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Tuning the Vehicle Dynamics of Formula Student Race Car using Aerodynamic Maps

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Abstract: This research paper focuses on the impact of Aerodynamics on the Vehicle dynamics and performance of a FSAE style race car. During a race the car is rarely in a straight-line head-on wind condition and thus, it is imperative to understand the effect of pitching, rolling and side winds on the aerodynamic stability of the vehicle. One method to obtain accurate information about the aerodynamic loads in dynamic conditions is demonstrated in this paper - the Aerodynamics Map (Aeromaps). This paper discusses the methodology used to generate and use the aeromaps for accurate predictions and provides the observation regarding the various vehicle setup and reduction in error to predict laptimes. Numerous Computational Fluid Dynamics (CFD) models are prepared and studied for various vehicle configurations; the data from these is later incorporated in MATLAB to obtain 3D surface plots. These plots can then be used to develop accurate laptime simulation models using MATLAB, IPG, or Optimum Dyanmics or to obtain the best vehicle setup for a particular event and driver. For this study, the Ride height is limited to 25mm on either side of the mean and the roll is limited to 2^o. The effect of cross winds from 0^o to 180^o and effect of vehicle pitching on the ground effect and vehicle aerobalance have also been studied. These results were then used in the MATLAB model of the vehicle to obtain optimized vehicle integration and accurate laptimes.

Keywords: Vehicle Dynamics, Aerodynamics, Aeromaps, Computational Fluid dynamics, Formula Student, race car, MATLAB

I. INTRODUCTION

The Formula Student is a competition where teams from around the globe conceptualize, design, build and compete with a formula style race car in dynamic events like autocross, endurance, skidpad, and acceleration. All vehicles must adhere to the safety standards and the unyielding parameters laid down in the rulebook. This defines the domain in which the teams can alter their designs. Even at slow speeds, aerodynamics plays a vital role in the performance of the formula style race car. The additional downforce equates to additional grip which is paramount for the Formula Student track that comprises high speed sharp corners and slaloms. The autocross and endurance events have corners of up to 25m radius, slaloms and chikanes, whereas skidpad is a steady state event where the race car is made to go around an 8 shaped track of radius 9.125m.

Given the nature of these events, the car is expected to be either in corner exit or entry in a state of roll, pitch and yaw and thus straight line CFD simulations fall short in predicting the aerodynamic performance and vehicle dynamics accurately. Aero-balance being an important parameter in estimating the performance of the vehicle, any inaccuracy in it would result in an inaccurate vehicle model. Thus, this paper discusses one method in obtaining a better understanding of the aerodynamic forces and its effect on the car in the dynamic conditions using Aeromaps. These Aeromaps not only help improve the laptime simulation model developed but also provide necessary insights about various vehicle configurations. This provides better tuning of the car for each event and facilitates better system integration. Aeromaps can also be used to validate the aerodynamic package on the race car. Furthermore, they can be used to obtain the best vehicle configuration for a particular track, event, and driver. Thus, Aeromaps is one method to fine tune the Vehicle Dynamics of the Formula style race car.

II. LITERATURE REVIEW

Apart from the suspension various other parameters govern the vehicle dynamic performance of a car. Aerodynamics is one such crucial factor for performance vehicles built for the purpose of competing with one another. In an aerodynamic study the most important parameters involved are coefficient of lift, coefficient of drag, Reynolds number and general fluid properties. The coefficient of lift and coefficient of drag are the lift and drag of the subject non-dimensionalized with respect to the fluid properties and velocity of flow over the object. Reynolds number is a dimensionless number used to predict flow patterns in specific cases. The negative lift exerted on a vehicle is referred to as a downforce which is then transferred as mass less weight to the tires, thus improving the grip of the race car. Lift and drag coefficients affect the performance of a vehicle as the resultant of these forces directly influence the vehicle dynamics of the car. Downforce exerted on a vehicle helps it to attain more traction which is crucial for cornering at high speeds.

Drag is a force that acts opposite to the direction of motion of the vehicle thus, the driving force needs to overcome drag to keep the vehicle moving. The drag limited top speed of the vehicle is the speed at which the vehicle's drag equates the propulsive force of the engine or motor. The aerodynamic balance refers to the distribution of the aerodynamic load on the vehicle. It is usually specified as a ratio or percentage of loads on the front and rear axle respectively and signifies the impact of aerodynamic loads on stability.
The flow field around a vehicle keeps on changing dynamically depending upon factors such as manoeuvring of the vehicle, vehicle geometry, disturbance in the flow of air, incoming flow direction etc. The aerodynamic load on the vehicle is a function of the flow field around the vehicle and since these parameters keep changing with the different dynamic conditions it is imperative that all these factors are accounted for and are properly modelled while performing simulation. Aerodynamic Mapping refers to the mapping of the aerodynamic parameters with respect to all the different dynamic flow conditions that the vehicle might experience during the race. These aerodynamic maps can be used to develop accurate laptime simulation models of the vehicle and also to study the aerodynamic stability of the vehicle.

III.RESEARCH METHODOLOGY

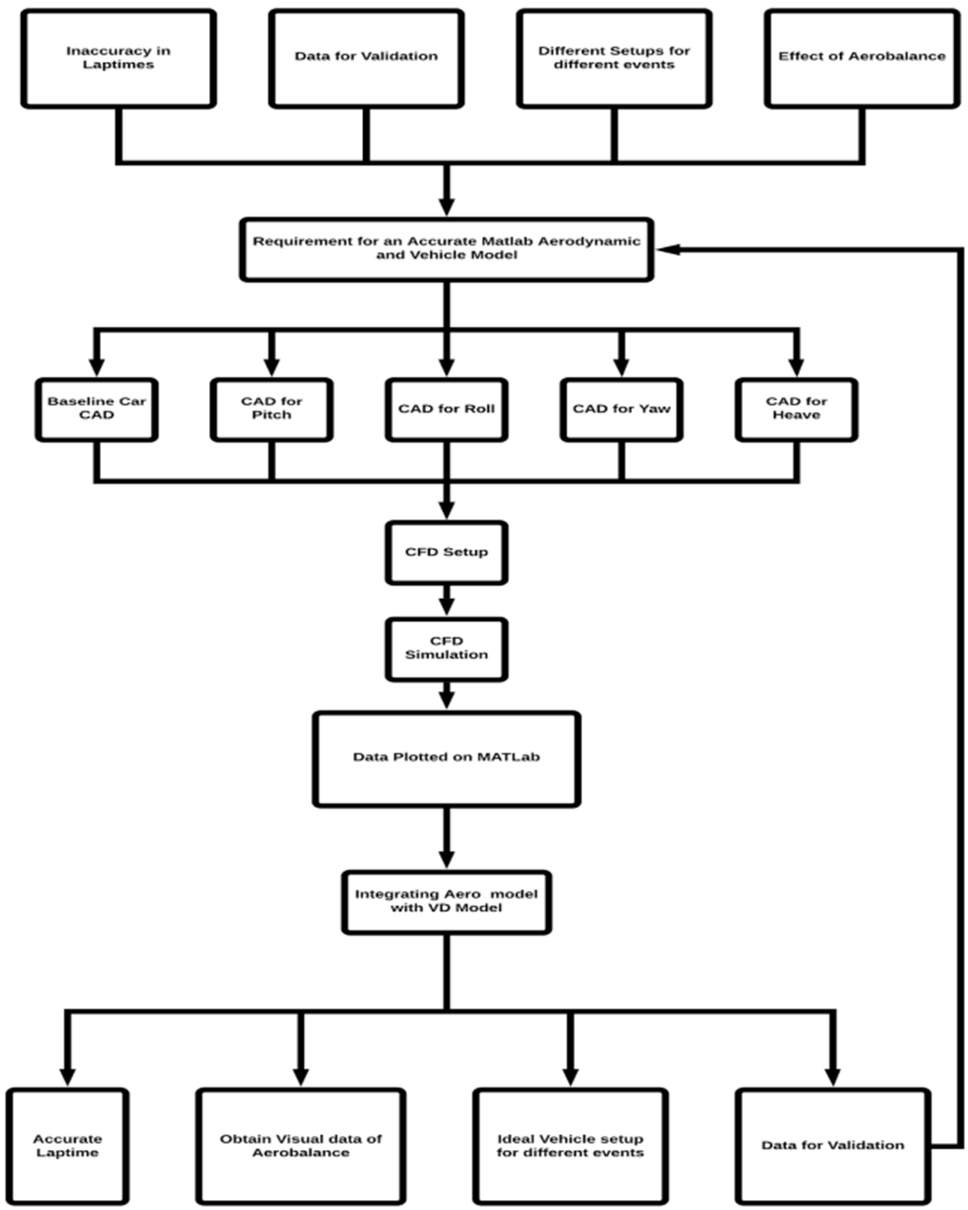

Figure 1: Research Methodology

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To obtain the aerodynamic loads and their effects on Vehicle dynamics in the dynamic condition a methodology was proposed. By performing baseline CFD simulations the team determined the performance parameters for the racecar in head on wind condition. Further, the CAD model of the car was changed to match the dynamic conditions that might arise during the race such as yaw, pitch, roll and heave and simulations were then initiated to obtain the desired Aeromaps. The results were then processed and fed into the MATLAB model to obtain 3D extrapolated surface graphs of the aeromaps which was used to fine tune the vehicle. Finally, during testing and validation the on-track data obtained via the gyroscope, wheel speed sensors, damper displacements, pitot tube, and lap time sensors were compared to the MATLAB model to accurately simulate the racecar in a virtual environment. Thus, the flow chart above presents the process followed for this research.

IV. PROCEDURE

Various factors need to be ensured and several steps need to be followed in order to obtain an accurate aeromap. The accuracy of the laptime simulations depend on the aeromaps which in turn depend on the CFD simulations and CAD models. Thus, the procedure is briefly discussed in this section.

A. Preparing a Clean CAD model for CFD simulations

The profiles in the CAD model define the flow of air around the body. If the profiles are not the same as the actual component on the car, the flow of air around the parts is not going to be the same and give completely different results. CAD Cleaning is a process of maintaining relevance between the geometry used for simulation and the actual part that is being investigated. Clean CAD is a CAD of the model with reduced complexities, but which retains the components that will influence major flow structures. The following parameters are important for a clean CAD. Similar Clean CADs were made for every configuration, that is Pitch, heave, roll and yaw.

1) To create watertight surfaces to ensure no interaction of fluid inside the object.
2) Creation of tessellated surface for ease of mesh generation and mesh conformation.
3) Mesh convergence errors are reduced as triangulated surfaces and open surfaces are eliminated.
4) To simplify the geometry and reduce the time taken to mesh and simulate the vehicle.

Figure 2: Actual CAD.

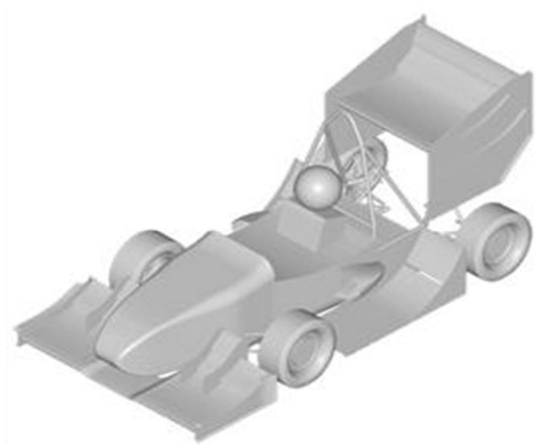

Figure 3: Clean CAD

B. Setting up CFD simulation

The accuracy of the CFD simulation depends on the turbulence model, the CAD model, the Mesh quality and Boundary conditions. All these parameters are described in this section

1) Turbulence Model: The k-ω SST turbulence model was used to model the domain for the CFD simulations. This model was selected as it helps predict the flow near the walls as well as away from the walls with higher accuracy. Steady state simulations were performed using the k-ω SST and k-ϵ and the results obtained was then verified with available data. The k-omega SST proved to be the most accurate model with error within 2% of expected values. The SST formulation switches to a k-ϵ behaviour in the free-stream from a k-ω model near the walls. Thich avoids the problem associated with k-ω that the model is very sensitive to the inlet free-stream turbulence properties, or the issue with k-ϵ in which the near wall region is overestimated for stresses. The following are the basic equations of the turbulent kinetic energy (k), Turbulence intensity, and Specific turbulence (ω) which can be used in the Navier Stokes Equation for the simulations.

The turbulent kinetic energy (k) is given by the formula: $k = \frac{3}{2}(UI)^2$,where U is mean flow velocity, and I is Turbulence intensity

Turbulence intensity is given by $= \frac{u\prime}{U}$, where u' is given by $\sqrt{\frac{2}{3}k}$ and U can be calculated by $\sqrt{U_x^2 + U_y^2 + U_z^2}$

Specific turbulence (ω) is given by $\omega = C_\mu{}^{\frac{3}{4}}\frac{\sqrt{k}}{l}$, where $C_\mu$is turbulence constant usually assumed to be 0.09, k is turbulence intensity, l is turbulent length scale, which describes the size of large energy-containing eddies in a turbulent flow.

Turbulent viscosity (ν_t) is therefore calculated by $\nu_t = \frac{k}{\omega}$

2) *Mesh Parameters and Quality:* Meshing was done in Simscale using the Hex-dominant mesh with parametric settings for the domain. The bounding box was sufficiently long to capture all wake flows with 14m behind the car, 8m ahead, 4m on either side and 6m above the car. Mesh refinements were then applied on all the bodies of the car and the mesh was finer closer to the car with special attention to the wings, diffuser and the suspension members. Multi-Rotating frames were used for the tyres to obtain the rotating zone of the wheels. The tyre contact patch was also meshed with sufficient refinement. Thus, the flow around the vehicle could be accurately modelled. further the y+ values for all surfaces were obtained and mesh was further refined. Additionally, inflation was given throughout the car to capture near wall flow structures like flow separation. Further, region refinements were also added near the car parts to have a better visualization of the wake turbulence and various vortices produced. The final mesh is shown below and had the following number of cells

Total number of parametric cells :1,66,98,723

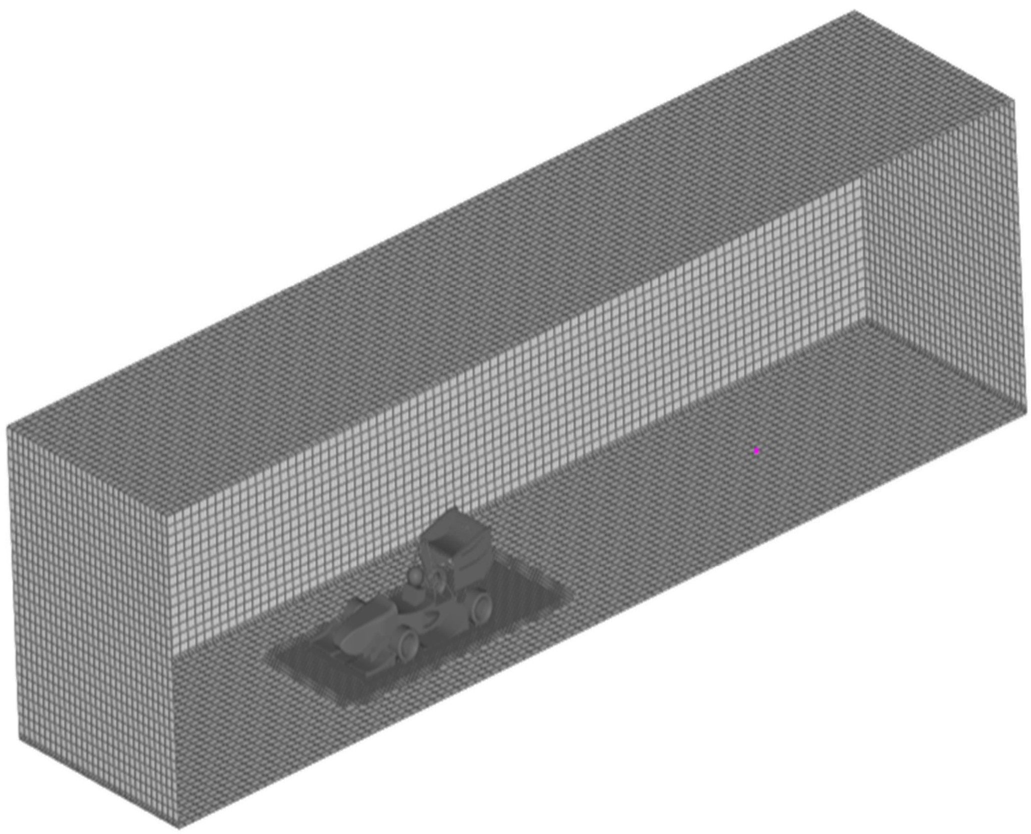

Figure 4: Mesh

The quality of the mesh is given by various parameters like the orthogonality, concavity, number of pyramid cells, Aspect Ratio of cells, skewness, interpolation weights, face twist, and volume ratio of neighbouring cells. The quality of the simulation based on these factors is presented in the table below. An accurate simulation depends on the quality of the mesh and hence having high quality is of utmost importance.

Sr. No.	Faces	Qty.
1	non-orthogonality > 75 degrees	0
2	faces with face pyramid volume < 1e-13	0
3	faces with concavity > 80 degrees	0
4	faces with skewness > 4 (internal) or 20 boundary)	0
5	faces with interpolation weights (0.1) < 0.01	0
6	faces with face twist < 0.005	0
7	faces on cells with determinant < 0.005	0
8	faces with volume ratio of neighbour cells < 0.0075	0

Table 1: Mesh Quality

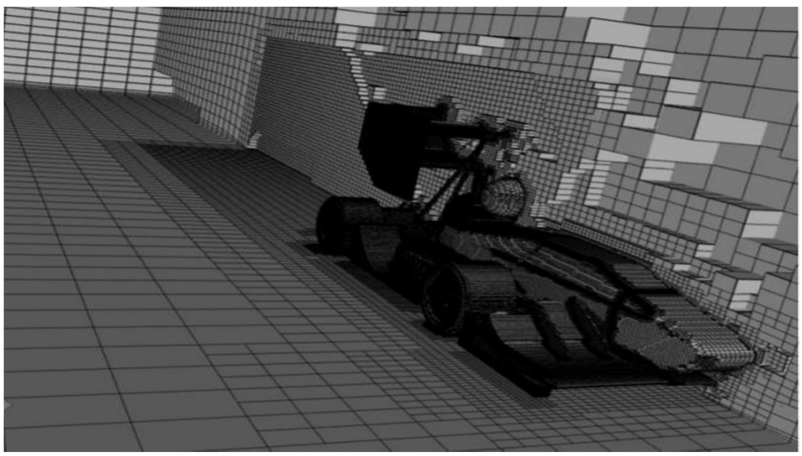

Figure 5: Mesh Clip

3) *Boundary Conditions:* The Boundary Conditions used for the simulation is mentioned in the table below, the CADs were changed for the pitch heave and roll simulations keeping the boundary conditions the same. However, for yaw simulations both the CAD and the Boundary Conditions were changed.

Sr. no.	Boundary Condition	Face/Position	Value
1	Slip Wall	Side and Top Faces	---
2	Moving Wall	Floor	-16m/s
3	Rotating Wall	Front Wheel	70rads
4	Rotating Wall	Rear Wheel	70rads
5	No slip Wall	Full Vehicle	---
6	Velocity Inlet	Inlet Face	-16m/s
7	Pressure Outlet	Outlet Face	0 Pa gauge pressure

Table 2: Boundary Conditions

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V. CFD RESULTS AND AERODYNAMIC MAPS

The CFD results obtained through the various simulations were then used to generate the Aerodynamic Maps on MATLAB. This section talks about the importance of aerobalance on vehicle dynamics and discusses the CFD results and Aeromaps thus obtained. The most important design consideration was aerodynamic balance rather than outright maximum down force. This means that the net aerodynamic force created by both wings acts near the car's centre of gravity.

A. A slight rearward aero bias where the centre of pressure (CoP) is behind the centre of mass is commonly used to ensure high speed stability. In low to mid speed turns the car needs a slight rear, this prevents the car suffering corner entry oversteer.
B. In faster turns the front wing can lead the car. The drivers turn in gentler in fast turns, which creates less lateral acceleration at the rear axle. Thus, at higher speeds you can have a CoP biased towards neutral or the front.
C. Designing for a good aero balance will ensure that the vehicle exhibits neutral handling characteristics rather than under-steer or over-steer because of unevenly distributed aero loads.
D. Thus, a slight front dominated downforce of 56% was selected as baseline. This however was adjustable by changing the flap angels for each driver according to their feedback.
E. The picture below shows the load distribution and the moments generated about the cg and the location of the line of pressure.
F. The distance between the mid wheelbase on the ground and the point where the cp intersects the ground in terms of percentage gives the balance of the vehicle.

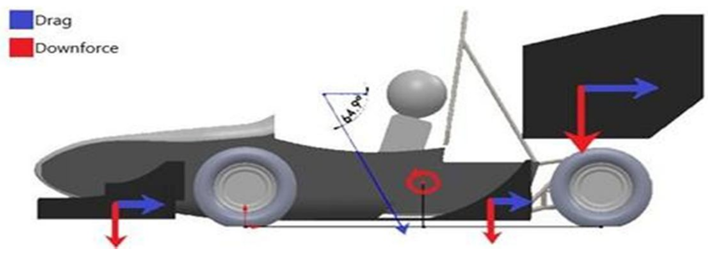

Figure 6: Forces and moments on the vehicle

The vehicle will, however, never be at a constant ride height, pitch, roll or yaw in the dynamic conditions and the variations in the aerodynamic coefficient and aerobalance are discussed in the further sections.

1) Variations with Heave: The table above shows the variation of the various aerodynamic loads, moments and aerodynamic balance with the ride height of the vehicle that is, when the vehicle either heaves positively or negatively. As the ride height decreases the downforce increases and the balance shifts towards the front because of the additional ground effect produced by the front wing. A +-5% change is observed in aerodynamic balance. The effect on drag and the moments can also be understood by the following map.

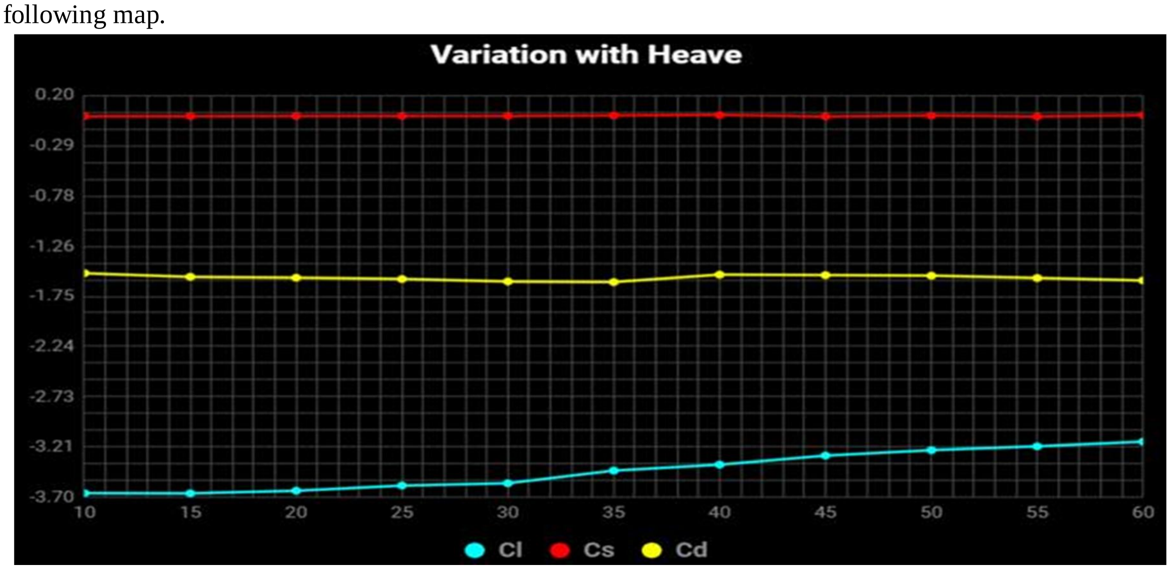

Figure 7: Variation with Heave

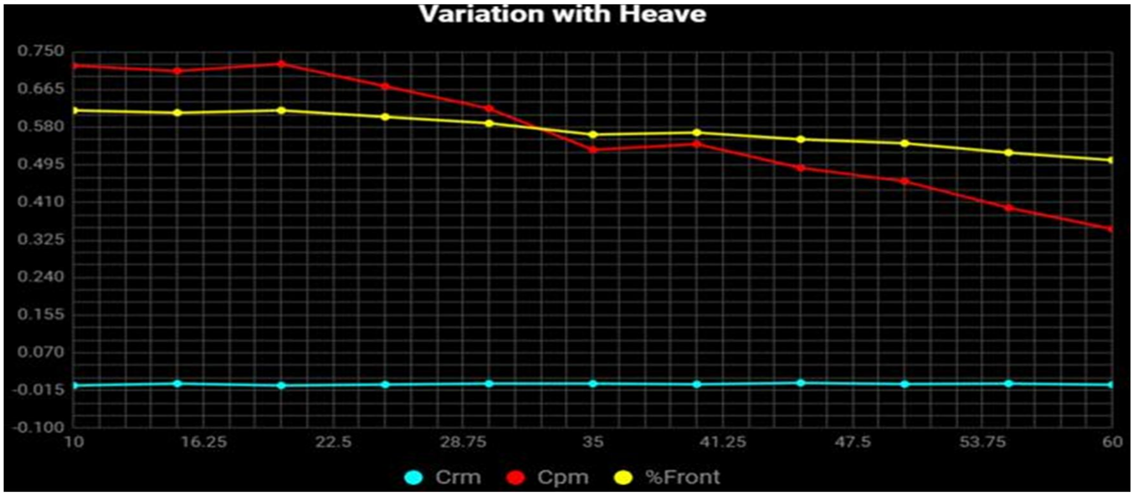

Figure 8: Variation with Heave moments and Aerobalance (% front)

The increase in ground effect of the front wing can be seen clearly as the car heaves down. This is also the reason that the aerodynamic balance moves forwards. Similarly, the effect when the car heaves up can be seen. The increase in lift produced by the front wheel with increase in ride height is also prominent. The cut plots show the wake region developed behind the vehicle. Drag increases when the vehicle is heaved down and reduces when the vehicle moves up.

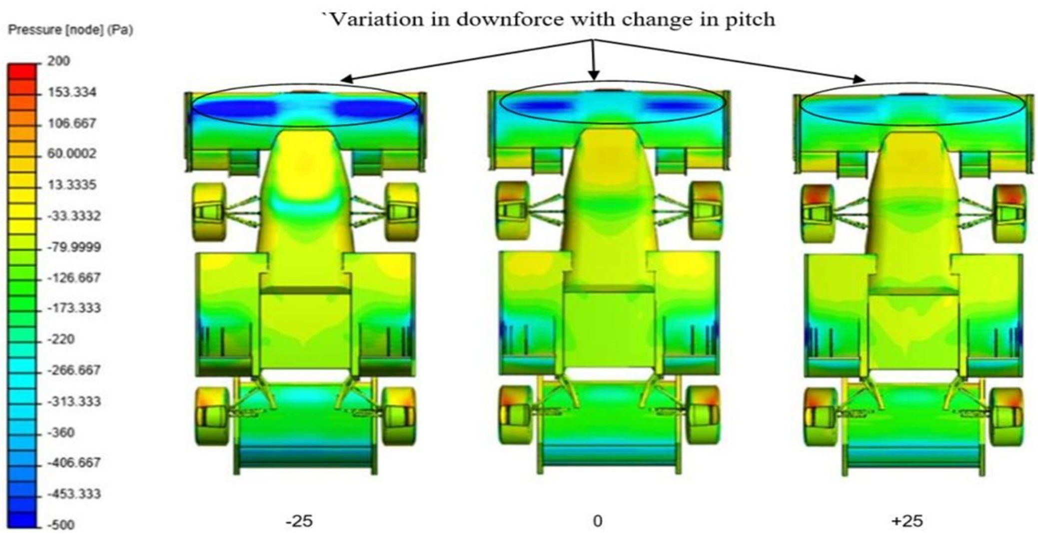

Figure 9: Pressure Plot at different pitch angles

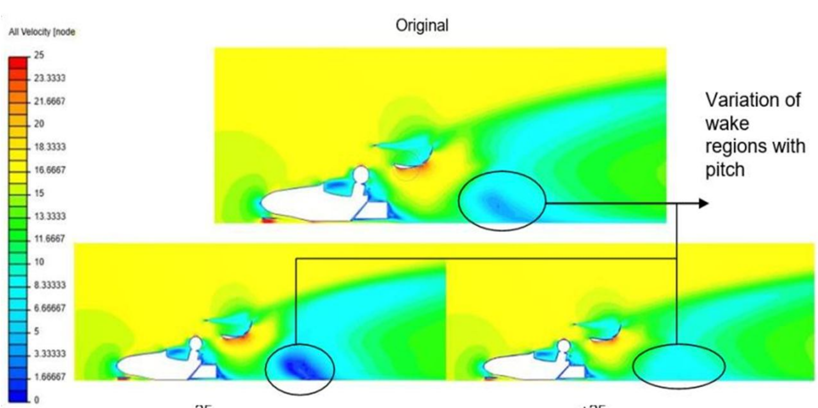

Figure 10: Variation of wake regions with pitch

2) *Variations with Pitch Angle*: The maximum pitch of the vehicle is between +0.5 to -0.5 degree, however iterations from -0.9 to +0.9 degrees were performed. The graph and table show that the aerodynamic balance does not change much with pitch angle. This is an important factor as it gives information on the pitch sensitivity of the car. The table and graph below show the variation with pitch angle.

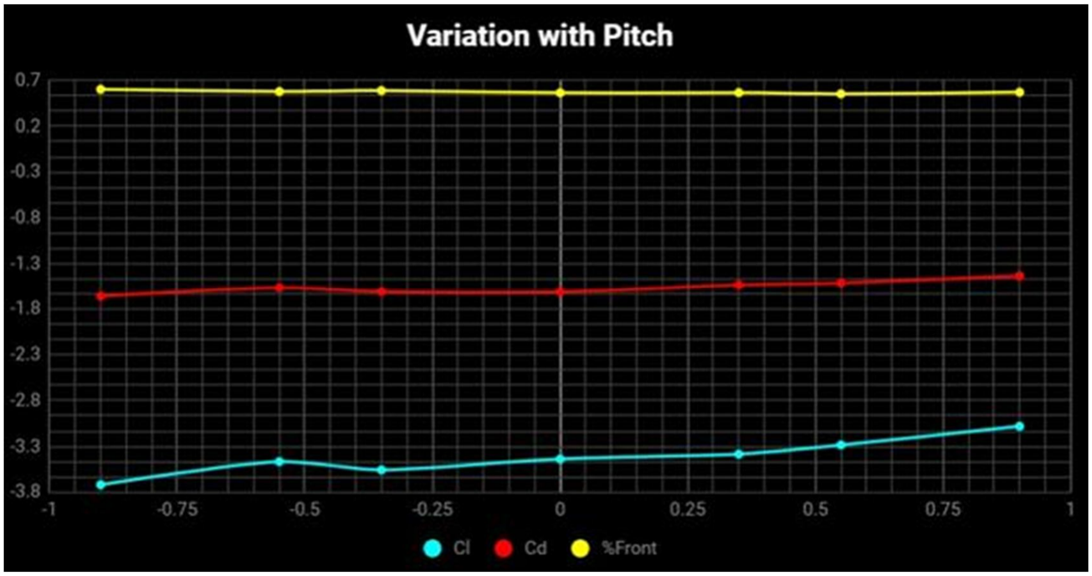

Figure 11: Variation with Pitch

3) *Variations with Ride Height*: The graphs and tables show the relation of the ride height with the aerodynamic balance, lift coefficient, and drag coefficient. The balance changes gradually as the ride heights increase but changes sharply with a decrease in ride height. With an increase in both front and rear ride heights the balance shifts behind, and with the decrease in both front and rear ride heights the balance shifts forwards. The drag decreases with decrease in rear ride height and increase in front ride height and increases with increase of rear ride height and decrease of front ride height. The downforce increases with increase in rear ride height and decrease in front ride height. The opposite is seen with an increase in front ride height and decrease in rear ride height.

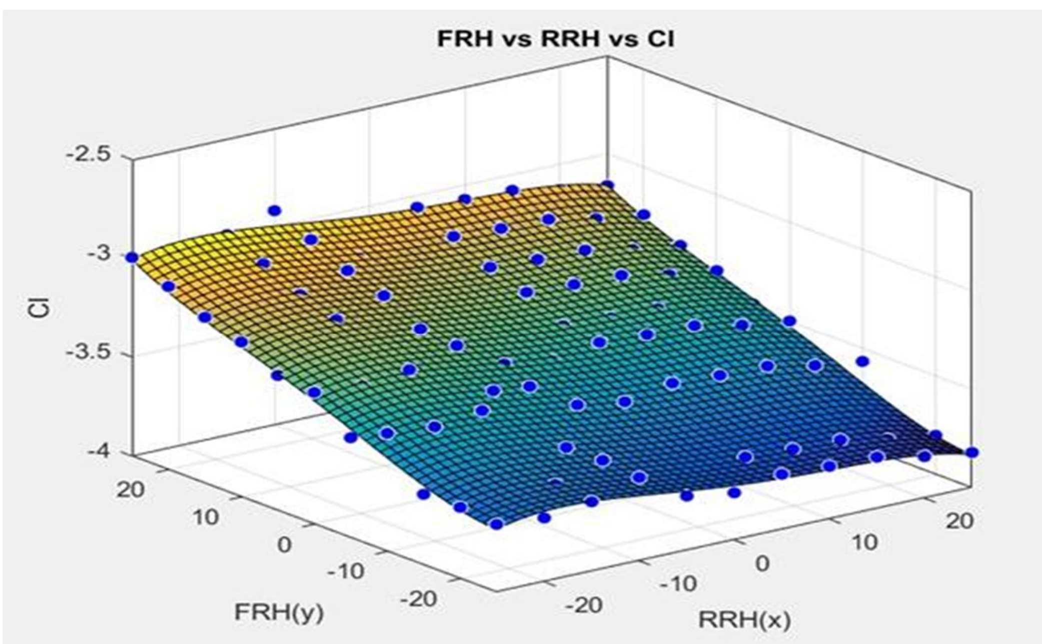

Figure 12: Surface Plot of FRH vs RRH vs Cl

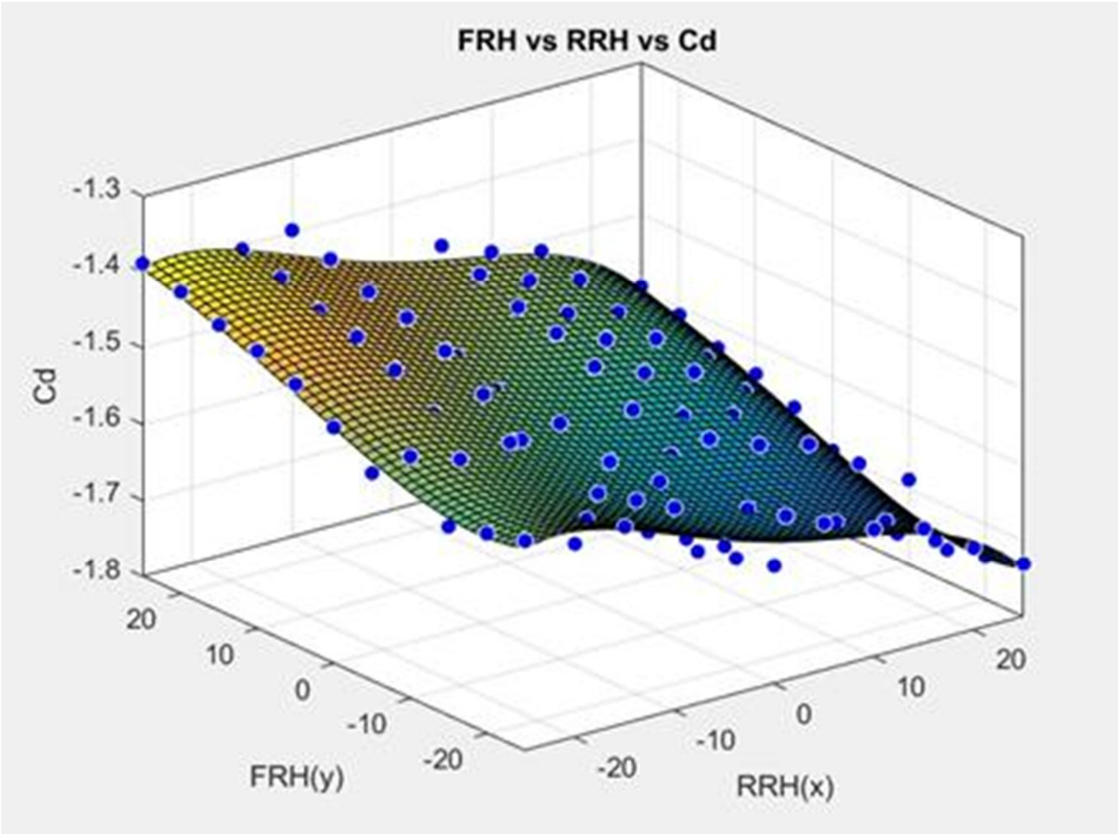

Figure 13: Surface Plot of FRH vs RRH vs Cd

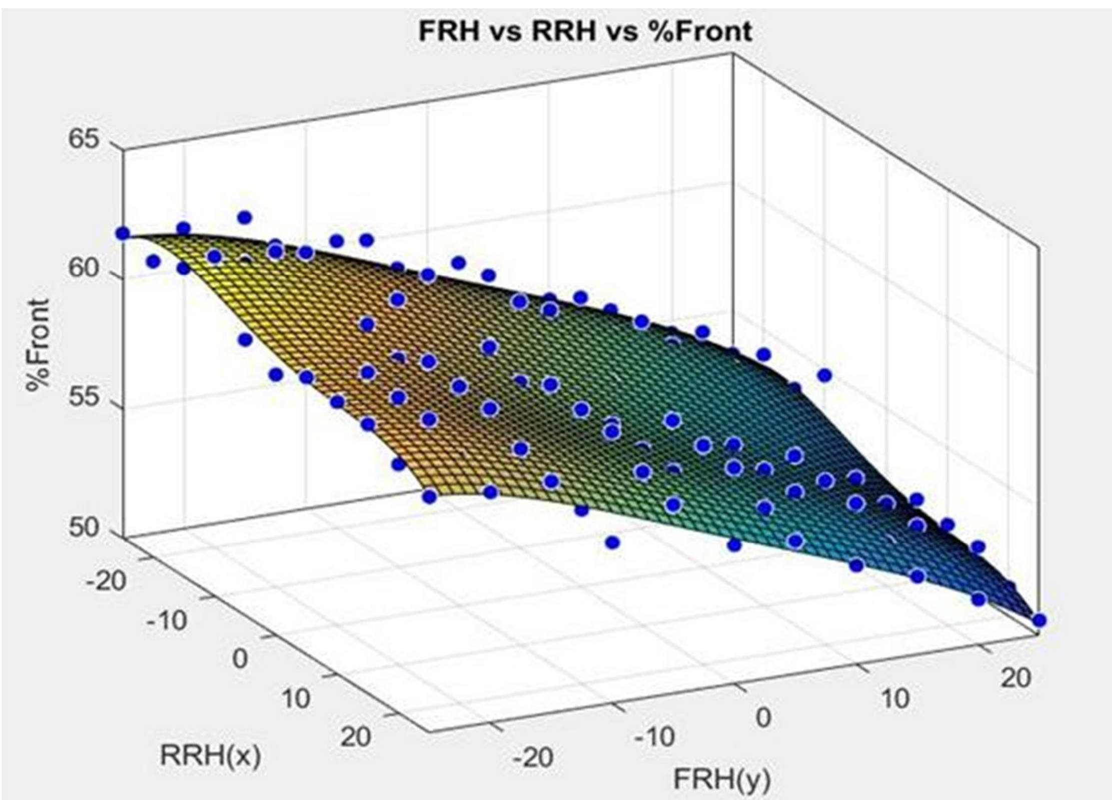

Figure 14: Surface Plot of FRH vs RRH vs %front

4) *Variations with Roll*: The following two plots show that the variation of aerodynamic balance, lift and drag coefficients as well as side force with roll is negligible. The pitching moment changes slightly and is responsible for the slight change in the aerodynamic balance. The slight increase in suction pressure below the front wing can be seen in this image. Thus, the effect of roll is increased in the downforce on one half of the vehicle. Roll moment is however a destabilizing moment. The roll moment due to aerodynamic loads produced is very less and does not affect the vehicle performance in turning.

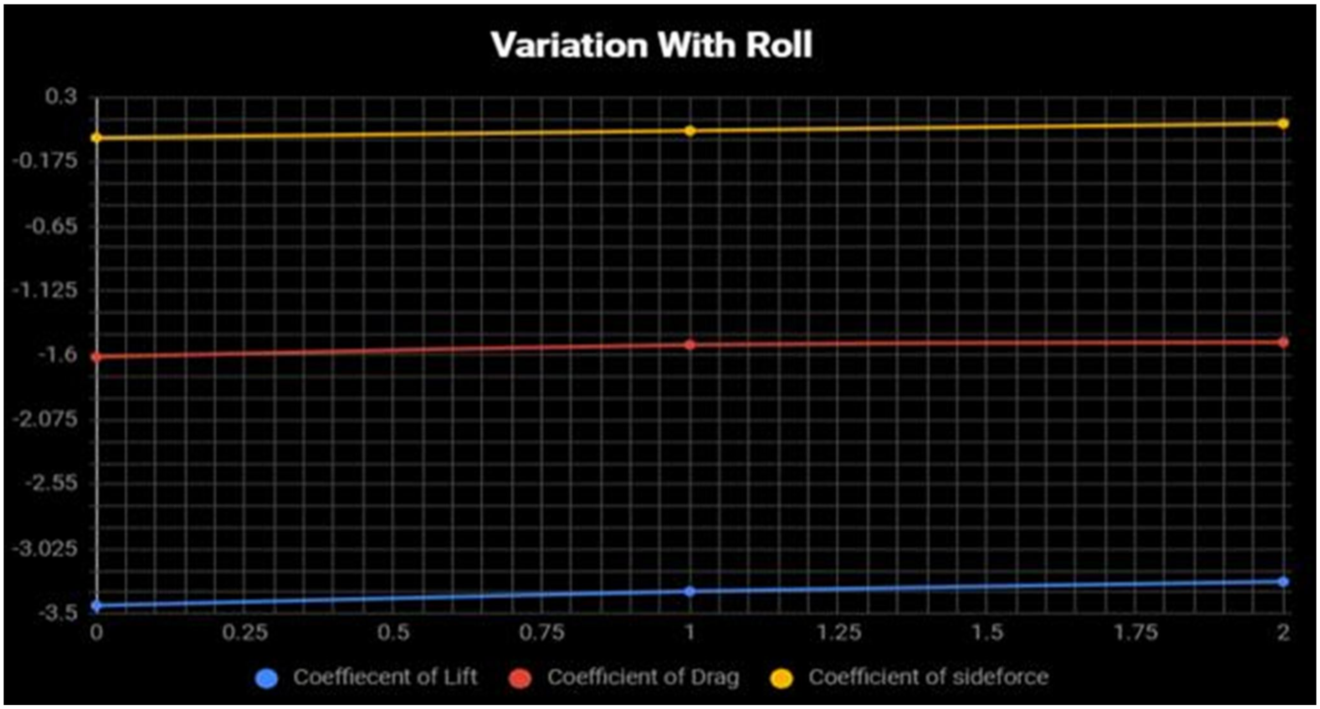

Figure 15: Variation with Roll

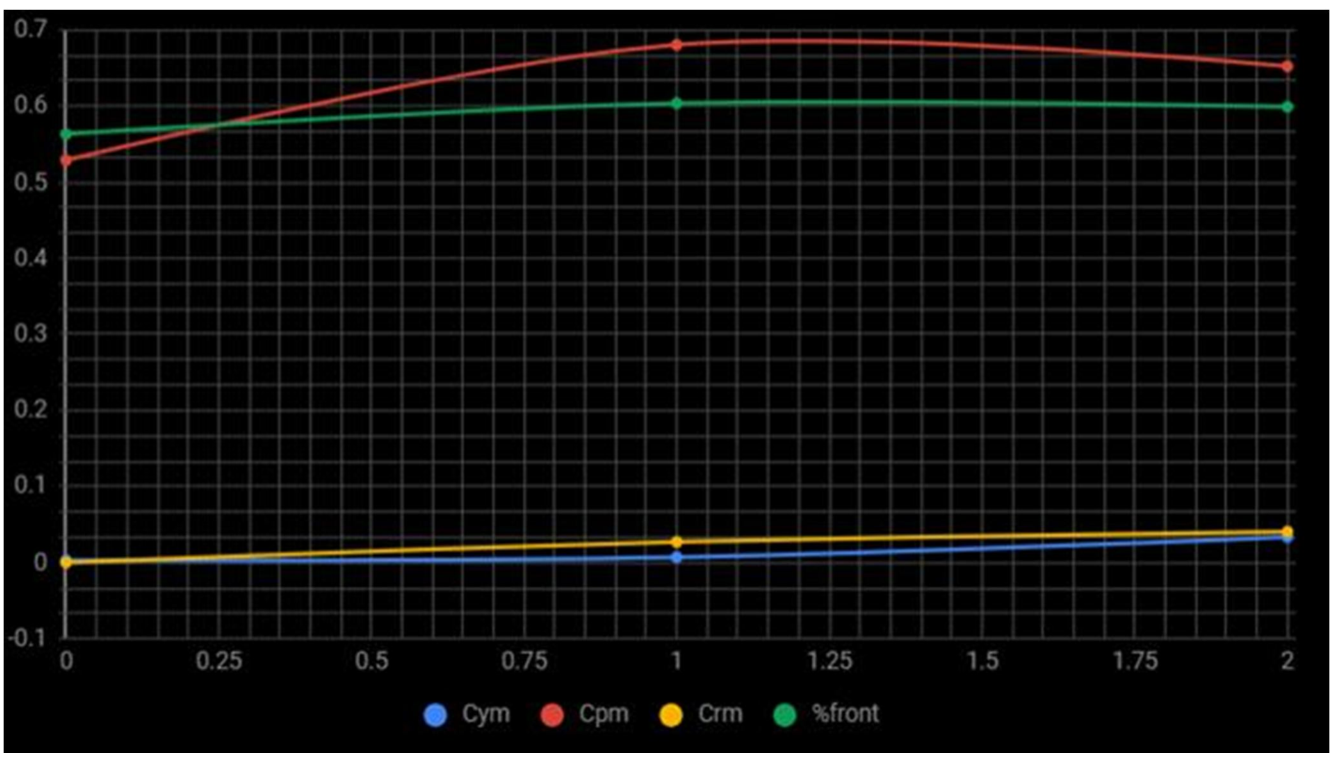

Figure 16: Variation with Roll aerobalance (%front)

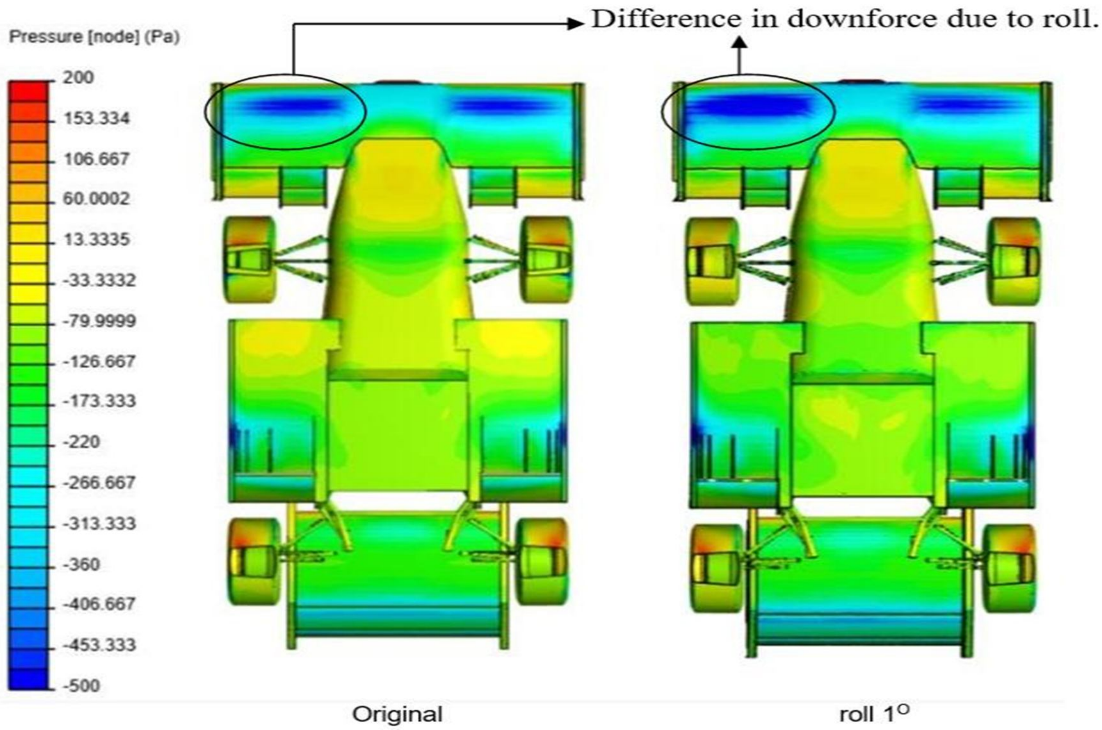

Figure 17: Pressure Plot at different Roll angles

5) *Variations with Yaw*: The downforce decreases as the angle increases; a similar trend can be observed for drag. This is because the relative velocity between the air and the car was taken to be a constant. The aero balance changes marginally as the yaw angle increases, and a decrease in pitch moment is also seen. The study of the aerodynamic forces when the car runs in a backward direction is important because it would be catastrophic if the car went flying outside the track into the public in case of crashes. The lift coefficient in 180^{O} is 0.87, which means the car will start producing lift equal to its weight at 273 kmph which will not be possible. However, the maximum lift coefficient is observed at 135^{O} and that is 1.058, which means that when the car will be travelling at 247 kmph the vehicle will start to lift off the ground. These scenarios however will not be possible as the drag when the car is moving back will limit the top speed that can be attained. The yaw moments as can be seen are negative, this means that the car will try to move into the direction of incoming air and try to stabilize itself instead of being pushed by the air.

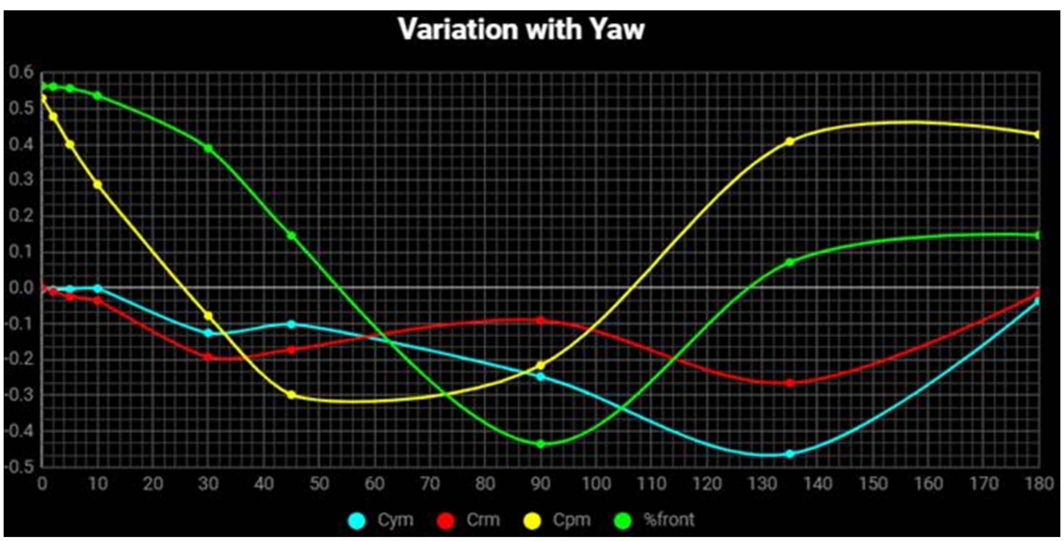

Figure 18: Variation with Yaw aerobalance (%front)

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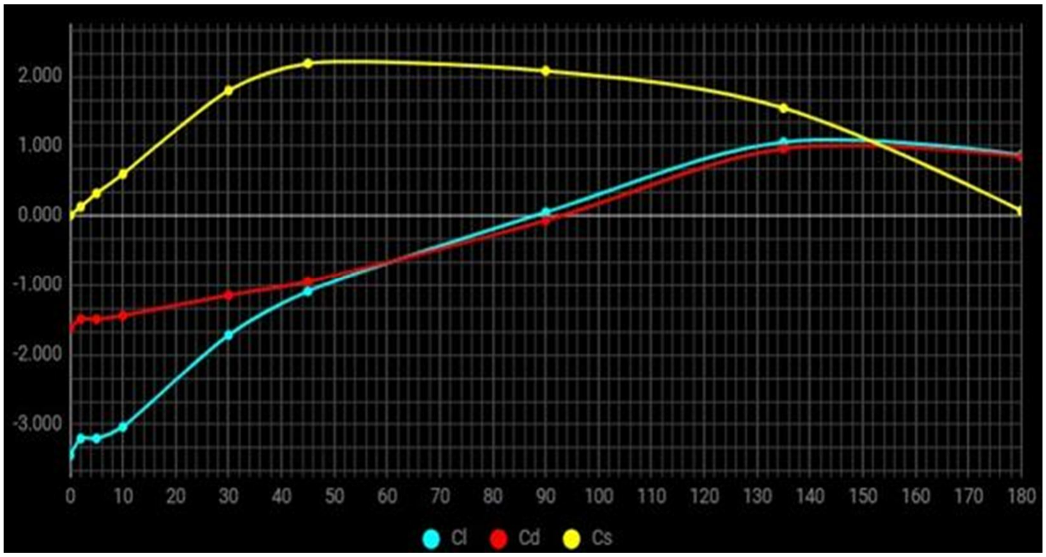

Figure 19: Variation with Yaw

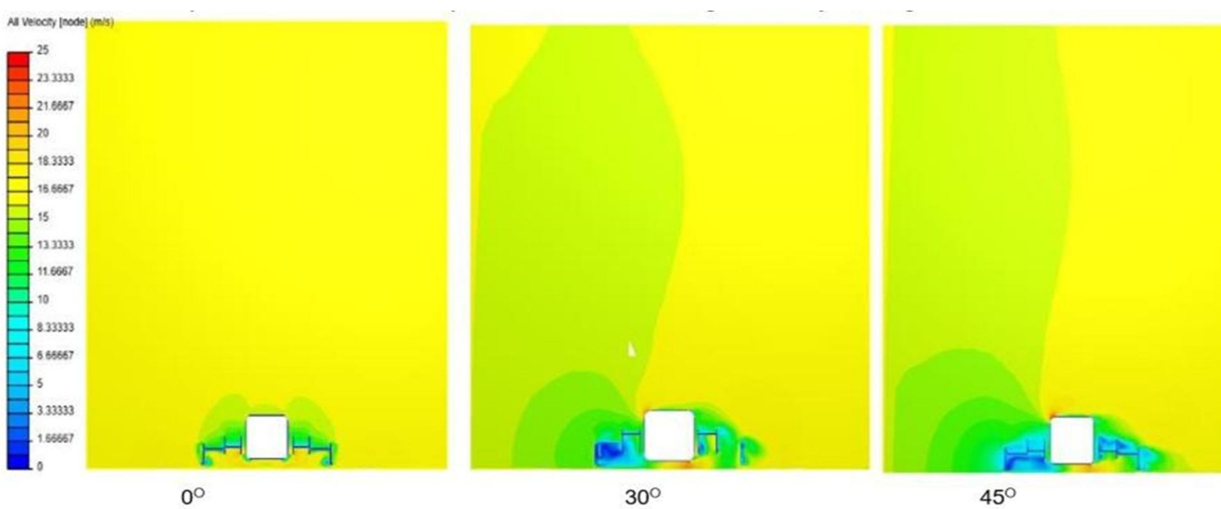

Figure 20: Velocity Plot at different Yaw angles (Front view)

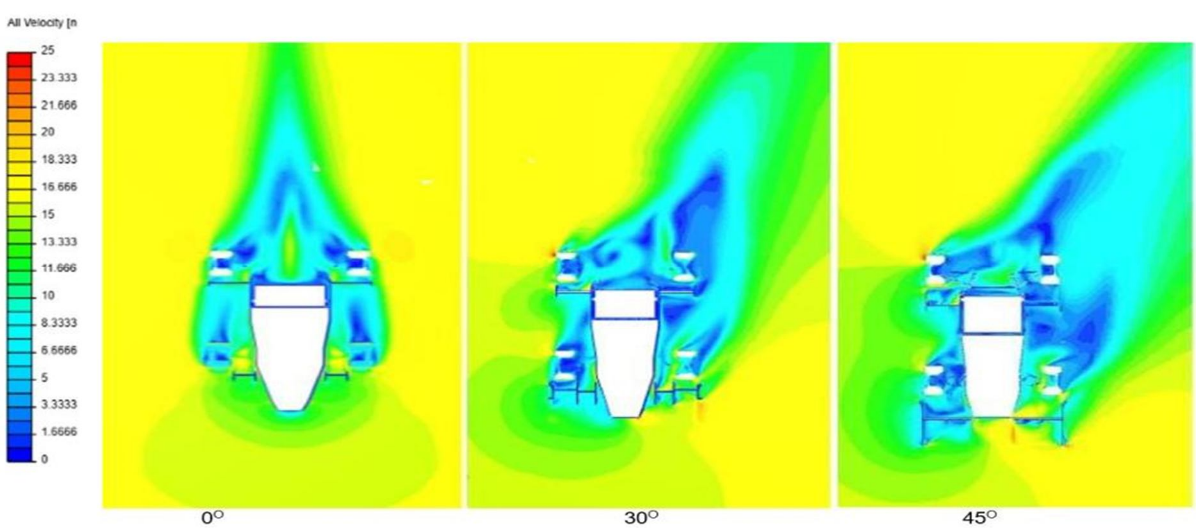

Figure 21: Velocity Plot at different Yaw angles (Top view)

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VI. OBSERVATION

The data obtained by the above generated aeromaps was then incorporated in the MATLAB model of the vehicle to obtain laptime for various events shown below. A comparison between the laptimes with and without the use of Aeromaps is discussed in the table below. The results were also checked using industry accepted software like IPG and Optimum Dynamics. The values obtained were later compared with On-track tests to obtain a percentage error. In all these simulations the error with the Aerodynamic Maps was sufficiently less than the error without the Maps. Thus, the dynamic vehicle conditions are better predicted using the aeromaps and hence an optimum vehicle setup can be achieved. These maps can also be used to validate the aerodynamic package of the FSAE race car, but that is beyond the scope of this paper.

The error in the laptimes can be because of a myriad of reasons including, but not limited to, inaccurate sensor reading, noise in the readings, human-errors, slight oversimplification of the Vehicle model in the simulation software, convergence errors in CFD simulations, and extrapolation errors.

The table below demonstrates the effect of Aeromaps on laptimes and the percentage error for various events.

Sr. No.	Track Layout	Laptime (s)												
		On track	Optimum Dynamics				IPG				MATLAB			
			Without Maps	% error	With Maps	% error	Without Maps	% error	With Maps	avg % error	Without Maps	% error	With Maps	% error
1	Acceleration	4.24	3.7	12.74%	3.81	10.04%	3.79	10.61%	3.95	6.79%	3.85	9.20%	4.1	3.30%
2	Skidpad	5.03	4.4	12.52%	4.54	9.82%	4.48	10.93%	4.67	7.13%	4.54	9.74%	4.95	1.59%
3	Autocross	76.54	67.67	11.59%	69.76	8.85%	68.69	10.26%	71.63	6.42%	69.67	8.98%	74.54	2.61%
4	Endurance	1483.92	1295.58	12.69%	1335.65	9.99%	1300.98	12.33%	1356.60	8.58%	1377.58	7.17%	1449.97	2.29%
5	Autocross with maximum 12.5m corners radius	90.26	78.76	12.74%	81.20	10.04%	80.69	10.60%	84.14	6.78%	84.26	6.65%	88.69	1.74%
6	Autocross with maximum 40m corner radius	69.42	58.05	16.38%	59.85	13.79%	60.18	13.31%	62.75	9.60%	66.25	4.57%	67.78	2.36%

Table 3: Laptimes

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VII. CONCLUSION

The aerodynamic maps were prepared using CFD simulations pertaining to all the various dynamic conditions which the vehicle will experience during the run. These Aeromaps of pitch, yaw, roll and heave were then incorporated in the Vehicle Dynamics MATLAB model to obtain Lap times for various events. Similarly, the data from aerodynamic maps was modelled in the open-source lap time simulation softwares like IPG and Optimum Dynamics to verify the results. These results were then compared to actual track tests. The MATLAB simulation results for the AutoCross event without the aerodynamic maps showed a deviation of 8.98 % from actual runs, whereas the simulations using the aerodynamic maps showed 2.61 % deviation. Thus, incorporating aeromaps in the model helped to reduce the error by 70.93 % and obtain accurate lap times simulation. This further helps in optimizing the vehicle integration and choosing the best vehicle setup for the event.

The Aerodynamic maps can be further improved by incorporating the data from the steering angle, and wind speed. Further, the yaw, pitch and roll can be incorporated in a single map to obtain a 5D map with Cl and Cd. These improvements to the aeromaps will help in reducing the deviations from the actual runs. The MATLAB model can also be further tuned to be more sensitive to changes in ride height and dynamic conditions and thus, further improvements can be made. Thus, the methodology, procedure, results, and observations of using Aerodynamic maps to tune the vehicle Dynamic model of the FSAE race car have been discussed in this paper and the areas of further research have also been discussed.

VIII. ACKNOWLEDGMENT

This Research was supported by K J Somaiya College of Engineering. Further, the research could not have been possible without the team Orion Racing India. We would further like to take this opportunity to thank Simscale, MATLAB, IPG and OptimumG for all their support without which this research would not have been possible. However, having said that any errors are our own and should not be used to tarnish the reputation of this esteemed institution, team, and companies.

REFERENCES

[1] S. McBeath, Competition Car Downforce, Haynes Publishers, 1998.
[2] R. H. Bernard, Road Vehicle Aerodynamic Design, MechAero Publishing, 2nd edition, 2001.
[3] X. Zhang, J. Zerihan, Aerodynamics of a Double Element Wing in Ground Effect, AIAA Journal, Vol. 41, No. 6, pp 1007-1016, 2003.
[4] J. Katz, Race Car Aerodynamics, Bentley Publishers, 1995.
[5] Milliken, W., & Milliken, D. (n.d.). Race Car Vehicle Dynamics,1995.
[6] Jensen, K. (n.d.). Aerodynamic Undertray Design for Formula SAE,2015.
[7] Milliken, W., & Milliken, D. (n.d.). Aerodynamics for Formula SAE: A Numerical, Wind Tunnel and On-Track Study,2006.
[8] John D. Anderson,Computational Fluid Dynamics: An Introduction,1992.
[9] Wordley, S., & Saunders, J. Aerodynamics for Formula SAE: Initial design and performance prediction,2006.
[10] UIUC. (n.d.). UIUC AIrfoil Database.
[11] Merkel, J. DEVELOPMENT OF MULTI-ELEMENT ACTIVE AERODYNAMICS,2013.
[12] Douglas Gogel and Hiroshi Sakurai, The Effects of End Plates on Downforce in Yaw, 2006-01-3647.
[13] Wael A. Mokhtar and Jonathan Lane, Racecar Front Wing Aerodynamics, 2008-01-2988.
[14] Volk, A. R. (n.d.). The Design, Manufacturing, and Testing of the 2014 Side-Pods for the Global Formula Racing Vehicle,2014.