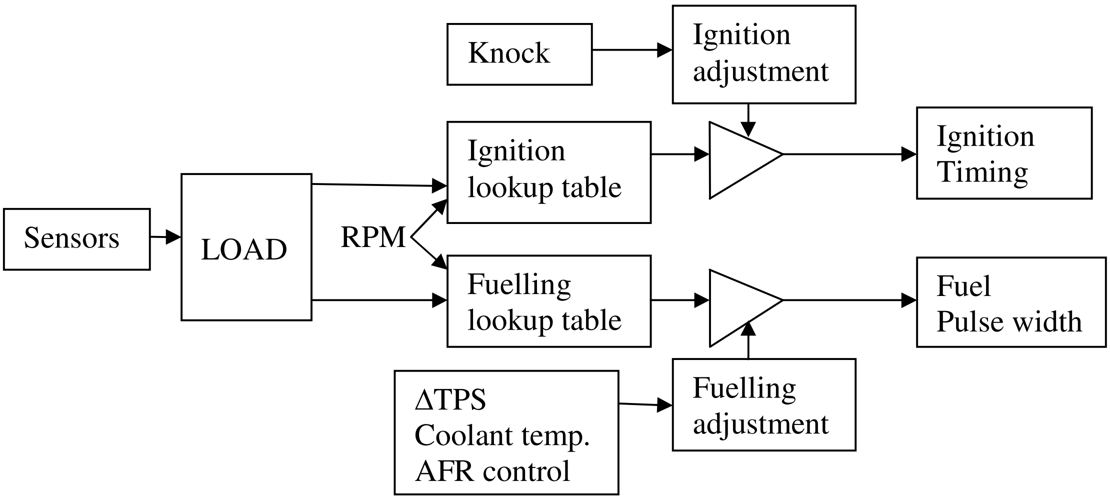


Figure 13 - Subaru Impreza ECU system flow diagram

The above flow diagram shows how the Impreza ECU operates to compute the necessary ignition timing and fuel pulse width for the engine at different load conditions. The ESL team obtained such information by reverse engineering the embedded code in the Subaru Impreza ECU.

The ECU reads the LOAD value to determine the amount of air entering the engine, and the load is calculated from the MAF/RPM sensors signal in the standard MAF system. In order to operate the new MAP system, a new analogy code has been designed for the MAP/MAT sensors (with scaling factors) to correlate with the standard MAF signal. For example:

$$MAF\ system\ load = LOAD = MAP\ system\ load \tag{3.1}$$

$$\frac{MAF}{RPM} = LOAD = \frac{MAP}{MAT} x\ VE\ x\ (scaling\ constant) \tag{3.2}$$

In order to minimise the chances of system error and conflict within the system, it is wise to keep the embedded code alteration to the minimal to operate the new MAP system. The design decision is to change the sensor to load analogy, and the system after the load analogy is remained unchanged. Such design does not only help to prevent system error, it also retains the comprehensive fuelling and ignition adjustment code designed by Subaru. For example: ignition retard when knock detonation is detected, AFR close loop control at low engine speed for emission control, warm up enrichment, acceleration enrichment and etc.

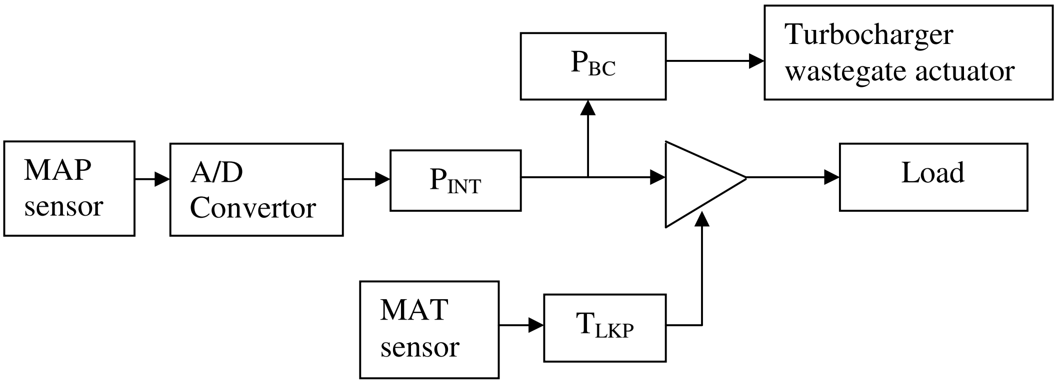


Figure 14 - Sensors to Load analogy flow diagram

Figure 14 shows the sensors to load analogy flow diagram, and the breakdown of each process is as follow:

MAP sensor to A/D converter:

The MAP sensor has an analogue output range of 0~5v, the A/D converter (Analogue to Digital converter) converts the analogue into 10-bit integer digital output with a resolution of 1024.

Hence:

P_{AD} (pressure digital value): 0 = 0v
1023 = 5v

A/D convertor to internal pressure P_{INT}:

This stage lets the pressure digital value to be integrated with offset scaling factors to represent true internal pressure value. The offset scaling calibrations allows the user to have a choice of different MAP sensors.

For example:

92-96 Impreza MAP sensor:

$$P_{INT} = \frac{500P_{AD} - 300}{256} \tag{3.3}$$

97-98 Impreza MAP sensor:

$$P_{INT} = \frac{642P_{AD} - 414}{256} \tag{3.4}$$

Storage of P_{INT} value:

The P_{INT} value is then stored as a 16-bit integer to the memory address of 12e2, the 12e2 is a unique memory address number located in the ECU. 16-bits integer has 32768 resolutions which give 8.7psi per byte (for 97-98 MAP sensor) and it is more than adequate.

P_{BC} boost control pressure value:

The P_{BC} value is same as P_{INT}, but it is stored as 8-bit integer at a different location (12d8) to control the turbocharger wastegate actuator. Hence the conversion from 16-bit to 8-bit integer is to divide the 16-bit value by 8.

$$P_{BC} = \mathrm{P_{INT}}/8 \tag{3.5}$$

MAT to T_{LKP}:

The manifold air temperature sensor signal is converted into digital signal by implementing a 64 element lookup table (appendix Table 10). (ie. 0 contains MAT at 0v and 64 contains MAT at 5v)

$$MAT = {}^{1}/_{T_{LKP}} \tag{3.6}$$

In order to minimise time delay in calculation, division is normally avoided where possible, as explained in chapter 2.6 - Integer arithmetic. Hence, the temperature lookup table with an inversion is performed at this stage.

Load derivation from P_{INT} and T_{LKP}:

The load is then derived by multiplying internal pressure, temperature and scaling constant.

$$Load = P_{INT}\ x\ T_{LKP}\ x\ VE\ x\ Scaling\ constant \tag{3.7}$$

4.2 Manifold air temperature strategy

After an extensive review of different types of MAT sensor in section 2.3, it was concluded that the NTC thermistor is more suitable for this project. The noise signal sensitivity and the additional needs of an amplifier for a thermocouple are considered impractical.

Since the MAF sensor has been removed from the system, the MAF input channel can be converted to receive the MAT signal. The pin-out B44-9 as shown in the ECU pin-out diagram Figure 15 and Figure 16 is the new input channel for the MAT signal. A full ECU pin-out description can be found in appendix-Figure 29

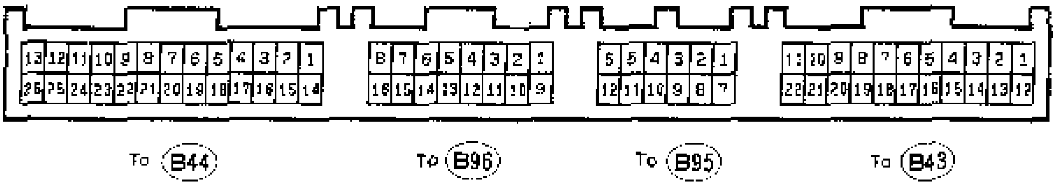


Figure 15- 92-96 Impreza ECU pin-out diagram

Content		Connector number	Signal (V)
Mass air flow sensor	Power supply	B44 – 8	12 - 13
	Signal	B44 – 9	0 – 5
	Ground	B44-10	0

Figure 16 - 92-96 Impreza ECU pin-out descriptions

A GM/Bosch NTC is chosen as the MAT sensor and the electrical resistance response to temperature curve is shown in Figure 17.

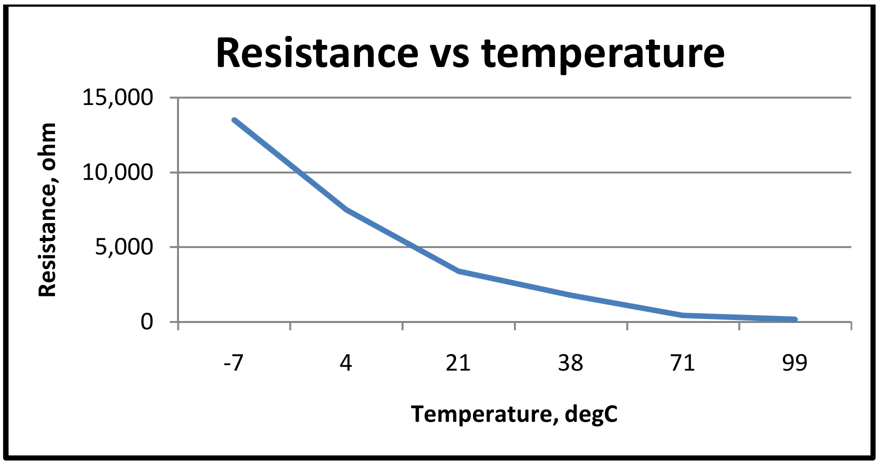


Figure 17 - GM/Bosch type NTC resistance vs. temperature graph

The B44-9 input channel has a process signal range of 0-5v; a voltage divider circuit (Figure 18) can be implemented for the MAT sensor to produce an output of 0-5v when sensing a range of -11 – 99 ºC. The 22kΩ resistor was calculated based on a trial and error method to ensure the circuit has an output range that satisfied above requirement.
The self heating error as mentioned in chapter 2.3.3, a simple calculation using ohm’s law has performed to ensure the current is not going to cause the thermistor to self heat; it was confirmed that 0.6mW at 30ºc is insignificant to cause any errors.

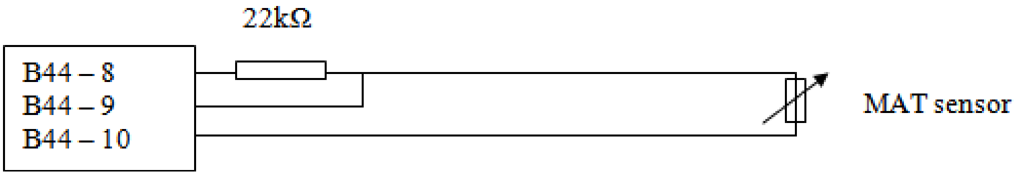


Figure 18 - MAT voltage divider circuit

The circuit arrangement as shown in Figure 18 along with GM/Bosch type NTC will produce an output voltage in respond to temperature in following graph.

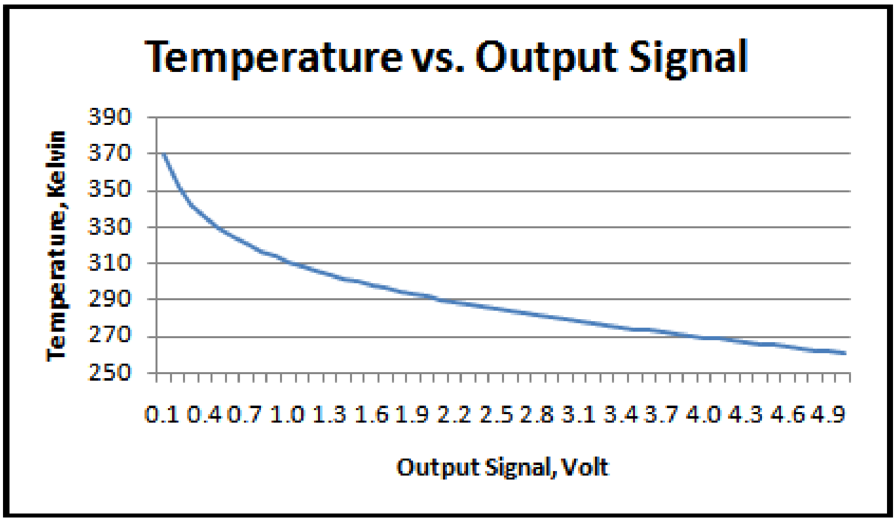


Figure 19 - MAT circuit temperature vs. output signal

3.3.1 MAT sensor location

The ideal location for the MAT sensor is at the inlet plenum and it should be as close to the combustion chamber where possible. It is also has to be at the equal distance from all 4 cylinder. An illustration of ideal location for the MAT sensor is shown in Figure 20 below:

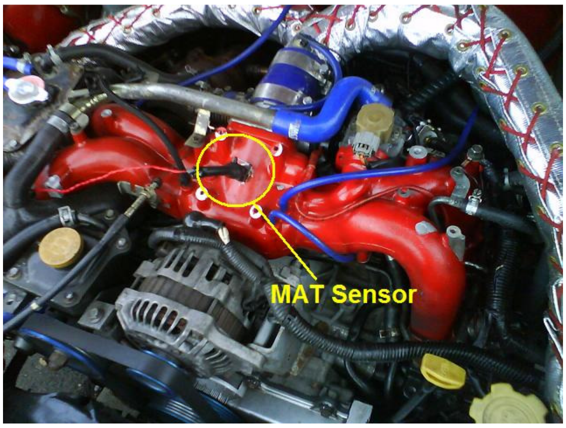


Figure 20 - MAT sensor location

3.3.2 Supply voltage stability

Supply voltage stability is vital for a voltage divider to produce a consistent and accurate output signal as mentioned in chapter 2.3.3. A voltage output test on pin B44-8 was carried out to examine the voltage fluctuation in different engine speed and electrical load conditions. The test was carried out by running the engine from idle to full engine speed at an increment of 1000 rpm step. The load conditions were simulated by minimal electrical load and full electrical load while the entire electrical ancillary was switched on to maximum. (ie. lights, windscreen wiper, heater blower. etc.)
The voltage was measured using a handheld multimeter (Sinometer M-830B).

Engine speed, RPM	**Pin B44-8 output voltage at minimal electrical load, volt**	**Pin B44-8 output voltage at full electrical load, volt**
1400	12.9	12.4
2000	12.8	12.4
3000	12.9	12.4
4000	12.9	12.3
5000	12.8	12.3
6000	12.8	12.3

Table 7 - Supply voltage fluctuation test

The results shown in Table 7 have indicated that the voltage at supply voltage pin B44-8 fluctuates about ±0.4v when referenced at 12.5v. The resultant output error is approximately ±1 kelvin (0.4% inaccuracy), which is too insignificant to cause any problem.

The error was calculated using the data derived from Figure 17 - GM/Bosch type NTC resistance vs. temperature graph) and equation 2.3. A fully analysed table can be found in appendix (Table 9) and the equation used is as follow:

$$MAT = -24.642Ln\left[\frac{22000V}{Vin - V}\right] + 497.08 \qquad (2.5)$$

4.3 Volumetric efficiency and scaling constant

This section is to investigate the correlation between the MAF and the MAP signal output; the correlated data can then be calculated to determine the VE and scaling factor which are required for the ECU to compute the load, as shown in equation 3.2, where the MAF/RPM = LOAD = MAP x VE x scaling factor/ MAT.

In order to gather the correlation data, a set of tests were carried out while the test vehicle was still in the MAF based system. A series of drive cycles were performed and output of MAF, MAP, and RPM were logged at the sample rate of 16Hz. The data logging software was designed by ESL using MatLab.

A section of the sensors correlation drive cycle test result is shown in Figure 21 and the full cycle result can be found in appendix (Figure 30). In order to ensure all the load range and engine speed are covered, combinations of driving styles were executed; these included smooth/part load/harsh acceleration, acceleration in different gears and speed.

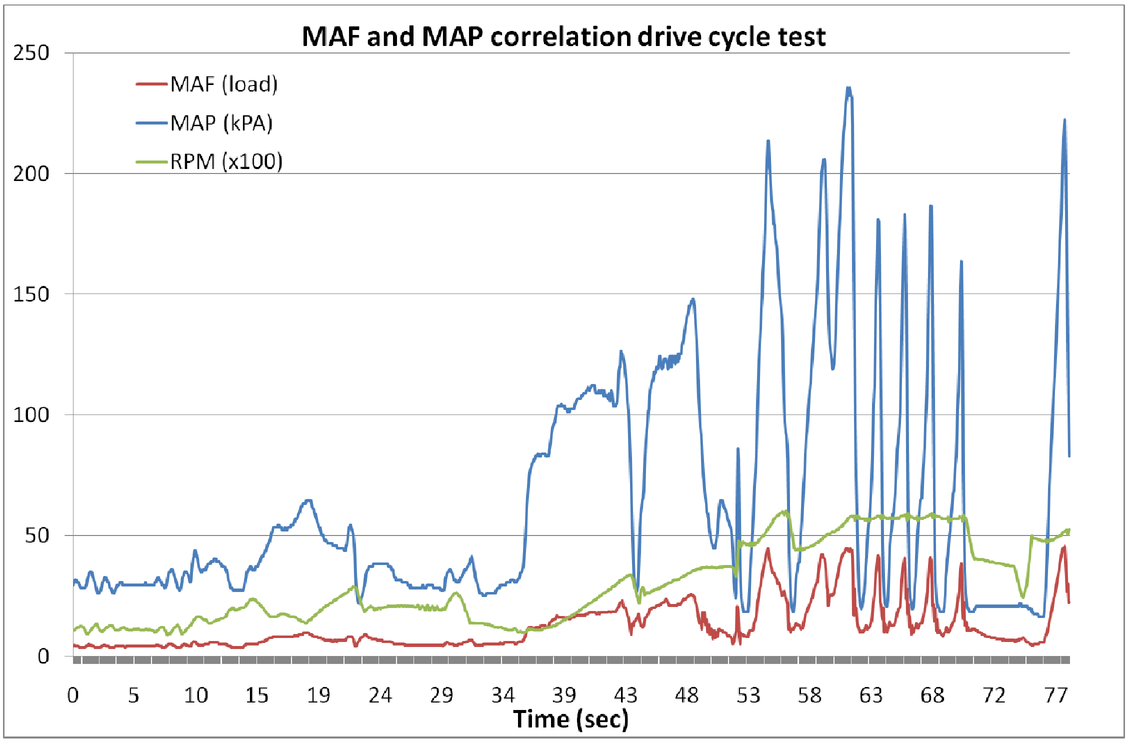


Figure 21 - MAF and MAP correlation drive cycle test (part section)

All the driving cycles data were combined and analysed; Figure 22 was then developed to confirm the coverage of all engine speed and load range. Despite of all the attempts to cover all load conditions, the coverage of load between 25~50 and below 3000rpm is not achievable due to the size of the turbocharger and the inoperability of the engine in these load conditions. Hence, the coverage of data was considered adequate.

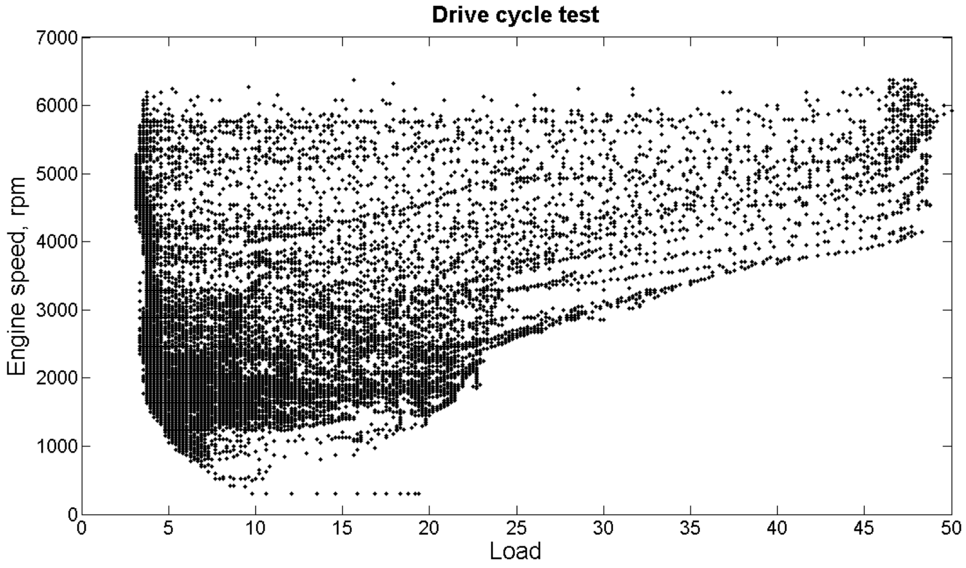


Figure 22 - Correlation data coverage

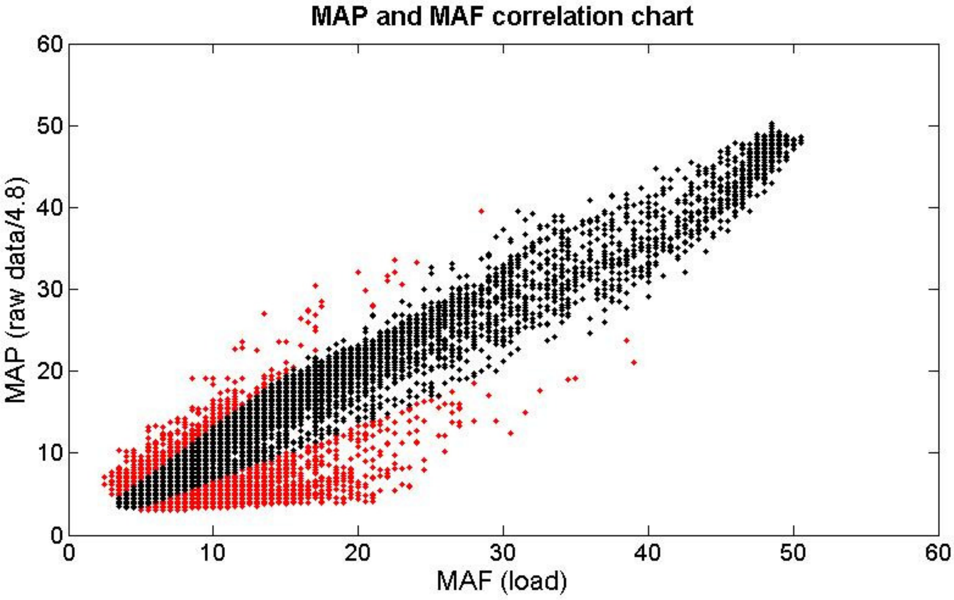


Figure 23 - MAP and MAF correlation chart

Once the data were combined, the mean division of MAP raw data and MAF load was then calculated; the correlation (or scaling) constant was found to be MAP raw data divided by 4.8 as shown in Figure 23. The points highlighted in red are the values that fall outside the 1st standard deviation. It shows that the scaling constant is not very effective at low load. This is due to the differences in measuring method of both sensors, and the over-fuelling issue caused by the reversal flow/blow off valve over-fuelling.

The MAP sensor can only detect air pressure within the inlet manifold. The volumetric efficiency of engine and MAT are required by the ECU to be able to calculate the air flow into the engine. Unlike the MAF sensor, air flow is directly proportional to sensor output; hence a VE table is needed along with the scaling constant to correlate both sensors.

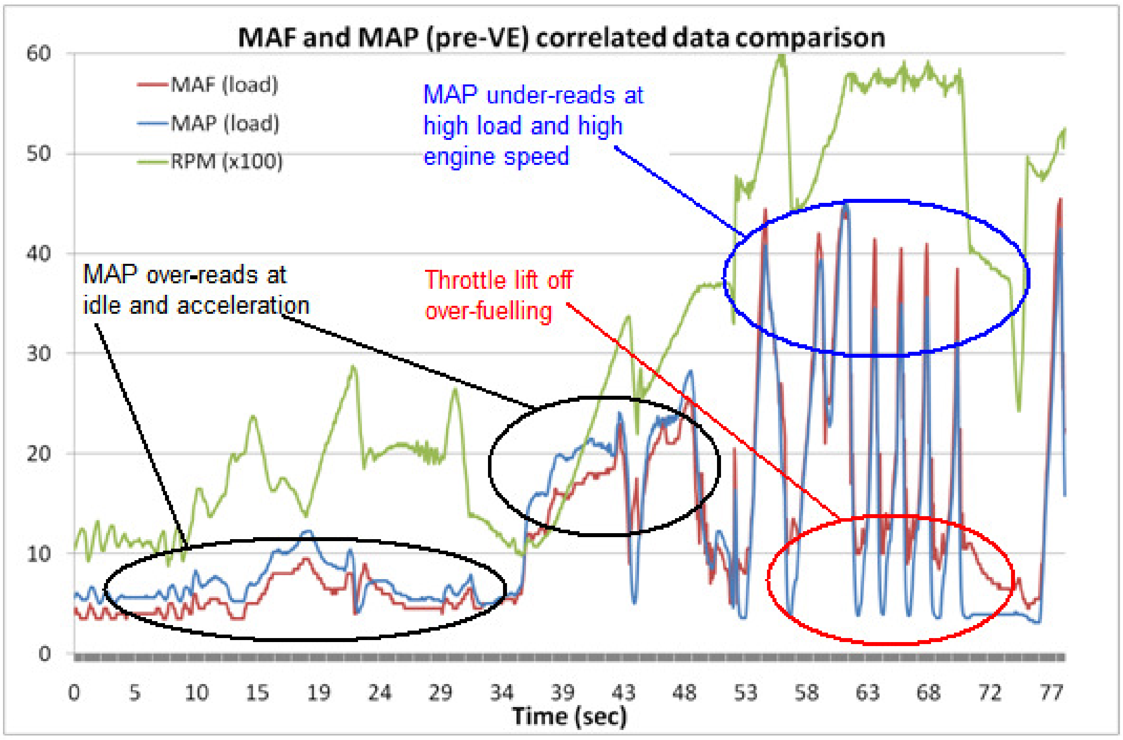


Figure 24 - MAF and MAP (pre-VE) correlated data comparison

Figure 24 shows that the MAP over-reads at idle and at acceleration, and under-reads at high loads. This agrees with the typical engine VE pattern (Figure 25) as suggested by Harrison (2008); poor VE at low engine speed, gradually increased as the speed increases until it reaches peak engine torque.

Furthermore, the MAF reversal flow and blow off valve over-fuelling issues are clearly shown in Figure 24 (area circled in red).

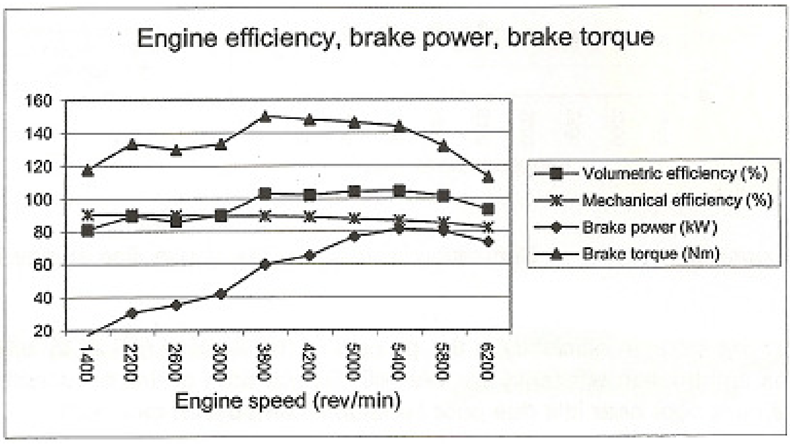


Figure 25 - Engine efficiency graph (cited from Harrison, 2008)

The VE table (Figure 26) was developed by measuring the load differences between MAF and MAP (with scaling constant) using the data from the drive cycle test. The VE table can then compensate the over and under-reading load values from the MAP sensor to match the MAF load. As a reference, the VE table also shows that the engine's volumetric efficiency varies from 80% at idle to 120% at peak power.

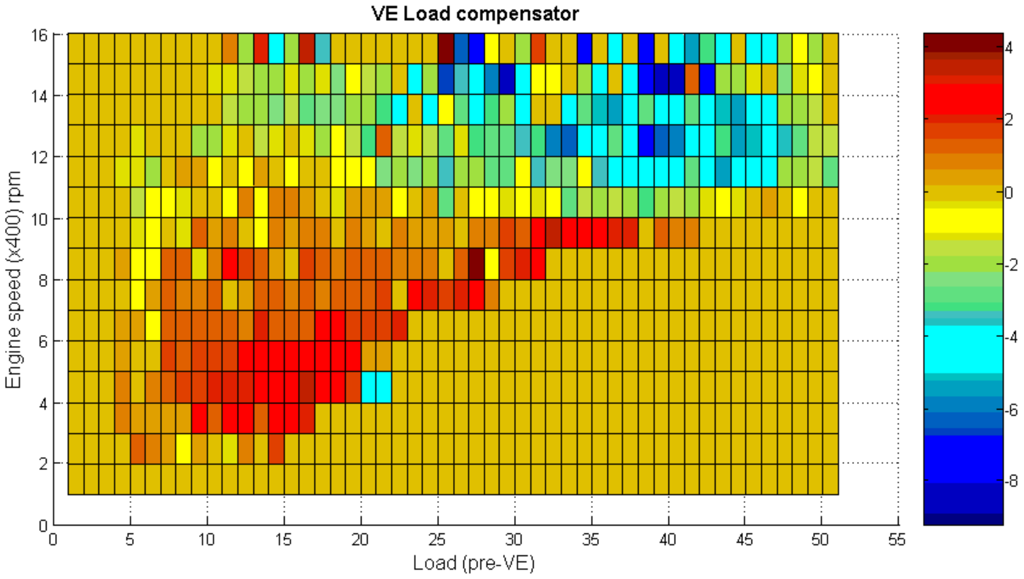


Figure 26 - VE load compensator table

4.4 Barometric correction

The concept of barometric correction has already been mentioned in the literature review chapter 2.5, and the studies of potential options for barometric strategy can also be found in chapter 2.5.1.

It has been identified that the boost pressure monitoring is to protect the engine and the turbo charger from over boosting, as well as to optimise the engine performance. The barometric correction is needed to accurately determine the pressure difference across the turbo compressor, but the new MAP system does not have the flexibility to sense the atmospheric pressure at idling.

Meanwhile, it is possible to implement an alternative method for the barometric correction; as laid out in chapter 2.5.1 (option 2, option 3, and option 4). However, the options as mentioned require extra sensor, wire loom alterations, and complex embedded code alterations. These options are undesirable due to the increase in material/labour cost and possible coding conflict within the system.

An alternative method as suggested in option 1, it is to monitor the boost pressure difference at a predefined standard sea level atmospheric pressure without barometric correction. A barometric pressure study was performed to show that the atmospheric pressure does not fluctuate high enough to cause a problem.

Conclusively, the design decision is not to perform barometric correction and use a predefined standard sea level pressure (101.3kPa) as a reference.

4.5 Sensor functional test

The ECU code includes run-time tests to ensure that sensors are giving sensible measurements. If the signals are giving strange unexpected values, the sensor is declared faulty. The ECU then adapts the strategy used to run the engine to achieve one of a number of goals:

1. Keep the engine running and allow the driver to continue, albeit perhaps with reduced performance or loss of smoothness.
2. Protect the engine from damage.

Due to a number of the sensors having changed, the original tests may not be appropriate. Hence, the following ECU signal tests will be disabled:

1. MAF sensor test
2. MAP sensor test
3. Pressure exchange solenoid test

Implementing these tests is seen as a lower priority than getting the engine running, but if time was available it would be valuable to consider new sets of sensor failure detection strategy.

One possible code can be re-used: in the event of a MAF fault, the existing ECU software switches to using an 8x8 map of engine load as a function of throttle vs. engine speed. This could be retained if a MAP fault is detected to enable the engine to continue running. This seems a risky strategy on a turbo engine, but it is the one that Subaru implemented.

5 System test

The system tests were very straight forward; the aim was to compare the engine power output and drivability of the MAF and MAP system. The power output test was performed by using a 4 wheels rolling road dynamometer, and the drivability performance was subjected to the driver feedback.

5.1 Preliminary test

In order to reduce development cost and time, a preliminary test was executed before the rolling road session. This gave the developer a chance to ensure the system functions as designed; the test included:

- System crash
- Engine start up
- Idling smoothness
- Air fuel ratio at different load conditions - (wideband lambda sensor and analyser - *Innovate Motorsport LC-1wideband controller*)
- Knock detection – (knock sensor and analyser – *Knocklink detonation display*)
- Peak boost

5.1.1 Results and discussions

The air fuel ratio (AFR) and knock detection are the basic engine parameters and should be closely monitored to prevent engine failure and to assess the engine performance; hence wideband lambda sensor and knock sensor were installed on the test vehicle.

The MAP system was programmed into the ESL system board, and the engine was then fired up to check for idling stability, load readings, AFR, and knock monitoring. Once the engine idling operation was satisfied, the vehicle was driven on the road to perform a drive cycle test.

The AFR was logged throughout the session and it is presented in Figure 27. The system performed as expected and the engine operated at the ideal AFR in all load conditions. For example:

- Stoichiometric AFR at idling.
- 12:1 AFR at mid-boost.
- 11:1 at peak boost.
- Injectors cut out during decelerations.

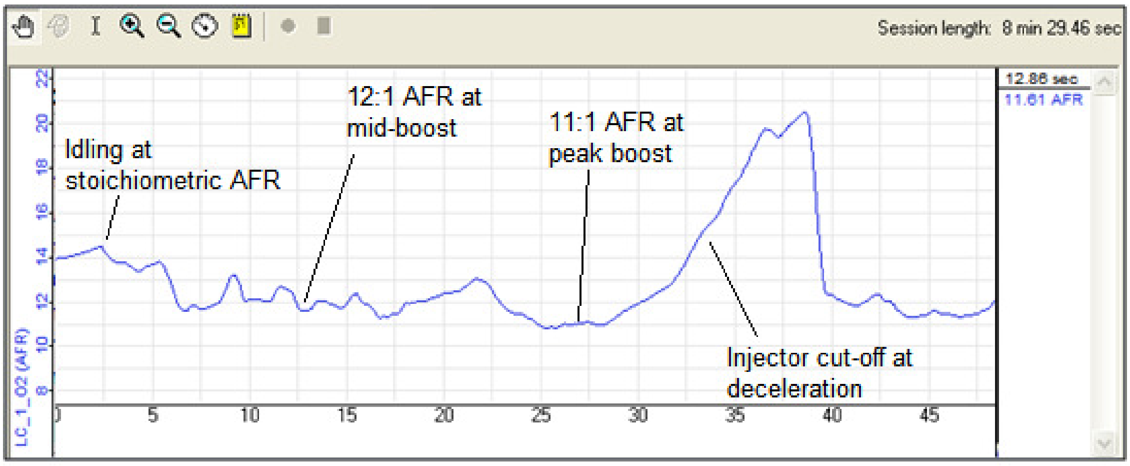


Figure 27 - AFR log for preliminary test

There was no engine knock detonation during the drive cycle test and the engine was boosting at the same level as it was in MAF system (1.6bar). However, the author and the driver felt the engine was not producing as much power (approximately 10% less power in their opinion) as it was in MAF system. The new MAP system will be tuned optimally during the rolling road session, and the new MAP system design is considered exceptional that it was able to operate the car on the MAF load fuelling/ignition table. Furthermore, there was no system crash reported during the test.

5.2 Engine power output test

Figure 28 - 4 wheels rolling road dynamometer (cited from http://www.zenperformance.co.uk)

One of the design objectives is that the MAP system on the test vehicle should not cause huge power output reduction differences when compared to the MAF system, and a 4 wheels rolling road dynamometer as shown in Figure 28 was the equipment used to measure and compare the engine power output differences.

5.2.1 Results and discussions

The procedure was to perform the power output test before and after the implementation of the new MAP system. For the purpose of fair testing, the plan was to compare both results by using the same dynamometer. However, the dynamometer that was used in the MAF system test was not available for a MAP system test within the project timescale constrain, hence an alternative dynamometer was used.

The results printout can be found in appendix (Figure 31 to Figure 34), and listed below are the summary of the results:

MAF system	**MAP system**
Maximum engine power 391.4bhp @ 6833rpm	Maximum engine power 391.8bhp @ 6500rpm
Maximum engine torque 307.5lbft @ 5597rpm	Maximum engine torque 345lbft @ 5150rpm
Dynamometer: Dastek	Dynamometer: Dyno dynamic
Location: Zen Performance	Location: APT
Barometric pressure: 998 mBar	Barometric pressure: 1019 mBar
Ambient temperature: 32ºc	Ambient temperature: 24ºc

Table 8 - Summary of the engine power output test

The accuracy of the power output result can be affected by many factors which include barometric pressure, ambient temperature, tyre pressure, fuel quality, and dynamometer.

It is observed that the MAF rich spike/over-fuelling issue at mid-boost (appendix Figure 31), between 4000~5000rpm) is eliminated in the MAP system, and this might have resulted in the maximum power and the torque occurring at lower engine speed. Conversely, the maximum power shift could also be affected by the ambient condition. As a result, the author could not be confident in this theory due to the lack of results repeatability and it is also beyond the scope of project. Despite all of the inaccurate contributory factors however, the author is confident that the MAP system can provide a similar or better performance when compared to the MAF system.

5.3 Drivability performance test

The drivability test can be performed by data logging the parameters such as engine speed, wheel speed, and throttle position. Alternatively, it can be achieved by obtaining feedback from a test driver. Due to the project timescale and resources constrains, the driver feedback test method is considered appropriate.

5.3.1 Results and discussions

The test driver (Steven Spencer, ESL) has experienced driving the vehicle with both MAF and MAP systems. The test driver reported later that the part-throttle engine hesitation which happens in MAF system had greatly improved in the MAP system. The part-throttle engine hesitation is the result of the reversal flow surge that causes MAF sensor reading error. Evidences can also be shown in chapter 0 from the drive cycle data log.

There were no engine stalling, idle instability, hesitation on load/part load, or other adverse effect reported. The results were conclusive; the test driver was satisfied with the drivability of the test vehicle.

6 Conclusions and recommendations

6.1 Conclusions

The main objective of the thesis was to convert the MAF to MAP based load system on the ESL system board.

- **Conversion project completion**
  The conversion of load operation has been successfully executed, and it has met all the objectives and the required specifications.

- **Load analogy design**
  The new MAP system has implemented a highly sophisticated temperature compensation load analogy that can only be found in an expensive reprogrammable ECU. The comprehensive fuel enrichment and ignition adjustment codes designed by Subaru are retained, so it will greatly reduce the engine tuner's time and labour cost. Furthermore, standard ancillaries (ie. radiator cooling fan) are still functional due to the retention of existing Subaru code.

- **Minimal alteration**
  The conversion only involves software upgrade, simple MAT sensor installation, and no loom alterations.

- **Improvement in performance**
  The engine drivability has improved and the power output has not been compromised. The possibility of increase in engine output is subject to more tests, but the available results have shown positive.

- **Upgrade package marketing**
  ESL has the option of offering the upgrade package to the existing customers for free in order to gain customers loyalty or alternatively, to sell the upgrade package to existing customers to generate extra revenue. Nevertheless, the new ESL system board sales are expected to increase with the MAP based system feature.

6.2 Further recommendations

The ESL MAP system can be improved by further studies in following areas:

- **Engine power output test**

  The engine power output comparison test was conducted using different dynamometers due to availability during the project phase. It would be ideal if the comparison test is repeated by using the same dynamometer in a similar ambient condition.

  The test results can also benefit by a further investigation on the shift in maximum power and torque occurs at lower engine speed on the MAP based system.

- **Spare output channel function**

  The new MAP system does not need a pressure exchange solenoid, which will free up an output control channel for other use. There are many possible functions that can be implemented such as anti-lag system and intercooler water injection system.

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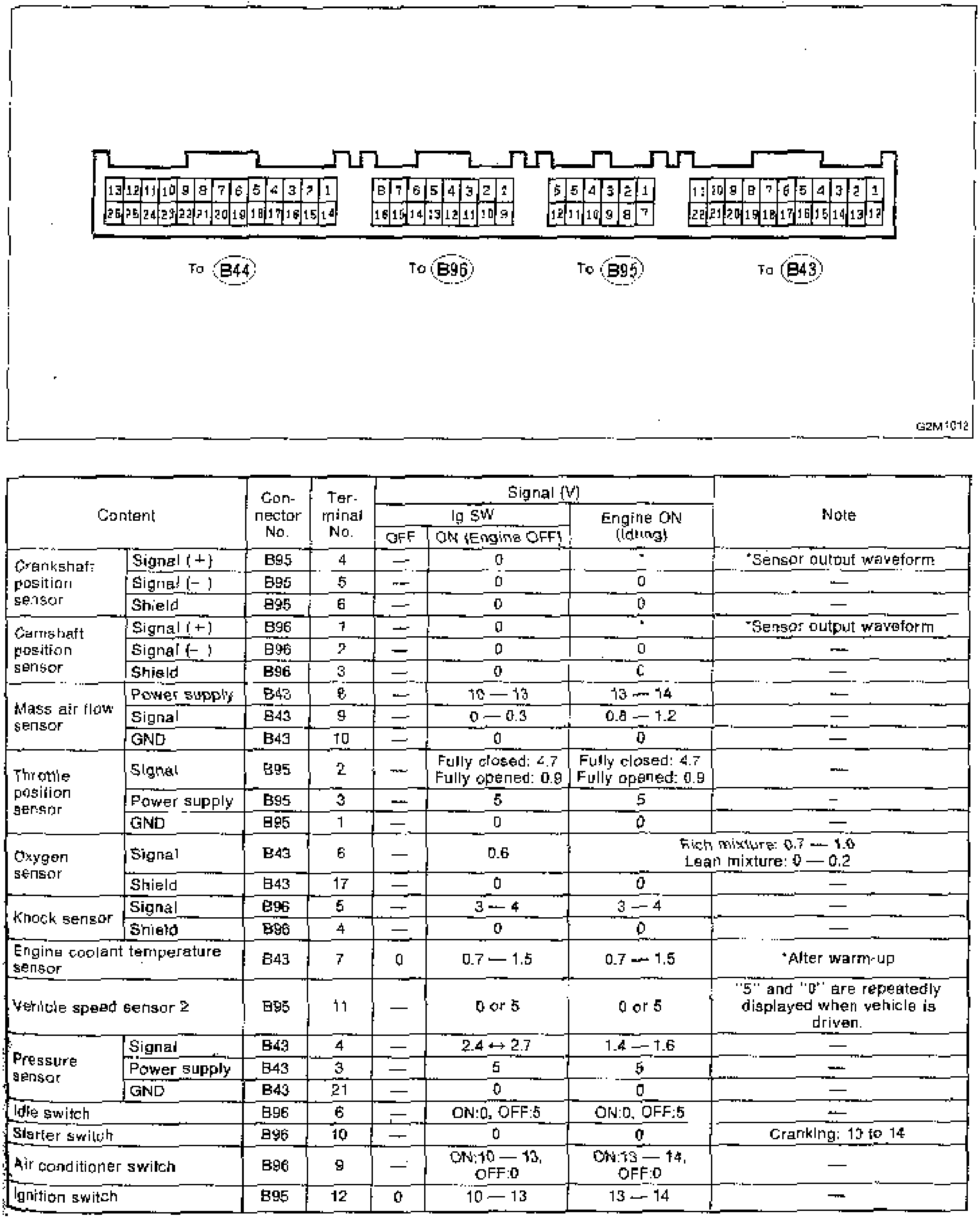
Appendix



Content		Connector No.	Terminal No.	Signal (V)			Note
				Ig SW		Engine ON (Idling)	
				OFF	ON (Engine OFF)		
Crankshaft position sensor	Signal (+)	B95	4	—	0	*	*Sensor output waveform
	Signal (−)	B95	5	—	0	0	—
	Shield	B95	6	—	0	0	—
Camshaft position sensor	Signal (+)	B96	1	—	0	*	*Sensor output waveform
	Signal (−)	B96	2	—	0	0	—
	Shield	B96	3	—	0	0	—
Mass air flow sensor	Power supply	B43	8	—	10 — 13	13 — 14	—
	Signal	B43	9	—	0 — 0.3	0.8 — 1.2	—
	GND	B43	10	—	0	0	—
Throttle position sensor	Signal	B95	2	—	Fully closed: 4.7 Fully opened: 0.9	Fully closed: 4.7 Fully opened: 0.9	—
	Power supply	B95	3	—	5	5	—
	GND	B95	1	—	0	0	—
Oxygen sensor	Signal	B43	6	—	0.6	Rich mixture: 0.7 — 1.0 Lean mixture: 0 — 0.2	
	Shield	B43	17	—	0	0	—
Knock sensor	Signal	B96	5	—	3 — 4	3 — 4	—
	Shield	B96	4	—	0	0	—
Engine coolant temperature sensor		B43	7	0	0.7 — 1.5	0.7 — 1.5	*After warm-up
Vehicle speed sensor 2		B95	11	—	0 or 5	0 or 5	"5" and "0" are repeatedly displayed when vehicle is driven.
Pressure sensor	Signal	B43	4	—	2.4 ↔ 2.7	1.4 — 1.6	—
	Power supply	B43	3	—	5	5	—
	GND	B43	21	—	0	0	—
Idle switch		B96	6	—	ON:0, OFF:5	ON:0, OFF:5	—
Starter switch		B96	10	—	0	0	Cranking: 10 to 14
Air conditioner switch		B96	9	—	ON:10 — 13, OFF:0	ON:13 — 14, OFF:0	—
Ignition switch		B95	12	0	10 — 13	13 — 14	—

Figure 29 - 92-96 Impreza full pin-out diagram and descriptions

Volt	Ohm	Kelvin	Eq(error)
0.1	177	369	370
0.2	358	352	353
0.3	541	342	343
0.4	727	335	336
0.5	917	329	330
0.6	1109	324	325
0.7	1305	320	321
0.8	1504	317	318
0.9	1707	314	315
1.0	1913	311	312
1.1	2123	308	309
1.2	2336	306	307
1.3	2554	304	305
1.4	2775	302	303
1.5	3000	300	301
1.6	3229	298	299
1.7	3463	296	297
1.8	3701	295	296
1.9	3943	293	294
2.0	4190	292	292
2.1	4442	290	291
2.2	4699	289	290
2.3	4961	287	288
2.4	5228	286	287
2.5	5500	285	286
2.6	5778	284	285
2.7	6061	282	283
2.8	6351	281	282
2.9	6646	280	281
3.0	6947	279	280
3.1	7255	278	279
3.2	7570	277	278
3.3	7891	276	277
3.4	8220	275	276
3.5	8556	274	275
3.6	8899	273	274
3.7	9250	272	273
3.8	9609	271	272
3.9	9977	270	271

4.0	10353	269	270
4.1	10738	268	270
4.2	11133	267	269
4.3	11537	267	268
4.4	11951	266	267
4.5	12375	265	266
4.6	12810	264	265
4.7	13256	263	264
4.8	13714	262	264
4.9	14184	262	263
5.0	14667	261	262

Table 9 – MAT sensor error

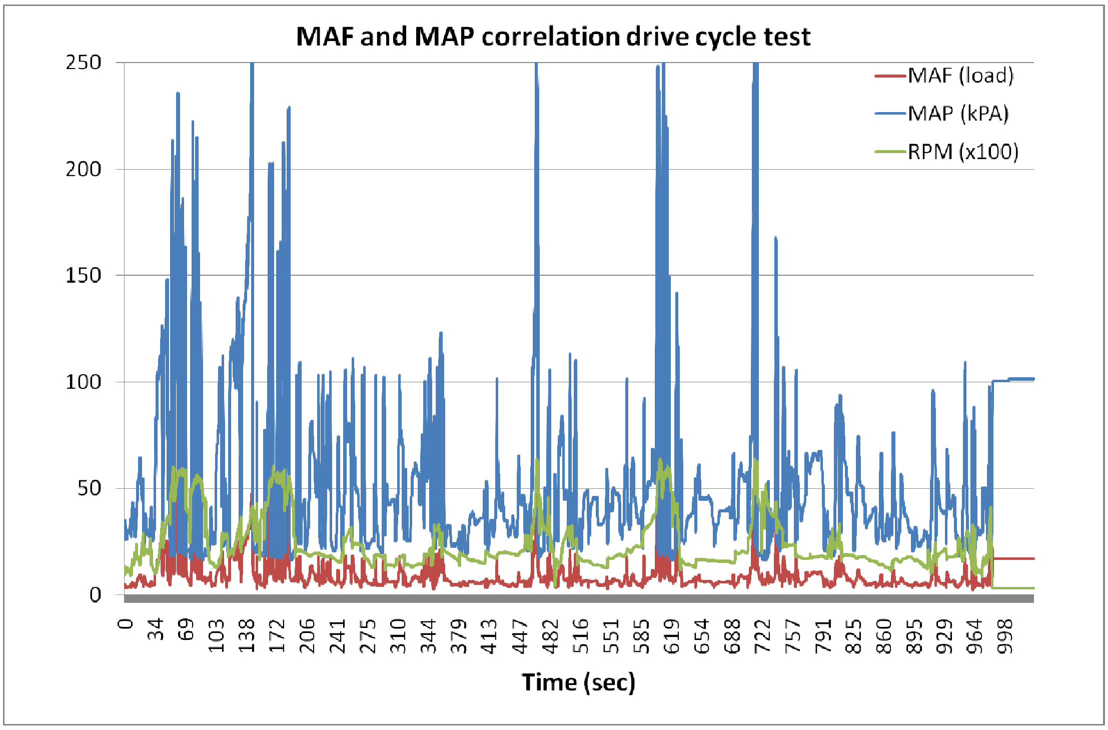


Figure 30 - MAF and MAP correlation drive cycle test

Element number	Volt	Kelvin	DegC	Value
1	0.08	369	96	12860
2	0.16	369	96	12860
3	0.23	352	79	13491
4	0.31	342	69	13893
5	0.39	342	69	13893
6	0.47	335	62	14196
7	0.55	329	56	14442
8	0.62	324	51	14651
9	0.70	320	47	14834
10	0.78	320	47	14834
11	0.86	317	44	14998
12	0.94	314	41	15147
13	1.01	311	38	15284
14	1.09	311	38	15284
15	1.17	308	35	15411
16	1.25	306	33	15530
17	1.33	304	31	15642
18	1.40	302	29	15748
19	1.48	302	29	15748
20	1.56	300	27	15849
21	1.64	298	25	15946
22	1.72	296	23	16038
23	1.79	296	23	16038
24	1.87	295	22	16127
25	1.95	293	20	16214
26	2.03	292	19	16297
27	2.11	290	17	16378
28	2.18	290	17	16378
29	2.26	289	16	16456
30	2.34	287	14	16533
31	2.42	286	13	16607
32	2.50	286	13	16607
33	2.57	285	12	16680
34	2.65	284	11	16752
35	2.73	282	9	16822
36	2.81	281	8	16890
37	2.89	281	8	16890
38	2.96	280	7	16958

39	3.04	279	6	17024
40	3.12	278	5	17090
41	3.20	278	5	17090
42	3.28	277	4	17154
43	3.35	276	3	17218
44	3.43	275	2	17281
45	3.51	274	1	17343
46	3.59	274	1	17343
47	3.67	273	0	17405
48	3.74	272	-1	17466
49	3.82	271	-2	17526
50	3.90	271	-2	17526
51	3.98	270	-3	17586
52	4.06	269	-4	17646
53	4.13	268	-5	17705
54	4.21	267	-6	17764
55	4.29	267	-6	17764
56	4.37	267	-6	17822
57	4.45	266	-7	17881
58	4.52	265	-8	17939
59	4.60	264	-9	17996
60	4.68	264	-9	17996
61	4.76	263	-10	18054
62	4.84	262	-11	18112
63	4.91	262	-11	18169
64	4.99	262	-11	18169

Table 10 - MAT signal 64 elements lookup table

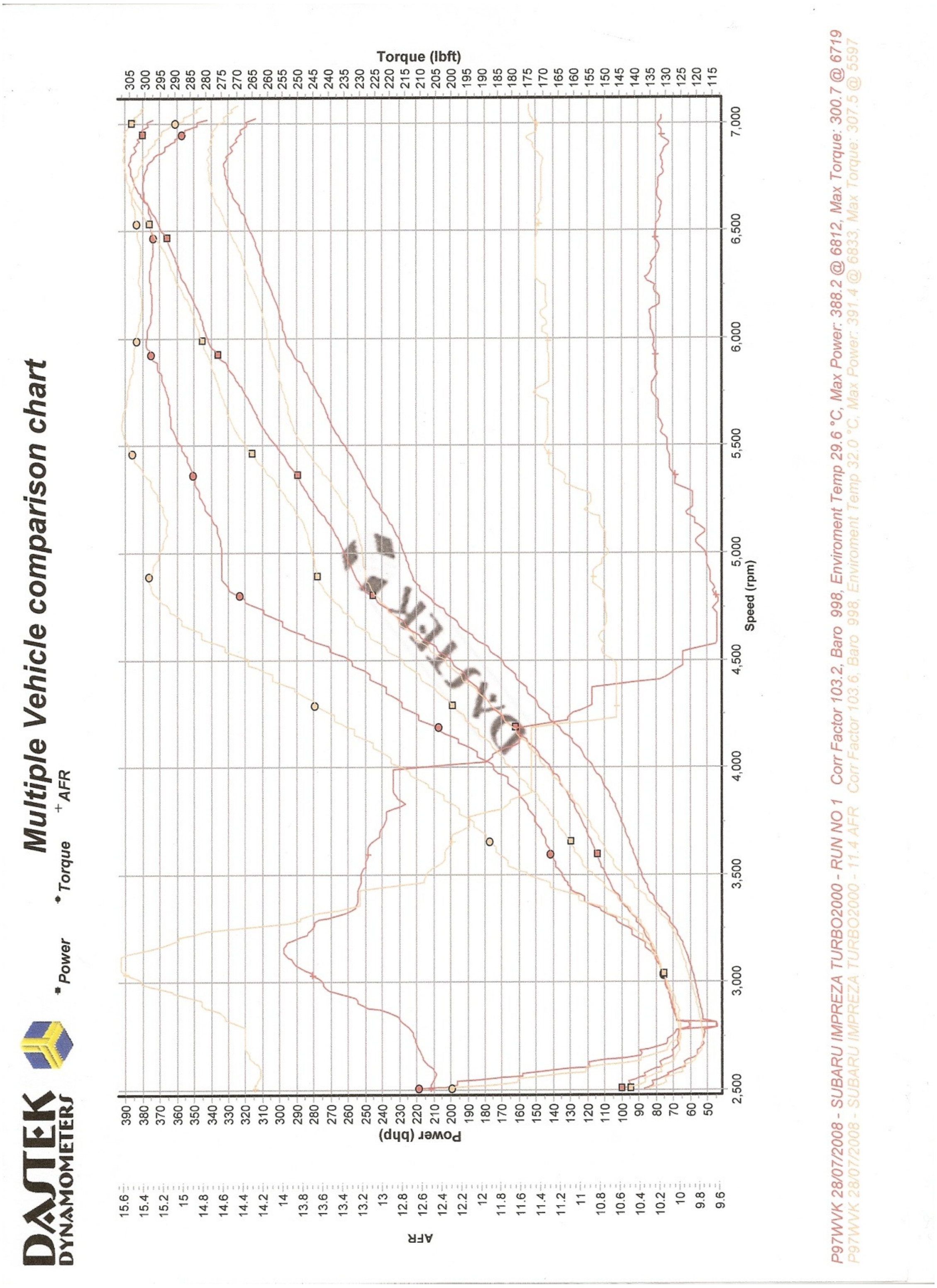
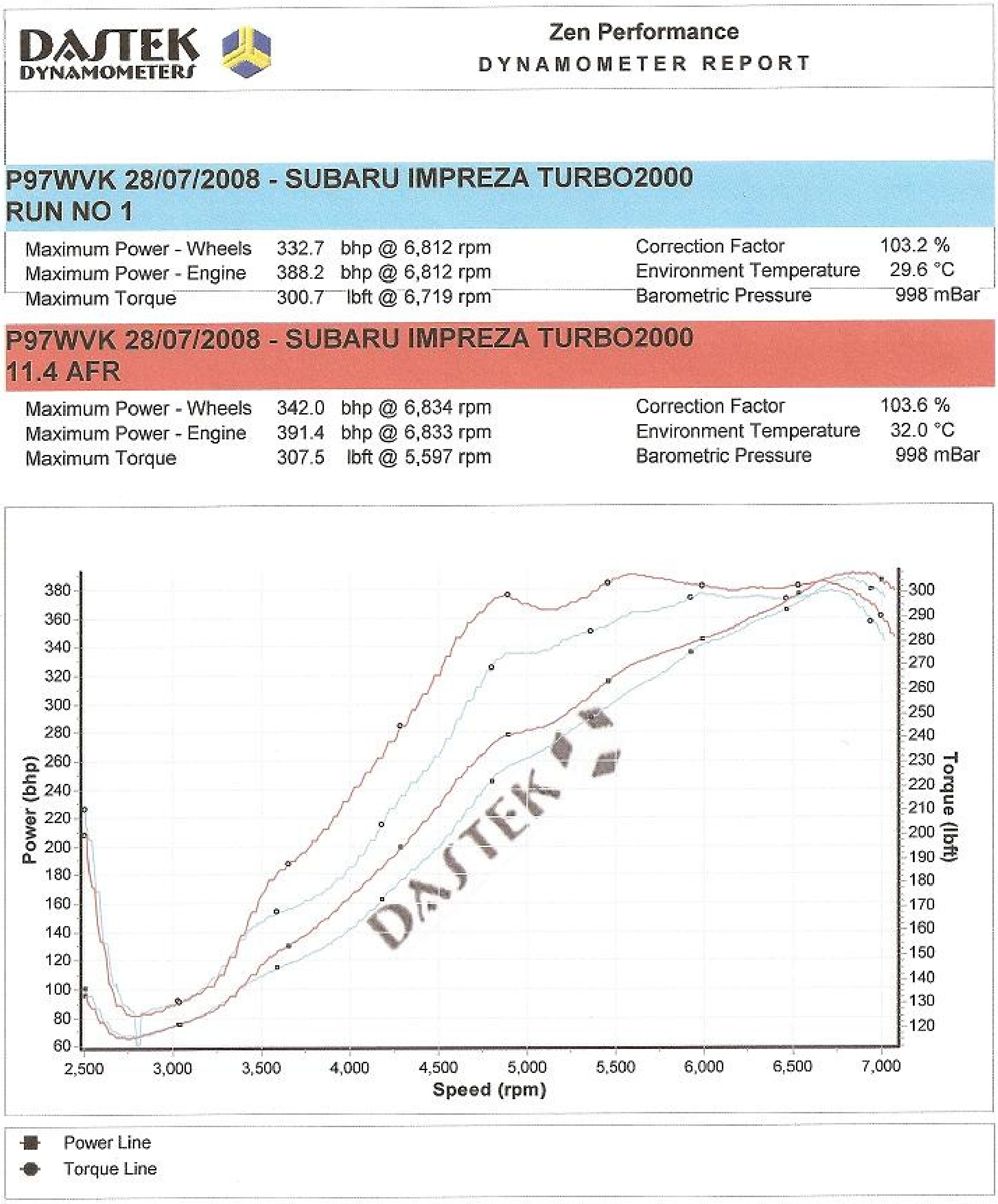


Figure 31 - MAF system power output (part 1)



DASTEK DYNAMOMETERS

Zen Performance
DYNAMOMETER REPORT

P97WVK 28/07/2008 - SUBARU IMPREZA TURBO2000
RUN NO 1

Maximum Power - Wheels	332.7	bhp @ 6,812 rpm	Correction Factor	103.2 %
Maximum Power - Engine	388.2	bhp @ 6,812 rpm	Environment Temperature	29.6 °C
Maximum Torque	300.7	lbft @ 6,719 rpm	Barometric Pressure	998 mBar

P97WVK 28/07/2008 - SUBARU IMPREZA TURBO2000
11.4 AFR

Maximum Power - Wheels	342.0	bhp @ 6,834 rpm	Correction Factor	103.6 %
Maximum Power - Engine	391.4	bhp @ 6,833 rpm	Environment Temperature	32.0 °C
Maximum Torque	307.5	lbft @ 5,597 rpm	Barometric Pressure	998 mBar

■ Power Line
● Torque Line

Figure 32 - MAF system power output (part 2)

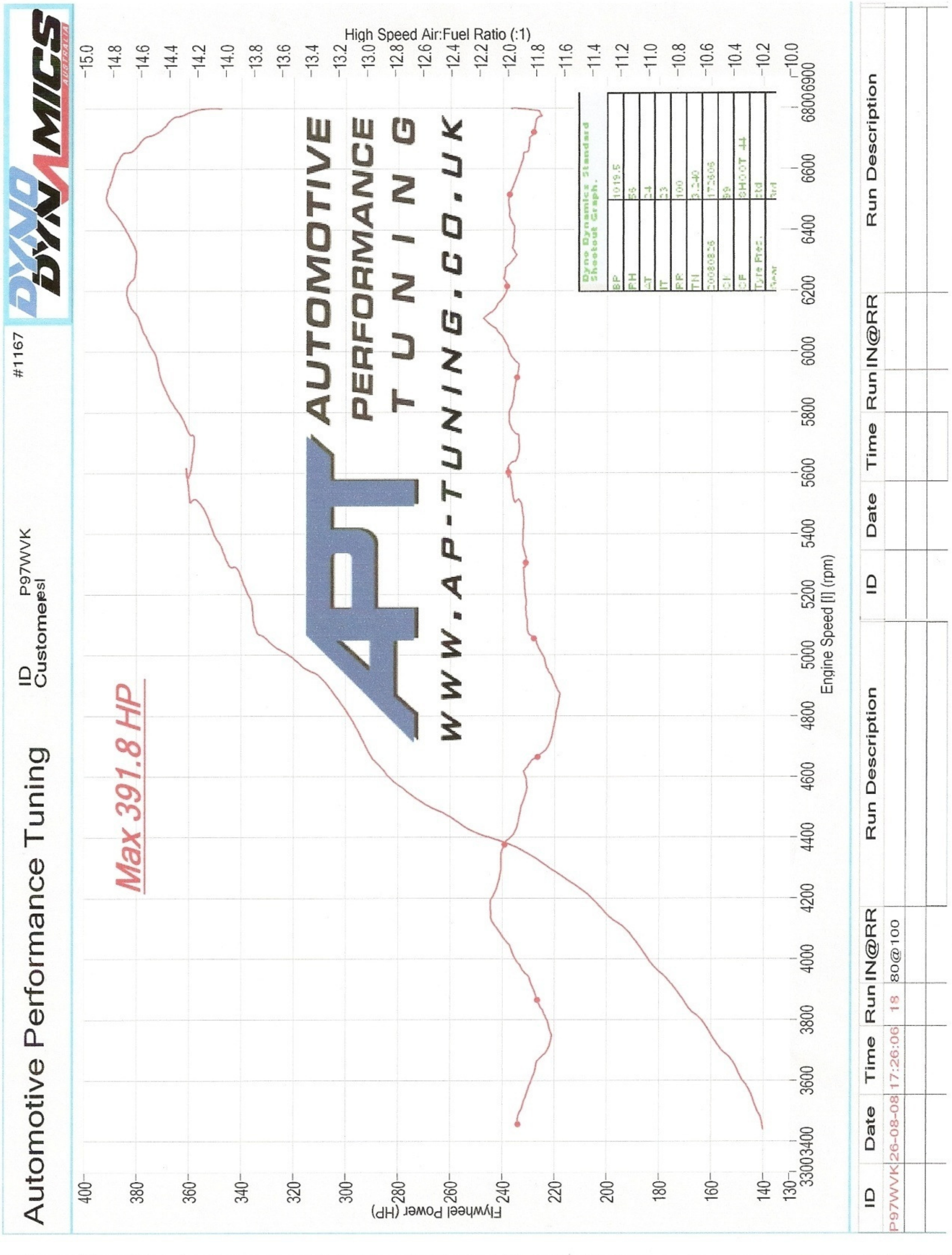


Figure 33 - MAP system power output (part 1)

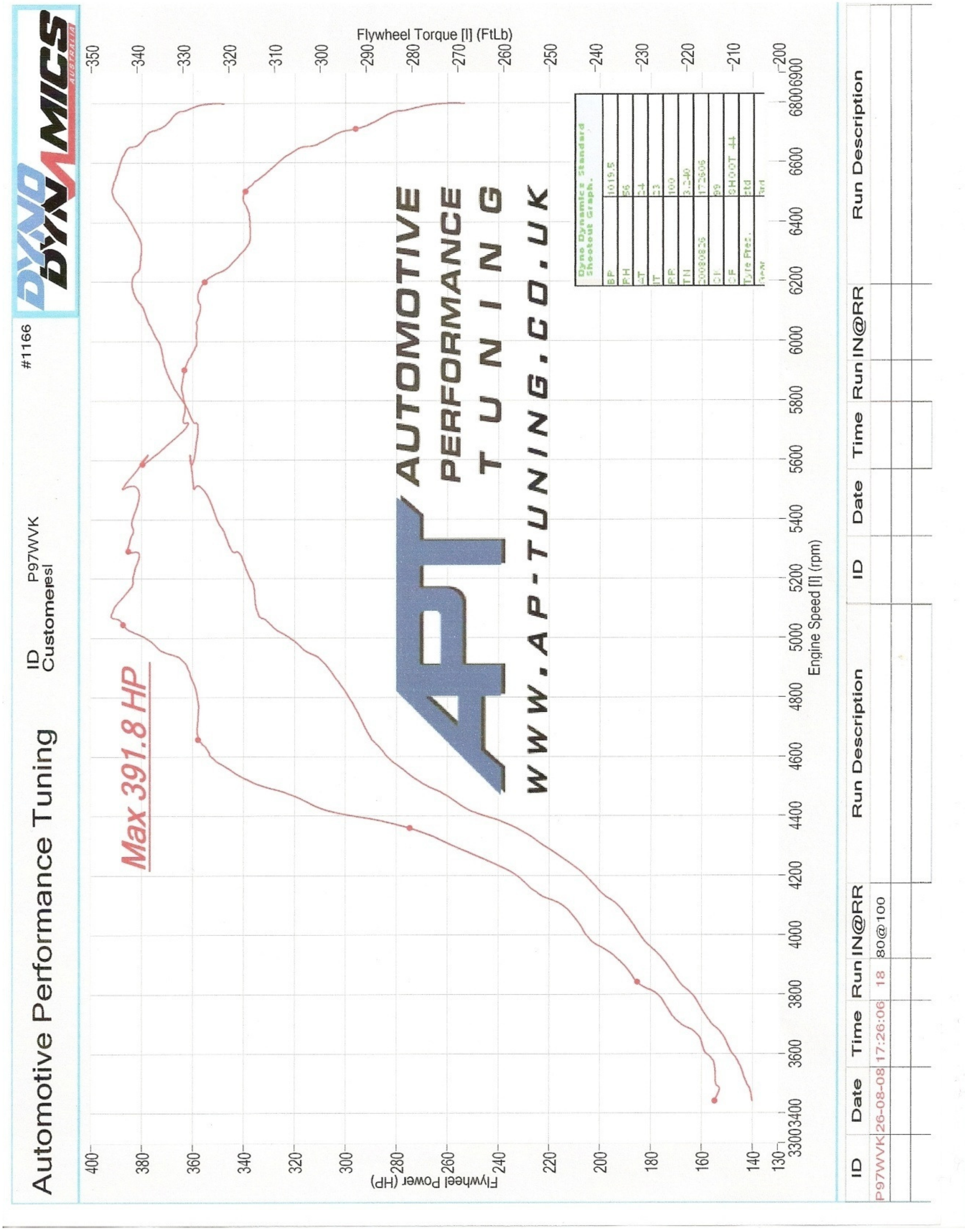


Figure 34 - MAP system power output (part 2)