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Front Aerodynamic Development of the Darrian T90 GTR+

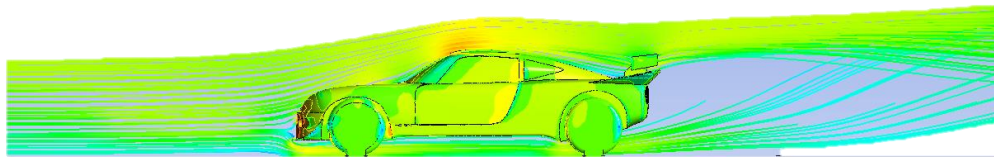
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Declaration of Authenticity

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

Abstract

An investigation into the aerodynamics of the Darrian T90 GTR+ is to be conducted with the aim of improving the front downforce/reducing front lift. This is because the vehicle is now creating too much front end lift due to a newly developed enclosed rear clamshell coupled with a more effective wing design that is now creating significantly more downforce than before. This has caused the centre of pressure to move towards the rear.

The current configuration will be thoroughly investigated to define the problem and from this, different aerodynamic devices that can help reduce front lift/create front downforce have been investigated to see if they would suit the application. From this, the devices can be modelled in SolidWorks and then run in ANSYS and the effect of each device thoroughly investigated and improved.

The main aim of the project is to get a more aerodynamically balanced vehicle to allow the driver to gain more confidence in the vehicle and improve stage times.

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I would like to thank Tim Tudor for the continued guidance and support throughout with both the ANSYS software and aerodynamics in general.

Also thanks to Tim Duffee for the suggestions of devices to use along with taking time out of a busy schedule to show me around the vehicle to get a better understanding of the final goal.

As well as Tim, I would like to thank Rhodri Duffee and Tim Tudor for the current Darrian CAD model that has been used throughout the investigation.

I would also like to thank Gavin Spring for use of the Design Expert software along with showing me any features and shortcuts in the ANSYS software.

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Abbreviations

CFD	Computational Fluid Dynamics
Cl	Coefficient of Lift
Cd	Coefficient of Drag
AoA	Angle of Attack
CofP	Centre of Pressure
CofG	Centre of Gravity
DOE	Design of Experiment
Cp	Coefficient of Pressure
-L/D	Lift over Drag (ratio)

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1. Introduction

"Aerodynamics are for people who can't build engines" was a quote very famously stated by the late great Enzo Ferrari. Since these infamous words were said, the world of aerodynamics has progressed so much that designing a suitable aero setup can gain as much if not more lap or stage time than a better engine.

Therefore, for a company that wants to be competitive on the track, or more recently on the rally stage, a well-balanced setup is essential. In the world of rally cars, aerodynamics are starting to play a bigger role than ever before especially in the World Rally Championship where aerodynamics have been the main feature of the 2017 season as documented by Collins (2017). This is also true for Darrian Cars with their updated T90, the GTR+ as they have tried to improve the car in this area. The first step that was taken was looking at the rear of the vehicle to gain downforce and it was found that by covering in the rear window to make a fastback shape and changing the wing profile that a large amount of downforce was generated. Unfortunately, this has now made the front of the vehicle lift due to an aerodynamic imbalance when going over jumps which is unsettling for the drivers.

Instead of simply reducing the downforce created at the back, a study will be conducted to look at increasing the front downforce and so reducing the front-end lift. There are certain items that can be investigated to improve this including dive planes and their positioning and arrangement, alternative front splitter design and placement, venting the front arches and the possibility of incorporating an aerofoil section into the top of the clamshell.

To get an idea of how the current aero arrangement is working, the Darrian CAD model will be put into ANSYS to acquire the drag and lift coefficient values as well as overall air flow characteristics the current setup gives so that there will be base values to use for comparison. These will also be compared to the MIRA data from 1998 and the CFD study conducted on the rear wing and fastback design in 2015. The current front aero parts that have been developed for the GTR+ can then be modelled and tested.

Research will be conducted on each of the items to investigate their effectiveness and how it will affect the car as well as looking at their design to get a better idea of how to effectively incorporate them into the Darrian bodywork. For this, special considerations need to be taken as it is a rally car meaning a higher ground clearance, longer suspension travel and an increased resistance to the elements need to be considered.

Once these parts have been modelled, they can be incorporated into the model which can then be put into ANSYS and the various designs can be evaluated using CFD. This will involve trialling each item individually to find the most efficient design and then start adding them together to help improve the overall downforce. This setup should work effectively with the rear of the vehicle to create an aerodynamically balanced car. Furthermore, pitch characteristics will be investigated to see how the car behaves travelling over jumps. Certain studies based on the domain size, mesh density, turbulence models and inflation layers will also be conducted to ensure a valid methodology.

2. Literature Review

2.1. Aerodynamic Principles

Creating downforce involves creating a pressure differential on the vehicle whether it is using the whole car or by adding devices to do this to push the car into the road. So, by adding a larger vertical load to the vehicle and specifically the tyres, a larger lateral and longitudinal force can be produced resulting in increased grip and higher cornering speeds.

This method of producing downforce due to a pressure distribution was observed by Bernoulli and documented by Katz (2005, p. 38) who states 'airspeed varies as it flows around an object, then the pressure will change in an inverse proportion to the square of the airspeed'. This essentially means the slower the air, the higher the pressure and the faster the air the lower the pressure. This is the foundation behind many aerodynamic devices.

Another observation of aerodynamics is that there will be a stationary layer of air on the car surface called the boundary layer. This boundary comprises of several layers with each one flowing slightly faster than the last until free stream velocity is reached. Furthermore, as the boundary layer builds towards the rear, so does the overall height of this layer as observed by Katz (2006). Along with this, to maintain low drag, a thin laminar boundary layer needs to be maintained although on curved surfaces like wings it is more desirable to have a turbulent boundary layer to avoid separation.

A further aspect of aerodynamics is the continuity equation. This states that the amount of fluid at the end is the same as the start after flowing around an object. This is a deciding factor for the solving software in CFD as to whether the calculations being conducted are valid.

An important part of defining the effectiveness of a vehicle's aerodynamics is by looking at where the centre of pressure (CofP) on the vehicle lies. This is described as the pivot point that the aerodynamic loads on the vehicle centre around. For this investigation, this will be a fundamental aspect of the vehicle to investigate and possibly change due to what seems like a current rearward balance. This will also be affected by the car's centre of gravity (CofG) as its mid-engine and the distance between the CofG and CofP is known as the static margin. To ensure an aerodynamically stable design, the CofP should be ahead of the CofG as observed by Hucho (1998).

2.2. Basics behind ANSYS

The ANSYS solver software Fluent utilises the Navier-Stokes equation with several derivatives allowing different types of flow to be predicted better by the software. For example, a commonly used model for vehicle aerodynamics is the k-epsilon realizable as it is proficient in predicting turbulent, reversible flows that are common behind a vehicle whereas the k-omega is better at predicting flow that separates from a vehicle's surface and so a study to find the most appropriate model will be conducted.

2.3. Aerodynamic Devices

To improve front downforce, a multitude of devices can be added. After a meeting with Tim Duffee, owner of Darrian Cars, a few items were suggested. Minutes for this meeting can be found in appendix 1.

2.3.1. Splitters

One of the simplest items to increase the front downforce of a vehicle is to add a splitter. The job of the splitter is to create a high-pressure region on the upper surface by slowing the air down and a low-pressure region underneath as the velocity of the air increases by leaving the trailing edge. This pressure differential induces downforce and pushes the front of the vehicle into the road.

Splitters are most effective when near the ground to utilise ground effect. Ground effect is the phenomenon found in the 1970's on Formula One cars that found that the closer proximity to the ground the vehicle was, the velocity of the air increased due to it being 'squeezed' under the car and so the pressure decreased causing a suction effect on the ground. Another positive of a splitter is that it reduces the airflow causing lift that is directed underneath the car, and directs it over the top of the car instead.

A slight disadvantage of the splitter is that it can increase the frontal area of the vehicle which correlates to an increase in drag but the downforce gain over drag ($-L/D$) is worth the penalty.

By looking at a study by McBeath (2015), the splitter should extend forwards and rearwards for most effective design as by shielding the front underside, the air cannot get trapped in any components under the front clamshell causing the airflow to stay attached along the underside and to not produce lift. 'if static pressure under the car is positive, which may still be the case even with a smooth undertray, then the airflow can be improved by shaping the undertray' (McBeath, 2015, p. 148). The study also showed that a splitter 100mm in length added 10% downforce with a very small increase in drag. But the study also suggests tests should be conducted on splitter length and splitter shouldn't extend beyond the edge of the high pressure 'bubble' caused on the upper surface of the splitter.

Another design consideration is that it should have a radius on the leading edge if thickness permits or if not should be upturned. This is because if it passes over a sharp edge it will lose velocity and energy. 'By easing the airflow under the splitter with a properly profiled leading edge, these flow separations can be reduced or avoided altogether, to betterment of downforce' (McBeath, 2015, p. 71). This helps downstream of the splitter as well so can help a diffuser for example.

2.3.2. Front Aerofoil

The Darrian currently has a piece of bodywork above the radiator that can be utilised to incorporate a front wing profile to aid front downforce. By properly profiling this shape, a large proportion of downforce should be able to be generated.

According to Katz (2006), a wing operates by utilising the fact that there will be a lower velocity on the upper surface and a higher velocity on the lower surface. Then per Bernoulli's equation, the velocity difference causes the pressure underneath the wing to be lower causing a resultant downward force. 'The effect of a wing is to reduce the static pressure below the suction side,



Figure 2-1: Darrian Front Aerofoil. Credit Matthew Harvey (2016)

the more cambered lower surface (in the race car context), and to raise the static pressure of the air over the upper, pressure side of the wing.’ (McBeath, 2015, p. 88)

To change the dimensions of a wing profile, certain parameters need to be considered. The leading edge is at the front and the trailing edge is the rear thin section. The imaginary line that joins the two is the chord line. This chord length describes the overall size of the wing section and is also used to describe the angle of attack of the wing as this is the ‘angle between the airfoil's chord line and the direction of airflow wind’ (Reddy, 2006).

Several design considerations can be considered when implementing the wing profile. This can include having a cambered surface meaning that the lower surface is more curved than the upper which helps to accelerate the air further improving the low-pressure region beneath the aerofoil section. The angle of attack of this wing section can also be changed to help further increase downforce. Although when the wing angle becomes too severe, stall occurs which is the separation of the air from the wing profile leading to an overall reduction in downforce with the drag penalty still present.

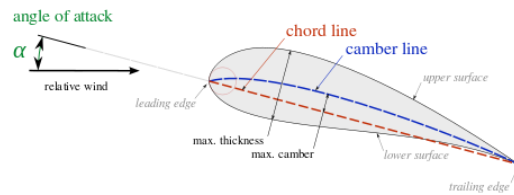


Figure 2-2: Source: University of Strathclyde.

Other design considerations could include the addition of extra elements behind the primary element to increase the camber of the wing profile and when positioned correctly, further improvements in $-C_l$ values. Another addition could be the introduction of a Gurney flap. This small strip of material with a 90° bend is placed on the trailing edge of the aerofoil with its primary job to increase pressure on the upper wing surface as well as creating small vortices behind the flap to stop separation occurring from the lower surface meaning higher angles of attack can be used before stall occurs.

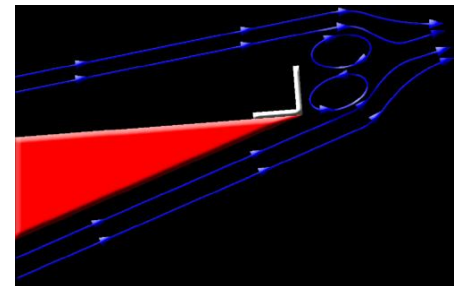


Figure 2-3: Source: allamericanracers.com.

Another study by McBeath (2015) on rear aerofoil sections has shown that a rearward biased camber is said to have a greater effect on downforce generation with a more progressive stall. Along with this, the aerofoil need to be quite thick to help generate downforce (18-20% for max downforce) as produces a nicer leading edge that helps flow with a leading-edge radius of 1-3% of chord.

2.3.3. Dive Planes

Dive planes can be mounted to the front bumper of a vehicle and are used to produce a vortex down the side of the car to help seal the underside and help with ground effect in certain situations. Along with this, they can also act as small aerofoils and produce a pressure differential across the upper and lower surfaces.



Figure 2-4: Darrian Dive Plane. Credit Matthew Harvey (2016)

Another advantage is that they can move aerodynamic balance forwards by adding to the front and taking away from the rear. This is because the vortices produced can influence the rear wing causing the loss or gain of downforce by disturbing the air flowing over certain portions of the wing span.

Due to them being placed at relatively steep angle to generate downforce, there is a drag penalty and so an efficient design is required to reduce the effect of this. If more than one dive plane is used, the top one should be pointing towards the top of the wheel arch and the second one equidistance between the top of the dive plane and splitter.

2.3.4. Arch Venting

The aim of venting the arch is to reduce the high-pressure region behind the front wheels of the vehicle to reduce the lift of the vehicle. This high pressure is built up by the air bleeding in to the arch from the sides and underneath of the vehicle which then gets trapped causing the velocity to reduce and so the pressure to build.

One way to reduce this lifting effect is to vent the arches to allow the air to escape by using louvres on top of the wheel well or a vent from the wheel well that feeds out on to the door. 'The cutaways often present on the vehicle sides behind the front wheels also assist air to escape not only from the wheel wells, but also from under the entire front of the car. As such these features often work in concert with front splitters and diffusers, providing an exit for air that has been exploited further forwards on the car'. (McBeath, 2015, p. 185-186). The aim is to then feed this air into the boundary layer of the vehicle to prevent turbulence and disrupt any upstream aerodynamic devices.



Figure 2-6: Darrian Arch Vent Exit Location. Credit: Matthew Harvey (2016)



Figure 2-5: Arch Vent Guide. Credit: Matthew Harvey (2016)

2.3.5. Other Considerations

If the splitter is effective, it can be improved by utilising a small diffuser on the underside to increase the air velocity due to smoothing airflow and allowing it to expand meaning lower pressure which increases downforce. Along with this, it improves the air flow leaving the rear of the car, especially if a diffuser was used at the rear of the vehicle as well. To choose the right one, testing would need to be conducted as there is a chance of flow separation if the angle of the diffuser is too steep.

All items that will be investigated are usually used on vehicles specifically made for smooth race tracks where proximity to the ground is desirable and so the effect on the Darrian is likely to be reduced for the splitter and dive planes due to a raised ride height to clear rough ground. Another consideration is that due to the rough conditions that the vehicle will be operating in, all parts need to be more resilient to

cope with the rough terrain. Also, any device shouldn't extend too far from the cars original bodywork as there is a high chance that any item can be easily damaged by clipping verges etc. when cornering.

The effect that these devices have on the rear wing of the vehicle needs to be closely monitored as this is the main device that is providing downforce on the vehicle currently and so any disturbed air caused by an addition at the front could have a negative effect on the rear.

Other considerations include directing air flow to both the brakes and radiator as an effective aerodynamic design may deprive these components of the airflow that is necessary to keep them operational.

2.4. Pitch Sensitivity

The main problem with the current Darrian specification is how the front end is lifting/not creating enough downforce which has caused the car to become unstable in the air. This implies that the car is very sensitive to changes in pitch caused by the aerodynamics. As the angle of attack of the vehicle changes, so do the aerodynamic properties. Figure 2-7 shows the how ride height change front and rear affects a certain vehicles centre of pressure as there is around a 10% aerodynamic balance shift depending on vehicle height which can make the vehicle unstable in certain conditions.

Therefore, an investigation looking at pitch sensitivity will be conducted with the aim to see how any aerodynamic device change will affect the vehicles behavior.

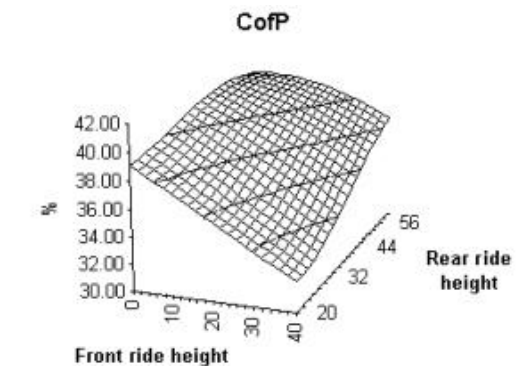


Figure 2-7: Source: Cosworth



Figure 2-8: 'Darrian Anglesey'. Credit: SMJ Photography (2016)

2.5. Parameterised Devices

- Splitter
 - Length: 25mm to 150mm in 25mm increments
 - Thickness: 10mm to 50mm in 10mm increments

Both length and thickness will be dependent on which material is chosen due to the large amount of forces exerted upon the splitter.

- Front Aerofoil
 - Wortmann FX 63-137 and NACA (63)3-618
 - Angle of attack: 10° to 30°
 - Chord length: 250mm
 - Gurney flap: 2.5% of chord length

- Dive Planes
 - Size: 50mm to 150mm
 - Placement from top of splitter: 15mm to 130mm
 - Angle of attack: 5° to 60°

Due to the number of variables in designing a dive plane, design of experiment will be implemented to find the best possible solution in a shorter time and so other parameters (camber and number per side) can be investigated separately.

- Arch Vent

A nominal vent of 115 x 170 mm inlet with a 10 x 170 outlet on to the door. This model will be run with rotating wheels to simulate the car moving through the air more accurately.

2.6. Design of Experiment

Design of experiment (DOE) is a system that can assess inputs to changes on an object and then use the results to find the optimal solution to a problem far faster than by the conventional one factor at a time approach. To do this, the controllable factors (settings changed by user) need to be identified to get the best outcome from the experiment including the items limits.

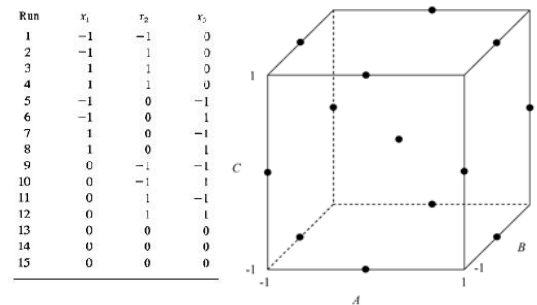


Figure 2-9: Source: IUSER

By investigating various methods, the Box-Behnken method was selected which involves choosing three experimental factors known as levels to parameterise the chosen device. This is due to a lower number of runs being required to achieve a robust result. From this, the maximum values are given a value of 1, minimum -1 and the intermediate 0. A list of seventeen runs is then conducted (including reruns for the central value to get an estimate of experimental error) incorporating a range of these values and then the response from this, -Cl in this case, are recorded and then input back into the DOE and then values based on the effect of each level can be calculated.

To assist with the investigation, a software package called design expert will be used. This package simplifies the process involved in predicting the responses from the process by allowing the user to simply input the maximum and minimum limits on the levels to generate the runs. These runs are produced in a random order to help eliminate the effect of any other variables that cannot be controlled. After all runs are completed, a series of visual responses can be generated as well as a series of sliders that allow the user to change any level to find the optimal solution.

3. Methodology

3.1. Ahmed Body CFD

To create a suitable meshed domain for the Darrian model, certain meshing strategies are required to ensure an accurate result. To learn these, a study was completed on the Ahmed body which is a bluff body

used in wind tunnels for calibration. As it has simple geometry and known drag and lift values, all results can be validated. This study can be found in appendix 2.

3.2. Darrian CFD

After the study on the Ahmed body was completed, the methodology used to create a suitable meshed domain could then be applied to the Darrian model and valid results could be taken from this. The plan for the project can be found in appendix 3.

3.2.1. Domain Setup

To assess the vehicles aerodynamics, the Darrian model needs to be put into a domain. This initial box was sized in relation to the Ahmed body study found in appendix 2 along with the named selection choices on each face.

3.2.2. Meshing Software

Initially, the meshing software selected for the Darrian was the ANSYS mesher used for the Ahmed body study. But after several failed meshes using the conventional meshing method, a cutcell mesh was then investigated. Instead of using tetrahedrals, this method utilises cubes to create the mesh and was the method used by Thomas (2015) to conduct the rear wing study on the Darrian. From this mesh, results were acquired but they were poor and meshing the model was inconsistent and so the decision was taken to use ICEM CFD to generate the mesh using the Octree method.

This software can produce a good quality mesh from a poor-quality CAD model and so this software was used throughout.

3.2.3. Initial run

To see where the main pressure and wake regions are situated on the Darrian, a simple mesh was created and the results studied.

Figure 3-3 shows the main wake region behind the vehicle along with the smaller region behind the rear window. There is also the stagnation zone in front of the vehicle along with the region where the air is accelerated over the vehicles windscreen and so all of these aspects need to be captured effectively within the mesh to produce accurate results.

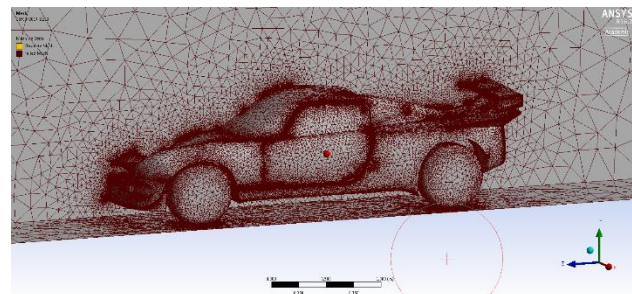


Figure 3-1: Failed Prism Layers

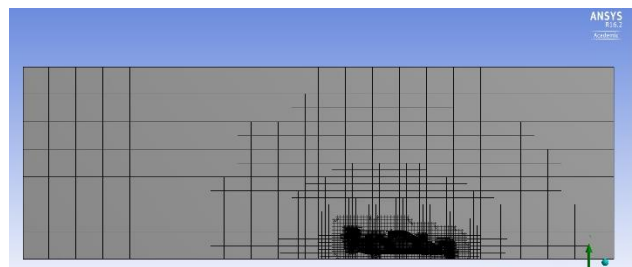


Figure 3-2: initial Cutcell Mesh

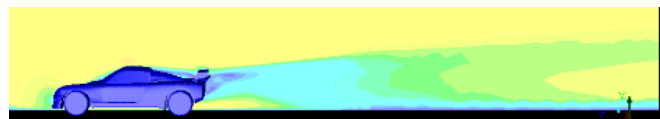


Figure 3-3: Initial Run Velocity Contour

3.2.4. Meshing Strategy

From the initial run, several areas of the mesh were improved by utilising a car box with reasonably small elements (0.19m) to capture the main wake region. The element sizing on the vehicles surface was then investigated to find the optimum size between capturing the car and keeping the element count low. This value was found to be 10mm and was applied to all aspects of the vehicle. The maximum element size in the domain was then set to 1m so that elements did not exceed this value as having elements too large would skew the result.

3.2.5. Fluent Setup

Another option that was changed was the solution method scheme that was changed from simple to coupled. This allowed the run to finish once a set of criteria was reached relating to the continuity value. Along with this, all available sub sections were changed to second order due to the mesh not always being aligned with the flow (where first order is used) and this helps to improve accuracy within the result.

Due to the turbulent flow leaving the car model, the Courant number and relaxations factors were lowered to keep the continuity line smooth and allow the model to converge.

An option when opening Fluent is to include double precision for the calculations. This adds further decimal points and increases the accuracy of the solution but also increases computing time substantially and so the decision was made not to use this.

3.2.6. Skewness, Orthogonal Quality and Aspect Ratio

To ensure a good mesh is achieved, the meshing software includes a 'check' system that looks at the quality of the mesh. The main aspects are skewness, orthogonal quality and aspect ratio. These values can then be compared to the mesh metric in Figure 3-4 and depending on the mesh quality, the mesh can be used and effectively solved in the Fluent software.

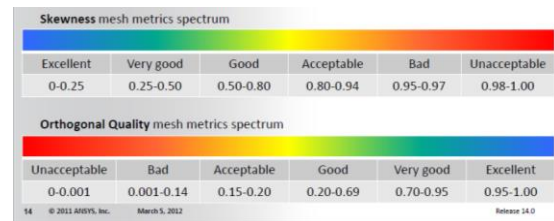


Figure 3-4: Source: ANSYS Inc

Skewness is the shape of the tetrahedral in relation to an equilateral triangle. This is determined by dividing the optimal cell size minus the actual cell size over the optimal cell size to get a value that should be no higher than 0.98 and preferably better than 0.94.

Orthogonal quality is calculated by relating the vector from the centre of the element to the centre of the adjacent elements in relation to the vector leaving perpendicular to the face of the initial element. Therefore, the more skewed the cell, the likelihood is the orthogonal quality will be poor as well.

3.2.7. Domain Independence Studies

Before starting the investigation into the aerodynamics of the Darrian, the domain size (the enclosure the car model sits within that ANSYS uses to calculate what is happening to the air around it), the mesh size (size of elements and growth rate) and turbulence model (series of equations ANSYS uses to calculate air flow) need to be decided.

This starts with determining the size of the domain. If it is too small, the values generated for lift and drag will be adversely affected and too big and it will take too long to compute. To find the optimum size, a study is run by starting with smaller domain and working up to larger ones. Graphs can then be plotted with the results and when these results level out, it will show that the domain is not influencing the results.

With some research, a manual on CFD for automotive use was found (Lanfrit, M. 'Best practice guidelines for handling Automotive External Aerodynamics with FLUENT') which suggested that having a domain three car lengths in front and five behind was an optimal value. This will therefore be used as a median point. It was then decided that the smallest domain would be kept to the same ratio of 3:5, and so for every 3 metres in front, there will be 5 metres behind. It was also assumed that the domain dimensions above and beside the car would be the same as the length in front of the car.

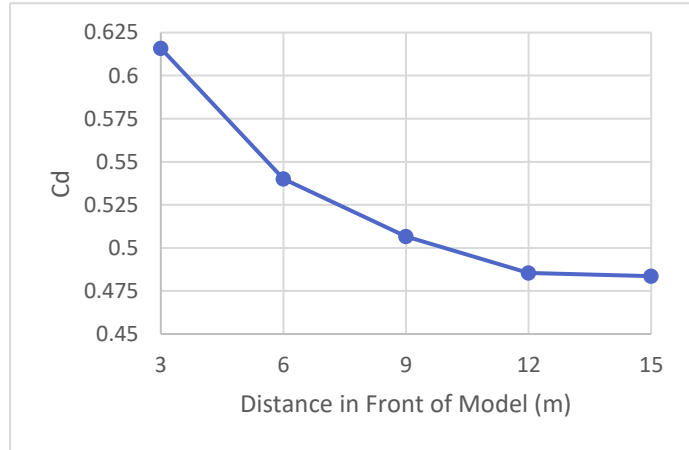


Figure 3-5: Domain Independence Study

By looking at Figure 3-5, the results show how much of an impact the domain has on the result but as the distance in front of the car becomes 12 metres (approximately 3 car lengths), the variance between the results is negligible and so this domain size was verified and selected.

Table 3-1 shows the results obtained from this study with the % representing the percentage different from the wind tunnel result.

Table 3-1: Domain Independence Study

	Cd	Cl	Delta Cd	%	Delta Cl	%
3	0.6159	-0.6303	-0.0339	-5.82	-0.0043	-0.69
6	0.5401	-0.6099	0.0419	7.2	0.0161	2.57
9	0.5066	-0.528	0.0754	12.96	0.098	15.65
12	0.4855	-0.4702	0.0965	16.58	0.1558	24.89
15	0.4836	-0.5493	0.0984	16.9	0.0767	12.25

3.2.8. Mesh Independence Studies

After the domain independence study, a mesh independence study can then be conducted. This involves choosing the most appropriate domain size and using it to create a suitable mesh density. The reason for the study is to get the most accurate results with the shortest amount of computing time.

For this, the 12m in front domain size tested was used and then the mesh was scaled up and down with the minimum value being 0.7 and the max value being 2.

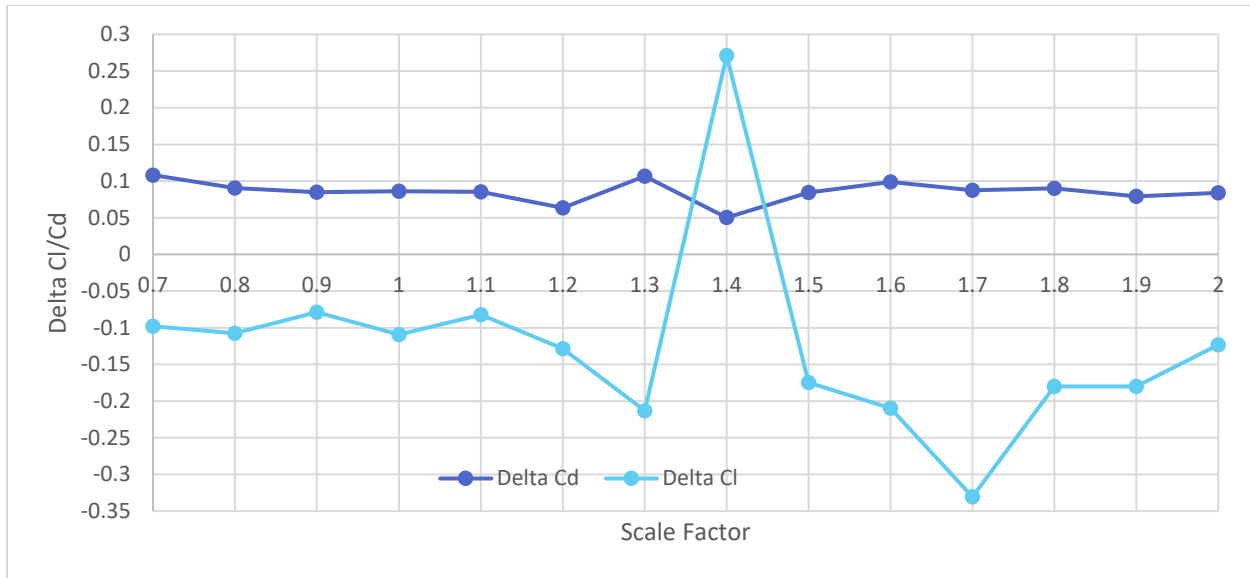


Figure 3-6: Mesh Independence Study

The densest mesh (0.7) had a total of 14.27 million elements while the smallest (2) had a total of 812000. The results in Figure 3-6 show that even with a large range in number of elements, the results show little variance in drag values whereas lift varies significantly more especially at 1.4 where there is a large spike in the test. This is because of a large majority of bad elements skewing the result and so this value can be negated. The graph shows the results start to level out around 1.1 and so this was taken to be the optimal value where the mesh has become independent of the result.

Table 3-2: Mesh Independence Study

Size	Drag	Lift	No of elements	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
0.7	0.4739	-0.5281	14271779	0.1081	-18.57	108.1	-0.0979	-15.64	-97.9
0.8	0.4916	-0.5184	10015009	0.0904	-15.53	90.4	-0.1076	-17.19	-107.6
0.9	0.4973	-0.5474	7111843	0.0847	-14.55	84.7	-0.0786	-12.56	-78.6
1	0.4961	-0.5166	5361487	0.0859	-14.76	85.9	-0.1094	-17.48	-109.4
1.1	0.497	-0.5436	4094263	0.085	-14.6	85	-0.0824	-13.16	-82.4
1.2	0.5184	-0.4974	3189294	0.0636	-10.93	63.6	-0.1286	-20.54	-128.6
1.3	0.4755	-0.413	2538961	0.1065	-18.3	106.5	-0.213	-34.03	-213
1.4	0.5319	-0.897	2119038	0.0501	-8.61	50.1	0.271	43.29	271
1.5	0.4978	-0.4513	1797655	0.0842	-14.47	84.2	-0.1747	-27.91	-174.7
1.6	0.4831	-0.4161	1479739	0.0989	-16.99	98.9	-0.2099	-33.53	-209.9
1.7	0.4944	-0.2955	1268447	0.0876	-15.05	87.6	-0.3305	-52.8	-330.5
1.8	0.4922	-0.4461	1072489	0.0898	-15.43	89.8	-0.1799	-28.74	-179.9
1.9	0.5028	-0.4459	911858	0.0792	-13.61	79.2	-0.1801	-28.77	-180.1
2	0.4979	-0.5025	812321	0.0841	-14.45	84.1	-0.1235	-19.73	-123.5

3.2.9. Prism Layer Study

A study was then conducted on how many prism layers the model needs to incorporate to increase the accuracy of the result by accurately representing the boundary layer. This involved running several simulations with prism layers starting at 1 and then up to 9 in stages of two.

Before this could be started, the initial element height of the first layer (also known as y) value needed to be calculated. This involves a set of equations that consider flow velocity, Reynolds number, density, viscosity and length of the vehicle.

To start with, the initial equation as given in the ANSYS turbulence tutorial was investigated. This equation starts with the y^+ (wall distance vector) and is rearranged to find y :

$$y^+ = \frac{\rho U_\tau}{\mu y}$$

Equation 1: Source: ANSYS Inc

This is then rearranged for y :

$$y = \frac{y^+ \mu}{U_\tau \rho}$$

Equation 2: Source: ANSYS Inc

The y^+ is a target value and so is a number that is specified between 30 and 300 and so 100 was chosen for this. The μ value can be calculated by using an online viscosity calculator. This takes into consideration the temperature of the air and gives a value dependent on this. In this instance at 288°K, the viscosity of air is 1.811×10^{-5} kg/m s. The density is the standard value for air which is 1.225 kg/m³. This leaves μ_τ as the only unknown.

The equation for μ_τ is given as:

$$\mu_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

Equation 3: Source: ANSYS Inc

This leaves another unknown in the form of τ_w which is given as:

$$\tau_w = \frac{1}{2} C_f \rho U_\infty^2$$

Equation 4: Source: ANSYS Inc

From this another unknown is present in the form of C_f . This is given as:

$$C_f = 0.058 Re_l^{-0.2}$$

Equation 5: Source: ANSYS Inc

This then gives another unknown in the form of the Reynolds number (Re). This can be calculated using the equation:

$$Re = \frac{\rho U L}{\mu}$$

Equation 6: Source: ANSYS Inc

Other values can be taken from the model, known real world values and set criteria.

Table 3-3: Known Values for Prism Layer Calculation

ρ (density of air)	1.225 kg/m ³
U (flow velocity)	27.5 m/s
μ (viscosity of air at 288°K)	1.811x10 ⁻⁵ kg/m/s
L (length of car)	3777.64 m

As there are no unknowns, the Reynolds number is:

$$Re = \frac{1.225 \times 27.5 \times 3.77764}{1.811 \times 10^{-5}} = 7.027 \times 10^6$$

Equation 7

This then gives the C_f value as:

$$C_f = 0.058 \times 7.027 \times 10^{-6} l^{-0.2} = 2.478 \times 10^{-3}$$

Equation 8

$$\tau_w = \frac{1}{2} \times 2.478 \times 10^{-3} \times 1.225 \times 27.5^2 = 1.148 \text{ kg/ms}^2$$

Equation 9

$$\mu_\tau = \sqrt{\frac{1.148}{1.225}} = 0.968 \text{ m/s}$$

Equation 10

$$y = \frac{100 \times 1.811 \times 10^{-5}}{0.968 \times 1.225} = \mathbf{1.527 \text{ mm}}$$

Equation 11

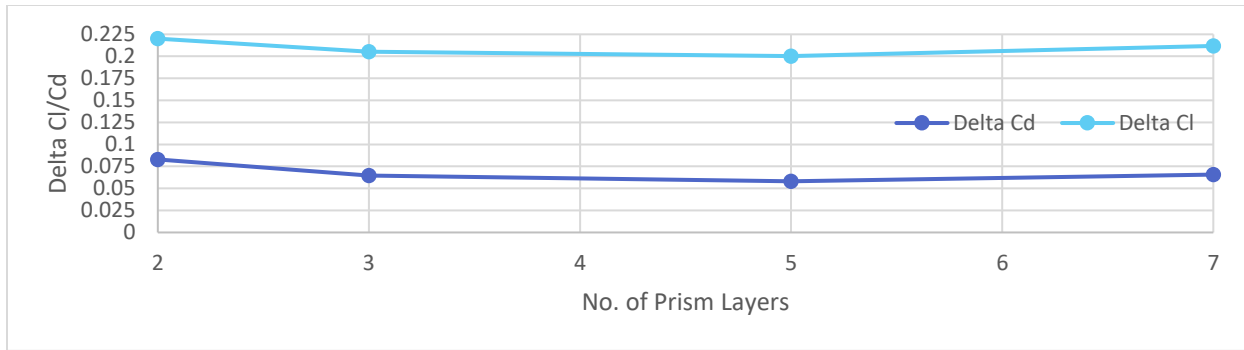


Figure 3-7: Prism Layer Study

Figure 3-7 shows the results obtained from the prism layer study and there is very little variation in results although there is less variance between three and five and two and three meaning that three layers will be used. One prism layer was trialed but this was found to diverge significantly so the results from this weren't included.

Table 3-4: Prism Layer Study

No of prism layers	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
2	0.4991	0.4059	0.0829	14.24	82.9	0.2201	35.16	220.1
3	0.5175	0.4207	0.0645	11.08	64.5	0.2053	32.8	205.3
5	0.5239	0.4257	0.0581	9.98	58.1	0.2003	32	200.3
7	0.5162	0.4143	0.0658	11.31	65.8	0.2117	33.82	211.7

3.2.10. Mesh Refinement

When the mesh was created in the domain and the mesh quality checked, it could be seen that a high number of poor cells originated from the point where the wheels intersect the ground plane.

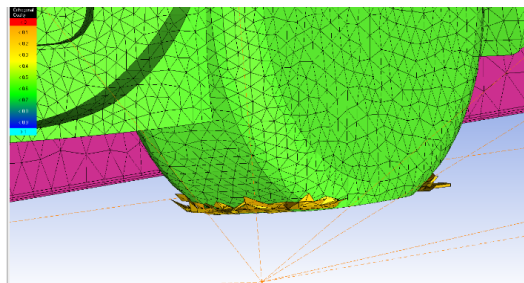


Figure 3-10: Skewed Elements Around Wheel Base

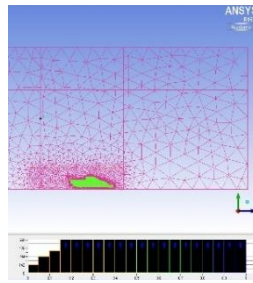


Figure 3-8: Skewness

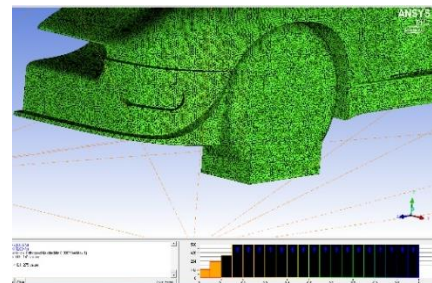


Figure 3-9: Wheel Blocks Added Removing Poor Quality Elements

Therefore, to eliminate this, several methods can be used. One is to make the wheels intersect the ground plane producing a cut in the wheel and eliminating the sharp intersection. This method reduced the number of poor quality cells but didn't eliminate them and so a wheel block was used. This involved adding a block 1/3rd of the wheel diameter around both the front and rear wheels.

Table 3-5: Wheel Block Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
0.526	-0.546	0.056	-9.62	56	-0.08	-12.78	-80

This method eliminated the poor-quality elements at the disadvantage of slightly disturbing the flow results.

Although the poor elements around the wheel had been removed, there was still a lot of poor quality elements elsewhere. Upon further investigation, it was seen that these were on the trailing edge of the rear wing and on the top of the front wheel. A cut plane was used on the model and it could be seen that the prism layers were causing a problem as two layers were attempting to merge into one. The decision was made to separate the wing and wheel from the rest of the car to negate the need for prism layers on these parts of the geometry.

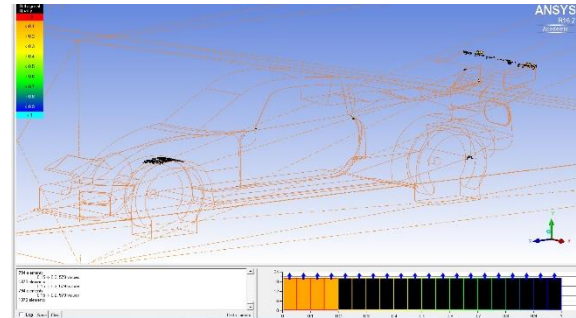


Figure 3-11: Regions of Highly Skewed Elements

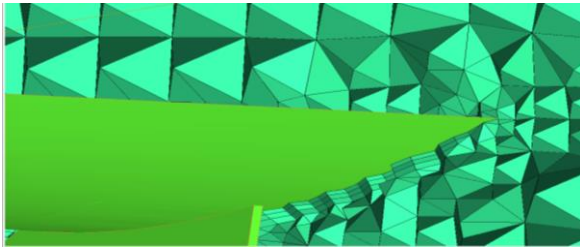


Figure 3-12: Cut Planes Showing Poor Elements

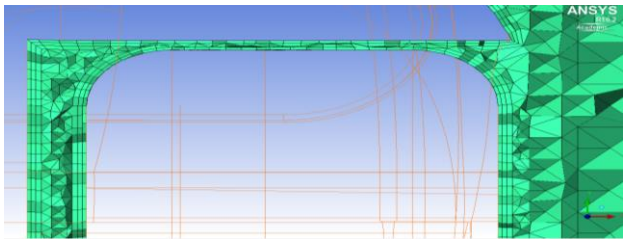


Table 3-6: Removed Prism Layers on Wing and Arch Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
0.5345	-0.5368	0.0475	-8.16	47.5	-0.0892	14.25	-89.2

From the results, it was seen that the model was still a noticeable margin away from the expected results. It was seen that the elements on the rear wing were too large and weren't effectively capturing the thin trailing edge. To solve this, smaller elements were specified for the rear wing only (5mm to 1mm) and then re-meshed.

Table 3-7: Smaller Elements on Rear Wing Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
0.5399	-0.5756	0.0421	-7.234	42.10	-0.0504	-8.05	-50.4

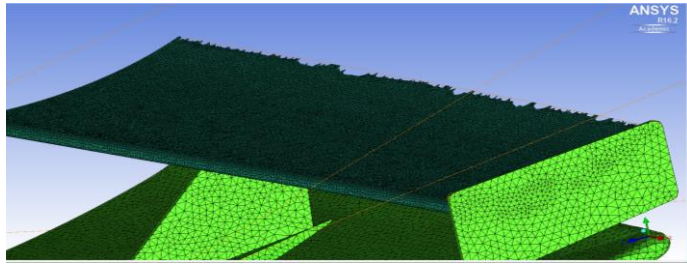


Figure 3-14: Trailing Edge Not Fully Captured

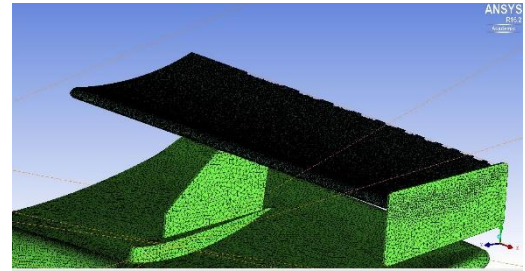


Figure 3-13: Element Size Reduced

This increased the number of skewed elements due to their proximity to larger elements on the end plate and in the domain. Therefore, the decision was made to half the original size (5mm down to 2.5mm) and then re-mesh. This produced a good quality mesh which was run in Fluent.

Table 3-8: Half Size Elements on Rear Wing Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
0.578	-0.5916	0.004	-0.687	4	-0.0344	-5.495	-34.4

It was then realized that the blocks drawn around the wheels to eliminate the skewed elements were too big ($2/3^{\text{rd}}$ wheel diameter instead of $1/3^{\text{rd}}$) and so this was rectified and the model re run.

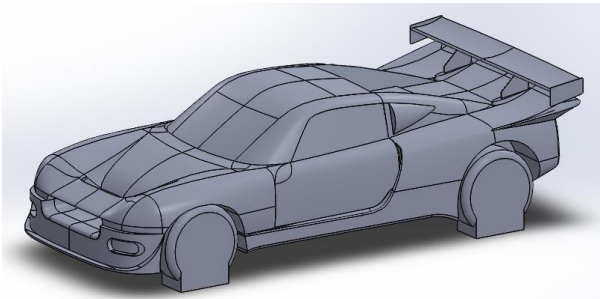


Figure 3-16: 2/3 Diameter Wheel Blocks

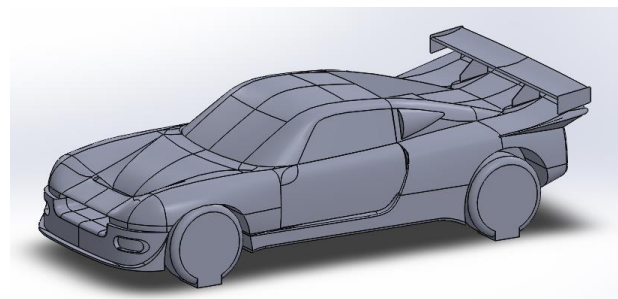


Figure 3-15: 1/3 Diameter Wheel Blocks

Table 3-9: Rectified Model Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
0.5807	-0.6256	0.0013	-0.22	1.3	-0.0004	-0.06	-0.4

The results obtained from this test show almost identical values to the wind tunnel testing with 1.3 counts off the Cd value and 0.4 from the Cl value. This was then taken as the base case from which all meshes will be generated. The final mesh settings can be found in appendix 4.

The pressure and streamline plot in Figure 3-17 shows the streamlines over the original Darrian model. By looking at

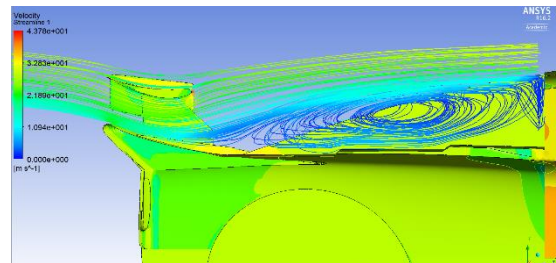


Figure 3-17: Streamlines and Pressure Contour for Base Case Run

the streamlines from the rear roofline over the engine cover, reversed flow can be seen due to separation occurring from the roof leading to a large area of disturbed air that has a negative impact on any devices downstream.

3.2.11. Turbulence Model Study

Although the k epsilon, realizable, non-equilibrium wall functions has been suggested, there are several other models available in the Fluent solver software that employ different equations within the main Navier Stokes equation to predict different types of flow. Therefore, a study of a select few of these studies has been conducted to see the variance in the result and whether a different turbulence model can predict the results more effectively. Where possible, non-equilibrium wall functions have been used because 'in complex flows involving separation, reattachment, and impingement where the mean flow and turbulence are subjected to pressure gradients and rapid changes. In such flows, improvements can be obtained, particularly in the prediction of wall shear'. (Fluent Inc, 2006)

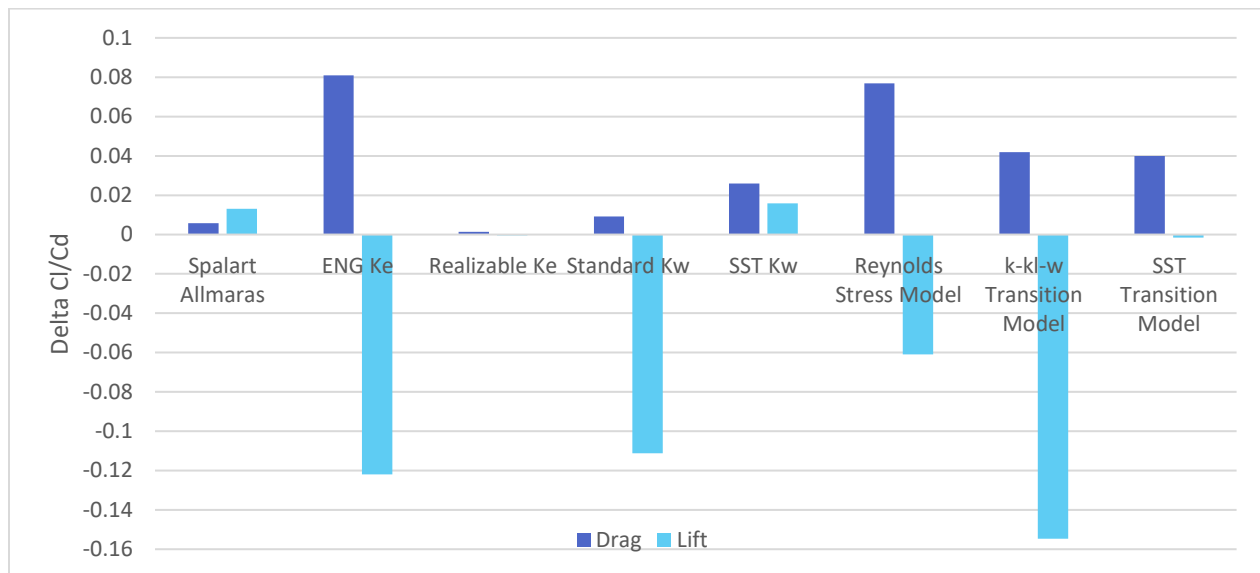


Figure 3-18: Turbulence Model Study

The results show that no turbulence model got as close to the wind tunnel results as the k epsilon realizable with non-equilibrium wall functions although the Spalart Allmaras showed relatively close results with a reduced computing time due to this being a simple one equation model. The SST transition model also showed very little difference in the lift value and perhaps with a refined mesh, this model could be used. The results also show that several models failed to predict the lift value meaning choosing the correct model is vital.

Table 3-10: Turbulence Model Study Results

Turbulence Model	Drag	Lift	Drag	% diff	Counts Off	Lift	% diff	Counts Off
Spalart Allmaras	0.5763	-0.6391	0.0057	0.98	5.7	0.0131	-2.09	13.1
ENG Kε	0.5011	-0.5041	0.0809	13.9	80.9	-0.1219	19.47	-121.9
Realizable Kε	0.5807	-0.6256	0.0013	0.22	1.3	-0.0004	0.06	-0.4
Standard Kω	0.5728	-0.5148	0.0092	1.58	9.2	-0.1112	17.76	-111.2
SST Kω	0.5561	-0.6418	0.0259	4.45	25.9	0.0158	-2.52	15.8
Reynolds Stress Model	0.5052	-0.565	0.0768	13.2	76.8	-0.061	9.74	-61
k-kl-ω Transition Model	0.5401	-0.4714	0.0419	7.2	41.9	-0.1546	24.7	-154.6
SST Transition Model	0.5421	-0.6245	0.0399	6.86	39.9	-0.0015	0.24	-1.5

3.2.12. Initial Fastback Run

By comparing the two designs, the fastback version shows separation occurring once from the rear clamshell causing a lower drag value. On the standard car, the increased drag is due to the secondary separation caused by flow detaching from the roof causing a laminar separation and hence a laminar bubble (as observed by Katz, 2006, p.35) that the vehicle is then effectively dragging with it which the fastback version eradicates. The streamlines in Figure 3-19 show a difference in velocity over the two along with the more attached and laminar flow caused by the fastback. Figure 3-20 further shows the increase in air velocity over the enclosed centre section meaning less disturbed, higher velocity air is passing over the wing, increasing downforce. Along with this, the angle at which the air is coming over the bodywork and hitting the wing is increased leading to the wing essentially having a larger angle of attack when compared to the standard vehicle leading to an increase in downforce.

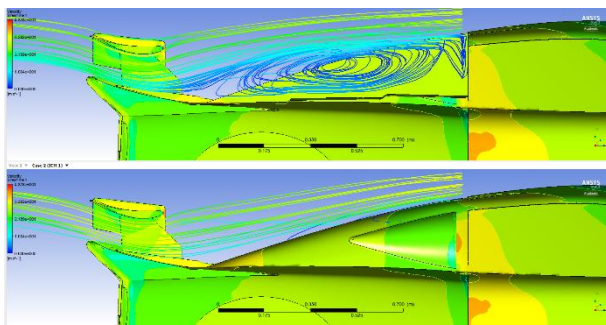


Figure 3-19: Initial Fastback Run Streamlines

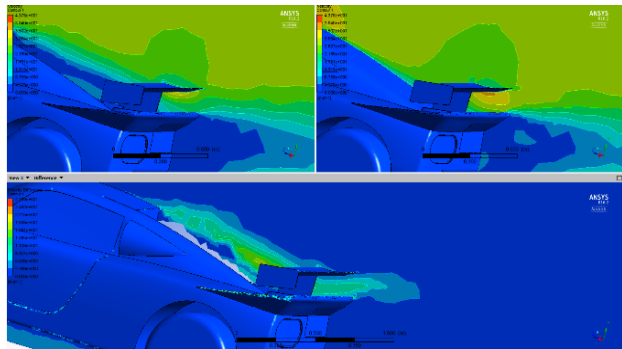


Figure 3-20: Initial Fastback Run Velocity Contour

The results in Table 3-11 the results obtained from the testing with the delta values representing the different to the study by Thomas (2015). The results show very similar values to those previously attained further validating the set methodology.

Table 3-11: Fastback Run Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
0.558	-0.6303	0.004	-0.71	4	-0.0197	-3.03	-19.7

3.2.13. Polyhedra Meshing

Fluent offers the option to convert the tetrahedral domain into a polyhedral domain. This has the effect of reducing run times due to combining several tetrahedrals together to make one element as well as helping to reduce the number of skewed cells within the domain. Even though the computing time and power is significantly reduced, the accuracy is said to be within a few percent of the actual result and so the decision needs to be made between overall accuracy and computing time.

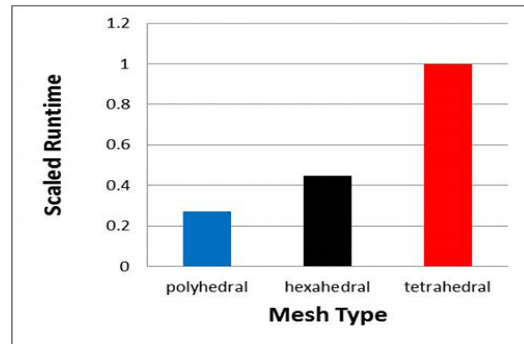


Figure 3-21: Source: Symscape

Although both runs produced similar drag values, the lift values were seen to be considerably different. The pressure contour plot in Figure 3-22 shows the polyhedral mesh in the top left and the octree mesh in the top right. It can be clearly seen that there is a large pressure build up in the polyhedral mesh that is not present on the octree. This is therefore causing lift and skewing the overall result. Therefore, the decision was made to not use this method to maintain accuracy.

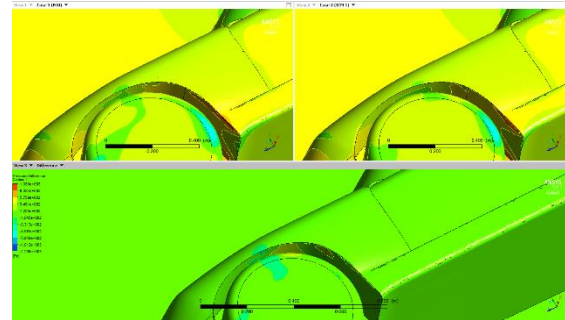


Figure 3-22: Polyhedra Pressure Build Up

Table 3-12 shows the results obtained from this test with the % values now representing the difference to the base case results achieved in section 3.2.12.

Table 3-12: Polyhedra Mesh Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
0.5669	-0.529	0.0151	-2.5945	15.1	-0.097	-15.4952	-97

3.2.14. Meshing Methods

Along with the Octree mesh, there is the Delaunay method. This employs a slightly different process in which a face mesh is initially generated with a volume fill afterwards. This method produces very good quality meshes due to a lack of arrangement in their structure which also greatly reduces the number of elements required to get a good quality mesh meaning a much faster solve time.

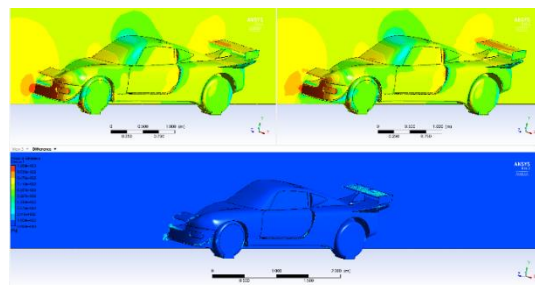


Figure 3-23: Octree vs Delaunay

Both the standard and fastback model were studied using the Delaunay method and the results shown in Table 3-13. The delta values relate to the initial runs in sections 3.2.10 and 3.2.12 and show different results than was achieved by the Octree mesh especially with the Cd value for the standard car being 80.5 counts off showing mesh refinement would be needed. As it can be seen in the pressure contour in Figure 3-23, there is very little difference between the two although it can be seen the less defined curvature on the plots in the upper right corner show that the mesh could be refined to get closer to the wind tunnel results and the validation run results.

Table 3-13: Delaunay Mesh Results

	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
Standard	0.5002	-0.6226	0.0805	-13.86	80.5	-0.003	-0.48	-3
Fastback	0.5526	-0.6642	0.0054	-0.97	5.4	0.0339	5.38	33.9

3.2.15. Centre of Pressure

With initial runs now completed on both variants of the Darrian, the centre of pressure for each type can be found. This is found by using a centre of pressure forces calculator in Fluent. To do this, half the height of the car is found (Figure 3-24) and this

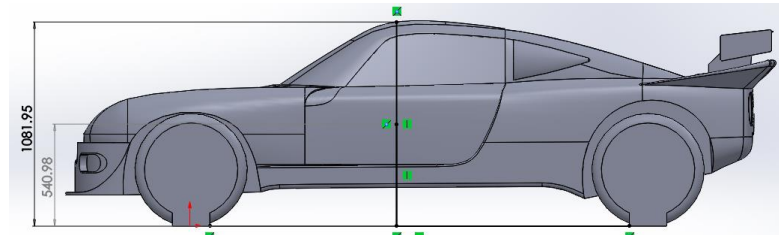


Figure 3-24: Half Height of Darrian

value input into the calculator to find the centre of pressure in the -Z plane. For the standard car, this was found to be 1.568m from the front wheel centre line and for the fastback 1.588m showing how adding the fastback has moved the centre of pressure further rearwards. Therefore, the centre of pressure can be found by dividing this value by the wheelbase of the vehicle:

$$\text{CofP for standard car} = \frac{1.568}{2.43} = 64.5\% \text{ rear bias}$$

$$\text{CofP Fastback} = \frac{1.588}{2.43} = 65.3\% \text{ rear bias}$$

To find the static margin, the CofG needs to be found. By using SolidWorks, this was found to be 1.329m (55%) from the front wheel centre line giving the static margin as 0.259m as shown in Figure 3-25. Therefore, by comparing this to section 2.1, the car doesn't meet the criteria of being aerodynamically stable meaning a large aerodynamic balance change is required with a value nearer to 50/50 aerodynamic distribution desirable although a value close to the current CofG would greatly improve the car.

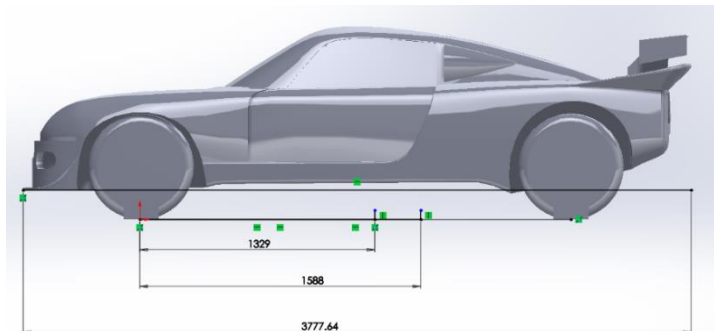


Figure 3-25: CofP and CofG Locations for Standard and Fastback

3.2.16. Wing Study

To see the effect that the wing has on the aerodynamic balance of the vehicle, a study changing the wing angle and how it affected the drag and lift values along with the CofP was conducted.

By looking at the current configuration of the Darrian, the angle of attack is currently at 10.7° and so the decision was made for values between 10° and -10° (20° angle to 0° angle).

By looking at the lift values in Figure 3-27, it can be seen a large amount was lost when the overall angle of attack was set to 0° whereas a noticeable increase was found at 15° with a small reduction from this at 20° showing that the wing is starting to stall. It can also be seen that the CofP has a direct relation to the $-Cl$ value showing how much effect the wing has on the vehicles aerodynamics. By investigating the plots in Figure 3-29 and Figure 3-28 with the 20° on the left and 0° on the right, the pressure difference across

the upper surface of the wing is very visible with a large high pressure bubble on the upper surface of the 20° wing. These results follow findings by McBeath (2015, p.137) that showed when the wing angle was increased, the downforce increased and reduced the downforce balance by moving it rearwards.

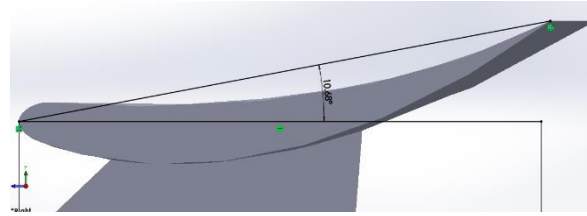


Figure 3-26: Rear Wing Angle of Attack

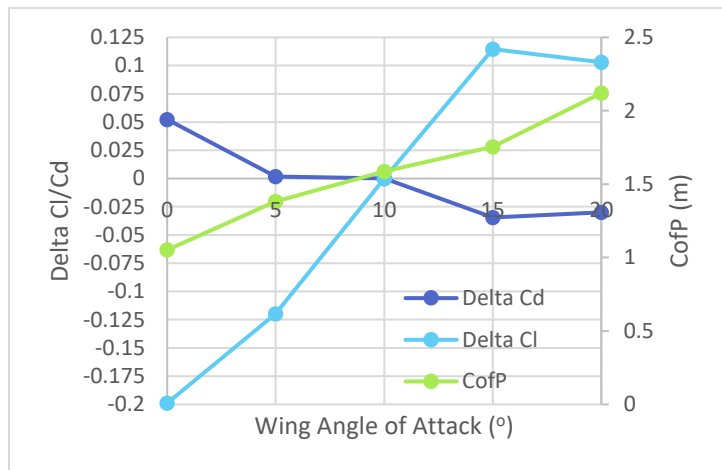


Figure 3-27: Angle of Attack Study

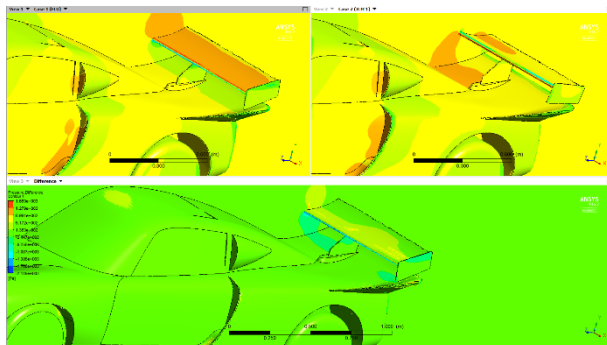


Figure 3-29: 20 and 0 Degree Case Comparison Pressure Contour

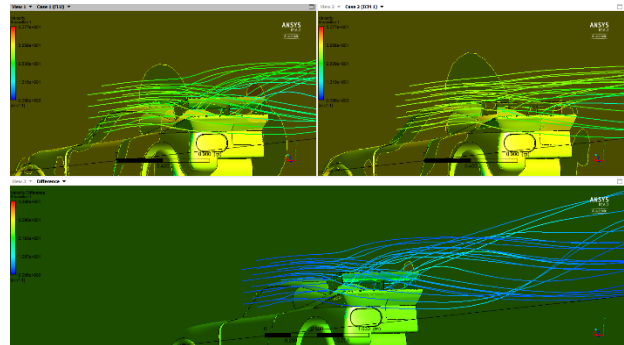


Figure 3-28: 20 and 0 Degree Case Comparison Streamlines

Even because of this, the centre of pressure changes consistently throughout the study shown by the results in Table 3-14 with the 0° angle showing the centre of pressure nearer the front of the vehicle with 5° , the CofP was found to be close to the optimal position and so reducing this wing angle would be an

option to produce a more aerodynamically balanced vehicle although this would take away downforce, reducing the vehicles performance.

Table 3-14: Wing Angle Study

Wing Angle	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP (m)	%
0	0.5057	-0.4314	0.0523	-9.37	52.3	-0.1989	-31.56	-198.9	1.052	43.29
5	0.5561	-0.5106	0.0019	-0.34	1.9	-0.1197	-18.99	-119.7	1.383	56.91
10	0.558	-0.6303	0	0	0	0	0	0	1.588	65.35
15	0.5925	-0.7449	-0.0345	6.18	-34.5	0.1146	18.18	114.6	1.754	72.18
20	0.5881	-0.7332	-0.0301	5.39	-30.1	0.1029	16.33	102.9	2.12	87.24

3.2.17. Pitch Study

To thoroughly investigate the problem presented by Darrian, a pitch study has been conducted with both wheels off the ground and one on the ground to give an idea of what might be happening to the car as it becomes aerodynamically unstable due to its overall change in angle of attack. The expected result is that as the vehicle rotates backwards, there will be a loss of downforce due to the front and rear wings having a greatly reduced angle of attack with the inverse happening as the vehicle rotates forwards until separation occurs.

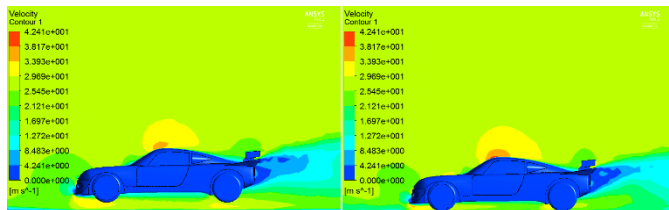


Figure 3-30: Darrian Air vs Fastback Run Velocity Contour

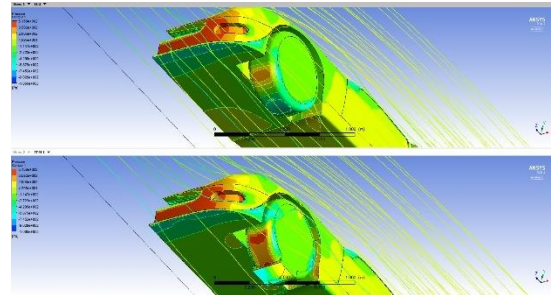


Figure 3-31: Darrian On and Off Ground Comparison

To examine the change in lift and drag, the vehicle was modelled in the air with the wheels off the ground as seen in Figure 3-30. The results in Table 3-15 show that the -Cl increased by a substantial amount. Upon further investigation, it can be seen in Figure 3-31 that as the air moves across the smooth, curved surface of the wheels the velocity increases causing a low-pressure region on both wheels effectively pulling it down. There is also a large difference in the magnitude of the velocity leaving the windscreen and going over the roof on the grounded model meaning a lower pressure region causing lift. The wake region is also quite different in both scenarios with the grounded model showing a more refined shape and although the wake is similar off the ground, it has a lower velocity region towards the centre being caused by the fact that the air going under the vehicle isn't being 'squeezed' as much as before reducing velocity and therefore increasing pressure in this region compared to the car on the ground.

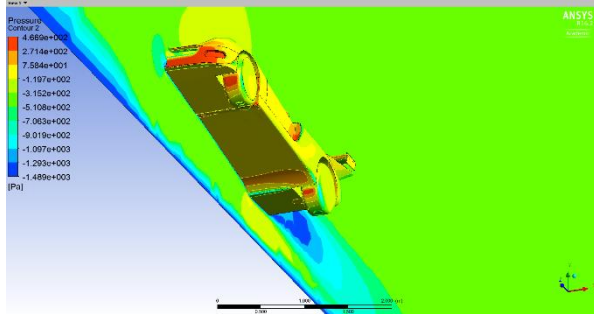


Figure 3-32: 10 Degree Pitch in Air

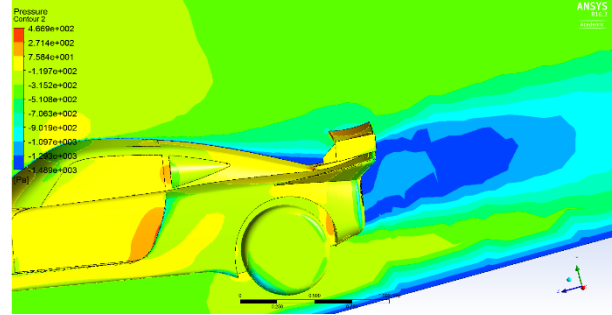


Figure 3-32 shows an extreme pitch case that caused the centre of pressure to move six metres behind the vehicle causing a large moment. Upon investigation of the velocity contour, there is a high-pressure region on the cars underside causing lift whilst the low velocity near the rear wing is producing another high-pressure region, further accentuating the rearwards moment.

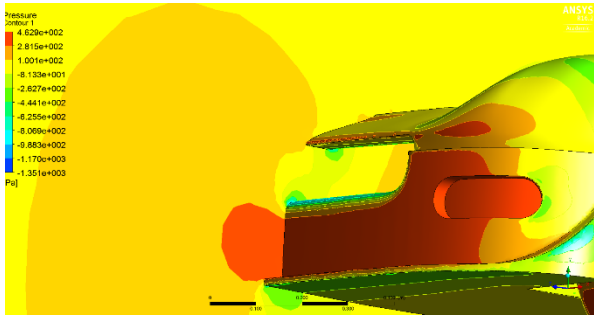
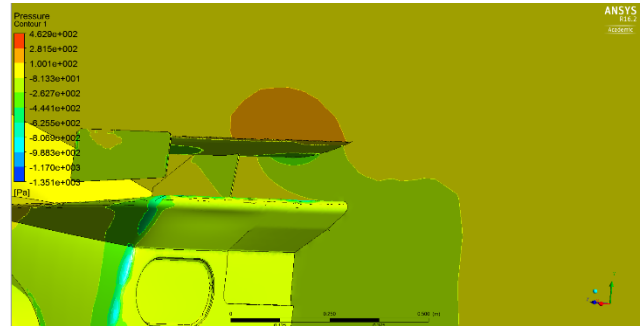


Figure 3-33: 3.3 Degree Pitch in Air



By investigating Figure 2-8, it could be seen that the car was pitching backwards over a jump. By studying the picture, the car was pitching at 3.3° . A model was setup to recreate this to assess the initial problem stated by the drivers of the vehicle. The pressure contours in Figure 3-33 show less low pressure on both the front and rear aerofoil when compared to Figure 3-19.

Both $-C_l$ and C_d values will be plotted along with CoP as this should significantly change depending on pitch angle.

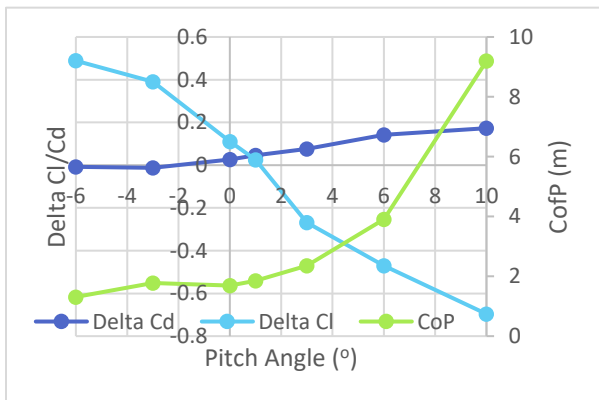


Figure 3-35: Pitch Study (Off Ground)

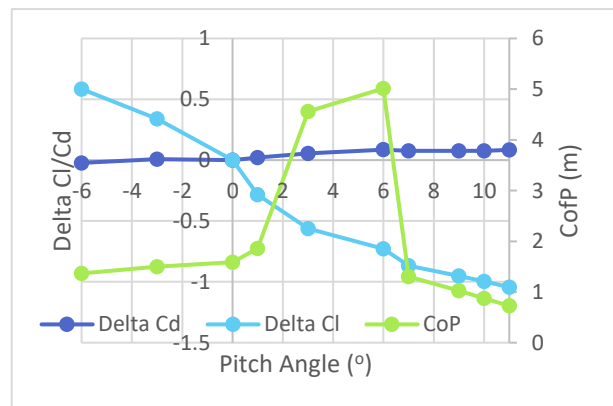


Figure 3-34: Pitch Study (One Wheel on Ground)

Both Figure 3-34 and Figure 3-35 show similar trends in the drag value as well as lift although the delta - Cl values have a larger range with one wheel on the ground compared to one wheel off the ground. Figure 3-35 shows a large increase in the centre of pressure as the pitch of the car increases with 10° showing the centre of pressure (represented by metres from the front axle) to be 9 metres showing at this angle of attack, the vehicle is highly unstable. With one wheel on the ground, the CofP shows a very different trend with a large increase at 3° and 6° pitch that rapidly decline at 7° onwards. The lift values from 7° also show a similar trend to the Cl results showing how the proximity of the rear of the vehicle to the ground produces more lift that also moves the centre of pressure towards the front of the vehicle.

The study has shown how the pitch of the vehicle has a great impact on the aerodynamic properties of the vehicle and so any chosen device will be assessed in this way in case it has a negative effect on the vehicle as it pitches over jumps.

Table 3-15: Pitch Off Ground Study

Pitch (°)	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
-6	0.5662	-1.119	-0.0082	1.47	-8.2	0.4887	77.53	488.7	1.3099	53.91
-3	0.5704	-1.0214	-0.0124	2.22	-12.4	0.3911	62.05	391.1	1.773	72.96
0	0.5307	-0.7406	0.0273	-4.89	27.3	0.1103	17.5	110.3	1.694	69.71
1	0.5125	-0.6555	0.0455	-8.15	45.5	0.0252	3.998	25.2	1.852	76.21
3	0.4819	-0.3616	0.0761	-13.64	76.1	-0.269	-42.63	-268.7	2.353	96.83
6	0.4163	-0.1596	0.1417	-25.39	141.7	-0.471	-74.68	-470.7	3.91	160.9
10	0.3849	0.066	0.1731	-31.02	173.1	-0.696	-110.5	-696.3	9.194	378.4

Table 3-16: Pitch On Ground Study

Pitch (°)	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
-6	0.5805	-1.2144	-0.0225	4.03	-22.5	0.5841	92.67	584.1	1.369	56.34
-3	0.5503	-0.9703	0.0077	-1.38	7.7	0.34	53.94	340	1.496	61.56
0	0.558	-0.6303	0	0	0	0	0	0	1.588	65.35
1	0.5376	-0.3454	0.0204	-3.66	20.4	-0.285	-45.2	-284.9	1.856	76.38
3	0.5014	-0.0679	0.0566	-10.14	56.6	-0.562	-89.23	-562.4	4.558	187.57
6	0.4722	0.0985	0.0858	-15.38	85.8	-0.729	-115.63	-728.8	5.014	206.34
7	0.4807	0.2382	0.0773	-13.85	77.3	-0.869	-137.79	-868.5	1.305	53.7
9	0.4821	0.3222	0.0759	-13.6	75.9	-0.953	-151.12	-952.5	1.025	42.18
10	0.4819	0.367	0.0761	-13.64	76.1	-0.997	-158.23	-997.3	0.875	36.01
11	0.4732	0.4136	0.0848	-15.2	84.8	-1.044	-165.62	-1044	0.726	29.88

This study quite clearly shows the problems that the current Darrian experiences with very small changes in rearwards pitch causing a dramatic change in the vehicles CofP and therefore aerodynamic balance. As the car has a more rearwards weight distribution, this will accentuate this effect leading to further complications.

Along with this, the study also shows that if the car was raked forwards then the $-C_l$ value increases significantly with both a forward shift in the CofP and without a large drag penalty and so (ride height permitting) this could be a change made by the team.

3.2.18. Splitter Study

As suggested by the literature review in 2.3.1, an extended splitter was modelled to see if any benefits could be gained from a simple device. The study looked at different lengths as well as thicknesses.

Figure 3-36 shows the difference in flow velocity with a 25mm and 100mm splitter. The flow from the 100mm splitter has excited the air more leading to an increase in velocity and therefore effectiveness although this has been balanced by affecting the air flow going over the front of the vehicle and so the net gain in downforce is very low.

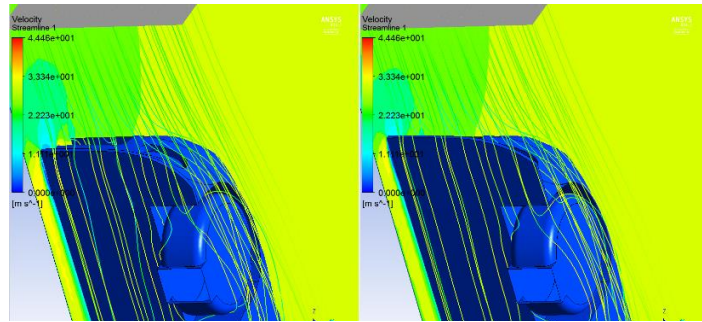


Figure 3-36: 25mm Splitter vs 100mm Splitter (Length)

Figure 3-37 shows the pressure differences along with streamlines on the two extremes of the splitter thickness study. The two pressure contours show very similar results on the vehicles surface with only the streamlines leaving the vehicles sides being the only noticeable difference due to their interaction with the curved surface in front of the wheel.

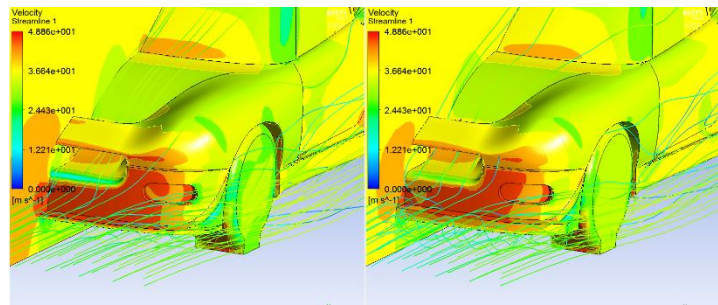


Figure 3-37: 20mm vs 50mm Splitter (Thickness)

The results show that very little benefits could be gained by changing the thickness and length. Some produced unexpected results due to this splitter interfering with other aspects of the vehicle as well as some runs not producing usable data. This is similar to results found in a study by McBeath (2015, p.67) that showed on a basic NASCAR model, the splitter length had very little effect on the downforce even though this vehicle is in close proximity to the ground.

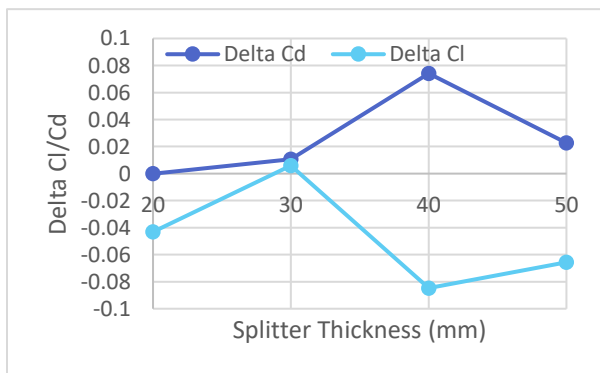


Figure 3-39: Splitter Thickness Study

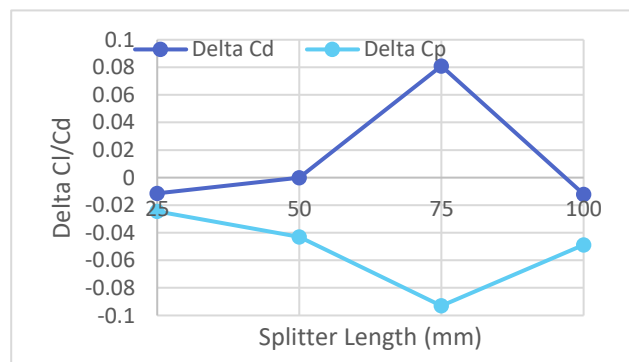


Figure 3-38: Splitter Length Study

Figure 3-38 and Figure 3-39 show the low variance in results apart from the 40mm thickness and 75mm length that produced results that were not expected. By looking at the acquired values, both lift and drag for these runs are lower than expected. This is likely due to poor elements within the mesh distorting the result.

The only noticeable improvement was found with an extended 50mm splitter with a thickness of 30mm (twice standard). By looking at Figure 3-40, the main increase in downforce can be seen by the splitter supporting the high-pressure bubble caused by the stagnation zone at the front of the vehicle.

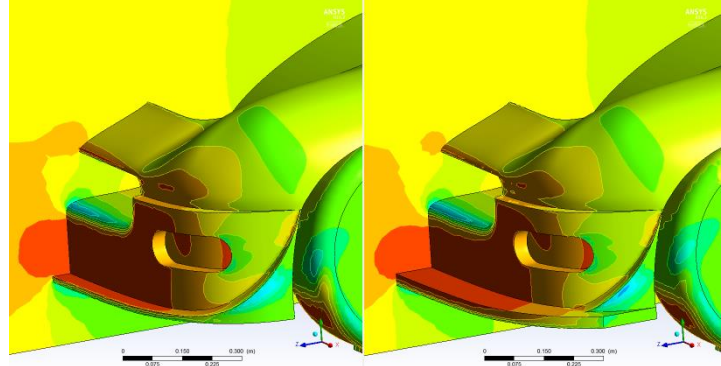


Figure 3-40: Standard vs 50mm length, 30mm thickness splitter

Table 3-17: Splitter Length Study

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
0.5581	-0.5872	-1E-04	0.018	-0.1	-0.0431	-6.84	-43.1	1.638	67.41
0.5473	-0.6362	0.0107	-1.92	10.7	0.0059	0.94	5.9	1.6568	68.18
0.4839	-0.5456	0.0741	-13.28	74.1	-0.0847	-13.44	-84.7	1.756	72.26
0.5354	-0.5646	0.0226	-4.05	22.6	-0.0657	-10.42	-65.7	1.537	63.25

Table 3-18: Splitter Thickness Study

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
0.5695	-0.6058	-0.0115	2.06	-11.5	-0.0245	-3.89	-24.5	1.601	65.88
0.5581	-0.5872	-1E-04	0.018	-0.1	-0.0431	-6.84	-43.1	1.638	67.41
0.477	-0.5373	0.081	-14.52	81	-0.093	-14.75	-93	1.6308	67.11
0.57	-0.5814	-0.012	2.15	-12	-0.0489	-7.76	-48.9	1.6041	66.01

A further study was conducted on a splitter extended sideways as seen on the Medi-Cell team Darrian T90 GTR+ to investigate whether the team's efforts to balance the vehicle by increasing the front downforce worked.

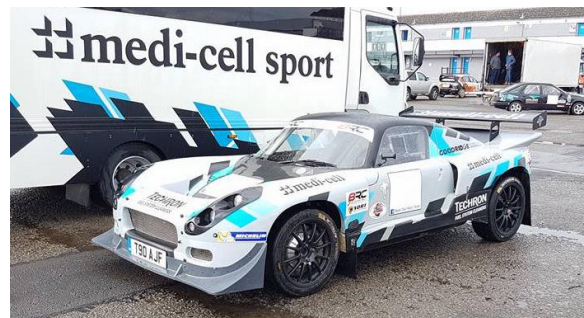


Figure 3-41: Source: Twitter. Credit: CAM Autos

By investigating the pressure contour plot in Figure 3-42, the splitter on this model is forcing air into the wheel well causing lift with an increased drag penalty. Further implications of this design show how the splitter causes a large disturbance in the air flowing along the side of the vehicle which also affected the flow on the rear wing, also reducing downforce.

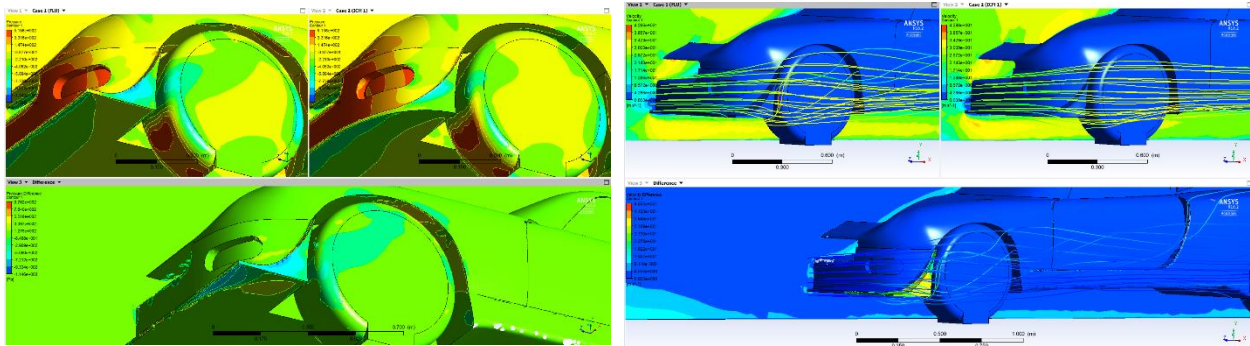


Figure 3-42: Extended Splitter Contours and Streamlines

But due to the current model not taking into the account the facelift and so new features of the GTR+, the changes made may negate this effect although the study conducted on the available CAD model showed a negative effect.

Table 3-19: Bib Splitter Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
0.5988	-0.5406	-0.0408	7.31	-40.8	-0.09	-14.23	-89.7	1.657	68.19

The main reason for a lack of improvement using the splitter is due to the ride height of the vehicle. As Katz (2006, p. 208) witnessed, a vehicle with smooth underbody flow will have both drag and lift decrease depending on vehicle height. Therefore, the splitters extra surface area cannot be utilised in this way which has meant that the pressure differential between the upper and lower surface is not great enough to affect the aerodynamics significantly.

3.2.19. Mesh Problems

Several problems were encountered through the project when any aero devices that caused a significant amount of turbulence were run in Fluent. Through further investigation it was found the prism layers on the vehicle were causing mesh quality problems causing the solution to diverge and in extreme cases Fluent to produce an error. Therefore, the decision was made to not use prism layers and so the initial fastback mesh was rerun and so results from the various device studies will be compared to this.

As the boundary layer is not being captured as effectively as before, the results will change dramatically due to the change in velocity changing the skin friction characteristics as witnessed by Katz (2006, p.104).

Table 3-20: Fastback No Prism Layers Run

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
0.5312	-0.6181	0.0308	-5.48043	30.8	-0.0319	-4.90769	-31.9

3.2.20. Aerofoil Study

One main area of the Darrian that can be improved is the aerofoil section on the top side of the clamshell. By investigating the current model, the car has a poorly shaped section that is only producing small amounts of downforce as seen by some of the previous studies. The current AoA of this section is at 22.73° that could possibly be producing stall due to the lower surface being far more cambered than the top. Also as this has such sharp change in angle, separation is more likely to occur.

Two separate aerofoils were modelled by using a co-ordinate system to plot out the points and create the 2D shape. The chord length of this can then be changed by adding a point from the trailing edge to the leading edge. The original wing profile was then cut out and the new ones positioned in the correct position. Various angles of attack were investigated ranging between 10° and 30° .

Figure 3-45 shows the NACA profile on the left and Wortmann on the right. The latter can be seen to be a thinner profile but with a larger camber, favorable for larger amounts of downforce at lower angles of attack.

The difference between the two is minimal when investigating the pressure contour although at different angles, this may change.

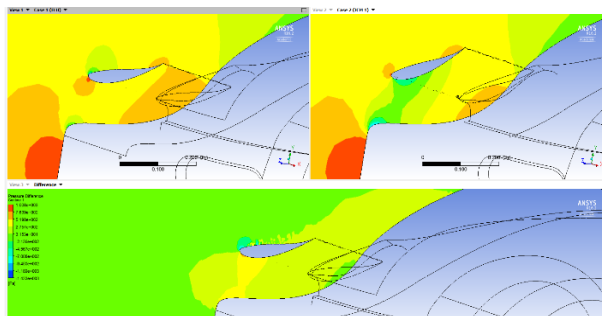


Figure 3-47: 10 vs 20 degree Wortmann

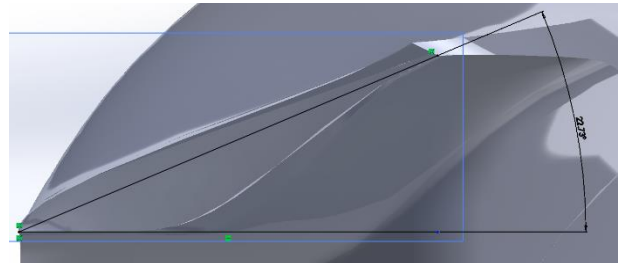


Figure 3-44: Darrian Aerofoil AoA

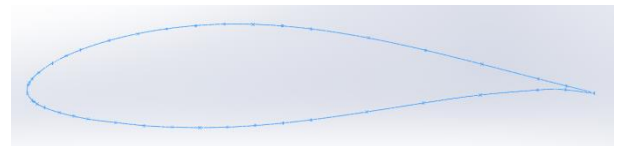


Figure 3-43: NACA 63(3) 618 Co-ordinates

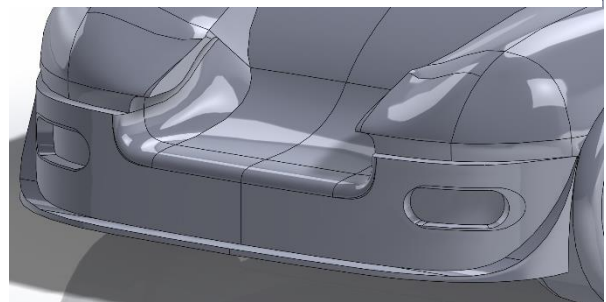


Figure 3-46: Removed Wing Section

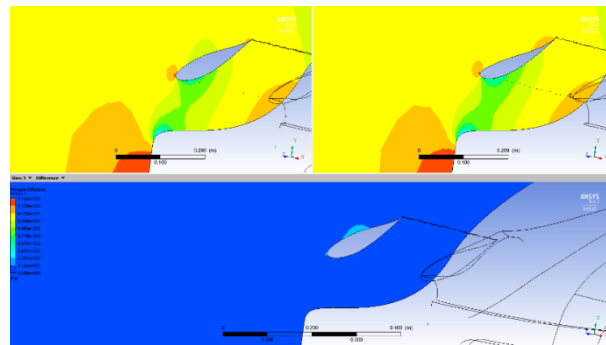


Figure 3-45: NACA vs Wortmann

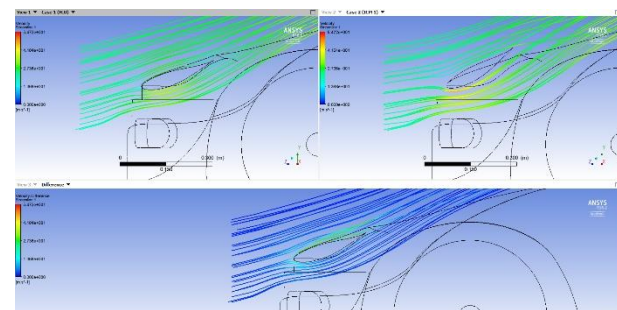


Figure 3-48: 20 vs 30 Degree NACA

Figure 3-47 shows the difference in pressure coefficient between a 10° and 20° Wortmann. There is a much lower pressure beneath the 20° and by investigating the results, more downforce was generated at this angle. Figure 3-51 shows the streamlines show 20° and 30° NACA profiles that produced very different results. On the trailing edge of the 30°, the flow starts to separate which explains the lower downforce value as a low-pressure region needed for downforce cannot be produced near this edge. This is also witnessed by Katz (2006, p. 115) which states in the sense of an aerofoil on a plane that as the flow separates, a reduction in ‘the magnitude of the suction on the upper surface resulting in a loss in lift and a large increase in drag’. This trailing edge also has the largest effect on the aerofoils performance and so attached flow in this region is vital.

A selection of pressure distribution plots were created for the basic aerofoils to investigate how the pressure changed on the vehicles surface. These can be found in appendix 5.

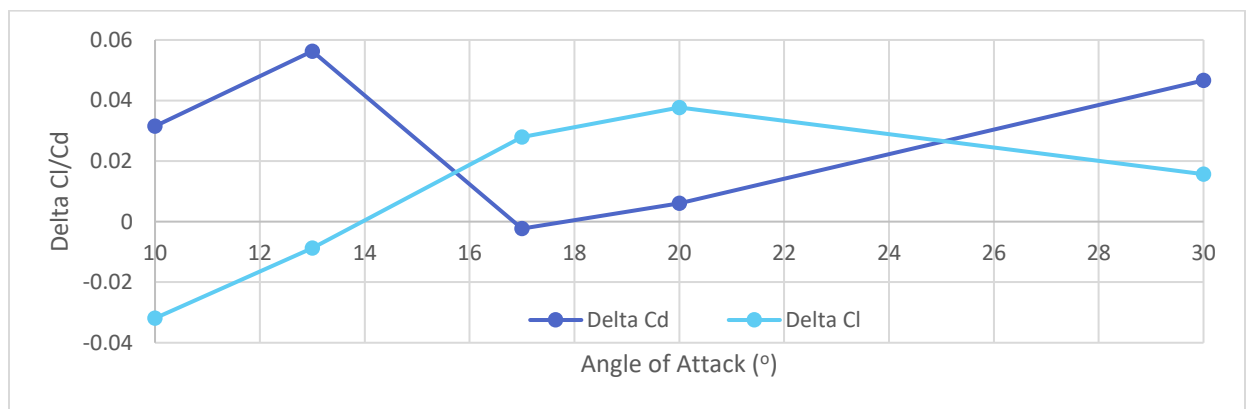


Figure 3-49: NACA 250mm Chord Plotted Results

Table 3-21: NACA 250mm Chord Results

AoA	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
10	0.5265	-0.5984	0.0315	-5.65	31.5	-0.0319	-5.06	-31.9	1.682	69.22
13	0.5017	-0.6215	0.0563	-10.09	56.3	-0.0088	-1.4	-8.8	1.582	65.1
17	0.5603	-0.6582	-0.0023	0.41	-2.3	0.0279	4.43	27.9	1.589	65.39
20	0.5519	-0.668	0.0061	-1.09	6.1	0.0377	5.98	37.7	2.03	83.54
30	0.5114	-0.646	0.0466	-8.35	46.6	0.0157	2.49	15.7	1.71	70.37

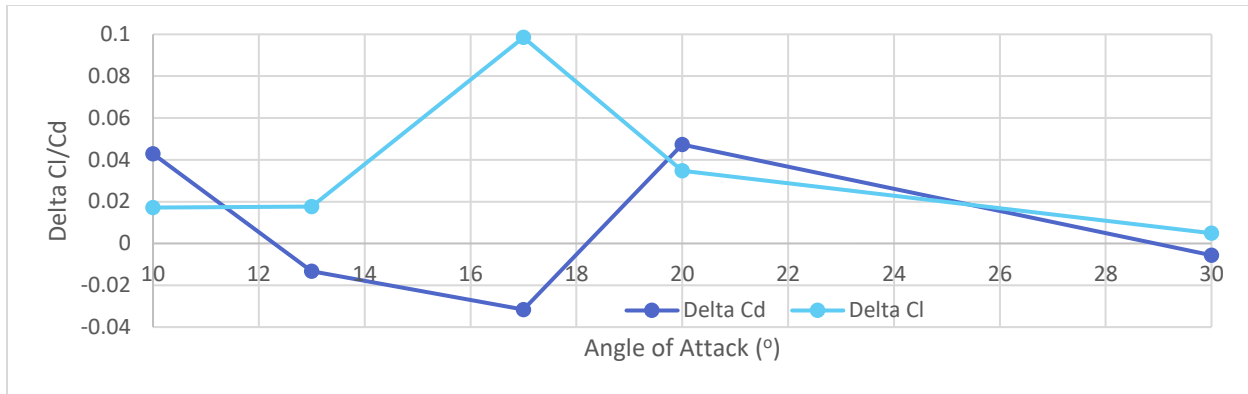


Figure 3-50: Wortmann 250mm Chord Plotted Results

Table 3-22: Wortmann 250mm Chord Results

AoA	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
10	0.5152	-0.6475	0.0428	-7.67	42.8	0.0172	2.73	17.2	1.725	70.99
13	0.5713	-0.6479	-0.0133	2.38	-13.3	0.0176	2.79	17.6	1.537	63.25
17	0.5896	-0.7288	-0.0316	5.66	-31.6	0.0985	15.63	98.5	1.793	73.79
20	0.5107	-0.665	0.0473	-8.48	47.3	0.0347	5.51	34.7	1.629	67.04
30	0.5637	-0.6352	-0.0057	1.02	-5.7	0.0049	0.78	4.9	1.682	69.22

Once these runs were conducted, the most successful designs incorporated a Gurney flap and the test rerun to see the impact this has. This was found to be the 17° and 20° for both profiles.

The larger region of pressure can be clearly seen in the top right of Figure 3-51 which has contributed to the downforce value by causing a larger pressure differential on the aerofoil section due to the reduction in boundary layer thickness on the suction side as observed by Katz (2006, p. 143).

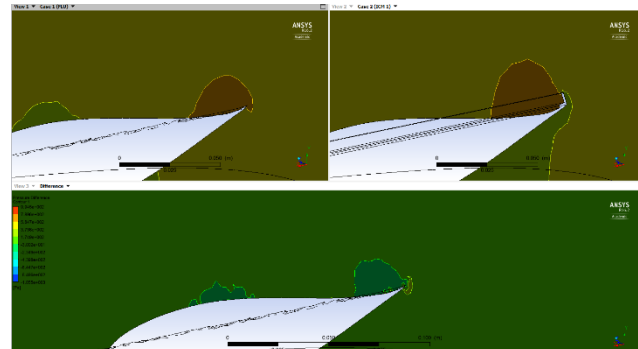


Figure 3-51: Gurney Flap Pressure Contour Comparison

Table 3-23: NACA 250mm Chord Gurney Results

AoA	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
17	0.5271	-0.635	0.0309	-5.54	30.9	0.0047	0.75	4.7	1.836	75.56
20	0.5508	-0.6707	0.0072	-1.29	7.2	0.0404	6.41	40.4	1.579	64.98

Table 3-24: Wortmann 250mm Chord Gurney Results

AoA	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
17	0.5504	-0.6563	0.0076	-1.36	7.6	0.026	4.13	26	1.662	68.4
20	0.5656	-0.6177	-0.0076	1.36	-7.6	-0.0126	-2	-12.6	1.577	64.9

Along with this, the aerofoil section was moved up into less disturbed air to see what impact the positioning could produce a positive effect as Figure 3-45 shows how the low-pressure regions interacting with each other, causing the low pressure to act on the upper surface of the bodywork causing lift. This was also observed by Katz (2006, p.260) that also stated that the drag penalty also remains meaning moving the aerofoil should have a positive effect on both lift and drag.

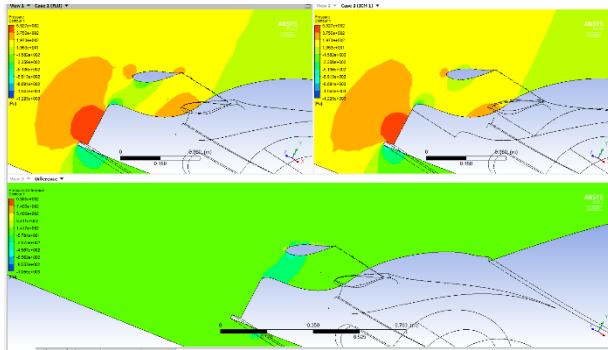


Figure 3-53: Standard Position vs Moved Up and Back

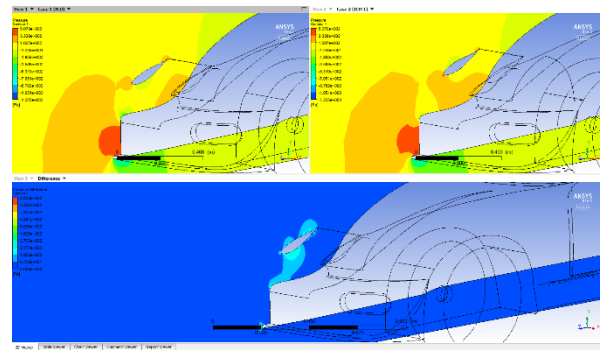


Figure 3-52: Moved Up and Back Further Case Comparison

By moving the aerofoil towards the back of the car and upwards, the interaction between the two was reduced. Even though this was the case, the results show that only the NACA 20 moved up slightly produced similar results to the NACA in the standard position although with an increased drag penalty. With it moved up further, the effect is reversed albeit with a larger reduction in downforce. The Wortmann profile shows that wherever it is moved, it doesn't impact the results although both tests have shown a significant reduction in downforce without a significant change in the CofP when compared to the results in Table 3-22.

Table 3-25: NACA 250mm Chord Placement Change Results

AoA	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
20 Moved up	0.5643	-0.6621	-0.0063	1.13	-6.3	0.0318	5.05	31.8	1.634	67.24
20 Moved Up More	0.5494	-0.648	0.0086	-1.54	8.6	0.0177	2.81	17.7	1.565	64.4

Table 3-26: Wortmann 250mm Chord Placement Change Results

AoA	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
20 Moved up	0.5648	-0.6397	-0.0068	1.22	-6.8	0.0094	1.49	9.4	1.629	67.04
20 Moved Up More	0.5664	-0.6398	-0.0084	1.51	-8.4	0.0095	1.51	9.5	1.603	65.97

As well as moving the aerofoil section to stop it interacting with other parts of the bodywork, a small 'blocker' was put around the mouth of the vehicle to stop the air flow over the lip in the bodywork. This was modelled with the aim of producing a similar result to moving the aerofoil higher.

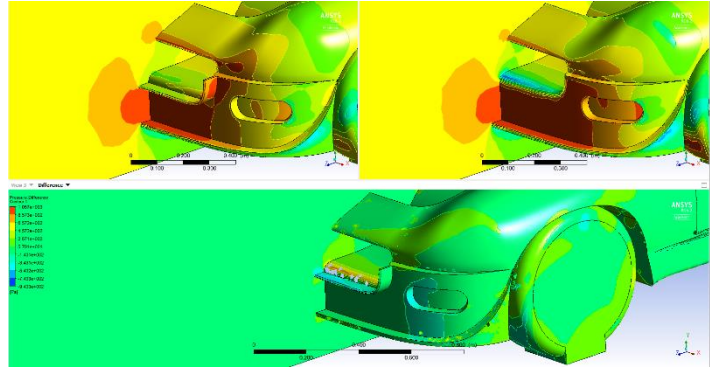


Figure 3-54: 'Blocker' Case Comparison

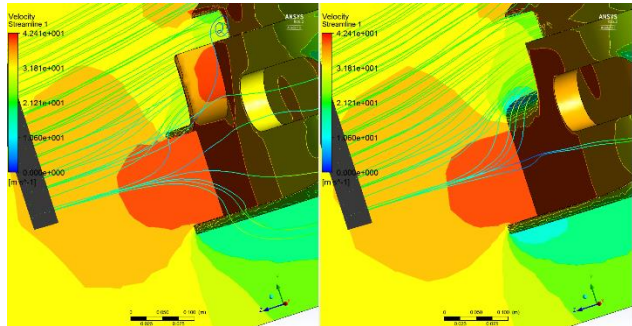


Figure 3-56: 'Blocker' and Initial Fastback Run Streamlines

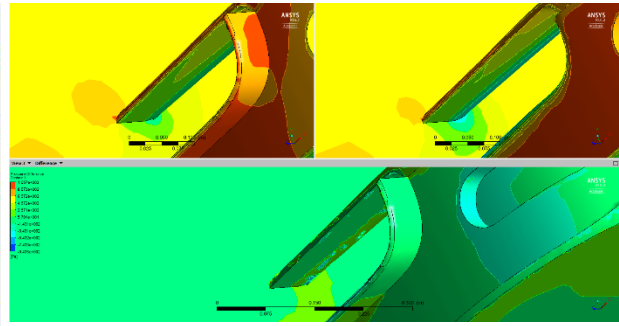


Figure 3-55: 'Blocker' and Initial Fastback Run Pressure Contour

The results show that even though the interaction between the aerofoil and the bodywork was reduced, the overall downforce value was reduced although the drag value was reduced even further than this meaning an increase in $-L/D$ value and so if a drag reduction setup was required, this could be considered. Figure 3-56 shows how the air flowing around the mouth of the standard model (right) is accelerated meaning a pressure drop on this area. The problem with this is a negative pressure on the upper surface of the vehicle is then causing lift. The 'blocker' removes this effect by slowing the air down in this area and creating a higher pressure on this upper surface. This also has a negative effect as seen by Figure 3-55 as the underside of the front aerofoil is now experiencing less low pressure resulting in reduced downforce.

Table 3-27: NACA 250mm Chord 20mm AoA Front 'Blocker' Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
0.5074	-0.5878	0.0506	-9.07	50.6	-0.0425	-6.74	-42.5	1.794	73.83

A larger chord length was also investigated with the intention of gaining additional downforce in the space provided on the front clamshell. The theory behind this is that this will increase the aspect ratio (AR) of the wing due to the span staying the same will produce a higher lift coefficient as expressed by the equation:

$$Cl = \frac{2\pi}{1 + \frac{2}{AR}}$$

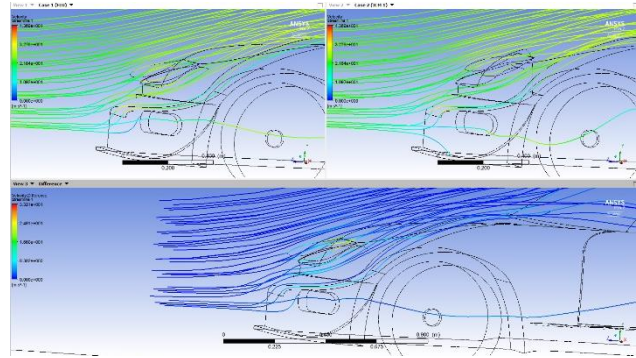


Figure 3-57: 250mm Chord vs 400mm Chord

Equation 12: Source: Katz (2006)

The results have shown an increase in drag with a reduction in downforce without a positive change in the centre of pressure meaning the aerofoil was ineffective. When investigating the streamlines in Figure 3-57 the air velocity is faster leaving the 400mm chord aerofoil although this air is then being forced to change direction immediately as it leaves the aerofoil, reducing its effectiveness.

Table 3-28: NACA 400mm Chord 20 AoA Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
0.5664	-0.6227	-0.0084	1.51	-8.4	-0.0076	-1.21	-7.6	1.652	67.98

From the study, it was shown that the 20° angle with a gurney produced an effective amount of downforce as well as marginally moving the centre of pressure forward.

By comparing it to the original in Figure 3-58, the smoother curved section of the NACA profile reduces the separation that occurs, leading to increased downforce along with a reduction in drag showing a positive net gain in the vehicles aerodynamics.

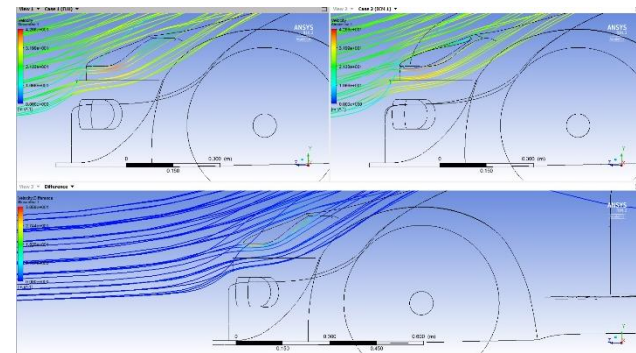


Figure 3-58: Original Aerofoil Compared to NACA 20 Gurney

Changing the aerofoil shape has been shown to have several benefits including a mild balance change in the right direction meaning other aerofoils in different positions could be investigated to see whether a larger gain could be acquired.

3.2.21. Dive Plane Study

The final study completed was on dive planes. Due to the number of variables defining the sizing and placement of the device, the decision was made to use design of experiment to allow the optimal result to be found within a much shorter timeframe by using the Box Behnken method.

As the current Darrian model has a curved splitter leading from the floor of the car to the top of the wheel arch, a smoothed model was created to allow a wider range of dive planes to be used without interference from the bodywork. This model was the run as a new base case and the results showed a reduction in downforce with a small reduction in drag although this could be counter acted by the dive planes as seen at the top of Table 3-29.

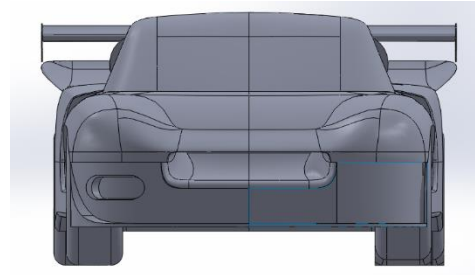


Figure 3-59: Smoothed Darrian Model

The three levels were chosen to be overall length (50-150mm), height placement on car from the splitter (15-130mm) and angle of attack (5° to 60°). These factors were chosen as these were decided to have the biggest effect on the result. Other levels that could have been investigated are the fore and aft placement on the bumper, camber of the dive planes to increase angle of attack along with number of dive planes.

With these responses input into design expert, a list was generated of all runs. This list can be found in appendix 6. All other variables within the testing were kept the same.

Table 3-29: Final Dive Plane Study

DOE	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
Smoothed	0.5302	-0.5984	0	0	0	0	0	0
Run 1	0.5613	-0.5906	-0.0311	5.865711	-31.1	-0.0078	-1.30	-7.8
Run 2	0.5272	-0.6108	0.003	-0.56582	3	0.0124	2.07	12.4
Run 3	0.5592	-0.5668	-0.029	5.469634	-29	-0.0316	-5.28	-31.6
Run 4	0.5592	-0.5668	-0.029	5.469634	-29	-0.0316	-5.28	-31.6
Run 5	0.5408	-0.5871	-0.0106	1.999246	-10.6	-0.0113	-1.89	-11.3
Run 6	0.5264	-0.6013	0.0038	-0.71671	3.8	0.0029	0.48	2.9
Run 7	0.525	-0.6136	0.0052	-0.98076	5.2	0.0152	2.54	15.2
Run 8	0.547	-0.5938	-0.0168	3.168616	-16.8	-0.0046	-0.77	-4.6
Run 9	0.5272	-0.5761	0.003	-0.56582	3	-0.0223	-3.73	-22.3
Run 10	0.5588	-0.5561	-0.0286	5.394191	-28.6	-0.0423	-7.07	-42.3
Run 11	0.5247	-0.6261	0.0055	-1.03734	5.5	0.0277	4.63	27.7
Run 12	0.5271	-0.6043	0.0031	-0.58469	3.1	0.0059	0.99	5.9
Run 13	0.547	-0.6194	-0.0168	3.168616	-16.8	0.021	3.51	21
Run 14	0.558	-0.5613	-0.0278	5.243304	-27.8	-0.0371	-6.2	-37.1
Run 15	0.5592	-0.5668	-0.029	5.469634	-29	-0.0316	-5.28	-31.6
Run 16	0.5592	-0.5668	-0.029	5.469634	-29	-0.0316	-5.28	-31.6
Run 17	0.5362	-0.5895	-0.006	1.131648	-6	-0.0089	-1.49	-8.9

Through the first runs, there were some notable results that didn't follow the trend but these were still put back into the software and a validation case created with a target -CI value of -0.6111.

Table 3-30: Poor DOE Runs

	Drag	Lift	Delta Cd	%	Counts Off	Delta CI	%	Counts Off
Run 11	0.5215	-0.6527	0.0087	-1.64	8.7	0.0543	9.07	54.3
Run 17	0.422	-0.468	0.1082	-20.41	108.2	-0.1304	-21.79	-130.4

The initial DOE run produced significantly different results than expected as seen in Table 3-31 with the -CI response value being 48 counts and 8% from the expected result.

Table 3-31: Validation Run 1

Drag	Lift	Delta Cd	%	Counts Off	Delta CI	%	Counts Off
0.5544	-0.5631	-0.0242	4.564315	-24.2	-0.048	-8.02139	-48

The poor result was put down to run 17 and so this was re-meshed and rerun (results in Table 3-29) and a second validation case modelled and trialed with a target result of -0.6242.

Table 3-32: Validation Run 2

Drag	Lift	Delta CI	%	Counts Off
0.55	-0.5993	-0.0249	-4.20608	-24.9

The results in Table 3-32 show a significant improvement although is still not within an acceptable region to validate the design of experiment method.

It was therefore decided that the -CI value produced by run 11 was too high and so this was also re meshed and rerun with a new target -CI value of 0.5942.

Table 3-33: Validation Run 3

Drag	Lift	Delta CI	%	Counts Off
0.5223	-0.5935	0.001495	0.252534	1.495

This run produced a result 0.2% from the predicted verifying the method. From this, any point within the set levels can be selected and confidence can be had from the results.

Figure 3-60 and Figure 3-61 show the best and worst run from the design of experiment (run 11 and 10 respectively). The worst on the left is a small dive plane that can be seen to produce a lower pressure underneath aiding downforce but can be seen to increase pressure in the wheel well causing lift.

The best results were obtained from a long dive plane at a shallow angle of attack mounted low down. This is likely to have had the best results due to producing vortices low down and therefore helping to reduce the airflow under the vehicle reducing lift. The difference in balance was also significant with the steep dive plane moving balance further rearwards.

By comparing this to a study by McBeath (2015, p. 201), a similar test was conducted on a Jaguar XJ-16 in a wind tunnel with opposing results attained as a shallow dive plane decreased downforce by 52 counts whereas a steep dive plane showed a 23 count decrease to the baseline with the steep showing a marked balance change forwards. The reason for the opposing results is likely due to ride height characteristics along with the Jaguar incorporating more aero devices downstream.

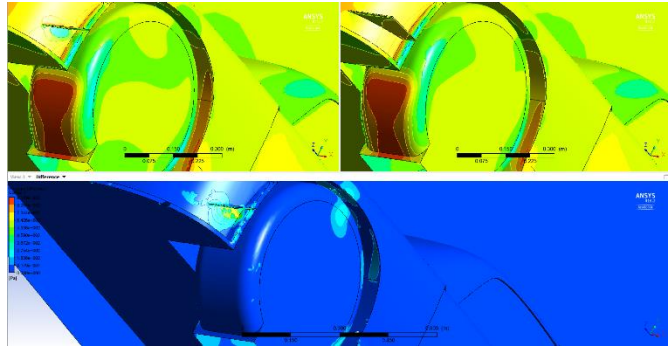


Figure 3-60: DOE Dive Planes Pressure Contour Difference

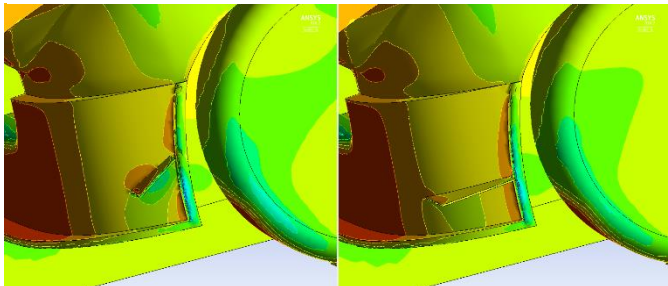


Figure 3-61: DOE Dive Plane Pressure Contour

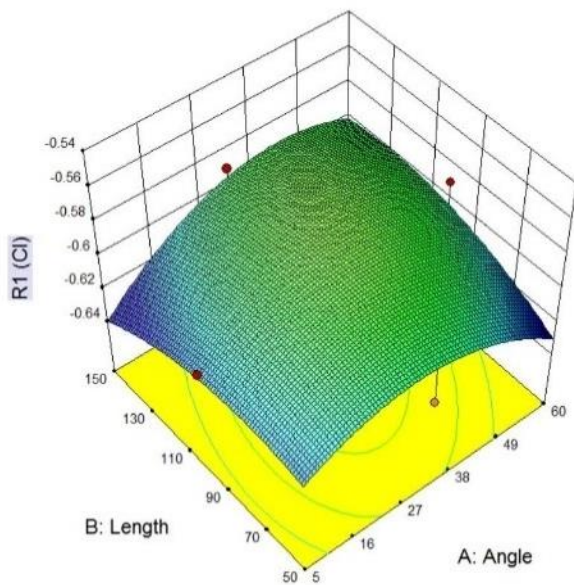


Figure 3-62: Design of Experiment 3D Response Surface

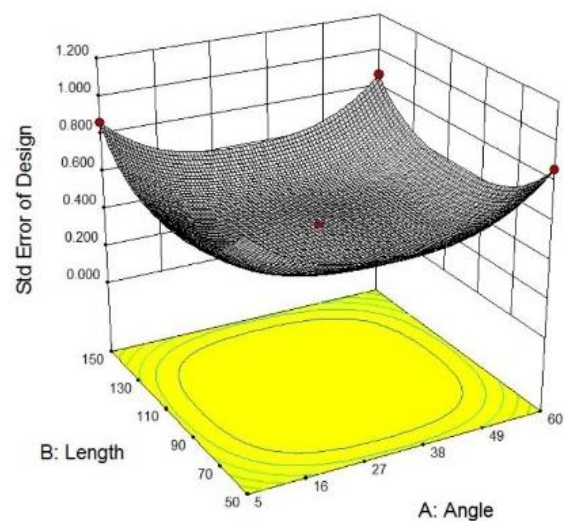


Figure 3-63: Design of Experiment 3D Error Response Surface

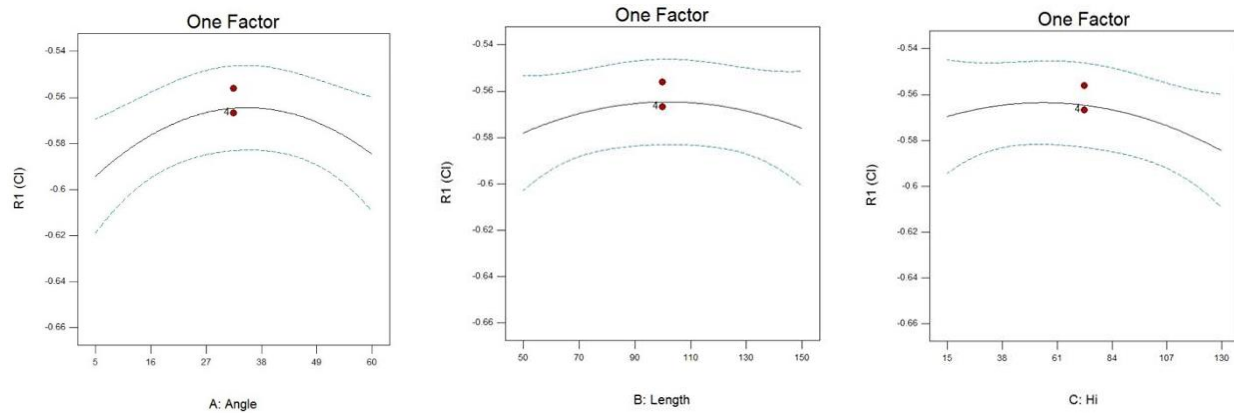


Figure 3-64: Single Factor Responses

As the results could be validated, the optimal dive plane size was then found by investigating the 3D response surface in Figure 3-62 that shows that at a height of 130mm, 5° AoA and a length of 150mm, the best result was a -CI value of 0.6417. It could also be seen that at 60° AoA and a 50mm length produced a suitable amount of downforce.

This was also confirmed by investigating the one factor responses in Figure 3-64 that show the best individual responses are obtained at the extremes of the investigation although this is less present on the height placement that shows after the median value, the higher the dive plane, the more effective it is.

Table 3-34: Predicted Best Dive Plane

Drag	Lift	Delta CI	%	Counts Off
0.5272	-0.603	-0.0387	-6.03086	-38.7

As Table 3-34 shows, the result was far from the expected although the methodology had been validated. This could be because the optimum sizing of the dive plane is at the extremes of all levels leading to the conclusion that there is a larger margin of error at the extremities of the experiment.

By looking at one factor response plots, it could be seen that the best predicted results could be acquired by the longest dive planes. Therefore (space permitting) a larger dive plane should be able to produce further downforce and so a further investigation into this should be conducted. Therefore, a dive plane with a 200mm length was modelled and the effects investigated.

Table 3-35: 200mm Dive Plane Results

Drag	Lift	Delta Cd	%	Counts Off	Delta CI	%	Counts Off
0.5585	-0.6219	-0.0283	5.337608	-28.3	0.0235	3.927139	23.5

Table 3-35 shows a marked improvement over both the predicted best result and the initial smoothed run result showing the concept of a larger area does benefit downforce due to a higher aspect ratio although the result acquired still doesn't come close to the DOE's highest predicted result, showing further error with the test conducted.

Through this study, the benefits of utilising the design of experiment methodology could be clearly seen although it was also noted how sensitive the study is to any runs that produced unexpected values and so to save time and resources, these would need to be scrutinised before the validation case.

3.2.22. Other studies

To reduce the buildup of pressure in the wheel well, an arch vent has been created to allow this pressure to bleed back out onto the cars surface.

To assess the impact of the arch vent, the wheels were set to rotate in Fluent to disturb the air within the arch and see if the vent worked effectively. This involved setting the wheels

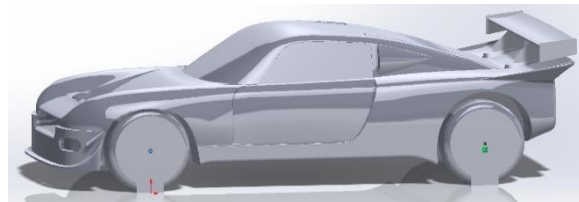


Figure 3-65: Centre of Rotation for Rotating Wheel

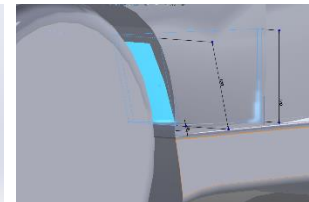


Figure 3-66: Arch Vent Dimensions

as individual parts and when setting boundary conditions, the centre point of rotation of the wheels is set along with the axis of direction and wheel velocity. This was then run and then vectors were plotted to see the magnitude and velocity in this area. The result was not as expected and so an investigation using a rotating cylinder was conducted.

A simple cylinder floating in the centre of a domain was created with the inlet velocity set to 0.0001 m/s. This would show the wheel disturbing stationary air creating the vector plot shown on the right of Figure 3-67.

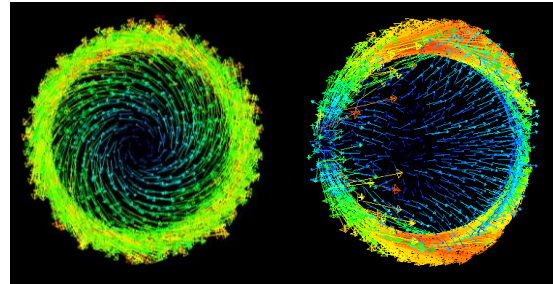


Figure 3-67: Rotating Cylinder Velocity Comparison

The inlet velocity was then set to 20 m/s with all other settings the same and the vector plot on the right of Figure 3-67 was created. The results from this showed the same as the Darrian model showing that any inlet flow velocity caused either a graphical error or a fault with the turbulence model unable to predict the flow effectively.

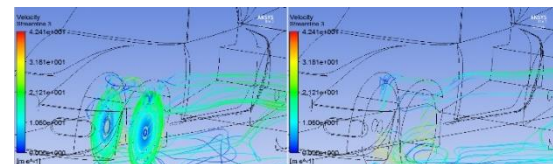


Figure 3-69: Rotating Wheels and Standard Streamlines

From this, the standard fastback and example arch vent were input into Fluent and results obtained. Throughout the run, both models started to diverge and so the Courant number and relaxation factors were reduced to compensate for this.

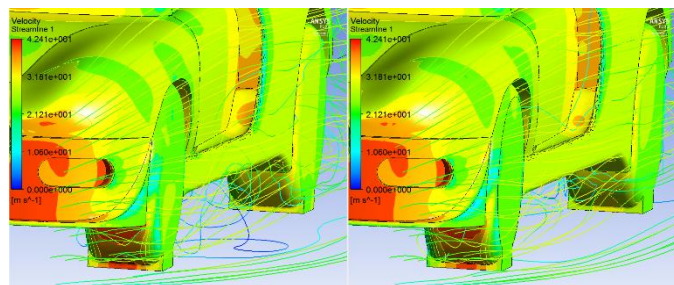


Figure 3-68: Rotating Wheels vs Stationary Case Comparison Streamlines

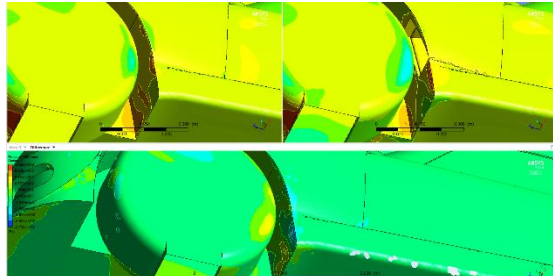


Figure 3-70: Arch Vent Case Comparison Pressure Contour

Figure 3-68 shows how the rotating wheels distort the air velocity flowing downstream of the vehicle which is contributing to the difference in results when compared to the stationary model. Furthermore, the rotating wheel is propelling high velocity air into the underside of the wheel well further contributing to the decrease in downforce.

Figure 3-70 shows the difference between the standard car with rotating wheels and the modelled arch vent. It can be clearly seen on the case comparison, less high pressure regions within the wheel arch due to the high velocity air being able to escape through the arch instead of circulating and slowing down causing high pressure regions.

From the results in Table 3-36, there is a marked improvement in the -Cl values over the standard car. It can also be seen that these results are far lower than expected. This is due to additional negative pressure on the upper surface of the wheel generating additional lift as observed by Katz (2006, p.213).

Table 3-36: Arch Vent Results

	Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off
Arch vent	0.5555	-0.6464	0.0025	0.4	2.5	0.0161	2.55	16.1
Standard	0.5123	-0.5837	0.0457	7.25	45.7	-0.0466	-7.39	-46.6

By looking back at aerodynamics on rally cars, one noticeable design is the MG 6R4 front wing (Figure 3-72). This utilises an aerofoil at a high angle of attack on the front of the vehicle to generate both downforce and direct airflow over the front of the vehicle.



Figure 3-72: Source: Flickr. Credit: Knight, R

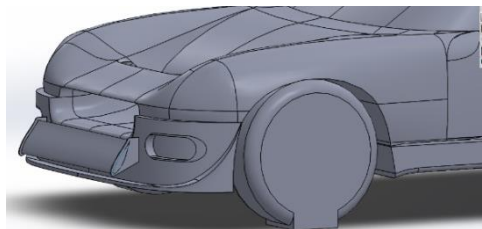


Figure 3-71: Darrian 6R4 Wing

To see what effect this would have, an additional NACA 63 (3) 618 front wing was modelled on the Darrian with a 250mm chord length and a 60° angle of attack as this is similar to the 6R4. It was mounted in a way to try and direct airflow to the front aerofoil section.

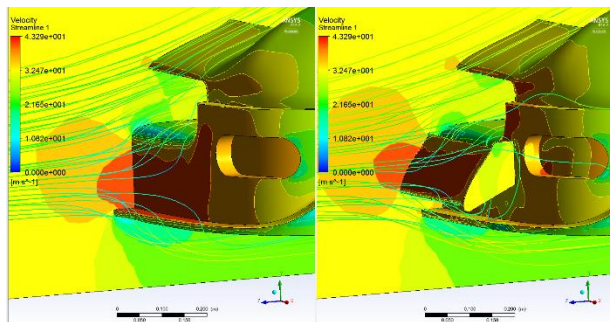


Figure 3-74: Initial Fastback Run and 6R4 Wing Streamlines

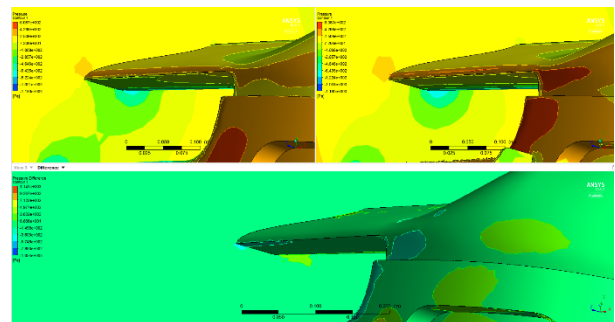


Figure 3-73: Initial Fastback Run and 6R4 Wing Pressure Contour

Figure 3-74 shows the 6R4 wing on the right producing a large high pressure region on its upper surface of similar magnitude to the one produced by the standard vehicle. But unlike the standard vehicle, the air is being pushed into the front aerofoil of the Darrian producing a lower pressure region underneath the wing as shown by Figure 3-73. Although the results in Table 3-37 show a marginal increase in downforce, the CofP was moved further backwards showing the 6R4 wing is aiding the rear wing further.

Table 3-37: 6R4 Wing Results

Drag	Lift	Delta Cd	%	Counts Off	Delta Cl	%	Counts Off	CofP	%
0.5414	-0.6663	0.0166	-2.97	16.6	0.036	5.71	36	1.78	73.25

Further studies were conducted that combined all positive elements in one model along with different variations of all devices along with certain devices that may work using basic aero principles. It was seen that none produced the desired effect due to a poor mesh quality leading to a lack of prism layers whilst others were seen to poorly interact with each other leading to greatly reduced lift values. Due to time constraints, this final model was not taken any further as it would require further optimisation to get the desired effect.

3.2.23. Aerodynamic Device Justification

To answer the initial question set by Darrian, the model that produced the most aerodynamic gain at the front of the vehicle was used for a pitch study to investigate whether the vehicle would lift less when in the air and be more aerodynamically stable.

This involved using the NACA 63 (3) 618 wing section incorporated into the front clamshell at 20° with the Gurney as this produced the most downforce with an increase of 40 counts and a marginal balance change forwards. For the study, the model will only be pitched backwards and all wheels will be off the ground as this will answer the original question as well as having a more comparable set of data from the original pitch study in section 3.2.17.

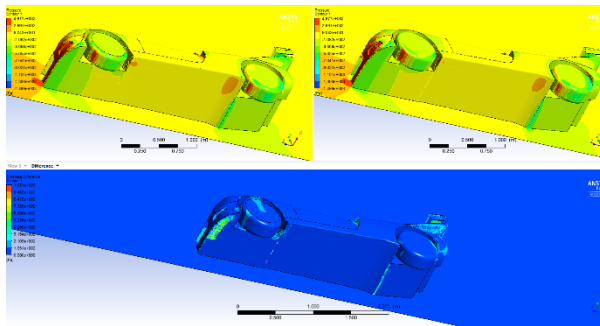


Figure 3-75: 3 Degree Pitch Comparison Front Pressure

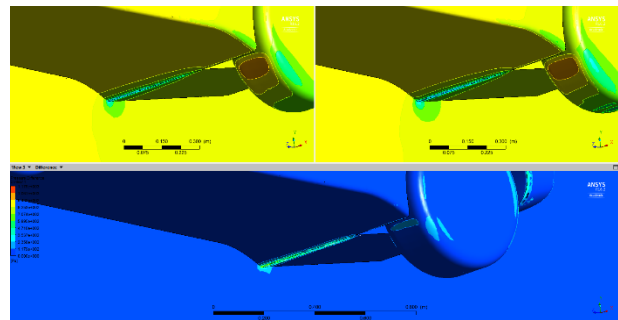


Figure 3-76: 3 Degree Pitch Comparison Rear Pressure

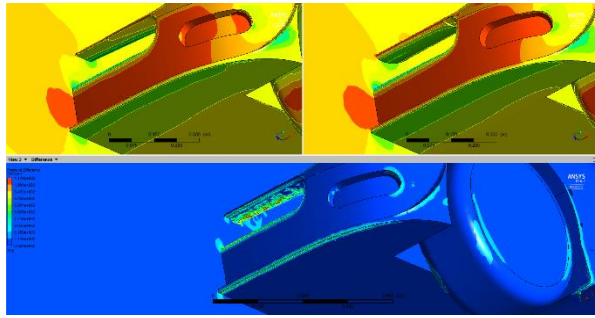


Figure 3-77: 3 Degree Pitch Comparison Front Pressure

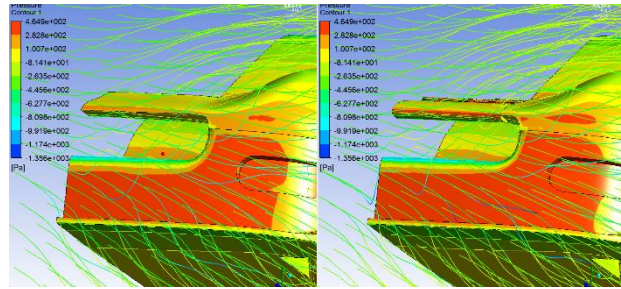


Figure 3-79: 3 Degree Pitch Comparison Streamlines

This final justification study has shown that by adding the shaped aerofoil, it has allowed the CofP to be moved further forward along with a higher overall downforce value than in the study conducted in section 3.2.17 with the results shown in Table 3-15. This has therefore shown to improve the current aerodynamic setup and with optimisation, could be further improved still. Figure 3-80 shows a similar trend to the original study whereas the lift value decreases, the centre of pressure moves further rearwards causing aerodynamic instability.

Table 3-38: 20 Gurney Pitch Results

Pitch	Drag	Lift	Delta Cd	%	Count s Off	Delta Cl	%	Count s Off	CofP	%
1	0.5152	-0.6749	0.0428	-7.67	42.8	0.0446	7.08	44.6	1.75	72.02
3	0.4858	-0.3609	0.0722	-12.94	72.2	-0.2694	-42.74	-269.4	2.253	92.72
6	0.4519	-0.2052	0.1061	-19.01	106.1	-0.4251	-67.44	-425.1	3.674	151.19
10	0.3784	0.0574	0.1796	-32.19	179.6	-0.6877	-109.11	-687.7	9.028	371.52

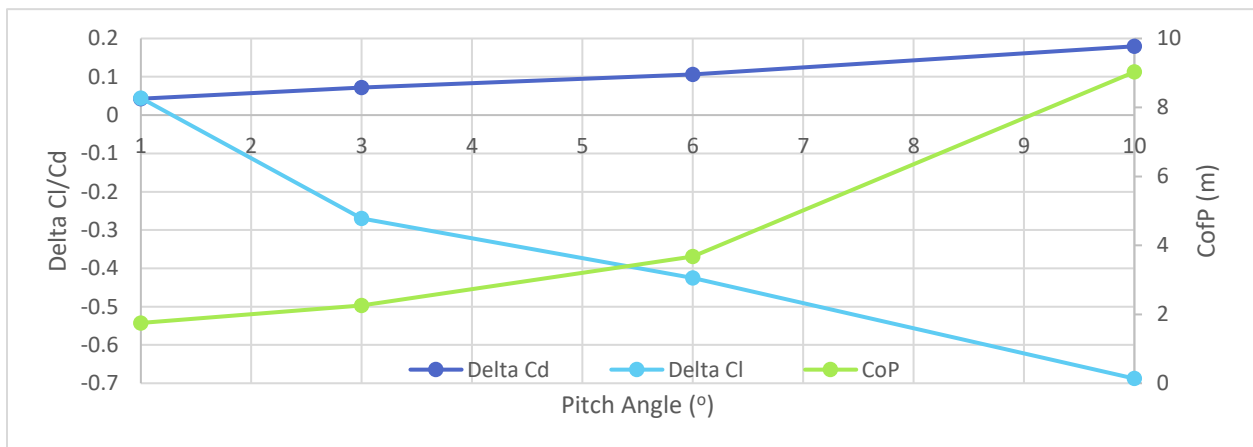


Figure 3-80: 20 Gurney Pitch Plotted Results

3.3. Recommendations for Further Work

To get a better representation of the current vehicle, an updated CAD model could be created that considers the current aero configuration for the GTR+. Another benefit of a new CAD model is that it would hopefully reduce the amount of errors within the model that caused a problem in ICEM and so a more accurate solution could be achieved and all models could utilise prism layers.

Along with this, the current car could be taken to the MIRA wind tunnel to get updated results and test a multitude of aero devices, including the suggested items in this study to verify their effectiveness. The surface of the car could then be completely pressure tapped and a pressure plot diagram generated. Using this diagram, a more accurate mesh could be created and so any added devices could be further validated.

The results showed that the biggest improvement came from changing the aerofoil section at the front of the vehicle. Although this was effective, other profiles with a higher camber angle could have been investigated as these would be likely to generate more downforce at lower angles of attack. Design of experiment could also be utilised to find the optimal profile and angle of attack. A similar method of optimization could also be conducted on the other items although their effectiveness would not be as great.

From this series of optimised devices, a model with the most beneficial devices could be created and the result investigated and changes made accordingly due to the different devices possibly having a negative effect on each other.

As the overall front downforce increase resulting in the centre of pressure moving forward was not achieved, a redesigned front would be one option to get the desired result. By redesigning the front clamshell for aerodynamic gain, there should be more avenues to explore with different devices to allow the aerodynamic balance of the vehicle to be changed.

4. Conclusion

To conclude, the study has shown that the current Darrian design isn't very susceptible to aerodynamic change with only relatively small gains being made throughout the investigation. Even because of this, there were signs of a balance change and so this research can be built upon to find an optimal solution.

The main problem noticed by Darrian was clearly shown with the pitch study with the centre of pressure moving further back as the car was pitched backwards. The items that were then added to help move this centre of pressure forward did little to help although by reducing the rear wing AoA and possibly raking the vehicle, the aerodynamic balance could be improved.

Utilising design of experiment was also seen to be very beneficial and if this method was conducted from the start of the investigation, a larger variation of devices could have been investigated with a more refined answer to the original problem found. The time saved by doing a fraction of the runs to generate a range of solutions was beneficial as witnessed by Phadke (2014) as with a total 201 runs completed with an average overall time (design modeler, meshing and Fluent solver) of 2.5 hours, a total of 503 hours of CFD has been completed with 650GB of data collected to assess the different aspects of the vehicle which would have been greatly reduced.

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6. Appendices

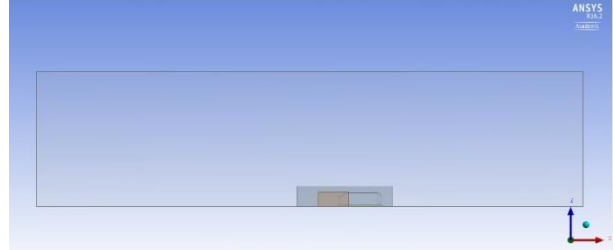
Appendix 1: Darrian Meeting Minutes

- Discussed front aerofoil section. Found previously made fibreglass panel and demonstrated the idea and we discussed how best to go about it. Talked about radiator placement as this would likely affect airflow along with stopping the air going to places it shouldn't (under front clamshell).
- Talked about splitter design and length and how, due to being a rally car, splitters are susceptible to damage.
- Talked about venting the arches and found a previously made fibreglass panel that when the front clamshell has the holes cut into it, the panel will help guide the air out.
- I suggested venting the top of the arches to help release pressure but this depended on where the debris from the stage would go.
- Discussed sheeting the underfloor to stop air going into the components under the front clamshell. Sump guard already in place so discussed whether it would be worth doing.
- Dive planes were also discussed with previously made ones placed on the car to give an idea of shape and positioning.
- Went to the mould stores and Tim showed previous splitter designs from other rally car variations and the GT style.
- Tim then mentioned how they were suffering from brakes overheating and how small ducts were added to increase effectiveness. This would need to be taken into consideration for the devices.
- Rhodri mentioned the new Darrian T90 GTR+ CAD model would be finished by Christmas.
- The new rear clamshell and wing was then discussed with the new wing profile shown.

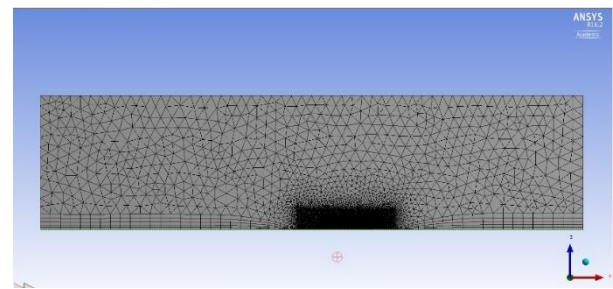
Appendix 2: Ahmed Body CFD Study

To get an idea of the meshing strategy required to produce and aerodynamic study around an object, a study on the commonly used Ahmed body was conducted using a series of tutorials to produce a set methodology that can be implemented on the Darrian.

This involved creating a domain around the body with dimensions recommended by Lanfrit (2005) of three car lengths in front, above and beside and five behind. A Boolean operation was then used to remove any unnecessary geometry to reduce the element count. The faces are then labelled with the front face the velocity inlet, rear face pressure outlet and bottom face the road. The other three faces are named as symmetries as the pattern of flow will be symmetrical in these sections.



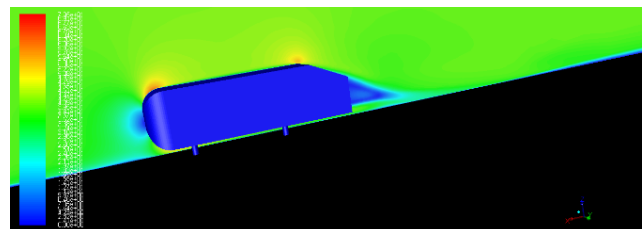
This domain was then put into the ANSYS mesher to produce a suitable mesh to gather results. This included setting the max elements size in the domain, the face sizing on the Ahmed body as well as adding prism layers to the floor and the body itself. Different boxes were then added to reduce the element size in a region of interest (under the vehicle, behind the vehicle, strong wake regions). The quality of these elements was then assessed to see if the mesh was within the suitable limits.



After the mesh was completed, Fluent was opened and the meshed domain loaded in. From here, several settings were changed to increase the accuracy of the result. This included the turbulence model which was set to the k epsilon non-realizable with non-equilibrium wall functions as used in most vehicle aerodynamic studies along with the inlet flow velocity and direction. As well as this, the frontal area of the body was calculated within Fluent using the projected areas found under the reports tab. The scheme was then set to coupled to allow the results to be acquired faster albeit with a slightly lower level of accuracy with all settings changed to second order to allow for a more accurate result. Under solution controls, the Courant number and relaxation factors were reduced to aid convergence and reduce computational time.

Drag and lift monitors were then added so that these results could be tracked through each iteration. From this, the solution was then initialized using standard settings and the simulation started.

Results such as coefficient of lift and drag values were then recorded and various contour plots generated to investigate regions of pressure and velocity.



Appendix 3: Actual Plan

Darrian Front Aero Project	03-10-16	10-10-16	17-10-16	24-10-16	31-10-16	07-11-16	14-11-16	21-11-16	28-11-16	05-12-16	12-12-16	19-12-16	26-12-16	02-01-17	09-01-17	16-01-17	23-01-17	30-01-17	06-02-17	13-02-17
Planning																				
Meet with Tim																				
Problem Analysis																				
Background Research																				
Design Research																				
Learn ANSYS																				
Read Scipy References																				
Read Darrian Case Study																				
Run Baseline Geometry																				
Develop CFD Method																				
Compare Results to MIRA																				
Domain Study																				
Mesh Study																				
Prism Study																				
Turbulence Model Study																				
Polyhedra vs Standard																				
Component Design																				
Update Darrian Geometry																				
Compare New Geometry to Baseline																				
Investigate Roll, Pitch, Yaw																				
Design New Aero Items																				
Compare New Aero to Updated Geometry																				
Design Solution																				
Progress Seminar 1 Poster																				
Interim Oral Examination																				
Progress Seminar 2 Poster																				
Dissertation Final Report																				
Final Oral Examination																				

Darrian Front Aero Project	20-02-17	27-02-17	06-03-17	13-03-17	20-03-17	27-03-17	03-04-17	10-04-17	17-04-17	24-04-17	01-05-17
Planning											
Meet with Tim											
Problem Analysis											
Background Research											
Design Research											
Learn ANSYS											
Read Scipy References											
Read Darrian Case Study											
Run Baseline Geometry											
Develop CFD Method											
Compare Results to MIRA											
Domain Study											
Mesh Study											
Prism Study											
Turbulence Model Study											
Polyhedra vs Standard											
Component Design											
Update Darrian Geometry											
Compare New Geometry to Baseline											
Investigate Roll, Pitch, Yaw											
Design New Aero Items											
Compare New Aero to Updated Geometry											
Design Solution											
Progress Seminar 1 Poster											
Interim Oral Examination											
Progress Seminar 2 Poster											
Dissertation Final Report											
Final Oral Examination											

Appendix 4: Final Mesh Settings

Domain

Size (m)	36 x 8 x 8
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Mesh

Mesh Type	Tetrahedrals
Scale Factor	1
Max Element Size (m)	1.5
Initial Prism Height (m)	0.001527
No. of Prism Layers	3
Max Element Size on Car (m)	0.01
Max Element Size on Rear Wing (m)	0.0025
Density Box Element Size (m)	0.19
Density Box Scale	X: 1.7 Y: 1.7 Z: 2
Meshing Method	Robust (Octree)
Total Number of Elements	5,986,580
Maximum Skewness	0.93
Minimum Orthogonal Quality	0.05 (1 element)

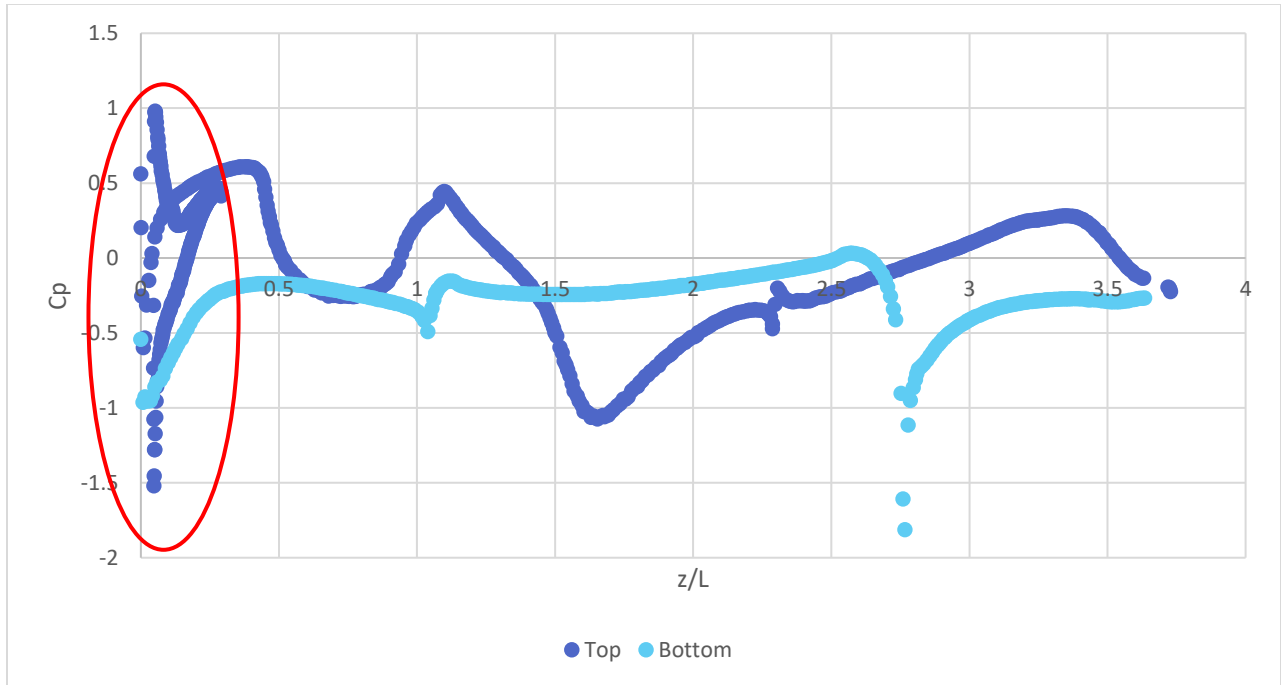
Fluent

Solver		Pressure Based, Absolute, Steady
Turbulence Model		K epsilon, realizable, non-equilibrium wall functions
Material		Fluid, Air
Velocity Inlet	Velocity (m/s)	27.5
	Turbulent Intensity (%)	5
	Turbulent Viscosity Ratio	10
Pressure Outlet	Gauge Pressure	0
	Backflow Turbulent Intensity (%)	10
	Backflow Turbulent Viscosity Ratio	10
Reference Values	Compute From	Velocity Inlet
	Area (m²)	0.7927387
	Density (kg/m³)	1.225
	Temperature (°K)	288
	Viscosity (kg/m-s)	1.7894e-05
	Reference Zone	Body

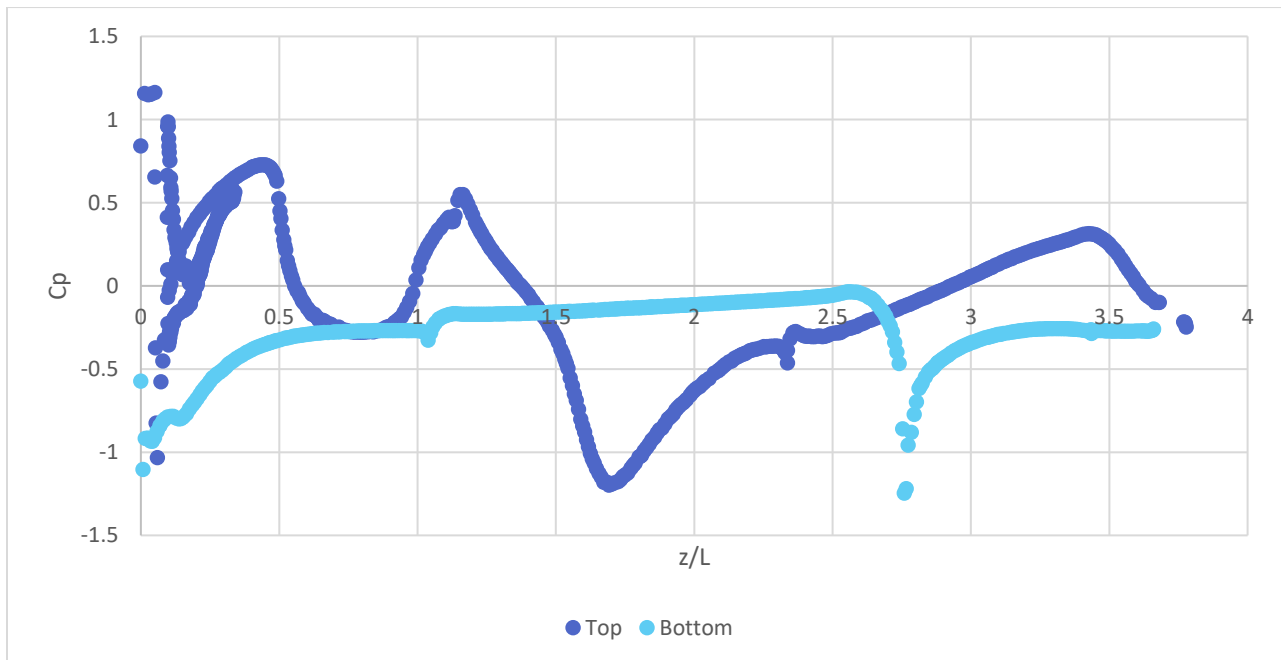
Solution Methods	Scheme	Coupled
	Gradient	Least Squares Cell Based
	Pressure	Second Order
	Momentum	Second Order Upwind
	Turbulent Kinetic Energy	Second Order Upwind
	Turbulent Dissipation Rate	Second Order Upwind
Solution Controls	Flow Courant Number	50
Explicit Relaxation Factors	Momentum	0.25
	Pressure	0.25
Under Relaxation Factors	Density	1
	Body Forces	1
	Turbulent Kinetic Energy	0.8
	Turbulent Dissipation Rate	0.8
	Turbulent Viscosity	0.9
Monitors	Drag	Print, Plot, -Z
	Lift	Print, Plot, Y
Initialization	Number of Iterations	10
Explicit Under Relaxation Factor	Scalar Equation-0	1
	Scalar Equation-1	1
	Reference Frame	Relative to Cell Zone
Run Calculation	Number of Iterations	700

Appendix 5: Aerofoil Study Pressure Plots

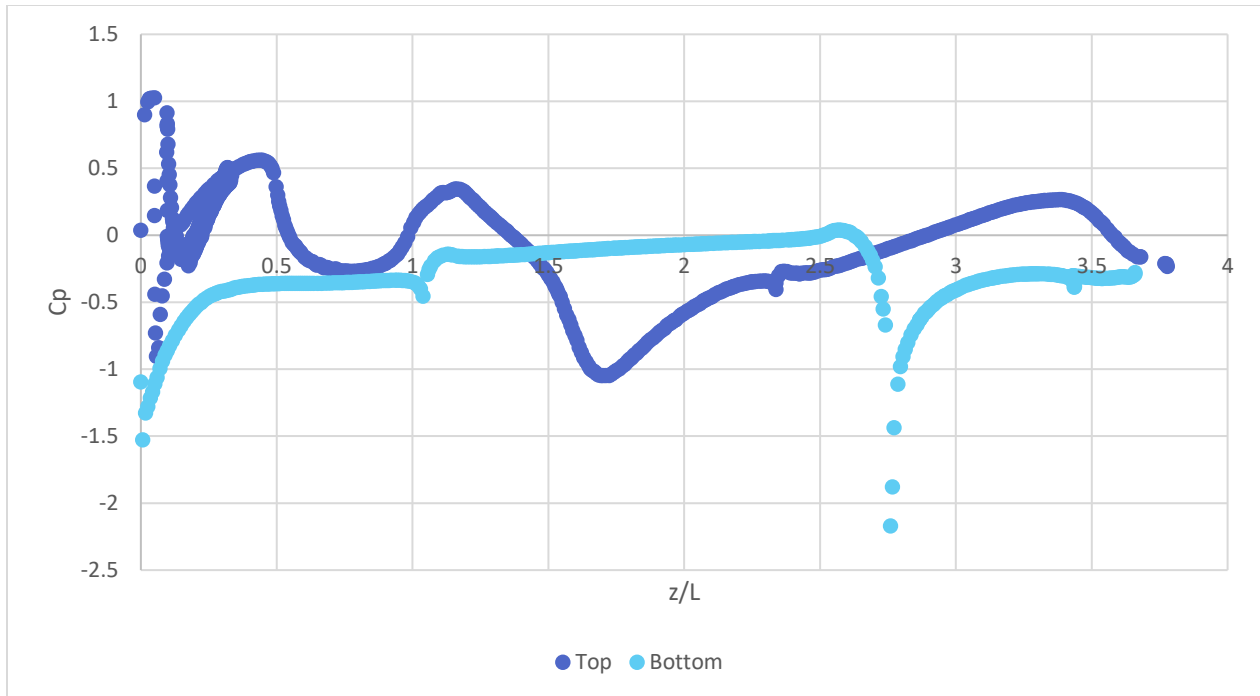
The pressure plots below represent the points on the vehicles surface with 0m representing the front of the vehicle and the end points at 3.777m. The point circled on the NACA 10 diagram is the aerofoil section and so it will be this point where the most change will occur.



NACA 10

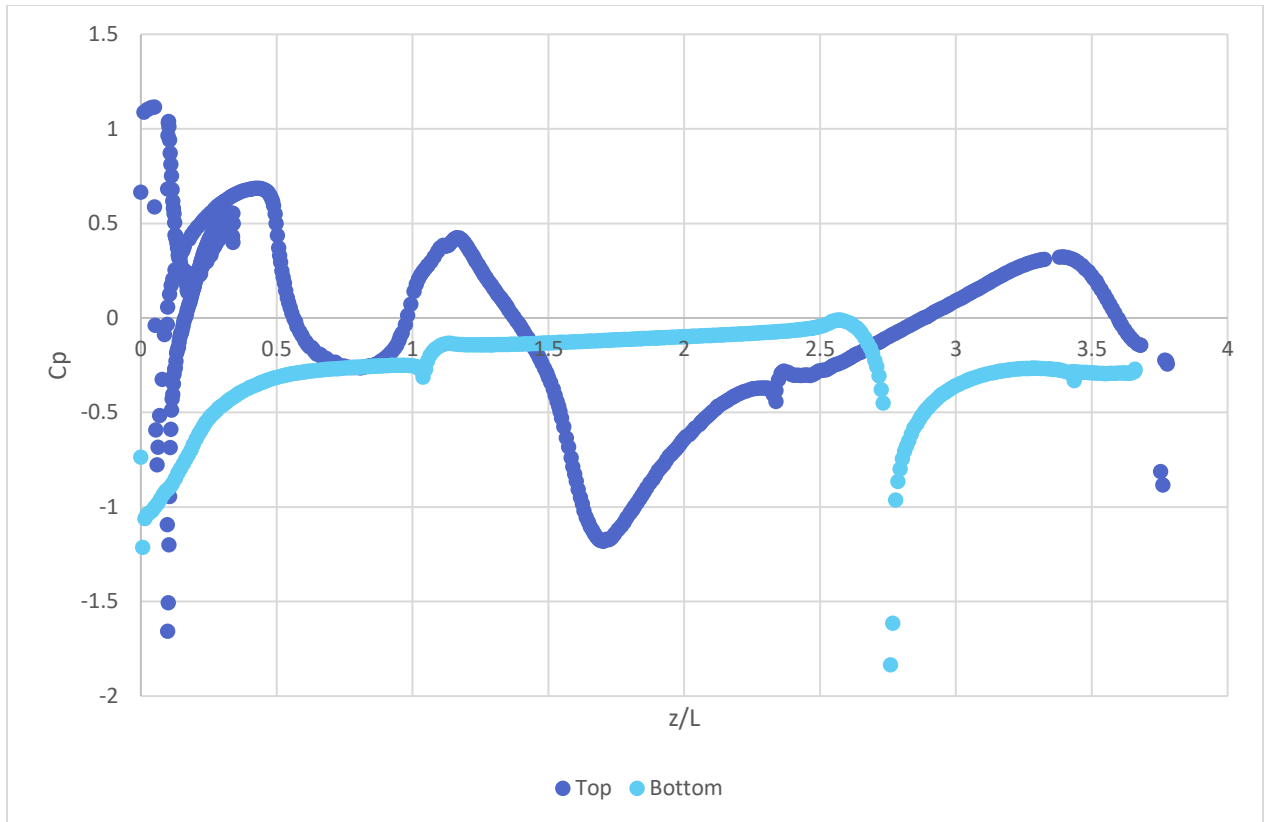


NACA 13

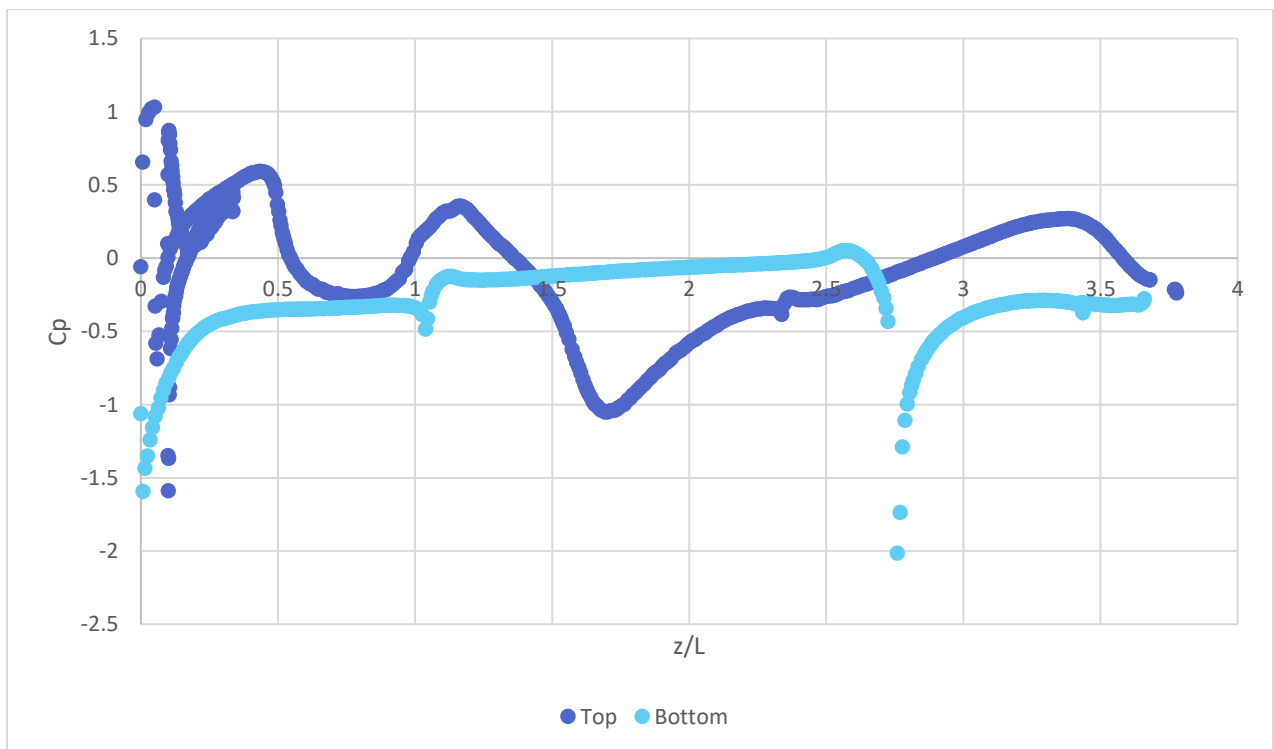


NACA 17

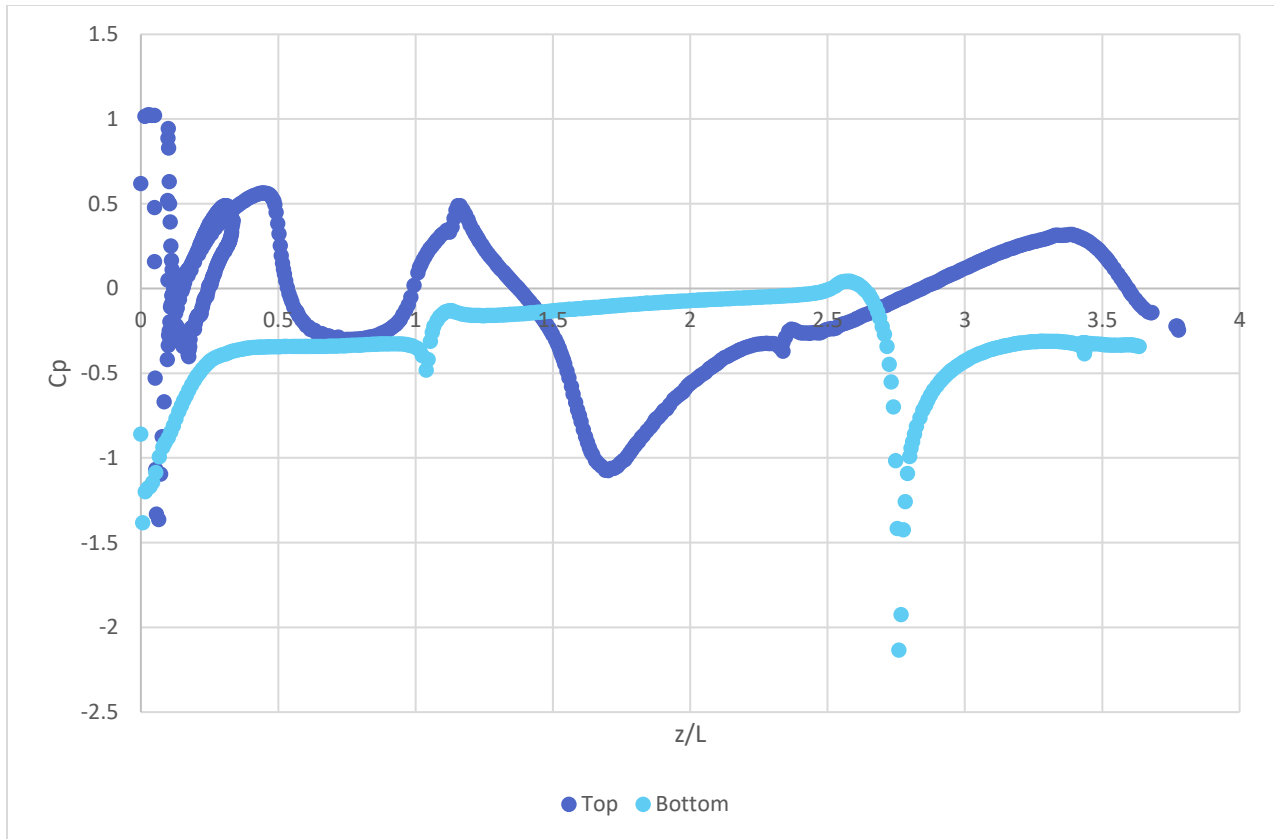
By investigating the three NACA profiles, the higher the AoA, the higher the overall pressure on the upper surface of the aerofoil section aiding downforce. It can also be noted that the different angles affect the lower surface as well as the pressure recovery on the underside of the 17 occurs much sooner down the length of the vehicle than the 13. Where the underside of the vehicle curves down, large low pressure spikes occur with these values ranging greatly between the three profiles with the 17 again showing the lowest pressure sucking the underside of the vehicle to the road.



Wortmann 10



Wortmann 13



Wortmann 17

The Wortmann profiles show a very similar story to the NACA profiles although the variation in angles doesn't seem to produce a variation in high pressure on the upper surface of the profile showing this profile is not as useful in high downforce situations.

Appendix 6: Design of Experiment List of Runs

Run	Angle of Attack	Length	Height
1	32.5	150	130
2	5	100	15
3	32.5	100	72.5
4	32.5	100	72.5
5	32.5	50	15
6	60	150	72.5
7	5	100	130
8	60	100	15
9	5	50	72.5
10	32.5	100	72.5
11	5	150	72.5
12	60	50	72.5
13	32.5	50	130
14	32.5	150	15
15	32.5	100	72.5
16	32.5	100	72.5
17	60	100	130