Analysing the effects of air flow on a formula prototype vehicle to optimize its performance

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Abstract: FSAE (Formula Society of Automotive Engineers) is an engineering design competition which challenges students to design and build their own Formula Style race-car. The race-car is being judged on basis of various criteria namely, design, cost, business and performance. For the race-car to participate in the dynamic events and traverse through different sorts of challenging tracks in the least time possible, the tyres must generate appropriate amount of lateral and longitudinal force. The car must not topple even at high speeds and needs to manoeuvre quickly. To achieve the above-mentioned criterion, there is a need of implementing aerodynamics in the car. The optimum amount of downforce necessary to execute a smooth and rapid active behaviour of our car with maximum achievable performance is to be measured keeping vehicle dynamics into consideration. In this paper, vehicle dynamics and aerodynamics are related to an extent where all the above criterion can be achieved successfully, thereby bringing about a trade-off without any sort of compromises in either of them. The co-ordination between aerodynamics and vehicle dynamics has been depicted with a detailed methodology, accompanied by Computational Fluid Dynamics (CFD) simulations of the wings and the full body of the car using STAR CCM+. Further the results has been discussed properly in the later sections of this paper. With a systematic approach, thoroughly done with several iterations on MATLAB followed by CFD simulations and analysis, the desired performance was accomplished.

1. Introduction

Vehicle aerodynamics is a broad term incorporating field that describes the forces acting on an object when it passes through the fluid. When stationary, the exterior surfaces of an automobile experience atmospheric pressure; the upper and lower surface as well as the front and rear surfaces all have the same pressures exerted and ultimately achieve equilibrium with the summation of forces being equal to zero. Under dynamic conditions, the changes in pressure create forces acting on the surface of the vehicle that may drastically hinder or improve the performance. Aerodynamicists study this natural phenomenon to try and minimize forces that inhibit motion and in some cases, develop these forces and use them to improve performance and safety [1, 2, 4, 5].

Aerodynamics concern with two major forces; lift and drag. The negative lift, in automobile industry, is commonly known as down-force. The management of these forces is crucial to the performance of any vehicle however the philosophy of vehicle aerodynamics differ significantly depending on the application. For instance, the automotive and transportation industries seek to minimize the drag force to improve fuel economy at highway speeds whereas the Formula 1 race cars also require additional down-force at a cost of induced drag, to achieve a significant increment in the performance of the car [2, 7].

Earlier, the use of aerodynamics wasn't widely known. The phenomenon of down-force was lately understood in 1960s and only the recent 40 years of implementations have been accurately justified. Race car wings were the most initial step as an added component in this field. Air flows at different speeds over the two sides of a wing (by having to travel different distances over its contours) and hence creates a difference in pressure. A phenomenon known as Bernoulli's Principle which states, 'Difference in pressure varies inversely to the square of velocity' and as this pressure tries to balance, the flow tries to move in the direction of the low pressure [4, 5, 7]. A modern F1 car can develop 3.5g of lateral acceleration and 5g of braking because of the aerodynamic down-force [3,4]. Works of many FSAE teams and their method have been successfully accepted. Chris et al in their work have described how the addition of 1000N of down-force has helped them to gain an added 40 points in the dynamic event [8]. To validate the results, its crucial to test the wings on the wind tunnel and on the tracks, as described by Wordley and Saundres [1, 6]. Studies show that in a FSAE vehicle with a full aerodynamic package (front and rear wings and under tray) generate up to 97% of down-force from the wings alone.

FSAE vehicles are often appreciated when built under following three constraints i.e. all other things being equal; the car with the lowest mass will win, all other things being equal; the car with the lowest c/g of the suspended mass will win and lastly all things being equal, the car with the lowest polar moment of inertia in all axes will win as quoted by Pat Clarke. Hence, reducing the weight, lowering the centre of gravity and centralising the weight was vital. Keeping these three factors in mind, the fact that adding the aerodynamic components adds on to the total weight of the car, violating the first rule of the above-mentioned ones. But at the same time the benefits in the performance of the car which is attained by the down-force and an increase in the stability overrules the rest [1, 3, 5, 7].

This paper addresses that how the aero package, added on the FSAE (electric) vehicle affects and governs the subsequent changes in the dynamics of the vehicle. With the addition of downforce, its known how cornering is improved, at the same time the effects due to other forces and moments have also been taken into consideration. With the help of CFD simulations, analysis has been made on how the traction can be improved due to down-force. Analysing the dynamics of the car is significant since the motion study is the key parameter to justify the designs. The vehicle when considered a point mass, has six degrees of freedom, namely: The three forces, longitudinal force; lateral force and normal force and the three moments, roll; pitch and yaw. Tyres being the most significant component, governs the motion of a car since it is the only part which interacts with the road. Therefore, forces which is produced by the tyres such as longitudinal forces and the lateral forces are directly proportional to the normal force which is generated by the wings. This is where aerodynamics come into play. Aerodynamics can not only aid in increasing the down-force, but it also helps in achieving stability. Aerodynamics and Vehicle dynamics are highly inter-related. Hence a trade-off has to be achieved considering both the facets. The car achieves a substantial amount of roll and pitch during braking, acceleration and cornering. These bring about a lot of change in the expected downforce from the inverted wings during dynamic conditions. Hence the variation of the moments is such that the performance is not compromised [3, 5, 9]. Thus, the paper revolves about attaining a balance and control on the vehicle's performance.

2. Methodology

Ground effects are extremely pronounced when the wing is kept excessively closer to the ground. Considering the same, firstly, an observation was made in changes of the pitch of the car by varying it in small quantities and plotting these variations in Cl of the wing with respect to the pitch angle. Pitch angle was then limited to that point where the wing lost almost 40% of its down-force. With this method, the pitch sensitivity of different wings was observed, which could be used for the car.

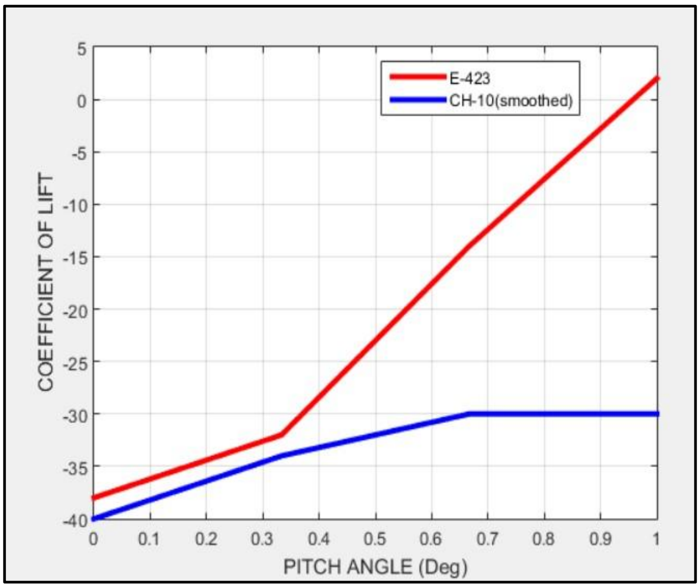

Figure 1. Simulation result at multiple pitch angles

For achieving the required down-force, it was important to select the optimum profile of an airfoil. To serve the purpose for FSAE events, high-lift and low velocity, was the most optimum criterion. In this cluster of airfoils, EPPLER (e423 and e421) and Chunch Hollinger (CH-10-48-13) were appropriate to fulfil the purpose. In order to recline to one of the former mentioned, it was significant to see their effects with fixed parameters of aspect ratio, angle of attack and the distance from the ground. The ground clearance, for any front mounted aerodynamic devices was restricted to be 30mm. Hence, the two air foils were tested for different pitch angles at a velocity of 15m/s and concluded the following plot as shown in Figure1.

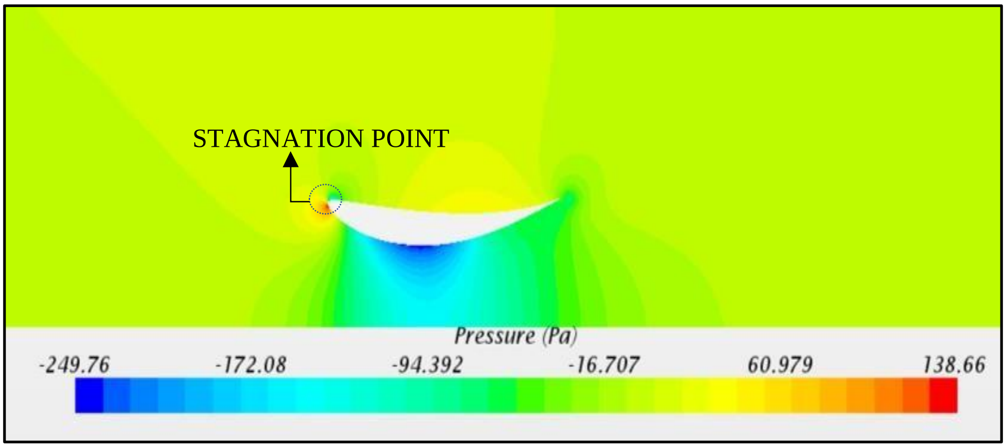

Figure 2. Pressure contour for CH-10sm at 1.2-degree pitch (60mm ground clearance)

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By observing the above plots, as depicted in Figure 1 and Figure 2, CH-10sm was chosen to serve the required purpose, since it exhibited least sensitivity in Cl (Coefficient of lift) when varied at different pitch angles.

2.1. Vehicle Parameter

Table 1. Describing the vehicle parameters

PARAMETERS	VALUES
Weight of car including driver	640 pound-force
Centre of gravity to Roll axis distance (H):	0.6397 ft.
Roll Centre height front (Z_f):	0.14435 ft.
Roll Centre height rear (Z_r):	0.15748 ft.
Front Track Width (T_f):	3.871 ft.
Rear Track Width (T_r):	3.608 ft.
Wheelbase (l):	5.2821 ft.
Static weight distribution:	50:50
Tyre Spring stiffness:	503.7 lb/inch
CG to Front axle distance (a):	2.641 ft.
CG to rear axle distance (b):	2.641 ft.
Front motion ratio (MR_f)	0.79
Rear Motion ratio (MR_r)	0.78
Lateral acceleration (A_y)	2.7 m/s^2

The friction ellipse obtained from the tyre data, depicts the coefficient of friction and its variation generated by the tyres during cornering as well as braking and acceleration. The extreme points in the contour on y-axis corresponds to the coefficient of friction during pure braking/acceleration conditions and that on the x-axis corresponds to the coefficient of friction during pure cornering (left hand/right hand). From the friction ellipse, the maximum longitudinal and lateral acceleration which can be generated by our tyres were procured.

2.2. Ride Calculations

The vehicle parameters in Table 1, desired pitch angle from CFD analysis of wings and the G-G diagram procured from the tyre data, model development for ride parameters were done using the following methodology:

With the chosen pitch values, a frontal wheel deflection of 16.9 mm and a rear wheel deflection of 15.5 mm was observed. From the friction ellipse procured by the tyre data the car could reach a maximum deceleration of 1.6g thereby producing a longitudinal weight transfer of 71.85N. A ride stiffness of 20.8 N/mm and 22.7N/mm of front and rear respectively was obtained. Using these ride rates and a tyre stiffness of 88N/mm wheel rates could be procured. Then with the desired motion ratios achieved in our geometry spring rates of 43.6N/mm and 50.2N/mm of front and rear respectively were calculated.

2.3. Roll Calculations

With the derived values from ride calculations and spring rates, the roll model was developed. Roll rates for front and the rear were derived. A front roll rate of 252.6 N-m/deg and a rear roll rate of 239.29 N-m/deg was observed. A roll distribution (Magic Number) of 0.5136 was attained. With these values of roll rates, a roll gradient of 1.1 deg/g was further accomplished. As this value was too high for the car, some additional roll stiffness-es to reduce this roll gradient and get it to our desired values was to be induced. At the same time, a very high roll stiffness could bring about wobbling of the car at high frequencies and cause fatigue to the driver after a significant amount of time or jacking in worse come worst case scenario. Therefore, a trade-off had to be accomplished. Hence a graph was plotted as shown in Figure3 where roll gradient with respect to the anti-roll bar rates was iterated based on equations (1) and (2) required to compensate for the extra roll stiffness-es needed and achieve the desired roll of the car [3, 9]. Following were the governing equations used to calculate the anti-roll bar stiffness: -

Anti-Roll Stiffness required to achieve RG_{des} (desired roll gradient) :-

$$K_{fARB} = (K_{ftotal}*12*K_t*t_f^2/2) / ((12*K_t*t_f^2/2) - K_{ftotal}) - (12*K_{wf}*t_f^2/2) \text{ (front)} \quad (1)$$

$$K_{rARB} = (K_{rtotal}*12*K_t*t_r^2/2) / ((12*K_t*t_f^2/2) - K_{rtotal}) - (12*K_{wr}*t_f^2/2) \text{ (rear)} \quad (2)$$

Where, K_{wf} :- Front wheel rate
K_{wr} :- Rear wheel rate
K_{ftotal} :- Desired Total front roll rate
K_{rtotal} :- Desired Total rear roll rate

From the below plot, a roll gradient of 1.7 deg/g was chosen and a corresponding anti-roll bar rate of 56.95 and 57.3 respectively to achieve it. An anti-roll bar besides reducing the roll of our car, it is also used to provide stability to the car by achieving a dependent suspension system for our car.

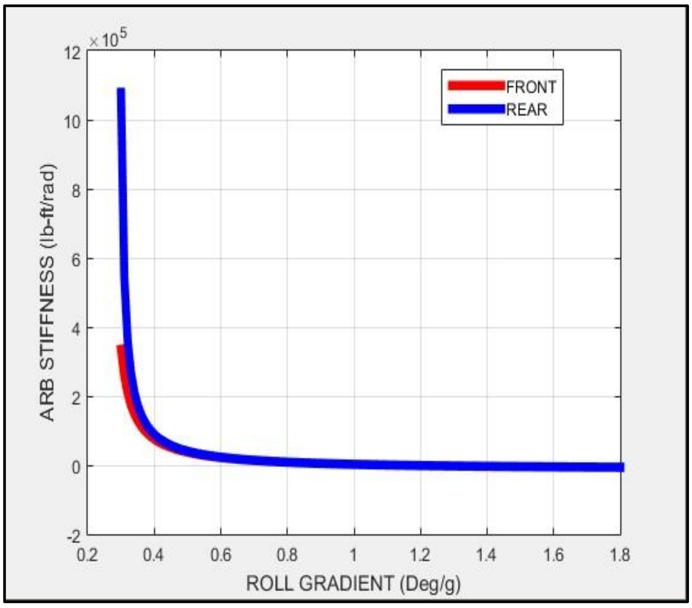

Figure 3. Iterating roll Gradients to choose an apt ARB stiffness for the car

The derived values of ride and roll rates are used to determine the dynamic load transfer at both the axles and the normal load on each tyre. Considering the minimum turning radius during manoeuvring in a Skid Pad event that is (3 m) and an average speed of our car (that is 54 km/hr), the lateral acceleration produced by the car during cornering was calculated. Also from the tyre data, it was observed that the tyres were capable of generating a maximum lateral acceleration of 2.7 g considering compliance and other unaccounted factors into this [3, 9].

$$\Delta W_f = A_y * (W/t_f) * (H * Nmag) * (b/l) * Z_f \text{ (front axle)} \quad (3)$$
$$\Delta W_r = A_y * (W/t_r) * (H * Nmag) * (a/l) * Z_r \text{ (rear axle)} \quad (4)$$

The parameters defining the variable in equations (3) and (4) obtained from Table 1, a graph for dynamic load on the inner wheels with respect to magic number (Nmag) was derived, as plotted in Figure 4.

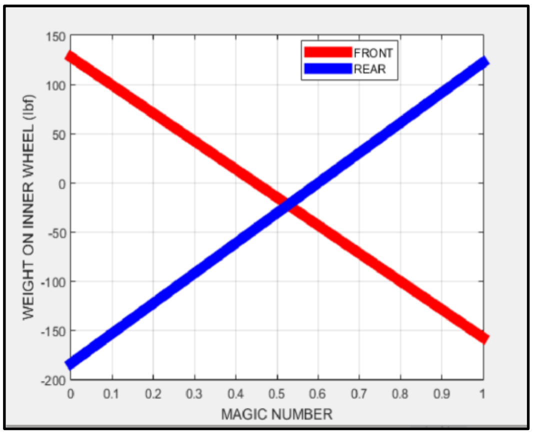

Figure 4. Load on inner wheels to know lift off condition and procure target downforce

There comes a point on the graph where the inner wheels have negative loads, that's when the car lifts off. This difference in the load from the point it just lifts off, to the point where it has the most negative load is to be compensated with the help of wings. This extra down-force which is required to prevent the car from toppling was the required target downforce.

2.4. Downforce distribution and Centre of pressure

With the value of target down-force acquired, the distribution of down-force to the front and the rear wings and hence a location of centre of pressure (COP) was to be determined. Mathematical equations were developed to satisfy certain conditions. The conditions were subjected to serve the following purposes:

1) All four wheels must stick to the ground with the respective down-force distribution.
2) All wheels must undergo equal lateral acceleration while cornering.

Using these conditions, a graph was plotted by iterating the down-force distribution. As shown in Figure 5, where the point on x-axis corresponding to the place where both lines intersect gives us the downforce distribution. The corresponding point on the y axis gives us the actual lateral acceleration achieved by all the wheels under the above-mentioned conditions. Thus Table 2 shows the distribution of the downforce on the front and rear of the car, as obtained by the location of coefficient of pressure (COP).

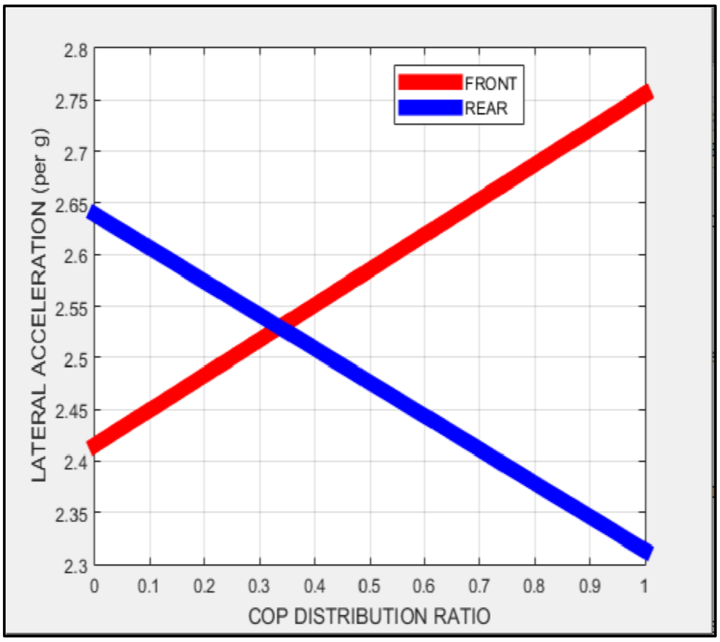

Figure 5. Iterate down-force distribution with respect to actual lateral acceleration to get COP

Table 2. Downforce distribution on the car.

DOWNFORCE DISTRIBUTION	
FRONT	35% *of* 200N= 70N
REAR	65% *of* 200N= 130N

3. Design and Analysis:

Aerodynamics not only brings about an added downforce, it also helps in tallying stability, by enhancing the flow around the car. Front wings were installed not only for adding down-force, but also to reduce turbulence allowing the flow to streamline. One very important part of the wings is the endplate. The endplate is used to direct the airflow around the front tyres, since the tyres are certainly not designed to be aerodynamically efficient and can create a lot of drag, thereby allowing the airflow to continue back to the sidepods. They also reduce the vortices generated at the tip of the trailing edge of the wing. The purpose of a multi-element wing is to produce the required amount of downforce without stalling. Thus the angle of attack was optimized by carrying out multiple simulations and the design was rendered as shown in Figure 6.

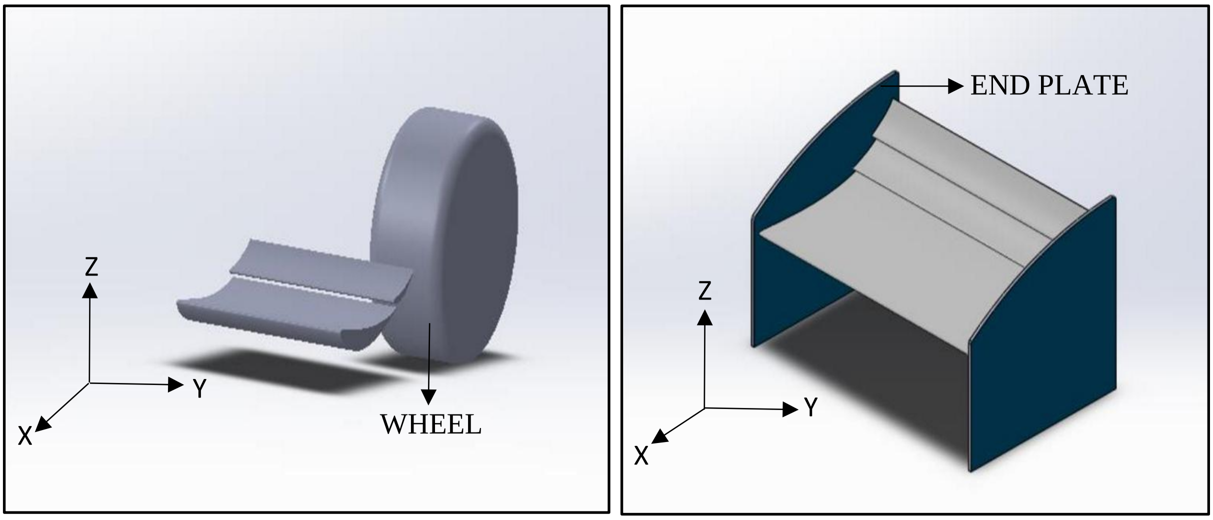

Figure 6. Front and the rear deign of the wings

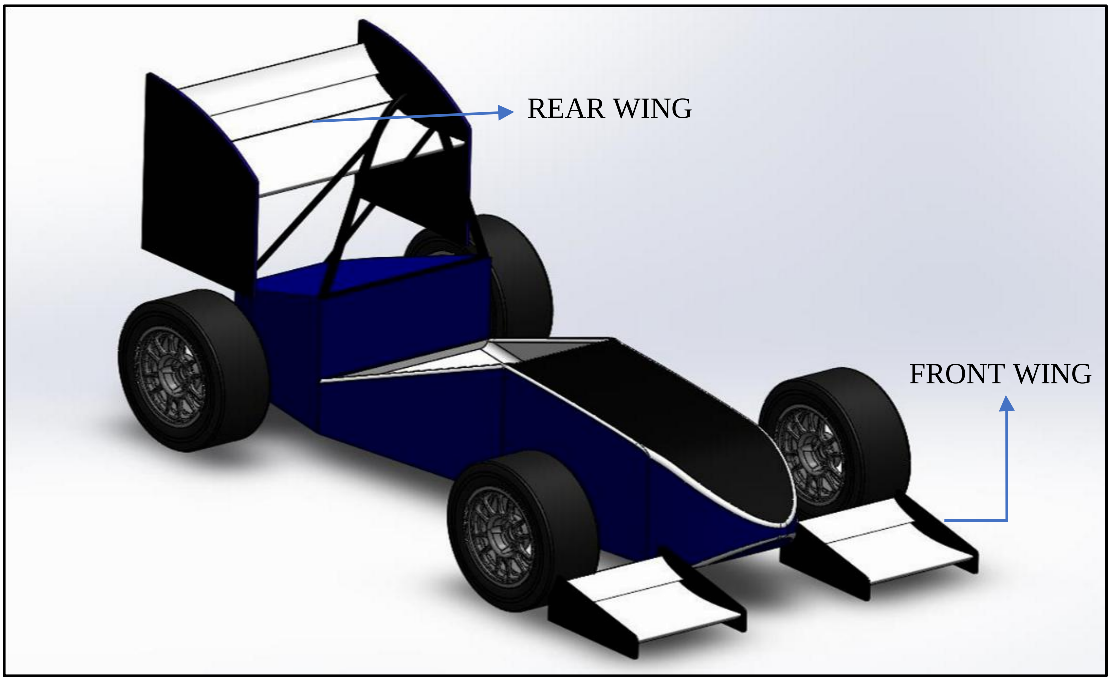

Figure 7. Bluff body of the car for CFD analysis

The down-force distribution, based on vehicle dynamics modelling, was then to be achieved by multiple iterations. To achieve 70N of Downforce on the front, double element wing with 0.05158m^2 frontal area was analysed in CFD. Similarly, for the rear, 3 element wings with 840mm of span and 0.168m^2 of frontal area was designed to reach the target. The wings were designed keeping the FSAE rules in mind. The minimum clearance for the front wing was kept 30mm and for the rear the height should lie within 1200mm from the ground. To attain the best results the wings parameter and set up was varied multiple time. For the front wing, the major concern was least possible drag and turbulent region being formed behind the wing should be minimised as much as possible in order to avoid any sort of hindrance in the flow to the sidepod (used for cooling the powertrain). For the rear, the aim was to minimize the wake region being formed behind the vehicle. A bluff body, as shown in Figure 7 was designed with the outlining features to carry out CFD simulations.

3.1. CFD domain and mesh setup

To perform the simulation, mesh parameter as shown in Table 3 was set up. In the physics model, Turbulence parameters are demonstrated using the shear stress transport (SST) (Menter) K-Omega model, coalescing the Reynolds-Averaged Navier-Stokes (RANS) equation to model the boundary layers. The surface of the car was defined Non-slip and the simulation was carried out at 15m/s. The wheels were kept rotating and the results were achieved for straight-ahead manoeuvring [10, 11, 12].

Table 3. Mesh Parameters for the model.

Parameters	Specification
Mesh Model	Trimmer/ polyhedral
Cell count	6,329,452 cells
Optimization cycle	3
Threshold quality	0.7

4. Simulation Results and Discussions

To accomplish the requirements, it was obligatory to achieve a configuration of the wing elements such that they gave us maximum downforce at an expense of minimal aerodynamic drag. The iterations converged at the arrangement shown in Figure 8. Also, the ground clearance and the rear wing height from the ground had to be decided considering the mounting points and other rules. Table 4 shows the converging results of both, front and rear wing.

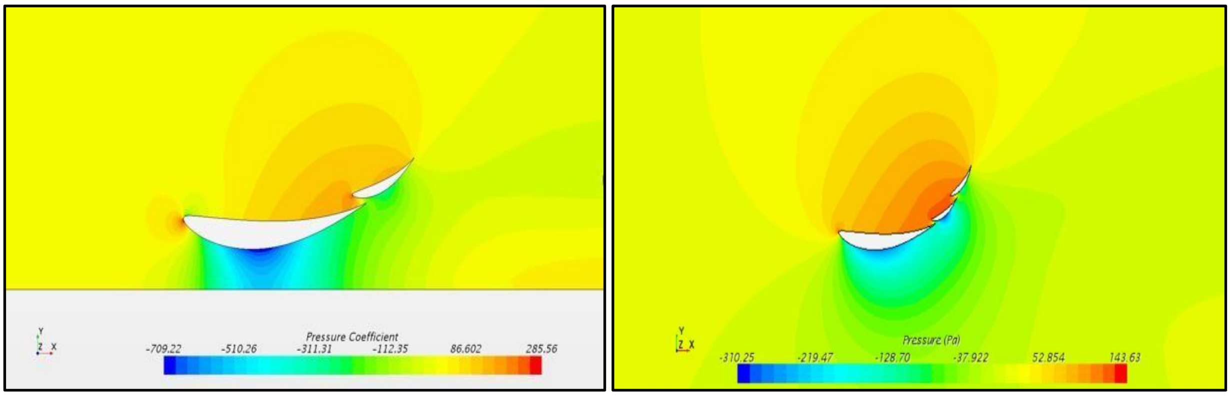

Figure 8. Pressure coefficient and Pressure contour on the front wing and the rear wing

Table 4. Simulation results

Parameters	Front	Rear
Cl	2.71	2.65
Downforce	76N	172N
Cd	0.702	0.76

Drag	16N	44.2N

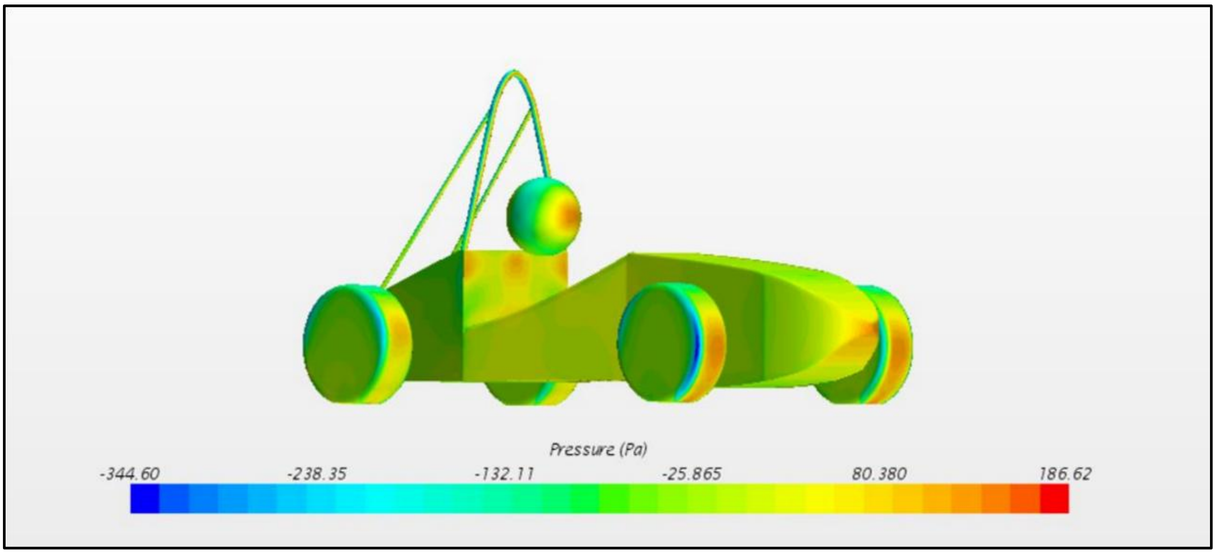

Figure 9. Pressure distribution without aerodynamic components

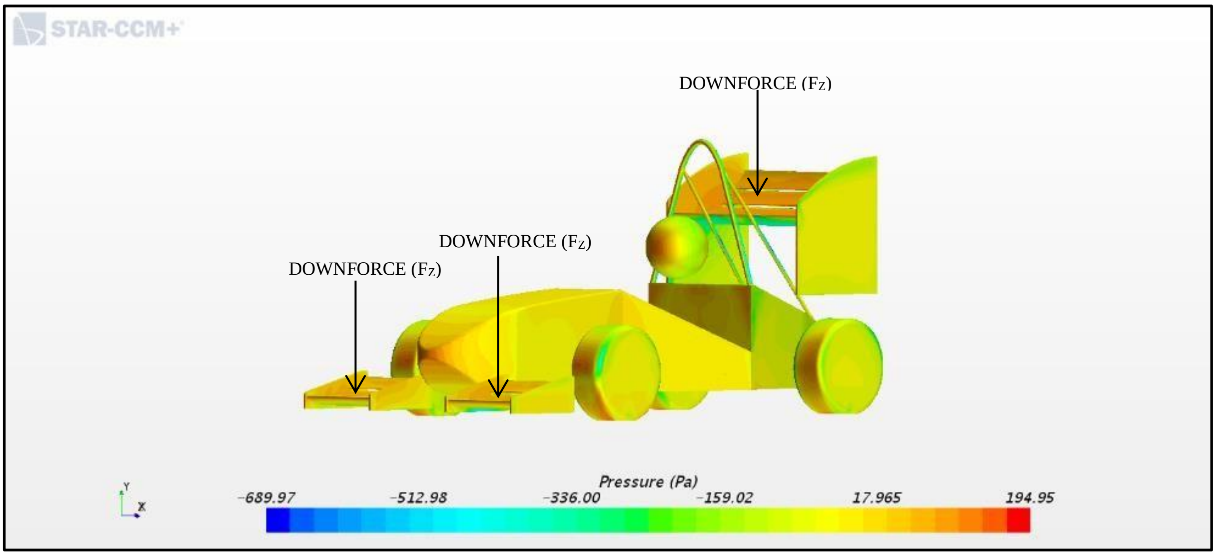

Figure 10. Pressure contour with aerodynamic components

When compared to the CFD analysis of the previous car, the one with the inclusion of aerodynamic components was witnessed to have a flow which was less hindered, which gave unbiased pressure distribution above all it generated a net downforce, in contrast to the net lift generated by the older design. The difference in the pressure contours can be seen in the Figure 9 and Figure 10, where a relative scale gives the pressure values at different points. The tip of the nose cone, with a red contour shows the high-pressure value (or the stagnation pressure value) at that point.

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In Figure 11 (a), the region around the cockpit and behind the car had an immense recirculation of the flow. With the addition of wings, the net wake region being formed in and around the car was decreased, as the flow was then directed at varying speeds and pressure. The resultant drag being experienced was comparatively more. From the simulation results, it was easy to conclude how wings have aided to improve the performance of the vehicle, as shown in Figure 11 (b). Table 5, depicts the resultant values of the force which the car experiences at 60kmph. However, these effects would be more pronounced at higher speeds.

Table 5. Comparison of the results.

	With Downforce	**Without Downforce**
Coefficient of lift	-0.76	0.54
Coefficient of drag	0.67	0.38
Normal force	-196N	24N

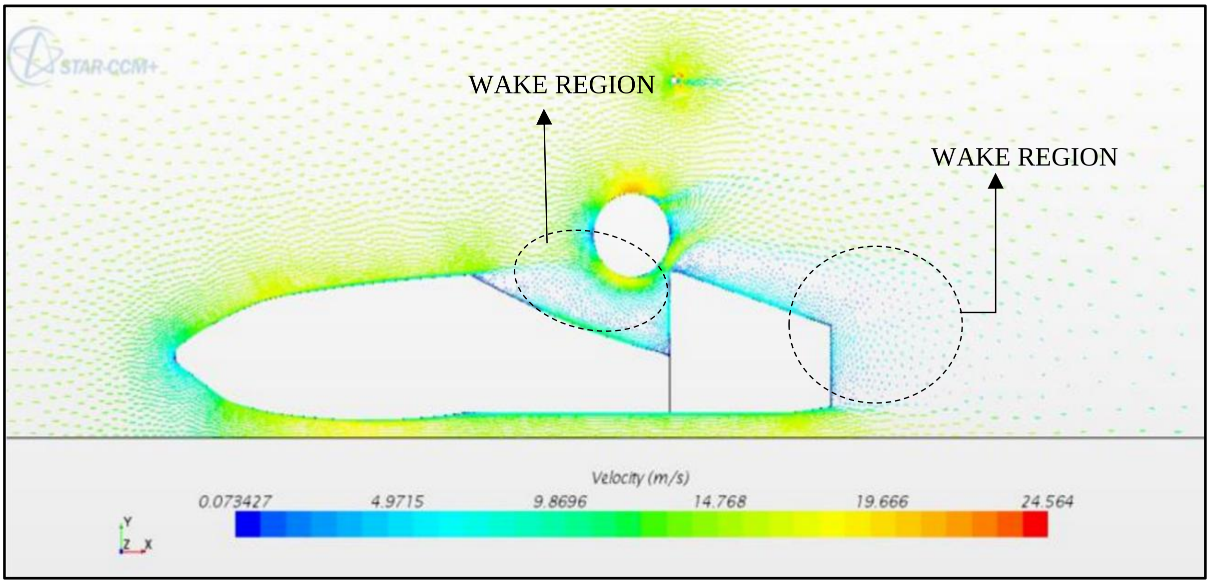

Figure 11 (a). Flow circulation around the car, without aero devices

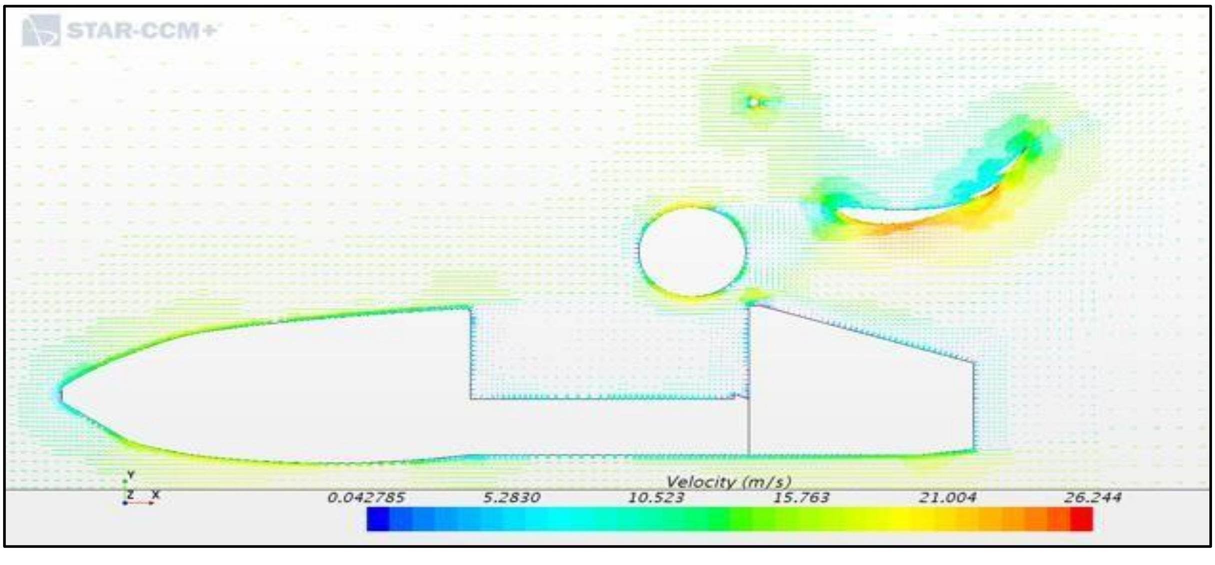

Figure 11(b). Flow circulation around the car with aero apparatuses

5. Conclusion

From the above study, it can be observed how vehicle dynamics is related to aerodynamics and the way both of them affect each other. In order to maximize the car's performance and improve its cornering capability extra downforce was achieved with the help of wings. Dynamic behaviour of the car during its manoeuvring was not compromised at any cost. Also, keeping safety and comfort as our priority, a trade-off was made between them. By achieving the required amount of downforce from the front and the rear wings, the maximum amount of lateral and longitudinal force which can be generated by the tyres was attained, thereby harnessing its full potential. The tyres used, have the capability to generate a lateral acceleration as high as 2.7g and hence it needs to be made sure that the vehicle does not topple due to the centrifugal force acting on it. As per the calculations, these wings generate an appropriate amount of downforce to keep all 4 wheels intact to the ground.

As shown in the simulations, the flow in and around the vehicle was observed to be smooth as there was no turbulence observed. The flow was streamlined since formation of wake region was not prominent after installation of wings. Undoubtedly induced drag was generated due to the wings but the downforce provided by it improved the performance of the car thereby over ruling the negative effects of the induced drag. Vehicle dynamics and aerodynamics share a relationship which is very vast and involves a lot of factors. Analysing these factors and carry out iterations based on trade-offs must be done to design an aerodynamic package and further simulate it and optimize it to achieve the required results.

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