

University of Wales Trinity Saint David
School of Engineering

Group Project – Aerodynamics
M5X00400

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1 Introduction

The goal for the project was to design a single seater electric hill climb car. For a race car to be competitive, an aerodynamic package has to be designed for the vehicle. Aerodynamics assists in making the car have more friction at high speeds. This is done by increasing the reaction force acting on the road which is shown by the equation $F = \mu R$ where F is friction, μ is coefficient of friction and R is reaction force. This increase in friction allows the car to corner at higher speeds therefore increasing run times.

The objectives for the project were to achieve a $C_L = -1.92$ and a $C_D = 0.77$. This was a reasonable goal as most vehicles in this class achieved numbers similar to these.

2 Project Organisation

There were four members in the group; Duke Asamoah, Alexander Baldwin, Dion Billing and Zhendu Fang. The roles of each were; rear wing, group leader and front wing, sidepods and diffuser respectively. Even though each person had a separate part of the car to work on, communication was a must because each section would have to work together rather than individually.

3 Duke Asamoah (1706143)

Duke has a differential deadline. Report sent separately.

4 Alexander Baldwin (1801714)

4.1 - Introduction

The goal was to design the front wing of the open wheel electric hill climb car. Front wings come with some challenges such as not ruining the airflow for the rest of the aerodynamic elements further down the car and diverting air around the wheels to minimise drag. Furthermore, they are different to rear wings as they act in ground effect. Ground effect speeds up the airflow in the gap between the main element and the ground which creates a low pressure therefore increasing downforce (Katz, 1995). Multiple studies done for different wing profiles acting in ground effect and not in ground effect. End plate design study and multiple wing designs with different number of elements and aggression.

4.2 – Experimental, Design Work and Testing

4.2.1 - First Concept

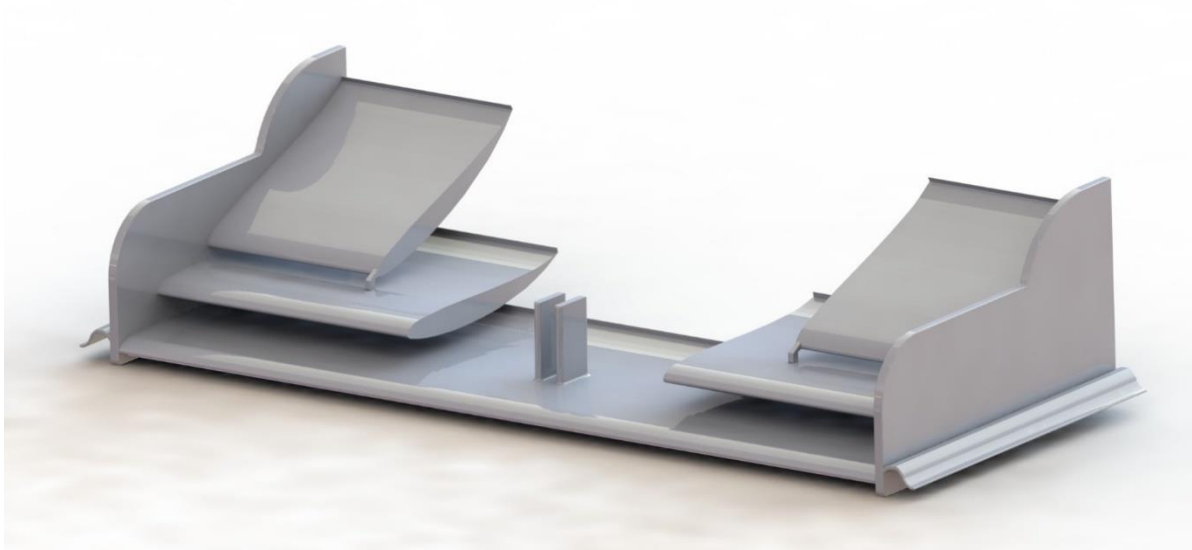


Figure 1 - Picture showing the first front wing design concept.

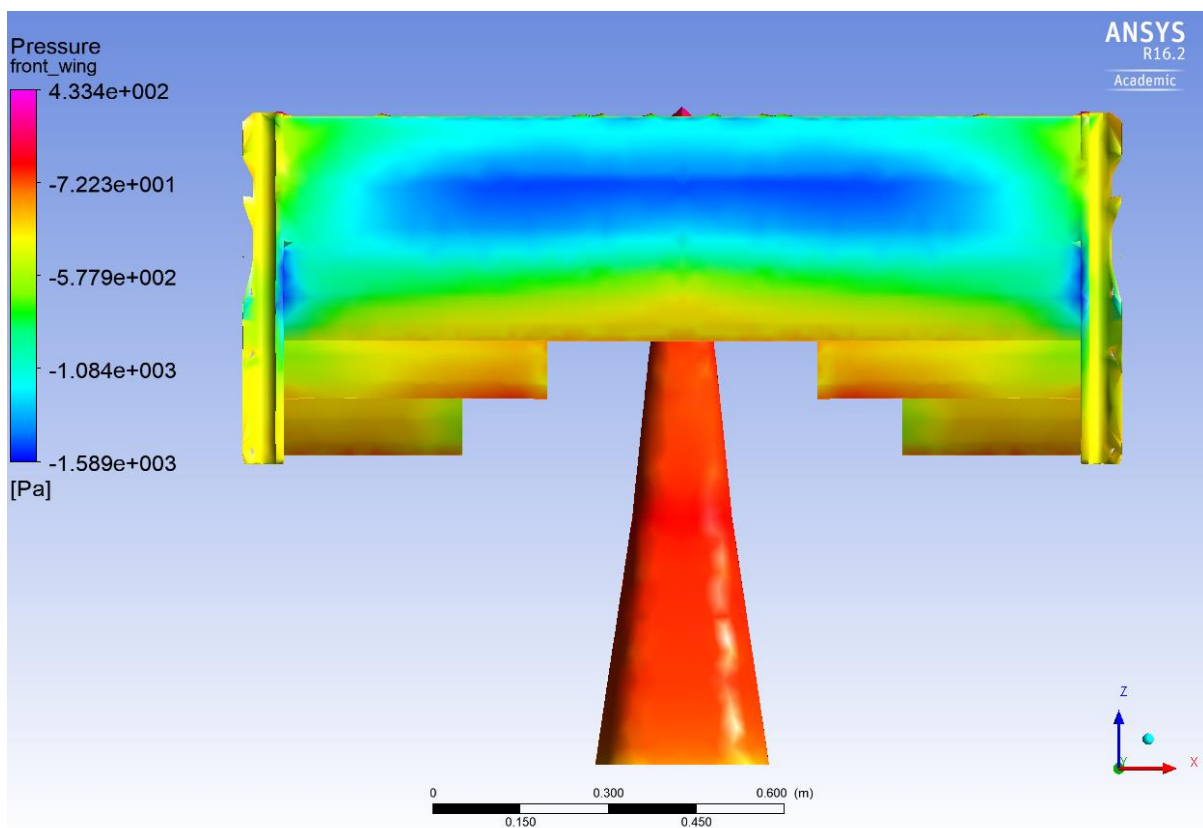


Figure 2 - Picture showing pressure plot beneath the first front wing design concept.

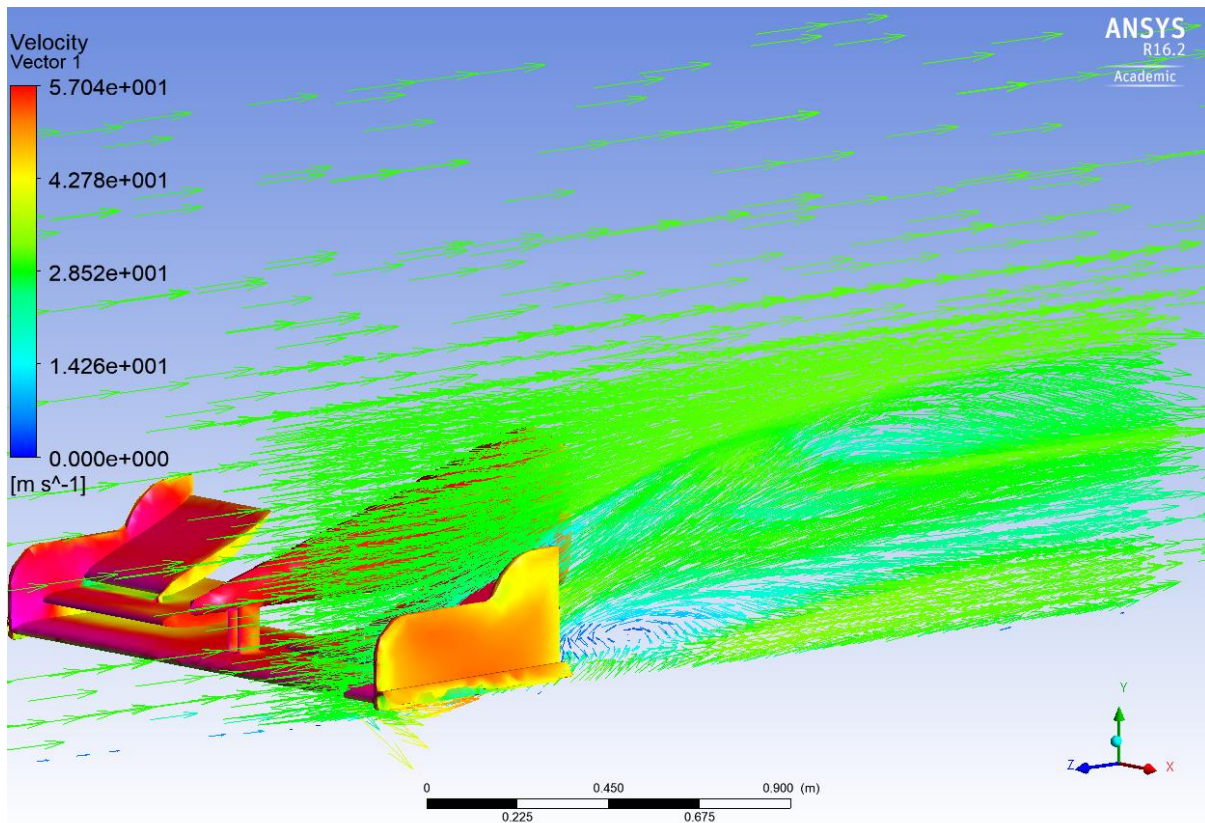


Figure 3 - Picture showing velocity vectors for the first front wing design concept.

The first front wing design was made without any calculations or tests done. The goal for the first aerodynamic package concept was to just have a body which could be run in CFD so knowledge on the use of the software could be gained. As shown above in Figure 1, the wing was designed quite aggressively. Gurney flaps were used which are small vertical extrusions on the trailing edge of a wing which go across the entire wingspan. These flaps create a swirl of positive pressure in front of them which causes air to flow over therefore increasing the angle of attack of the wing. Unfortunately, they do cause a decent amount of drag but they are very simple and effective way to increase downforce when utilised properly. Figure 2 shows how ground effect works on the main element of the front wing. The dark blue indicated a very high pressure which is what is expected. Figure 3 shows that this front wing generates a lot of turbulence which is why the drag is quite high. The downforce, drag and efficiency calculated for this wing were 640.33N, 128.77N and 0.201 respectively.

4.2.2 - Second Concept

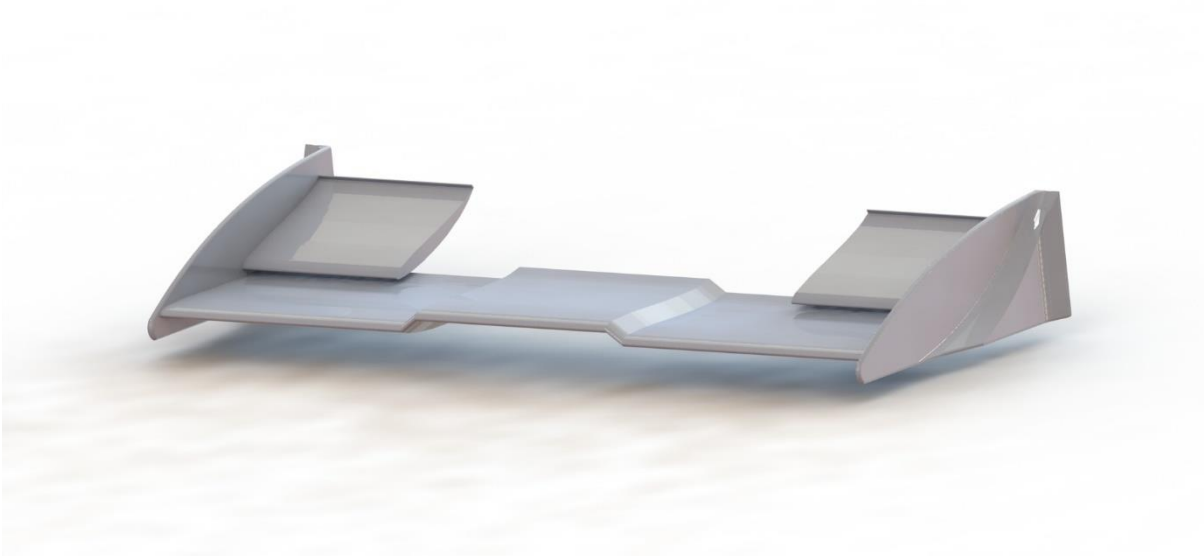


Figure 4 - Picture showing the second front wing design concept.

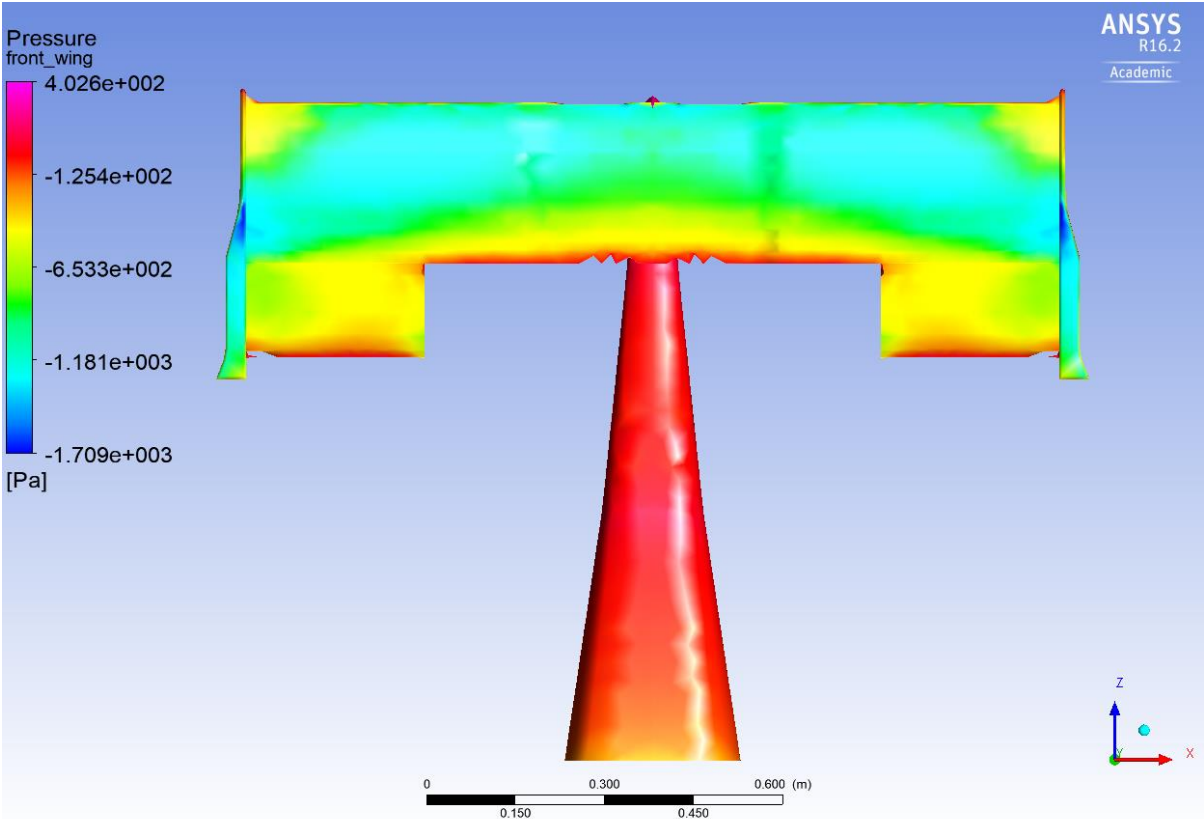


Figure 5 - Picture showing pressure plot for the second front wing design concept.

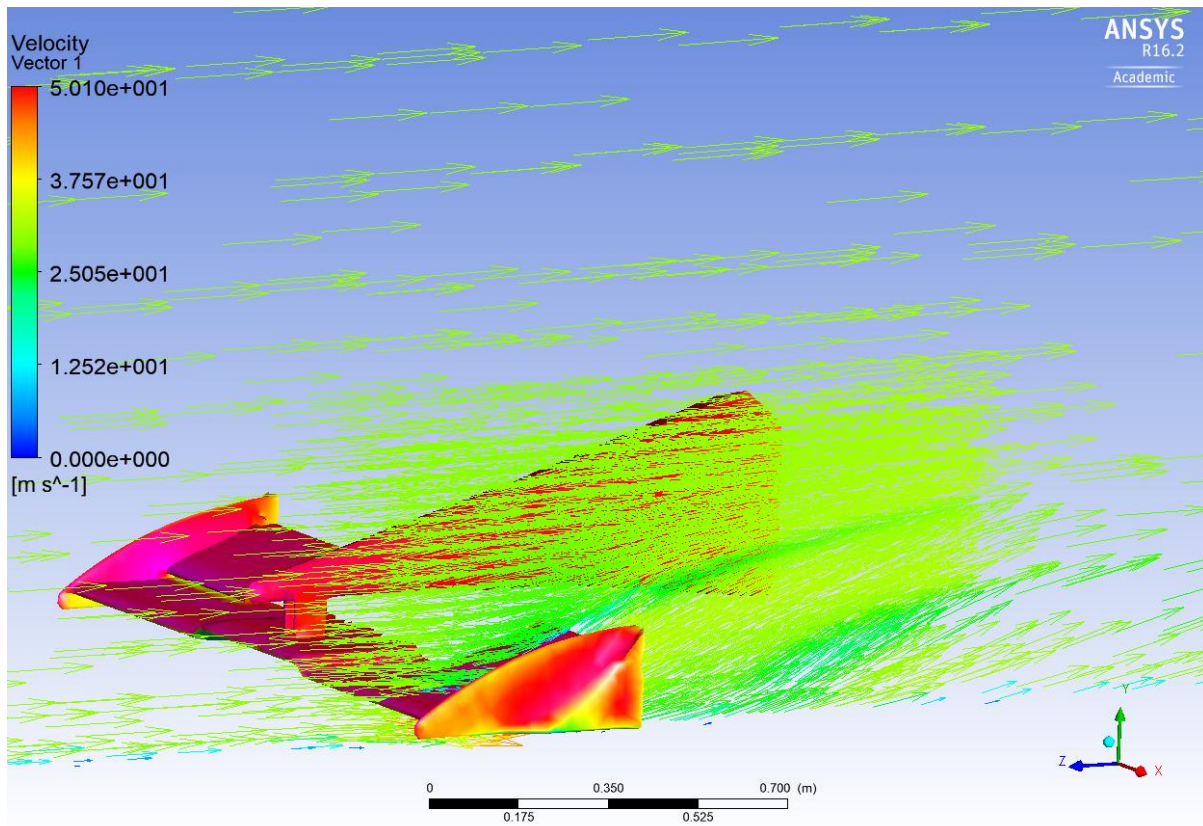


Figure 6 - Picture showing velocity vectors for the second wing design concept.

The first front wing design was made without any calculations or tests done. This was due to the fact that there was not much aerodynamic knowledge at the beginning but an initial package had to be designed. The goal for the first aerodynamic package concept was to just have a body which could be run in CFD so insight on the use of the software could be gained. As shown above in Figure 1, the wing was designed quite aggressively. Gurney flaps were used which are small vertical extrusions on the trailing edge of a wing which go across the entire wingspan. These flaps create a swirl of positive pressure in front of them which causes air to flow over therefore increasing the angle of attack of the wing. Unfortunately, they do cause a decent amount of drag but they are very simple and effective way to increase downforce when utilised properly. Figure 2 shows how ground effect works on the main element of the front wing. The dark blue indicated a very high pressure which is what is expected. Figure 3 shows that this front wing generates a lot of turbulence which is why the drag is quite high. The downforce, drag and efficiency calculated for this wing were 640.33N, 128.77N and 0.201 respectively.

4.2.3 - Third Concept



Figure 7 - Picture showing third front wing design concept.

4.2.3.1 – Aerofoil Profile Design

The final design concept was a longer process than the previous two. Wing profiles were researched and tested. Wing profiles tested in ground effect were the ones which could be used as the main front wing element. The other profiles not tested in ground effect would potentially act as the other elements in the wing. The elements that were tested in ground effect were NACA 632615 and NACA 8610 and the profile not tested in ground effect was NACA 7312 (McBeath, 2017). Each one was also tested at different angles of attack to see where each profile stalls and when it reaches maximum downforce. Each wing profile was run in CFD at different angles of attack. Domain size and mesh sizes remained constant during all test to try get the most accurate result possible.

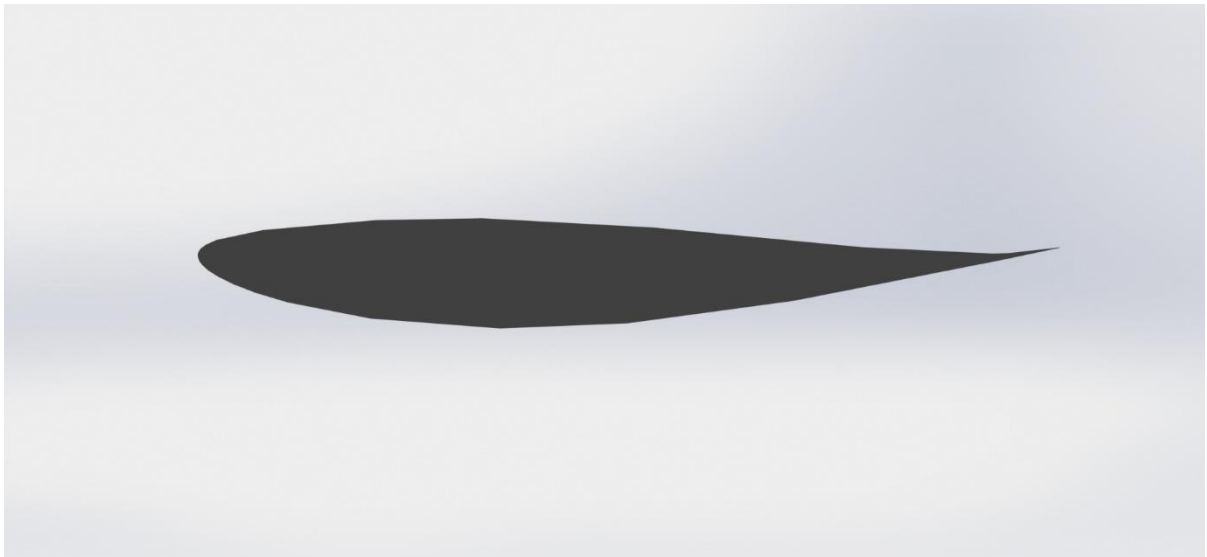


Figure 8 - Picture showing side profile for NACA 632615.

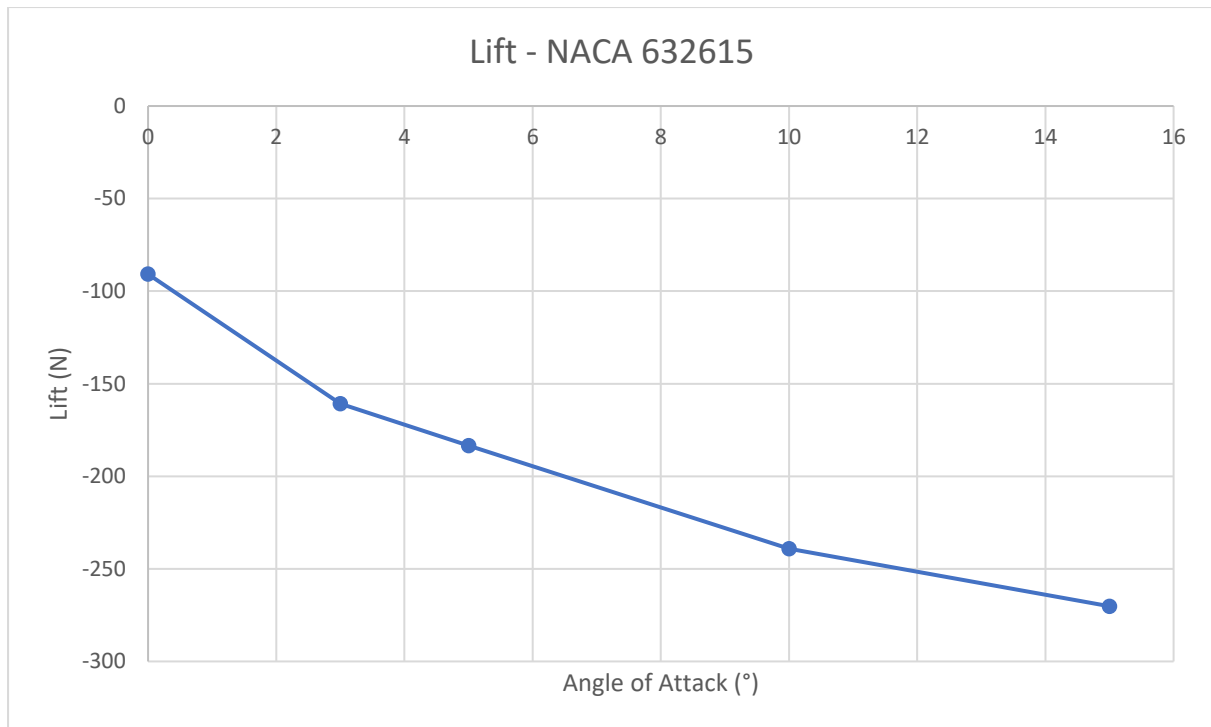


Figure 9 - Graph showing lift against angle of attack for NACA 632615 wing profile.

The lift decreases exponentially which means that the downforce increases exponentially for every increase in angle of attack.

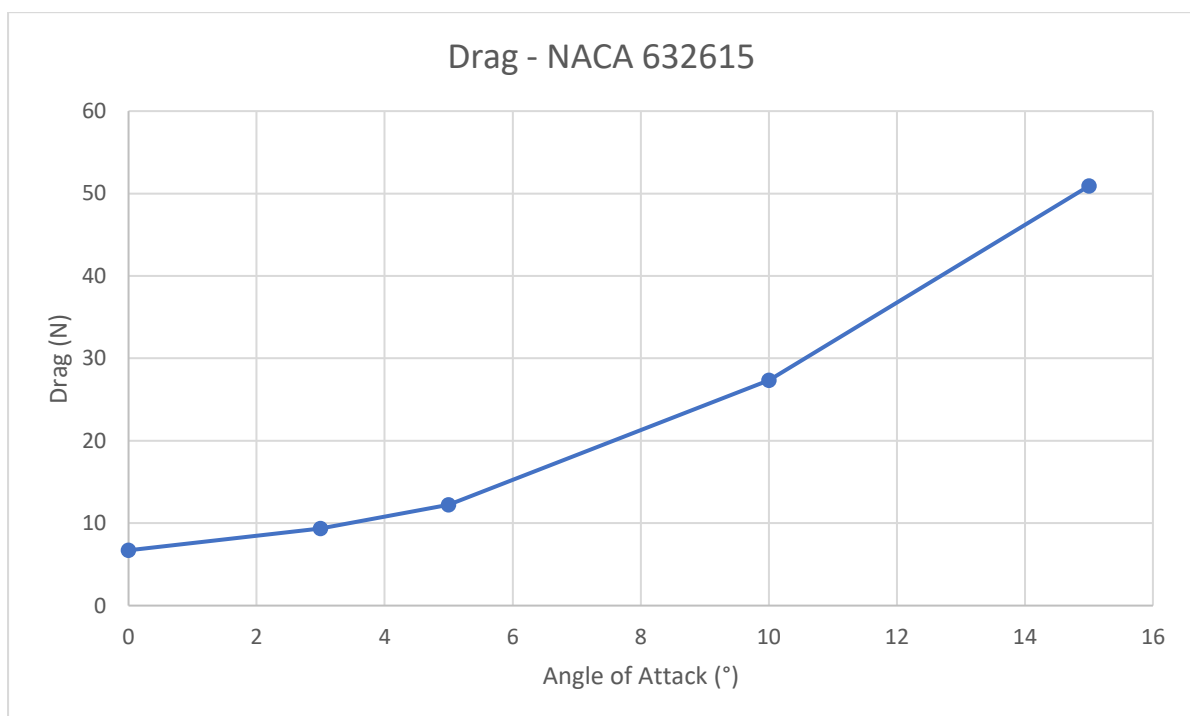


Figure 10 - Graph showing drag against angle of attack for the NACA 632615 wing profile.

The drag increases exponentially for every increase in angle of attack.



Figure 11 - Picture showing side profile for NACA 7312.

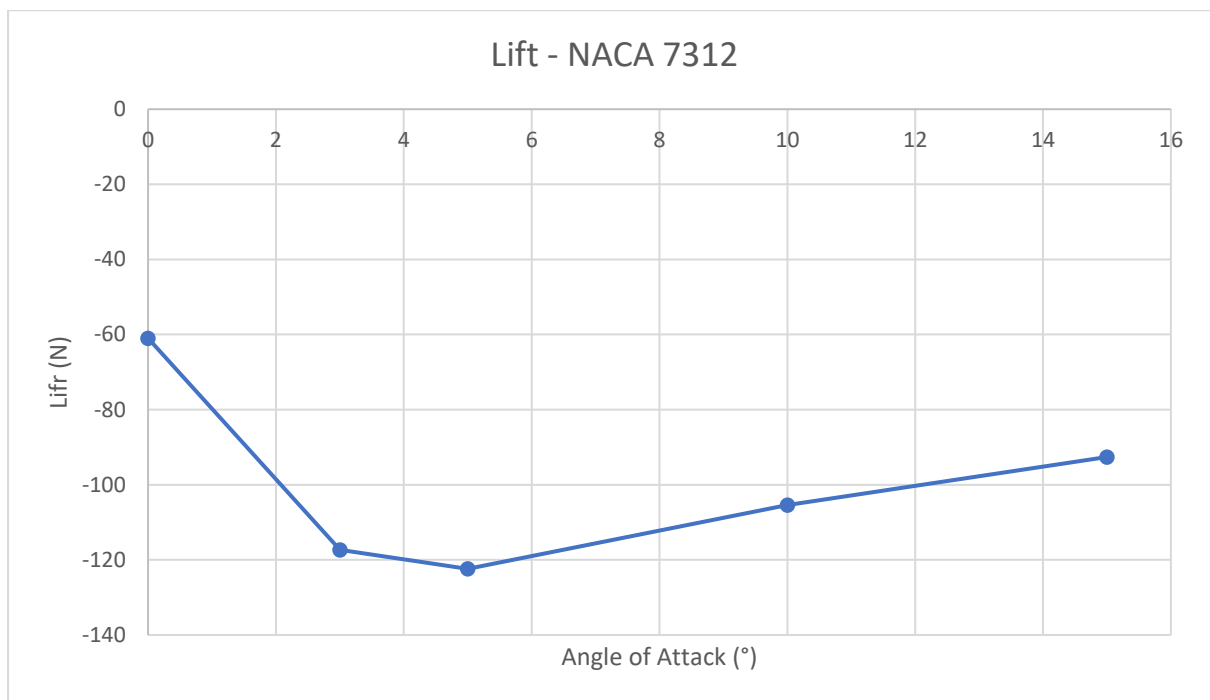


Figure 12 - Graph showing lift against angle of attack for NACA 7312 wing profile.

The downforce starts to increase then drops off after 5°. This shows that the profile is starting to stall slightly.

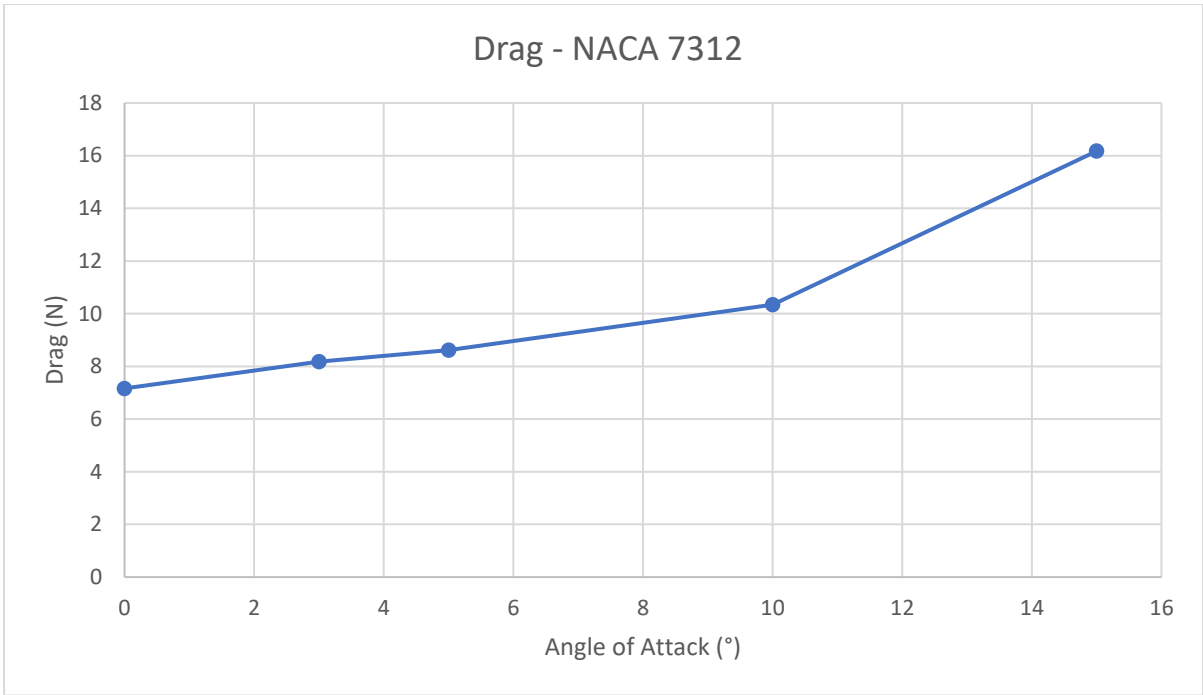


Figure 13 - Graph showing drag against angle of attack for NACA 7312 wing profile.



Figure 14 - Picture showing side profile for NACA 8610.

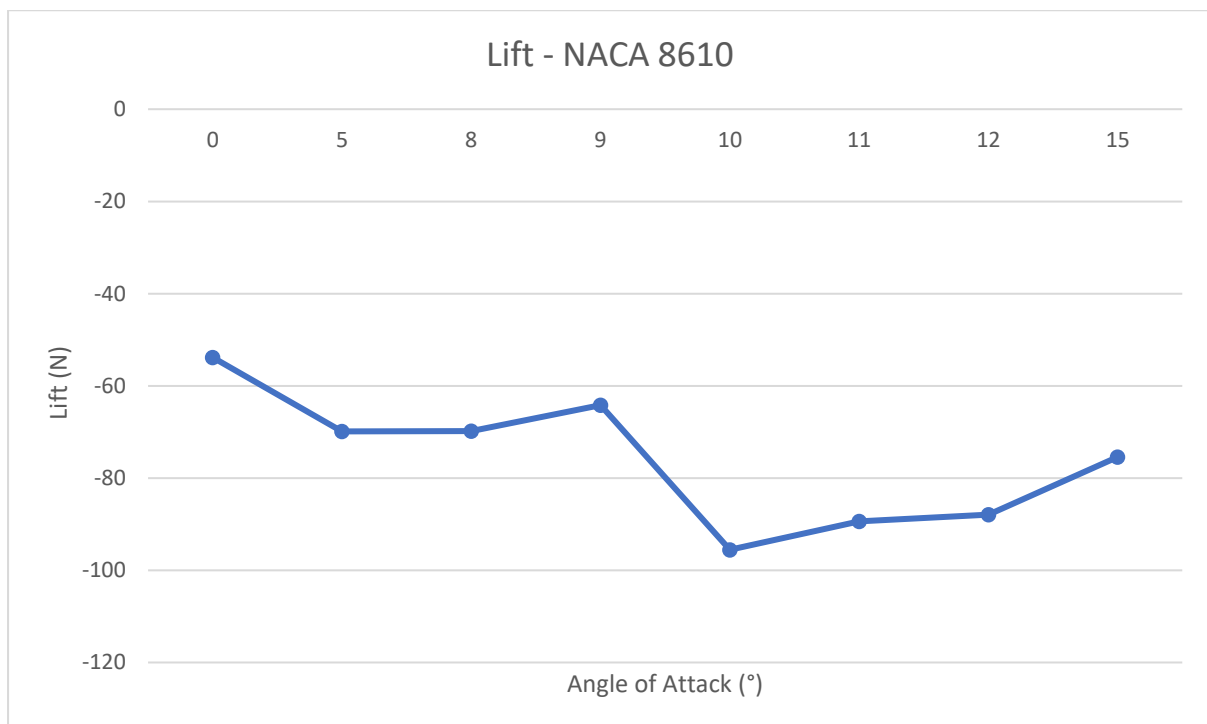


Figure 15 - Graph showing lift against angle of attack for NACA 8610 wing profile.

Downforce increases as then starts reducing after 9° but there is an error in the results as a spike occurs at 10° then downforce continues to decrease. This could have potentially been an error in the calculations done.

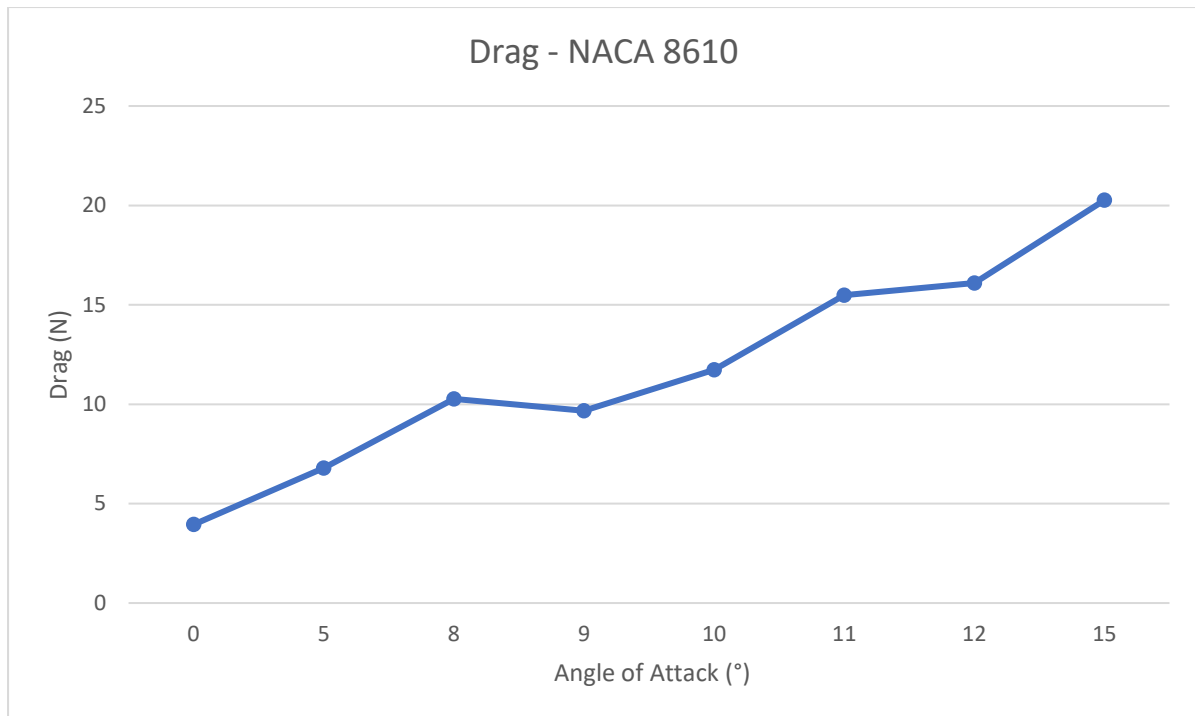


Figure 16 - Graph showing drag against angle of attack for NACA 8610 wing profile.

The drag does not indicate the stall very well but there is a general mostly linear increase in drag.

4.2.3.2 – End Plate Design

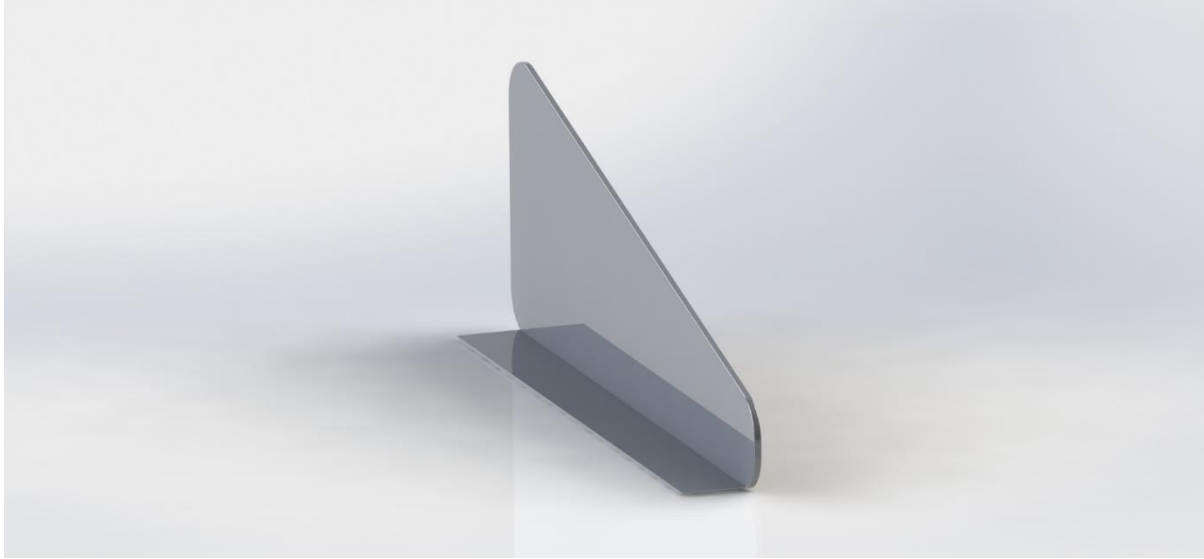


Figure 17 - Picture showing the final end plate design.

The end plates for the third concept were simpler than the previous 2 designs. It was researched that legs on the outer part of the endplate assist to more downforce even though the wingspan was decreased. This increase in downforce is about 10% more (McBeath, 2017). The leg aids in preventing the positive pressure on top of the wing bleeding to the negative pressure underneath. This bleeding can cause large losses in downforce. The legs were also tested with a base test of 10mm and then increased in length to 50mm after looking at the post processing in CFD. The percentage increase in downforce was 2.66%.

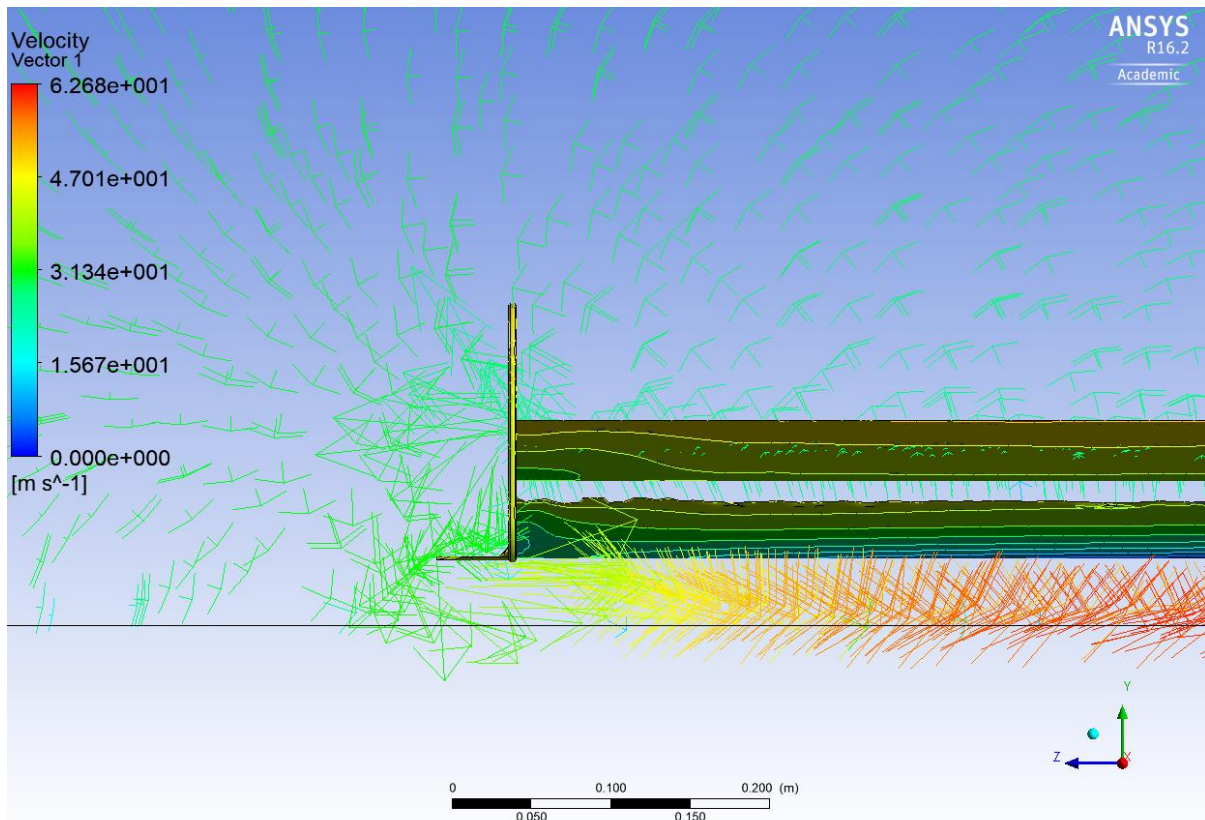


Figure 18 - Picture showing velocity vectors around the end plate of the front wing.

Figure 15 shows that the legs of the end plate stop the pressure bleeding from the top element to underneath the wing.

4.2.3.3 – Front Wing Design

The best profile for the main element was NACA 632615 at an angle of 5° . The second element used was the NACA 7312 at 10° . The angles were kept low to not spoil the airflow too much when entering the diffuser. This low angle of attack allowed to add another element on the front wing. The NACA 7312 profile was used again for the third element but at 15° angle of attack. The second element was moved further back which reduced the turbulence behind the front wing to allow more clean air for the diffuser.

The wing was mounted to the nose cone directly. This allowed for changes to be made more quickly if the front wing were to be damaged. The nose cone was also designed to allow mounting points for the front suspension.

The downforce, drag and efficiency for the third design concept were 789.65N, 72.80N and 0.0922 respectively. This was a huge increase from the previous two designs (67.91% more efficient from the second design) which therefore makes it the best choice.

4.2.3.4 – Engine Cover

The engine cover of the vehicle was designed around the powertrain to accommodate the volume of the batteries, motors and gearbox.

4.2.4 – Assisting the rest of the group

Design process for the rear wing and some ideas given to assist the other group members was also done.

The final rear wing design was not up to standard compared to the rest of the car so a few design changes were made. Second element was angled more aggressively, 20° from 5° , and the end plate was flipped and lengthened to accommodate for a second wing which was designed below the main rear wing. This second wing was to assist the diffuser in making it longer. A longer outlet increases the downforce on the car.

The diffuser was having some problems in the final design concept. There was a lot of pressure bleeding from the rear wheels underneath the car therefore making the diffuser not very efficient. I assisted my teammate in finding a solution to the problem. Both communicated and ran different ideas into CFD to share the workload and not waste time testing the same ideas. The issue was finally resolved therefore the vehicle had a better coefficient of lift which was closer to our initial goal.

5 Dion Billing (1701657)

5.1 Introduction

In my section of the report the main objective was to work with the aerodynamics group in designing an aero package for a 1999 formula 3 tub. Along with making an aero package we will be working closely with the dynamics team as well as the powertrain team. The team would have weekly meetings to update their progress and then set targets for the next week. Over the weeks the car will gradually get the car to a point where we can run a full version on a simulator and test it that way. The team will begin by brainstorming and researching into their specified areas and design concepts. These concepts will then be run through CFD to analyse how effective they are by themselves, and then as a whole car if they are looking promising originally.

5.2 Research

In tandem with going through the process of designing the sidepods for the car, research was conducted to see how to improve the shaping and increase the effect it has on the aerodynamics of the car. Since the vehicle was a former formula 3 car, the main inspiration for the shaping was cars such as formula 3 and formula 1 cars. Investigating how these vehicles had their sidepod shapes can be seen in the concepts below in terms of how they influence those concepts also. Using the images as inspiration it allowed me to then improve upon my own concepts by taking one aspect from one design and adding it onto another. The early concept builds of the sidepod was inspired by the 80s formula one cars. It was very basic and was effective but could still be improved. As you can see the rounded square profile of this car has its similarities with the first sidepod concept.



Figure 19 - Ferrari F1/87 (Classic Driver)

Dion Billing (1701657)

From here the development of the sidepod was evolving and took inspiration from the newer formula 1 cars.



Figure 20 - McLaren F1 2012 (McLaren, 2012)

It is visible in the photo above where the other concepts influence is at. It is visible that the sidepod tapers away at the rear of the vehicle allowing the air to flow to utilise the diffuser. This is what the team wanted as the diffuser was not working as good as it was first thought.

With the possibility of cooling for the motors becoming a factor in the sidepod design some research into opening the sidepods was required. Therefore, the first idea was to open the sidepods and allow air to flow through them rather than over and around them. With the CFD this shows how much air would be travelling through the sidepods. With the meetings progressing the research also needed to continue to ensure everything was on schedule. When researching about cooling and the rate of heat transfer in sidepods it was noted by (C. M. DE SILVA*) that addition of gills and chimneys to the sidepods disperses heat dramatically with minimal drag penalty due to the changes. Testing gills on our concept was not possible due to falling behind schedule and not actually having a working concept due to what has been explained in the next section.

Dion Billing (1701657)

5.3 Design, Testing and Development

To begin the designing process all the research was compiled together to give the best knowledge possible on how a sidepod works best in terms of its shaping. This would then be transferred into designing several sidepod concepts on a CAD software, which will then be tested through CFD to eliminate the weaker ones. The strongest one would then be developed further to maximise its potential. The CAD software used was 'Solidworks 2019'. The first few weeks of the designing phase it was a matter of designing concept ready for development. Usually the concepts aren't very strong at the beginning but with more meetings research and development the design becomes clearer over time and eventually a final design will be chosen to go onto the vehicle.

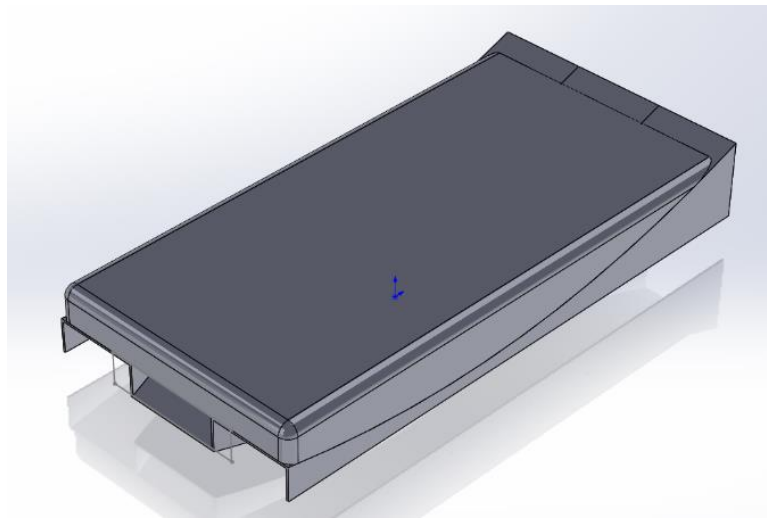


Figure 21 - Concept

The first sidepod concept (as seen above) was designed was a simple square sidepod with rounded edges. The sidepod matched the width of the diffuser but was slightly shorter to allow the diffuser to deflect the air towards the rear wing. There was no opening for cooling purposes as the team had not given any confirmation on if cooling was required. This concept was run with the full car in preparation for the first viva. The second concept was also ready before the first viva as the diffuser changed slightly some changes needed to be made to the sidepod.

Dion Billing (1701657)

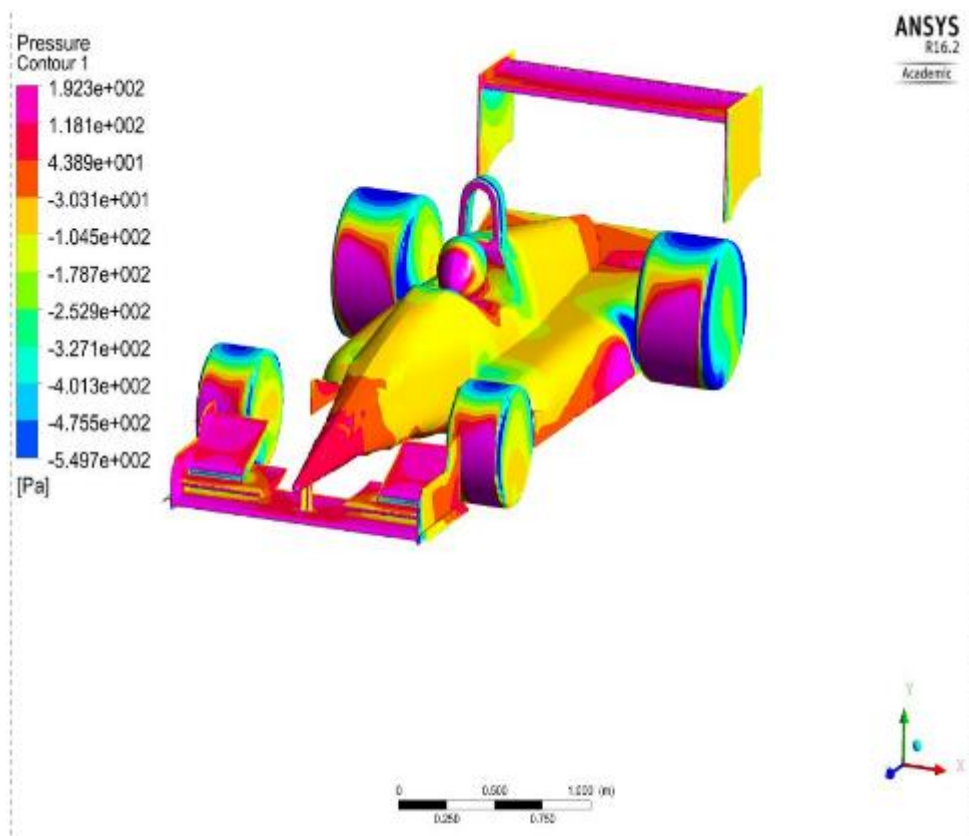


Figure 22 - CFD of Concept 1

With the first complete concept we ran it through CFD so we could see on which areas we could improve. The general consensus was that every part of the vehicle could be improved further which allowed us all to go back to the drawing board and bring up more concepts.

Dion Billing (1701657)

The second concept was narrower than the first in an attempt to get the diffuser to work better, as well as it has a full rounded edge at the front and trailing right to the end of the diffuser.

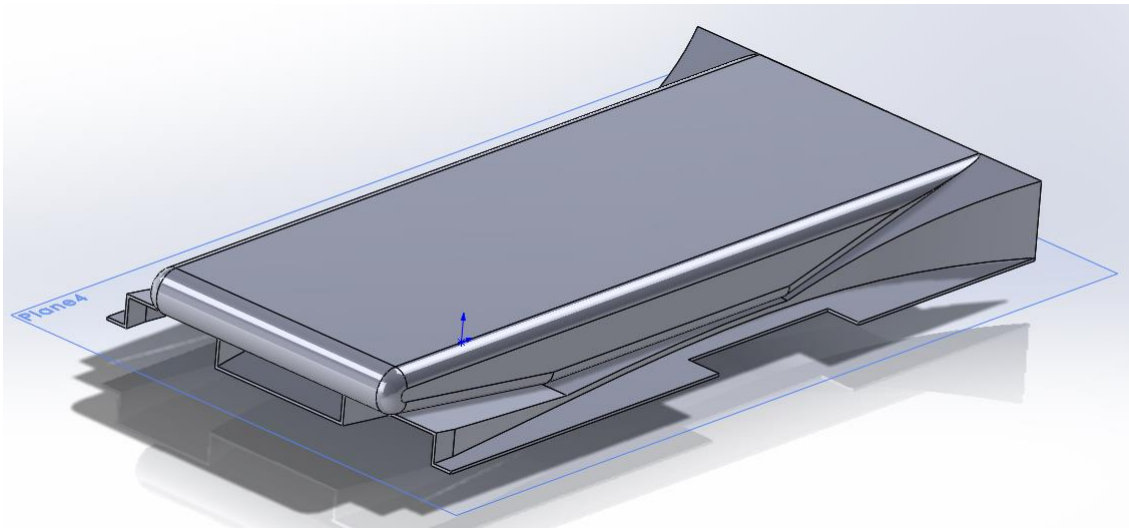


Figure 23 - Concept 2

This once again was an improvement on the last concept but, it was still too flat and not really doing much on the top surface. From here further development of the sidepod continued as it was clear that there were some areas that needed to be improved. As the meetings continued the progress of the aerodynamic package was closely monitored by all sections of the build to ensure that we were on track with our progress however, there was not a clear answer about the cooling requirements from the powertrain department for some time. With this development of the sidepods particularly was very minor and was decided that it was best to run CFD with potential cooling factors implemented into the sidepods also just in case the cooling was required to come through the sidepods. After running another concept through CFD which can be seen in *Figure 4*. This concept seemed to work very well in tandem with the diffuser therefore the team decided it would be best to optimise this concept further to see if changing factors such as the length, height of the curve and the amount it tapers in improves the values seen in CFD. It is noted that using just the diffuser and sidepod for CFD will not give the best results however the full package was not completed at this point and a rough estimate was needed to allow to progress further.

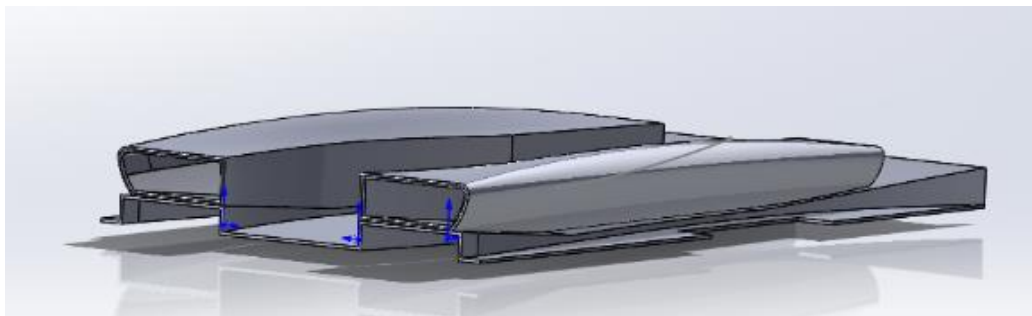


Figure 24 - Concept 4

When running the CFD the final lift and drag values were noted down and compared to each other to see which parameters act the best.

Sidepod Length (mm)	Cl	CdA
2000	-4.57370	0.69986
2110	-4.62990	0.70042
2220	-4.62280	0.70147
2330	-4.48360	0.71011
2440	-4.18680	0.72760
2550	-3.88200	0.74050

Table 1 - Sidepod Length Values

The table above shows all of the sidepods' coefficient of lift and drag values and how they change when the length changes. As a team it was decided that the 2110mm length was the best to continue to optimise although the 2000mm did actually produce less drag. The height of the curve on the sidepod was then investigated. The original height was at 60mm, 70mm was tested however, it was significantly worse off than the 60mm. therefore, it was decided to discard these results and go down in 10mm increments rather than up.

Height (mm)	Cl	CdA
30	-5.70460	0.78464
40	-4.89410	0.72526
50	-4.72670	0.71223
60	-4.62990	0.70042

Table 2 - Height Values

Investigating the height values, it was clear to see that the lower the height comes down the better the lift and drag values are for the vehicle. We then moved onto the taper of the sidepod. The values on the left side of *Table 3* are the values of the scale that the rear end of the sidepod differs from the front and then the 1.8 is the scale increased from the 0.7. As you can see the less taper is applied the more negative lift and less drag it produces.

Taper	Cl	CdA
0.7	-2.77690	0.84843
1.8	-4.40470	0.74016

Table 3 - Taper Values

However, progress on this development of the sidepod had to be stopped as the diffuser had completely changed and the sidepod had to be re-shaped to fit the diffuser and all the different iterations had to be run again with very little time to do so.

With the change of the diffuser and fitting the new sidepod concept onto it, the full car was assembled and was put through the CFD process by the team and saw some improvements on previous concepts. However, when investigating the airflow particularly at the start point of the sidepod and diffuser it was seen that the majority of the airflow was entering the sidepod rather than the diffuser making the diffuser almost ineffective. The team had a discussion and decided to try and move the sidepods back slightly to see if this would improve the situation, which it did.

From here some research into the materials that were going to be used was taken. There were a few clear options which was a type of carbon fibre, a light metal such as aluminium or a type of fibre glass. It was decided that the carbon fibre was too expensive, the aluminium would be a little on the heavy side and the process of manufacturing would be too expensive which left the fibre glass. The type of fibre glass is called S-glass fibre. According to (AZO materials, 2001) this particular type of fibre glass is; high strength, high stiffness, resistant to heat and relatively low density. However, it is relatively insensitive to moisture but this could be helped by adding some paint or lacquer.

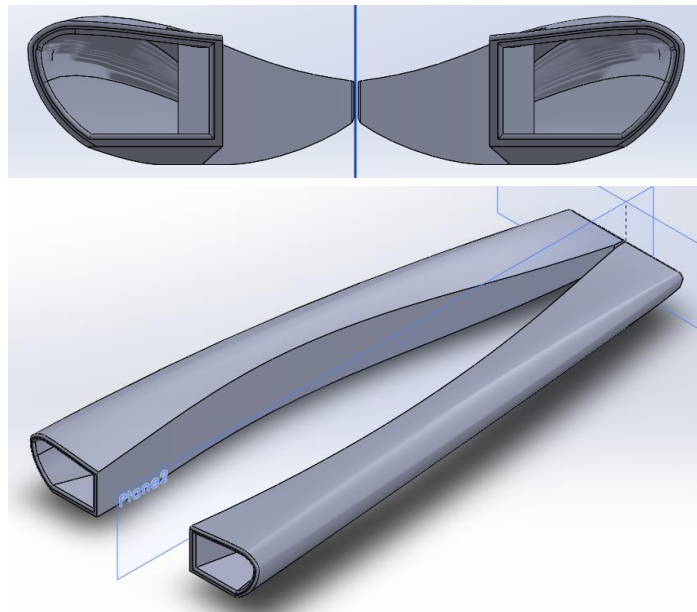


Figure 25 - Final Sidepod Design

Above is the final sidepod design by itself, it is visible that they taper round towards the rear, this is to guide the air over the diffuser and maximise the effectiveness of the diffuser as it wasn't working very well when the sidepods were running straight.

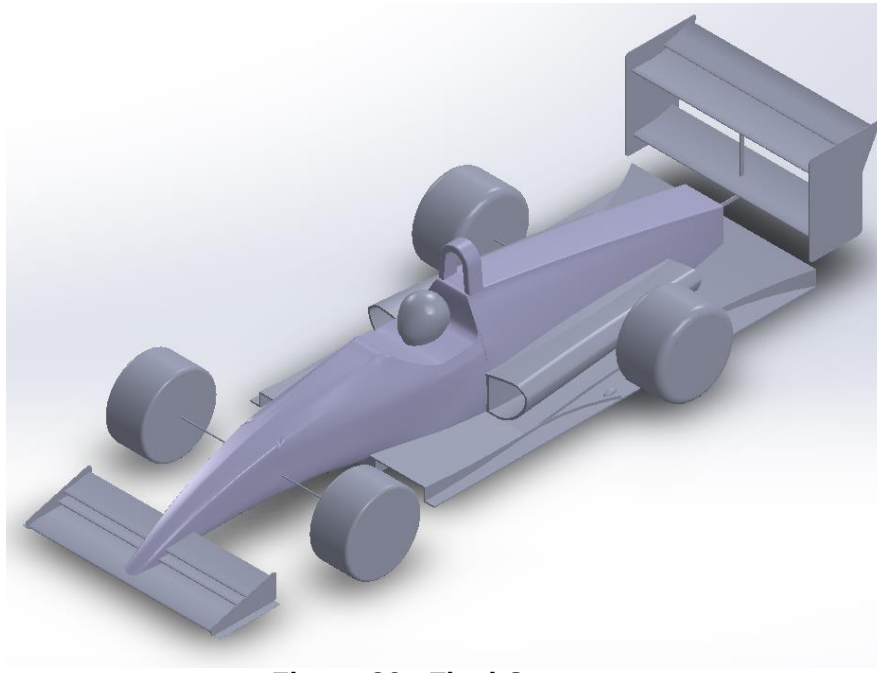


Figure 26 - Final Concept

5.4 Analysis

Analysing the team performance, I believe the team could have done better in all areas of the project. Although the entire team were learning the skills necessary to do the project while going along some were still lacking, this includes myself as my cad skills are still not as good as I believe they should be. One of the main negatives about the group was communication. There have been several occasions where I have messaged the group and not had an answer back off them regarding progress or what they needed me to do for a particular section of work. It is very hard to work within a group when the group do not let everyone know that they are having a meeting and then progressing without letting an individual know of the change in plans. An example of this was when Fang changed his diffuser two weeks before hand in while I was working on running different variations of my sidepod and failed to let me know even though he knew I was doing the changes to the sidepod and spending hours on end running CFD on what was an obsolete design. Another incident was when the final design was put together the team did not let me know there was an issue with my sidepods matching the engine cover and altered my design without consulting me. There have been times where we have been behind schedule while working on the project however, not all of the issues were coming from our end as the powertrain group never let us know how much cooling they wanted or if they needed cooling at all.

If given more time and better teamwork I would've done a lot more testing in terms of adding gills and chimneys to the sidepods and ran those through CFD to see if this would improve the vehicle. I would also do some more research into how the sidepods could be improved and perhaps come up with another completely new concept to test.

Dion Billing (1701657)

6 Zhendu Fang (1904716)

6.1 Work content

A well-designed underbody can produce significant levels of downforce with a small penalty of drag. Generally, the underbody works as a result of ground effect and the expansion of diffuser.

Ground effect means that the proximity of the car and the ground has a considerable influence on the airflow underneath the car, which can be positive or negative. It can be demonstrated by the figure(Zerihan and Zhang, 2000), an inverted airfoil in ground effect.

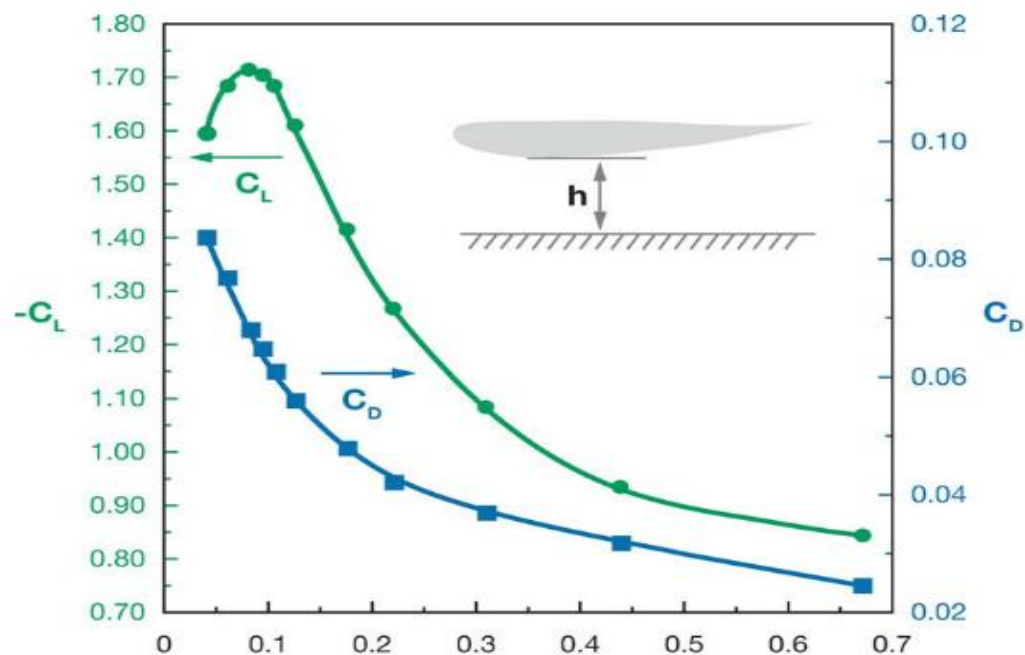


Figure 27 Downforce and drag coefficient versus ground clearance for an inverted LS(1)-0413 airfoil

It shows that the coefficient of lift increases as the ground clearance drops until it reaches a specific value. The result is similar when it comes to the undertray of the car. It can be explained to consider the undertray-ground system as an analogous venturi system. The airflow accelerates when it enters the space between the undertray and ground, resulting in a lower pressure compared to the static pressure according to the Bernoulli's equation. However, when the ground clearance is small enough that it is less than the sum of the boundary layers thickness under the body and over the ground, the flow experienced considerable friction so that the downforce decreases sharply(Cooper et al., 1998).

The diffuser at the rear car plays a paramount role as well. On the one hand, it helps the air flows through the underbody as the air tends to fill the expansion area of the diffuser. On the other hand, the velocity of the flow decreases in the diffuser for a broader cross-section area leading to a pressure recovery compared to the low pressure before. Therefore, the flow can reach the wake behind the car as smoothly as possible(Tudor, 2020).

6.2 Design process

Ideally, the process of undertray design can be simply divided into three parts:

- Think about several general concepts of the undertray after some research on the about aerodynamics. Then build the initial CAD files of these concepts. The dimensions of the CAD files can be set by a general impression.
- Test the parameters of each concept with all other aerodynamic devices in CFD software ignoring the other parts of the car and compare the results.
- Find the best concept and do some subtle modification of the dimensions for the necessary compensation with other parts of the car, such as driveshaft and wishbones.

However, the project is far away from the ideal case because of various reasons.

For the limited access to CFD software, the time-consuming computational process and unfamiliarity with CFD at the beginning, only one concept is thoroughly tested during the whole project. Besides, the performance of the undertray is profoundly affected by all other aero devices, including the front wing, rear wing, sidepod and even the wheels. It is reasonable to test the undertray with these parts. Nevertheless, the other devices are also in development and changing all the time. As a result, the undertray is tested individually during the first half project and gradually interacting with others. Finally, because of the deficient cooperation with other groups and unexpected close of school, the final result is generated without the chassis component.

6.3 CAD design

Three-dimensional design

The initial undertray design is shown as figure 2 below

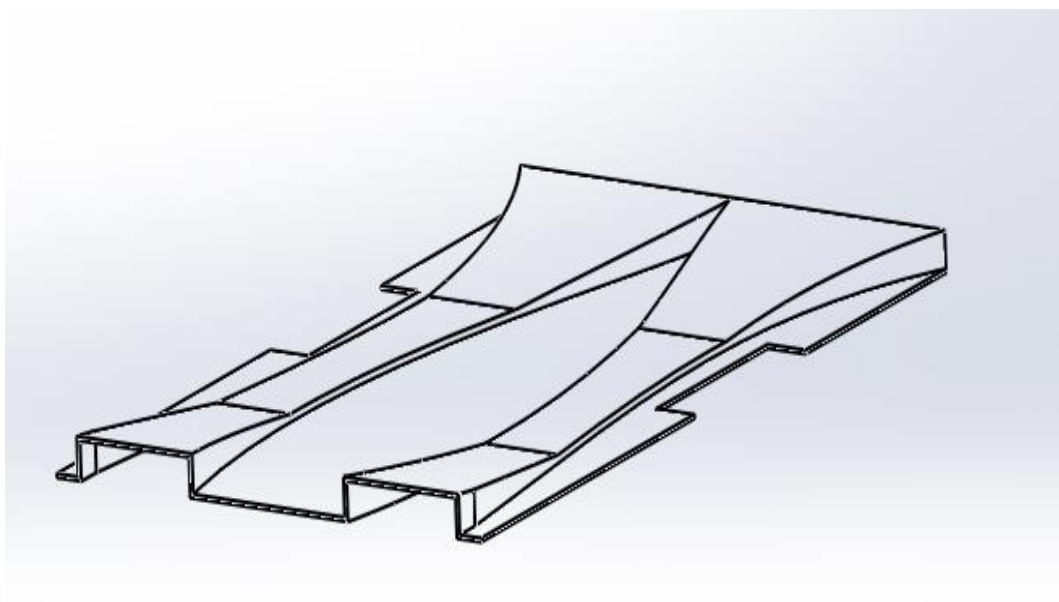
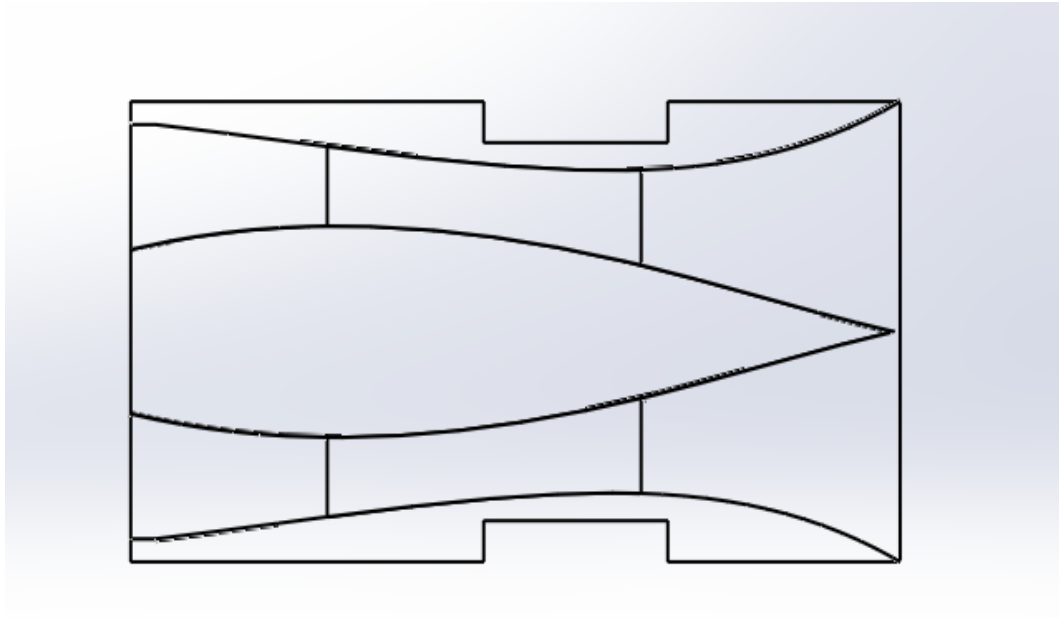


Figure 28 3D view of the undertray

As it shows, the undertray has a central flat area and two side tunnels.

The central area is under many restrictions because there must be enough space to place the battery, gearbox, etc. the shape of this area is designed as an incomplete ellipse, which can be demonstrated by the following figure 3.

*Figure 29 Top view of the undertray*

Firstly, it is compensation for the shape of the provided tub. More importantly, this shape produces a smaller cross-section area in the middle of the side tunnel and a more significant expansion area in the diffuser. As mentioned above, the side tunnels work as a venturi system. Therefore, this shape provides a larger velocity gradient of air along the tunnels resulting in more downforce.

For the same reason, the outer profile is designed as curvature as well. Another function of the inward angle of the outer profile is to direct the airflow inboard of the rear wheels. Allowing the airflow to impinge on the rear wheels caused major turbulence in the diffuser, caused major turbulence in the diffuser, seriously affecting the efficiency of the tunnels (McBeath, 2015, p.158). This phenomenon will be discussed detailedly in the next section.

Strictly speaking, the undertray consists of all investigation of three-dimensional parameters. In other words, both of the shapes of 'walls' as mentioned above and 'roofs' which is essentially at a right angle to maximize the performance of the tunnels need to be considered seriously, as well as their joint. However, the three-dimensional design is much more complicated than two-dimensional, and few researches can be found about the 'wall' design. Therefore, this project only conducts two-dimensional research of venturi shape in side elevation. As a result, there is no test investigating the shape of the 'walls' and just use the initial idea in the final result.

Two-dimensional design

The essential geometric parameters governing the performance of the tunnels can be divided into three parts, as shown in the following figure: inlet area 1, throat 2, diffuser 3.

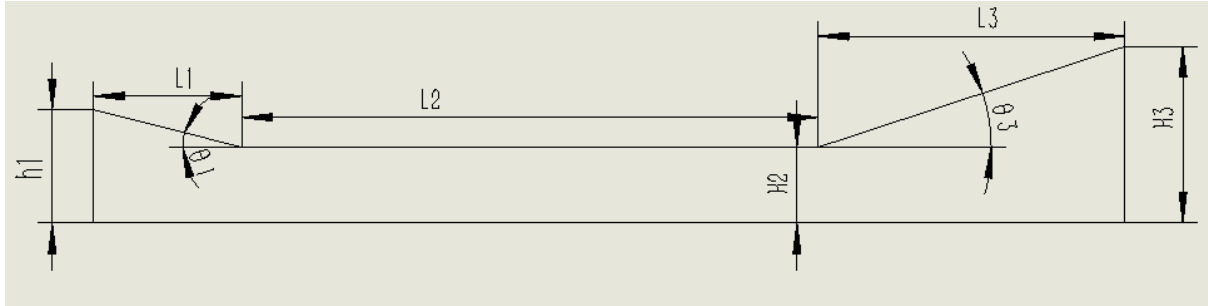


Figure 30 tunnel geometry parameters

All the parameters above will be tested in this project. Among them, the most paramount parameters are the inlet angle θ_1 , the ground clearance H_2 and outlet angle θ_3 .

Ground clearance

As mentioned [above](#), more downforce will be generated as the ground clearance gets smaller and smaller until it reaches the boundary layer thickness. The turbulent boundary layer over a flat plate is given by (Weyburne and science, 2014):

$$\delta \approx 0.37x / \text{Re}^{\frac{1}{5}} \quad (1)$$

$$\text{Re} = \frac{\rho vx}{\mu}$$

Where x is the distance downstream from the start of the boundary layer, equivalent to the length of the tunnel, ρ is the density of air, v is the velocity of air, μ is the viscosity of air. To estimate the maximum boundary layer thickness, the x is assumed to 3m, which is longer than the actual tunnel length. Besides, all the test is running at the velocity of 30m/s, and the density and viscosity at 15°C is 1.225kg/m³ and 1.802e-5kg/m·s. As a result, the estimated maximum δ is 0.05m. However, equation 1 is applicable for freestream passing a flat plate. When it comes to the tunnel, it is rougher and the flow through the tunnel is affected by the front parts of the car. Therefore, the actual boundary layer is much less than 0.05m. And the minimum allowable ground clearance is 0.04m which is the distance between the edge of the tunnel and ground, the actual displacement between the tunnel roof H_2 is 0.05m. As a consequence, this height is considered as the best value.

Diffuser and inlet area

On the one hand, you. The theory of the diffuser has been discussed in the first section. Then the conclusion can be drawn that a larger diffuser angle means more downforce because there will be more vacuum area near the slope needed to be filled by the air resulting driving more air to flow through the

tunnel. The aero ratio AR, which is defined by Cooper(Cooper et al., 1998), can illustrate this mathematically.

$$AR = \frac{H_3}{H_2} = 1 + \left(\frac{L_3}{H_2} \right) \tan \theta_3 \quad (2)$$

The aero ration presents the expansion degree of the diffuser and combined all the parameters to one non-dimensional quantity. The height of the diffuser can be generated by the length and angle. In our study, the H_2 is already confirmed. As a result, a more substantial length and angle create more downforce.

However, an excessive diffuser angle can produce a negative result because of flow separation. The airflow can not attach to the roof resulting in a low-pressure area near the roof. Then vortexes come to being which in turn decrease the flow velocity in the tunnel.

The conclusion of the diffuser is also applicable to the inlet area. But the reasons are slightly different. A large inlet angle means more mass flow getting through the tunnel and higher acceleration. When the angel is too steep, the viscous force between air is not large enough to ‘drag’ the flow adjacent to the roof and ground to accelerate. It can be clearly shown by the following figure(McBeath, 2015,p.150).

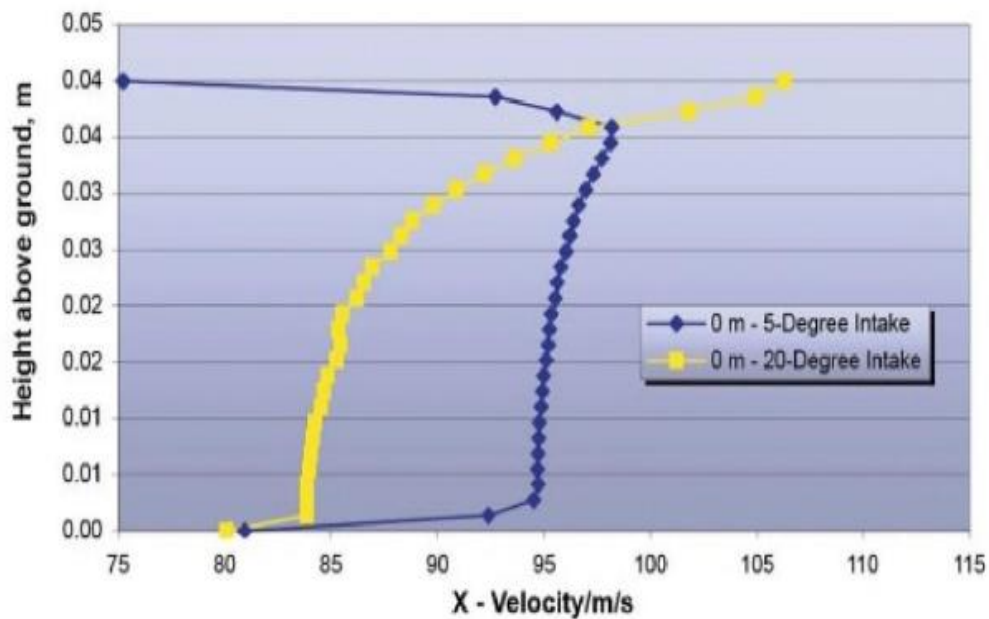


Figure 31 The vertical velocity profile at the start of the undertray

In other words, overall acceleration decreases instead as the angle increases to some degree.

6.4 CFD test

CFD demonstration

More and more engineers choose to use computational fluid mechanics to solve aerodynamic problems for its convenience and low cost. This project is doing all the test by CFD software Ansys Fluent as well. The process can be divided into four parts: CAD file build, mesh, solve and post result. All the settings of the CFD are basically generated from CFD tutorial video(Tudor, 2018) except the domain size and mesh size. The domain size is four times the length of the diffuser at the front of the diffuser, six times downstream, three times width and three times width. The mesh size is 0.01. All the setting is validated by running the Mira car. The result is shown below:

Table 4 Comparison of CFD result and wind tunnel result

	Cl	Cd
Mira wind tunnel	-0.08	0.2963
CFD software	-0.14	0.30

Though there is much difference in the values of Cl, the setting is applicable for the undertray because the diffuser is much smaller and run at a higher velocity of the Mira car.

Diffuser test

The basic methodology is ‘variable control’. The first test parameter is the diffuser angle. The test is running without any other devices. The initial dimensions of other parameters are shown as the table below

Table 5 Dimensions of other parameters while testing on θ_3

L_1 /mm	L_2 /mm	L_3 /mm	θ_1 /degree
651.54	798.45	858.37	7

And the result is shown below.

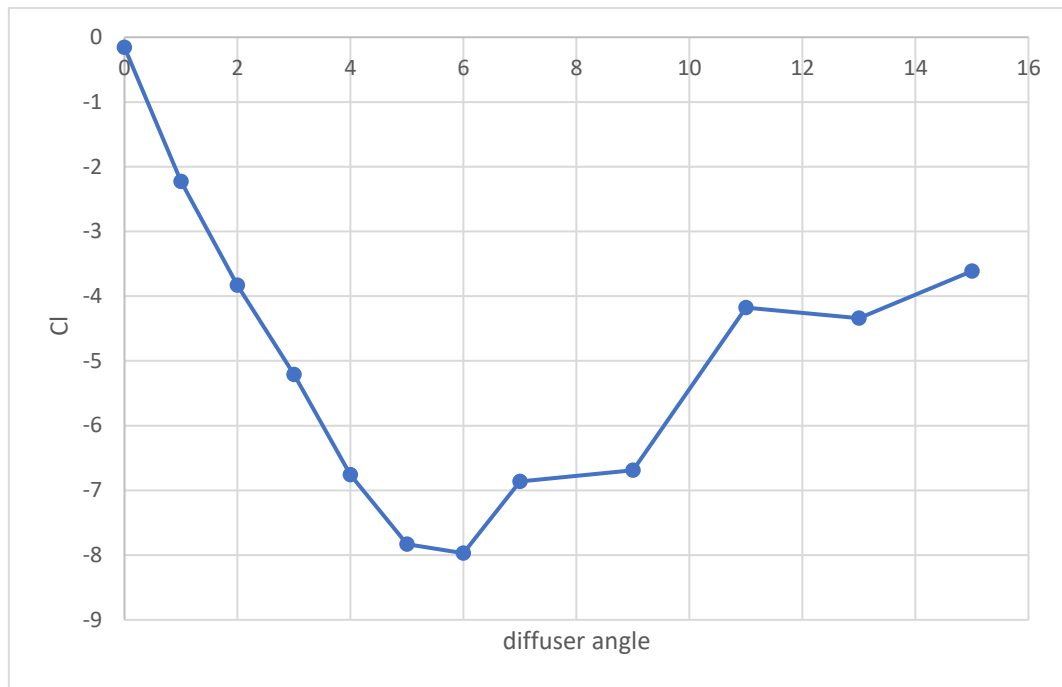


Figure 32 The Cl versus diffuser angel while running in CFD itself

As mentioned above, the coefficient of lift rises sharply as the diffuser angle increases until it reaches 6° , where the flow separation occurs. As the Cd is meaningless when there is only the undertray and the drag of undertray has little influence on the overall drag of the car. It is not discussed here.

Then as the sidepod have developed to some degree. The test is running again with sidepod assembled. The CAD model and result are shown below:

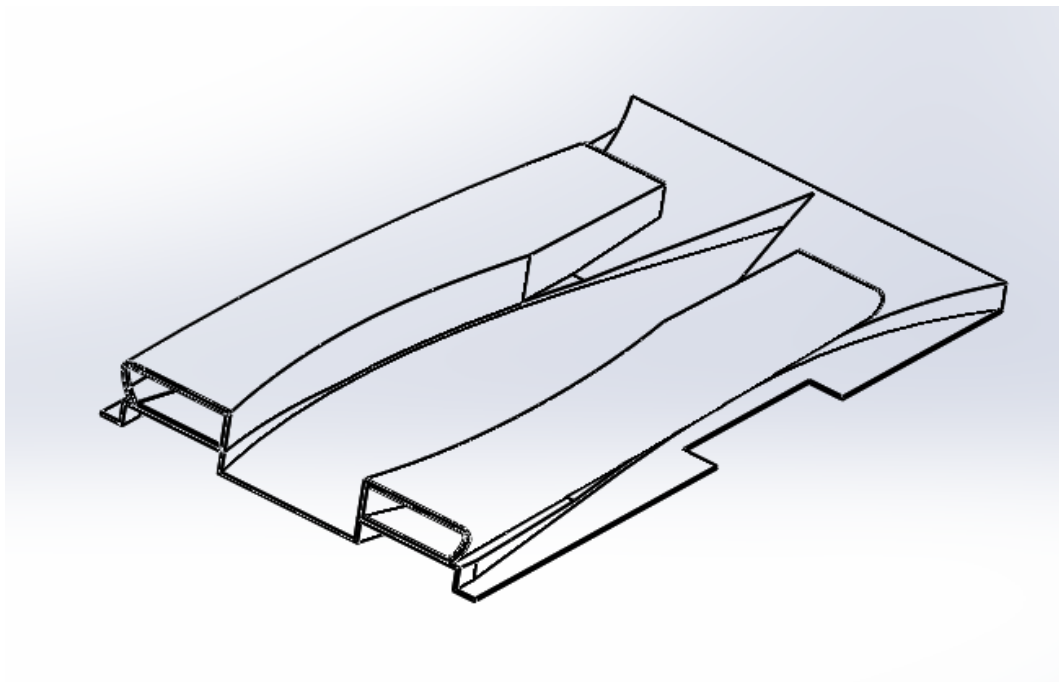


Figure 33 undertray with sidepod

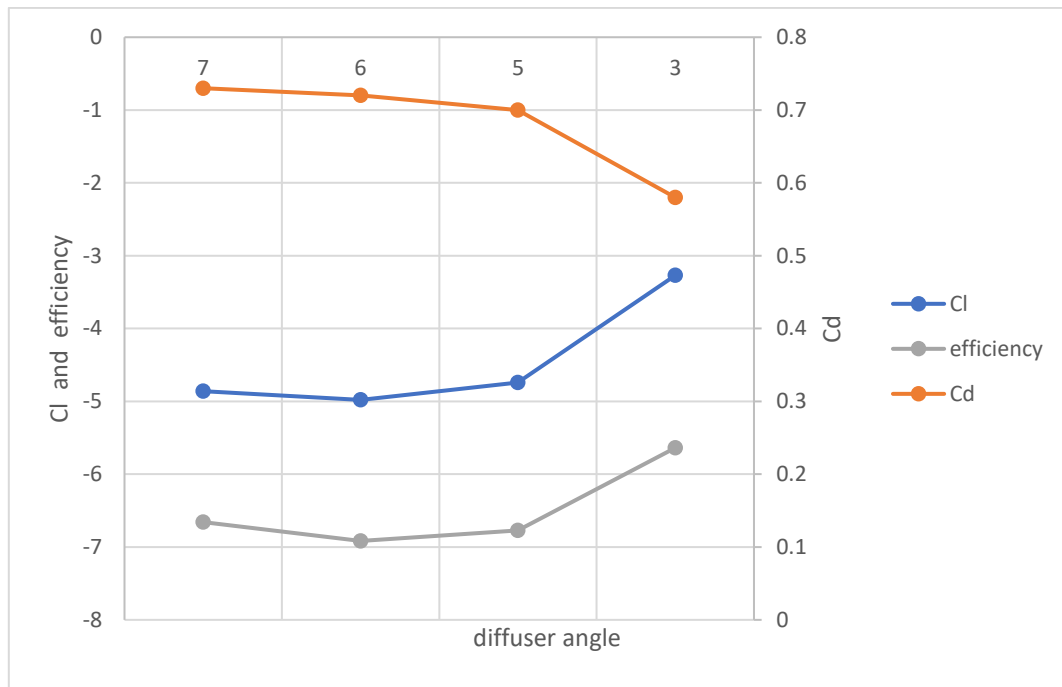


Figure 34 aero result of diffuser angle assemblies with sidepod

Figure 8 indicates, the Cl decreases overall compared to the separate undertray because the assembled shape is more complicated, which affect the airflow. But the trend and conclusion are identical. The maximum downforce is generated when the angle is 6° . Also, the drag increases slightly, but the efficiency is highest at 6° as well. Therefore, the sidepod does not influence the performance of the undertray.

We find the steepest diffuser angle is 6° . But can we get steeper angle without separation flow? There are two ways: the first one is to interaction with rear wings. If the low-pressure space below rear wing just locates at the position where the airflow exited from the diffuser passes by, it will help drive more air through the tunnel and allow a more aggressive angle. The figure below (McBeath, 2015, p.155) shows how the rear wing drives the flow in reality.

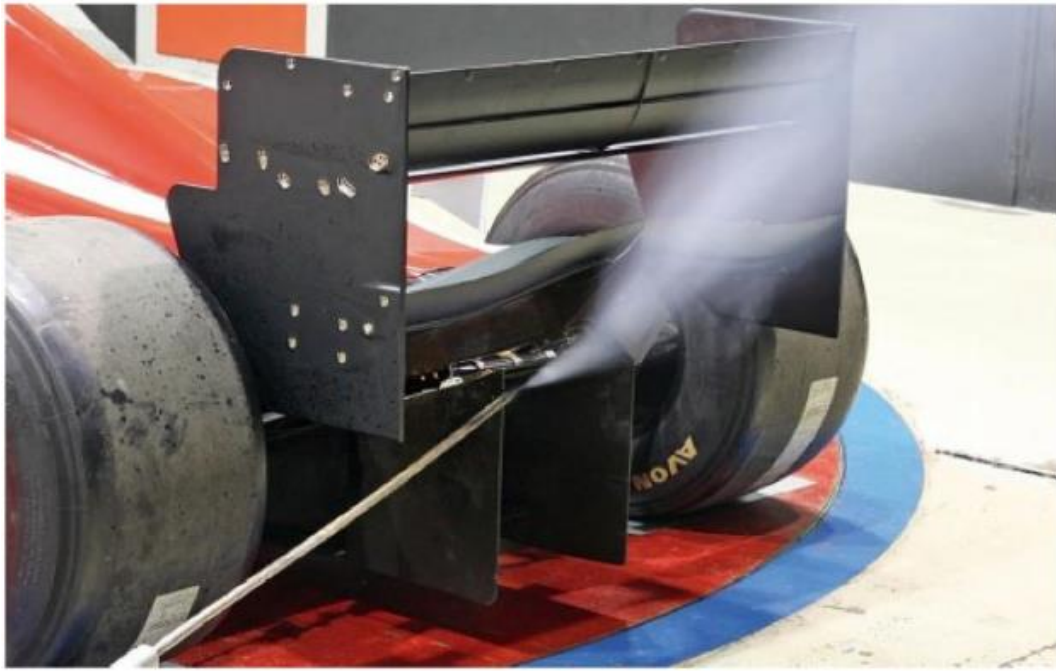


Figure 35 airflow with the help of rear wing

Another way is to curve the diffuser roof instead of a straight line with a specific angle as shown in figure 10. The geometry angle θ_4 (the angle between the tangent line at every point of the curve and ground) of a smooth curve increases gradually but keep the flow attached to the roof. The result is more downforce is generated and a steeper equivalent angle θ_5 (the angle between the ground and the line connected by the start and endpoint).

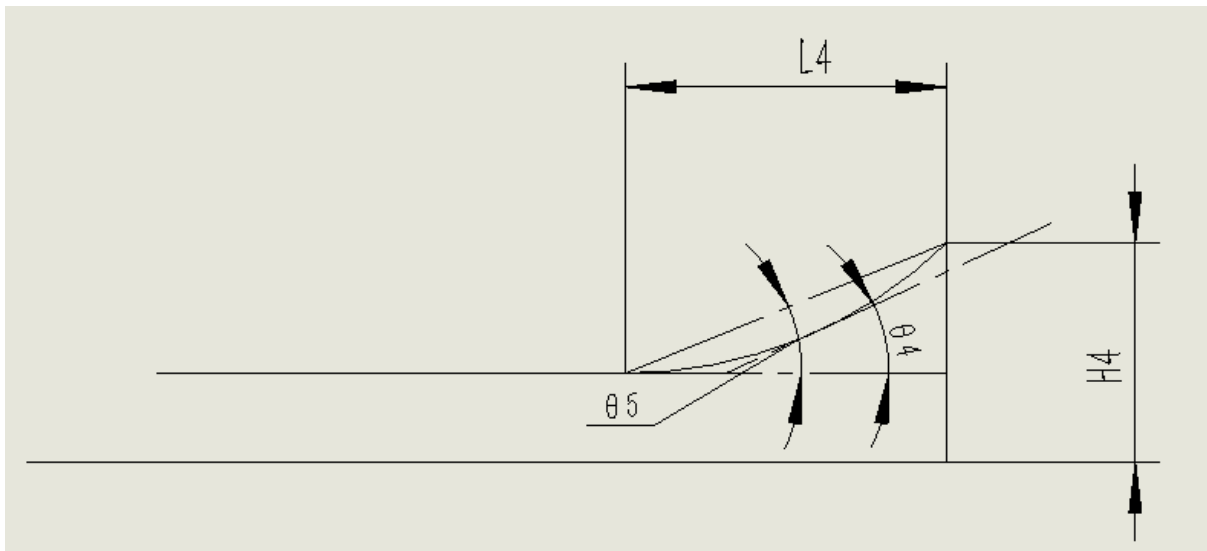


Figure 36 geometry of curvilinear diffuser

The figure below shows the result of the curvature diffuser height with other parameters keeps initial dimensions.

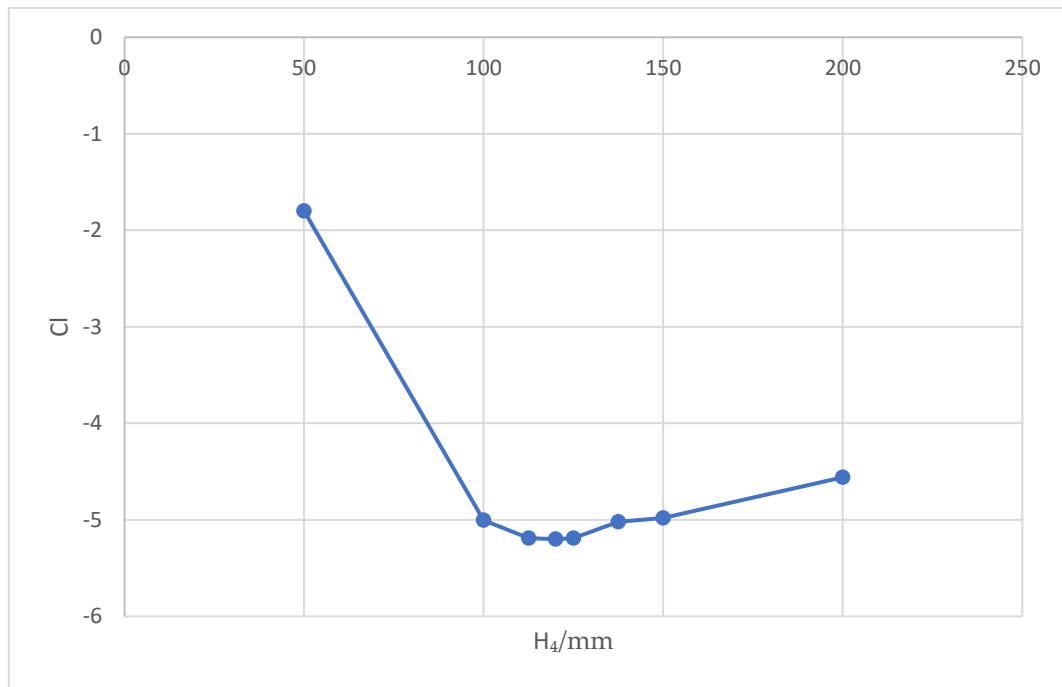


Figure 37 Cl versus curvilinear diffuser height

The result shows that maximum downforce is generated when the height is 125mm. Then keep the height as 125mm and do the same test with various diffuser length. The result is shown as below:

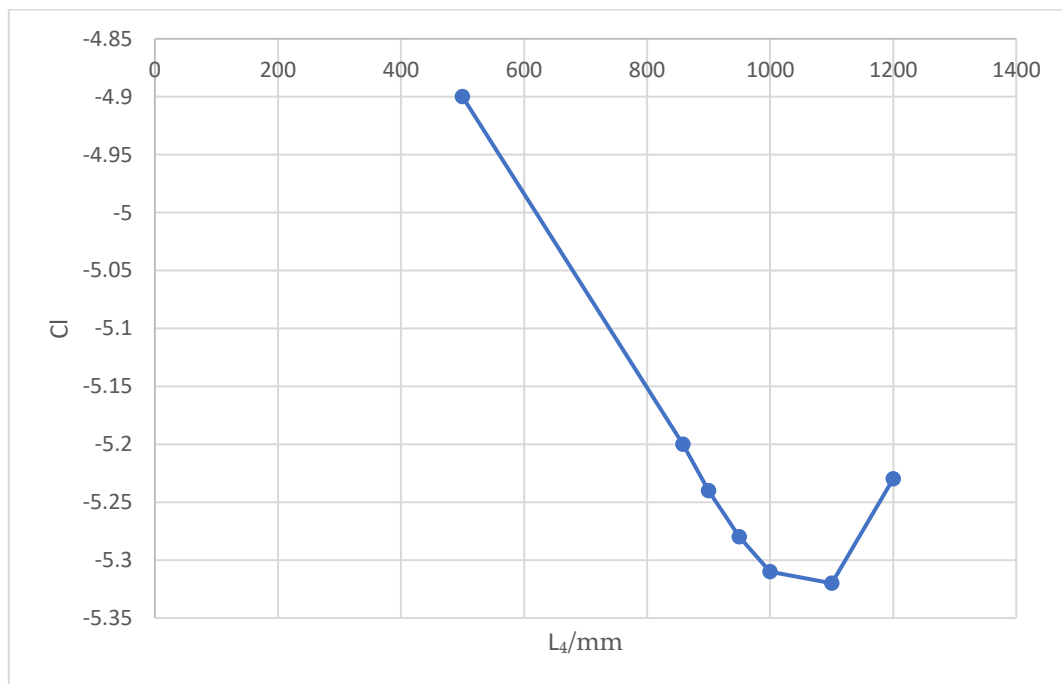


Figure 38 Cl versus curvilinear diffuser length

The best Cl -5.32, which is better than the -4.98 of a straight diffuser, occurs when the length is 1100mm. And the equivalent angle is 6.5° , slightly steeper than the straight. The result is completely following the theory.

Inlet and throat test

The test procedure is almost the same as the diffuser parameters. As the diffuser parameters are already generated. The process of the test is: firstly, keep the diffuser parameters best value and other parameters the initial dimensions, get the CI result versus various inlet angle. Then renew the inlet angle with the best one, test inlet length. Finally, repeat the above method, test the throat height. The results are shown below:

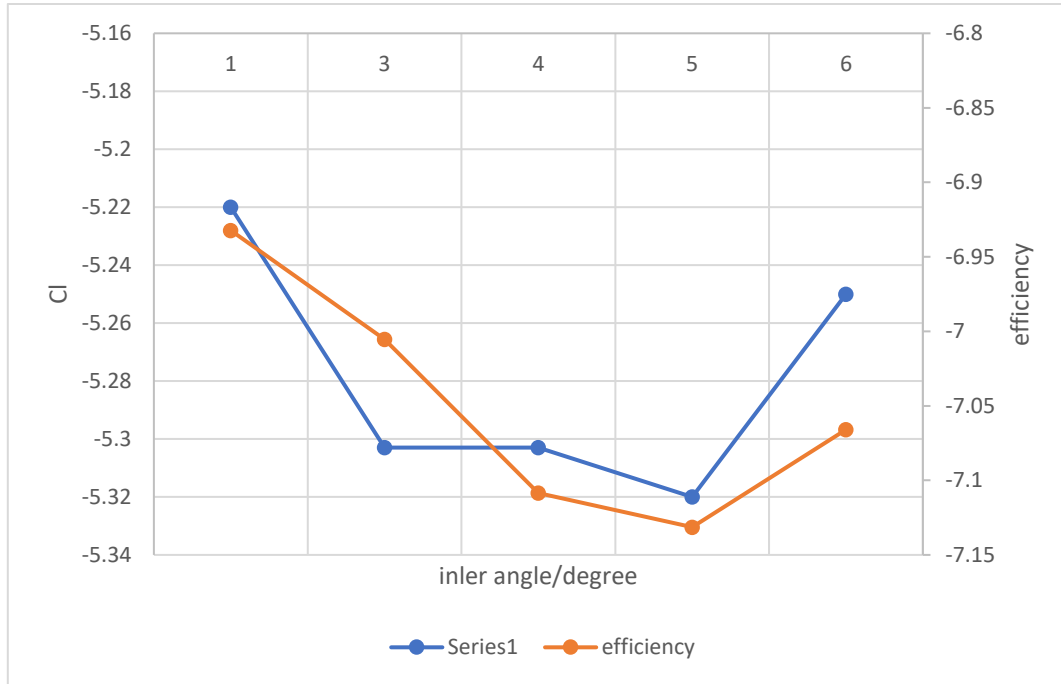


Figure 39 CI versus inlet angle

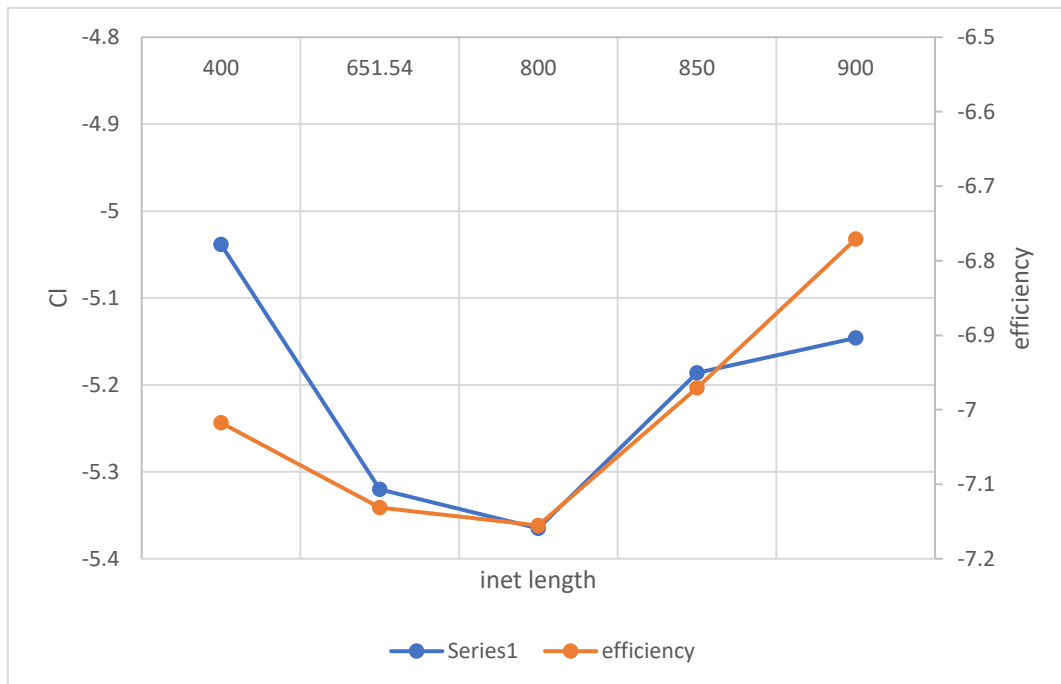


Figure 40 CI versus inlet length



Figure 41 Cl versus throat length

Now all the parameters of this design have been tested. The figures above indicate that the Cl is generally increasing and the efficiency almost has the same trend with the Cl, which shows again that the undertray can generate enormous downforce with a small drag

The final result is shown below:

Table 6 Final dimensions(the unit is millimetre)

Inlet angle	Inlet length	Throat length	Diffuser length	Diffuser height	Equivalent diffuser angle	Cl	efficiency
5	800	1200	1100	125	6.5	-5.56	-7.1

Test with wheels

Though the best-performed undertray is found, it is tested only assembled with sidepod. The rear wheels have a huge influence on the performance of the undertray. Firstly, as the air flows over wheels, there will be high pressure at the front and bottom of the wheel and low pressure at the rear and top of the wheel, resulting in significant lift and drag. A rotating wheel can slightly minimize this phenomenon. Secondly, the flow around the wheel is most turbulence. And the air will get into the undertray from the high-pressure area at the front of rear wheel laterally, which blocks the air through the tunnel longitudinally and create high pressure. Therefore, it is necessary to investigate how much the influence is. The table below shows the result:

	Undertray + sidepod	Undertray + sidepod +rotating rear wheels
Cl	-5.56	0.9

As we can see, the coefficient of lift rises from negative to positive. it is partly because the wheels create lift itself. The figure below demonstrates the effect of wheels on the undertray clearly:



Figure 42 pressure distribution along the tunnel centreline

As it indicates, two conclusions can be drawn. Firstly, the pressure at the two connections between the throat and inlet and diffuser are lower than adjacent areas, and the latter one is the lowest pressure of the tunnel. Secondly, the wheels increase the pressure of the whole tunnel. The pressure of the first half tunnel is even positive.

Adding strakes and minimizing the gap between the wheel and undertray as much as possible are tried to reduce the effect, but none of them works. Theoretically, the narrow gap can block some air getting into the diffuser and the strakes can restrict the effect of the wheel in parts of the tunnel—the reason why they defunct needs further study.

6.5 Final development

As all other aero devices are developed well, it is applicable to test the performance of the undertray in the whole car. After the assemble, I found the diffuser overhang is so long that it is highly possible to hit the ground when our car climbs some cliffy slope though the overhang meets the regulation. As a result, the diffuser length is modified to 900mm from 1100mm with little loss of downforce, as shown in the figure. The assembled test is running by my partner Alex, but for the unexpected close of school, we have no access to the data. What we know is that C_l and C_d are -1.45 and 0.77. We have already known that the wheels harm the undertray and make some attempts. Now, these attempts will be tested again in the full car with a moving floor and rotating wheels. The result is shown as the following table

Table 7 various attempts and the results

ATTEMPT	Cl	Cd
Vortex generator in the inlet	-1.47	No significant difference, all of them is around 0.77
Strake in diffuser	-1.38	
Upward skirt edge	-1.29	
Flow diverter small bubble at the front of the wheels	-1.67	

Only the last attempt works. And it is the final design of the whole aero group as well. The CAD model and CFD result is shown below

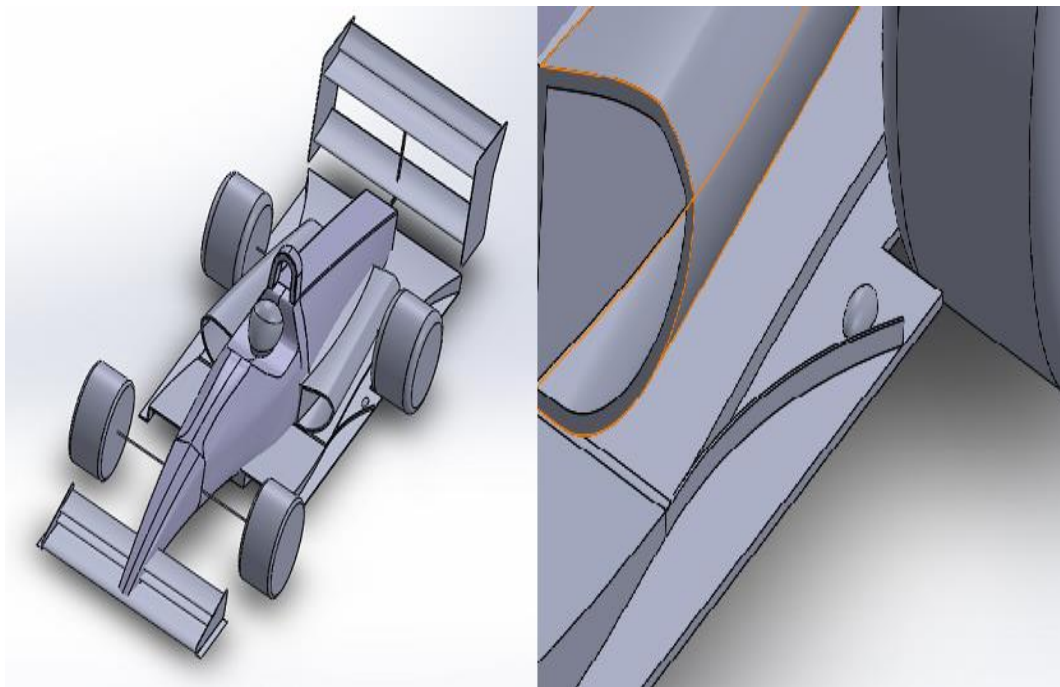


Figure 43 CAD model of the final design

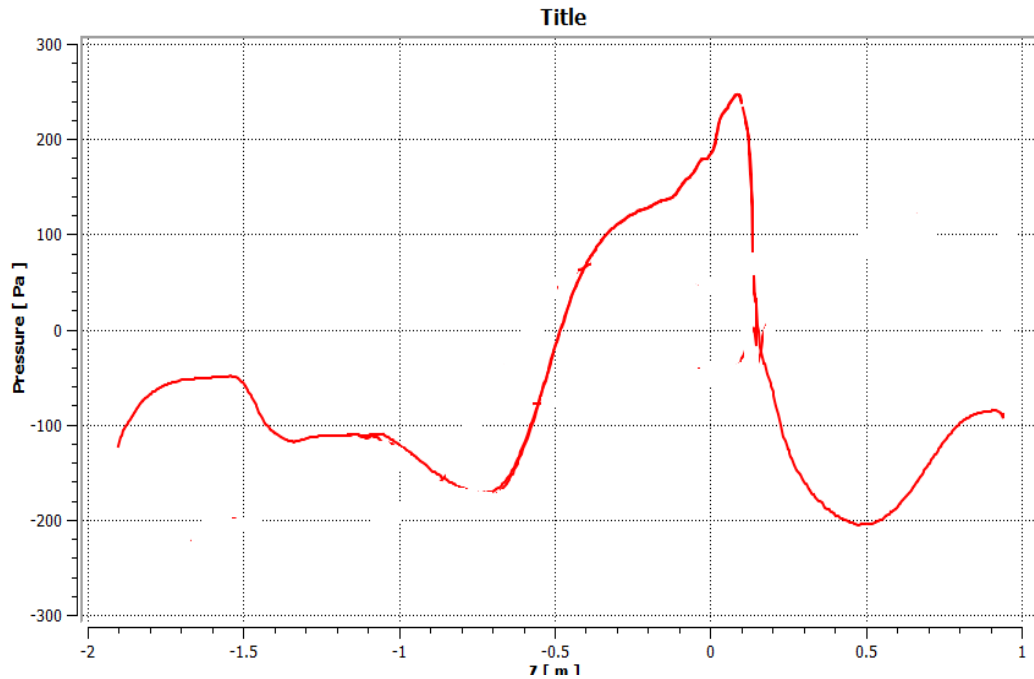


Figure 44 pressure distribution along tunnel centreline

As this figure indicates, there is noticeable improvement compare to figure 16 though there is still a high presser area near the rear wheels. The flow diverter can reduce the mass of the airflow hitting the rear wheel. As for the bubble, it can create a local flow separation which helps reduce the pressure in front of the wheel.

6.6 Analysis

Figure 19 below shows the vortex generated by the car. It is distinct that there are vortices produced by the front wing getting through the tunnel directly. This turbulent flow may reduce the efficiency of the undertray.

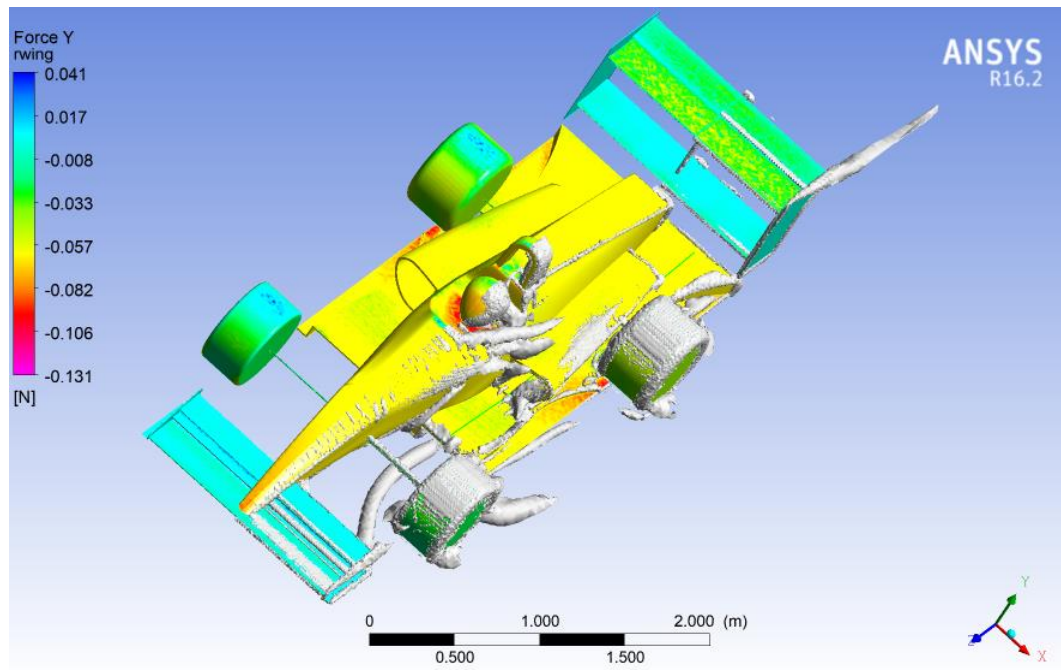


Figure 45 vortex

Figure 20 below shows the downforce distribution of the bottom of the car. The diffuser area is producing high downforce, which is more significant than the front and rear wings. However, the front half of the undertray is creating lift which cancels out a lot of downforces.

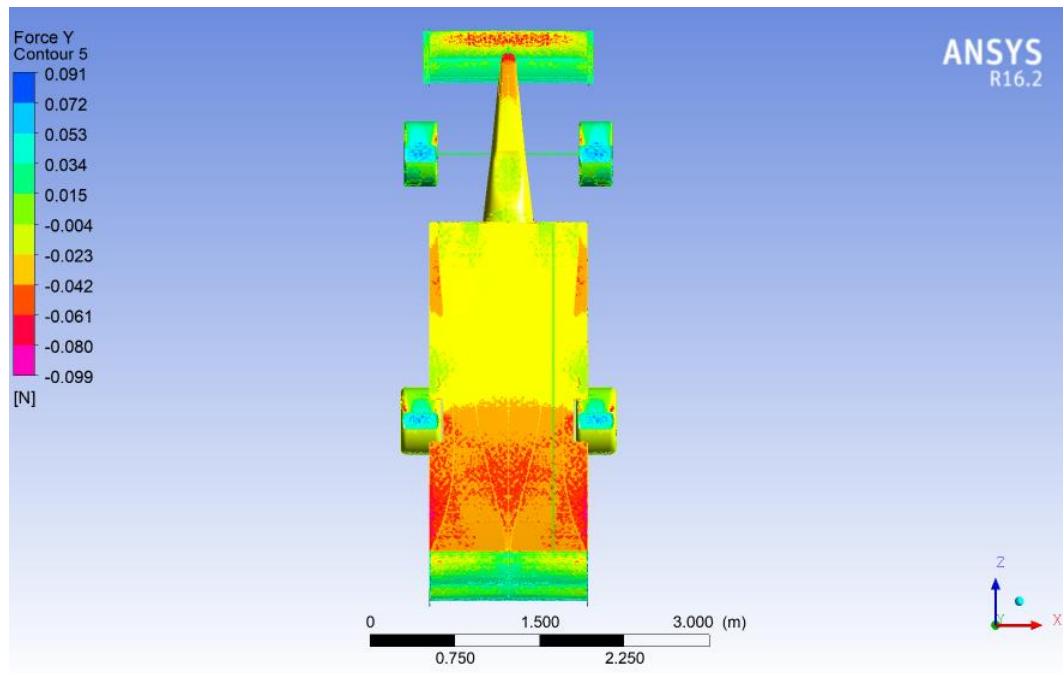


Figure 46 downforce distribution

The figure below shows the velocity vector in the central plane of the tunnel. The blue vector under the car shows that the air is accelerated in the tunnel and recovered in the diffuser. Also, the direction of the outlet flow from diffuser means the rear wing drives the air to some degree. A problem needed to be noticed is that there is a downstream along with the engine cover and hitting the outlet of the diffuser. This will decrease the efficiency of the undertray as well.

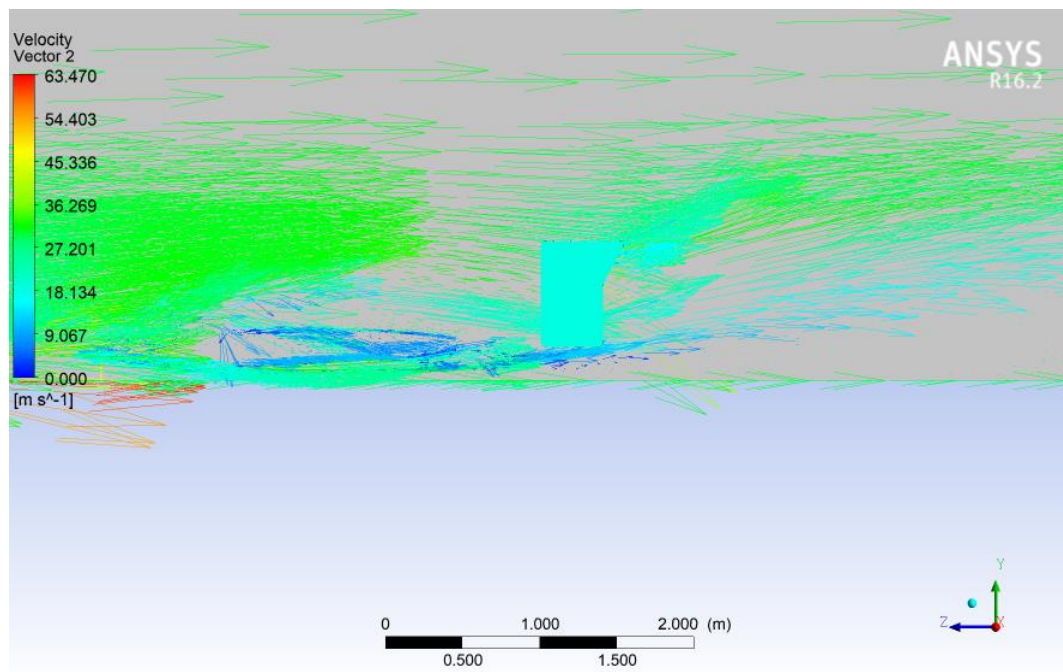


Figure 47 velocity vector in the centre plane of tunnel

7 Achievements and Failures

7.1 Achievement

The table below shows the comparison of our initial target and present completion.

Table 8 Project Completion

	Target	Present achievement	Completion rate
Cl	-1.92	-1.67	87%
Cd	0.77	0.77	100%
Downforce@top speed	6000N	5013N (front area: 1.16 m ²)	83.5%
CoP	60:40(front:rear) (match the CoG)	53:47	88%
Overall Completion			89.6%

Seriously speaking, we failed the project because we do not reach our target. However, ninety percent of completion is a great achievement for us. It is the first time we use CFD software and the theory behind it is a mystery for us. Once we are in trouble solving the result in CFD, it is quite challenging to find where the problem is because of the unfamiliarity of concerning theory. The only way is trying to find some clue online and try again and again. During this period, we took a quite long time and learned a lot as well.

7.2 Failure

Compared to the achievements, we have a lot of deficiency.

- We failed to reach our target.
- We are unable to create the prism layers successfully for the full assemble model. As a result, all the result about the whole car is slightly worse than the intact computational result, which in turn indicated that we could have finished more than present.
- The design of engine cover, rear wing lacks enough CFD tests.
- There is not enough study on the undertray interaction with the front wing, rear wing and sidepod, which could have made an excellent improvement for the performance of the whole car.
- The undertray design only studied on one concept and lacked three-dimensional design.
- There is not enough cooperation between groups and aero group members. As a result, the final package lacks all other components from other groups—besides, the mount of the rear wing and a formal engine cover model miss.
- The actual finish time is nearly one month later than the Gant chart we set at the beginning

of the project.

- All the failures indicated one thing: we could have performed much better than present in this project.

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