

# **Mechanical design of custom intake manifold targeting distinct RPM range**

**VAG AKL engine**

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## Abstract

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Title of the thesis <b>Title of the thesis</b> Mechanical design of custom intake manifold targeting distinct RPM range		
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Abstract <p>The optimization of intake manifold design plays a pivotal role in internal combustion engine behavior. The thesis work studied how alteration of intake manifold parameters shifts the peak torque from 3800 to 3000 RPM in VAG AKL engine.</p> <p>By reviewing specific literature key parameters affecting the performance were identified and described. SolidWorks was utilized to develop the conceptual design and refine the geometry. Model was subjected to CFD simulations in Ansys Fluent to evaluate air distribution and airflow parameters such as dynamic pressure and velocity.</p> <p>The final prototype model provides the insights on how the combination of plenum volume and runner dimensions affect acoustic supercharging effect that increases volumetric efficiency of naturally aspirated engines at desired RPM range.</p>		
Keywords Intake manifold, engine performance, CFD, mechanical design		

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## List of symbols and abbreviations

AFM	Air-fuel mixture
AFR	Air-fuel ratio
AKL	VAG engine code
BDC	Bottom dead center
CFD	Computational fluid dynamics
ECU	Engine control unit
EGR	Exhaust gas recirculation
HP	Horsepower
ICE	Internal combustion engine
IM	Intake manifold
ITB	Individual throttle body
kPa	Kilo Pascal
MAF	Mass airflow
MAP	Manifold absolute pressure
N/A	Naturally aspirated
Nm	Newton meter
TB	Throttle body
TDC	Top dead center
VAG	Volkswagen automotive group
VCDS	VAG COM diagnostic system
VE	Volumetric efficiency
WOT	Wide-open throttle

## 1 Introduction

This research is dedicated to developing a custom IM for VAG AKL engine and demonstrating the relationship between custom IM geometry and engine performance. The initial experiment involved swapping intake ducts, which unexpectedly led to noticeable shifts in engine behaviour, i.e., improved throttle response, torque delivery, and variations in power output. These observations highlighted the significant influence of intake system modifications on engine dynamics. This practical experience ignited a deeper interest in exploring how customized IM design could intentionally influence engine performance within specific RPM range.

Custom IM design requires profound comprehension in engine performance-oriented parameters and fluid dynamics nuances; hence, core aspects of these factors must be considered. The thesis is focused on understanding how modifications of runner length, diameter, plenum volume, and resonance tuning techniques influence VE, air distribution, and torque characteristics within desired RPM range.

Developing intake manifolds is crucial for optimizing ICE performance. Tailoring the IM to specific engine characteristics, such as through purposely designed runners, enhances torque or power output at desired RPMs. This adaptability is essential for meeting diverse performance requirements in various applications. Additionally, well-designed IM contributes to improved fuel efficiency and reduced emissions, aligning with environmental regulations. As automotive technology advances, the ongoing development of intake manifolds remains essential for achieving the delicate balance between power, efficiency, and environmental considerations.

## 2 Engine performance and parameters

### 2.1 General engine performance optimizations

N/A engine performance optimization involves enhancing various aspects to achieve improved efficiency, power/torque output, and overall operation. Several key areas are targeted to maximize engine performance:

- Air intake upgrades help to increase density and velocity of air entering intake ports, provide less turbulent airflow within the system, adjust ambient pressure and temperature, evenly distribute air to each cylinder.
- Upgrades to the exhaust system yield the most apparent advancements in engine performance. By evaluating factors such as the configuration and size of the exhaust manifold, the placement of the muffler, as well as backpressure and scavenging effects, one can achieve less interfered exhaust gas flow. Therefore, this leads to an improvement in power output.
- Performance camshafts alter valve lift and duration affecting the amount of air/exhaust gas passing through the valves, hence, resulting in improved power/torque output at distinct RPM ranges.
- Boosting performance upgrades require ECU tuning to adapt AFR map/MAF//lambda sensors values, VE readings, and other parameters that affect engine operating cycle.

There are more options additionally to those presented: ignition system upgrades, installing reinforced and lightweight components, upgraded fuel delivery system etc. By implementing upgrades consequently, performance level reaches certain tuning stage. Stage 1 generally includes basic chipping, installing sport filters, and sport intake/exhaust pipes. Stage 2 requires more investments as enhanced intake/exhaust manifolds, long/short duration camshafts, injectors, headers etc. are installed, followed by hardware conversion. Stage 3 combines fortifying engine with forged pistons, piston rods, bespoke crankshaft, and drive train i.e., engine is upgraded with the intention to introduce car on track. Stages 4 and more include custom parts tuning.

## 2.2 Overview of intake systems working principles

Discussing the intake system working principles in ICEs, it is crucial to be focused on the aspects specific to the type of engines that do not have forced induction, i.e., are not supercharged, or turbocharged. Intake system in N/A engine generally comprises following components:

- Variation of air intake (air filter box/ram intake/cold air intake pipe)
- TB/ITBs section
- IM, which consists of plenum and runners, in case of single TB
- EGR, if installed
- Tumble flap system, if installed

Intake pipes are responsible for drawing in air from atmosphere. TB/ITBs control the amount of air entering engine/individual inlet ports; driver adjusts TB valve position by pressing accelerator pedal. IM plenum provides equal air distribution to each cylinder, runners direct and accelerate air entering engine inlet ports. EGR uses IM to reintroduce a portion of exhaust gas into the combustion process, reduces emissions by lowering the amount of oxygen, thus, controlling combustion temperature. Tumble flaps provide a stable airflow across all RPM ranges and created swirl at right angles to the cylinder axis providing improved AFM atomization.

## 2.3 Influence of targeted RPM range alteration on engine behaviour

Altering the targeted RPM range in ICE has a significant impact on its behaviour and characteristics. The RPM range refers to the range of engine speeds at which it operates, and modifications can be made to optimize performance for specific driving conditions. Changing targeted RPM range influences shape of the torque curve e.g., shifting peak of torque curve to lower RPM enhances low-end torque and drivability in traffic, and vice versa shifting peak of torque curve to higher RPM improves high-end torque.

### 3 IM design parameters

#### 3.1 Resonance tuning effect and plenum volume

Air behaves like a compressible elastic fluid. In the realm of intake design theory MAF is analysed in terms of its acoustic properties, focusing on its behavior as a sound wave and its corresponding frequencies. Within an IM runner, sound waves spread as pulsating undulations, carrying energy with their frequencies. As air is drawn into the engine during the intake stroke, but it can also be forcefully directed into the engine, even in N/A setups.

In a N/A engine, the downward motion of the piston creates a vacuum region within the combustion chamber. When the intake valve opens, air is set into motion within the IM runner. Air, behaving as a sound wave, does not stop when the intake valve closes, instead, upon valve closure, the air wave rebounds off the valve's back face, traveling back towards the IM plenum at the speed of sound. This reflected wave possesses its own frequency, amplitude, and negative pressure. Upon reaching the plenum, the resonance wave is isolated, and the plenum chamber acts as a resonance chamber. Air resonates at a specific frequency within the plenum, accumulating energy. The air wave is then reflected at the speed of sound through the IM runner towards the intake valve, drawing in additional air from the resonance chamber, thereby increasing VE by introducing more air. This phenomenon is called acoustic supercharging (Michael Delaney, 2002).

There is no specific formula to determine the plenum volume. Various factors directly influence plenum volume including application, engine displacement, targeted RPM range with following runner metrics alterations, and desired throttle response. Typically, plenum volume is established through dyno-testing or live diagnostics, with subsequent adjustments. Nonetheless, the initial value is often chosen from a specific range. For N/A setups, plenum volume is typically selected from 75 to 125% of engine displacement.

#### 3.2 Runner length and diameter

Longer IM runners create a longer path for the air to travel before reaching the combustion chamber. This design is effective at enhancing low-end torque and can improve throttle response.

Shorter IM runners provide a more direct, less turbulent, and shorter path for the air to reach the combustion chamber. This design is beneficial for high-RPM performance as it allows for quicker air delivery and cylinder filling, supporting better airflow at higher engine speeds. Short runners can contribute to increased horsepower in the upper RPM range.

Small diameter runners are effective at increasing air velocity; hence it is crucial at lower engine speeds, nevertheless it becomes a restriction at high RPMs. Small diameter runners enhance throttle response and low-end torque, sacrificing power.

Large diameter runners provide greater amount of air entering combustion chamber, increasing power at high engine speeds, and restraining torque at lower RPMs.

### 3.3 Other influential parameters

Camshaft profile plays critical role in defining IM geometry. Camshaft controls the opening and closing of the engine's intake and exhaust valves, influencing the amount of air that enters and exits the combustion chambers. Profile of the camshaft, including lift, duration, and timing, directly affects the engine's airflow and, consequently, the VE. Designing IM camshaft duration is the primal characteristic to be explored. Camshaft duration refers to the time expressed in degrees of crankshaft rotation when the intake valve is open. Longer duration keeps intake valve open for a greater portion of the cycle which allows more air to enter combustion chamber, therefore enhancing high-end power. Conversely, shorter duration amplifies low-end torque at the expense of high-end power.

The throttle body is a crucial component in the intake system of an ICE, playing a significant role in regulating the airflow. Primary function is to control the amount of air entering plenum. In terms of IM design TB calibration influences air velocity and MAP; at WOT MAP is higher, as air velocity is decreased, flow is less turbulent, and it facilitates dynamic effects e.g., acoustic supercharging.

## 4 Tools

### 4.1 Experimental setup and testing procedures

Collecting data is executed across all RPM ranges via VCDS. Main parameters to be defined are: MAF, MAP, instant cylinder pressure, and torque as they might deviate from values provided by manufacturer due to the engine age.

VCDS allows to create graphs and log live data with the car running. It automatically reads fault codes from all car systems and performs basic setting functions, adaptations, and soft coding. To read desired parameters certain path must be followed: main screen "Select Control Module" -> "01 Engine" -> VCDS Controller "Meas. Blocks." as shown in Figure 1. Then, by using "Up" and "Dn" buttons, various measurement blocks are selected depending on user requests.

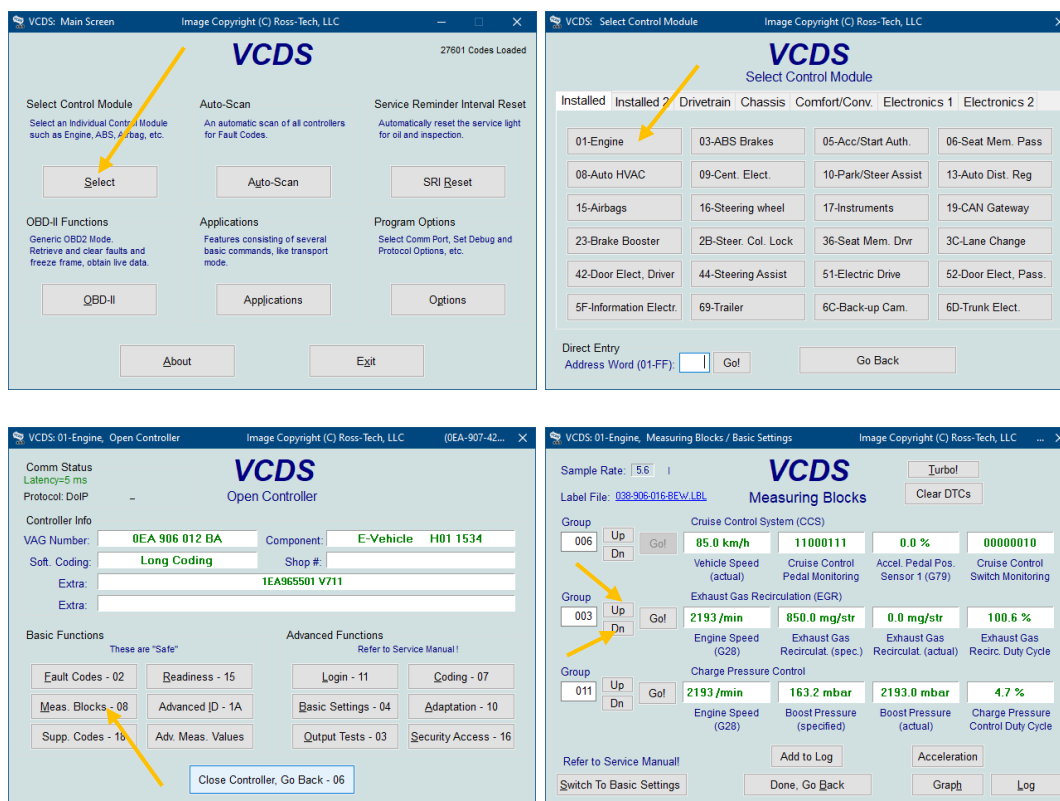


Figure 1. Reading MAF and MAP values (Ross-Tech, LLC)

## 4.2 CFD simulation

Ansys Fluent 2021 is utilised to simulate airflow, pressure distribution, and airflow behaviour within the IM at desired RPMs. This method allows virtual testing of various designs and modifications before physical implementation.

Ansys Fluent 2021 CFD simulation process is divided into several steps as shown in Figure 2. Model is streamlined through following stages:

1. In Geometry menu user identifies what part or assembly is subjected to CFD simulation, defines solid bodies, examines, and fixes geometry imperfections or incompatible arrangements, and creates watertight volume unless it is executed in the imported model.
2. In Mesh menu user specifies computational domain, mesh settings, boundary conditions zones, fluid volume and walls.
3. In Setup menu environmental or medium conditions, input and output values are set. User specifies configuration of the analysis.
4. In Solution menu solution data is exported or shared to downstream system, e.g., output of one analysis might be set as input of another analysis.
5. In Results menu graphical representation of results is performed, user adjusts animations and other visual effects of selected solution data.

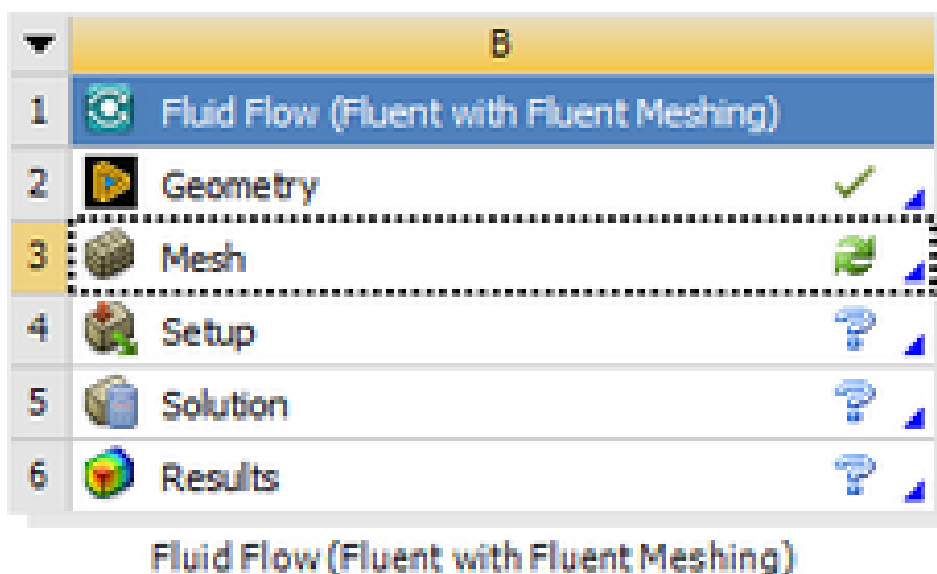


Figure 2. Ansys Fluent workbench (Ansys Learning Forum, 2024)

The ICE operates as a heat engine, relying on changes in pressure and volume within its cylinders. Heat engines are identified by a pressure-volume diagram, also known as a pV diagram, as presented in Figure 3. This diagram illustrates how pressure within the cylinder varies in relation to its volume over a full engine cycle.

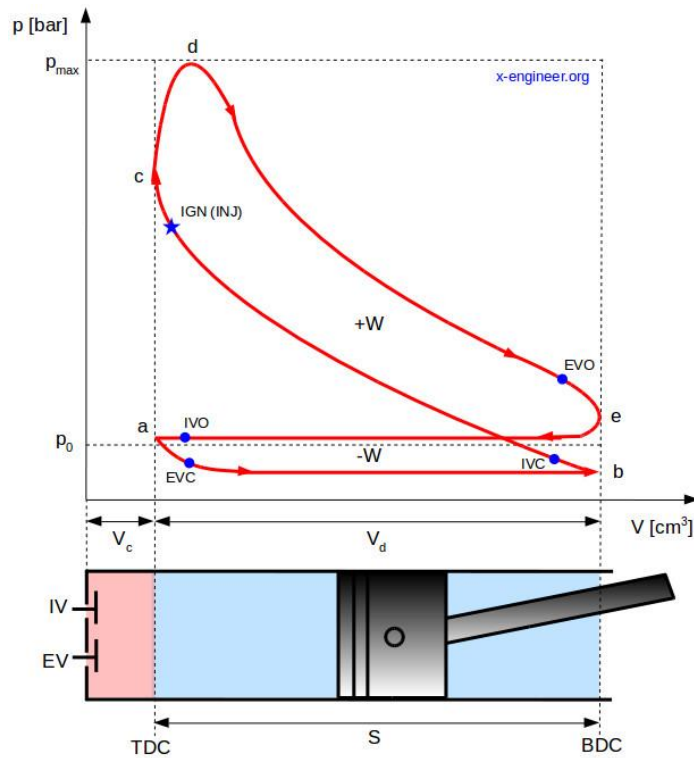


Figure 3. pV diagram for a 4-stroke engine (x-engineer, ICE components & systems)

Throughout the intake stroke (a-b), the intake valve remains open allowing the piston to move from TDC to BDC. As the volume expands constantly, maximum value attained when the piston reaches BDC (x-engineer.org).

Throughout the entire stroke the pressure is below atmospheric pressure ( $p_0$ ) due to the piston movement that increases volume; hence, air is drawn into the cylinder because of the vacuum effect. Cylinder pressure is constant, and valves operate instantly. Considering these factors boundary conditions for simulations are defined in CFD simulation results.

## 5 Empirical results of the stock IM

### 5.1 Physical parameters

Stock IM for AKL engine in Figure 4 is made from durable materials such as composite plastics and aluminium. The design incorporates following features: tumble flap system (1) and resonance chambers (2). Resonance chambers are represented by plenum that is drafted towards driver side of the engine bay and tapered to 1<sup>st</sup> cylinder chamber. This design of the plenum restricts airflow and creates turbulence in runner entries, nevertheless, tumble flap system compensates the flow imperfections across all RPM ranges.

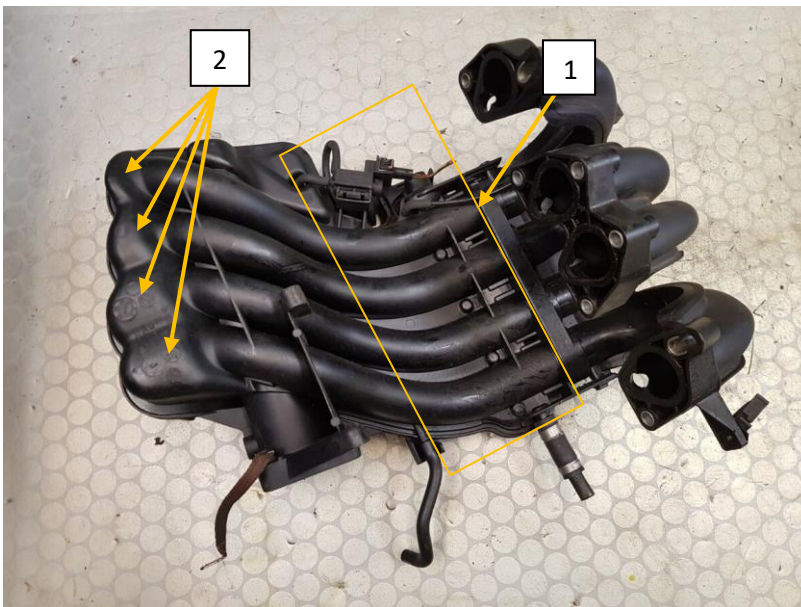


Figure 4. Stock IM (eBay 2022)

The intake gasket that is presented in Figure 5 was acquired, and analysis of desired parameters was conducted. This involved measurement and assessment of various factors critical to the experimental setup such as runner diameter at the inlet port and distance between runners. Injector hole size and fastener hole pattern are crucial details; however, those values do not affect CFD simulation results and are utilized at the stage of manufacturing injector fitment flange. After completing measurements following values were obtained:

- Distance between 1<sup>st</sup> and 2<sup>nd</sup> or 3<sup>rd</sup> and 4<sup>th</sup> runners  $d_1 = 88$  mm
- Distance between 2<sup>nd</sup> and 3<sup>rd</sup> runners  $d_2 = 51$  mm

- Inlet port/runner diameter  $D = 34$  mm

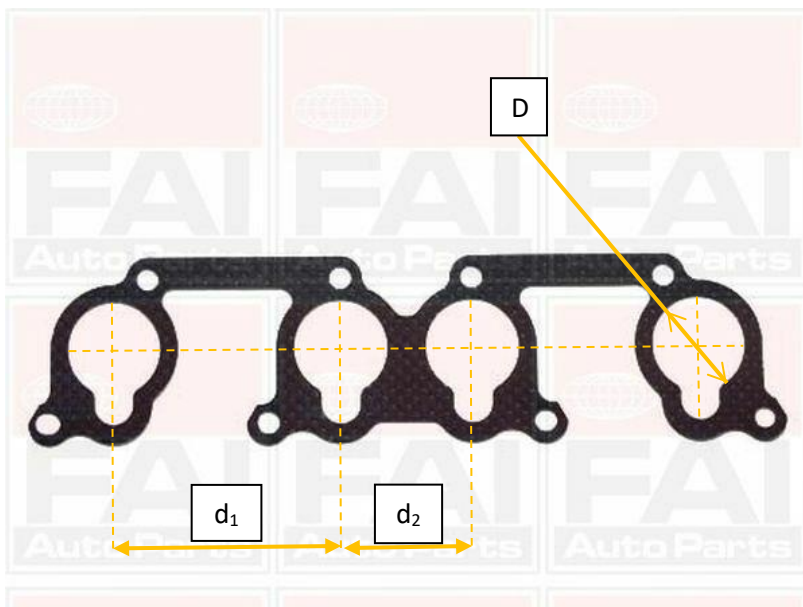


Figure 5. Intake gasket (eBay 2024)

Additionally, stock IM runner tube length and inlet port depth were measured to define the initial values which are used in design as starting points. Runner length is a distance from the back face of the intake valve to runner opening in plenum. It is important to specify that runner length is a sum of runner tube length and inlet port depth; hence, mentioning runner length implies utilizing this magnitude.

- Runner tube length  $L_t \approx 600$  mm
- Inlet port depth  $L_{port} = 90$  mm
- Runner length  $L \approx 690$  mm

## 5.2 Test results across all RPM ranges

The engine is tested at discrete RPM points across its entire operating range, from idle to redline, from 900 to 5600 RPM respectively. At each RPM point, the engine is operated under steady-state conditions for a sufficient duration to ensure stable data collection. Based on the measured data, VE map shown in Figure 6 is created. Peak torque value is obtained at WOT or when the engine load is maximum and equals 145 Nm at 3800 RPM.

Cylinder pressure during intake stroke is approx. 35 kPa at peak torque RPM. MAF is approx. 0.035 kg/s.

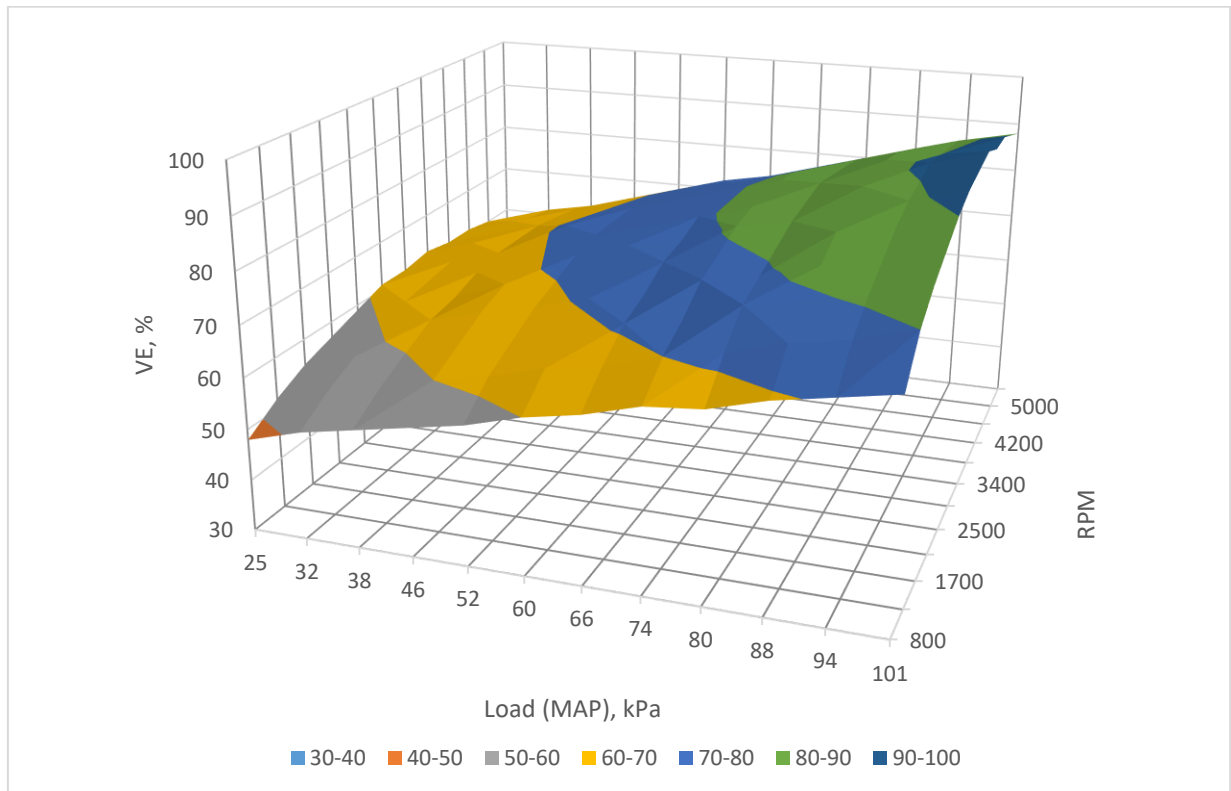


Figure 6. Engine VE map with stock IM

## 6 Product design and development

### 6.1 Deriving desired parameters of custom IM

Product development of a custom IM involves a systematic process aimed at optimizing engine performance and efficiency. The initial phase encompasses research and analysis to understand the specific requirements of the vehicle and the desired outcome. This includes considerations of engine type, performance gains, and the intended use of the vehicle. Through iterative design cycles and advanced simulations, the manifold's geometry is refined to improve airflow dynamics and ensure maximum VE at 3000 RPM.

Key parameters and their effects are described in IM design parameters chapter. Considering plenum volume, runner length and diameter, cam duration and throttle body diameter basic model is created.

#### 6.1.1 Runner design

Input values for runner diameter calculation:

Engine displacement (V) = 1.595 L = 1595 cm<sup>3</sup>

Targeted RMP (TRPM) = 3000 rev/min = 50 rev/s

Achievable volumetric efficiency (VE) = 0.95

David Vizard's equation for ideal runner diameter (D):

$$D = \sqrt{\frac{TRPM * V * VE}{3330}} = \sqrt{\frac{3000 * 1.595 * 0.95}{3330}} = 1.168 \text{ inches} = 29.68 \text{ mm} \quad (1)$$

D = 29.68 mm represents 30 mm internal diameter pipe, cross sectional area of the pipe (A):

$$A = \frac{\pi * D^2}{4} = \frac{\pi * 30^2}{4} = 706.9 \text{ mm}^2 \quad (2)$$

Input values for runner length calculation:

Cam duration (CD) = 272 deg

Pressure wave speed in air ( $v$ ) = 343 m/s

Angle of crankshaft at which camshaft operates once ( $\alpha_{tot}$ ) = 720 deg or 2 full rotations

Angle of the crankshaft at which intake valve is closed is computed by subtracting cam duration from double rotation of crankshaft:

$$\alpha_{closed} = \alpha_{tot} - CD = 448 \text{ deg} \quad (3)$$

Angular speed ( $\omega$ ) of crankshaft at targeted RPM is defined as follows:

$$\omega = TRPM * 360 \frac{\text{deg}}{\text{rev}} = 18000 \frac{\text{deg}}{\text{s}} \quad (4)$$

From

$A = \frac{\pi * D^2}{4} = \frac{\pi * 30^2}{4} = 706.9 \text{ mm}^2$  (2) and  $\alpha_{closed} = \alpha_{tot} - CD = 448 \text{ deg}$  (3) time ( $t_{closed}$ ) of intake valve being closed is calculated:

$$t_{closed} = \frac{\alpha_{closed}}{\omega} = \frac{448}{18000} = 0.02489 \text{ s} \quad (5)$$

By selecting suitable runner length ( $L$ ) air pulse reaches intake valve back face precisely when the valve opens during next intake stroke:

$$L = \frac{t_{closed} * v}{16} = \frac{0.02489 * 343}{16} = 0.53355 \text{ m} = 533.55 \text{ mm} \quad (6)$$

Where 16 is number of cycles at which air reaches the intake valve back face, stacks up, bounces towards plenum, hits the volume of air in the plenum and then pulse is pushed back into the runner. This value must be even and might vary depending on space limitations in the engine bay.

Runner comprises bell mouth pipe end for smoothening airflow entering the runner. Bell mouth height is 21 mm. Runner length is defined as length of the centerline from the runner plenum opening to the intake valve back face, therefore,  $L = 533.55$  mm includes inlet port depth, runner tube length and injector flange. Runner tube is shown in Figure 7.



Figure 7. Intake runner tube

### 6.1.2 Plenum design

Plenum volume for N/A engine is selected from the 75 - 125% of the engine displacement, for AKL is corresponds 1200 – 2000 cm<sup>3</sup>. Initial plenum volume ( $V_{\text{plenum}}$ ) was selected to be 1600 cm<sup>3</sup> or 100% of engine displacement. This is the value used for following calculations. Taper is set to be 10°.

Input values for resonance frequency calculations ( $f_{\text{res}}$ ):

Pressure wave speed in air ( $v$ ) = 343 m/s

Runner length ( $L$ ) = 533.55 mm

From (2) runner cross sectional area ( $A$ ) = 706.9 mm<sup>2</sup>

Plenum is considered as a resonance chamber; hence, it follows Helmholtz resonance frequency equation for its volume:

$$f_{res} = \frac{v}{2*\pi} * \sqrt{\frac{A_{runner}}{V_{plenum}*L}} = \frac{343}{2*\pi} * \sqrt{\frac{706.9*10^{-6}}{1600*10^{-6}*0.53355}} = 49.67 \text{ Hz (7)}$$

Resonance frequency of the plenum must be equal to sound pulsations frequency in the runner to guarantee acoustic supercharging effect. In other words,  $TRPM = f_{res}$ . Since TRPM is set to be 3000 rev/min or 50 rev/s and from (7)  $f_{res} = 49.67 \text{ Hz}$  which corresponds to 2980.2 rev/min, it is concluded that initial plenum volume and runner parameters combination selected ensure acoustic supercharging effect at desired RPM.

Main function of the plenum is to equally distribute air entering each cylinder, this is achieved by TB positioning and, in case of side arrangement of TB, taper. Ideally, TB is located behind the plenum facing all runners, this design offers optimal air delivery to each cylinder. TB can also be attached to the side of the plenum. Typically, main issue of such arrangement is remotest cylinder air starving, therefore, to compensate air shortage, plenum is tapered towards that cylinder which allows faster air delivery. Both cases are depicted in Figure 8.



Figure 8. CDAA engine IM with TB situated in the middle of the plenum (D2P Car parts 2024), AKL engine IM with side TB attachment (Re Cife, 2023)

### Plenum model

Custom plenum is made of 6061 aluminum alloy and consists of following components:

- Base – sheet metal part, 2 mm thickness
- Side plates – sheet metal part, 2 mm thickness

- Upper ca – 90x2.5 aluminum pipe cut lengthwise
- Front covers are represented by segmented 90x2.5 aluminum pipe cut lengthwise

Runner entry holes are allocated in the base part as shown in Figure 9 copying distances between holes in intake gasket to prevent complex geometries and undesired angles during assembling and welding stages.

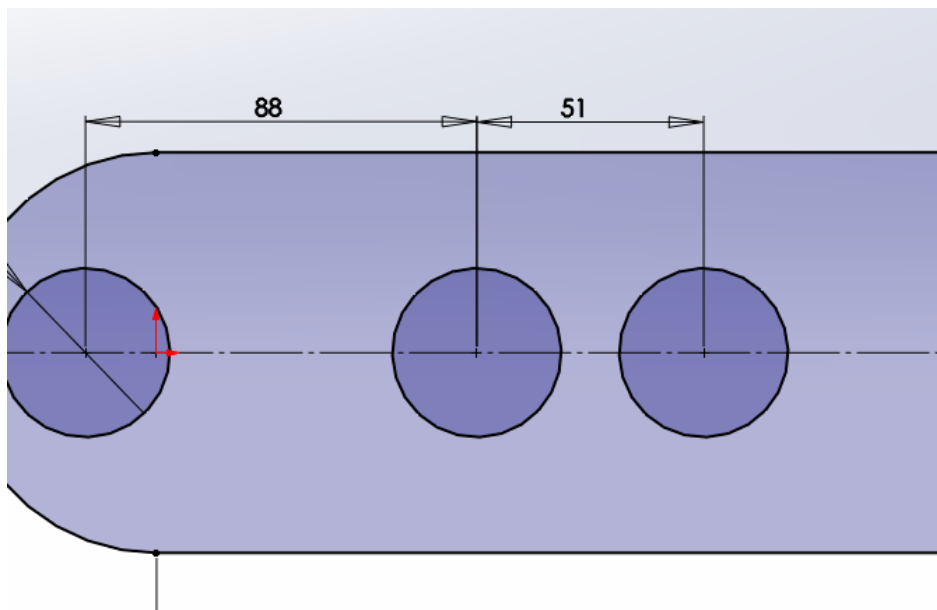


Figure 9. Base part hole allocation

Plenum is assembled in the following manner: that two segmented 90x2.5 pipe parts complete the front cover, base part includes 2 bends of 50° and 40° to prepare vertical wall for TB attachment. 90x2.5 pipe cut lengthwise is a top cover which connects segmented front end and bended flange of base part. Two sidewalls conclude the volume and seal the plnum. Plenum volume  $V = 1578 \text{ cm}^3$ . By utilizing this value in (7) corresponding resonance frequency is 49.7 Hz which deviates by 0.6% from targeted value. The basic model is shown in Figure 10.

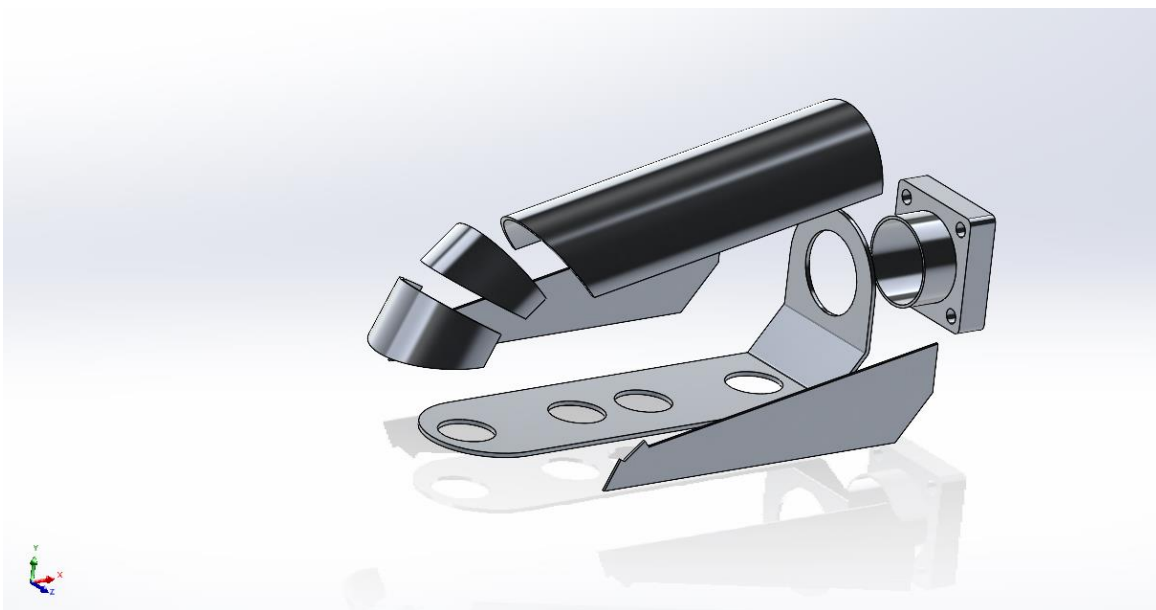


Figure 10. Exploded view of custom plenum

Typically, in most of the custom IMs TB attachment or plenum neck is tilted to runners to establish uniform airflow in the plenum volume center, however, in AKL engine bay this leads to runner-inlet port misalignment and requires angled runners/TB connection which cuts its manufacturability.

### 6.1.3 Injector flange

Since the base material of stock IM is plastic, it allows to utilize complex shapes and integrate essential elements, e.g., fuel injectors are mounted at the end of the runners. In custom IM injector attachment is represented by aluminum flange shown in Figure 11 made of 300x85x17 aluminum bar. Figure 11, that is situated between runner ends and inlet ports. It incorporates intake gasket cavities, injectors, and fasteners holes.

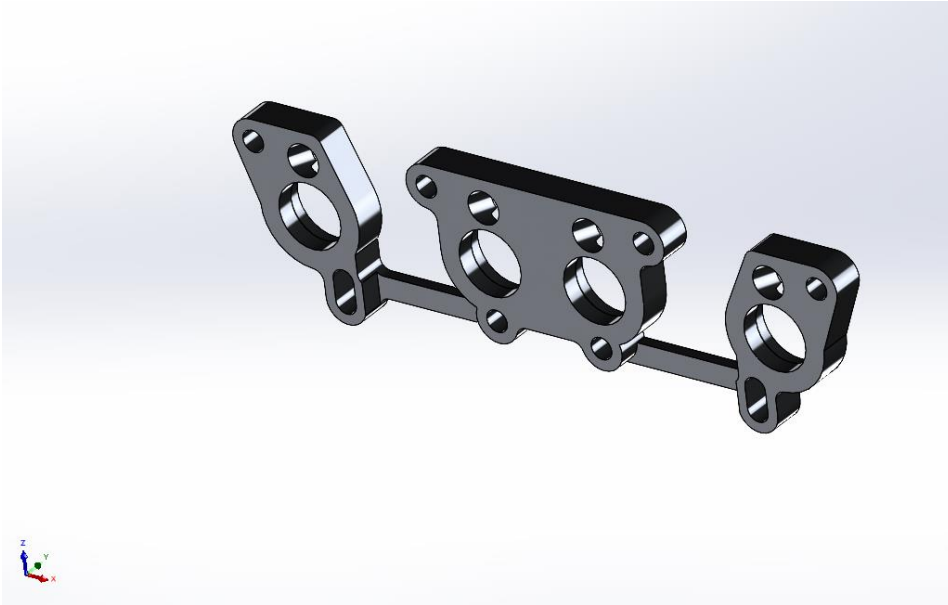


Figure 11. Intake flange

#### 6.1.4 TB attachment

TB attachment shown in Figure 12 allows to connect plenum to the TB. It is manufactured by welding 60x2 L25 aluminum pipe to 80x80x20 rectangular aluminium bar. Both parts include 54 mm hole which is an inner diameter of stock TB. TB is mounted via four M10x1.5 machine screws and 66.5x1.8x7.5 ring is used to seal the connection.

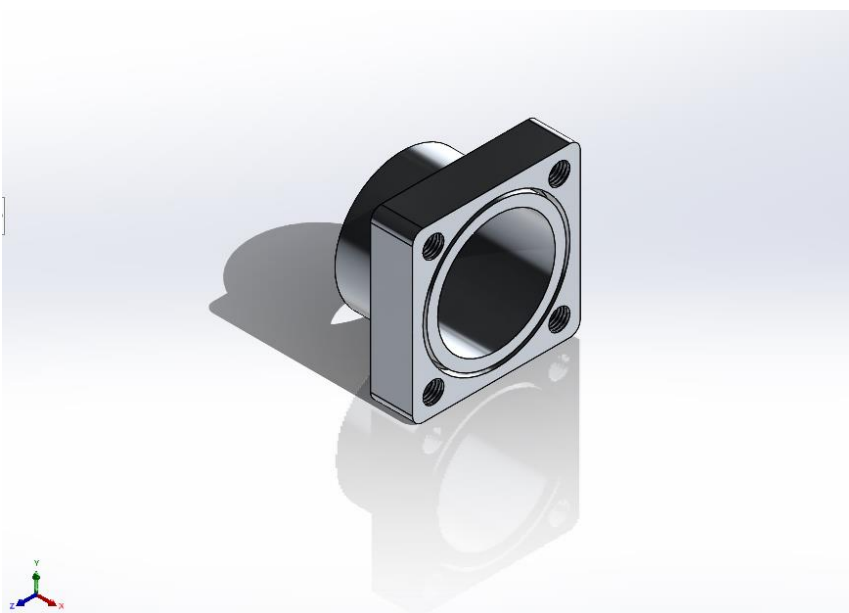


Figure 12. TB attachment

## 6.2 IM assembly

Plenum model illustrated in Figure 13 meets the requirements for acoustic resonance and match desired geometry to cover the engine. Since runners can rotate freely in plenum it is possible to adjust the horizontal position of the plenum which guarantees convenient and precise installation. Note: MAF sensor hole in the upper cover is not presented in the model.



Figure 13. Custom IM assembly

## 6.3 CFD simulation results

The IM model was introduced to Ansys Fluent to obtain data at runner exit to verify desired cylinder filling, examine flow dynamics within plenum, and select the most suitable option for subsequent manufacturing. Selection criteria are dynamic pressure and velocity at runner exit. This location allows to measure desired metrics before fuel injection point.

### **Boundary conditions**

In Ansys Fluent pressures follow the equation: absolute pressure ( $p_{abs}$ ) = operating pressure ( $p_{op}$ ) + gauge pressure ( $p_g$ ).

$$p_{op} = 101.3 \text{ kPa}$$

Plenum inlet MAF = 0.035 kg/s

Plenum inlet  $p_g = 0$

Runner exit  $p_g = -65$  kPa

Operating temperature  $T = 273$  K

Air is set to behave as compressible fluid with Ansys Fluent preset values.

K-epsilon standard viscous model for turbulence is used in simulations.

### 6.3.1 Simulation results

Despite intake stroke takes approx. 0.025 s to be completed, time  $t = 1$  s is set. The 1<sup>st</sup> reason is that timeframe is narrow for simulations and only local maximum of dynamic pressure is found, which is not indicative as combination of average and maximum dynamic pressures that define the cylinder filling in general. The 2<sup>nd</sup> reason is to observe in details dynamic pressure fluctuations that depend on air density and airflow within plenum and runner entry. Dynamic pressure is proportional to density and square of its velocity; therefore, dynamic pressure and velocity are shown via graphs, yet airflow via streamlines. Cylinders are filled one by one according to fire order of AKL engine 1-3-4-2, in Figure 14 - Figure 25 graphs of dynamic pressure/velocity and streamlines of airflow inside of the IM are shown in cylinder numerical order.

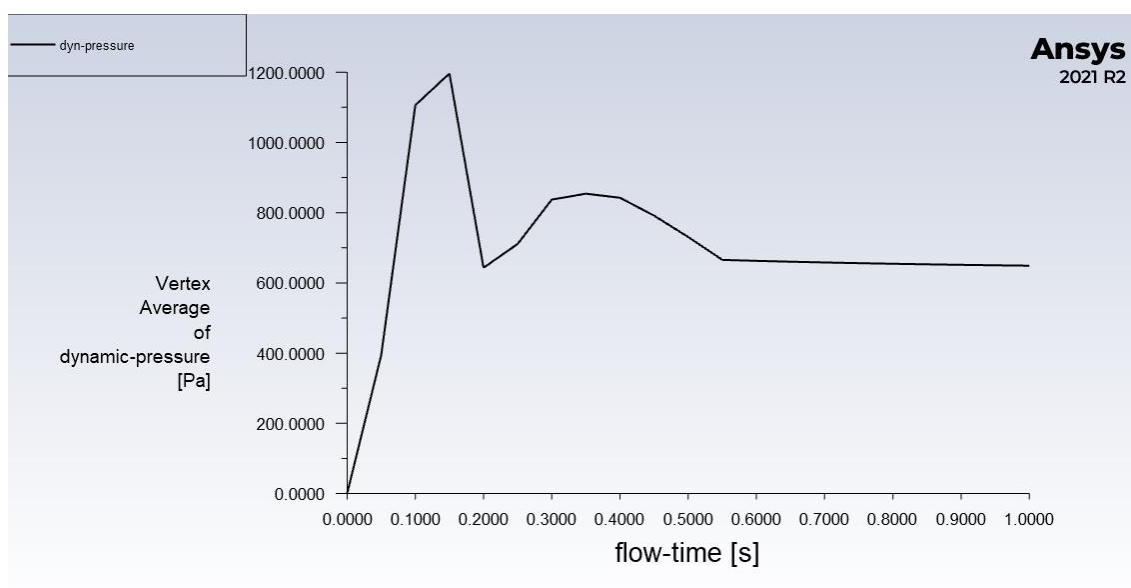


Figure 14. Dynamic pressure at runner exit of the 1<sup>st</sup> cylinder

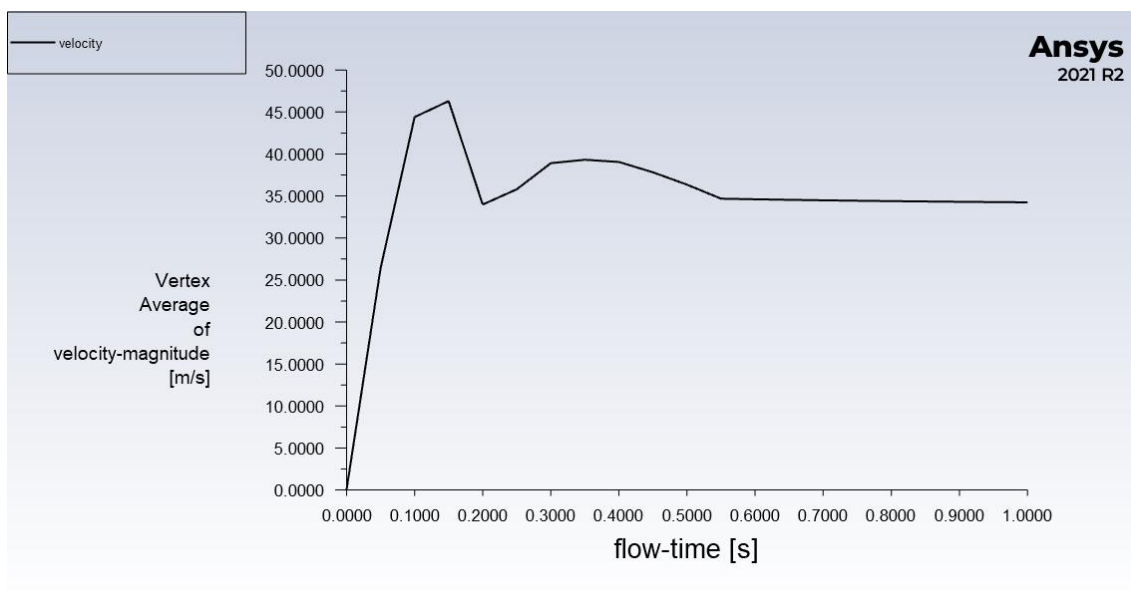


Figure 15. Air velocity at runner exit of the 1<sup>st</sup> cylinder

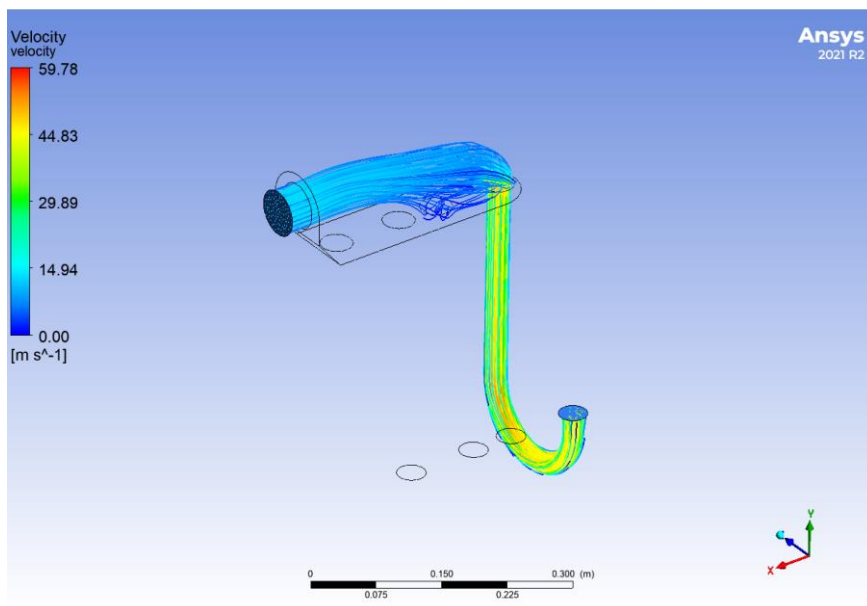


Figure 16. Airflow within IM during 1<sup>st</sup> cylinder intake stroke

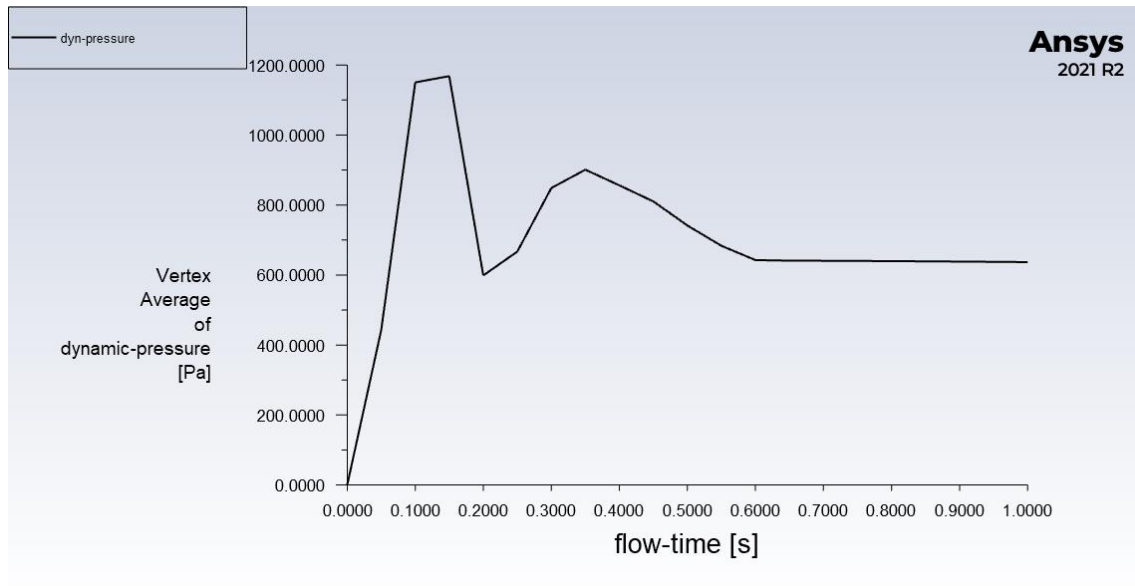


Figure 17. Dynamic pressure at runner exit of the 2<sup>nd</sup> cylinder

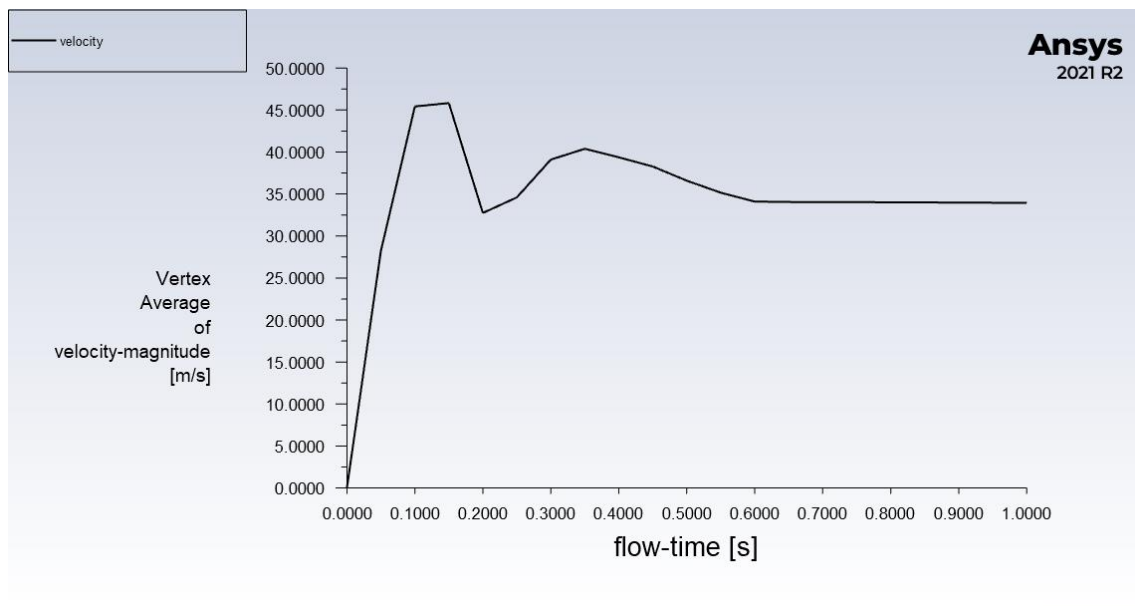


Figure 18. Air velocity at runner exit of the 2<sup>nd</sup> cylinder

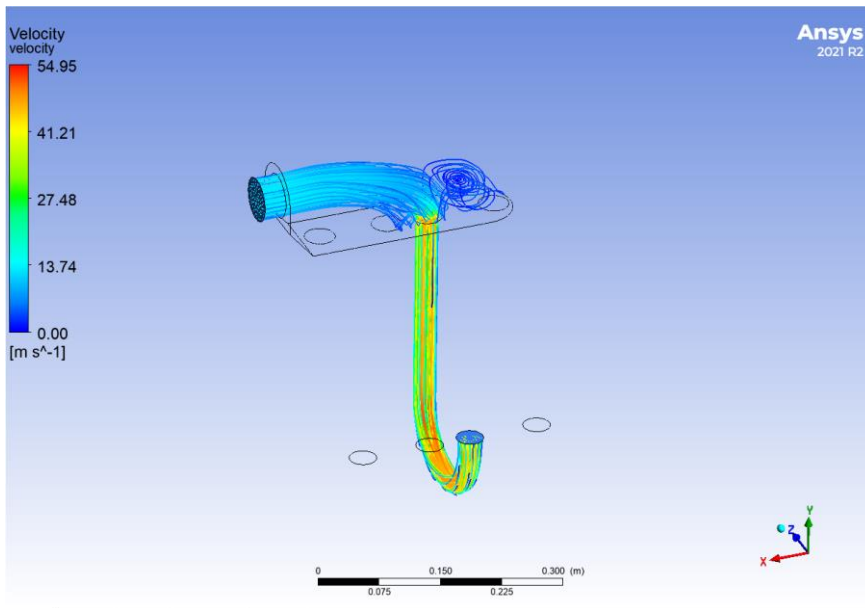


Figure 19. Airflow within IM during 2<sup>nd</sup> cylinder intake stroke

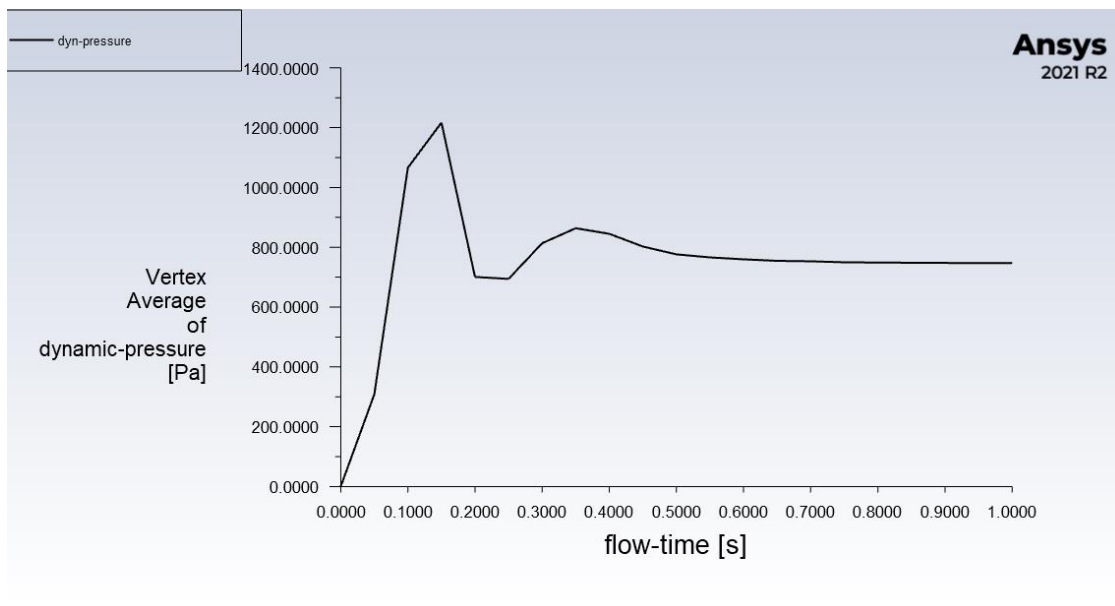


Figure 20. Dynamic pressure at runner exit of the 3<sup>rd</sup> cylinder

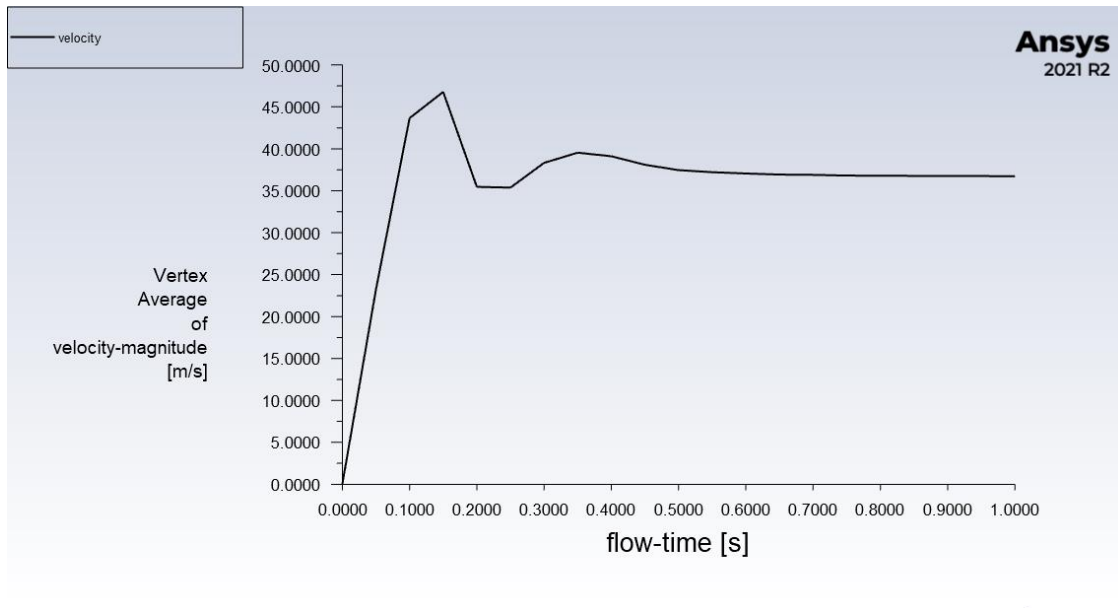


Figure 21. Air velocity at runner exit of the 3<sup>rd</sup> cylinder

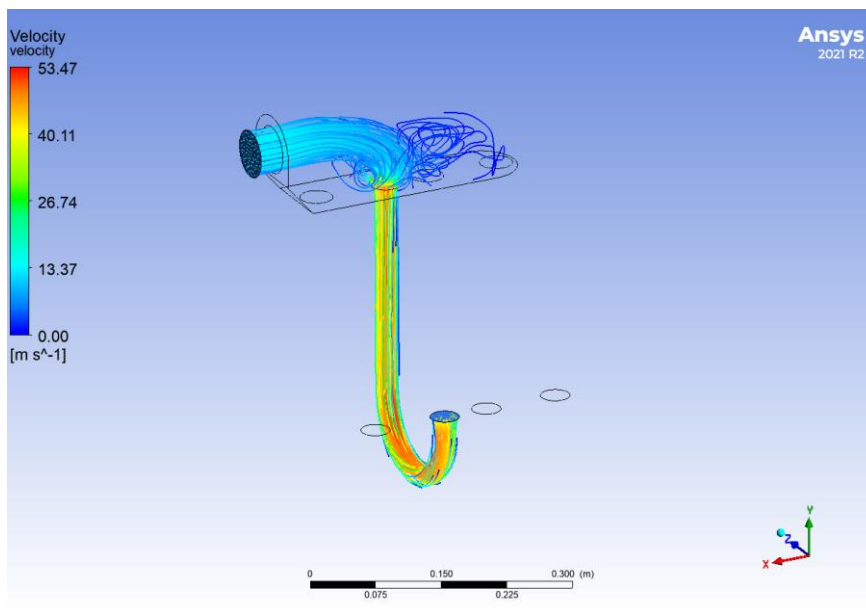


Figure 22. Airflow within IM during 3<sup>rd</sup> cylinder intake stroke

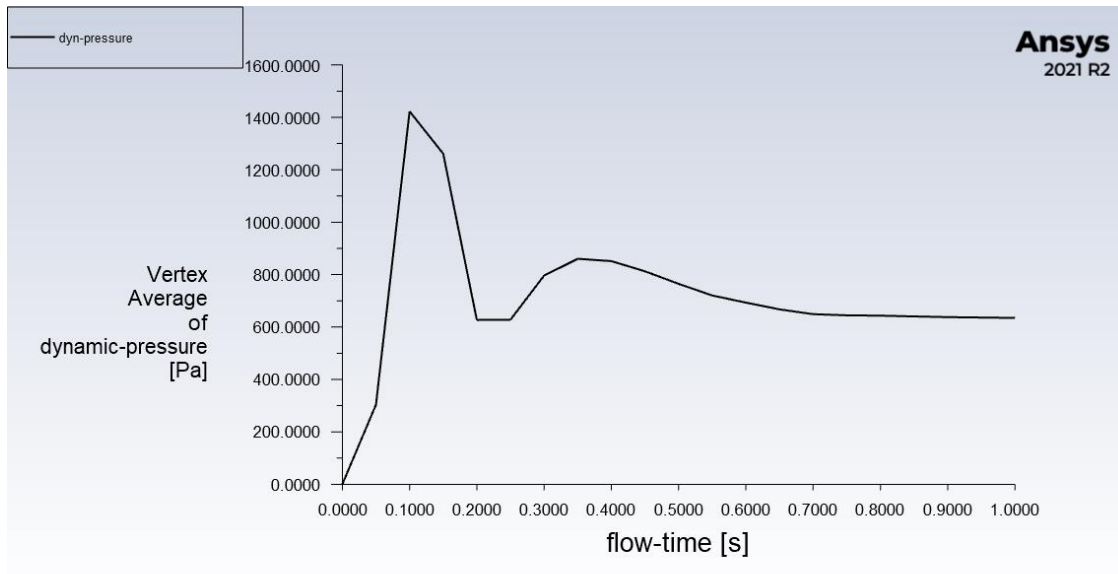


Figure 23. Dynamic pressure at runner exit of the 4<sup>th</sup> cylinder

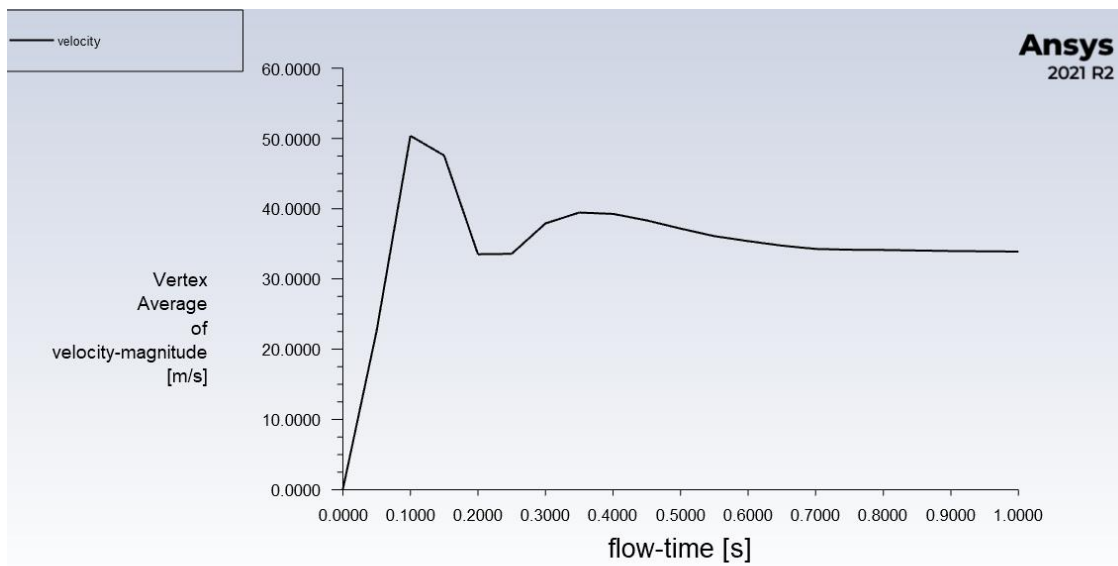


Figure 24. Air velocity at runner exit of the 4<sup>th</sup> cylinder

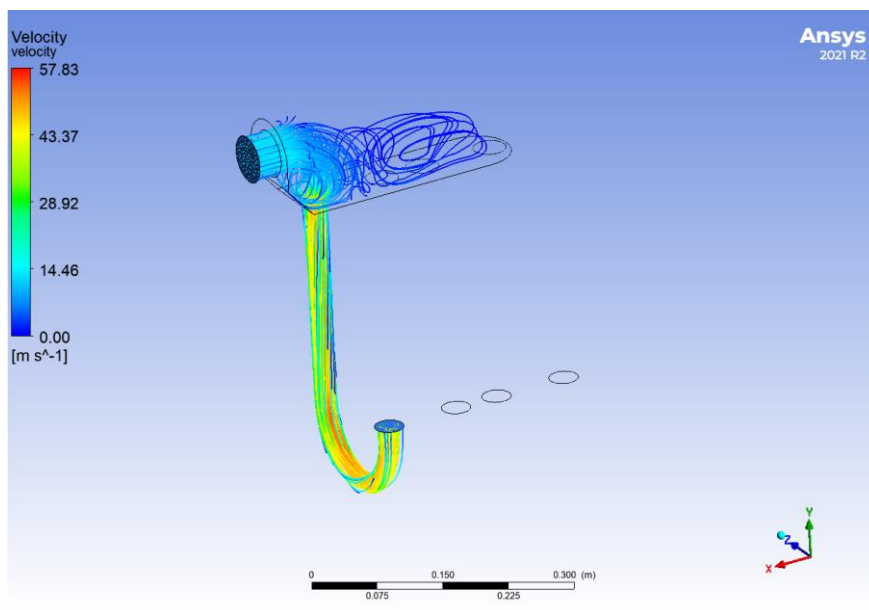


Figure 25. Airflow within IM during 4<sup>th</sup> cylinder intake stroke

### 6.3.2 Simulation results assessment

Simulation results are considered genuine. 65 kPa of static pressure difference sets air into motion immediately after intake valve opens. Airflow reaches its maximum velocity, then velocity drops, and it takes 0.2 – 0.4 s, depending on the cylinder, to establish uniform flow. In Table 1 all desired metrics of airflow within IM are presented.  $p_{\max}$  and  $p_{\text{unif}}$  are dynamic pressures at overall maximum and uniform flow respectively.  $v_{\max}$  and  $v_{\text{unif}}$  are velocities at overall maximum and uniform flow respectively.

	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
$p_{\max}$ , Pa	1200	1180	1220	1420
$p_{\text{unif}}$ , Pa	650	650	750	650
$v_{\max}$ , m/s	46	45.5	46.5	50.5
$v_{\text{unif}}$ , m/s	35	34.5	37	34.5

Table 1. Airflow metrics

In ideal IM model all presented metrics for each cylinder are in proximity; however, in case of side TB positioning there might be reduction in peak dynamic pressure values as cylinder is located further from TB. In case of this model the 3<sup>rd</sup> cylinder is distinguished with 15% higher uniform airflow dynamic pressure and ~5% higher uniform airflow velocity. It is explained by 3% higher, comparing to other cylinders, air density defined by less dispersed airflow entering the runner opening. This is clarified by combination of runner hole-TB distance and tapered plenum shape. The 4<sup>th</sup> cylinder peak dynamic pressure is distinct from other entities since 4<sup>th</sup> cylinder is the closest to TB, hence, airflow loses less energy while traveling towards runner opening. The 1<sup>st</sup> cylinder dynamic pressures are close to the respective values of the 2<sup>nd</sup>/4<sup>th</sup> cylinder which means cylinder starving is not present.

It is essential to understand that absolute or total pressure is the sum of static and dynamic pressures; therefore, obtained values of peak dynamic pressure make up approx. 2.2% of total pressure difference for 1<sup>st</sup> cylinder and approx. 1.8% for 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> cylinders.

## 7 Comparative analysis

In a comparative evaluation between experimental findings on a stock IM and theoretical results of a custom-designed counterpart, physical entities dimensions and components effect on desired parameters are considered. Initial testing involves stock IM, subjected to experimental analysis across all RPM ranges. Data on MAF, pressure values, and VE are gathered and tabulated.

Since TB size is not changed MAF at distinct RMP range is permanent for stock and custom IMs. To shift peak torque to 3000 RPM with the help of custom IM, plenum geometry and runner parameters are designed to provide acoustic supercharging effect. Component modifications are presented in Table 2.

	Runner diameter, d, mm	Runner length, l, mm	Plenum volume, V, cm <sup>3</sup>
Stock IM	34	~690	<<<1578
Custom IM	30	533.55	1578

Table 2. Component sizes of stock and custom IM

Stock plenum is incalculable due to its complex geometry and inability to disconnect it from stock IM, although visually it is significantly less than custom IM plenum. Custom IM runner is 156.45 mm shorter than original and its diameter 4 mm less. Reviewing this fact, it is concluded that shorter runners can be used for altering peak torque to lower RPM only by grouping with certain runner diameter and plenum volume.

## 8 Conclusion

This study was aimed to create custom IM for VAG AKL engine to shift peak torque from 3800 to 3000 RPM. Important characteristics to be considered were manufacturability and ease of installation.

Such technical aspects as runner and plenum geometries, VE and airflow behavior were examined and explained. Acoustic supercharging effect was investigated and implemented utilizing Helmholtz resonance theory.

To design an IM for distinct RPM range, it is important to undertake a comprehensive analysis to achieve the ideal balance of airflow dynamics and VE. Targeted RPM range serves as a guiding principle, dictating the plenum geometry and runner dimensions. CFD simulations done in Ansys Fluent played a pivotal role providing data about airflow behavior, pressures, and turbulence within IM. By iterative refining IM components in SolidWorks, close to equal air distribution to individual cylinders was ensured. Furthermore, the IM resonance tuning effect was adjusted to enhance cylinder filling amplifying torque output at 3000 RPM. Ideally, for better understanding and precise results replaceable elements are 3D printed and assemblies are dyno-tested, delivering factual data to work with for future modifications before actual manufacturing.

As automotive technology continues to evolve, the findings of this study serve as a foundation for further exploration and strive to optimize engine performance at certain RPM range.

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