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An Investigation Into Water/Methanol Injection Tested On A Chassis Dynamometer

School of Engineering

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

Signed:

Date:

Abstract

Present automotive engine emission regulations have led to the increase of downsized turbocharged engines. With engineers aiming to increase Brake Mean Effective Pressure and thermal efficiency, the propensity of engines to knock is increasing. Current solutions to reduce knock are over fuelling, and a retarded ignition point. This however causes issues such as exhaust valve damage, and poor fuel consumption. A solution to this problem is Water Methanol Injection. This is a process to reduce intake temperature with the evaporation of the water, increasing Octane rating of the fuel using methanol, and aid the reduction in emissions such as CO₂, NO_x, and UHC. Water/Methanol injection assists in using stoichiometric fuelling, in turn lowering fuel consumption levels.

In this study, a water methanol injection system has been installed on a 2.0 Litre 4 cylinder Turbocharged Gasoline engine. The Water/Methanol was injected into the intake plenum of the vehicle. A 50/50 mixture, a 100% water mixture, and a 100% methanol mixture has been used to analyse their impacts. The effect the Water/Methanol injection has on knock propensity, exhaust temperatures, and emissions has been critically assessed.

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1.0 Introduction

The aim of this project was to examine the impact of a water methanol injection (WMI) process in a modern forced induction engine. Over 130 test runs using a chassis dynamometer have been completed for this project, taking over 300 hours.

A Nissan 200SX was used for the project, shown in figure 1. The 2.0 4 cylinder engine was fitted with a Water/Methanol Injection system and was tested on a chassis dynamometer with a variety of sensors to measure multiple outputs. Exhaust temperatures, lambda, mass air flow and power were all measured and analysed.



Figure 1 S14 in Dyno Cell

This project has been undertaken alongside Jack Hazlewood's investigation into vehicle ECU calibration. The same vehicle has been used, with some of the work undertaken at the same time. Both reports have vastly different aims. This report investigates the effect of WMI on exhaust temperatures, knock, and ignition timing, while Jack Hazlewood's report considers varying fuel octane ratings, and calibrating an ECU.

The main aim of water/methanol injection is to act as a knock suppressant. It sprays a fine mist of a water/methanol mixture into the intake of the engine, in order to lower combustion temperatures and increase octane levels.

Modern turbo charged engines run with very high temperatures, as a result of higher compression ratios, pressure charging, and down-sized engines with high specific

outputs. Many engines are limited by knock. Knock is started by the spontaneous ignition of the unburned charge ahead of the flame front (Berni, Breda, D'Adamo, & Fontanesi, 2015). This can lead to negative work done and a loss of power due to a retarded ignition point. Prolonged knock can result in damage to engine components, such as the head gasket, piston rings and bearings.

To prevent Knock from occurring, manufacturers are increasingly using methods such as enriching fuel mixtures to lower temperatures and retarding ignition points, sometimes to even after TDC (Top Dead Centre), or reducing boost levels. Having an unnecessarily rich fuel mixture can lead to poor brake specific fuel consumptions.

WMI is a process that can reduce intake temperatures, reduce the likelihood of knock, lower exhaust temperatures and even lower emissions.

2.0 Aims and Objectives

The aims of this project are;

- Install a water/methanol injection system to the engine.
- Examine the effectiveness of the water/methanol on two levels using a chassis dynamometer;
 1. Knock control
 2. Exhaust temperatures

A water methanol system will be added to the S14, to inject a water/methanol mixture into the intake charge of the vehicle.

The vehicle will be tested on the Maha Dynamometer with multiple sensors.

The data will be analysed to find;

1. Ideal Mixture for the Water/Methanol
2. Ideal Flow level for optimum performance
3. Effect of water/methanol on combustion and emissions

2.1 TIMING PLAN

The investigation began in October 2018. Initial discussions with supervisor Malcolm McDonald established the report would be based around a WMI system, and the Nissan S14.

A Gantt chart was produced to follow a timing plan, shown in figure 2.

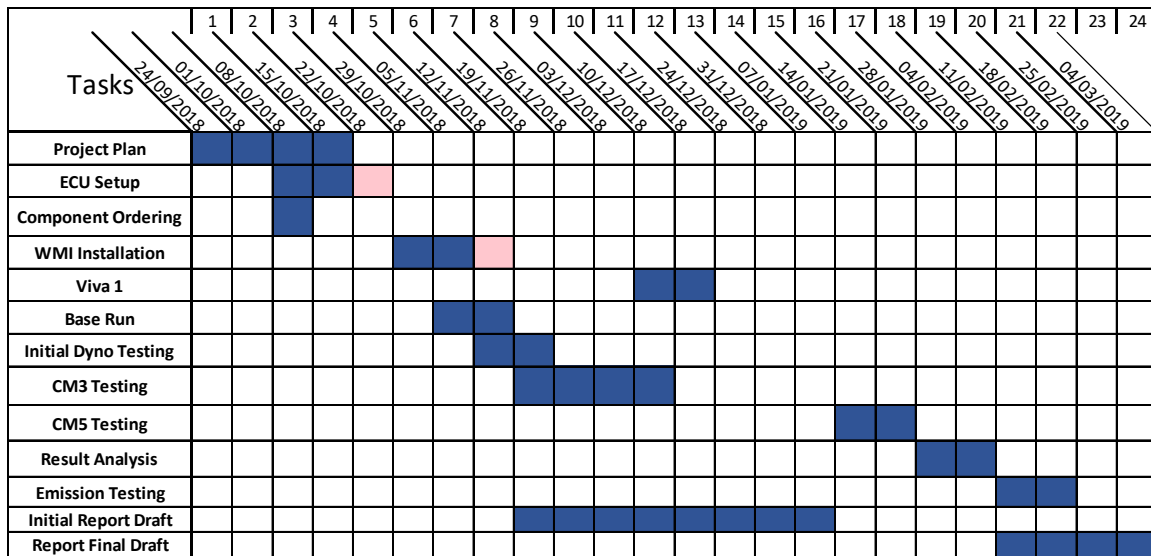


Figure 2 Gantt Chart

Due to issues with the vehicle, limitations on access to facilities, and other issues, the Gantt chart was not a realistic depiction of timing. The chart was useful for initial planning stages and as a general idea to test timing.

3.0 Literature Review

3.1 NISSAN 200SX

The vehicle was a key part of this project. It is a 1998 Nissan 200sx S14a, which is a sports touring car and is particularly popular to be used as a drift car. This is because of the front mounted engine with rear wheel drive. This allows more ability to control torque to the rear wheels, a pre-requisite of initiating and sustaining drifts (Abdulrahim, 2006).

The engine is a Nissan inline 4, four stroke engine. It was produced between 1989 and 2005 in various displacements and power outputs. The engine, an SR20DET, was featured in the S14 and sold in the UK from 1995, it produced 197 bhp and was sold with a 5 speed manual transmission. It was originally released in Japan in 1993, facelifted in 1996, with production ceasing in 2000 (Auto-Express, 2018).

3.2 WATER METHANOL INJECTION

One of the main aims of Methanol injection is to act as a knock suppressant. Knock occurs when the air fuel mixture in the cylinder begins to ignite before the ignition point. This can be caused by multiple factors;

- Low quality fuel
- High intake temperature
- Advanced Ignition point
- Lean air fuel ratio
- Higher Boost pressure
- Carbon Deposits

Knock is an increasing issue in the Automotive Industry. Downsizing engines in order to meet emissions targets, in addition to higher levels of pressure charging, is resulting in higher cylinder pressures and temperatures, further increasing the problem (Khatr, 2019).

Higher intake temperatures can be caused by a few different factors. As the ignition point is advanced, this can lead to higher cylinder pressures and temperatures. Retarding the ignition point is a proven method of reducing the propensity of knock (Wang, Liu, & Reitz, 2017). This is a commonly applied strategy, and is included in most modern vehicles as an ignition trim if knock is detected, or more likely to occur. Retarding the ignition point can reduce cylinder pressures. This is partially due to the combustion occurring in a larger volume area, reducing cylinder pressure. A study by Desmond E Winterbone in 2015, in his book Advanced Thermodynamics, analysed the impact on pressure and temperature when changing the amount of spark advance. Winterbone found that advancing the ignition point increased peak pressure in the cylinder, in addition to increasing peak temperature. Release temperature was however lower with the advanced ignition point. Retarding the ignition point reduced peak pressure and temperature, despite an increase in release temperature. Retarding the ignition clearly can reduce the propensity to knock, could reduce NOx emissions due to the higher exhaust temperature, however may have an impact on exhaust valves (Winterbone, 2015). 692° is the base-line in figures 4 and 5, or interpreted as 28° before top dead centre, with 687° being 5° advanced, and 697° and 702° being retarded 5°.

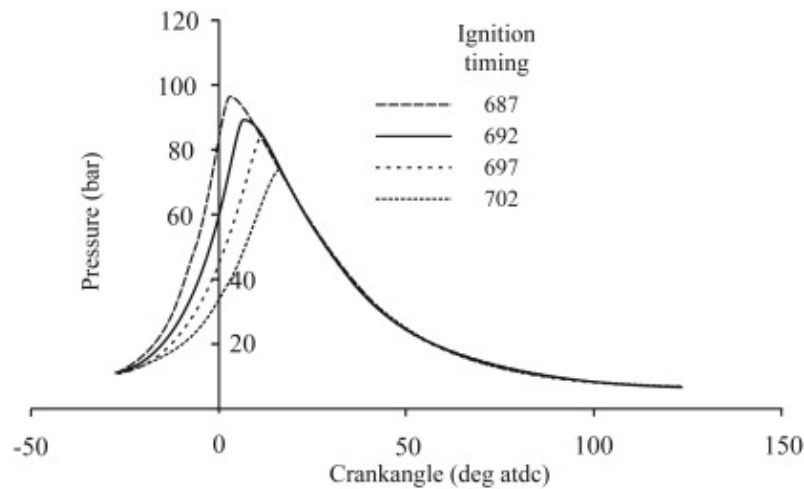


Figure 3 (Above) Cylinder Pressure Diagram for varying ignition timing (Winterbone, 2015)

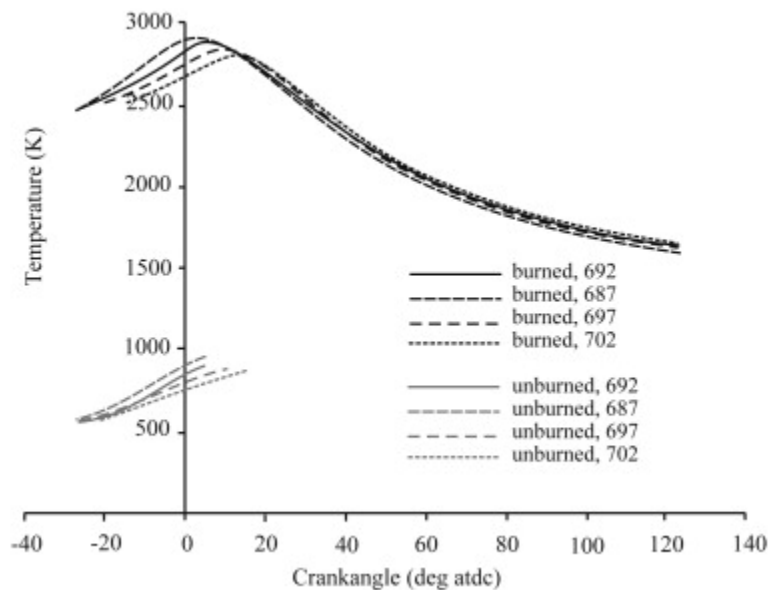


Figure 4 (Above)Cylinder Temperature Graph with varying ignition timing (Winterbone, 2015)

Retarding the ignition point has multiple negative impacts. Mean effective pressure is lower, poor combustion phasing and higher exhaust temperatures (Khatri, 2019). Manufacturers who take this approach often enrich the fuel mixture to control the exhaust temperature, this has a negative impact on BSFC.

A report from the 37th International Vienna Motor Symposium, 2016, titled Optimization of Gasoline Engines by Water Injection, claimed that with use of water injection, ignition advance can be close to MBT timing in the knock limit operating area, meanwhile operating the engine at a Lambda of 1, therefore reducing fuel consumption and CO₂ emissions (Pauer, Frohnmair, Walther, Schenk, & al, 2016).

Research by R. Lanzafame in 1999 examined in thorough detail the impact of water injection. Lanzafame claimed that water injections main benefits are to reduce NO_x emissions, and to replace the anti-knock additive in the petroleum refining industry (Knock inhibitor). Lanzafame injected water into the intake of a CFR (Cooperative Fuel Research) engine, at a flow rate of 13 cc/min (Lanzafame, 1999). The conclusions from this research found;

1. Water increased Octane rating of a fuel, from RON 70 to 93
2. NO_x emissions were approximately 50% reduced. With rich mixtures carbon monoxide emissions decreased, however when water flow was equal to fuel flow, hydrocarbons increased around 20%

Further research into water injection in 2019 by Jayesh Khatri et al. found that as quality of fuel rises the amount of water required decreases. Khatri found that water injection allowed MBT timing with spark advance, the MFB50 (Mass fraction burned 50%) timing improved despite increasing burn duration. Regarding emissions, Khatri's research further emphasised the point that with a water injection system allowing stoichiometric conditions, CO emissions were reduced, however NO_x levels are increased. The conclusion of Khatri's report is that water injection is an alternative for knock suppression, however requires further research.

A leaner mixture can result in a slower burn, and a less adiabatic reaction. This can lead to more heat transfer and cause cylinder temperatures to rise.

By injecting water methanol into the intake charge, two problems are being solved. The injection into the intake plenum causes a drop in temperature due to the evaporation of the water. In addition to reducing the intake charge temperature, by adding methanol to the intake charge, this is effectively increasing the octane rating of the fuel. Pure methanol has an octane rating of around 110 RON (Eyiodogan, 2010). The water

methanol injection does not lead to power increases in itself, but allows for further changes, such as advanced ignition timing or increased boost pressure. These benefits will be analysed in depth throughout this project.

Water methanol injection is not a new concept, with the first traces of the idea going back as far as the early 20th century. The first experimentation can be attributed to Sir Harry Ricardo. It was discussed in his book, *The High Speed Internal Combustion Engine*, in 1927. This research was allegedly used by Germany in WW2 in the BMW 801 and DB605 air craft engines. MW50 (Methanol/Wasser), water/methanol with a 50% mixture, allowed significant power increases when necessary, such as take-off or combat situations (Jane, 1989). Figure 5 shows the significant increase in power (HP) with the use of MW50.

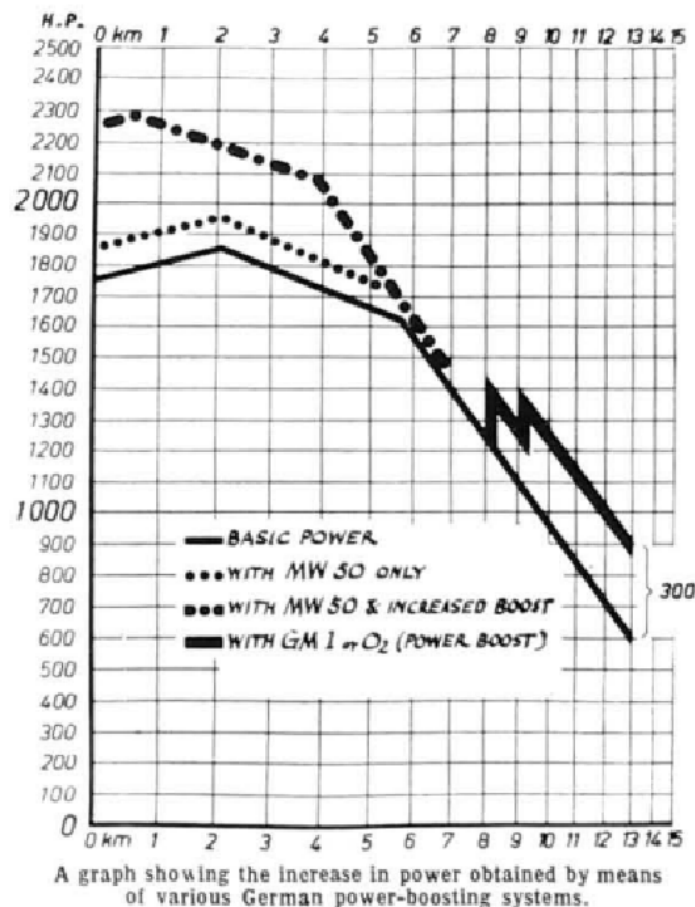


Figure 5(Above) Graph showing increase in power with MW50 (Jane, 1989)

The increase in maximum speed is also considerable. On the DB603 engine, top speed can be increased by circa 25 mph, which could be incredibly useful in a combat situation. This engine was famously used in the Messerschmitt BF 109 (Jane, 1989).

Engine	Altitude (ft.)	Normal h.p.	Increased h.p. using MW50	Normal max. speed (m.p.h.)	Increased max. sp'd using MW50 (m.p.h.)
DB 603 L	sea level	1,800	2,100	339	359
"	37,000	—	—	439	—
"	34,400	—	—	—	463
"	29,600	1,450	1,750	—	—
DB 603 E	sea level	1,800	2,250	342	370
"	27,000	—	—	417	—
"	22,300	—	—	—	434
"	18,000	1,630	1,900	—	—

Figure 6 Table showing increase in power and speed with MW50 (Jane, 1989)

Research by Yong Sun and Michael Fischer concentrated on water collection systems in the exhaust to negate the need for a consumer to constantly fill the water tank. In their testing they found that water injection allowed fuel enrichment to change from 15% to just 1%, yielding a 13% increase in fuel economy. This in turn reduced HC and CO emissions by 84% and 93% respectively. Thermal efficiency was also found to improve by 4.5%. Furthermore, the water injection was found to have a minimal effect on the three way catalyst efficiency. Water collection efficiency was very high, except at low engine speed situations, allowing a near pH neutral condensate to be collected (Yong & Fischer, 2018).

Early usage of water injection in aircraft engines found that injection of water at a 1:10 ratio to fuel increases octane levels and engine output, up to almost 50% (Johnson, 1977).

The first automotive application was the 1962 Oldsmobile Jetfire. This was the first mass produced vehicle to utilise a water methanol system. Figure 7 shows the marketing of the Jetfire, making emphasis of it being an “Automotive first”.



Figure 7 Marketing poster for Oldsmobile Jetfire

This vehicle used “Turbo Rocket fluid to prevent detonation during supercharged operation.” Oldsmobile utilised a control valve to inject the “Turbo Rocket Fluid” into the vehicle intake when pressure reaches 1psi over atmospheric. Turbo Rocket fluid is a 50/50 mixture of water and methanol (Lewis, Burrell, & Bell, 1962). Figure 8 shows a cross section of the Oldsmobile engine, with the injection system visible on the right hand side, highlighted.

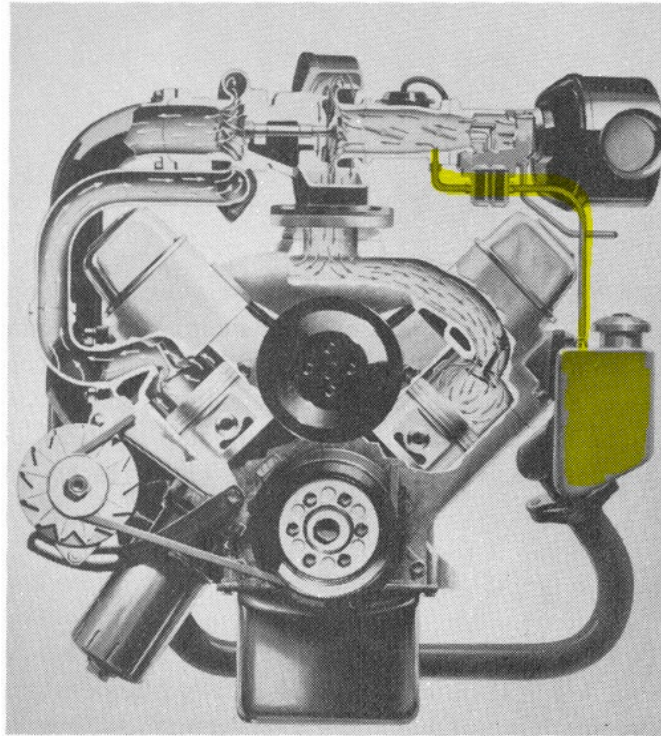


Figure 8 Cross section of Jetfire engine (Lewis, Burrell, & Bell, 1962)

In recent years few vehicles have used a Water Methanol system. Saab produced a water injection system on its 99/900 Turbo models, changing it to a Turbo S. The installation of the water injection system is shown in detail in the manual provided when purchasing the system. The manual quotes an increase in engine output from 145 to at least 160 bhp (Saab-Scania AB, 1988). The installation of the methanol injector is situated in the pressure pipe, before the intake plenum. This is shown in figure 9.

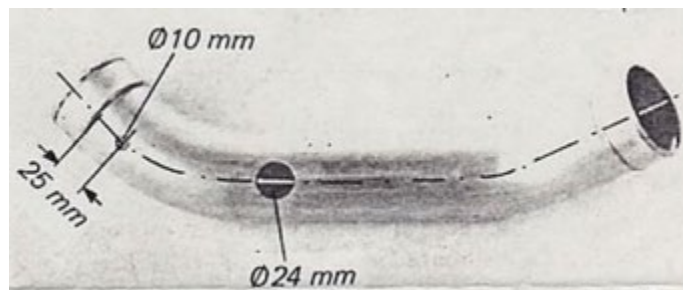


Figure 9 Diagram of injection installation from Saab manual

BMW have been the most recent manufacturer to mass produce a water injection system. The BMW M4 GTS is a high performance sports coupe produced since 2016.

This had a higher engine power output, achieved by use of a Water Injection system provided by Bosch. The water injection reduced intake air temperature by 27°C (Brooke & Birch, 2016). Figure 10 shows the system as a cross section.

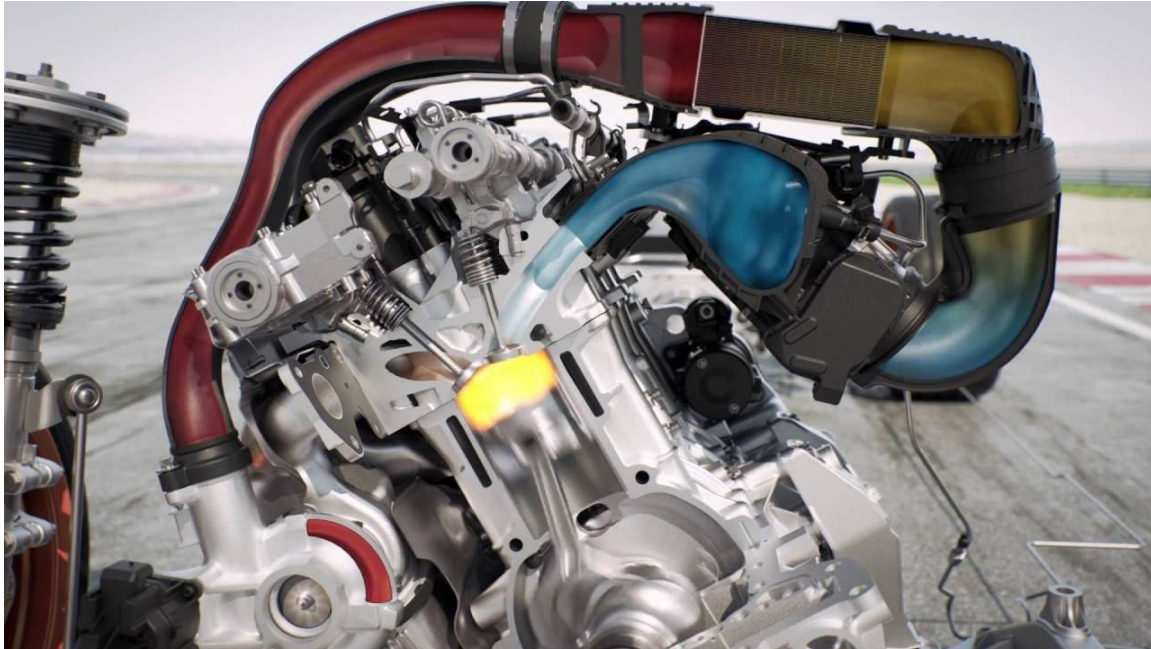


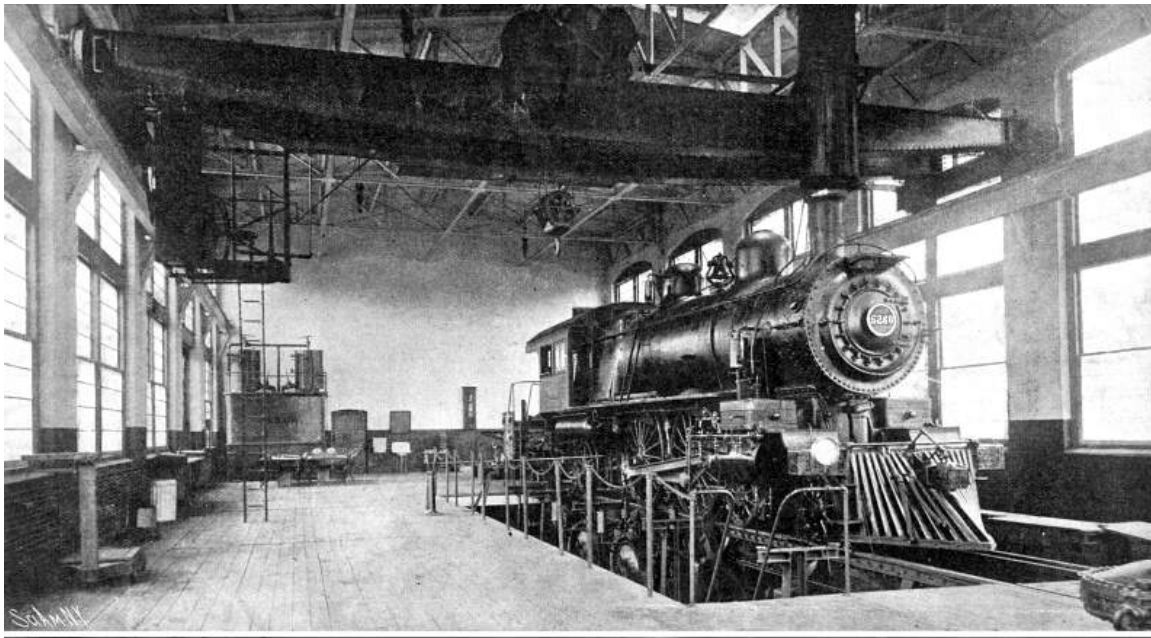
Figure 10 CGI Cross section of BMW Water Injection (BMW AG, 2016)

Khatri's research makes note of the fact of the benefits of water injection not being measured at low engine speeds, due to the low air flow mass and lower exhaust temperatures (Khatri, 2019). This is further emphasised by Berni et al in 2015, who found the lower intake temperature at low rpm conditions to negate some of the benefits of water methanol injection. These results are echoed in the first WMI test completed, which used methanol injection from low rpm's and resulting in a considerable drop in torque, shown in figure 31. It is worth noting that research suggests a pressure charging system is required for water/methanol injection to work effectively. Lanzafame found a low intake temperature and pressure, does not give water sufficient time to vaporise in the compression stroke, not vaporising until after combustion is under way (Lanzafame, 1999).

3.3 DYNO TESTING

Using the UWTSD chassis dynamometer has been an integral part of this project. Therefore an understanding of the dyno procedure, and how it works has been important in order to both carry out testing, and subsequently interpret the results.

Dynamometers originated in the era of the steam engine. Steam locomotives required development, and testing could not all be completed on the already busy train lines. These first dynos measured work, tractive force, power, velocity and others, to a resolution of around 0.1s (Vierling, 2010).



Interior of Main Laboratory of the Locomotive Testing Plant.

Figure 11 Locomotive on early dynamometer (Vierling, 2010)

The term horsepower was coined to market James Watt's steam engine. Watt observed that an average work horse could turn a mill wheel of a 3.7m radius, 144 times an hour (2.4 times per minute). Watt estimated the average work horse to have a tractive force of 180 pounds, or 800 N.

$$Power = \frac{Work}{Time} = \frac{Force \times Distance}{Time}$$

Watt calculated a value of 32,572 ft.lbf/min (foot pound force per minute) (Vierling, 2010). This value was used to market his engines to potential customers who were not using steam engines, but still using horses.

In the modern era, power measurement requires standardization in order to remain comparable from region to region. The *Système Internationale d'Unités*, adopted in 1960, determined one metric horsepower (Pferdestärke), to be 735.49875 watts. There are now many standardization factors, to account for various changes such as humidity, pressure etc. These include SAE net power, DIN 70020, and ISO 1585. Vierling's book led to the choice of ISO 1585 for this product, due to its popularity.

Dynamometers in the automotive industry remained in the domain of the manufacturers and motorsport for a considerably long time. It was only with the introduction of regular emission tests around the 1970's that dynamometers became mass produced. These emission regulations were driven by "the risk of air pollution, the oil crisis, and the increased ecological consciousness (Vierling, 2010)".

Modern dynamometers have multiple options for applying a braking force. The main technologies are;

- Hydrokinetic
- Inertia Systems
- Eddy Current

Hydrokinetic systems make use of a water brake, similar to that of a classis torque converter automatic transmission. These systems are relatively cheap to produce, and able to be used on nearly any scale. However there are a considerable number of disadvantages to hydrokinetic systems. Accurate modulation of braking force is difficult due to numerous variables, and the systems are prone to defects and faults (Vierling, 2010).

Inertia systems use their rotating masses in order to brake. These cannot apply a load at a constant velocity, or simulate a varying load drive cycle. Inertia systems are mostly used for simply measuring maximum power, which is only a small task required of modern day dynamometers.

Eddy current systems are able to use AC and DC motors as both driving motors and braking generators. They are relatively expensive and large, mostly finding applications in the automotive industry. These systems are most suitable for performance and emission testing. Electro-magnetic induction is used to create a torque against the driven wheels and brake selectively. These braking systems are effective up to around 1000kW. Excluding bearings, these systems are also virtually friction and therefore maintenance free (Vierling, 2010).

The most popular systems are a hybrid, making use of an inertia system, and also an eddy current system, to make the best of both worlds (Vierling, 2010).

The actual rollers are an important feature of a dyno. Small rollers do not accurately depict the real behaviour of a tyre. Rollers that are too small will cause extra flex in the tyre, therefore resulting in larger rollers having a more accurate result. Many dynos use 2 rollers, one driving and one braking, with the wheel situated between. This setup is used by SCM Remaps, based in Llanelli, using a Dyno Dynamics Dynamometer, shown in figure 12.



Figure 12 Dyno featuring double roller (SCM Remaps, 2019)

For more realistic simulation of power, the tyre is situated on top of one larger roller. Due to the higher mass and less tyre deflection, these are more suited to high performance vehicle testing. This roller is used in the UWTSD dyno.

Ventilation is vitally important for vehicle testing. A cool air supply is needed, in addition to adequate extraction. An ambient air temperature that is too high can have a severe impact on the accuracy of results. When determining what extraction system for basic workshop conditions, the following formula is used from Vierlings book.

$$V = 1.2 \times V_h \times 0.0363 \times n$$

V = Required extraction volume

V_h = Engine displacement

n = Engine speed (RPM)

Using this formula would show an extraction system providing 609 m³/h.

When considering performance testing, temperature should be taken account for. This is shown in the formula below, where λ is volumetric efficiency (Vierling, 2010).

$$V = V_h \times t \text{ (Celcius/K)} \times \lambda$$

Assuming an exhaust temperature of 500 degrees, and a VE of 1.2, an extraction of 1115.8 m³/h. Overlooking the temperature could result in the installation of an extraction system not suitable to its operating conditions. This oversight may have been made when choosing the ventilation system for UWTSD's dyno. The extraction system in the University dyno is not adequate and has caused multiple issues throughout testing.

Power is not measured using a dyno. It is calculated by multiplying the torque and engine speed. Rolling resistance on a dyno is considerably more than when on the road.

Vierlings book on Emission Test procedures explains, in good detail, the theory and mathematics behind dyno testing.

The motor drives the wheels and then the dyno rollers, with force F_a . This force exerts torque (M_a) on the dyno roller. Torque from the dyno (MB) is applied as a braking force

as required using the eddy current brake on the rollers. The amount of torque is determined by a strain gauge. The below formula is valid (Vierling, 2010);

$$Ma = J_{Dyna} \times \omega + M_B$$

M_a = Drive torque

J_{dyno} = moments of inertia of the dynos rotating components

M_B = Brake torque of eddy current braking system

ω = Acceleration of dyno's rotating parts (Angular)

This leads to the additional following formula

$$F_a = (M_{Dyna} + M_{rot}) a + F_B$$

Where;

M_{dyno} = rotating dynamometer masses correlated to roller circumference

M_{rot} = Mass of rotating parts of drive train

a = acceleration of roller circumference

F_B = Counterforce of the brake

From this the power can be calculated, as M_{dyno} is known as is F_B , motion variables V and a are known, therefore (Vierling, 2010);

$$P_a = F_a \times v$$

This provides the basis for calculating engine power using a dynamometer.

The Dyno used is a Maha MSR500/2 dyno for cars, with 4 wheel drive ability. Maha is a German company which has made brake testers since 1968. They are well renowned in the industry and provide dynamometers for many high end companies, including Nissan GTR tuning specialist Litchfield Motors, based in Cheltenham, and ECU specialist Emerald in Norwich (MAHA UK, 2019).

The MSR 500 is well suited to performance measurements, with a maximum speed of 300km/h, and maximum power per roller of 1000kW. The front and rear roller speed can be synchronised making it suitable for vehicles with active power distribution, such as Haldex systems. It has the ability to standardise power to multiple standards, such as DIN 70020, ISO 1585 and the Japanese standard JIS D 1001. It can test up to 1000 kW, more than suitable for its place in a Motorsport engineering university.

For the testing of this project, all results were corrected to ISO 1585. This is a common standard in the UK, and allowed for more accurate comparison of results as the standard was applied to all tests completed.

3.4 LINK ECU

Link, manufacturers of the ECU used for this project, specialise in motorsport electronics. They are based in New Zealand, and their ECU's and other devices are found in many different applications, from aircraft to Jet skis, to specialist Drifting cars (Link ECU's, 2019). Link have proven popular as an aftermarket choice for Japanese vehicles, partially due to their prominence in drifting cars, as shown in figure 13 in a 200SX sponsored by Link.



Figure 13 Photograph showing Nissan 200sx drifting (Link, 2015)

Link began with a partnership with New Zealand Rally driver Possum Bourne, who, at the start of the transition from carburettors to fuel injection in motorsport, was searching for a supplier of ECU's for his Subaru WRX cars (Denholm, 2018). The ECU used is designed for a Nissan 200SX. A unique selling point of this ECU is that the vehicles loom does not require modification.

4.0 Methodology

This project has not been a theoretical one. A substantial amount of practical work has been required, with many days spent not only testing, but rectifying issues with the vehicle and calibrating equipment.

4.1 EQUIPMENT COSTS

Before any work could be carried out, multiple components were required in order to accurately carry out this project. A table of costs has been made to show all costs relative to this Water Methanol Investigation. Some of the costs are also applicable to Jack Hazlewood's project. These costs have been shared between both Jack Hazlewood and the author. This also does not include fuel and other consumables such as oil, which has also been a considerable cost. This has not been measured, it is estimated to have cost over £400, assuming 3 miles per test, 130 tests, and 8 miles per gallon. The table of costs is shown in figure 14.

Item	Cost
Link G4+ ECU	£1,300
Coolingmist WMI Kit	£300
CM3 Injector	£40
CM5 Injector	£40
Knock Sensor	£100
Methanol (25 Litres)	£70
AFR Gauge	£170
Turbo Gaskets	£30
Tyres (Rear x2)	£90
Total Cost	£2,140

Figure 14 Table of costs of project

4.2 DYNO SETUP



Figure 15 Photograph showing S14 on Dyno from rear

The initial steps in this project required becoming proficient with and understanding the MAHA dyno. The Dyno was installed in 2018, and was used sparsely before this testing began. Becoming familiar with the process, sensors, software was imperative. Operating the dyno requires a “dyno operator”, and a “safety staff” member. Due to the scale of tests requiring completion, it was not feasible to have two members of staff present at all times throughout testing. For this reason, the author becoming the first student authorised to act as a Dyno-Operator has been vitally important.

Securing the vehicle to the dyno is a vitally important part of the process. The dyno is provided with 2 ratchet straps for the front of the vehicle, and two adjustable chains for the rear, shown in figure 15 and 16. The two rear chains connected to the rear tow hook, and connected to the rear subframe. The front straps connected to the two front tow hooks. These connections ensured a secure fixing to the test bed. Figure 16 shows the front and rear securing of the vehicle.



Figure 16 Photograph of S14 securing points on dyno

Adjusting the test bed wheelbase is also required. This is controlled by the Maha system using the remote control. As other tests on different vehicles were completed throughout the year, the bed required adjusting before most test days.

Exhaust extraction has been an issue throughout testing, with new equipment being provided. The Dyno cell contains two forms of exhaust extraction, both of which are required for testing this vehicle. The main extractor is placed directly behind the exhaust, with the secondary extractor placed over the top to remove any excess gas. Initial testing was completed using a smaller bore hose, composed of rubber. Due to the high temperatures of the exhaust gas, this caused hose failure which stopped many test runs due to the carbon monoxide level reaching 50ppm. Waiting for new hoses caused many delays but was ultimately solved. A hose that has failed is shown in figure 17, which occurred in November 2018.



Figure 17 Photograph showing failed exhaust extraction hose

Multiple sensors were required to accurately measure the results from this test. Exhaust gas temperature was to be measured. To achieve this, the exhaust headers were removed from the car. This took considerable time due to the complexity of the turbo cooling lines. It was decided early on during supervision meetings, that temperature would be measured before and after the turbocharger.



Figure 18 Photo of exhaust manifold being welded

To install these sensors, drilling of the exhaust manifold was required. Due to high risk of shrapnel in the turbo, the manifold needed to be removed from the vehicle. Once removed, a hole was drilled into the manifold near cylinder 1. Two holes were drilled with only one being used. The extra hole required sealing, shown in figure 18. This was made close to the cylinder to give a more accurate temperature reading

of the exhaust gas. The hole was tapped with a tapered thread to ensure a seal. After the turbo charger there was a conveniently placed hole for a lambda sensor, which was blanked with a bolt. The bolt was removed, the same size hole drilled as the manifold, and refitted with two thermo-couplers. The exhaust was refitted, in addition to braided turbo coolant lines due to a small leak.

The thermos-couplers connect to a signal box, shown in figure 19 (L). This box is the interface for all sensors, ambient pressure and temperature sensor, OBD and rpm monitors. The thermos-couplers can be seen in figure 19 (r) seen by the right hand side of the engine with green wires, and seen connected to the signal box.

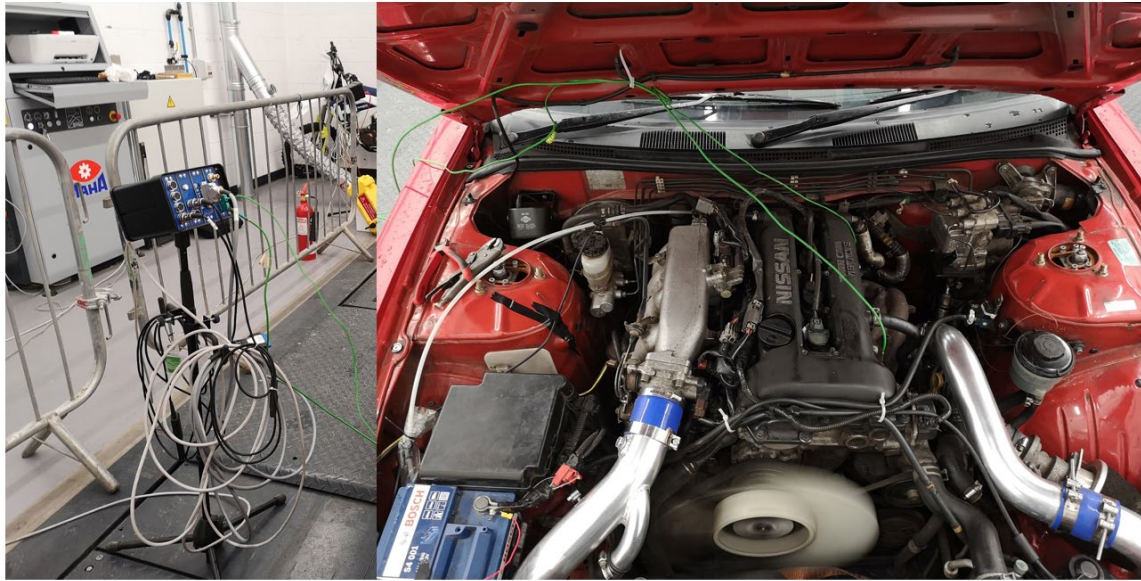


Figure 19 Photograph showing sensors connected to dyno

4.3 BASE RUN

An initial test run was completed with the vehicle as standard. This was to gain a base line and identify any issues with the vehicle that could be rectified early on, minimising impact on the project timing. It was also decided at this stage that throughout testing, only Tesco Momentum 99 fuel would be used. This is due to its high octane level of 99 RON, and cost effectiveness when compared to its competitors such as Shell V-Power.

The base test was completed using the standard Nissan ECU. This was to understand how the vehicle is performing before any changes are made.

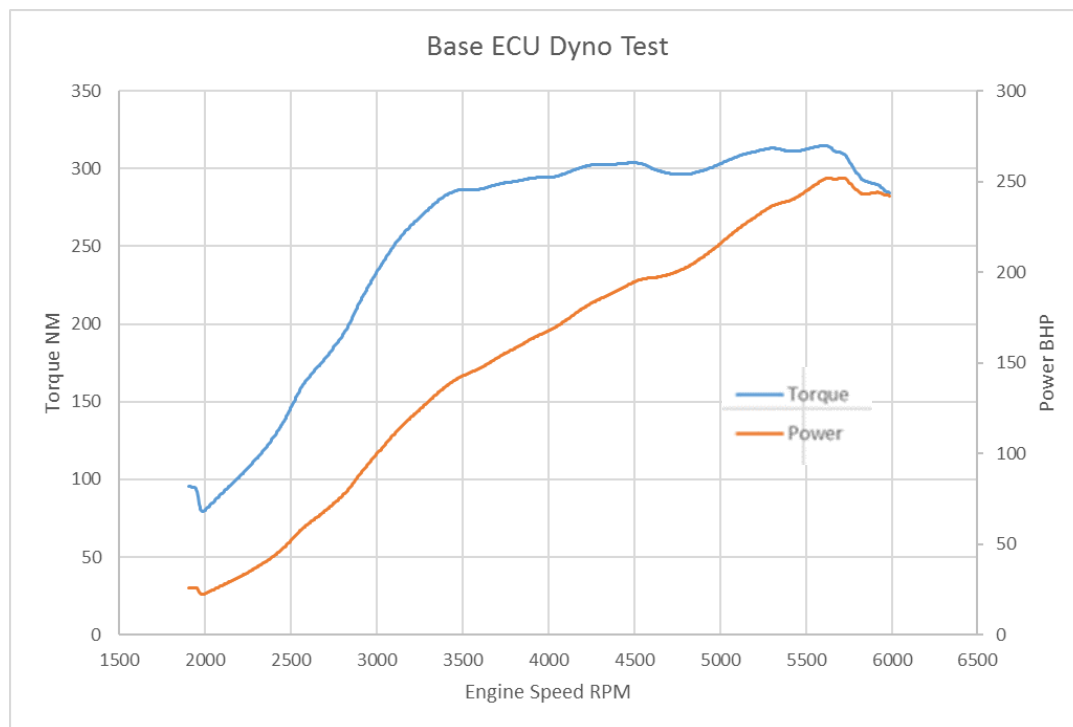


Figure 20 Power/Torque Curve from original ECU

The torque curve was as to be expected, shown figure 20. Torque peaks closely before 3500 RPM. This may be due to the propensity of knock to occur. The ignition timing may be retarded after the ideal timing point, also known as Maximum Brake Torque timing (MBT). Torque drops after 5600 rpm considerably. This may be due to an increase in friction losses as the speed increases.

The vehicle produced a maximum power figure of 252 bhp. This is considerably higher than the standard 197 bhp which was quoted when the vehicle was produced (Auto-Express, 2018). This may be due to 3 reasons;

- Exhaust and Air Filter modifications
- Possible ECU changes
- Low quoted power output

The vehicle was purchased with an aftermarket exhaust and air filter fitted. This may have caused the increase in power. It is also possible the ECU may have been modified, in a process called Flashing. The final possibility is the vehicles original quoted power output being low.

4.4 LINK ECU INSTALLATION

The *Link* G4+ ECU was installed in November 2018. This required removing of the standard ECU. The Link ECU did not come in a protective case, so care had to be taken to ensure static electricity did not harm the components when handling. An anti-static bracelet was use when handling. The case required minor modification to allow a diagnostic cable to be used. Installation required little setup, with a base map for the vehicle being provided. This map did not run perfectly, idle for example was very low. With some modifications to the map the issue was solved.

After installation of the Link G4+ ECU, a test run was completed to ensure the ECU was operating correctly. The base map provided by Link was unchanged. The results were interesting, and an obvious drop in performance was visible.

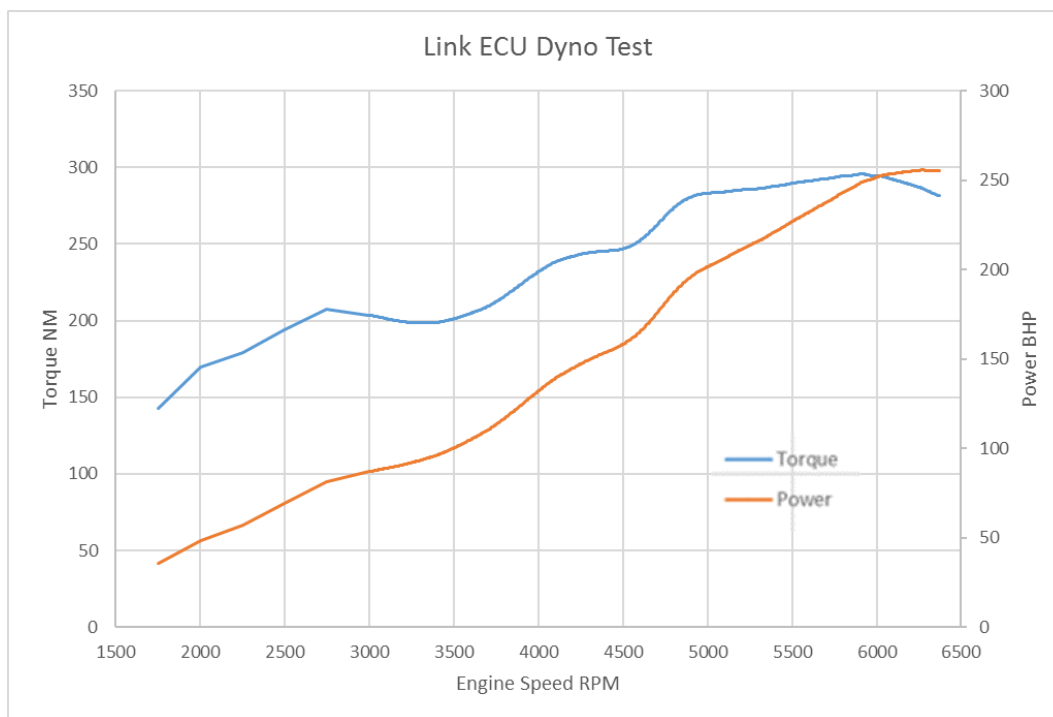


Figure 21 Power/Torque Curve from Link ECU base map

The torque curve (figure 21) is constantly climbing and does not plateau. This may be because of the safe nature of the map. It is designed to be used on any vehicle with this engine, regardless of its modifications. It is not nearing any knock limits, and is not

designed to be used permanently. Jack Hazlewood completed tuning of this map, using the Link software, the dyno, and lambda sensor in order to create an improved map. This is further detailed in his project.

4.5 METH INSTALL

A test was done of the WMI kit before installing to ensure all worked correctly. It was connected to a 12v battery and the injector was connected. When turned on, it worked as it should, delivery a fine mist in a cone shape. The system was checked for leaks, for any delays between activation and delivery of the spray, and to check the flow. Flow was tested over 1 minute, this delivered the quoted value of 270cc/min for the injector, with a pump pressure of 200psi.

The methanol injection kit required installing correctly before any test runs could be completed. The pump and tank required a custom bracket made to fit in the boot. It was situated to the left of the boot, to ensure limited obstruction in the boot. The bracket made use of the CD changer, holder and was riveted into the rear of the boot (figure 22).



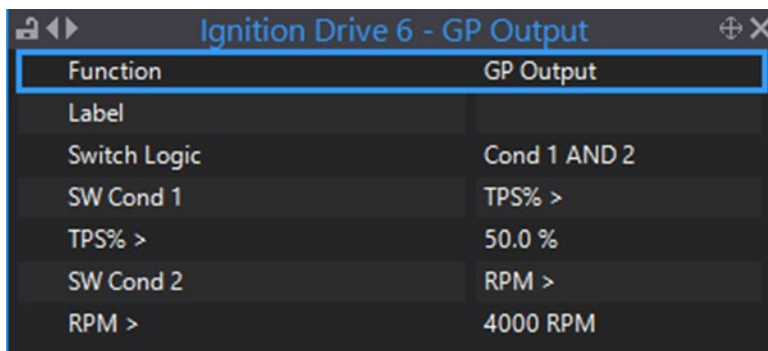
*Figure 22 Photograph showing
Water/Methanol Installation in vehicle*

This ensured it was stable, as a loose fitting could cause considerable problems. The pump was connected to the battery, and had a toggle switch in the centre console. The fluid line was run along the sill of the car, through the firewall into the engine bay.

The aluminium intercooler pipe was removed. A location was selected directly before the throttle body on the intake plenum. An aluminium boss was welded on and using a pillar drill, a 7mm hole was drilled & tapped to fit the water methanol injector. Issues were caused by this as the injector was poorly inserted causing the thread to strip. A good seal on this is a necessity due to the pressures involved.

A control solenoid was fit to the fluid line which opens and closes stopping the flow. The Link ECU was used to control this. Most aftermarket units make use of a controller, utilising a boost sensor. As this project required multiple modifications, the ECU allowed accurate control of the flow. An analog output was set up on the ECU, with the option for 2 conditions to be met when to allow flow. The general conditions to be used will be;

- TPS >80%
- Engine RPM >3500 (Subject to change)



Function	GP Output
Label	
Switch Logic	Cond 1 AND 2
SW Cond 1	TPS% >
TPS% >	50.0 %
SW Cond 2	RPM >
RPM >	4000 RPM

Figure 23 Screenshot showing how WMI is calibrated in PCLink

The throttle position sensor (TPS) condition is set to ensure that water/methanol is only injected under near wide open throttle conditions, as this is when the system is required. The engine RPM condition is set so water methanol is not injected in low engine speed situations. These conditions can be seen in figure 23. High temperatures are rarely found at low engine speeds, so the WMI is not necessary. Aftermarket WMI kit's normally operate using a boost actuated controller (Coolingmist UK, 2019).

The pump has specialist technology, so that when the flow is blocked, i.e. solenoid closed, the flow would stop as pressure builds. When the solenoid opens flow continues. This ensures an accurate control of flow, with little delay as the pump is constantly primed.

There are some issues found with the *Coolingmist* kit. The nozzle has a small outlet, and with the Coolingmist Kit an inline filter is not provided. Debris from the tank, build up from the water, or from any damaged line connectors could cause the nozzle to become blocked. It would not be clearly noticeable flow had stopped. If the vehicle was using an ignition/fuel map designed for meth, this could cause severe consequences. The map may be expecting the cooler intake charge and could run with ignition timing that could cause knock.

On the other hand, if the solenoid was to fail, water/meth could be continuously pumped through the system and could result in a “Hydro-lock” situation, leading to either the engine stalling or considerable damage to components like connecting rods. A further issue is the use of 100% methanol. Methanol is a highly flammable liquid and burns with a nearly clear flame. During testing, on two occasions the methanol kit connectors began to leak. The first leak was on the methanol injector, this leaked a fine mist over the intake plenum. Temperatures around this area are relatively hot, and if mist was to go near the exhaust could easily result in a fire. This leak was rectified using PTFE tape. The second leak, which was more serious, was caused by the connection from the pump to the solenoid failing. Due to the lack of pressure, the pump continuously pumped fluid through the link and behind the trim panel where the solenoid is located. A large amount of liquid leaked, soaking the sound proofing material behind the panel and leaking onto the dyno floor. The wiring for the solenoid was located there and could easily spark and ignite if pure methanol was to have leaked.

In order to carry out combustion analysis, air flow was required. The vehicle is fitted with a mass air flow (MAF) sensor. This is located directly after the air filter. Unfortunately, the Link ECU did not read this sensor. To solve this, the sensor was removed from the car and placed on a flow bench. The positive and negative wires were connected to a 12v battery, and the signal wire was connected to a multi-meter.

With no air flow, a voltage of approximately 0.5v showed. Flow was increased in 0.5v steps and measured. This gave an accurate linear relationship.

4.6 KNOCK SENSOR

A knock sensor was also required for this project. The engine had a knock sensor fitted from factory. This however had two issues. Firstly, the sensor was possibly fitted from factory and may not have been changed. This could affect the accuracy of the sensor due to its unknown history. It may not have been fitted with the correct torque. Another issue is the Link ECU did not detect any reading, through the vehicle loom, for the sensor. To solve this, a Link knock sensor was purchased. This connects directly to the ECU so does not rely on the vehicle loom. The sensor was located under the intake manifold, between cylinders 2 and 3.

After installation, the knock sensor was reading in the ECU. Balancing the sensor was the first step. As the sensor is closest to cylinders 2 and 3, balancing is required to get a more accurate reading of noise levels. The engine was held at 4000 rpm, and noise levels for each cylinder noted. Cylinder gain levels were adjusted to ensure the noise levels were as balanced as possible.

The next step was to input the “non-knock” noise levels. To do this, a dyno run was completed, from idle to max rpm. This was recorded using the ECU to read noise levels. A safe map was used to lower any possibility of knock. The noise at each rpm was noted on average. This is the noise the sensor is reading when no knock is occurring. The knock table can be filled in using this data. The knock table shows the amount of noise to be read before knock is detected and shown on the knock counter. At each RPM, the noise level was increased by 20%. This was to take into account occasional noise spikes.

The accuracy of this was tested on the dyno. Knock was induced by a run at low load and low rpm with the ignition slowly increased. It was noticeable after a certain point that the knock counter increased rapidly. The vehicles map could now be adjusted safe in the knowledge that knock would be clearly visible to prevent damage. The ECU has the ability to automatically adjust the ignition timing when knock is detected. For example it can retard by 5 degrees with a decay of 3 seconds. The decay is to slowly reduce the amount of retard that is added, in order to reduce temperatures and slowly return to

normal conditions. Figure x shows the knock counter from the PCLink software. When the counter raised rapidly, knock was occurring.

Initial runs using the water methanol injection were carried out. The first settings for the WMI was to inject at 90% throttle and above. This was found to cause issues with the engine bogging at low engine speeds so a further condition was added to only inject methanol at 4000 rpm and above. The initial tests showed a drop in torque which was to be expected.

4.7 WMI INJECTOR

It was decided that, in order to gauge the effectiveness of methanol injection, a larger injector was to be used. The injector was removed and replaced with the larger CM5 injector. This supplies 440cc/min, compared to the CM3's 270cc/min. The main tests completed for the CM3 were repeated for the CM5, in order to provide a fair comparison.

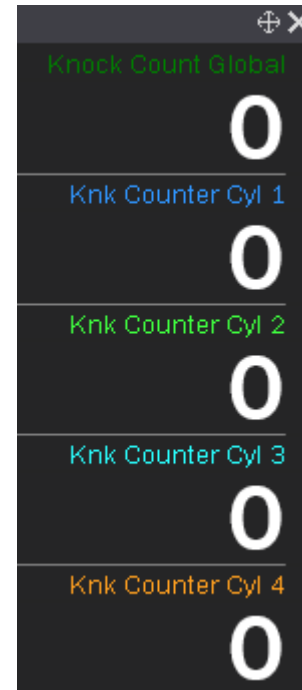


Figure 24 Screenshot showing Knock counter in PCLink

4.8 EMISSIONS TESTING

Emissions testing was carried out using the Bosch Emissions Analyser at UWTSD. Two tests were completed on the vehicle to further examine the vehicle emissions. Each test was separated into two parts. First section was to idle the vehicle for 15 seconds, accelerate to 3000 rpm and hold for 15 seconds, then return to idle. The second part was to hold the vehicle at 3000 rpm. The test was completed twice, one with standard fuelling, secondly using water methanol injection at 3000 rpm. The data was collected from the Bosch BEA 850, shown in figure 25.



Figure 25 Photograph of Bosch Gas Analyser (Bosch 2014)

5.0 Results 2000

5.1 IMPROVED MAP

Data gathering began after the Link ECU was installed. With significant changes to base the map and larger injectors fitted, another test was completed. This is the standard map being used and any changes to timing or fuelling are completed from this map.

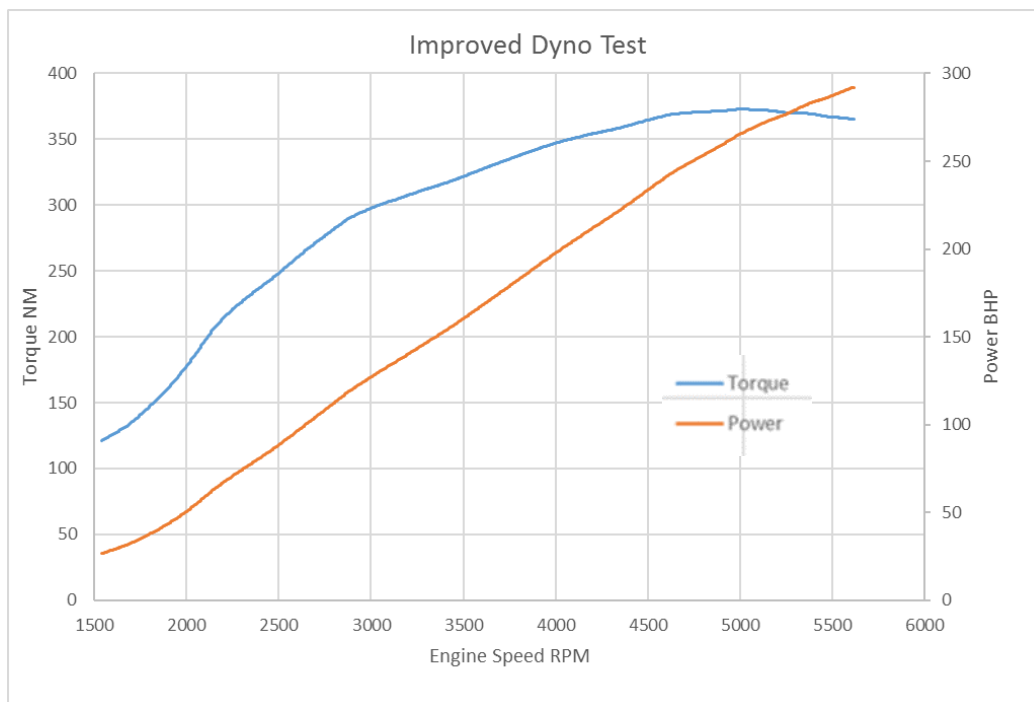


Figure 26 Power/Torque Curve after changes to Link base map

Considerable improvements have been made for this map. The torque curve (figure 26) no longer drops in the mid-range as it did with the Link Base map. Power peaks at the end of the test, at 5870 rpm, hitting 298 bhp. This suggests that power would be higher if the test was completed to, or past, 6000 rpm. Unfortunately, due to exhaust extraction equipment that is not fit for purpose, testing at these engine speeds is difficult and not always possible due to carbon monoxide emissions in the test cell.

The torque from this improved test was compared to the Link ECU. The results show a drastic improvement from the Link base map, torque has improved drastically.

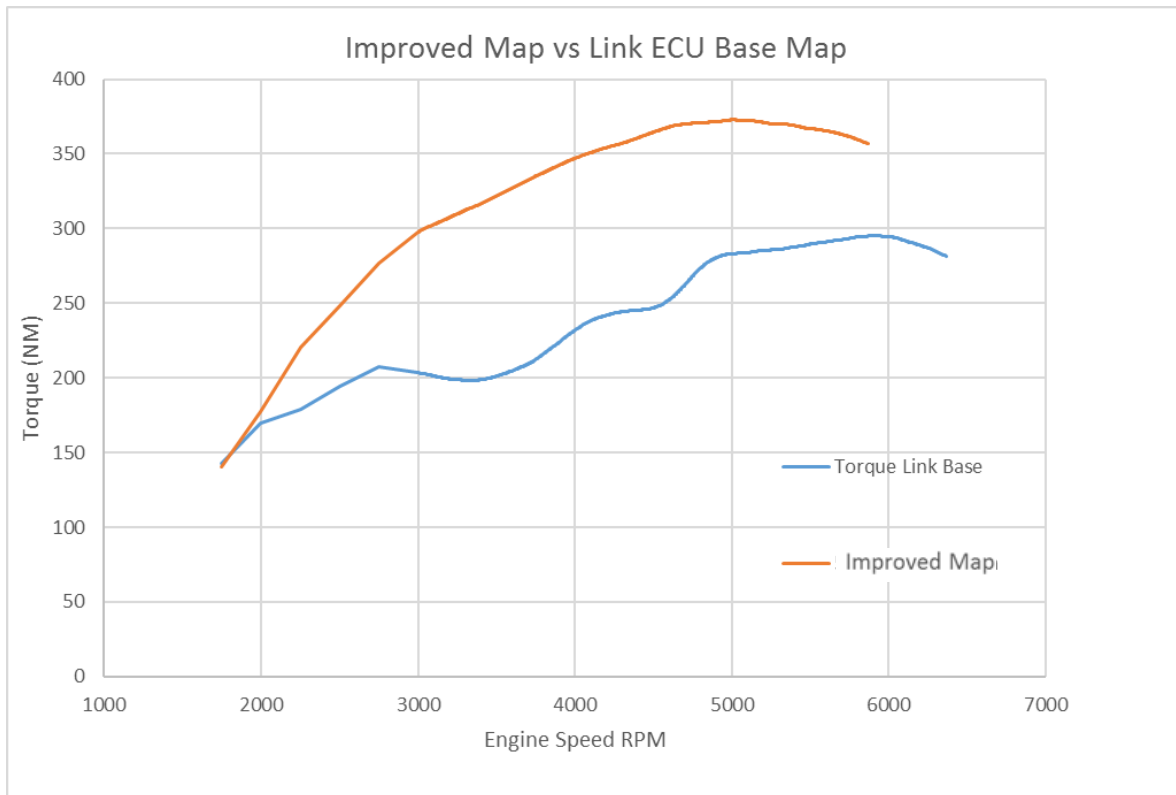
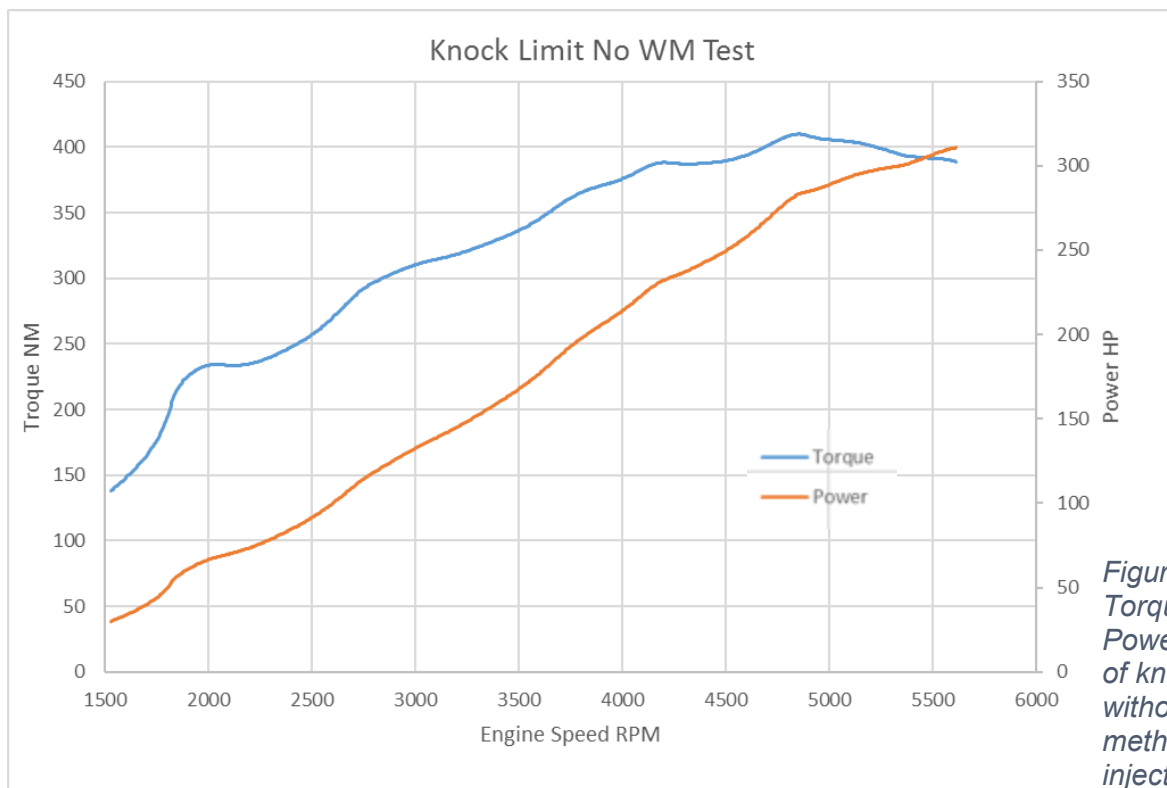


Figure 27 Torque from Link base map compared to improved map

These tests, due to the test settings on the Maha dyno, do not begin at the same engine speed, although this does not affect the validity of the results.

5.2 KNOCK LIMIT

A test was carried out to discover the knock limit. At this stage the knock sensor had been fitted, resulting in being able to be altered to find the point where knock occurs, without causing damage to the engine. Multiple tests were completed, increasing the spark advance 1 degree per test. This was repeated until considerable knock was visible on the counter. Spark advance was retarded 1 degree to just before the point of knock.



This shows a considerable increase in power and torque (figure 28). Torque peaks at 409 NM at around 4800 RPM. The torque curve is not ideal, and could be improved. Fuelling could be adjusted to improve this. Figure 29 shows the lambda values for this test.

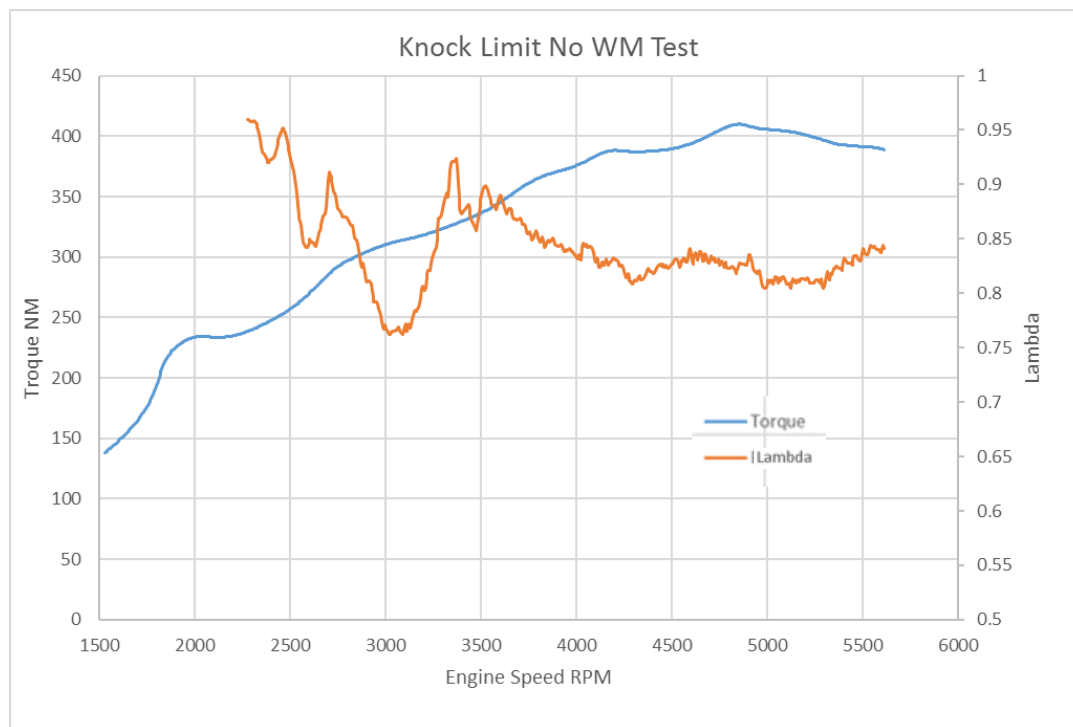


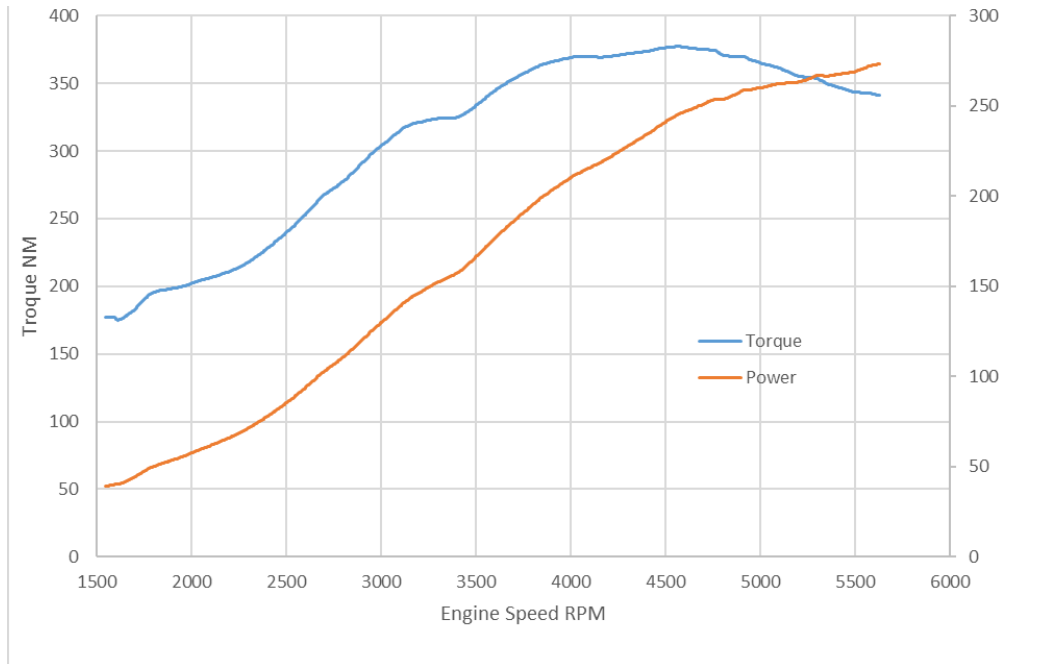
Figure 29 Graph showing torque and lambda values from exhaust

The sensor malfunctioned until 2500 rpm. This is possibly due to insufficient pressure for a reading in the lambda test tube which may affect the validity of these results. Despite the issue, fuelling does seem to be erratic before 4000rpm. Fuel at 3500 could be increased to keep lambda near to 0.85.

5.3 FIRST WMI TEST

The first test using the Water methanol injection was completed. This test was completed with constant WM flow. It was constantly injected throughout the run and did not start at a set RPM. This causes issues with not all water evaporating, affecting combustion.

Figure 30 Power/Torque curve with Water Methanol Injection (Below)



Comparing the torque to the previous test without WMI, the impact of Water Methanol is considerable, shown in figure 31.

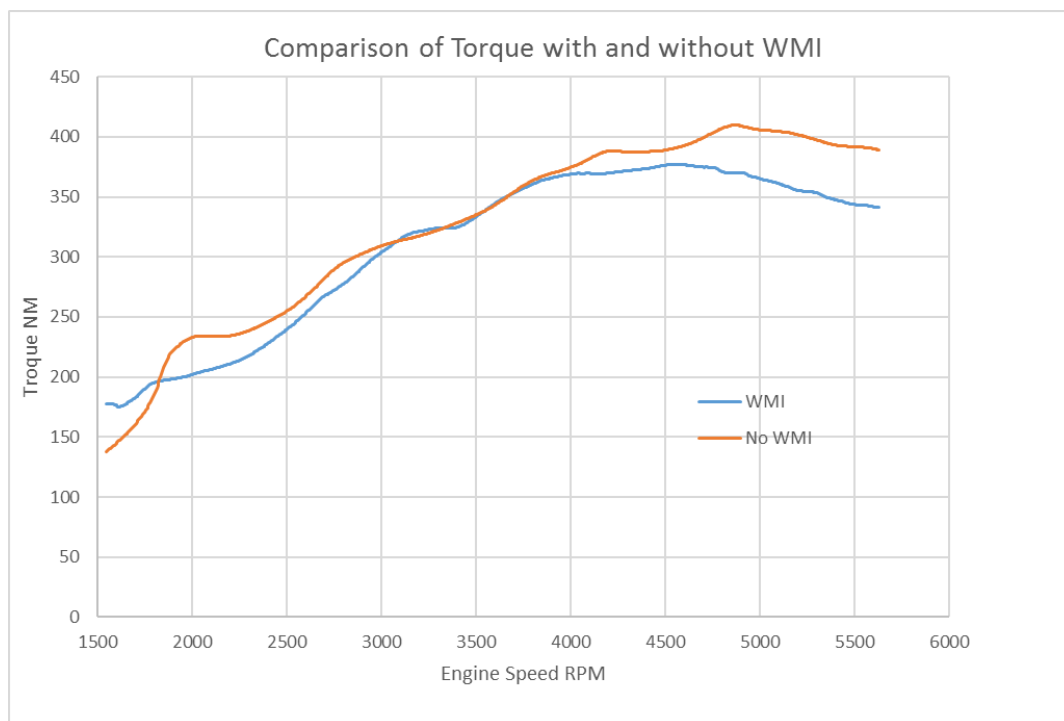


Figure 31 Torque Comparison with and without water methanol injection (above)

There are 2 unique features of this comparison. The low end, around 2000 rpm, is a considerable drop. This could be due to the poor combustion as a result of excess water in the combustion chamber. A similar effect could be causing the drop in torque at the high rpm. As seen in the Lambda values, fuelling is particularly rich at the high rpm. Rich fuelling in addition to the water/methanol could be causing poor consumption and a loss in power. This suggests that in addition to the water methanol injection, fuel could be removed in order to improve the combustion efficiency.

5.4 SECOND WMI TEST

This test continued on from the previous test, however the water/methanol injection did not begin until 4000 RPM. This is to attempt to rectify poor combustion at low engine speeds.

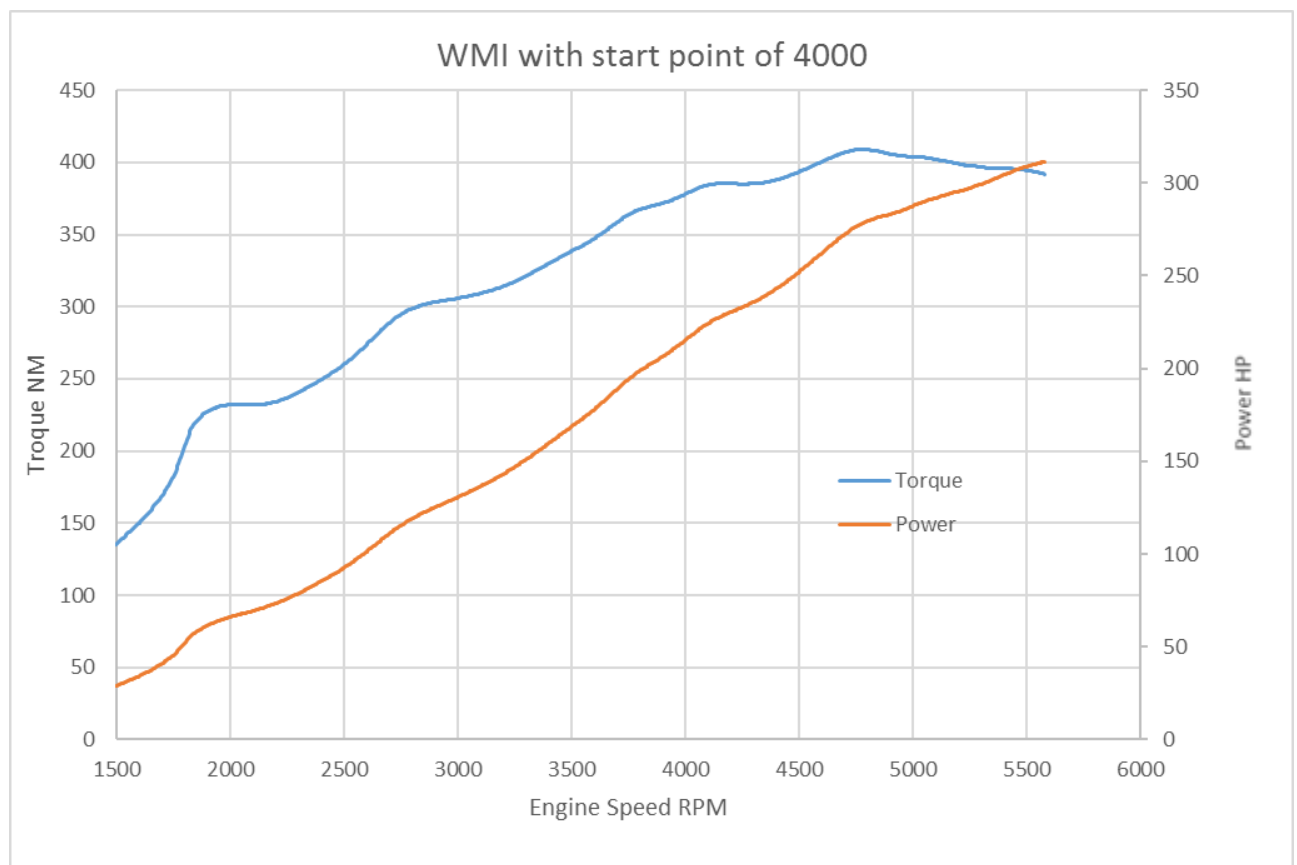


Figure 32 Power/Torque curve with water methanol injection starting at 4000 rpm

The torque curve is still not perfectly smooth and could be improved with fuelling or ignition changes, shown figure 32.

Torque from this run was compared to the torque curve from the test run with constant flow.

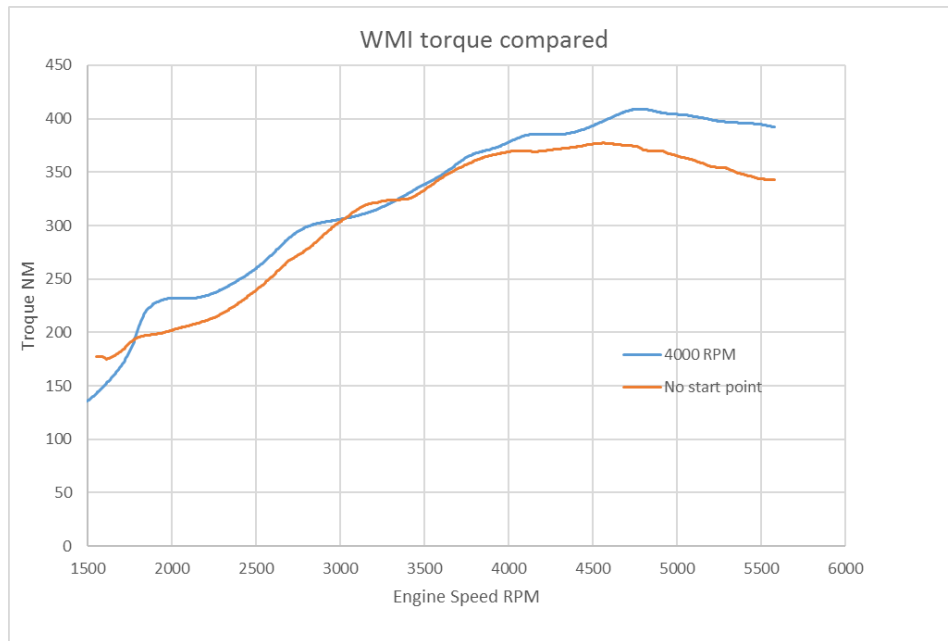


Figure 33 Torque Compared with and without start point of injection

Torque is increased at the low engine speeds as there is no WM injection. The mid-range remains similar in torque levels. Removing fuel at the high rpm's has resulted in a considerable increase in torque.

5.5 100% WATER

A test was completed to analyse the impact of injecting only water into the intake. This would only impact the intake charge temperature and may not increase the octane rating of the fuel as before. The start point for the injection of this test was set at 3300. The decrease in torque is evident immediately on the injection of the water.

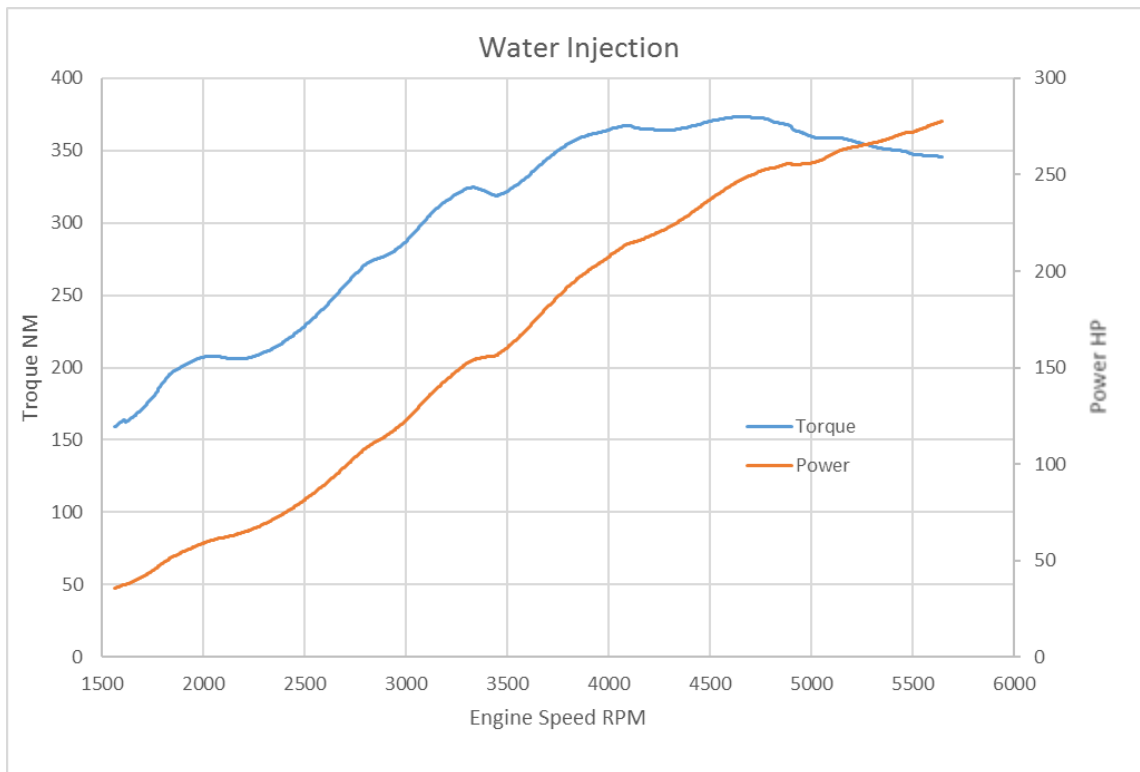


Figure 34 Power/Torque curve injecting 100% water at 3300 rpm

The loss of torque could be due to poor combustion as a result of the increased water. Exhaust temperatures have been compared from this Water test to test 3 due to the similarity in fuel and ignition maps.

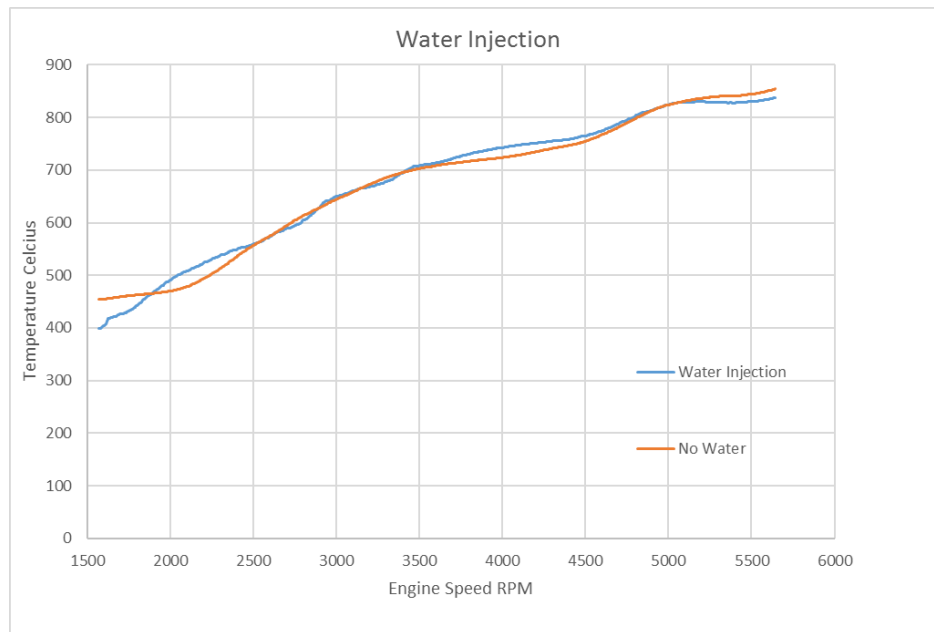


Figure 35 Graph plotting exhaust manifold temperature with and without water injection

There is minimal change in the exhaust manifold temperatures (figure 35). Temperatures have changed minimally in this comparison. Temperatures at 2200 rpm are higher with the water test. Water was not injected at this point which suggests another factor may be causing higher temperatures which has an impact on the validity of the whole test.

5.5 100 % METHANOL

A test was completed injecting 100% methanol. Care was taken on this test due to the high risk of fire injecting methanol. The entire system was checked carefully for leaks prior to and during testing.

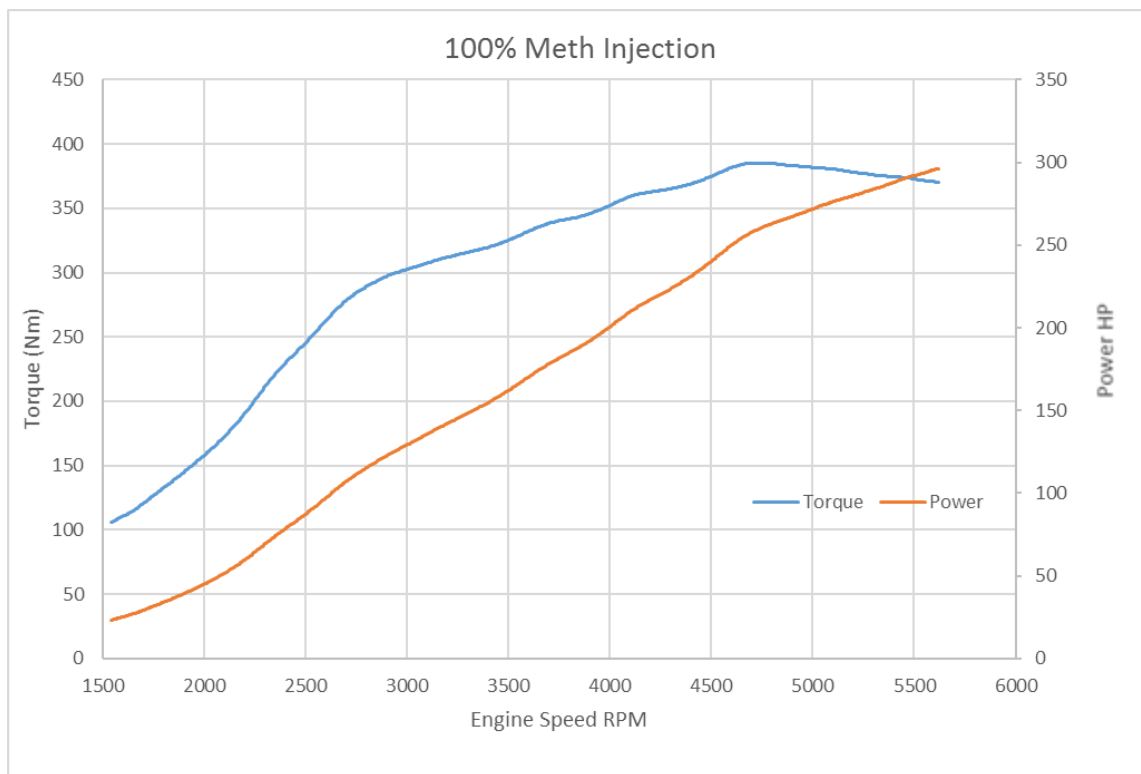


Figure 36 Power/Torque Curve injecting 100% methanol

In these results, figure 36, there is no noticeable drop in torque at 3500 rpm, which suggests the methanol may have a positive impact.

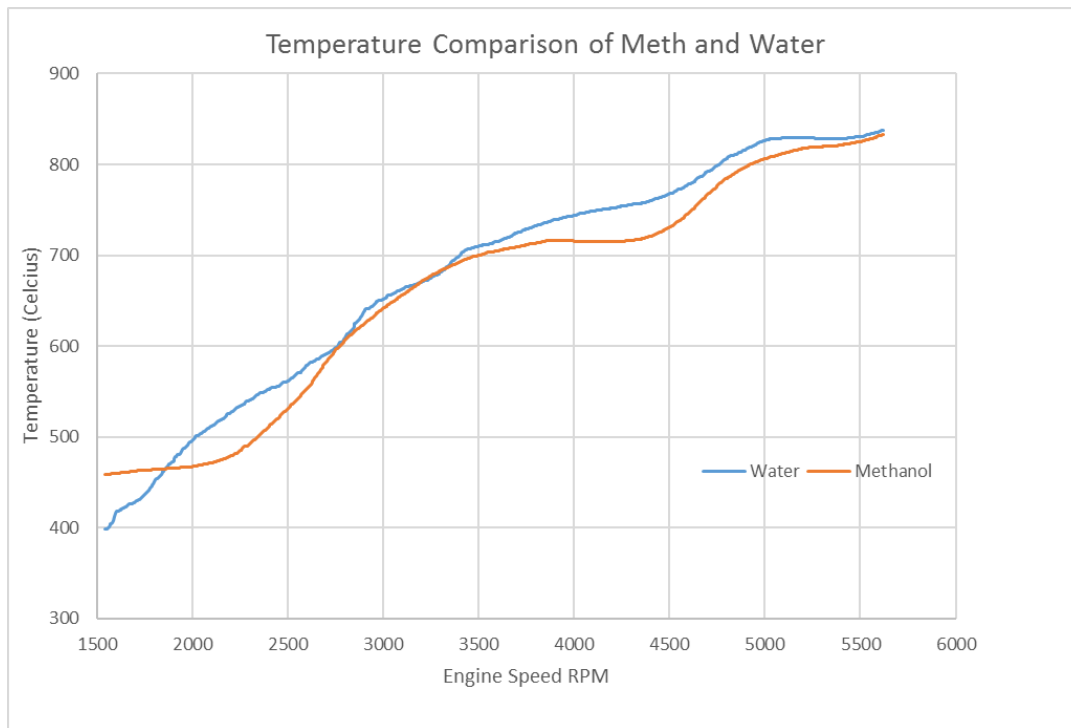


Figure 37 Comparison of exhaust gas temperature with 100% water and 100% methanol

Looking at the exhaust manifold gas temperature, methanol causes a reduction in gas temperature at both low and high engine speeds. This suggests that methanol has a higher impact on exhaust gas temperatures than water.

5.6 CM5 INJECTOR WM

Tests were completed with the larger water methanol injector fitted. At this stage of the testing it was decided to examine the extent to which water/methanol will impact the combustion. To prove this, a larger injector was ordered to attempt to demonstrate this, instead of making assumptions. The larger injector supplied by Coolingmist UK and

allows a volume flow of 440cc/min, as opposed to the CM3 injector which flows 270cc/min (Coolingmist UK, 2019). A 50/50 mixture was used, injecting at 3800 rpm.

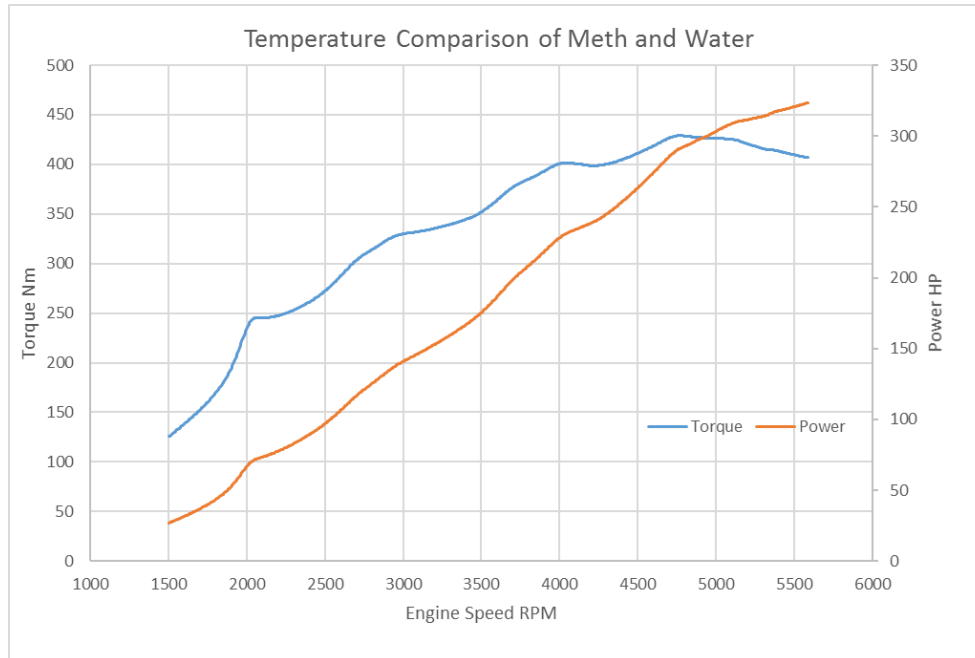


Figure 38 Torque/ Power curve with water methanol injection using larger injector

There are some erratic areas of the torque curve (figure 38), which may be a fuelling issue. A considerably higher amount of water and methanol is being injected which may be causing this. The fuel map could be further optimised by reducing fuel injector duty cycle where necessary to account for the extra fuel.

5.6.1 CM5 METHANOL

The CM5 injector was used for a subsequent test, with a 100% methanol mixture. This test was completed immediately after the previous test with a 50/50 mixture.

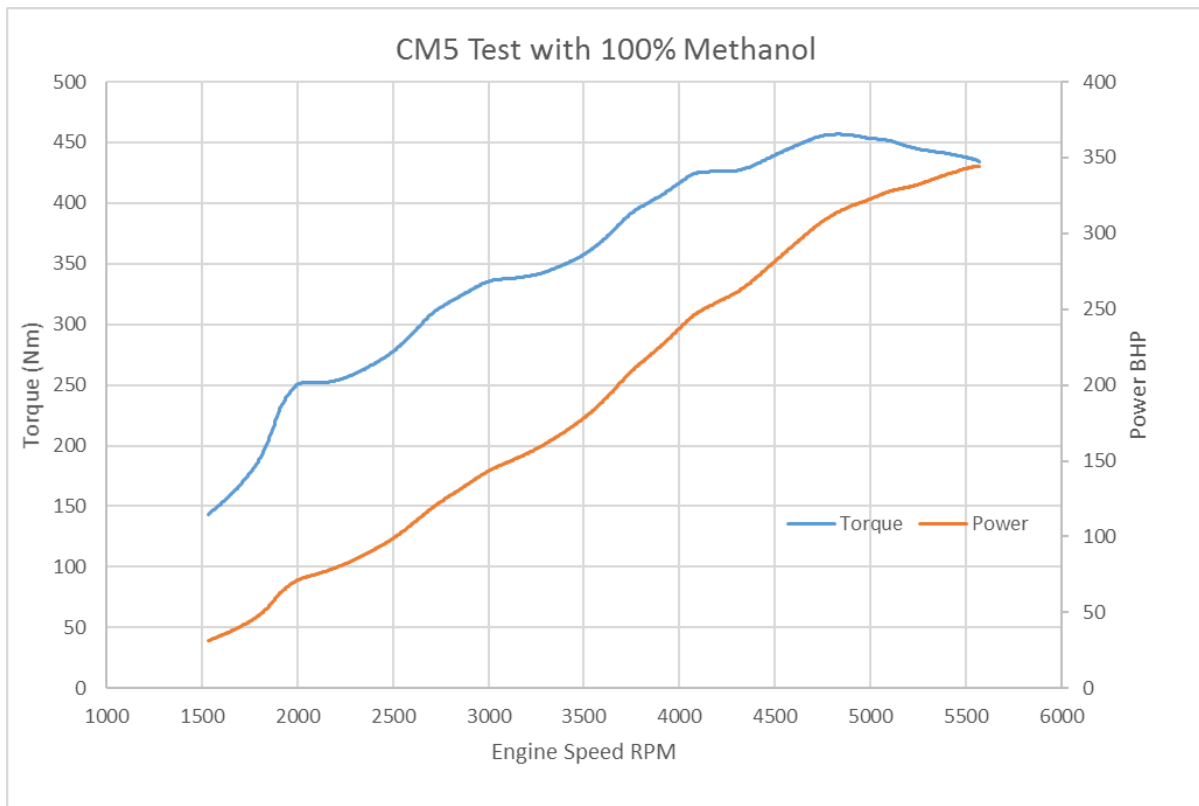


Figure 39 Torque/Power curve with larger injector and 100% methanol

This test shows a very high torque figure (figure 39), peaking at over 450Nm at 4750 rpm. Power peaks at approx. 345 BHP at the maximum speed tested. If this test could have been continued power would likely climb further. Unfortunately, this is not possible due to the exhaust extraction limitations.

On comparison of torque between the 50/50 mixture and 100% methanol (figure 40) there is a clear difference in results.

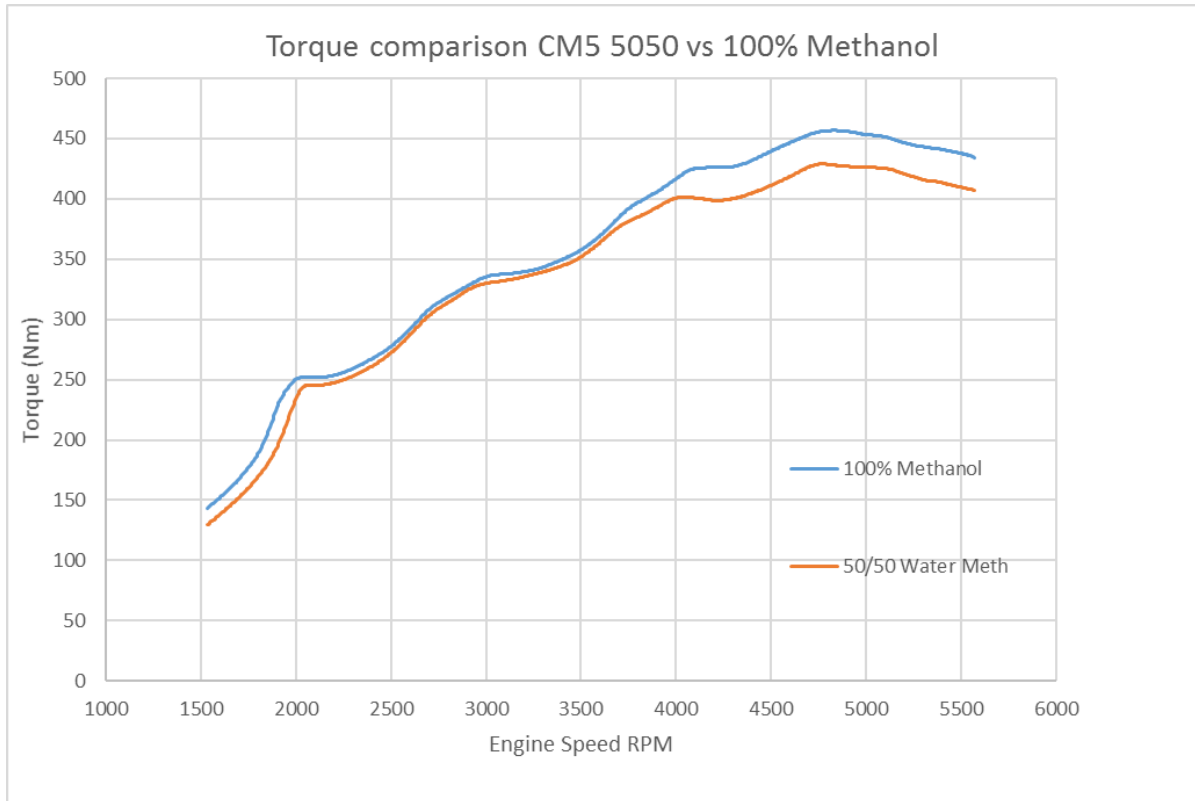


Figure 40 Comparison of torque between water methanol injection and 100% methanol

Torque is considerably higher from 3800 rpm onwards. This may be due to the additional fuel power with the methanol, and the added effect as an octane booster.

On comparison with the exhaust temperature between the 2 mixtures, it is clear that the water/methanol is having an increased effect on reducing temperatures.

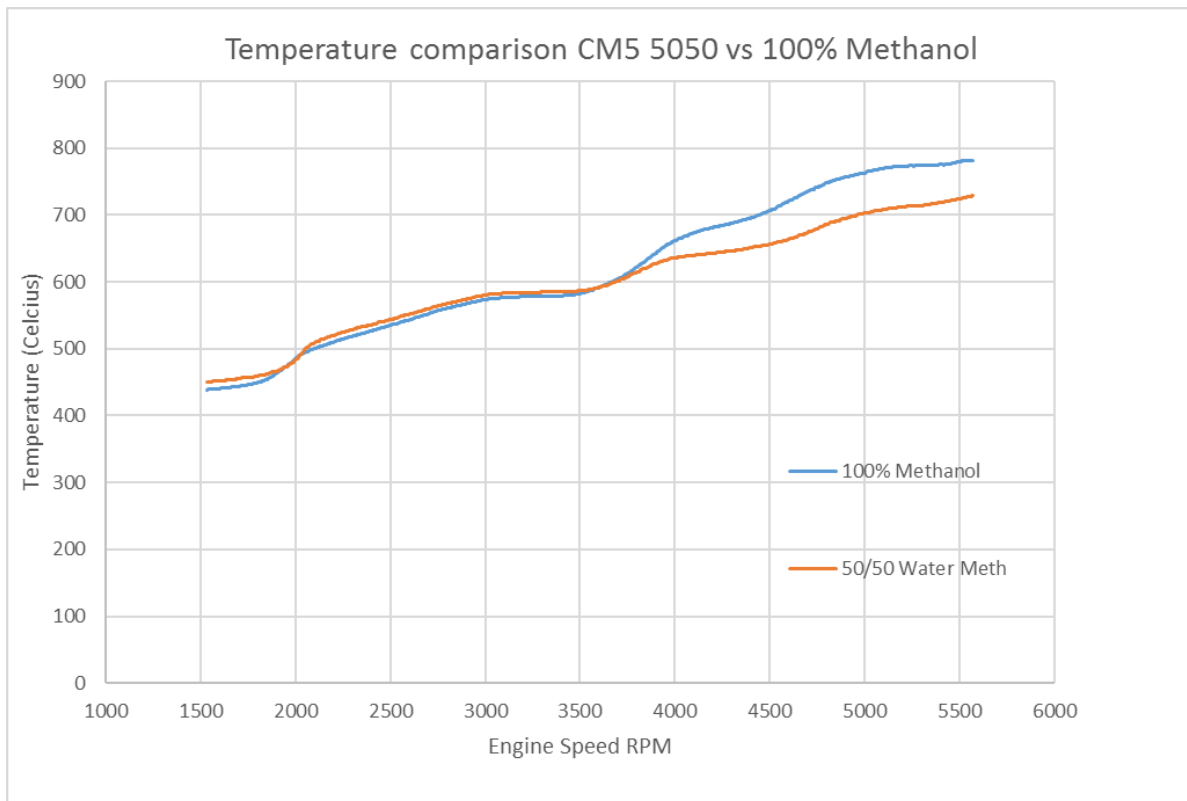


Figure 41 Exhaust temperature comparison between 50/50 and 100% methanol

From the point of injection, which is approx. 3800, the 50/50 mixture clearly reduces temperatures more than the methanol (figure 41). With this ignition timing, it may be more beneficial to use a higher % of methanol in the injection mixture. If timing was to be advanced, the temperature reducing effects of the 50/50 may help reduce the propensity to knock, more than the 100% methanol.

5.7 TEMPERATURES

There is a clearly visible impact on exhaust temperatures from the injection of Water Methanol. 2 tests were completed under the same conditions. The same fuelling and ignition timing were used on both tests (figure 42).

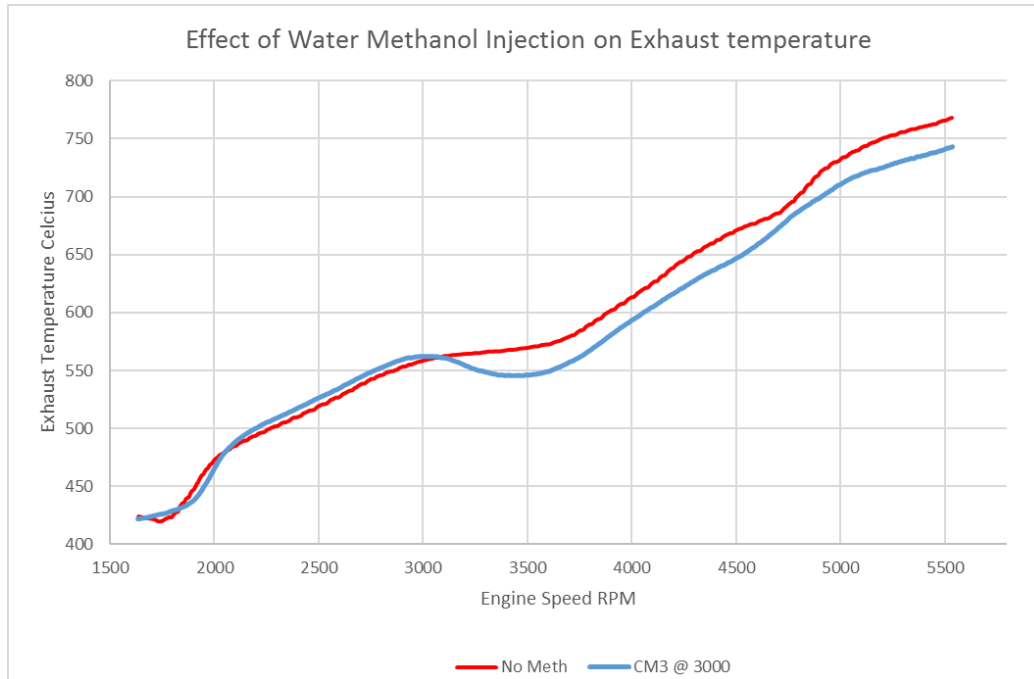


Figure 42 Impact of CM3 water methanol injection of exhaust gas temperature

The impact of both water and methanol was considered. This was done to compare the impact of each component and to gain an understanding of whether a higher ratio of water or methanol would be more beneficial. Figure 43 shows the difference in exhaust gas temperature when the mixture used was 100% water and 100% meth.

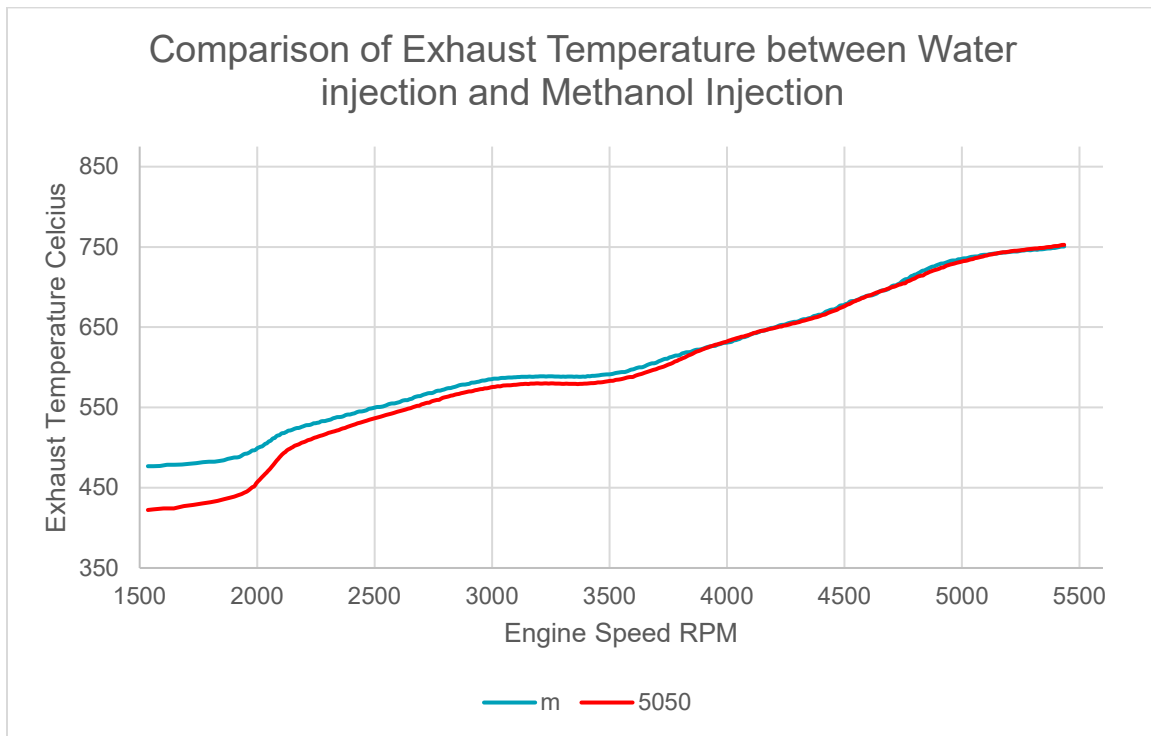


Figure 43 Comparison graph showing exhaust gas temperature between 100% water and 100% methanol

5.8 KNOCK LIMITS

With every change to the mixture and injector size, testing was done to find the level of spark advance possible before knock occurs. This was tested by increasing the ignition timing by 1 degree and completing a power run, monitoring the knock sensor for considerable knock detection. The entire ignition table was increased from the base map in order to ensure repeatability. The results from this testing is shown in figure 44.

Injection = Test= Degrees SA Until Knock	No WMI	WMI CM3		WMI CM5	
	Standard	100% Meth	50/50	100% Meth	50/50
	4	7	8	11	12

Figure 44 Table showing the maximum increase in ignition timing before knock occurs

The standard fuelling, Tesco Momentum 99, allowed a further 4 degrees of spark advance before knock occurred. The CM3 injector allowed improvement, with 7 degrees allowed with pure methanol, and an extra degree when using 50/50. This shows that not only is

the methanol acting as an octane booster, but that also the water is having a positive impact reducing temperatures further lowering the propensity of the engine to knock. The results are similar when considering the CM5 injector, allowing 11 degrees with methanol and an additional degree when using water. It is worth noting that the methanol tests produced more torque, possibly as a result of the increased fuel power, or the fact the addition of water could be impacting the combustion process.

5.9 CALCULATIONS

Fuel analysis has been carried out to further understand the impact of the water methanol injection. This is being studied for three tests, no injection, CM3 and CM5 (270cc and 440cc of water/methanol injection respectively). Basic analysis has been carried out from the lambda values and mass air flow. Knowing lambda, it is possible to calculate air fuel ratio.

To complete these calculations, a value for lambda is required. Fuelling was kept identical for each test. As the water methanol will have an impact on lambda readings due to the increased amount of oxygen in the reactants, lambda values from the no injection test have been used. This is to ensure an accurate measurement of air fuel ratio.

Air flow is measured in litres/minute. This value is multiplied by 0.0012, as this is the density. This changes litres/minute to kg/min. The following formula is used to calculate air mass flow per cycle;

$$\text{Air Mass Kg per Cycle} = \frac{\text{Air Mass Kg/Min}}{\text{RPM} \times 1.5}$$

This takes into account the fact this is a 4-stroke engine. With the air mass Kg/Cycle, this can be used to calculate the fuel mass per cycle. Dividing the air mass by the air fuel ratio will give a relatively accurate value for the fuel mass per cycle. It is also possible to now find the water/methanol mass. WM flow is known, it is 270/440cc/min depending on which injector is used. CC/Min can be converted to kg/min by multiplying by the density. As the mixture being considered is 50/50, the density is approximately 894.5 kg/m³. The cc/min can be multiplied by 0.8945 to give mass flow in Kg/min. Minutes are converted to cycle using a similar formula to air mass.

$$WM \text{ Mass Kg per Cycle} = \frac{WM \text{ Kg/Min}}{RPM \times 1.5}$$

Now that air flow, fuel flow and WM flow have been calculated, combustion analysis can be continued. The ratio of WM to fuel is known from the masses calculated. The results from the CM3 (270cc injector) are shown in figure 45.

RPM	Meth as % fuel
1500	0.00
1750	0.00
2000	0.00
2250	0.00
2500	0.00
2750	0.00
3000	0.00
3250	0.00
3500	0.00
3750	0.00
4000	31.54
4250	27.54
4500	21.10
4750	18.98
5000	16.91
5250	15.92
5500	14.54
5750	13.48

Figure 45 Table showing the amount of water/methanol injected as a % of fuel mass

The values are 0 until 3750 as the injector condition is set to only inject over 4000 RPM. With the meth to fuel mass ratio known, combustion analysis can be carried out.

For this, the standard combustion balancing equation has been modified. Instead of stoichiometric, the fuel equivalence ratio for each rpm site is used to ensure a higher accuracy of result.

To account for the methanol, the following value for the reactants of combustion is being used (where ϕ is fuel equivalence ratio and WM% is the WM as a % of fuel i.e. 31.54%);

$$\phi(C_8H_{18} + 12.5(O_2 + 3.76N_2) + WM\%(CH_3OH + H_2O))$$

This formula has been adapted using Excel, to provide an accurate model at each RPM site. Considering that RPM sites fuel equivalence ratio and water methanol %. From this, the amount of the products is found as a percentage of exhaust, of CO₂ H₂O CO & N₂. This is shown in figure 46.

CO ₂ %	H ₂ O %	CO %	N ₂ %
10.36%	14.80%	2.80%	72.04%
11.08%	14.55%	1.86%	72.51%
10.23%	14.85%	2.97%	71.95%
8.50%	15.45%	5.23%	70.82%
7.61%	15.75%	6.39%	70.25%
6.89%	16.00%	7.33%	69.78%
8.78%	15.35%	4.86%	71.01%
7.65%	15.74%	6.34%	70.27%
6.85%	16.01%	7.38%	69.75%
6.30%	16.20%	8.10%	69.39%
6.58%	16.11%	7.74%	69.57%
6.54%	16.12%	7.79%	69.55%
5.90%	16.34%	8.63%	69.13%
5.94%	16.33%	8.57%	69.16%
7.12%	15.92%	7.03%	69.93%
7.58%	15.76%	6.44%	70.22%
7.27%	15.87%	6.83%	70.03%
7.08%	15.93%	7.08%	69.90%

Figure 46 Table showing calculations for each component as a %vol of exhaust gas

This value can be compared to the Bosch Gas Analyser test to validate the results, shown in section 5.9.2.

The Net Enthalpy per K/mol was divided by the molecular weight of the constituents, approximately 1800, and multiplied by the weight of the air+ fuel mass. This gives the net enthalpy per cycle.

	Net Enthalpy MJ / Cycle		
RPM	No WMI	CM3	CM5
1500	0.00200	0.00200	0.00200
1750	0.00207	0.00207	0.00207
2000	0.00203	0.00203	0.00203
2250	0.00188	0.00188	0.00188
2500	0.00218	0.00218	0.00218
2750	0.00229	0.00229	0.00229
3000	0.00258	0.00258	0.00258
3250	0.00268	0.00268	0.00268
3500	0.00306	0.00306	0.00306
3750	0.00338	0.00338	0.00338
4000	0.00386	0.00401	0.00410
4250	0.00407	0.00421	0.00430
4500	0.00465	0.00478	0.00486
4750	0.00530	0.00543	0.00550
5000	0.00584	0.00597	0.00604
5250	0.00524	0.00536	0.00544
5500	0.00616	0.00627	0.00635
5750	0.00635	0.00646	0.00653

WMI from
4000rpm

Figure 47 Table showing increase of enthalpy with injection of water/methanol at 4000 rpm

Figure 47 shows that the addition of methanol increases the enthalpy released, increasing the fuel power with the larger injector, the CM5. The CM3 provides 270cc/min of water/methanol, and the CM5 provides 440cc/min.

5.9.1 ENTHALPY CHANGE

The change in Enthalpy in the exhaust temperature was to be considered. To complete this, combustion analysis needed to be carried out. Using Excel, a table was made to show the main components of the combustion at a given lambda.

Fuel used was considered to be Iso-Octane. It is worth noting that this is not exactly the chemical composition of gasoline. However, Iso-Octane is one of the main components of gasoline, and is suitable for carrying out combustion analysis.

When burning octane, C_8H_{18} , in air, the products of the reaction can be calculated. When burning at a stoichiometric rate, the products are 8 CO_2 , 9 H_2O and 47 N_2 . This has a net enthalpy release of 5100.1 MJ. As this testing has not been done at a stoichiometric rate, changes have been made to account for the difference in fuelling. This testing has been completed with a fuel equivalence near 1.15. This leads to the production of carbon monoxide which has been modelled.

The enthalpy tables were plotted in Excel for each component of the exhaust, CO_2 , H_2O , CO , O_2 and N_2 . For each component a polynomial equation was made. To ensure the most accurate results, the equation was made as a third order polynomial to 22 decimal places. Figure 48 shows the polynomial equation on the graph.

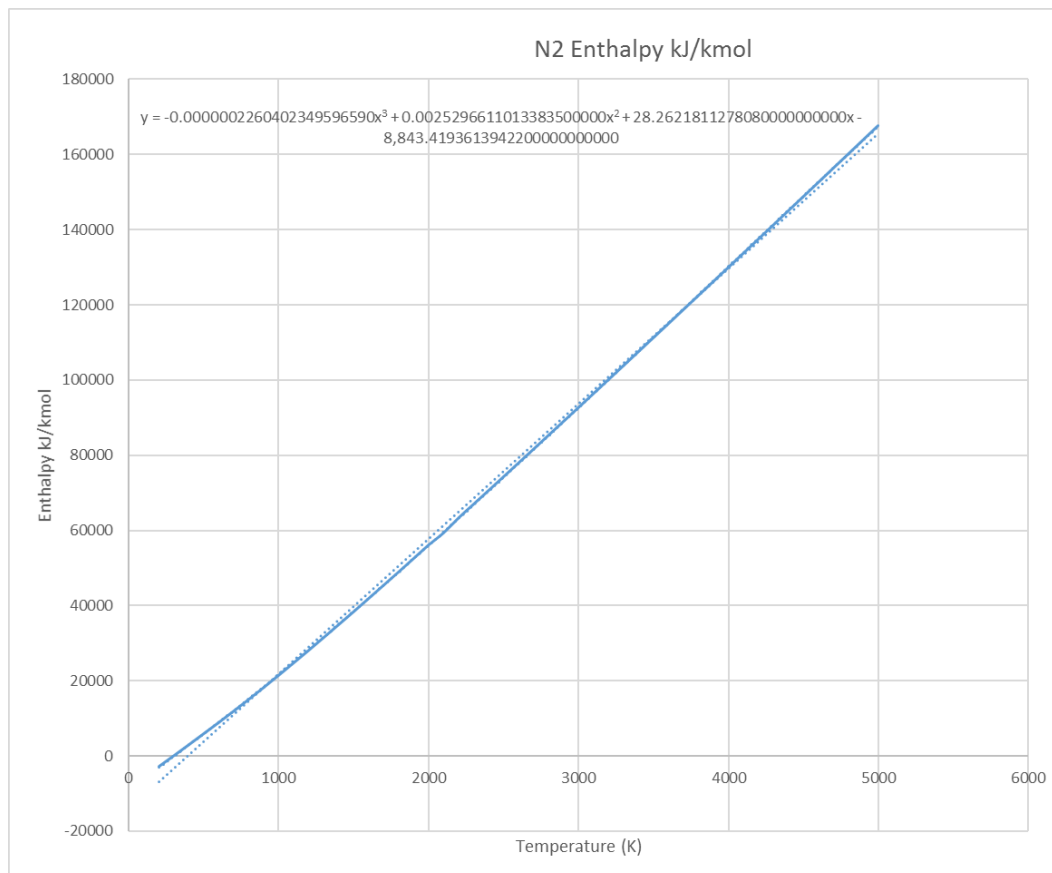


Figure 48 Example graph used to produce polynomial equation for enthalpy calculations

The data gathered from the exhaust thermo-couplers was then used with this equation. The data, in Celsius, was converted to kelvin. The temperature was then input into the polynomial equation for each exhaust component. The sum of these were divided by the molecular weight of the exhaust. This provided the enthalpy per Kmol of the exhaust. As temperature in the manifold and after the turbo were known, by subtracting the 2 enthalpy figures it is possible to calculate the change in enthalpy over the turbo.

Figure 49 shows the enthalpy/Kmol in the manifold

	No WMI	CM3	CM5
RPM			
1750	605.0567	466.0839	503.4954
2000	639.8296	513.9243	535.8085
2250	656.9083	563.3407	587.6014
2500	680.1736	589.7525	611.7323
2750	721.0935	617.3309	636.4806
3000	753.6444	634.318	657.1507
3250	759.0412	620.5381	662.3032
3500	798.1015	614.4237	665.6466
3750	830.7121	633.7042	691.491
4000	851.4117	673.7219	727.0524
4250	865.3179	709.555	738.2483
4500	888.1101	741.2885	753.0738
4750	927.3313	784.4011	783.0352
5000	948.8652	822.4059	812.6999
5250	959.7027	844.9085	825.8013
5500	980.8962	861.4675	839.823
5750	1011.361	880.1737	858.8753

WMI from
4000rpm

Figure 49 tables showing enthalpy Mj/kmol in exhaust

It is clear the water methanol injection is reducing the enthalpy in the exhaust. The test without the water methanol injection clearly has the higher enthalpy. This is to be expected as the enthalpy is directly related to temperature.

When considering the reduction in exhaust gas temperature over the turbo, the amount of enthalpy lost over the turbo drops with the introduction of water methanol. This is likely to be a result of the lower initial temperature in the manifold. If the waste-gate flow value was known, it would be possible to study the change in work done on the turbo with the introduction of water/methanol.

5.9.2 EMISSIONS

The emissions testing was completed using the Bosch Gas Analyser. A 35 second test was completed at 3000 rpm using the same fuel and ignition map, with the only variable being WMI. Four gases were compared.

CO

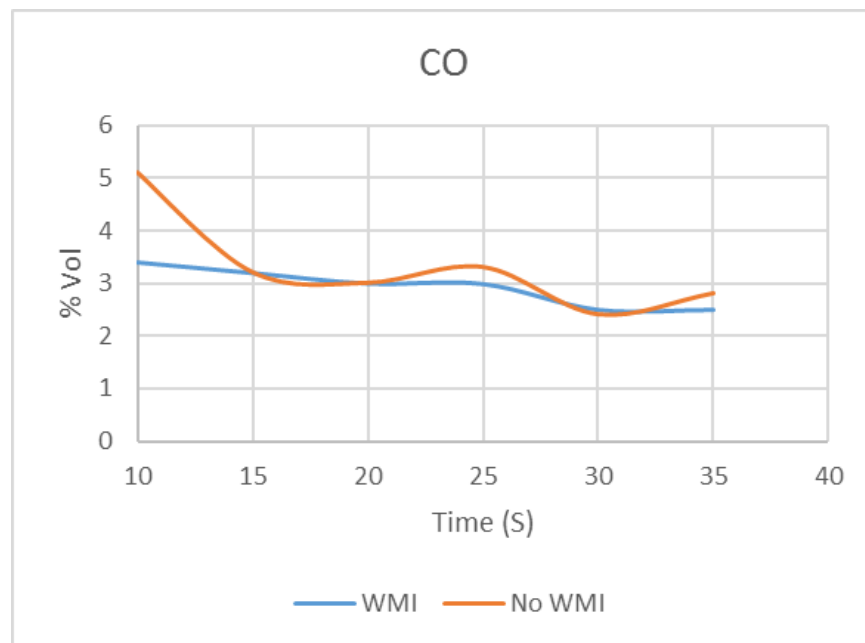


Figure 50 Graph showing levels of CO in emissions test with and without WMI. Test at 3000 rpm

Figure 50 shows minimal change during the testing between WMI and No WMI. The initial spike with No WMI may be an anomaly. If the fuelling was changed to stoichiometric, instead of $\text{Lambda}=0.85$, the results may show a drop in Carbon Monoxide. The WMI may ensure running stoichiometric fuelling is safe, due to the WMI reducing temperature instead of temperature control being a result of over-fuelling.

O2

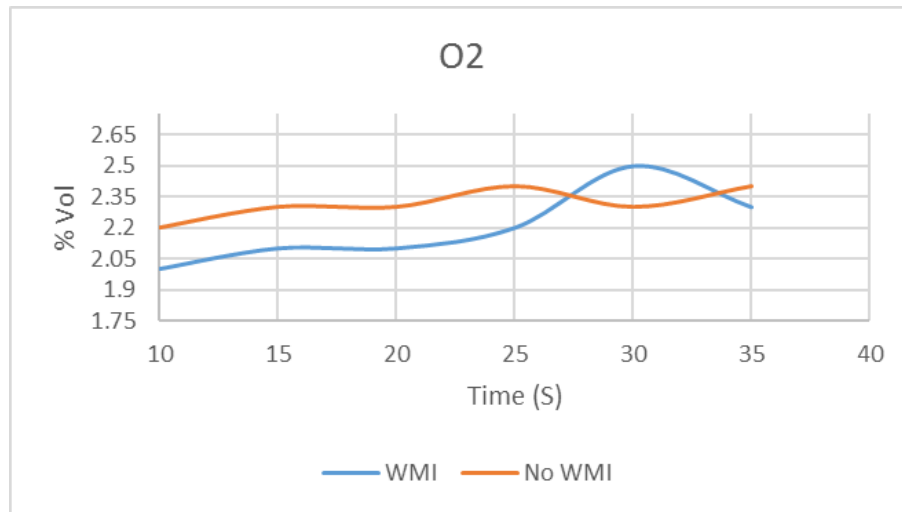


Figure 51 Graph showing levels of O2 in emissions test with and without WMI. Test at 3000 rpm

Figure 51 demonstrates the WMI test having lower O2 levels, until the end of the test where a peak occurs. This may be an anomaly and WMI begins to reduce again. This reduction in O2 levels suggest that with the correct fuelling, WMI could reduce NOx levels in the exhaust. NOx testing was unavailable at the time of testing.

CO₂

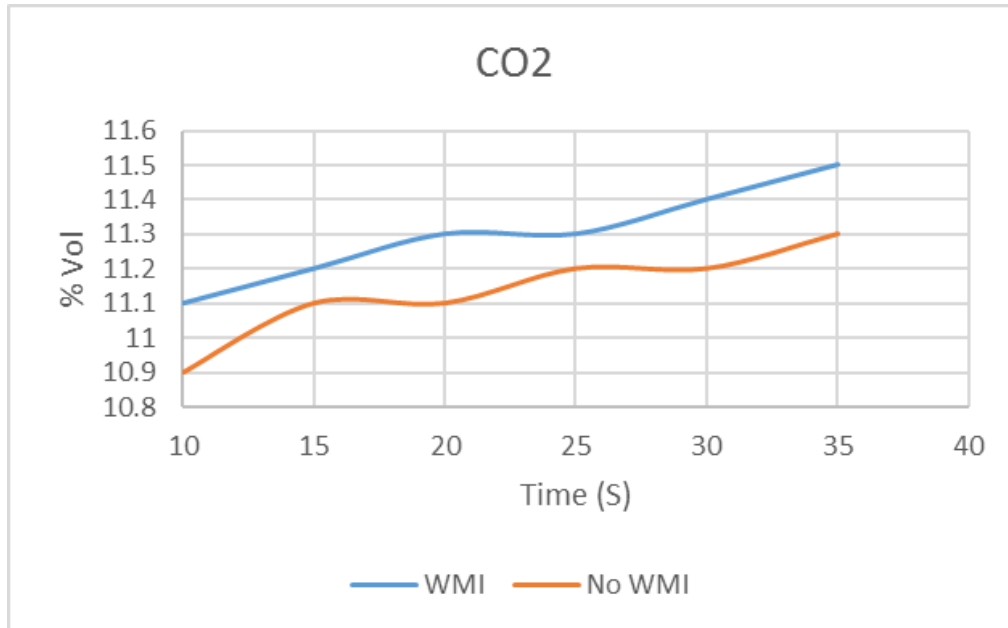


Figure 52 Graph showing levels of CO₂ in emissions test with and without WMI. Test at 3000 rpm

CO₂ emissions increase with the introduction of Water Methanol, shown figure 52. This may be a result of the addition of methanol, CH₃OH, providing more carbon into the combustion process.

HC

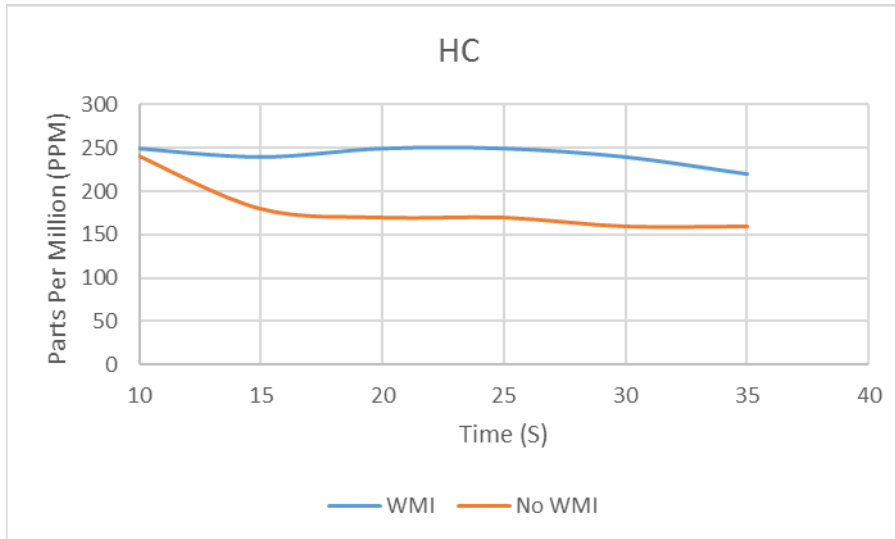


Figure 53 Graph showing levels of hydrocarbons in emissions test with and without WMI. Test at 3000 rpm

The change in hydrocarbon levels is significant, shown figure 53. The introduction of WMI leads to an increase of hydrocarbons of approximately 80ppm. The increase in the level of hydrocarbons suggests that the WMI may be causing poor combustion and a lower mass fraction burned, and a higher unburned mass. If modelling this engine, this would have an impact of the Wiebe function. Lower temperatures during combustion could cause unburned fuel particles. This contradicts research from O. Ghazal, in the report Effect of Water Injection on SI Engine Performance and Emissions.

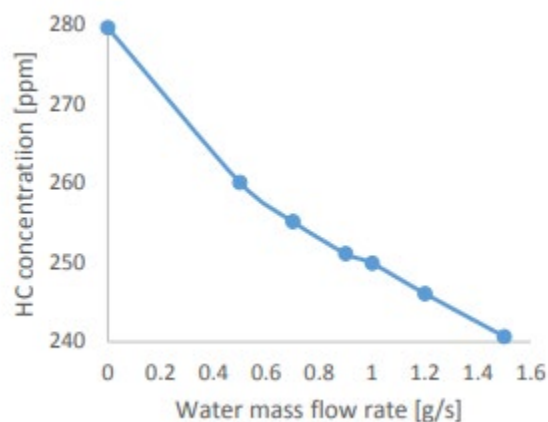


Figure 54 Graph from Ghazal's study showing reduction in HC levels with water injection

Figure 54 demonstrates that Ghazal found as water mass flow rate increases, the level of hydrocarbons decreases. This contradicts the findings from the Bosch gas analyser. This test was completed using the larger 440cc/min injector, with a 50/50 mixture is injecting 3.66g/s of water. This is considerably more than Ghazal tested up to, only 1.5 g/s (Ghazal, 2018). The excess water could be causing poor combustion. If this test was subsequently repeated using the CM3 injector, which injects 270cc/min, 2.25g/s would be injected. This may result in a reduction in hydrocarbon production, in line with Ghazals study.

Comparison to Calculated Values

The values calculated during the combustion analysis were compared to the values from the Bosch gas test. This will validate 2 points;

- Do the values calculated in Excel Represent real values from emissions test?
- Is the change in emissions with WMI similar in both Calculated and Test Values?

Figure 55 shows the values from Excel Calculated values and the values from the Bosch Gas Test.

% Vol	CO		CO2	
Test	Calculated	Test	Calculated	Test
WMI	8.543%	3.027%	6.490%	10.925%
No WMI	7.741%	2.950%	6.578%	11.180%
% Change	10.36%	2.62%	-1.34%	-2.28%

Figure 55 Table showing % volume of exhaust, of both CO and CO2. Calculated Excel values compared to Emissions test levels at FER 1.2

The table shows that the CO %Vol Calculated values show a decrease of 10% with the introduction of WMI. The test values show an increase in carbon Monoxide with the introduction of WMI. When considering the CO2, the difference in calculated and test values is minimal, only -1.3% and -2.3% respectively. This supports the calculations in that there is a minimal decrease in CO2 emissions. The calculated values show that there should be approximately 8% of CO in the exhaust, whereas the test values show 3% CO. This may be due to Iso-octane, the fuel used in Excel calculations, not being entirely representative of the Tesco Momentum 99 fuel used in the vehicle. It is worth

noting that the trend between the values is similar, although the actual proportions are not.

6.0 Analysis

It was found that the initial testing using the water/methanol injection, without adjusting fuelling will result in a loss of power. This was found in the test 5.3 and supported by testing by Berni et al in 2015. The author surmises that this is a result of over-fuelling having a negative impact on combustion, thus effectively flooding the engine, exceeding the flammable limit. This idea is further reinforced by the emission testing carried out. The testing, shown in figure 53, shows an increase in hydro-carbon emissions with the introduction of water methanol injection. Hydro-carbons are unburned fuel emissions, effectively an indicator of poor combustion.

Another critical point of this project is the difference between the calculated combustion and the tested emissions, demonstrated in figure 55. There is a large difference in calculated CO₂ and measured CO₂. This questions the accuracy of the calculations, as the calculated values suggest an 8% volume of CO emissions, but only 3% were measured, tested and calculated at 3000 rpm, with a fuel equivalence ratio of 1.2. The author has noted multiple factors which may be leading to this difference;

1. All calculations are based off the fuel equivalence ratio, calculated from the lambda readings. A faulty lambda sensor could cause a mis-reading, affecting calculated values. This point is negated somewhat by the air fuel ratio reading in vehicle, indicating an air fuel ratio of around 12.5. This equals a lambda 0.85, and a fuel equivalence ratio of 1.17. This would have a minimal impact on the results and is not deemed likely to be the issue.
2. Fuel used has been considered to be iso-octane. This is a large component of gasoline, however is not entirely representative. Gasoline's chemical composition varies too widely to accurately use for these calculations. It is dependent on individual crude oil barrel, and additives used by the seller of the fuel. This may have an impact on the calculated results.

Test 5.5 shows that under the same conditions, pure methanol increased the torque compared to the 50/50 mixture. This may be as a result of increased fuel power being added with the methanol. An alternative possibility is the water causing a reduction in torque, rather than methanol adding performance. This idea is supported by the increase in hydro-carbons with WMI suggesting a decrease in combustion quality. A further possibility is shown by figure 49, which shows the calculated enthalpy in the exhaust gas. Water/methanol injection lowers the exhaust gas temperature, in turn possibly leading to less work done on the turbo, lowering boost levels. The Author is unsure on this suggestion.

The problems experienced with the water methanol kit, and hypothesized, can be rectified by using an inline filter to prevent the nozzle becoming blocked, and occasional inspection of the nozzle to ensure it is flowing correctly. AEM electronics are able to supply a Water methanol failsafe, which monitors flow in the system, detecting any leaks or blockages. This can then trigger a change in map to prevent engine damage. The failsafe gauge costs approximately £230. If using a water/methanol kit permanently, this would be a worthwhile addition to a setup perhaps preventing engine failure (AEM Electronics, n.d.).

Considering both the advantages and disadvantages of water methanol injection, there is a strong argument for using a specialist racing fuel instead of water methanol injection. *Sunoco* can provide E85 racing fuel, which has an ethanol content of 85%. This has a quoted octane rating of 120 RON. Further testing could compare standard fuel with water methanol injection, to E85 racing fuel. The disadvantages of E85 fuel is the increased deterioration of fuel hoses and rubbers due to the high ethanol content. The high cost of the fuel is also a limiting factor as to the eligibility of using E85. Sunoco E85 racing fuel can be provided by *Demon-Tweeks* for £132.30 for 25 litres delivered (Demon Tweeks, 2019). The cost of methanol is £48.50 delivered by *Bonnymans* (Bonnymans, 2019). The considerable price difference makes E85 not attractive for daily usage, however could be considered for dyno testing or race use.

7.0 Conclusions

This project has demonstrated the impact of Water Methanol Injection in a modern turbo-charged gasoline engine. A water/methanol injection kit was fitted to a turbo-charged engine, and tested on a chassis dynamometer, considering different injection ratios, flows, and start points. The following conclusions have been made;

1. Without adjustment to fuel or timing, water/methanol injection can lead to a drop in power, shown in 5.x. This is a particular issue at low engine speed where combustion may be negatively impacted as a result of over fuelling.
2. Water/Methanol injection allows significant spark advance before knock occurs. This validates its use as a knock suppressant, shown in figure x. This supports the use of water/methanol in performance vehicles, where knock propensity limits performance. It is also comparatively cost effective when considering alternative fuels such as E85.
3. Water/Methanol injection in this case has led to an increase in hydro-carbon emissions. This is contradictory to other research, such as that by Ghazal. This may be as a result of excess water flow, a theory supported by J Parsey Wilson in 2011.
4. Exhaust temperatures are reduced with the introduction of water methanol injection, facilitating a more stoichiometric fuel mixture and negating the need for over-fuelling to reduce cylinder temperatures. This can reduce wear on exhaust valves.
5. Water injection has a larger impact on reducing inlet temperatures, whereas methanol is more aimed at increasing octane rating of the fuel. If one improvement was desired more than the other, the mixture could be adjusted to suit.

8.0 Further Work

There are multiple areas of work which would ideally have been covered, but due to time and equipment constraints meant this was not achievable.

In order to increase the accuracy, and repeatability of results, the engine should be removed and installed onto an engine dynamometer. This would allow controlled conditions on every test with less variables.

Further investigation into the efficiency of the turbo would be beneficial. The turbo could be removed from the vehicle and a test bed made to allow flow testing on the Flow Bench. This would provide a value for the amount of exhaust flow through the turbo waste gate. This would allow a more accurate understanding of the turbo efficiency.

Furthermore, using 2 thermo-couplers on the intake would provide more data on the temperature drop caused by water-methanol injection. This could be realised by a sensor before the WMI in the intercooler pipe, and after in the intake plenum. This could provide an accurate value for the drop in temperature of the intake charge.

Word count: 11231

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Appendix

Additional data has been provided to elaborate on processes completed.

Below are the base fuel and ignition maps used throughout this testing.

Fuel Table 1 (%)		Engine Speed (RPM)																
	0	500	750	850	1000	1450	1550	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	
MGP (kPa)	-100	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.9	9.9	9.0	9.0	9.0	9.0	9.0	10.0	
	-80	15.7	15.0	15.0	15.0	15.0	28.0	28.0	28.0	28.0	27.7	27.7	30.6	30.6	30.6	31.5	31.5	35.0
	-70	19.8	27.0	27.3	27.3	24.0	30.0	28.5	28.0	30.0	29.7	29.7	31.5	31.5	31.5	32.4	32.4	36.0
	-60	19.9	28.0	27.5	28.5	35.0	35.0	29.3	31.3	39.2	32.9	33.7	32.4	32.4	32.4	34.2	34.2	38.0
	-55	25.5	28.0	28.5	28.5	35.0	35.0	30.0	33.0	40.0	33.7	34.6	33.3	33.3	33.3	34.2	34.2	38.0
	-50	26.9	26.9	35.0	35.0	26.2	36.0	35.0	35.5	41.0	35.6	37.6	35.1	37.8	39.6	41.4	42.3	49.0
	-40	27.5	27.5	27.5	29.7	29.7	37.0	43.4	39.9	43.6	38.5	41.5	39.6	42.3	44.1	46.5	47.0	52.2
	-20	28.9	28.9	28.9	31.2	31.2	37.5	44.4	42.0	44.0	43.0	43.6	41.4	45.0	45.9	47.5	48.0	53.3
	0	31.9	31.9	31.9	31.9	31.9	38.0	43.3	44.0	44.0	44.0	47.5	45.0	45.9	46.3	48.0	48.5	53.9
	20	37.2	37.2	37.2	37.2	37.2	39.0	43.6	45.0	45.0	45.0	48.5	45.4	46.8	47.7	48.6	49.5	55.0
	40	39.4	39.4	39.4	39.4	39.4	40.0	38.1	46.0	46.0	46.0	49.0	45.4	47.7	48.6	49.8	50.4	56.6
	60	42.7	42.7	42.7	42.7	42.7	42.5	43.7	47.0	47.0	47.0	49.5	45.9	48.6	49.5	50.4	51.2	57.0
80	51.5	51.5	51.5	51.5	51.5	51.2	52.7	48.5	47.5	48.0	50.0	45.9	46.7	50.4	51.4	52.0	58.0	
100	59.0	59.0	59.0	59.0	59.0	54.0	53.7	49.4	48.5	49.0	50.0	45.9	47.9	51.3	51.6	52.2	58.6	
120	58.7	58.7	58.7	58.7	58.7	59.8	63.0	58.0	49.0	50.0	50.5	46.8	48.7	52.2	52.7	53.1	59.0	

Figure 57 Fuel Map from Link ECU (Above)

Ignition Table 1 (+ °BTDC, -- °ATDC)		Engine Speed (RPM)																
	0	500	750	850	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	7000	
MGP (kPa)	-100	16.0	16.0	14.0	13.0	13.0	18.0	32.0	33.0	33.0	33.0	33.0	33.0	33.0	35.0	35.0	35.0	
	-80	16.0	5.0	8.0	8.0	13.0	20.0	33.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	
	-60	16.0	5.0	8.0	8.0	8.0	20.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	
	-40	16.0	5.0	8.0	8.0	8.0	20.0	30.0	30.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	
	-20	16.0	15.0	14.5	14.5	14.5	17.5	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	
	0	8.0	8.0	6.5	6.5	6.5	12.0	18.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	
	20	8.0	8.0	5.0	5.5	5.5	8.0	24.0	25.0	13.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	
	40	3.5	4.0	4.0	4.0	4.0	7.0	20.0	22.0	24.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	
	60	3.0	3.0	3.0	3.0	3.0	3.0	8.0	20.0	26.0	21.0	21.0	21.0	20.0	19.0	18.0	18.0	12.0
	80	1.0	1.0	1.0	1.0	1.0	1.0	8.0	17.0	21.0	20.0	19.0	17.0	16.0	15.0	15.0	9.0	
	100	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	8.0	16.0	16.0	16.0	14.0	13.0	12.0	12.0	6.0
	120	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	1.0	14.0	14.0	15.0	14.0	13.0	12.0	12.0	4.0
	140	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	1.0	10.0	10.0	10.0	9.0	8.0	7.0	7.0	3.0

Figure 56 Ignition map from Link ECU (Above)

Below are excerpts showing Excel calculations step by step, and excerpts of dyno data

RPM	Engine BHP	Lambda	Fuel Equivalence Ratio	Air Fuel Ratio	Air flow LPM	WM Flow L/min	WM Kg/min	WM Kg/cycle	Air mass flow kg/min	Air mass flow kg/cycle	Fuel mass flow kg/cycle	AF Mass kg/cycle
1500	25.926	0.932	1.07	13.7004	1349.282	0	0	0	1.619138	0.000719617	5.25253E-05	0.000772
1750	39.908	0.954	1.05	14.0238	1592.789	0	0	0	1.911347	0.000728132	5.19212E-05	0.00078
2000	68.476	0.928	1.08	13.6416	1827.254	0	0	0	2.192705	0.000730902	5.35789E-05	0.000784
2250	79.541	0.878	1.14	12.9066	2028.032	0	0	0	2.433638	0.000721078	5.58689E-05	0.000777
2500	96.841	0.854	1.17	12.5538	2702.191	0	0	0	3.242629	0.000864701	6.88796E-05	0.000934
2750	119.503	0.835	1.20	12.2745	3201.422	0	0	0	3.841706	0.000931323	7.58746E-05	0.001007
3000	134.764	0.886	1.13	13.0242	3661.925	0	0	0	4.39431	0.000976513	7.49768E-05	0.001051
3250	149.876	0.855	1.17	12.5685	4309.117	0	0	0	5.17094	0.001060706	8.4394E-05	0.001145
3500	170.308	0.834	1.20	12.2598	5451.36	0	0	0	6.541632	0.001246025	0.000101635	0.001348
3750	196.363	0.82	1.22	12.054	6606.357	0	0	0	7.927628	0.001409356	0.00011692	0.001526
4000	219.132	0.827	1.21	12.1569	7946.654	0.27	0.24152	0.0000403	9.535985	0.001589331	0.000130735	0.00172
4250	236.923	0.826	1.21	12.1422	8931.798	0.27	0.24152	0.0000379	10.71816	0.00168128	0.000138466	0.00182
4500	257.849	0.81	1.23	11.907	11093.213	0.27	0.24152	0.0000358	13.31186	0.001972127	0.000165628	0.002138
4750	283.276	0.811	1.23	11.9217	13326.475	0.27	0.24152	0.0000339	15.99177	0.002244459	0.000188267	0.002433
5000	298.301	0.841	1.19	12.3627	14720.88	0.27	0.24152	0.0000322	17.66506	0.002355341	0.00019052	0.002546
5250	307.038	0.853	1.17	12.5391	13624.099	0.27	0.24152	0.0000307	16.34892	0.002076053	0.000165566	0.002242
5500	317.568	0.845	1.18	12.4215	16971.778	0.27	0.24152	0.0000293	20.36613	0.002468622	0.000198738	0.002667
5750	324.066	0.84	1.19	12.348	18436.65	0.27	0.24152	0.0000280	22.12398	0.002565099	0.000207734	0.002773

AF +WM Mass kg/Cycle	Meth as % fuel	C	H	O	n1+n2	2n1+n2+n3	2n1+n2	CO ₂	H ₂ O	CO	N ₂
0.000772142	0	8	18	12.5	8.5837	25	15.3433476	6.759657	9.656652	1.824034	47
0.000780053	0	8	18	12.5	8.3857	25	15.5660377	7.180294	9.433962	1.205451	47
0.00078448	0	8	18	12.5	8.6207	25	15.3017241	6.681034	9.698276	1.939655	47
0.000776947	0	8	18	12.5	9.1116	25	14.7494305	5.637813	10.25057	3.473804	47
0.000933581	0	8	18	12.5	9.3677	25	14.4613583	5.093677	10.53864	4.274005	47
0.001007197	0	8	18	12.5	9.5808	25	14.2215569	4.640719	10.77844	4.94012	47
0.00105149	0	8	18	12.5	9.0293	25	14.8419865	5.812641	10.15801	3.216704	47
0.0011451	0	8	18	12.5	9.3567	25	14.4736842	5.116959	10.52632	4.239766	47
0.00134766	0	8	18	12.5	9.5923	25	14.2086331	4.616307	10.79137	4.976019	47
0.001526276	0	8	18	12.5	9.7561	25	14.0243902	4.268293	10.97561	5.487805	47
0.001760318	30.78941	8.307894	19.53947	13.11579	10.046	26.23158	14.4181118	4.372291	11.81346	5.673531	47
0.00185763	27.36033	8.273603	19.36802	13.04721	10.016	26.09441	14.3704323	4.353963	11.72398	5.662506	47
0.002173534	21.60269	8.216027	19.08013	12.93205	10.143	25.86411	14.0862468	3.943004	11.77786	6.200239	47
0.002466622	18.00469	8.180047	18.90023	12.86009	10.086	25.72019	14.0677619	3.981391	11.65243	6.10498	47
0.002578063	16.90217	8.169022	18.84511	12.83804	9.7135	25.67609	14.4720984	4.758636	11.20399	4.954826	47
0.002722288	18.52343	8.185234	18.92617	12.87047	9.5958	25.74094	14.6470501	5.05123	11.09389	4.54459	47
0.002696635	14.73023	8.147302	18.73651	12.7946	9.6418	25.58921	14.502516	4.860738	11.08669	4.78104	47
0.002800835	13.47961	8.134796	18.67398	12.76959	9.6843	25.53918	14.4237199	4.739439	11.11546	4.944842	47

Mol wt	Exh wt	Moles	CO ₂ %	H ₂ O %	CO %	N ₂ %	CO ₂ (g)	H ₂ O (g)	CO (g)	N ₂ (g)	Net Ent Release	Net Ent / wt * mass
28.1776	1838.318	65.24034	10.36%	14.80%	2.80%	72.04%	7.46E-05	0.000107	2.01E-05	0.000518	4770.803	0.002004
28.317	1835.497	64.81971	11.08%	14.55%	1.86%	72.51%	8.07E-05	0.000106	1.35E-05	0.000528	4882.478	0.002075
28.1518	1838.845	65.31897	10.23%	14.85%	2.97%	71.95%	7.48E-05	0.000109	2.17E-05	0.000526	4749.93	0.002026
27.8146	1845.841	66.36219	8.50%	15.45%	5.23%	70.82%	6.13E-05	0.000111	3.77E-05	0.000511	4472.967	0.001883
27.643	1849.489	66.90632	7.61%	15.75%	6.39%	70.25%	6.58E-05	0.000136	5.52E-05	0.000607	4328.505	0.002185
27.5022	1852.527	67.35928	6.89%	16.00%	7.33%	69.78%	6.42E-05	0.000149	6.83E-05	0.00065	4208.25	0.002288
27.8704	1844.668	66.18736	8.78%	15.35%	4.86%	71.01%	8.58E-05	0.00015	4.75E-05	0.000693	4519.382	0.002576
27.6503	1849.333	66.88304	7.65%	15.74%	6.34%	70.27%	8.12E-05	0.000167	6.72E-05	0.000745	4334.687	0.002684
27.4946	1852.691	67.38369	6.85%	16.01%	7.38%	69.75%	8.54E-05	0.0002	9.2E-05	0.000869	4201.769	0.003056
27.3878	1855.024	67.73171	6.30%	16.20%	8.10%	69.39%	8.88E-05	0.000228	0.000114	0.000978	4109.376	0.003381
27.3003	1879.882	68.85929	6.35%	17.16%	8.24%	68.26%	0.000101	0.000273	0.000131	0.001085	4279.367	0.004007
27.3079	1877.156	68.74045	6.33%	17.06%	8.24%	68.37%	0.000106	0.000287	0.000138	0.00115	4258.707	0.004214
27.2065	1875.1	68.9211	5.72%	17.09%	9.00%	68.19%	0.000113	0.000337	0.000177	0.001345	4123.771	0.00478
27.2316	1871.864	68.7388	5.79%	16.95%	8.88%	68.37%	0.00013	0.00038	0.000199	0.001535	4117.139	0.005425
27.4714	1865.787	67.91745	7.01%	16.50%	7.30%	69.20%	0.000165	0.000389	0.000172	0.00163	4317.185	0.005965
27.555	1865.193	67.68971	7.46%	16.39%	6.71%	69.43%	0.000155	0.00034	0.000139	0.001441	4401.827	0.005363
27.5114	1863.302	67.72847	7.18%	16.37%	7.06%	69.39%	0.000177	0.000404	0.000174	0.001713	4334.187	0.006273
27.479	1863.069	67.79975	6.99%	16.39%	7.29%	69.32%	0.000179	0.000421	0.000187	0.001778	4296.399	0.006459

	Torque (NM)													
	No Meth					CM3								
	1	2	3	4	5	6	7	8	9	11	12	13	14	
	Link Base	OE Base	No Meth run	Knock lim	WMI 1	Cm3 Base	W 3.5	Meth 4k	cm3 5050k	cm5 m k	cm5 w m	cm5 ch	cm5 m 4k	
Date	07.11.2018	06.11.2018	28.02.2019	09.04.2019	04.02.2019	10.04.2019	05.02.2019	28.02.2019	10.04.2019	10.04.2019	10.04.2019	10.04.2019	10.04.2019	
1500						28.944			25.926			27.151		
1750	35.519		35.078	43.8	47.365	45.408	44.638	31.587	39.908	44.012	39.893	40.273	39.918	
2000	48.306	22.881	50.629	66.527	57.521	66.051	58.977	45.004	68.476	71.263	66.57	66.128	67.533	
2250	57.29	34.407	70.776	75.888	68.493	75.901	66.539	64.384	79.541	81.982	80.041	81.458	81.86	
2500	69.089	51.976	88.418	91.411	85.26	92.526	81.393	87.399	96.841	98.802	96.888	98.744	99.397	
2750	81.142	72.399	108.387	114.323	106.599	115.334	103.512	111.36	119.503	122.97	121.024	122.87	124.383	
3000	86.926	99.642	127.147	132.491	129.726	130.632	122.69	129.266	134.764	143.238	140.902	142.427	144.368	
3250	91.976	124.206	143.34	148.408	149.356	146.852	148.066	145.307	149.876	157.841	156.084	156.603	158.337	
3500	100.256	142.776	160.308	167.625	166.123	168.732	160.472	162.131	170.308	178.294	175.397	176.456	178.564	
3750	113.319	155.291	178.864	192.845	190.641	194.203	186.805	181.74	196.363	209.264	203.603	205.449	207.973	
4000	132.011	167.643	197.633	213.992	210.13	215.271	207.473	200.635	219.132	237.38	228.239	231.181	235.47	
4250	147.241	182.857	215.172	234.58	224.341	232.998	220.343	220.189	236.923	257.87	241.419	248.62	254.731	
4500	158.167	194.602	233.587	249.536	241.125	252.097	237.245	240.234	257.849	281.677	263.462	273.404	278.728	
4750	181.297	200.374	250.56	273.818	253.198	276.431	251.946	260.546	283.276	308.121	290.037	297.071	304.465	
5000	201.504	215.658	265.348	288.729	259.887	287.59	256.047	271.833	298.301	322.783	303.341	310.918	317.951	
5250	213.554	233.323	276.74	298.08	264.621	297.208	265.232	281.911	307.038	332.325	312.603	321.029	325.778	
5500	226.735	244.601	287.284	306.51	269.027	308.911	272.145	291.96	317.568	342.82	320.715	330.76	336.584	
5750	240.182	249.661	295.946	314.699	277.191	316.208	279.157	300.225	324.066		328.027	336.796	343.519	
6000	251.572				280.514									
6250	255.451													

Enthalpy drop over turbo													
Date	No Meth					CM3							
	1	2	3	4	5	6	7	8	9	11	12	13	14
	Link Base	OE Base	No Meth r	Knock lim	WMI 1	Cm3 Base	W 3.5	Meth 4k	cm3 5050k	cm5 m k	cm5 wm	cm5 ch	cm5 m 4k
	07.11.2015	06.11.2015	28.02.2015	09.04.2015	04.02.2015	10.04.2015	05.02.2015	28.02.2015	10.04.2015	10.04.2015	10.04.2015	10.04.2015	10.04.2015
1500						151.4568			68.19449			41.01619	
1750			149.8788		210.6872	144.1237	152.4513	148.7094	67.34993	93.18541	55.97632	40.25708	93.98846
2000			142.293		180.702	106.932	145.1953	142.5009	51.09617	68.92377	44.87531	36.13939	74.71854
2250			131.2407		162.6169	100.303	136.7795	133.0751	45.3925	58.31425	35.28683	33.81494	53.04084
2500			125.0405		149.8648	98.05402	133.9908	123.0233	46.89837	58.87756	36.95994	37.70025	51.50116
2750			126.3127		144.1775	98.05634	134.3921	123.552	51.49426	62.41882	42.06028	43.7836	53.81083
3000			127.0724		142.9682	95.89396	145.0714	125.969	54.59473	64.73394	47.23178	48.97619	57.08643
3250			129.5467		130.4187	90.87653	144.3703	122.7579	42.96898	62.75773	45.50744	48.1321	55.19914
3500			124.422		114.8136	82.78105	131.7258	116.7722	34.36098	57.21081	38.77819	42.06028	49.52021
3750			109.1344		96.71012	74.51986	112.8231	101.1708	30.01134	57.01273	35.29716	39.1008	46.83629
4000			92.27241		74.81441	63.46558	89.52845	86.28689	27.85551	54.30579	30.67166	32.70353	42.29921
4250			79.84838		62.77387	52.72205	66.82272	73.28288	24.18524	53.03739	21.37913	26.62839	40.79683
4500			70.50843		57.51142	52.89238	59.80271	70.57999	25.88606	53.96852	21.5348	28.09501	45.481
4750			67.01191		54.72712	51.52533	54.3645	76.72303	30.42288	57.04843	23.88064	30.24405	49.68469
5000			66.88847		49.20851	47.52612	47.47438	81.03816	31.96042	56.03159	27.88187	35.05736	54.59473
5250			63.35029		39.5107	39.58188	35.14227	79.27497	27.84634	48.69328	22.82266	31.63591	49.35113
5500			56.81004		37.46725	35.3224	23.34017	75.23721	25.18276	41.14138	22.29947	29.79125	46.08216
5750			61.84248		44.56731	40.42933	24.00431	76.91254	30.52377		29.12759	32.41912	47.3755
6000					55.65622								
6250													

			Temp 1					
			CO2	CO	H2O	N2	O2	ent/kmol
	Temp (K)							
1500	392.78		3658.18979	2637.28706	3034.323	2633.9692	2783.50208	99.63949
1750	387.906		3426.84507	2488.06046	2865.404	2487.09741	2628.00869	93.98846
2000	371.251		2638.1481	1978.9229	2290.452	1986.03387	2097.45353	74.71854
2250	352.45		1751.2507	1405.65066	1645.639	1421.92699	1499.9963	53.04084
2500	351.112		1688.27229	1364.91247	1599.921	1381.84314	1457.53658	51.50116
2750	353.119		1782.74684	1426.02272	1668.506	1441.97199	1521.22911	53.81083
3000	355.964		1916.73942	1512.67942	1765.817	1527.23858	1611.54608	57.08643
3250	354.325		1839.5363	1462.75226	1709.744	1478.11211	1559.51028	55.19914
3500	349.39		1607.24658	1312.49428	1541.116	1330.26747	1402.9027	49.52021
3750	347.056		1497.47323	1241.4676	1461.472	1260.38349	1328.87274	46.83629
4000	343.108		1311.91809	1121.37979	1326.91	1142.23047	1203.70442	42.29921
4250	341.8		1250.47797	1081.60912	1282.373	1103.10134	1162.25043	40.79683
4500	345.877		1442.04359	1205.59827	1421.266	1225.0917	1291.48626	45.481
4750	349.533		1613.97403	1316.84674	1545.998	1334.54995	1407.43917	49.68469
5000	353.8		1814.81267	1446.76224	1691.79	1462.37865	1542.8448	54.59473
5250	349.243		1600.33118	1308.02016	1536.098	1325.8653	1398.23944	49.35113
5500	346.4		1466.63019	1221.50901	1439.099	1240.74622	1308.07001	46.08216
5750	347.525		1519.52685	1255.73794	1477.47	1274.42415	1343.74659	47.3755

A power run document has also been provided showing the format and data supplied with each test.

