



CYLINDER HEAD FLOW OPTIMISATION OF A SPARK IGNITION MULTI-POINT INJECTION ENGINE FOR MOTORSPORT APPLICATION

This paper includes flow analysis of a production head and a modified head with validation carried out on a rolling road

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Nomenclature

VFR = Volumetric Flow Rate

FV = Flow Velocity

CD = Coefficient of Discharge

VE = Volumetric Efficiency

CFM = Cubic feet per minute

CID = Cubic inch Displacement

CC = Cubic Capacity

m/s = Metre's per second

m/s³ = Cubic metre's per second

ICE = Internal Combustion Engine

A_f^e = Effective area

A_f = Curtain area

m_f = Real Mass Flow

m_t = Theoretical Mass Flow

Ø = Diameter

T = Temperature

ρ = Air density

RPM = revolutions per minute

L_v = Valve lift

n/m = Newton per metre (Torque)

BHP = Brake Horse Power

PSI = Pounds per square inch

Abstract

In this paper the activity presented is focused on the volumetric flow rate of cylinder heads intake and exhaust ports for competition use. Volumetric flow rate (VFR) is the study of the amount air-fuel mixture that flows through an intake port. The process of burning fuel with a mixture of air in an engine as a means of propulsion is a very well documented craft. It is known as a craft as the easy part is to get the fuel into the cylinder but the more difficult part is supplying the air into the chamber efficiently. There are many parameters in the cylinder head that influence an engines performance. One of those methods is empirically discussed in this paper which includes modifying the intake and exhaust port geometry. The study of head port design on airflow is the main bulk of the analysis and how it effects performance output, there is just an acknowledgment of fuelling the engine but no in depth research on the topic just brief descriptions where needed. As this study is just involving volume and flow of air in an engine modified for racing, it will be ignoring flow characteristics such as the swirl and tumble effects as the study is just involving the volume and flow of air. This paper presents the application of practical experimental procedures with the help of a Superflow-300/600 Flowbench to measure both the production and modified head to view effects from increasing the volume of air to and from the engine and the speed at which that volume travels through the engine. The flow through an engine is equally important to have accurate values for coefficients of discharge (CD). During the testing of the cylinder heads the pressure of air mixture supplied to the intake port remains constant whilst a recording of the VFR is taken during a fixed valve lift between 1.4mm to 11.2mm (because the engine being tested has 10.80mm of valve lift) so a reading can be recorded as is typically done on a flow bench test. The flow velocity (FV) of the air in the intake port, is recorded in increments per valve lift to show how efficient the port design is in getting the air mixture to the combustion chamber and the flow velocity of the exhaust ports will show how quickly the gases are expelled. Modifications to improve the mass flow of air will be done by such methods as Porting and polishing the cylinder head after a comparison of the data is examined. The Production head will be assembled onto an engine block and mounted into the test car (Peugeot 106 GTI) and then the engines output, the same procedure will be done for the modified head. Both engines output will be calculated in the vehicle to give outputs with real world conditions by using a Dyno Dynamics rolling road to validate the research in this paper.

Chapter 1: Introduction

The development of the internal combustion engine (ICE) in the field of motorsport, processes in the industry have become more technical in aspects of performance and efficiency. The cylinder head has been thoroughly researched mainly the intake system, as it is a vital sub system of an engine that can impose a great effect on air-fuel mixture, consumption and exhaust gas formation. How the air is shaped does not concern the study in this paper because in this case the study is of a race engine, every part of research found for performance engine building ignores flow characteristics such as swirl and tumble but is more focused on volume of air and velocity of air in the intake ports i.e (how fast that air volume travels into the combustion chamber). Don't be mistaken by volume and the capacity of the overall engine, this volume increase is dedicated to the volume of air in the cylinder head ports whilst retaining the vehicles cubic capacity. "A good designed intake system can improve engine power, increase torque and volumetric efficiency" (Abdullah, 2013). To produce more horsepower from an engine you must be able to burn more fuel, one way of burning more fuel is done by increasing air supply to the engine. In order to extract the maximum performance from an NA engine, it is usually necessary to modify the cylinder heads ports. Without doing this you will never really see big gains. Putting "high lift" long duration camshafts into the ICE "will allow more air in" but a cast aluminium head from a production car today already has restrictions in the port itself that hinder big gains from performance camshafts. The casting process in production engines leaves excess material causing the restrictions (Vizard, 1990). This topic of the paper of increasing an engines power output by analysing the flow of gases in a production cylinder head with the intent of using techniques such as machine porting and polishing to remove these restrictions therefore increasing performance of the engine. This topic of study has been chosen because the ICE being used is from Peugeot 106 GTI rally car that is used for motorsport purposes, in this case stage rallying. In Ireland there is new stricter regulations for 2020 junior rallying set out by Motorsport Ireland to make junior rallying cheaper and more competitive. To explain why a stock head VS a ported and polished head experiment is beneficial for competition racing is carried out in the paper below.

1.1) Background

Obviously an ICE has a block full of components that influence combustion such as piston crown shape and the materials used in the engine plays a huge factor in the power output of an ICE but not as much of an influence as the cylinder head, this is because it is more difficult to get air mass into an NA spark ignition engine on the induction stroke than it is to get burnt gasses out because the “burnt gasses get pushed out during the exhaust stroke also with the help of the increased torque from the ignition stroke”. This is where the design and geometry of intake ports stands out with its operation of “volume of flow”. This is really the primary source of an engines power as stated by (Gollan, 1997). Here is some of the restrictions engine builders face when designing cylinder heads.

•**Legislation:** This is important as manufacturers have to fit legal criteria's throughout a democracy such as downsizing engines capacity to reduce emissions in the environment.

•**Homologation:** In terms of rally cars and race cars the size of cylinder head ports are restricted to a certain diameter for some classes so at a race meeting scrutineers may pull apart your engine to measure sizes and tolerances of such components. An example of this is the Peugeot 106 cup car class as the stock inlet manifold and throttle body are to remain untouched and but the cylinder head ports may be blueprinted (Trevor Gray, 2019).

•**Reliability:** Making the engine still be competent even with the new modifications being added.

•**Dimensions:** Cylinder heads in particular have to be compatible with the designed engine as there wouldn't be a need to have a very expensive large bore head on a road car that is cheap.

•**Efficiency:** The head in particular is the source of where air/fuel enters the engine, where the combustion process takes place, and where burnt gases exit therefore it must have a good casting process to be less restrictive depending on the vehicles designed application.

•**Noise:** Restrictions of the amount of noise your vehicle can produce has been implemented not only in road vehicles but also race cars therefore dictating the exhaust note which may hinder performance.

The biggest restrictions for cylinder heads designs are because of engine legislation to improve emissions/efficiency in recent years but since the test car being used for this project is a Peugeot 106 GTI rally car that is intended to be operated at full throttle nearly all the time unlike an economy vehicle, therefore no emissions quotas are implemented by the governing body that is motorsport Ireland. The investing into downsizing of engines and introduction to aluminium cylinder heads has improved efficiency vastly but has created problems such as low cc turbocharged engines producing low Co2 but high Nox particles because of high combustion temperatures (G.Sindhu, 2018). The benefit of aluminium cylinder heads in the case of high combustion temperatures is because these heads dissipate heat much faster than there iron counter parts but wont create more power unless they flow better (Baechtel, 2015).

1.2) Cylinder Head Operation

As stated above the head is where air and fuel mixes in an engine which is done by the opening of intake valves and the induction stroke of the engine. The mass and density of the air/fuel mixture is drawn into the cylinder at atmospheric during the intake stroke in relation to the air in the intake manifold (At regular atmospheric pressure). This is known as volumetric efficiency (VE) (Livesey, 2012). To create more horsepower you must be able to burn more fuel and to burn more fuel you must be able to get more air in (Hillier, 2014). This is why it was stated above that the cylinder head is the most important component to how powerful/efficient an engine is. The flow of gas is affected by a number of points such as:

- **Size, shape and number of valves:** This is why most engines fit 2 or 3 intake valves instead of one and you can get more “oxygen” inside depending on the bore of the



cylinder and size of the engine. Again it is dictated on the dimensions and space available (Livesey, 2012). The size of valve ports have been empirically studied by various tuning companies for example Connaught competition engines developed the 16valve big bore Warrior head that bolts directly onto a Pinto block designed for 8valve set up as seen in the image on the left. The valve ports are much larger also to create torque for rally and hill climb events (Price, 2003)

Figure 1: Image, Holbay warrior big valve head, By (Price, 2003).

- **Valve timing:** In recent years Honda have developed the valve timing on their engines, one in particular is the K20 cylinder head in which has a variable inlet camshaft which is controlled by the ECU and is capable of advancing the inlet camshaft up to 50degrees. With the cam angle being capable of making constant adjustments relative to the exhaust cam and crank position, the VTEC system can produce a very smooth power band across the rev range (Stafford, 2009).



- **Shape of ports and engine speed:**

Different techniques in shape of port such as the Peugeot TU5J4 head has its inlet ports angle pointing downward into the combustion chamber, this is known as a high approach port where a turn is necessary in the port design as shown in the image on the left. This was designed so that the ports follow the valve stem to the seat to create the phenomenon known as “swirl” (Baechtel, 2015).

Figure 2: Image, Vauxhall C20XE ported and polished cylinder head, By (Stafford, 2009).

Naturally aspirated engines typically run at 80-85% VE because the cylinder is pulling in a vacuum. Although at the era of naturally aspirated V10 engines in formula 1, manufacturers were able to achieve 125% VE, this was done by highly optimised inlet manifolds. As stated by Steve De Groote as part of F1 technical the plenum over the drivers cockpit on a formula 1 engine is there to take in air at high speed and then it branches off to all of the inlets where the air flow slows down and it cools to feed all cylinders. Different charge flow techniques



like this combined with port fuel injection improved fuel atomisation which is the reason for these high VE values (Groote, 2009). The result of increased efficiency means that the engine can run at "higher compression ratios" which is great for racing engines as you can "increase engine rpm (Increase the amount of times the cylinder will combust in a minute) as its now safe to run a higher lift cam" (Gollan, 1997).

Figure 3: Image, Renault V10 F1 engine operating at 125% VE, By (www.automotivepress.fr, 2013).

1.3) Motivations and Aims

The motivation for this investigation comes from a passion of motorsport competition and all things mechanical. As a rally/racing driver at clubman level competing in Ireland on a small budget, the competition level is high compared to many other FIA bodied countries. With entry fees rising due to expensive motorsport event insurance costs, there isn't many categories that are practical for a clubman driver until a new competition class created for the 2020 season. Due to the coronavirus spread of 2020, all motorsport competition was at a halt but the 2020 regulations for a junior rally class were brought into action to bring down overall costs for young drivers. The classes regs are very restricted to make competition fair between competitors and modifications are limited so massive sums of money spent that competitors have done in the past on a vehicle are unnecessary and not eligible for the class. The car used for this investigation is already eligible for the new junior class 16 rally series but it is slightly underpowered so a motivation for this paper is to modify the vehicles engine to increase the output while still being within the rules of modification of the class. How modifying the engine for the class will be linked into the paper is by using and displaying modern theory and techniques of improving an engines power output that is used in the motorsport fraternity today. The steps used for collecting the required data for optimising the engine for the class will be detailed in 4 different chapters. The 1st chapter introduces the project just as in this section and explains how the ICE part that will be modified works. The 2nd chapter is all of the research behind the theory and techniques used in the industry that links to the methods that is used in this project. The 3rd chapter is the methodology used to experiment on the engine such as steps of removing the cylinder head from the engine, flow bench testing the heads to show evidence involved to explore potential of the production Peugeot TU5J4 cylinder head by means of a Superflow 300/600 flowbench in the university workshop, optimising the cylinder head by methods of porting and polishing and detailing the rolling road testing method. Finally the 4th chapter will involve calculating/displaying and discussing results, this section will be comparing both the production head and the optimised head and then validating the performance and volumetric

efficiency upgrade by comparing the dynamometer sessions curve sheets of the production engine and optimised engine.

2020 Junior rallying engine regulations

- The engine homologation rules state that all engines must retain inlet and exhaust manifolds in their entirety.
- No modifications to throttle body are permitted, similarly the fitting of an aftermarket high flow manifold or larger throttle body from the same manufacturer.
- Engine must be from the original manufacturer of the chassis.
- Forced induction is not permitted with the exception of a 1000cc turbo diesel.
- All 2wd must be equal to or less than NA 1650cc multi-valve

Engine Specification	
Model	106 GTI
Coolant	Liquid Cooled
Cylinders	4
Number of Valves	16v
Aspiration	Naturally Aspirated
Bore	78.5mm
Stroke	82mm
Capacity	1580cc
Combustion System	Petrol multi point fuel injection
Maximum Speed	6600rpm
Power	120bhp
Torque	145nm

In this study the engine used in the flow analysis is a Peugeot TU5J4 taken from a 106 GTI. It is a 1.6L 16v 4 cylinder engine therefore the engine has 2 intake and 2 exhaust ports per cylinder and it comes well equipped with multi-point port fuel injection and “downdraft” ports design. This is a port shape technique used by many other engine manufacturers such as Honda in the B-series engine and Toyota in the 4AGE engine, where the inlet ports are angled downwards into the combustion chamber also known as a “High approach port”. This enables a turning motion in the port as shown in the image on the right. (Monroe, 2006) Earlier it was mentioned that production engines have excess material left over from the casting process that restrict the volume of airflow. Excess material is still prominent in engines from manufacturers like Peugeot which is such a large wealthy company with 74.03billion euro in revenue for 2018 and a deep history in World rallying/endurances racing at the highest level. So you’d expect a good product from them. But originally the Peugeot 106 GTI production was aimed at the economy market and not built for motorsport use. So this comes with drawbacks such as restricted airflow in the cylinder head ports to make for somewhat of an efficient fuel economy vehicle but enough power to be a sport hatchback vehicle. “The mass flow rate of a stock production engine have the optimum combination between intake port design and intake valve lift” but there designed in such a way to meet strict emissions, comfort and drivability criteria for daily usage (Muhammad A. M. Johar,

2019). Therefore performance in a spark ignition (SI) production engine is being compromised to meet an overall goal of the vehicle.

The study will look into optimizing the production SI cylinder to understand the performance limitations before using the Peugeot 106 GTI rally car in an event. Even though the TU5J4 engine is originally a production engine, it has been a successful rally engine used in the FIA R2 and S1600 classes. The engine can be found in the Citroen C2R2 Max cars that produced 190bhp and the engine can be found in the Peugeot 106 S1600, Citroen Saxo S1600 rally cars that produced 220bhp compared to the 120bhp of the production TU5J4. This evidence of increased power output and Volumetric Efficiency (VE) gave this investigation hope for some outstanding results.

Aims of the Investigation

- **Gain knowledge of ICE technology:** Previous fuelling systems and techniques from single carb to multi carbs up to modern day injection.
- **Gain mechanical hands on experience:** By disassembling the TU5J4 head from the block while the engine is in the 106 GTI rally car will give a mechanical knowledge of deconstructing an engine and understanding what components are to be removed in order. This will help when assembling all the head components back together like for instance when applying the head gasket and torqueing down the head bolts which is key attribute to have hands on experience that motorsport teams will look for.
- **Improve theoretical understanding through experimental procedures:** The theory involved in understanding how a cylinder head operates.
- **Increase Mass air-flow/Velocity of airflow and CD of TU5J4 engine:** (Bell, 2002), (Baechtel, 2015) and (Gollan, 1997) all state that increased mass or volume of air-flow is vital to NA SI engine performance.
- **Display and discuss the improvement of VE and its link to the dyno curve:** Show how the dynamometer curve sheet of the test car correlates to VE
- **Display and discuss Increases in power and torque output:** Validate the theory and experimental procedures discussed in the paper by getting real world output figures on a rolling road dynamometer.

Chapter 2: Literature Review

This chapter is all of the research found to have a deep knowledge of the intake and exhaust processes that is fundamental to optimize a modern combustion engine. The theory for the experimental analysis is vital to know for investigating what extent the mass flow and velocity of air in the intake system of a 4 cylinder spark ignition internal combustion engine depending on the experimental conditions at the steady state flow test bench.

2.1) ICE Volumetric Efficiency

Volumetric efficiency (VE) is the actual amount of air flowing through an engine, compared to its theoretical maximum or in other words it is a measure of how full the cylinders are. It is referred to in section 1.2) as a percentage, So if an engine is operating at 100% VE then you have contained 100% of the air your engine cylinder can theoretically hold by mass. "Volume always measures the same, but restrictions lighten the mass of air/fuel mixture compared to what a cylinder theoretically holds". "Inertial tuning of the Intake, head, cams and exhaust will make the volume heavier". The heavier the amount of air/fuel mixture that can be contained in a cylinder, which is then burned to make more power (Monroe, 2006). There are outside factors that are said to be influence VE of an engine and are therefore said to be an "uncontrolled environment". The environment is the factor that changes and engines VE for example Air density changes with temperature and altitude.

At lower altitudes near sea level the air is denser; this means that there are more air molecules inside the cylinder. As elevation rises the air gets thinner (less dense) which affects the air/fuel ratio of an engine because less air molecules are in the cylinder therefore less horsepower can be created. World rally cars experience such power losses every year for the Mexican and Argentinian events where elevation range is held on average at 2500m above sea levels with a highest point of 2737m. It has widely been reported on the impact of altitude on the engine with 20% power losses at these events due to less presence of oxygen which in turn leaves the engines struggling to breathe. Then on the other hand Corsica, Catalunya and Australia events are held very close to sea level (Watts, 2019). Formula 1 cars also experience severe power losses from altitude on events such as the Mexican GP where the circuit is mostly flat with only an elevation change of 2.8m but the height above sea level is 2000m+ compared to circuits like Spa-Francorchamps in Belgium where height above sea level is much lower but the change in elevation from its lowest point and highest point is 102.2m (Watts, 2019).

Also not to forget about the impact that temperature has on the VE of an engine. In the countries such as Mexico and Argentina where the climate is very hot, the additional temperature severely diminishes the power output because hot air is less dense than cold air. With the additional heat that an engine creates under the bonnet cannot be prevented, this is why world rally cars have vented bonnets and spacers placed on the bonnet hinges to lift the bonnet a few extra centre metres to let heat escape from the engine compartment (Watts, 2019). The automotive/motorsport industry is flooded with aftermarket products to improve an engine's VE by making it easier for the air to flow. Such products include bigger throttle bodies, independent throttle bodies, different length intake manifolds, cold air filter kits, porting and polishing/skimming the surface of cylinder heads, longer duration/higher lift cams, larger diameter valves and bigger bore/polished/different length exhaust manifolds. The displacement and efficiency of a naturally aspirated engine limit how much power it can make. This is because the engine can only inhale so much air because of the atmospheric force in which is pushing air into the engine is only 14.7psi (pounds per square inch) at sea

level and as stated above atmospheric pressure decreases with elevation therefore air density also decreases with temperature.

Those examples above are ways of improving the volumetric efficiency for naturally aspirated engines but other alternatives are by “forced induction” such as adding turbochargers, superchargers or nitrous oxide. A forced induction system overcomes the limitations of atmospheric pressure by pushing more air into the cylinders. “Consequently, the engines power output becomes a function of how much boost it gets and increasing the boost overcomes flow restrictions and flow limitations in the intake system and cylinder heads” (Bell, 2002). This is because it is more difficult to get air mass into an NA spark ignition engine when the engine is just relying on the vacuum during the induction stroke than it is to get burnt gasses out because the “burnt gasses get pushed out during the exhaust stroke also with the help of the increased torque from the ignition stroke” (Gollan, 1997). We know it is a naturally aspirated 1580cc engine but for the following formula we must convert displacement from cubic capacity (cc) to cubic inch (ci). The formula to estimate VE at different rpm from an engines dyno curve is shown below:

$$VE = \frac{\text{horsepower} \times 4235}{CID \times rpm}$$

2.2) Airflow Charge and Pressure Drop

Discharge coefficient is also known as the parameter used to quantify the breathing capacity of an engine's intake system. “When there is minimal difference between the geometrical passage area and the effective flow area, this will improve the efficiency of the intake system” (Algieri, 2013). In other words low differences indicate low resistance and allow the engine to operate close to its desirable condition. Discharge coefficient can be described as:

$$C_D = m_f / m_t$$

Where m_f the real mass is flow rate and m_t is the theoretical mass flow rate at the intake valve (Nagarajan, 2012). So the coefficient of discharge is the ratio between actual discharge to ideal discharge. CD is used to monitor the flow efficiency of a cylinder head based on the valve area, as a function of the $\frac{\text{Valve Lift}}{\text{Valve Diameter}}$ (flow per square inch of area) ratio (Nagarajan, 2012). As shown Below:

$$C_D = \frac{\text{Volumetric Flow Rate (VFR)}}{\text{Valve Flow Potential}}$$

Another way to determine the discharge coefficient is by effective area. Based on the assumption that an ideal orifice, the mass flow rate is proportional to area. Relationship between discharge coefficient and area is described as:

$$C_D = A_f^e / A_f$$

Where A_f^e is effective area and A_f is the curtain area. Effective area is the area of imaginary frictionless orifice which can produce the real mass flow rate (Lumley, 1999). Equation for compressible flow through a flow restriction is usually referred in order to define the mass flow rate through the poppet valve (Heywood, 1988).

To calculate the coefficient of discharge for both heads you are first to find the cylinder heads volumetric flow rate which is also called “mass flow” by (Vizard, 2012). This measurement represents the amount of air that can pass through the intake ports before reaching the cylinder for the combustion process to occur and this measurement could represent the mass flow of burnt gasses leaving the engine through the exhaust ports which would display how much air the TU5J4 engine can breathe and how much burnt gasses can be expelled. So it is simply the amount of air that can flow in that port for an increment of valve lift therefore given you an idea of the mass airflow changing between valve opening and valve closing just as if the engine was operating. The superflow bench gives the measurement in CFM so since Europe uses the metric system this is converted to m^3 / Sec and is shown below:

$$VFR = \frac{CFM}{3600} \times 1.7$$

Another helpful measurement that could be defining the speed at which the airflow charge enters the head through the intake ports signifying the suction of the intake stroke and the speed that the burnt gasses exits the cylinder head through the exhaust ports with the help of the push from the exhaust stroke. This measurement would be helpful as it would signify how efficient or inefficient the TU5J4 engine can get airflow charge to the cylinder head and get rid of burnt gasses. This measurement of cylinder head port speed is known as Flow Velocity (FV) and the unit is m/sec, the equation for working this out is below:

$$FV = \frac{VFR}{\pi r^2(\text{valve head } \emptyset) - \pi r^2(\text{valve stem } \emptyset)}$$

Air is an elastic medium and as such its rate of flow has to be measured under specific conditions. When testing cylinder heads on a flow bench it is common practice to use “standard pressure drop” throughout the valve opening range. The valve/port flow capability involves how much CFM flow can be produced by the ports for a given pressure drop. The more flow for a particular pressure, the better the head flow there is, therefore the head’s flow capability is typically the major flow restriction in the engine’s total flow capability. As stated in other words by (Vizard, 2012) “the greater the suction on a given orifice, the greater

the volume of airflow through that orifice". To make a comparison across the board for a number of different orifices we have to fix the amount of suction that's why the test pressure is the same for each valve lift increment. For instance the flow bench used in this investigation is a SuperFlow-300/600, this bench flows 575CFM @ 25" (pressure drop) of H₂O which in terms of power output the flow bench is good enough to test engines that "produce 150bhp per cylinder" as stated by (Superflow.com, 2020) which was a sufficient capacity to test the TU5J4 head because the engine is only a 1600cc NA four cylinder engine that produces 120bhp in total from the production line.

2.3) ICE Development and Fuel Injection Technology

Carburettors: In the motorsport fraternity at historic racing and clubman level competition carburettors are still used because of the simple operating principles that competitors can enrich or lean the fuel supply to their engine for optimising the output and they are often used because they are cost effective because at clubman level they need little maintenance as they just need to be cleaned out not very frequently. These early types of fuelling systems consist of three parts both connected in the carburettor body.

1. Regulating the entry of fuel to the carb according to the rate at which fuel is consumed. A float chamber is the form of a regulator used in this design.
2. Atomising the fuel and mixing it with the accurate amount of air. This known as the mixing chamber.
3. The throttle valve or butterfly valve which is there to regulate the vehicles power by controlling its airflow to the intake manifold and then to the intake ports.

Fuel enters the float chamber through the inlet connection where it then fills in the chamber. The float rises and cuts off the fuel inlet by the closing of the fuel needle, as this takes place the fuel leaves the chamber through the jet carb where the fuel now mixes with air. The air is drawn in by the opening of the throttle valve which causes a "pressure drop" inside the "choke tube". The air rushed through the choke tube if the velocity is adequate enough and the air/fuel mixture is drawn into the cylinder head depending on the rate of engine speed. This summary of a carburettors operation of how air and fuel is drawn into an engine has been described by (Hillier, 2014) and this operation be backed up by (Gollan, 1997).



Single Carburettor: For this layout of carburettor the same principles still apply as stated above. This inlet manifold is an example taken from a ford 2.0l pinto engine that has 4 runner manifolds branched off from the carburettor to feed all 4 cylinders. The design can only deliver a limited amount of air and fuel to the cylinders as there is only one throttle valve or body in which the air enters the engine. Fitting a larger carb or throttle body would improve performance as more oxygen can enter the engine as well as fuel to be burnt and as stated earlier by (Hillier, 2014) and this information can be backed up by (Livesey, 2012), the more air/ fuel mixture you can burn = greater power output.

Figure 4: Image, 2.0L Ford Pinto engine with single carb and intake, By (classiccarbs.co.uk, 2019).

As stated by (Ohata, 1986), Variable length intake manifold design travelling the intake heads ports is “to ensure correct gas flow is obtained at a range of engine speeds further improving the performance and efficiency of the engine”. The literature behind this evidence is also discussed in research papers focusing of variable length manifold design by (Vichi, 2015) and (Yide, 2012) too. Although this design has its drawbacks in terms of the amount of air it can let in, the manifold design shown in figure 4 of the single carburettor design and in figure 8 of the Peugeot 106 GTI the multi point fuel injection system both use variable length intake runners. This manifold design as shown in figure 8b) and 8c) is designed to correct flow into the cylinder head efficiently by “metering” the amount of air. As a means of fuelling the engine, these designs aren’t the greatest way of delivering airflow charge to the engine because of these drawbacks of metering; this design is meant for good fuel economy application. The following example refers to the use of a single carburettor shown in figure 4 and not the multi point fuel injection because the fuelling system in figure 8 can be controlled independently. For example since this design has to feed 4 cylinders through its 4 runner lengths from a single point of entry, the fuel is much denser than the air so therefore its slower to change direction of flow. In this case the air changes direction faster in runner lengths to cylinders that have less distance to travel to the cylinder and some cylinder will receive less air because the runner length to the cylinder is further. At high rpm in a racing situation some cylinders could run to lean and burn out spark plugs and some cylinders will receive excess fuel that will be unburnt (too rich).

Multi Carburettor’s: Above are examples of rally car engines fitted with the same design Weber dual choke carburettors. The dual carb design allows for air/fuel mixture to enter the intake manifold and give the engine more horsepower over a single carb depending on the size of the carbs, reed valves and the amount of valve duration and lift. The dual carburettor in the case of being used on a 4 valve per cylinder as shown above in figure .. and figure ..., “has two carburettors joined together by a single float chamber” as described by (Hillier, 2014). “The two throttles or butterfly valves are interconnected and should be synchronized to give the same opening time at all engine speeds”. The same operation principles on how the carburettor gets air and fuel are still the same but the difference is that each cylinder has its own independent throttle valve and air supply to the cylinder head. This means throttle response is faster as each cylinder should get similar air/fuel mixture.

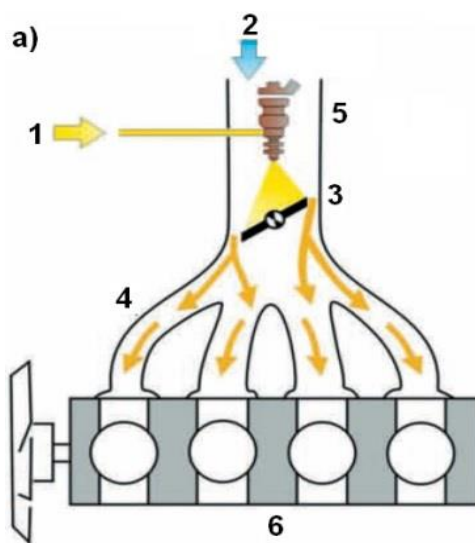
1. The fuel atomisation is better than a single carb if it is tuned right because the airflow is greater. All old Ferraris and Ferrari racing engines used multi Weber carburettors pre fuel injection.
2. The pressure drop in each inlet is greater over the variable/unequal length manifolds found on single point carburettors
3. The temperature of the mixture in the manifold is less over a single carb setup on classic mini engines or pre crossflow engines where the exhaust ports are on the same side as the intake ports and the exhaust is situated beneath the intake manifold. “Fuel evaporation occurs due to the heat soak that rises from the exhaust so less air/fuel mixture is burnt” as discussed by (Edelbrock, 2011) from a document on their website. The evaporation that takes place in a single carb “is an undesirable phenomenon because it reduces the mass of air and fuel that can enter the cylinder for combustion”.

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Figure 5: Photo, on the left is a 205 GTI rally car with twin weber 45mm carbs. Figure 6: Photo, on the right is a Mk2 escort rally car with twin weber 50mm carbs, By (Cunniffe, 2020).

Basically the larger capacity that you get with a multi-carb setup gives much more advantages to the power and efficiency of an engine over a single carb setup. The two engines above with dual Weber carbs have their intake manifold curved into the cylinder head to create a “downdraft” as referred to by (Smith P. H., 1977) for a means to increase the pressure drop of the intake manifold by trying to get as much oxygen into the combustion chamber as possible.



Single-Point Fuel Injection: This design was the first generation of the electronically controlled injection to disperse fuel through an injector. They require a pressure regulator, ECU and a fuel pump. Along with this setup they are a variety of sensors that monitor conditions. The variables monitored by these sensors include oxygen%, manifold pressure air temperature and a throttle position sensor. The design is also known as throttle body injection as the injector is placed behind the throttle body at the beginning of the intake manifold. It is placed in a very similar position to where a single carb setup is placed. Therefore the same limitations apply to this intake manifolds like single carb manifolds as stated earlier.

Figure 7: Diagram, example of a Single Point Fuel-Injection, By (Dave Rogers, 2013).

The benefit of this design has over carburetors is the way it is able to accurately control fuelling. Another benefit this system has over carbs is mentioned by (Hillier, 2014) when the “spray pattern of the injector and fuel is atomised at all engine speeds therefore an optimum air/fuel ratio can be achieved”. Also (Hillier, 2014) describes another benefit fuel injection has over carburetors for cold start procedures such as enrichment and deceleration will vary as the engine warms up by the ECU monitoring resistance decreasing and signals from these sensors. The Bosch Jetronic fuel injection system is a form of single-point injection and although it has many inferior capabilities over a multi-point setup it is the cheaper alternative. The Bosch Jetronic single-point fuel injection can be found in 80's-90's General Motors engines such as Opel Cadet's/Vectra's.

Multi-Point/Direct Fuel Injection: The two diagrams above in figure 8b) and c) are both examples of multi-point fuel injection although they differ ever so slightly. Firstly the difference over the single-point setup is the way this system has an injector for each cylinder with a single throttle body situated at the beginning of the intake manifold. For these examples of multi-point injection “the quantity of air induced for a given throttle opening depends on the manifold pressure”. The manifold absolute pressure (MAP) sensor, engine speed signal, engine coolant temperature, air temperature sensor and ECU coordinate against the throttle potentiometer. In the diagram on the left of figure 8b), atomisation is improved over single-point injection as fuel is sprayed at the back of the inlet valve at high pressure causing the fuel to be dispersed as a mist when the inlet valve opens. (Bell, 2002) and (Vizard, 1990) recommends that injectors be placed as close to the inlet valves as possible to minimise flow losses and improve vaporisation.

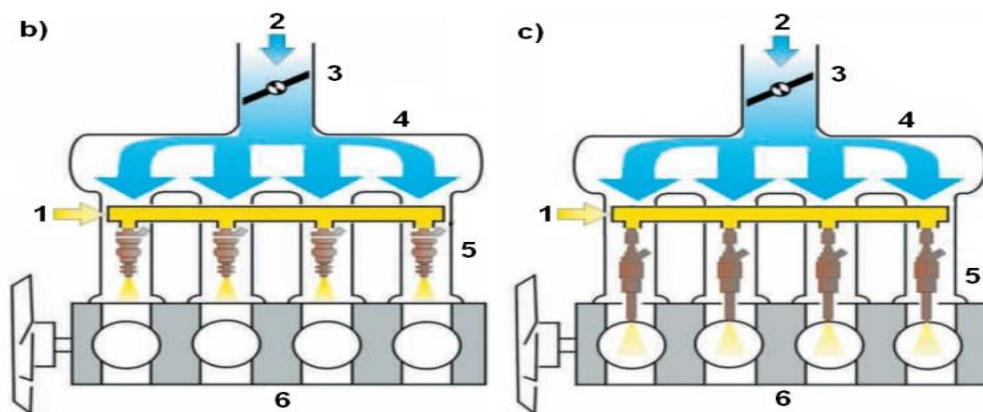


Figure 8: Diagram b) Multi Point Fuel-Injection and c) Direct Injection, By (Dave Rogers, 2013).

In the diagram on the right of figure.. , represents direct injection where the cylinder head is designed for injectors to be placed in the combustion chamber for each cylinder to be directly facing the piston crown. This is just another step above the multi-point injection as fuel flow losses are now out of the equation and the engine designer can just concentrate on getting more oxygen through the inlet ports as efficiently as possible.



Here is an example of a multi-point fuel injection setup with independent throttle bodies and 2 injectors per cylinder, 1 of the injectors is situated in the normal multi-point area in the intake manifold located after the throttle bodies and facing the back of the inlet and the other injector is placed before the throttle body where the spray is directed at the front of the throttle body. The induction design provides each cylinder with air at atmospheric pressure with its own direct supply of flow therefore for high rpm engines, there is greater pressure drop for air flow to be sucked into the cylinder by the vacuum of the intake stroke which is a benefit over a single throttle body that branches off to feed 4 cylinders.

Figure 9: Image, Honda K24 rally engine with multi point/direct injection, By (Stafford, 2009).

Chapter 3: Methodology

3.1) Removing TU5J4 cylinder head



The bonnet is taken off to begin with because it becomes a hindrance when removing engine components. To tackle the engine bay now, the battery must be disconnected and removed. Next is the forced induction air-box as you can see at the front of the engine bay in figure 10. The air-box is simple to get tools near and the silicone air-box hoses are held on by jubilee clips. The wiring harness or loom needs to be disconnected next and must be done carefully to avoid any tears in the loom. The ideal way to do this is jack up the car and place it on jack stands to secure the car from falling. From underneath the car now you can disconnect any of the wiring harness at the back and bottom of the engine bay etc. once that is removed then the ECU can come out.

Figure 10: Photo, Engine bay before removing cylinder head, By (Cunniffe, 2020).

Put tags on components that you aren't too sure on where or what way they go back on and put them in a neat storage not to lose parts. Next disconnect the coil-on plug packs and now remove spark plugs. From this point it is difficult to get at the back of the Intake manifold as it is located very close to the bulkhead. For some bolts you must get back underneath the car and place a $\frac{1}{4}$ " ratchet with enough leverage on them. Now it is important to drain the coolant from the car, This can easily be done by releasing a bung on the bottom left of the aluminium radiator or by getting a pry bar at one of the bottom coolant hoses. Place a basin underneath the bung or silicone coolant pipes to catch all the coolant. Now it is time to remove all stainless steel 8mm engine cover bolts that give access to the intake and exhaust camshaft cover.



Figure 11: Photo, TU5J4 ported cylinder head assembled to the engine, By (Cunniffe, 2020).

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Once that cover is removed you can get at the cylinder head bolts with either a ½" Ratchet with a multi-spline socket or a 3/8" ratchet with a multi-spline socket. Remove these in the formation that the factory laid the cylinder head onto the bottom end. Once this is done you are free to pry around at the upper part of the head to lift the head clean off the block. When assembling this again you should replace any broken components. Use sufficient amount of assembly oil and areas where needed use fresh gasket sealant between stacked components.



A key ingredient to a naturally aspirated race engine for achieving greater volumetric flow rate is one of the benefits of our TU5J4 engine and that is that it has a higher lift camshaft than the stock engine originally had which grants more valve lift and valves stay open for a longer duration. The outcome of this is a significant increase in horsepower and torque by providing more oxygen to the cylinder for the combustion process. With the addition of higher lift cams gives rise to poor idling because higher lift and longer opening duration means the rpm would be greater therefore the time the valves have to cycle (open and close) would be less in the higher rev range.

Figure 12: Photo, TU5J4 cylinder head removed with just the engine block left, By (Cunniffe, 2020).

When measuring the camshaft profiles of the stock TU5J4 head I noticed the cams were much higher lift and duration than normal so when testing the ported head I had to use the same camshafts so that when comparing results, the graphs are appropriate and correlate one another. The poor running at low rpm brought the invention of variable valve timing with different lobes to have variable lift and duration. Honda VTEC and BMW Vanos systems use these types of variable timing in their SI engines. Valve lift can be varied between 7mm-12.5mm, this system solved the pressure drop problem inside the cylinder which occurs at high valve lift and causes a large pumping loss but in the same time they apply earlier closing of the intake valves to decrease pumping losses.



Figure 13: Photo, Vernier timing pulleys and cylinder head bolts removed, By (Cunniffe, 2020).

3.2) Flow Bench Testing

The efficiency and performance of an engine now is known that the cylinder head design is heavily responsible for the output of an engine. The intake and the exhaust ports size, shape and surface are the key features of extracting power right down to the combustion chamber this is due to how the flow of gases and pressure drops with the design of the head. The University of South Wales Trinity Saint David provided a SuperFlow-300/600 flow bench in the university workshop for the experimental procedures to be carried out. The test was carried out @25" of H₂O (Pressure drop).

The SuperFlow-300 was the flowbench that we tested in the intake and exhaust ports from both of the Peugeot TU5J4 heads which was done at a pressure drop of 25" of H₂O of pressure drop. We then had to measure up the inlet and exhaust valve stems and head diameters so we could calculate the valve area that we would need later on to calculate the heads Flow Velocity (FV). Below in figure 14 is a CAD drawing of the layout of the TU5J4 combustion chamber that was drawn on SolidWorks 2019 software.

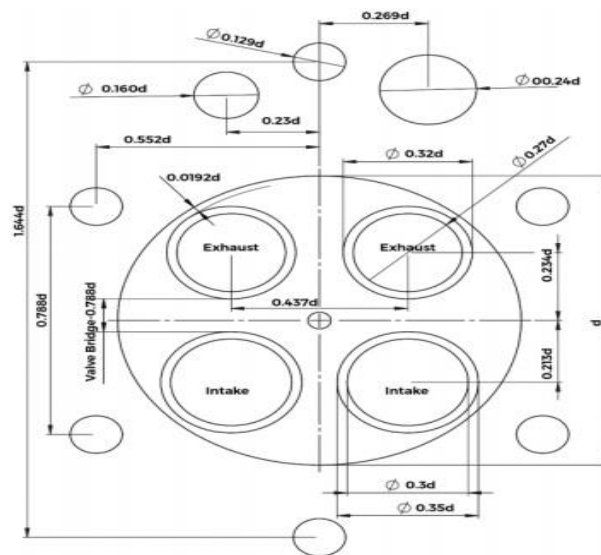


Figure 14: CAD Drawing, TU5J4 combustion chamber measurements, By (Cunniffe, 2020).

To set up the stock head first, the head was mounted and lined up on the flowbench. A 4" long cylinder adapter is used to mount to the flowbench. To seal the cylinder head airtight to the flowbench and the combustion chamber to the cylinder adapter we used bluetac, which would prevent any leak on both sides of the adapter. Next we tightened down clamps at each corner of the cylinder head so the pressure from the bench didn't move it and so that the valve lift DTA gauges were set and weren't giving false valve lift figures. A hand-made mount was made from a piece of aluminium in the university workshop for making valve lift adjustments in increments. The idea behind this came from instructions from (Vizard, 2012) which he directs you through a process of tapping a hole in the aluminium mount and then threading it so that a long bolt can be placed in it to move the valve buckets deep into the head to open the valve. By turning the bolt to open the engine valve into the combustion chamber simulates and camshaft lobe rotating to open an engine valve in an engine when it is operating. The DTA gauge are set to zero when the valve is closed so that it can record each increment of valve lift when the bolt on the mount is rotated. For increasing valve lift, two bolts had to be used because the engine is a 4-valve per cylinder engine with two intake and two exhaust valves.

The same procedures used when testing the intake valves had to be carried out on the exhaust valves too. (Ricardo, 1993) states that “both cylinder heads were to use the same amount of valve lift/valve diameter ratios”, so that we could start from valve closed and open the valve in the correct increments. Note: the valve lift/valve diameter ratios were different for the intake and exhaust as because the exhaust valve head diameters are smaller than the intake because air is more difficult to get into a cylinder from the suction of the vacuum on the intake stroke than it is to push burnt gases from the engine with the greater pressure from the rising piston. The testing of both heads was performed at the same ratio of $\frac{\text{Valve lift}}{\text{valve diameter}}$.

$L_v / \phi_v : 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40$

and in order to obtain the valve lift increment, the valve diameter was multiplied for each of the 8 L/D ratios.



Figure 15: Photo, 1st Flow bench testing of the TU5J4 head, By (Cunniffe, 2020).

When using the flow bench I noted the CFM values for each valve lift so that later I could use the conversion equation that were discussed in the literature earlier therefore graphs could be made. The bench testing took a full day to complete on the first day because I had to disassemble the head by removing camshafts, camshaft bearings, seals, bolts and measure the valve stem and valve head ϕ in the university workshop. Measuring the valve stem and valve head was recorded to use later on in calculating the net valve area. Since I was carrying out the testing on my own the test took longer than expected due to the accuracy level I demanded and for each measurement gathered had to be noted on a piece of paper. When testing the intake ports the flowbench measures air resistance where the air is sucked in through the head intake port past the back of the intake valve and into the combustion chamber where the air passes through the cylinder adapter and out of the back of the flowbench. For exhaust port testing the flowbench measures air resistance opposite to the intake port where the air is guided from the flowbench up through the cylinder adapter and out of the cylinder adapter past the combustion chamber by the exhaust valves and exiting the exhaust port which blows air out towards the person testing the head on the rig. Prior to this testing I had carried out the same tests on a smaller flowbench mostly used for motorbike engines, it was a SuperFlow-110 flowbench (@ 10" H₂O of pressure drop) and what occurred in them previous tests was that the air-flow temperature increased significantly. When testing the stock head ports the temperature was 18⁰ c and when testing the modified head directly after the temperature was starting the 31⁰ c and when I finished the test the temperature was at 35⁰ c. Due to this temperature difference, the air-flow results of the stock and ported heads couldn't be used to compare the efficiency of both heads which is why I repeated the test on a different test bench. So to prevent this phenomenon from occurring I used the bigger SuperFlow-300/600 flowbench and between tests I let the bench cool down to 18⁰ c before starting to compare the ported head which also took up a lot of time.

3.3) Port Optimisation: Porting and Polishing

This is the technique used across the motorsport fraternity for increasing the output of an engine by removing excess rough material from the casting process. As stated by (Nagarajan, 2012) “porting refers to removing the excess material to create greater port geometry”, which in turn improves the mass airflow of the cylinder head or getting that volume into the combustion chamber. It is done by using a Dremel or with modern techniques by means of a 5-axis CNC machine. “Polishing refers to the smoothening out the ports to make sure there is as little friction to slow the velocity of the air” as described by (Vizard, 2012) and mentioned in his other book (Vizard, 1990). For homologated racing classes such as formula ford 1600 series or in rallying such as the Peugeot 106 super cup challenge class in which certain cars must have the same diameter ports as the homologation papers state but competitors gain a slight advantage by blueprinting their cylinder engines within the required tolerances. This is done by ports matching the same diameter as the homologation papers state because there will always be excess material from the casting process as stated already. Studies such as (C. N. Grimaldi, 2004) have shown that a rough surface creates turbulence in the airflow that promotes air-fuel mixing in the port rather than having a squeaky clean port refined down by 400 grit sandpaper. Studies such as (Smith B. A., 2002) also have shown when testing a production cylinder head vs ported and polished head on a flowbench to calculate the mass air flow and flow velocity of the air, at opening valve lift of 1mm up to 7mm valve lift, the airflow recorded is slower on the modified head than the production head. This can be seen on the study of (Intake Port Flow Study on various cylinder head using a flow bench). The reason being for this makes clear understanding as it states the increase in port geometry means that the air has a larger cross sectional area to flow through, that’s why it would be slower than the production car and because the original ports as designed for the capacity of that engine. But the study shows at full open lift the volumetric flow is greater and the velocity.



Figure 16: Photo, on the left is our TU5J4 Stock intake ports By (Cunniffe, 2020). Figure 17: Photo, on the right is our TU5J4 Ported and Polished intake ports, By (Cunniffe, 2020).

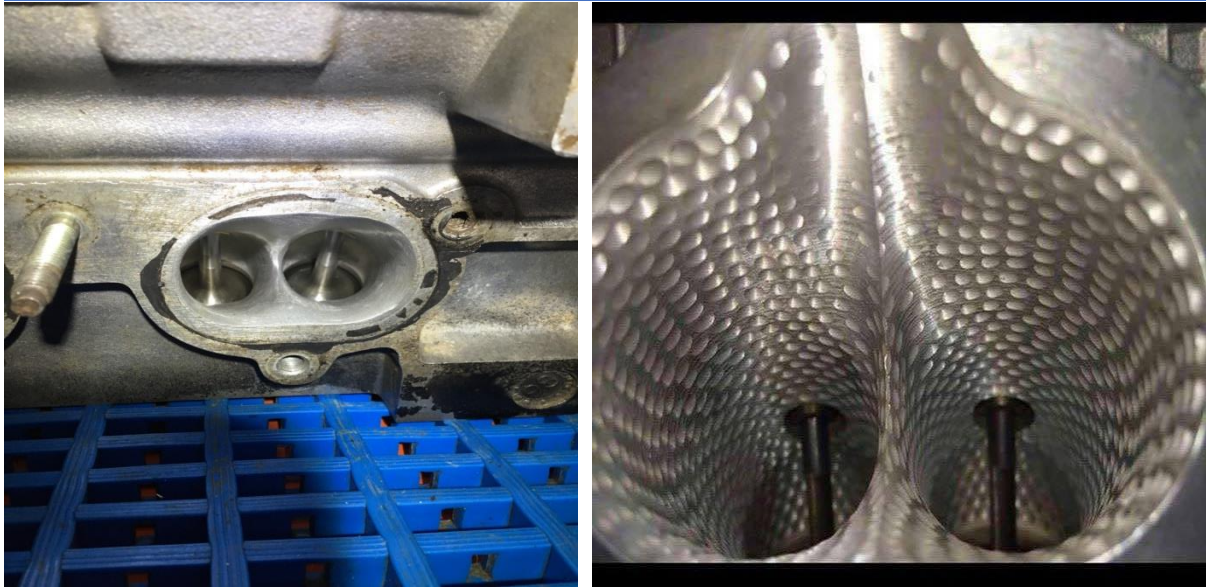


Figure 18: Photo, on the left is our TU5J4 head with smooth port surface, By (Cunniffe, 2020). Figure 19: Image, Dimple porting or golf balling of an intake port on a 6-axis CNC machine, By (Veicom Performance, 1991).

Martin Treacy at (Westward Precision Engineering, 1989) carried out the porting and polishing process in which took a week to complete. The basic understanding of a naturally aspirated engines breathing is the key to performance and efficiency improvement. As an engine is an air pump, increasing the ports sizes will expand the volume of air the ports can deliver to the combustion chamber which results to an increase in power and torque. Port shape, size and surface have a great impact on the flow velocity. Porting a cylinder head will increase the port size and can therefore improve the shape of the port by removing materials in the areas which restrict the air from flowing into the cylinder. Then regarding to the surface finish, polished surfaces will increase the flow velocity but that doesn't mean that they will increase power because flat polished surfaces will create less disruption for air/fuel mixture. "A surface with a certain degree of roughness on the port walls will help with fuel mixing" or metering due to "the turbulence to air flow they generate" (Baechtel, 2015). Many racing engines now are getting dimpling done to the intake ports for this reason of slightly generating enough turbulence to meter the air/fuel charge better. There is no need to dimple the exhaust ports as the air/fuel charge has already combusted in the cylinder and only burnt gasses are expelled and the exhaust gasses need to be removed as fast as possible to benefit high revving engines making torque higher up in the rpm band.

3.4) Rolling Road Sessions



Figure 20: Photo, Shot from the AP Performance workshop of the car on the rolling road, By (Cunniffe, 2020).

Early April 2020, the Stock cylinder head had to put back on the rally car and brought down for a dyno session with AP Performance to gather a ball park figure of what improvements might be seen when compared to that of the modified head. The session started at 9.00am in Oranmore outside of Galway city in the west of Ireland so the car was loaded up onto a car transporter at 7.00am that morning and brought for a one hour drive to AP Performance. Aengus aka the owner set up the car on the rolling road and secured it so that the car wouldn't take off from the eddy current rollers. This was done by attaching a chain to the rear towing eye of the car. The ECU was then hooked up to the dyno dynamics dynamometer so that Aengus could take control of the fuelling of the TU5J4 engine. A large fan was placed in front of the rally car as temperatures would rise significantly without the use of a fan and horsepower results would diminish due to heat soak. We removed the bonnet as it was composite and didn't want it getting blown back onto the windscreen of the rally car and getting damaged. He brought it for a few test runs and between each run he altered the fuelling of the engine throughout the rev range for example enriching fuel supply in a 500rpm increment and leaning the mixture back where it needed to be to get the most performance from the engine across the rev range. He set a limiter @ 7300rpm because prior to this he had been revving the engine beyond its capabilities.

Chapter 4: Results and Discussion

4.1) Production Vs Ported Head Flow Analysis

The results below in the tables and graphs below represent what was gathered from the flow bench testing in the university workshop, they include a comparison of both the production or stock head VS the modified head.

Intake Port CFM calculations: Stock head VS Ported Head

Valve lift (mm)	Stock Head Intake air flow (CFM)	Ported Head Intake air flow (CFM)
1.4	37.65	34.16
2.8	70.26	79.2
4.2	95.14	90.21
5.6	112.7	112.7
7	123.41	128.81
8.4	128.81	137.4
9.8	131	145.66
11.2	131.73	148.56

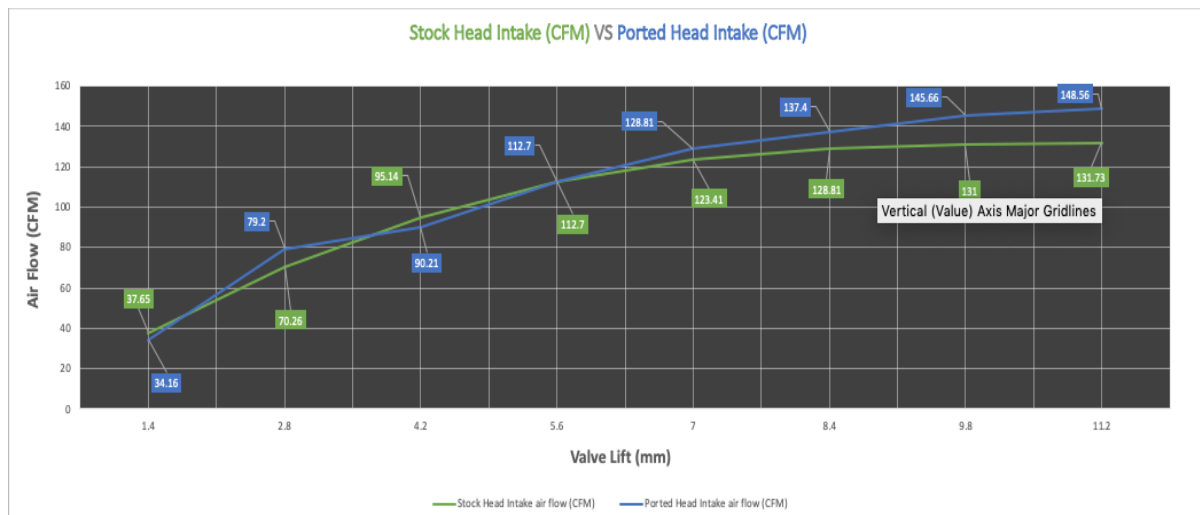


Figure 21: Graph, Intake port flow CFM calculations of both TU5J4 heads, By (Cunniffe, 2020).

The above table/graph in figure 21 represents the intake port air-flow in cubic feet per minute (CFM). The reason it is gauged in CFM is because the flowbench is an American brand so the first step to undertake is to calculate the volumetric flow rate (VFR) and from then the flow velocity of the ports air-flow and finally calculate the coefficient of discharge. As you can see in figure 21 and for the rest of the air-flow comparison graphs have the valve lift increments on the X-axis and the unit of measurement on the Y-axis. The green line for each of the graphs represents the stock cylinder heads air-flow efficiency from the initial testing and the blue line represents the modified cylinder heads air-flow efficiency. As an engine is an air pump, if you can improve the flow performance and efficiency will be greater. So an increase in the volumetric flow rate of an engine by means of porting and polishing removes restrictions to flow and gives rise to the greater volume of oxygen that a cylinder can consume in its induction phase of the cycle.

CYLINDER HEAD FLOW OPTIMISATION OF A SPARK IGNITION MULTI-POINT INJECTION ENGINE FOR MOTORSPORT APPLICATION

Exhaust Port CFM calculations: Stock head VS Ported Head

Valve lift (mm)	Stock Head Exhaust air flow (CFM)	Ported Head Exhaust air flow (CFM)
1.2	19.66	22.52
2.4	45.19	43.63
3.6	69	63.5
4.8	90.2	85.05
6	99.23	102.38
7.2	104.74	112.61
8.4	106.31	118.125
9.6	107.1	124.06

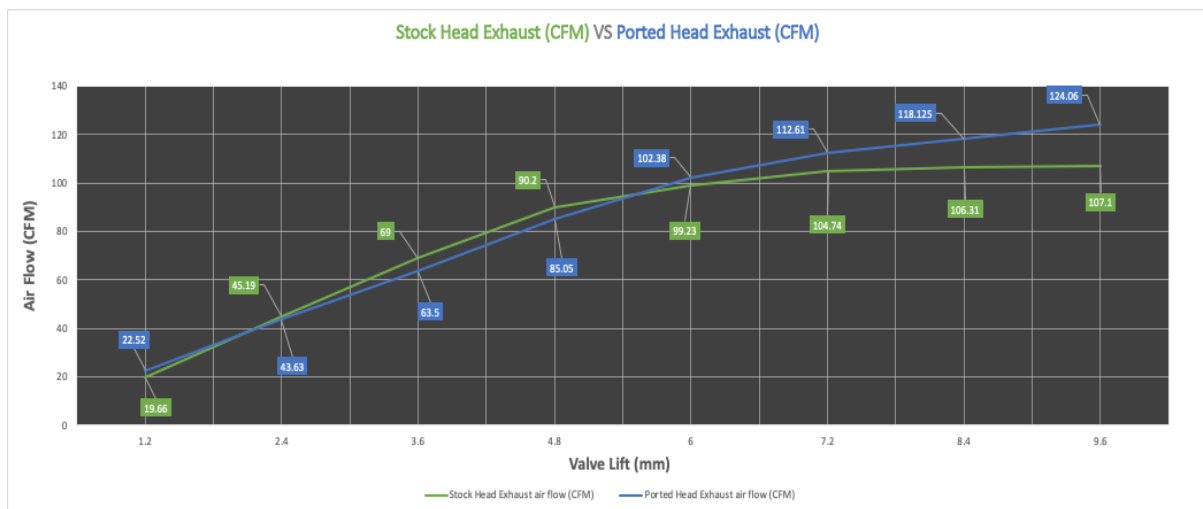


Figure 22: Graph, Exhaust port flow CFM calculations of both TU5J4 heads, By (Cunniffe, 2020).

The table and graph shown in figure 23 shows the volumetric flow rate (VFR) of both the stock cylinder head and the modified cylinder head. The VFR has been calculated based on the CFM readings taken from the flowbench testing. To obtain the VFR on m^3 / Sec , CFM has to be converted to m^3 / hr using the conversion table from (Superflow.com, 2020) or the SuperFlow 300/600 operator's manual. Conversion used: Cubic feet per minute multiplied by 1.700 to get cubic metres per hour and then the results obtained must be divided by 3600 to obtain the final VFR reading. This equation to convert can be written as follows:

$$VFR = \frac{CFM}{3600} \times 1.7$$

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Intake Port VFR (m3/sec) calculations: Stock head VS Ported Head

Valve lift (mm)	Stock Head Intake VFR (m3/sec)	Ported Head Intake VFR (m3/sec)
1.4	0.0178	0.0161
2.8	0.0332	0.0374
4.2	0.0449	0.0425
5.6	0.0531	0.0532
7	0.0587	0.0608
8.4	0.0608	0.0648
9.8	0.0619	0.068
11.2	0.0622	0.0695

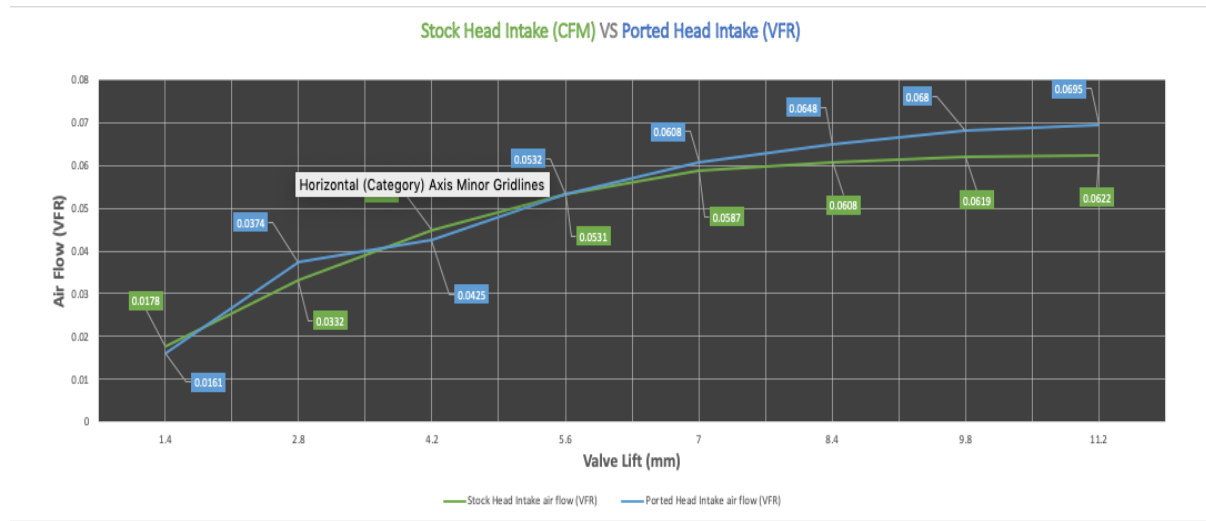


Figure 23: Graph, Intake port flow VFR calculations of both TU5J4 heads, By (Cunniffe, 2020).

Immediately you notice from first glance at figure 23 that the volumetric flow rate rises for both the stock and the ported heads as the valves open and continue to increase throughout to full lift. This is logical that the VFR increases as the valve lift over valve head diameter (L/D) increases which can be seen from valve opening ($0.017\text{m}^3 / \text{Sec}$ @ 1.4mm valve lift or @ 0.05L/D ratio increments to full valve lift of $0.062\text{m}^3 / \text{Sec}$ @ 11.2mm valve lift or @ 0.40L/D) ratio increments on the stock cylinder head and ($0.016\text{m}^3 / \text{Sec}$ @ 1.4mm valve lift or @ 0.05L/D) ratio increments to full valve lift of ($0.070\text{m}^3 / \text{Sec}$ @ 11.2mm valve lift or @ 0.40L/D) ratio increments. One occurrence that I didn't expect to see was that of the stock head air-flow being greater or equal to that of the modified head at some valve lifts. This phenomenon can be observed at initial valve opening (1.4mm) where the graph shows that the volume of air-flow is greater on the stock head than the modified head. This phenomenon has been discussed by (Stone, 2012) when he states "a larger passageway for the air to flow inside the port through the valve opening area, this area is then responsible for the volume of air allowed to pass". In other words large area = more volume, small area = less volume. Hence why the rate of this air movement inside the cylinder, through the head ports is referred to as volumetric flow rate. The rate of flow for the stock head is roughly similar to that of the modified head until the lift is recorded at (7mm), at this point the modified heads volume begins to flow much better than the stock head. This stock head is ($0.058\text{m}^3 / \text{Sec}$) and the modified head is ($0.0608\text{m}^3 / \text{Sec}$). With the valve lift wide open at (11.2mm) the modified head volume of air-flow is ($0.070\text{m}^3 / \text{Sec}$) which is much greater than that of the stock head ($0.062\text{m}^3 / \text{Sec}$). The reason for this is because the modified head has been ported (therefore the port has been bored out to increase capacity) and polished (the

surface has been smoothened) in which creates larger area for the air to flow hence a “greater mass of charge can enter the cylinder” (Stone, 2012). As stated above in the methodology, a smoother surface doesn’t create turbulent flow, this can be backed up by research carried out by (Smith B. A., 2002) where he states that the rough casting surface as seen on our stock head meters the fuel better because of the turbulence but drawbacks occur because the air/fuel charge is now turbulent and isn’t directly in its quickest path to travel to the cylinder. Since there is more area in the intake ports of the ported head and the surface is smoother, the greater volume of air-flow is subject to less friction than the rough surface in the stock head ports therefore more oxygen can get to the cylinder efficiently in the modified head. While the modified head has less flow at valve opening compared to the stock head and both heads flow equal at (5.2mm) valve lift ($0.0503m^3 / Sec$), this doesn’t affect the performance of the engine as the engine is built for racing and will be driving mostly in high rpm where the 4stroke cycle operates so quick that the difference at valve opening won’t be a problem. What is important is the greater the volume of flow across the valve lift range, the more oxygen that can be supplied.

As stated in the methodology a key ingredient to a naturally aspirated race engine for achieving greater volumetric flow rate is one of the benefits of our TU5J4 engine and that is it has a higher lift camshaft than the stock engine originally had which grants more valve lift and valves stay open for a longer duration. The outcome of this is a significant increase in horsepower and torque by providing more oxygen to the cylinder for the combustion process. With the addition of higher lift cams gives rise to poor idling because higher lift and longer opening duration means the rpm would be greater therefore the time the valves have to cycle (open and close) would be less in the higher rev range.

Exhaust Port VFR (m3/sec) calculations: Stock head VS Ported Head

Valve lift (mm)	Stock Head Exhaust VFR (m3/sec)	Ported Head Exhaust VFR (m3/sec)
1.2	0.0093	0.0106
2.4	0.0213	0.0206
3.6	0.0316	0.023
4.8	0.0417	0.0402
6	0.0469	0.0483
7.2	0.0495	0.0532
8.4	0.0502	0.0558
9.6	0.0506	0.0576

Stock Head Exhaust (VFR) VS Ported Head Exhaust (VFR)

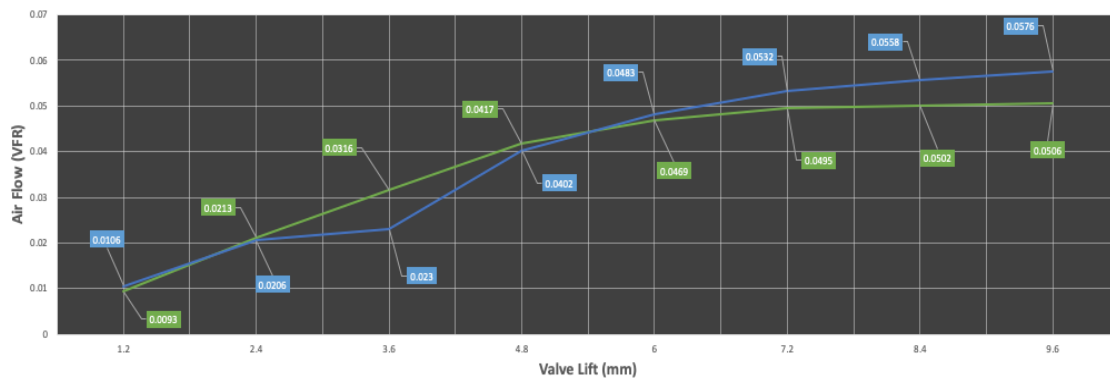


Figure 24: Graph, Exhaust port flow VFR calculations of both TU5J4 heads, By (Cunniffe, 2020).

The above table/graph shows same air-flow characteristics of the stock head flowing more efficient than the modified head which can be seen in figure 24 when testing the exhaust ports of the stock and modified cylinder head. When comparing VFR of the stock head at (2.4mm) valve lift ($0.0213\text{m}^3 / \text{Sec}$) and for the modified head ($0.020\text{m}^3 / \text{Sec}$). Even from the valve opening to mid range at (4.8mm) valve lift, the stock head ($0.0417\text{m}^3 / \text{Sec}$) is still flowing better than the modified head ($0.040\text{m}^3 / \text{Sec}$). But after this point the VFR for the modified head is much more efficient. This is due to once again the larger capacity in the modified heads exhaust ports at they have been ported so there is a greater surface area for a volume of mass to be pushed out from the exhaust stroke. Note: The flow bench blows air out the exhaust ports where the port is smaller near the back of the valve and expands as it travels to where the manifold is mounted, this expansion of the port occurs due to the porting process which allows more volume of air to be pushed out of the cylinder. The exhaust port VFR results are much lower figures than the intake stroke for both heads because the exhaust valves are smaller than the intake valves as air is difficult the enter the cylinder from the vacuum of the induction stroke compared to the pressure that the exhaust stroke has to expel the burnt gasses. The exhaust ports are smaller than the intake ports for that same reason.

CYLINDER HEAD FLOW OPTIMISATION OF A SPARK IGNITION MULTI-POINT INJECTION ENGINE FOR MOTORSPORT APPLICATION

Intake Port FV (m/sec) calculations: Stock head VS Ported Head

Valve lift (mm)	Stock Head Intake FV (m/sec)	Polished Head Intake FV (m/sec)
1.4	30.3	27.41
2.8	56.51	63.66
4.2	76.43	74.05
5.6	90.39	90.56
7	99.92	104.49
8.4	103.49	110.62
9.8	105.37	116.47
11.2	105.88	119.79

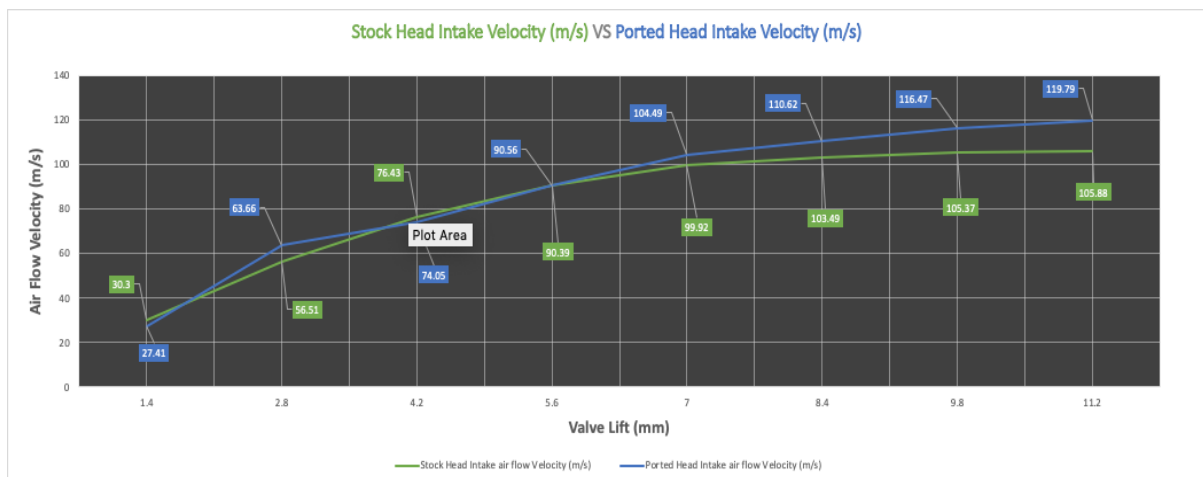


Figure 25: Graph, Intake port flow FV calculations of both TU5J4 heads, By (Cunniffe, 2020).

The above in the table/graph in figure 25 shows the flow velocity (FV) of both the stock and modified intake ports. To calculate the speed of the air at each valve increment is done as follows. $FV = VFR$ divided by valve area. So this is why measuring the valve stems and head diameter was necessary to do prior to testing on the rig.

$$FV = \frac{VFR}{\pi r^2(\text{valve head } \phi) - \pi r^2(\text{valve stem } \phi)}$$

To calculate valve area an example was given by (Superflow.com, 2020) or can be found in the SuperFlow 300/600 operator's manual. Formula a) and Formula b) are example for intake and exhaust ports flow velocity calculations:

$$\text{Formula a) } FV: \frac{0.0176}{[\pi(14 \times 10^{-3})^2 - \pi(3 \times 10^{-3})^2]} = 30.3 \text{ m/s}$$

$$\text{Formula b) } FV: \frac{0.0092}{[\pi(12 \times 10^{-3})^2 - \pi(3 \times 10^{-3})^2]} = 21.9 \text{ m/s}$$

The larger port shape and the polished surface of the modified head as shown in the above table/graph in figure 25 clearly show the effect that removing a lot of material in the porting process has on speed of air-flow in a cylinder head. The stock port as stated earlier clearly looks more restrictive to air-flow which can be seen at (8.4mm) of valve lift where the velocity is at (103m/s) and the modified head is at (110m/s). The stock head ports velocity stay between (103m/s-105m/s) at (8.4mm-11.2mm) whereas the modified head air-flow speed is much greater at these same valves lift and can be seen (110m/s-119m/s) . Port shape, size and surface have a great impact on the flow velocity. Porting a cylinder head will increase the port size and can therefore improve the shape of the port by removing materials in the areas which restrict the air from flowing into the cylinder. Then regarding to the surface finish, polished surfaces will increase the flow velocity but that doesn't mean that they will increase power because flat polished surfaces will create less disruption for air/fuel mixture. "A surface with a certain degree of roughness on the port walls will help with fuel mixing" or metering due to "the turbulence to air flow they generate". (Baechtel, 2015). As stated by (Smith P. H., 1977) "It is also vital in a naturally aspirated engine to not increase the port size more than what is necessary for the duration and lift of the camshafts" as larger port sizes will decrease flow velocity.

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Exhaust Port FV (m/sec) calculations: Stock head VS Ported Head

Valve lift (mm)	Stock Head Exhaust FV (m/sec)	Polished Head Exhaust FV (m/sec)
1.2	21.93	24.99
2.4	50.22	48.57
3.6	74.51	54.23
4.8	98.32	94.79
6	110.58	115.88
7.2	116.71	125.44
8.4	118.36	131.57
9.6	119.31	137.81

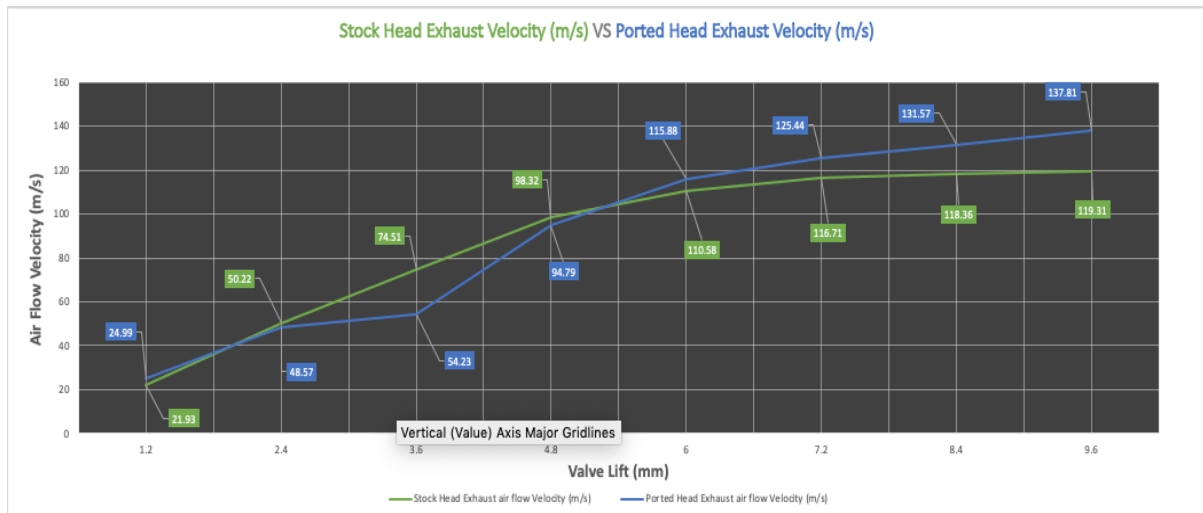


Figure 26: Graph, Exhaust port flow FV calculations of both TU5J4 heads, By (Cunniffe, 2020).

Above in the table/graph in figure 26 represents the exhaust air flow velocity of both the stock and the modified heads. As in the intake ports, the exhaust ports velocity is much greater than the stock cylinder head at high valve lifts but the stock cylinder head is much more efficient at expelling the air flow from valve opening to mid valve lift. This may be because the head was ported a little too much like what (Smith P. H., 1977) said “not increase the port size more than what is necessary for the duration and lift of the camshafts” as to large a port will decrease the speed at which the air can travel. But in the higher valve lifts from (6mm-9.6mm) the stock heads velocity ranges from (110m/s-119m/s) while between the same valve lifts the modified heads velocity ranges from (115m/s-137m/s), which is a huge advantage for engine breathing. As stated by (Heywood, 1988) “the area within the roof of the exhaust port is usually the most important flow restriction in the exhaust system”. Therefore here is a prime example of removing excess material in the exhaust ports improves an engines ability to breath and therefore increase performance in the higher rpm range.

4.2) Production Engine Dynamometer Analysis

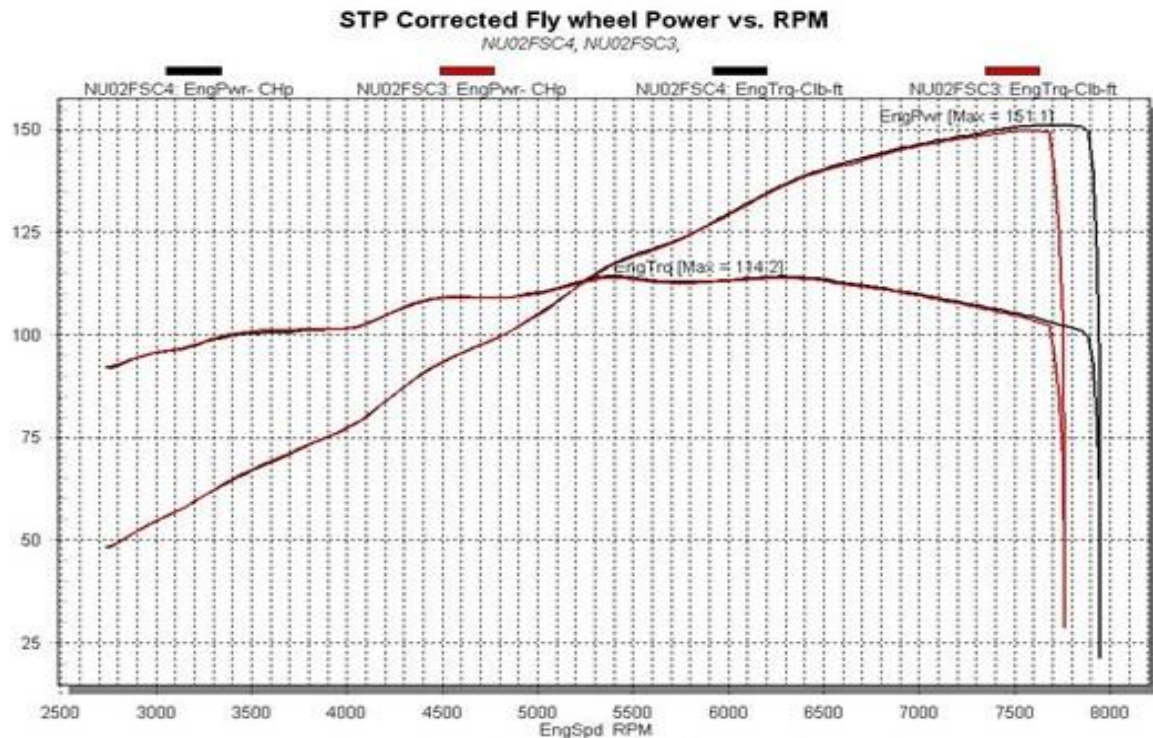


Figure 28: Image, Stock Head Peugeot 106 GTI dyno printout sheet, By (AP Performance , 2020).

VE is based on an engines horsepower dyno curve. The formula to estimate VE at different rpm from analysing an engines dyno curve The example in the graph above is a the production engines dyno run and we know it is a naturally aspirated 1580cc engine but for the following formula we must convert displacement from cubic capacity (cc) to cubic inch (ci). We know that its makes 151 horsepower at 7700rpm.

$$VE = \frac{\text{horsepower} \times 4235}{CID \times rpm}$$

$$151 \times 4235 = 639,485$$

$$1 \text{ cc} = 0.06102 \text{ ci}$$

$$96.418 \times 7700 = 742,418.6$$

$$639,485 \div 742,418.6 = 0.861 \text{ or } 0.86 (86\% \text{ VE})$$

Aengus from AP Performance ran the car on the rolling road and got 151bhp and 114lb ft of torque (114lbs ft multiplied by 0.738 = 154nm of torque) @7700rpm as can be seen in figure 28 above of the stock cylinder head dyno session. The car is 120bhp from the factory but as discussed in the methodology when taking apart the cylinder head, the camshaft didn't look as standard and when measured it turned out to be a 264deg duration camshaft with 10.8mm of valve lift compared to the 254deg duration with 9.0mm valve from the car stock engine. Since the bottom end of the engine is as standard from the factory with cast aluminium crank, cast aluminium conrods and cast pistons, Aengus advised that 7700rpm was too much for an ordinary engine block to handle and that it would be much safer to put a limiter on the engine @ 7300rpm so that the engine didn't blow up. So that is why the VE results below were calculated at the engine giving its highest power output and then when the limiter was set. The engine lost only 4bhp when dropping back 300rpm and the volumetric efficiency turned out to be greater when revved lower. The VE calculated below was 88%.

$$147 \times 4235 = 622,545$$

$$1 \text{ cc} = 0.06102 \text{ ci}$$

$$96.418 \times 7300 = 703,851.4$$

$$622,545 \div 703,851.4 = 0.884 \text{ or } 0.88 \text{ (88\% VE)}$$

4.3) Modified Engine Dynamometer Analysis

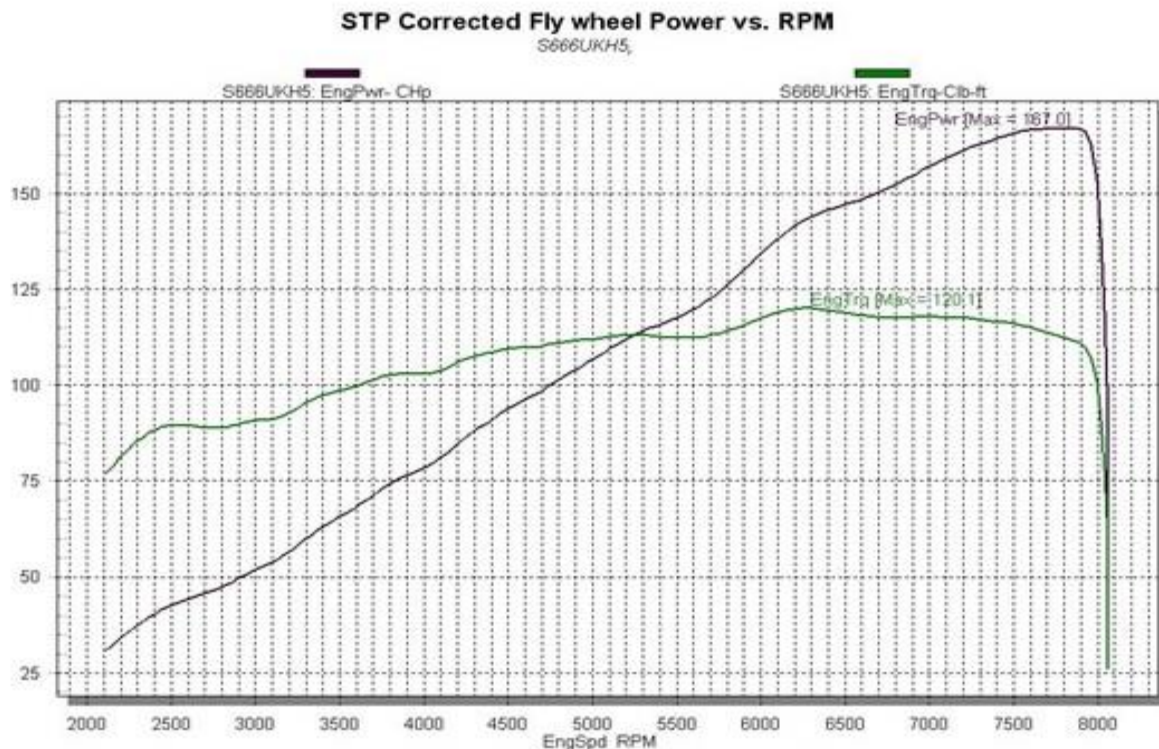


Figure 29: Image, Optimised head Peugeot 106 GTI dyno printout sheet, By (AP Performance , 2020).

The formula to estimate VE at different rpm from analysing an engines dyno curve is shown below. The example in the graph above is the modified cylinder head put onto the cars engine block and a dyno run. We know it is a naturally aspirated 1580cc engine but for the following formula we must convert displacement from cubic capacity (cc) to cubic inch (ci). We know that its makes 167 horsepower at 7700rpm.

$$VE = \frac{\text{horsepower} \times 4235}{CID \times rpm}$$

$$167 \times 4235 = 707,245$$

$$1 \text{ cc} = 0.06102 \text{ ci}$$

$$96.418 \times 7700 = 742,418.6$$

$$707,245 \div 742,418.6 = 0.953 \text{ or } 0.95 (95\% \text{ VE})$$

Once again Aengus advised that 7700rpm was too much to rev for the the TU5J4's standard set of block components so once again he cut the revs back to 7300rpm so that no damage would occur. It was a great surprise to see the engine running at 167bhp and even more impressing is that the engine made 163bhp and 120lbs ft of torque (multiply by 0.738 = 162nm torque) when Aengus cut the revs back 300rpm to 7300rpm. A gain of 16bhp and 8nm of torque was very impressive when taking into account the only modification made was to the size, shape and surface finish of the cylinder head ports. When calculating the VE it was found that whilst taking into account the vehicles engine capacity converting ci to cc, the volumetric efficiency gained was up 10% over the stock port cylinder head and VE was now calculated as 98%.

$$163 \times 4235 = 690,305$$

$$1 \text{ cc} = 0.06102 \text{ ci}$$

$$96.418 \times 7300 = 703,851.4$$

$$690,305 \div 703,851.4 = 0.980 \text{ or } 0.98 (98\% \text{ VE})$$

Conclusion

The paper completed detailed the methods used in current industry to accurately improve the flow of air and gasses in an ICE cylinder head. This was done by using modern techniques to measure volume of air-flow and the speeds at which that air-flow charge travels through cylinder heads ports. The intent of the paper was to improve the performance of the vehicle legally under the new 2020 junior rally championship in Ireland in which was achieved. Correct equations used in the paper were gathered and cited by experts in the automotive industry. Hands on labour was a crucial part in completing the project as removing and assembling the cylinder head to the project car was tedious work. In terms of literature reading and proof of knowledge on the subject was covered thoroughly in chapter 2 with the benefit of understanding units of measurement prior to flow bench testing and importance of VE and its link to dynamometer power curve before calculating volumetric efficiency. Both engines output will be calculated in the vehicle to give outputs with real world conditions by using a Dyno Dynamics rolling road to validate the research in this paper. So if an engine is operating at 100% VE then you have contained 100% of the air your engine cylinder can theoretically hold by mass. VE was calculated at 88% at 147bhp on the stock cylinder head and VE was calculated at 98% at 163bhp on the modified cylinder head, this was a very impressive +10% VE gain and +16bhp gain over the stock cylinder heads ports. It was amazing to see all of the results come into place after an intense month of prepping the car for two dynamometer sessions. Huge gains in the mass of air-flow in the ported cylinder head over stock cylinder head can be seen in figures 21-24 and incredible air-flow velocity can be seen in figure 25 and 26 where from (6mm) of valve lift to full valve lift on both the intake and the exhaust ports. What was more impressive was the velocity advantage of the exhaust ports over the velocity of the intake ports.

Evaluation

Due to the coronavirus pandemic that sent the world into lockdown in late March of 2020, I was put under heightened pressure to collect the rolling road data from the Peugeot 106 GTI rally car as nearly every business in Ireland had closed their doors. If there was something that I would have done differently during carrying out this project it would be that of getting the rally car put back together earlier on in the year such as January or early February as less stress and panic would have occurred to get the adequate data for the project to meet deadlines but luckily it got finished. Also the stock cylinder head shouldn't have been removed from the TU5J4 engine and the rally car should have been put on the rolling road prior to using the flow bench on the stock cylinder head as then less time would have spent pulling apart components from the engine.

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Peugeot 106 GTI Rolling Road Video Link

https://uowtsd-my.sharepoint.com/:f/g/personal/mcunniffe_148021_student_uowtsd_ac_uk/EmeFgzmU-rtBi3T9PxxoLg0BzFYSS9ADzcmCcTo5GOZSAQ?e=DwtezE

Appendices



Figure 1: Image, Holbay warrior big valve head, By (Price, 2003).



Figure 2: Image, Vauxhall C20XE ported and polished cylinder head, By (Stafford, 2009).

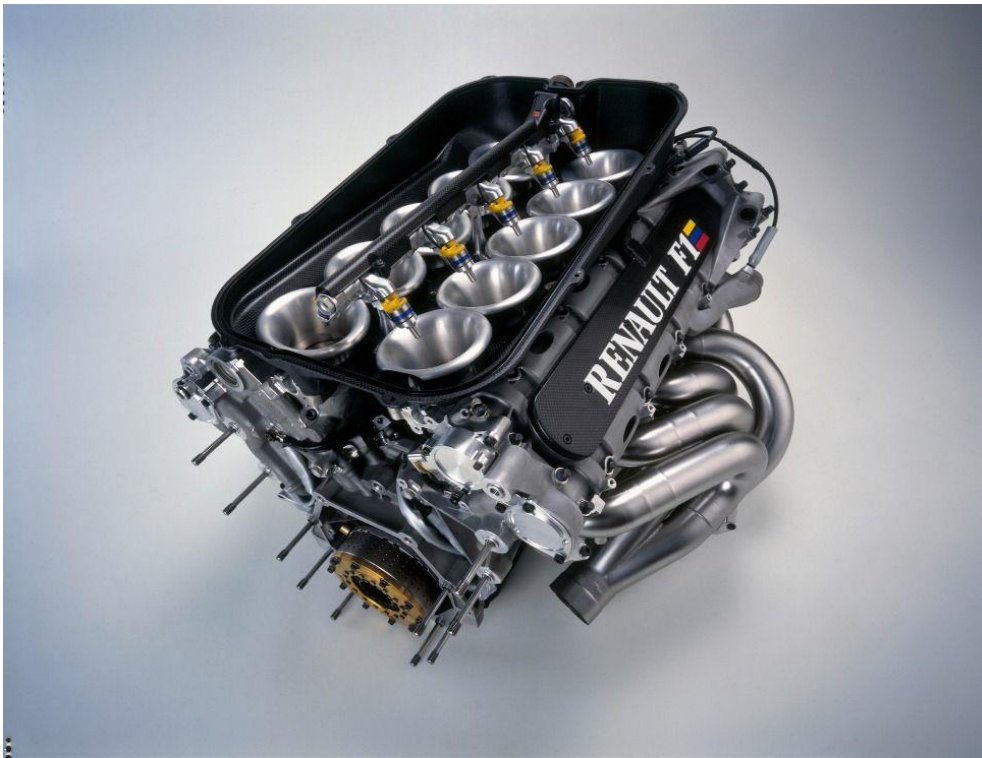


Figure 3: Image, Renault V10 F1 engine operating at 125% VE, By (www.automotivepress.fr, 2013).



Figure 4: Image, 2.0L Ford Pinto engine with single carb and intake, By (classiccarbs.co.uk, 2019).

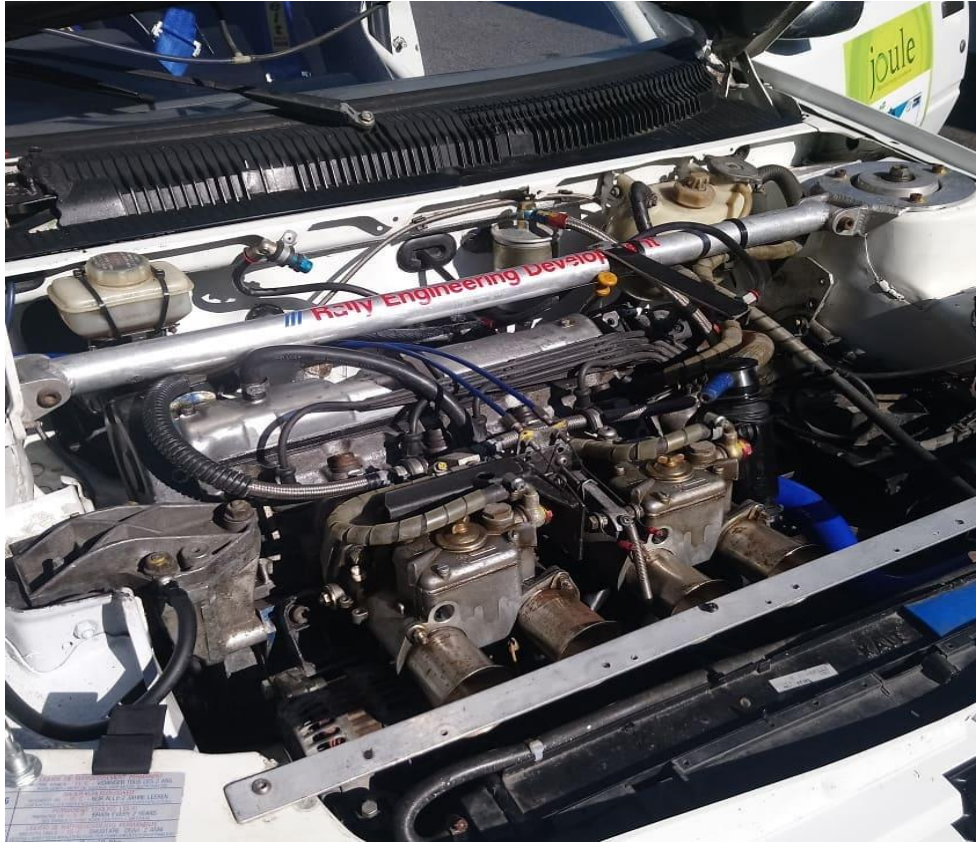


Figure 5: Photo, Is a 205 GTI rally car with twin weber 45mm carbs, By (Cunniffe, 2020).



Figure 6: Photo, Is a Mk2 escort rally car with twin weber 50mm carbs, By (Cunniffe, 2020).

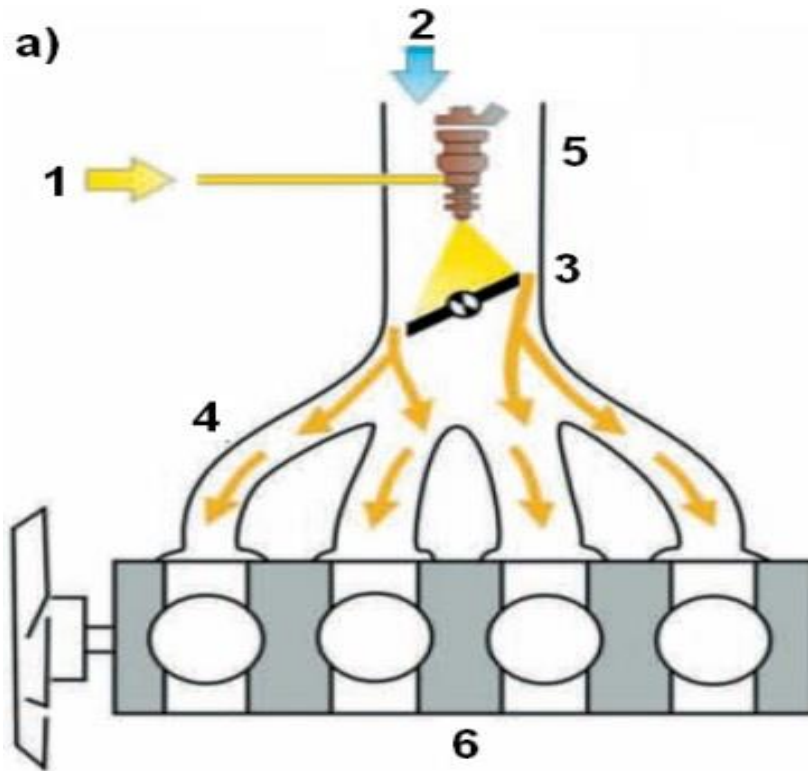


Figure 7: Diagram, example of a Single Point Fuel-Injection, By (Dave Rogers, 2013).

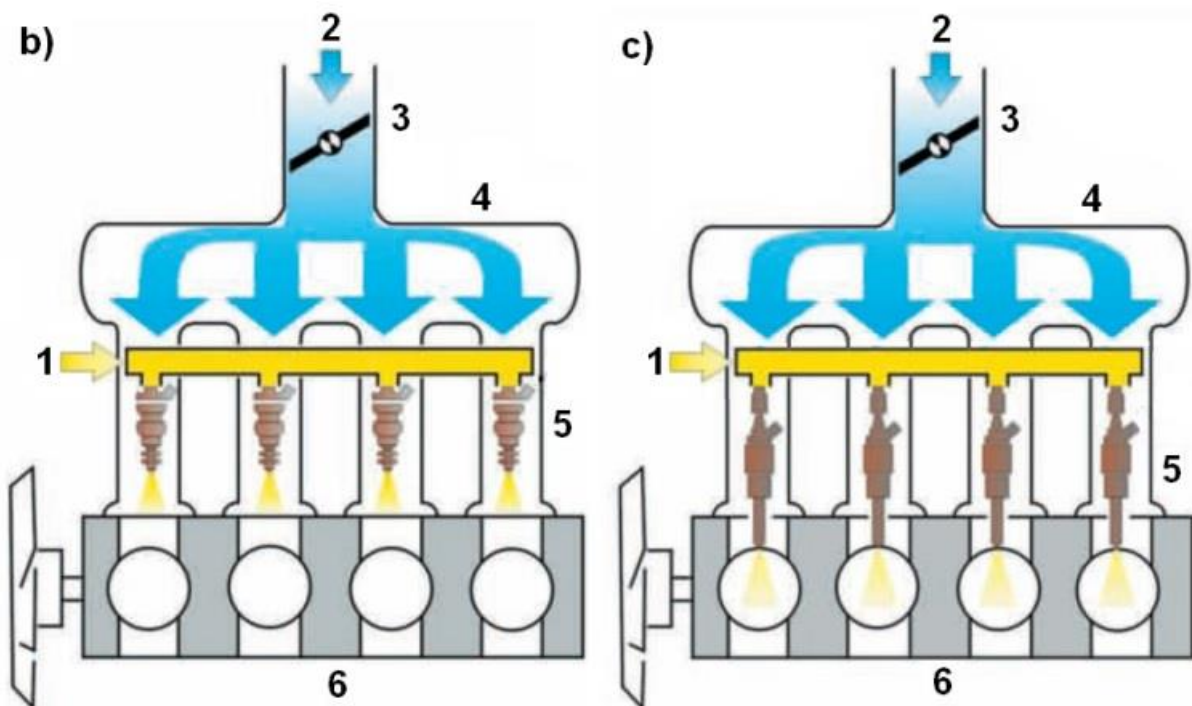


Figure 8: Diagram b) Multi Point Fuel-Injection and c) Direct Injection, By (Dave Rogers, 2013).



Figure 9: Image, Honda K24 rally engine with multi point/direct injection, By (Stafford, 2009).



Figure 10: Photo, Engine bay before removing cylinder head, By (Cunniffe, 2020).



Figure 11: Photo, TU5J4 ported cylinder head assembled to the engine, By (Cunniffe, 2020).



Figure 12: Photo, TU5J4 cylinder head removed with just the engine block left, By (Cunniffe, 2020).



Figure 13: Photo, Vernier timing pulleys and cylinder head bolts removed, By (Cunniffe, 2020).

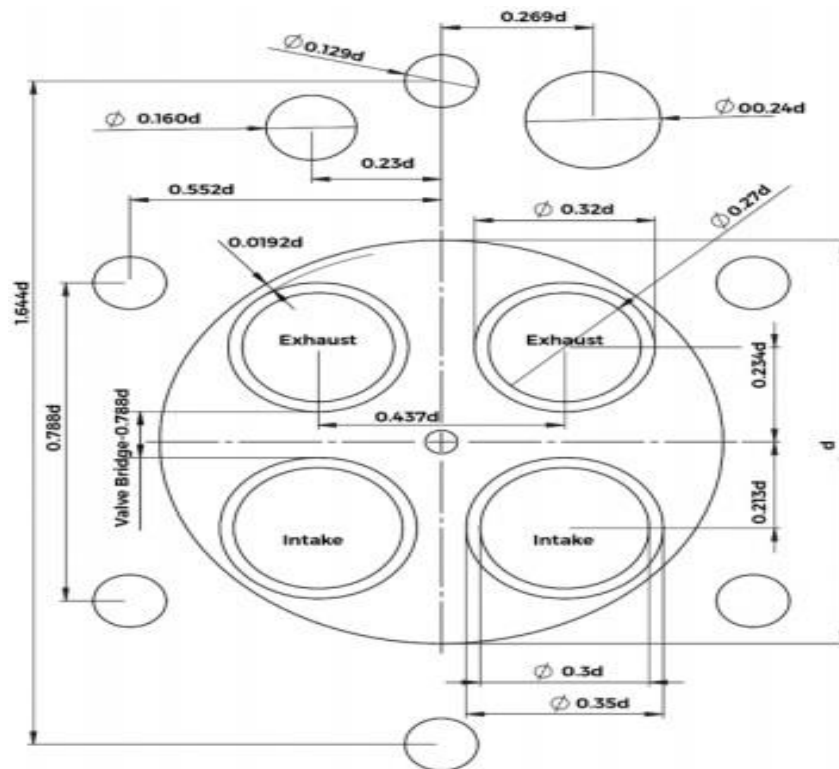


Figure 14: CAD Drawing, TU5J4 combustion chamber measurements, By (Cunniffe, 2020).

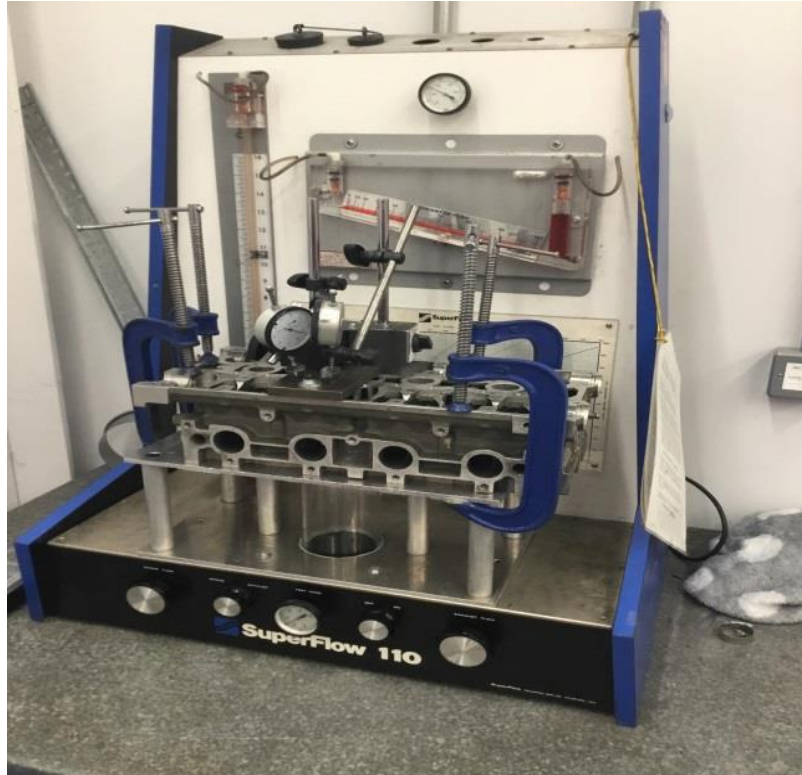


Figure 15: Photo, 1st Flow bench testing of the TU5J4 head, By (Cunniffe, 2020).



Figure 16: Photo, TU5J4 Stock intake ports By (Cunniffe, 2020).



Figure 17: Photo, TU5J4 Ported and Polished intake ports, By (Cunniffe, 2020).



Figure 18: Photo, Our TU5J4 head with smooth port surface, By (Cunniffe, 2020).

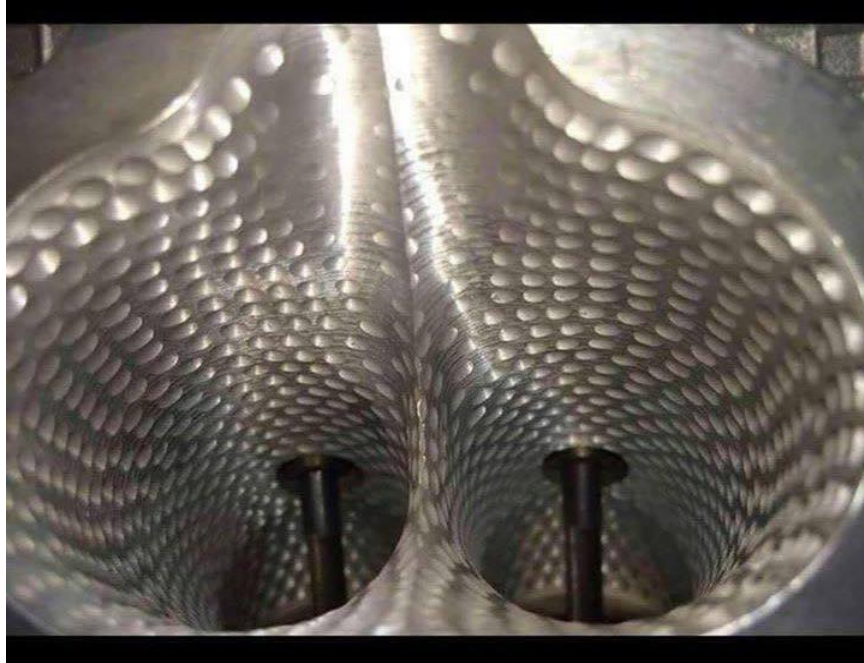


Figure 19: Image, Dimple porting or golf balling of an intake port on a 6-axis CNC machine, By (Veicomer Performance, 1991).



Figure 20: Photo, Shot from the AP Performance workshop of the car on the rolling road, By (Cunniffe, 2020).

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Valve lift (mm)	Stock Head Intake air flow (CFM)	Ported Head Intake air flow (CFM)
1.4	37.65	34.16
2.8	70.26	79.2
4.2	95.14	90.21
5.6	112.7	112.7
7	123.41	128.81
8.4	128.81	137.4
9.8	131	145.66
11.2	131.73	148.56

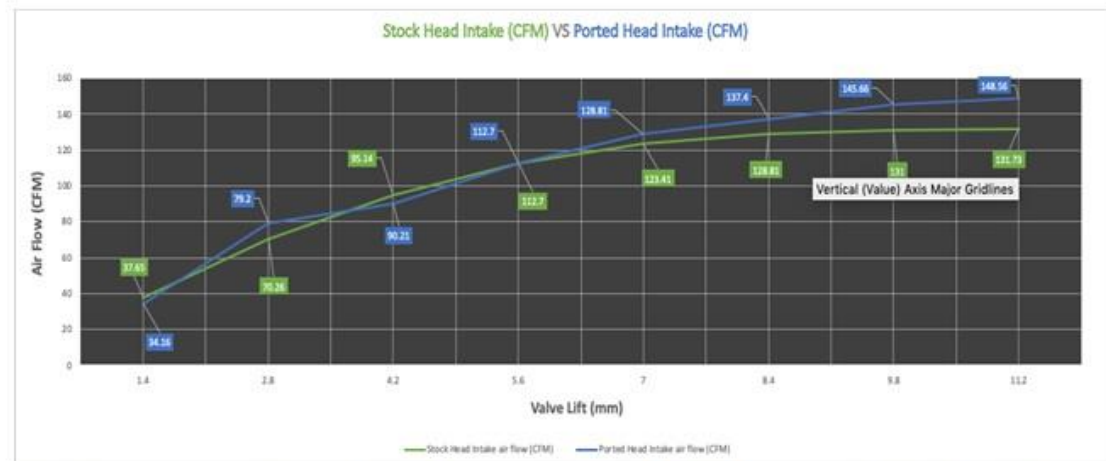


Figure 21: Graph, Intake port flow CFM calculations of both TU5J4 heads, By (Cunniffe, 2020).

Valve lift (mm)	Stock Head Exhaust air flow (CFM)	Ported Head Exhaust air flow (CFM)
1.2	19.66	22.52
2.4	45.19	43.63
3.6	69	63.5
4.8	90.2	85.05
6	99.23	102.38
7.2	104.74	112.61
8.4	106.31	118.125
9.6	107.1	124.06

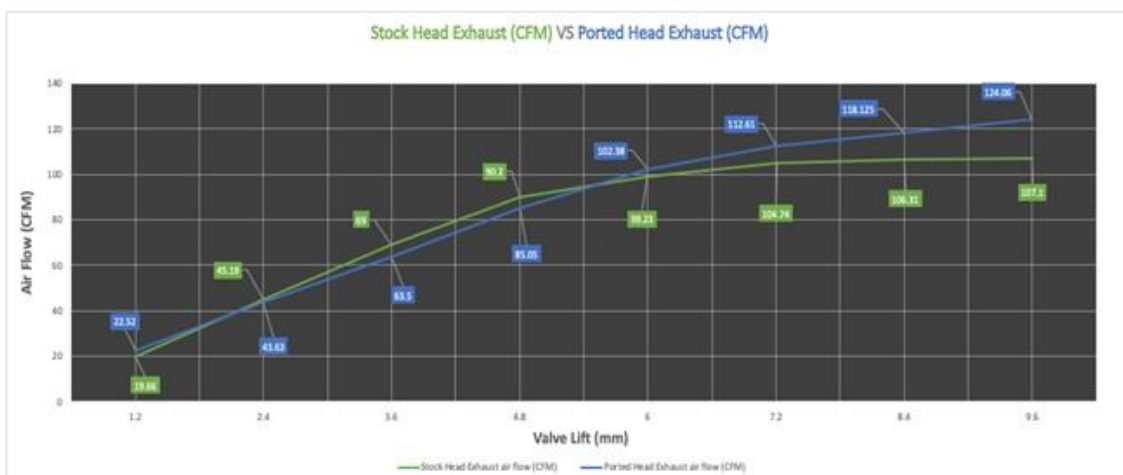


Figure 22: Graph, Intake port flow CFM calculations of both TU5J4 heads, By (Cunniffe, 2020).

CYLINDER HEAD FLOW OPTIMISATION OF A SPARK IGNITION MULTI-POINT INJECTION ENGINE FOR MOTORSPORT APPLICATION

Valve lift (mm)	Stock Head Intake VFR (m3/sec)	Ported Head Intake VFR (m3/sec)
1.4	0.0178	0.0161
2.8	0.0332	0.0374
4.2	0.0449	0.0425
5.6	0.0531	0.0532
7	0.0587	0.0608
8.4	0.0608	0.0648
9.8	0.0619	0.068
11.2	0.0622	0.0695

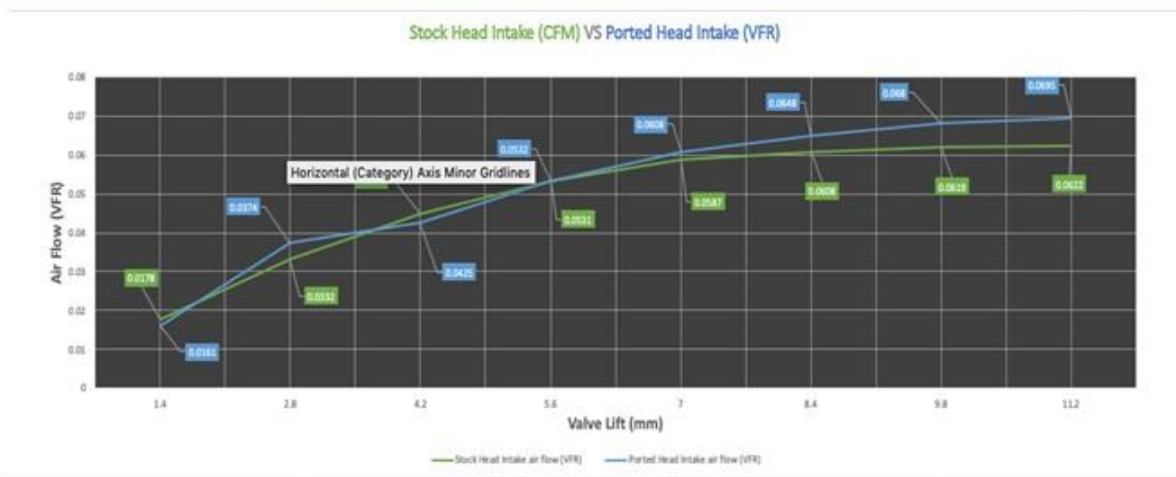


Figure 23: Graph, Intake port flow VFR calculations of both TU5J4 heads, By (Cunniffe, 2020).

Valve lift (mm)	Stock Head Exhaust VFR (m3/sec)	Ported Head Exhaust VFR (m3/sec)
1.2	0.0093	0.0106
2.4	0.0213	0.0206
3.6	0.0316	0.023
4.8	0.0417	0.0402
6	0.0469	0.0483
7.2	0.0495	0.0532
8.4	0.0502	0.0558
9.6	0.0506	0.0576

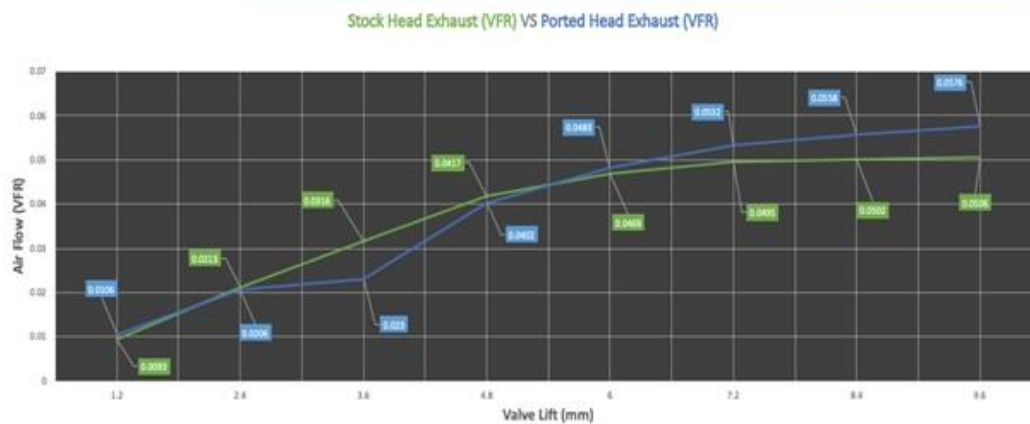


Figure 24: Graph, Exhaust port flow VFR calculations of both TU5J4 heads, By (Cunniffe, 2020).

CYLINDER HEAD FLOW OPTIMISATION OF A SPARK IGNITION MULTI-POINT INJECTION ENGINE FOR MOTORSPORT APPLICATION

Valve lift (mm)	Stock Head Intake FV (m/sec)	Polished Head Intake FV (m/sec)
1.4	30.3	27.41
2.8	56.51	63.66
4.2	76.43	74.05
5.6	90.39	90.56
7	99.92	104.49
8.4	103.49	110.62
9.8	105.37	116.47
11.2	105.88	119.79

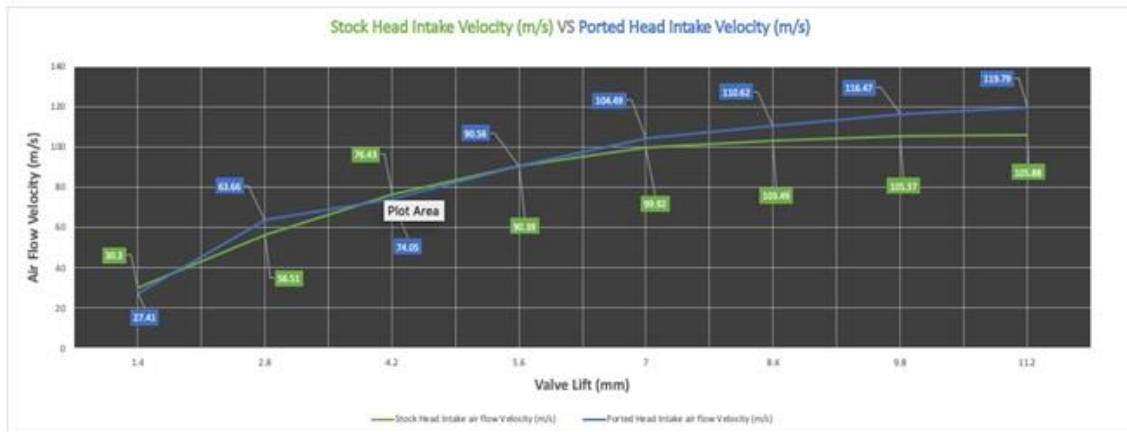


Figure 25: Graph, Intake port flow FV calculations of both TU5J4 heads, By (Cunniffe, 2020).

Valve lift (mm)	Stock Head Exhaust FV (m/sec)	Polished Head Exhaust FV (m/sec)
1.2	21.93	24.99
2.4	50.22	48.57
3.6	74.51	54.23
4.8	98.32	94.79
6	110.58	115.88
7.2	116.71	125.44
8.4	118.36	131.57
9.6	119.31	137.81

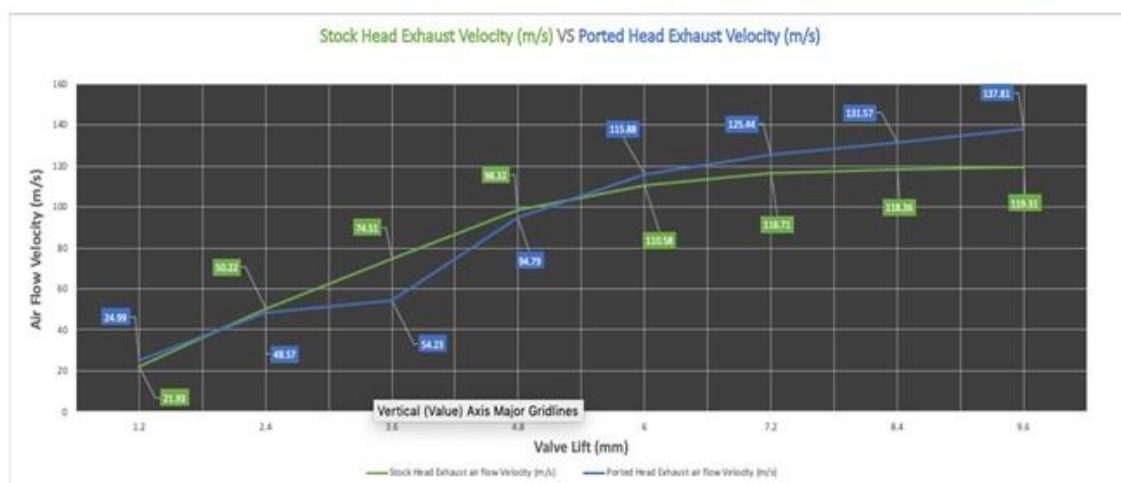


Figure 26: Graph, Exhaust port flow FV calculations of both TU5J4 heads, By (Cunniffe, 2020).

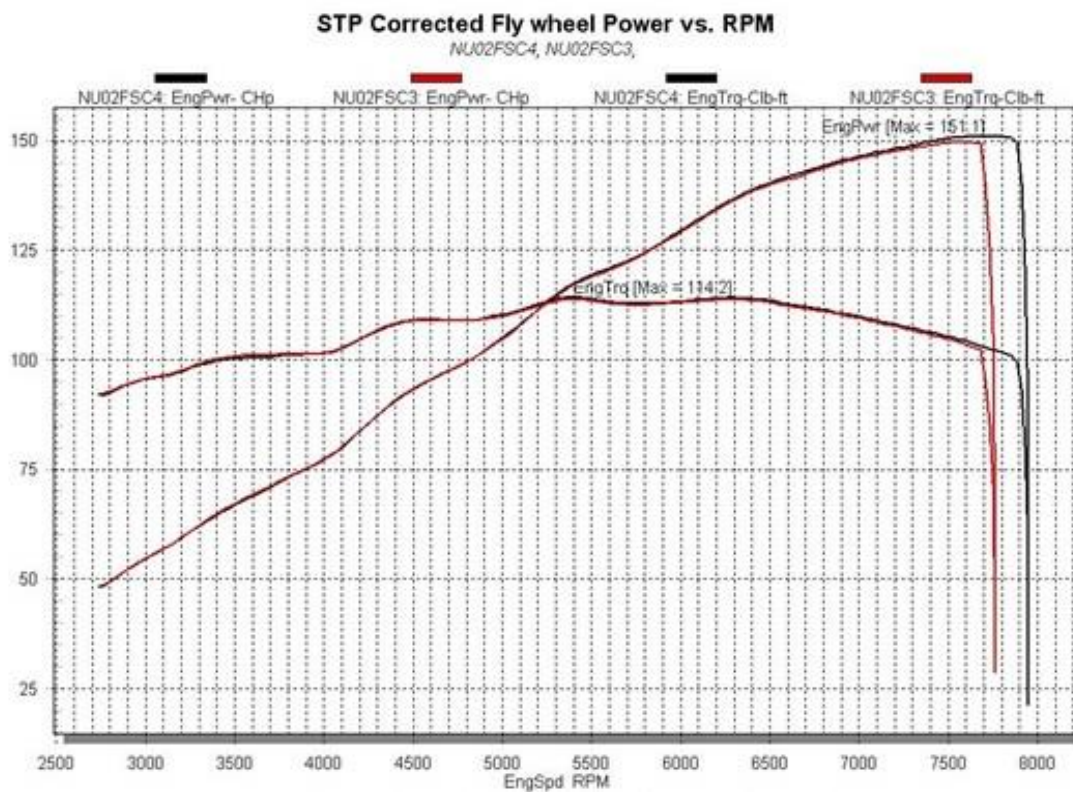


Figure 28: Image, Stock Head Peugeot 106 GTI dyno printout sheet, By (AP Performance , 2020)

CYLINDER HEAD FLOW OPTIMISATION OF A SPARK IGNITION MULTI-POINT INJECTION ENGINE FOR MOTORSPORT APPLICATION

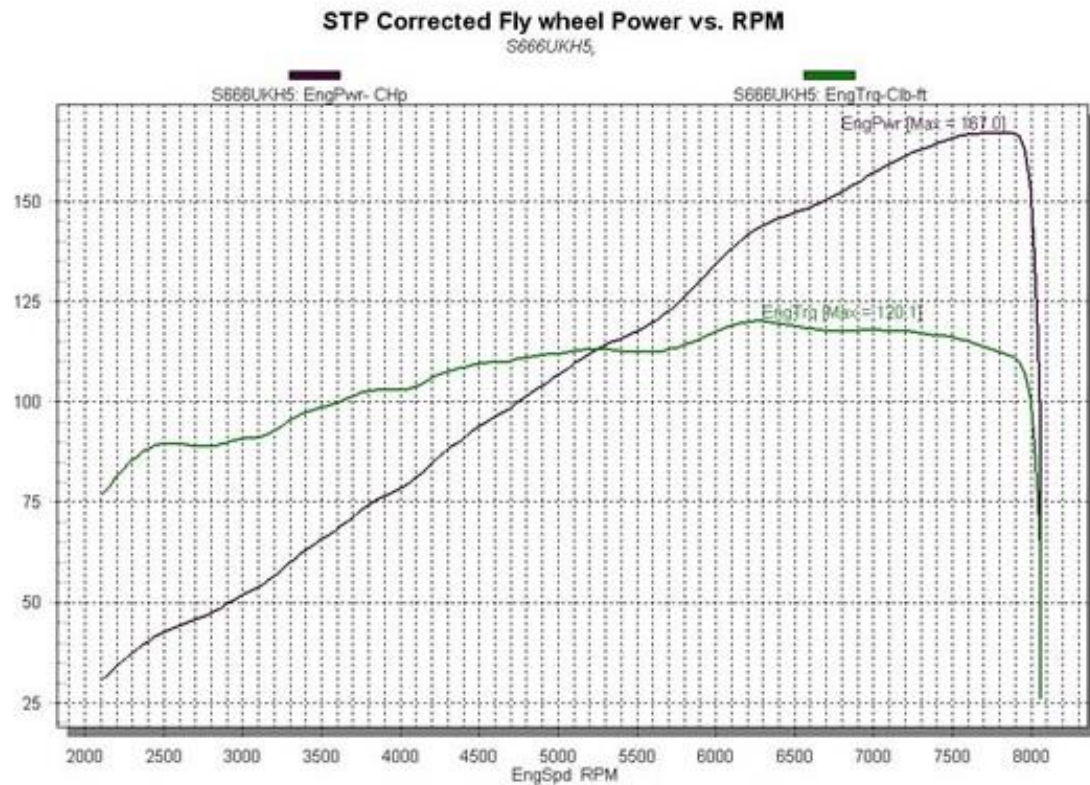


Figure 29: Image, Optimised head Peugeot 106 GTI dyno printout sheet, By (AP Performance , 2020).