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# A Computational Study of the Effect of Intake Design on Volumetric Efficiency for Best Performance in Motorsport

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***Abstract*—**This project was aimed at investigating the effect of velocity stacks on the intakes of internal combustion engines for motorsport applications. The intake systems in motorsport are predominantly fuel injection with a plate mounted for the stacks. Using Computational Fluid Dynamics software, the relationship between the stack length and power and torque delivery across the engine's rev range was investigated and the results were used to choose the best option for its intended motorsport discipline. The test results are expected to vary with engine geometry and its natural manufacturer characteristics. The test was also relevant in bridging between computational data and real simulation as the results show flow, pressure and velocity readings but the behaviour of the engine is inferred from the nature of each test. The results of the data analysis were tested in a real-life simulation on a dynamometer to prove the theory of stack length on power and torque delivery, which helps determine the most suitable stack for the Vauxhall engine for rallying in the Caribbean.

***Keywords*—**CFD simulation, internal combustion engine, intake system, dynamometer test.

## I. INTRODUCTION

THE internal combustion engine requires three elements to function; air, fuel and a source of ignition. The fueling and ignition in modern engines are managed by an Engine Control Unit (ECU) which is wired into various sensors across the engine, allowing full manipulation of the fueling and ignition across the rpm range of the engine. Other power delivery gains occur by mechanical means, one of which is the effective "breathing" of the engine through contributions by both the intake and exhaust geometry. The report targets the intake stroke of the Otto cycle for a naturally aspirated engine with multi-point direct fuel injection as used in modern motorsport, with the aim of obtaining the best geometry of velocity stack for an intended discipline of motorsport.

The intake manifold is a system designed to deliver air and fuel to each cylinder through runners. The design of the runner is such that it is large enough for high flow volume but small enough to ensure high mixture velocity and turbulence to help with air-fuel mixing before compression and combustion [2]. At the mouth of the runners is the velocity stack which is a trumpet shaped pipe that allows a smooth entry of fluid in a laminar fashion. When fluid flows into the intake, pressure waves are created that travel down the length of the flow passage and create a reflected pressure wave back along the path either when it reaches the end of the intake, or an obstruction such as the valve guide. Stacks of properly tuned length and overall diameter and taper help slightly increase the intake pressure over ambient atmospheric pressure through resonant frequencies. This provides the engine with a slightly denser charge of air, allowing more fuel to be burnt and resulting in more power over a specific rev range [1].

It is common assumption that an increase in stack length moves the bulk of the power delivery down the rpm range. With a short stack, high rpm power is more useable at the expense of lower rpm drivability; therefore, a compromise is necessary depending on the motorsport discipline and engine geometry. The theory of gas combustion suggests that the dynamics of the airflow past the valve is turbulent, allowing for better self-mixing of the fuel and air mixture thus improving combustion. As each engine has different characteristics, the test was carried out in this project using the C20XE Vauxhall engine due to prior experience working with this type of engine. The test was aimed at investigating the airflow of each intake at 3, 7 and 10 mm of valve lift using 'Fluent' and 'ICEMCFD' software in 2D domain. The throttle body type in question is the individual throttle body with direct fuel injection and velocity stacks. The experiment uses an intake plenum of 155 mm length with varying intake velocity stacks of 40, 90 and 120 mm [4]. The effect of each stack will have an impact on the overall characteristics of the engine to which it is applied.

## II. NOMENCLATURE

| | |
|---|---|
| A | Cross-sectional area ($m^2$) |
| $C_s$ | Isentropic flow velocity ($ms^{-1}$) |
| $D_{cyl}$ | Piston diameter (mm) |
| k | Ratio of specific heats |
| $M_{theor}$ | Theoretical mass flow rate ($kgs^{-1}$) |
| P | Pressure (Pa) |
| R | Ideal gas constant ($Jkg^{-1}K^{-1}$) |
| T | Temperature (K) |

Greek Letter

| | |
|---|---|
| $\rho_s$ | Density for reversible adiabatic flow ($kgm^{-3}$) |

## III. METHODOLOGY

### A. Objectives

The purpose of this project is to achieve the following goals:

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- Investigate the efficiency of the air flow through each intake type at different valve lifts.
- Validate the data using some characteristics of combustion engines such as carbon build up and deposits on certain engine components.
- Determine the best intake configuration for the given engine application.
- Validate the data in a real-life setting via a dynamometer.

Computational Fluid Dynamics (CFD) was used to investigate the flow characteristics through the intake geometry using the k-ε turbulence model in FLUENT solver. A baseline geometry was obtained from QED motorsport and a SolidWorks model was generated for simulation.

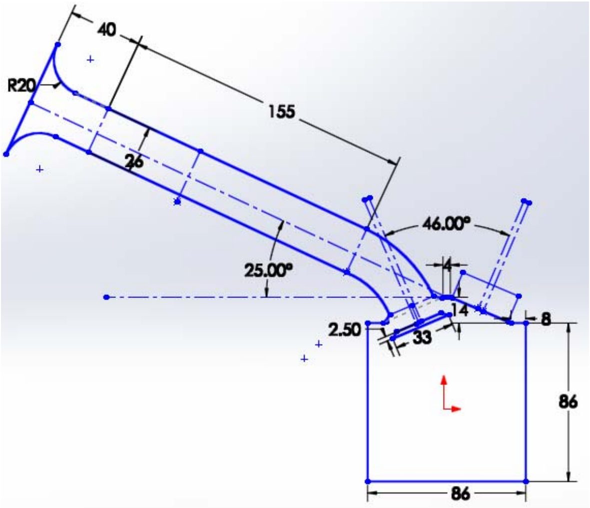

Fig. 1 Schematic diagram of the 40mm stack and intake plenum for the C20XE engine

Fig. 1 illustrated the geometry to be used in this research. Mass flow inlet was set for the stack mouth with all boundaries as stationary walls using the no-slip condition at varying valve lifts, (3 mm, 7 mm and 10 mm), for each stack length of 40, 90 and 120 mm.

### B. Model Parameters

The model geometry was imported to ICEM and the sections were defined as follows; engine as the static interior engine walls, valve at varying valve lifts, piston at bottom dead centre and interior geometry to define the fluid surface boundaries. The unstructured mesh type was then applied to the model using a global element scale factor of 1.0 with 0.15 max mesh element size. The resulting model was then exported to Fluent in 2D domain. Mesh refinement was not needed near to the walls as the mesh global mesh size was adequate to show any variations within this region.

### C. Input Data

The input theoretical mass flow rate was calculated given the cylinder bore cross-sectional area, operating temperature and pressure using (1)-(4) as listed blow [5].

$$A = \frac{\pi}{4} D_{cyl}^2 \tag{1}$$

Density for reversible adiabatic flow:

$$\rho_s = \frac{P_1}{R \times T_{std}} \left[\frac{P_2}{P_1}\right]^{\frac{1}{k}} \tag{2}$$

Flow Velocity for isentropic flow:

$$C_s = \sqrt{\frac{2k}{k-1} R T_{std} \left[1 - \frac{P_2}{P_1}^{\frac{k-1}{k}}\right]} \tag{3}$$

Theoretical mass flow rate:

$$M_{theor} = A \times \rho_s \times C_s \tag{4}$$

and the selected parameters are

- $R = 287.058$ Jkg$^{-1}$K$^{-1}$
- $T = 300$ K
- $D_{cyl} = 86$ mm
- $P_1 = 101325$ Pa (atmospheric) $P_2 = 100825$ Pa
- $k = 1.4$ for air

Boundary conditions for the present geometry are specified as:

Engine, Piston and Valve boundaries:

- Type: Stationary Wall
- Shear Condition: No Slip

Inlet:

- Type: Mass Flow Inlet: 0.235 kgs$^{-1}$ air
- Initial Gauge pressure (Pascal): 101325
- Specification Method: Intensity and Viscosity Ratio

The k-ε standard model was chosen using the pressure-based type with standard wall functions at steady state. Air was used as the working fluid with a mass flow inlet on the mouth of the velocity stack.

## IV. RESULTS AND DISCUSSION

All values were validated for the flow through a valve, as values increase with a closing valve [3]. The flow separates around the valve and creates vortices as it passes the valve head. The general conditions of airflow in an engine are observed such as 'Swirl - a rotational flow within the cylinder about its axis used to promote a fast burn and ensures rapid mixing between fuel and air in direct-injected engines' [6]. The shortest velocity stack resulted in the highest values of pressure around the valve, while the longer stacks have a higher pressure before the valve, which adds to the ram air concept whereby the pressure of the air behind a closed valve is great enough to cause a higher flow as the valve opens. It can also help to atomize the fuel and air before it enters the cylinder where it will further atomize.

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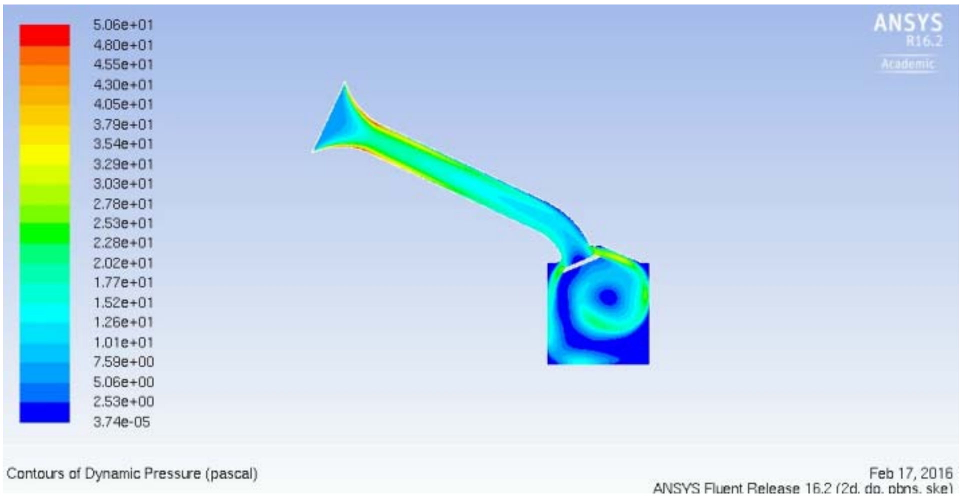

Fig. 2 Dynamic Pressure contours for 40 mm high valve lift

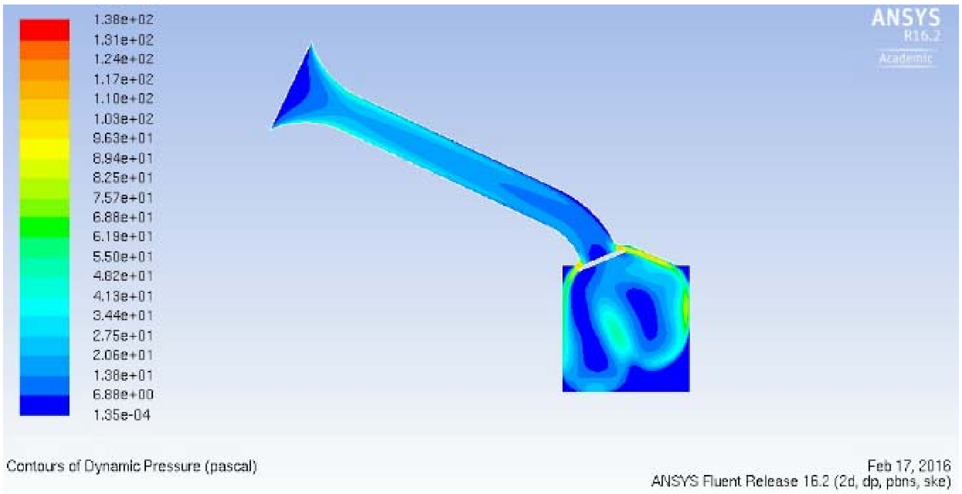

Fig. 3 Dynamic Pressure contours for 40 mm at medium valve lift

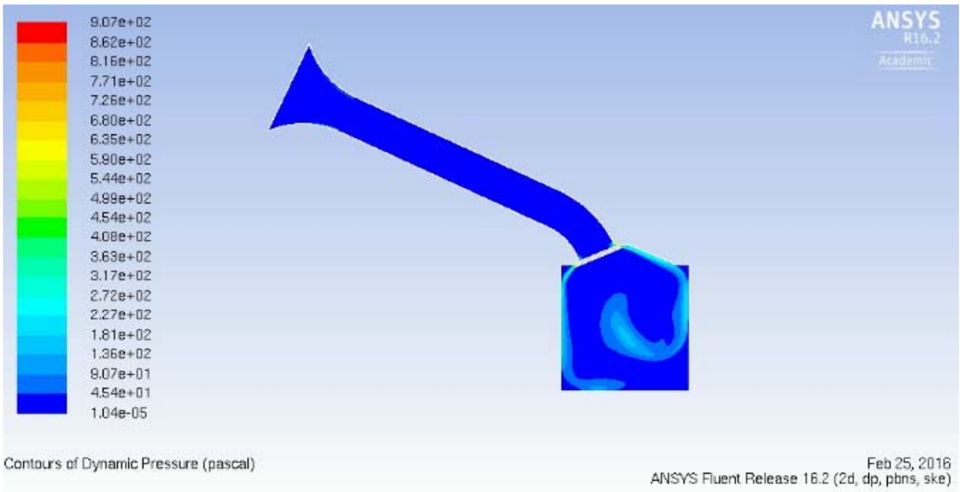

Fig. 4 Dynamic Pressure contours for 40 mm at low valve lift

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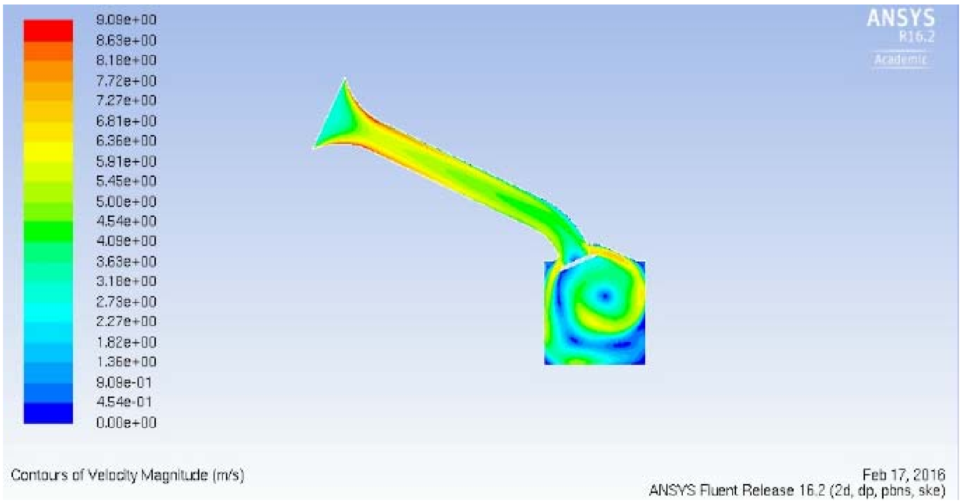

Fig. 5 Velocity contours for 40 mm at high valve lift

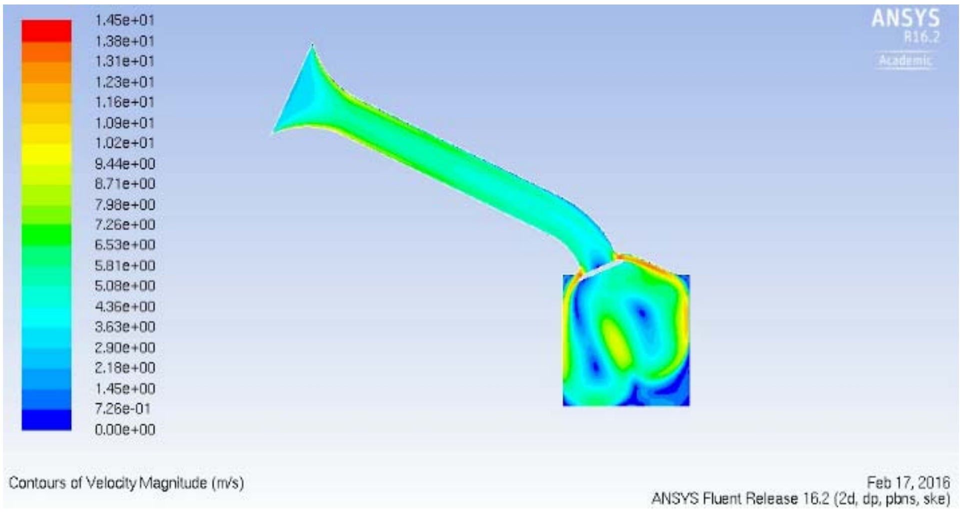

Fig. 6 Velocity contours for 40 mm at medium valve lift

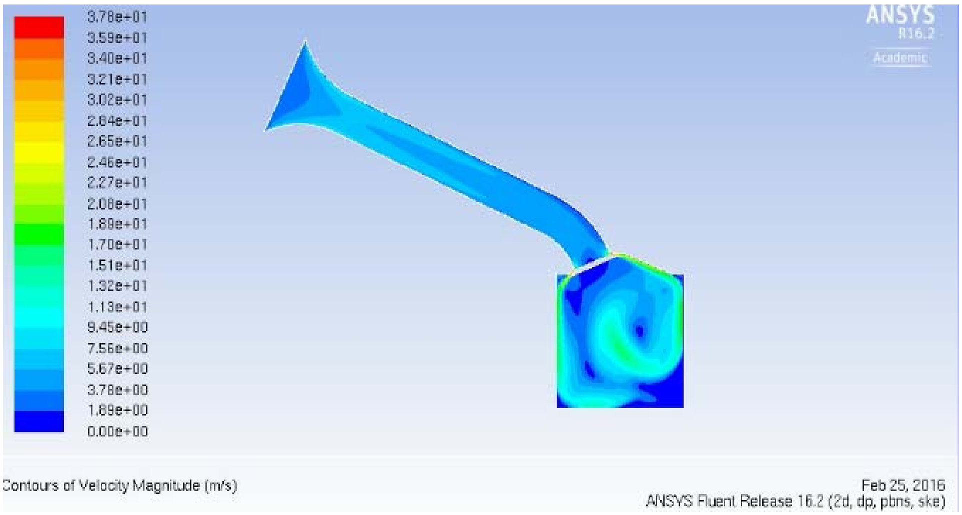

Fig. 7 Velocity contours for 40 mm at low valve lift

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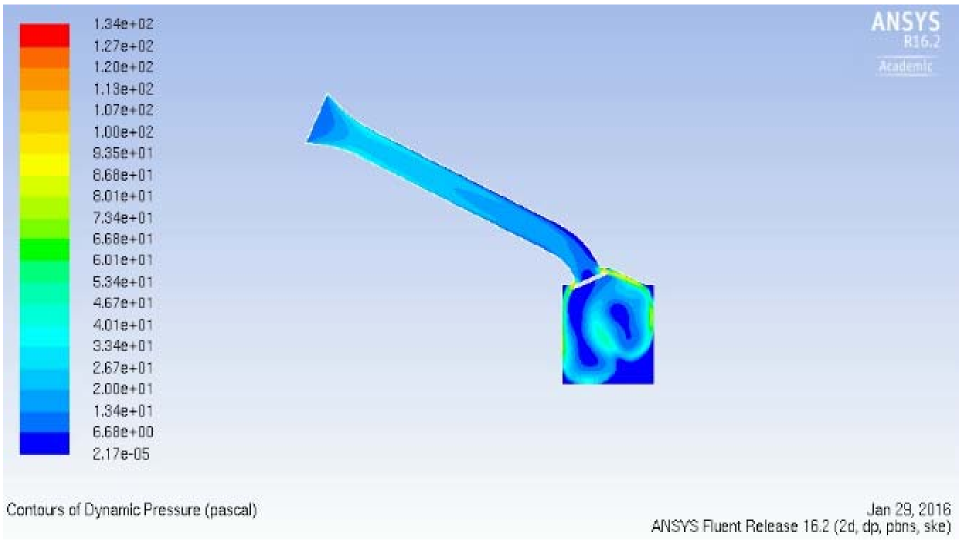

Fig. 8 Dynamic Pressure contours for 90 mm at medium valve lift

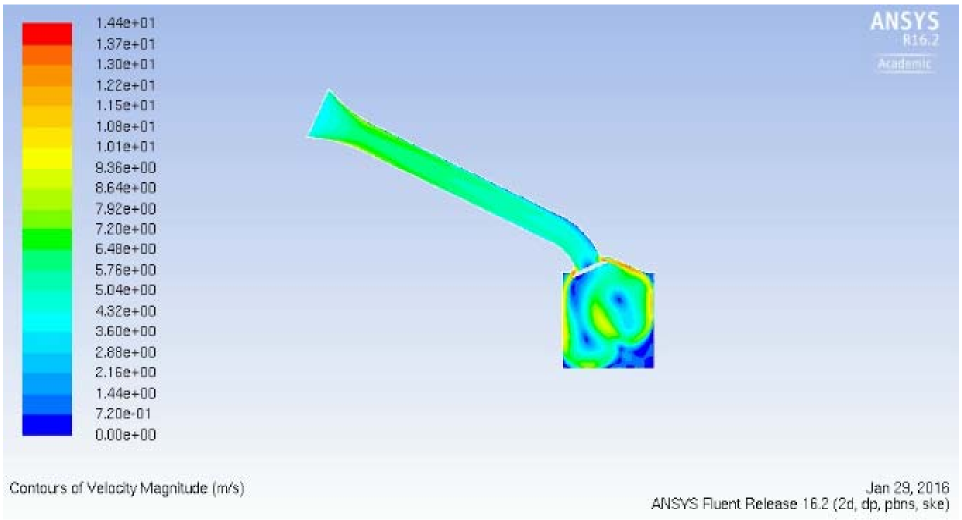

Fig. 9 Velocity contours for 90 mm at medium valve lift

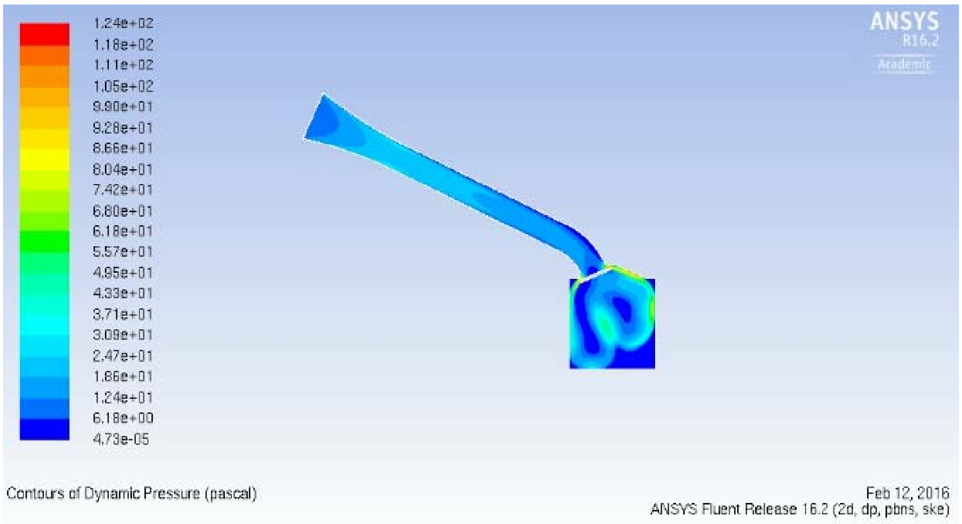

Fig. 10 Dynamic Pressure contours for 120 mm at medium valve lift

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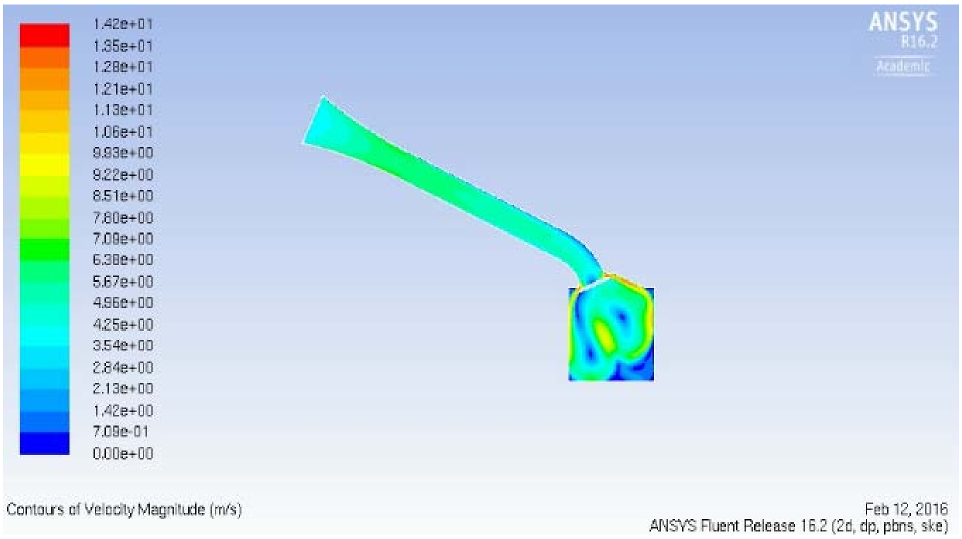

Fig. 11 Velocity contours for 120 mm at medium valve lift

The pressure and velocity contours for the 40 mm stack are shown in Figs. 2-7 as an example, and more information for the 90 mm and 120 mm stacks can be found in Figs. 8-11. The pressure contour results show the flow moving in waves or pulses through the stack and into the plenum. The pressure waves increase in intensity with increasing valve lift. The graphs show there are more waves in the plenum for higher valve lifts which shows the nature of each stack as the valve opens. The frequency of the pressure waves has an impact on horsepower. The total pressure fields inside the cylinder show two swirling motions extending down to the piston. More swirl helps for fuel atomization before the ignition stroke of the engine which results in power gains. The gains may happen across the entire rpm range, however, the graphs show that the longer stacks have more swirl at lower valve lifts. This indicates the power gains for longer stacks will occur at lower rpm and the inverse for a shorter stack. The pressure values locally around the valve head are higher for the shorter stacks but the flow patterns of the longer stacks are more desirable as the swirl occurs about the centre line from the top of the bore and down to the piston (y-axis). The shorter stack results in a higher swirl at the top of cylinder and the flow is not spread out evenly throughout the bore although this will be less noticeable at higher rpm. Choosing the correct length of velocity stack for each discipline is a result of a compromise between the velocity and pressure profiles.

The flow entering the cylinder undergoes an increase in velocity at the radius of the bell due to a change of cross-sectional area. The velocity is reasonably uniform through the plenum leading up to the valve head. As it enters the intake port the flow does not follow the roof profile of the port. This may be due to manufacture design to channel air past the valve guide and stem. In the location of the valve stem there is a low flow region which also suggests this design. This action may also be due to the flow travelling a shorter distance through the port on the opposite side to the valve stem. The flow has a longer distance to travel along the roof of the port due to the geometry and therefore is slower. The flow passes around the valve and vortices are present as it passes into the cylinder. The vortex extends to the cylinder walls and changes the flow direction making the airflow turbulent. The values of pressure and velocity between the 90 mm and 120 mm stacks are globally similar, however, at the edge of the open valve there is a very high pressure with the 120 mm stack. As the velocities of these two stacks are very similar a compromise must be made between the 120 mm and 90 mm stack depending on the application. The air is moving slower in the longer stack which suggests it work better at lower engine speeds or rpms. The trend follows with the 90 m and 40 mm stacks as the flow is moving faster. The 40 mm stack has a faster airflow through the intake; however, this may hinder the performance at lower rpm. At low valve lifts the flow through the 40 mm stack will not circulate throughout the cylinder efficiently and therefore will have a ‘flat spot’ in the power and torque curve. The short stack will thrive at higher rpms based on the velocity profiles.

The swirling motion inside the cylinder bore was proven to be valid and gave insight into some common engine issues such as carbon build up around the piston and valve. The flow does not extend down the cylinder wall onto the piston fully. The areas of no flow between the cylinder wall and piston match the regions where carbon build up is present in combustion engines. Carbon build up also exists in the exhaust ports and can also occur in the intake ports on engines that have significant overlap between the exhaust and intake valve timing. This suggests carbon build is a naturally occurring phenomenon which happens over the life span of an engine. There is low or no flow at the valve mouth towards the roof of the cylinder due to the blend of the port into the bore. This area also houses the valve guide (not modelled) which in some engines can protrude far into the flow field and obstruct the flow, however, the shape of the port can channel air around it without negating the desired flow into the cylinder. All contour graphs show the presence of waves that propagate through the plenum up to the valve as per theory. The flow becomes fully developed before reaching the valve. Changing

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the length of the stack and the radius of the bell will in turn shift the point at which the flow becomes fully developed. In an ideal situation, the fully developed region is desired closer to the valve than the mouth of the inlet.

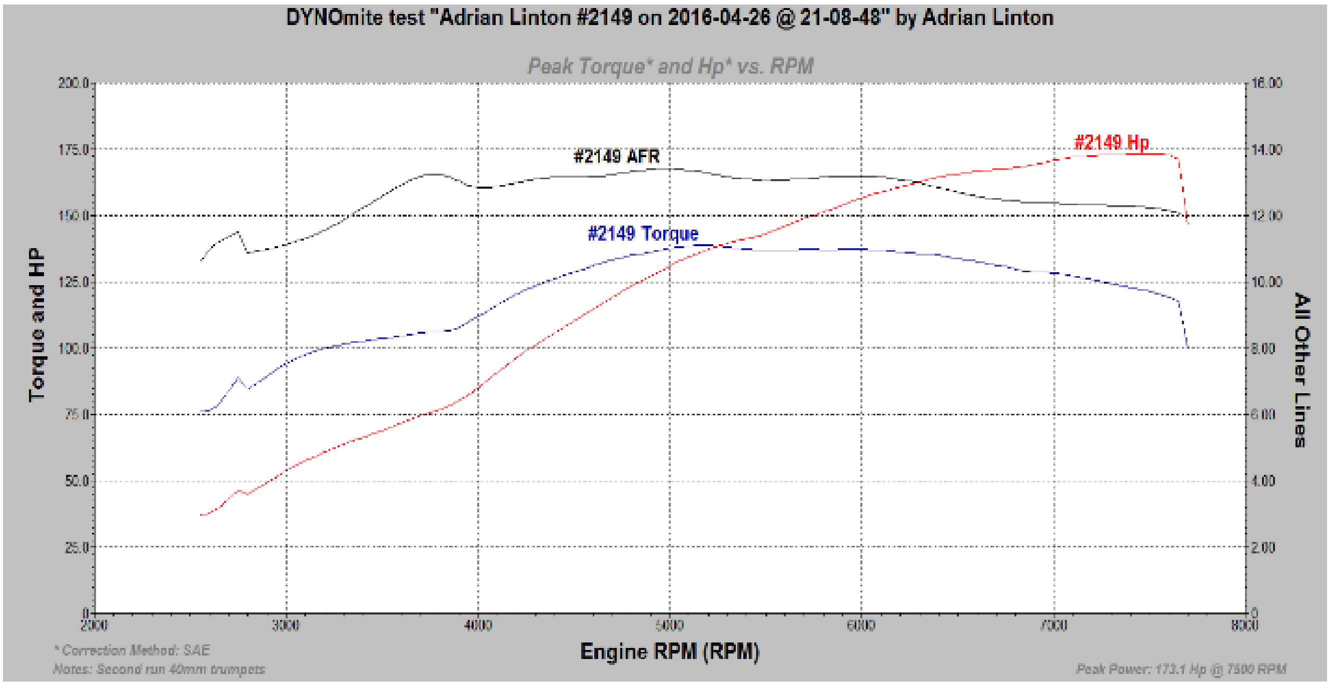

Fig. 12 Baseline dyno run with 40 mm stack

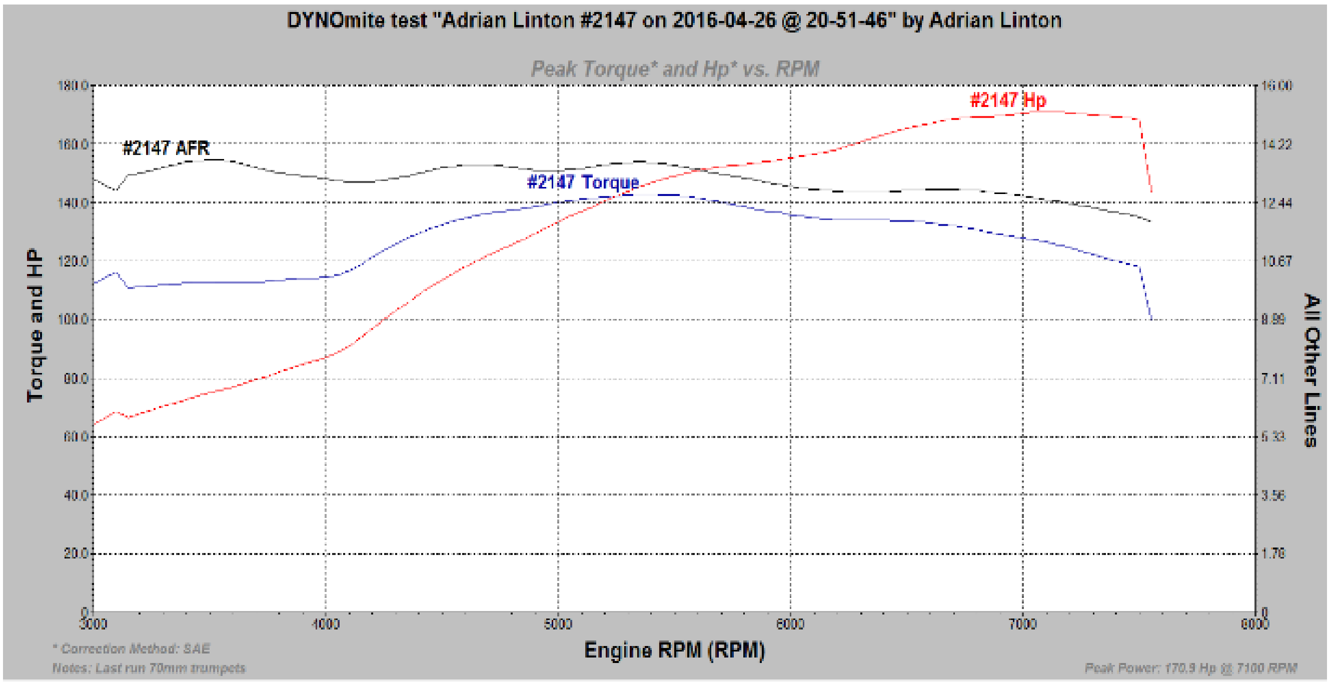

Fig. 13 Baseline dyno run with 70 mm stack

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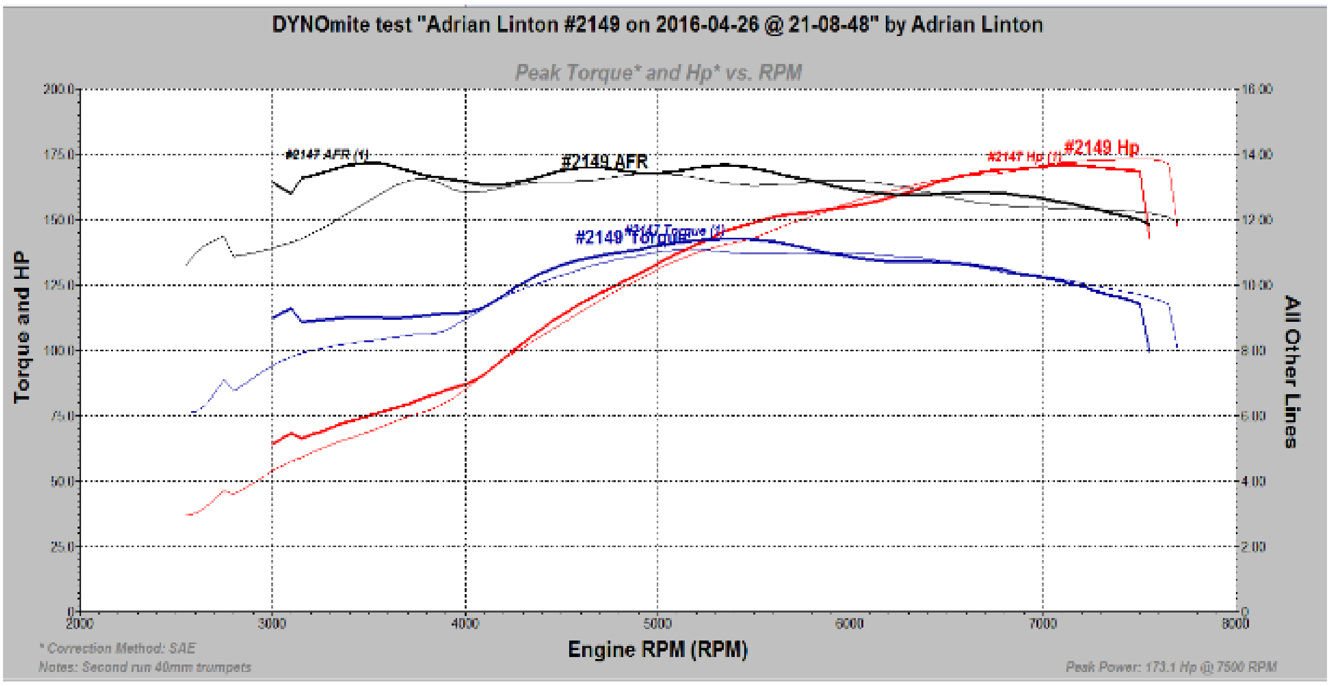

Fig. 14 Overlay of 40 mm stacks (light lines) against 70 mm stack (heavy lines)

The spacing between the vehicle bulkhead and air intake was measured to fit the stacks. Due to close proximity of the vehicle bulkhead in the test vehicle to the number four cylinder intake, the maximum length stack that could be fitted without potentially compromising the incoming airflow was 70 mm. The tests were carried out with a 70 mm and 40 mm stack to prove the stack theory. Each stack was tested multiple times to ensure consistency between each run. The sweep tests were conducted at full (100%) throttle opening from 2500-8000 RPM at a ramp rate of 500 RPM/s and the data from the tests show an increase in power and torque for both stacks as seen in Figs. 12-14. The data clearly show that the 70 mm stacks gave an increase in power and torque in the midrange between 4000 and 6000 rpm whereas the 40 mm stacks deliver the maximum power which occurs at the top end of the rpm range. The extent of stack length on power delivery is inconclusive due to inability to run longer stacks, however, the theory of stack length on power delivery is observed and confirmed. Some front wheel driven cars in motorsport use a reversed cylinder head in which the intake faces the front of the car for better drafting of air into the intake and also for ergonomics. This configuration allows for fitting of stacks longer than those tested on the dyno. Stack length can be taken further and used in commercial vehicles to help control emissions. The longer stack shows higher air fuel ratios (AFR) which means the engine runs lean on fuel. Also, the desired rpm in commercial vehicles is considerably lower than in motorsport, therefore, negating the use of short stacks for power and torque gains.

## V. CONCLUSION

The tests were carried out successfully and all results were validated and gave insight into naturally occurring phenomenon such as carbon build up in the cylinder. The project objectives were fulfilled and the results proved to be useful in selecting the best stack length for the given discipline of motorsport. Pressure and velocity contours around the valve guide show the effect of porting on smoothing the airflow into the cylinder. Opening the throat of the valve port helps to smooth the airflow into the cylinder and improve the power delivery. The resulting contours of each test prove the theory of stack length and the flow through a pipe. It shows that the shorter stack length is more suited for high rpm applications while the longer stack shifts the bulk of the power lower down the rpm range. Based on the CFD results the best stack for rallying in the Caribbean is the 90 mm stack as there is less separation of the fluid around the valve compared to the 120 mm stack and the flow extends further down the cylinder wall than the 40 mm stack. The results of the dynamometer confirm the effect of a longer stack on the intake of the test vehicle. The 70 mm stack was determined to be the more suitable stack for the Vauxhall engine for rallying in the Caribbean.

## ACKNOWLEDGMENT

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