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Aerodynamics Study of The Formula SAE Car using Analytical Approach

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Abstract

This paper presents the process of developing an aerodynamics package and a suspension system for a Formula SAE race car, with the help of computational methods for the aerodynamics design and analytical methods for the suspension design. Aerodynamics package involving Front and Rear wings and a suspension system involving a strut activated damper with double wishbones is developed. Vehicle parameters such as wheelbase, track width, etc. and the geometry for the front and rear wings are specified by conducting a review of the SAE rule book. 2D CFD simulations are performed on a wide range of high lift low Reynolds number Airfoils at various geometric configurations to select an airfoil configuration with best performance characteristics. 3D models of front and rear wings are made from the data obtained from 2D simulations to conduct 3D simulations of the wings and the entire assembly of the car with and without the wings. A kinematic analysis is performed on the suspension system since it plays a very important role in the dynamics of the vehicle. Data obtained from the aero simulations and suspension analysis is analyzed in a lap time simulator to predict and compare the performance and lap times of the car with and without the aerodynamic package.

Keywords: *suspension system, Aerodynamics, simulations*

1.0 Introduction

Aerodynamics is a study of forces and moments created by the interaction of air with a solid body, such as an aerofoil. When air flows around an aerofoil depending on the geometry of the foil it predominantly generates either lift or downforce along with drag force. Lift as explained by Bernoulli's principle is generated when high pressure regions are formed below an aerofoil due to flow of air with a lower velocity at the bottom region. Similarly, if the geometry of the wing is inverted along the horizontal axis, air flows with a higher velocity at the bottom surface and lower velocity at the top surface, thereby creating higher pressure zone at the top surface which results in generation of lift in opposite direction which is called as downforce.

Aerodynamics has been a critical subject in motor racing for the past 30-40 years with the sole purpose of increasing the vertical force (downforce) on the tyres which increases the grip available at the tyre contact patch without increasing the mass of the vehicle. Increased grip at the contact patch leads to improved performance of the race car resulting in quicker lap times. This factor in equal fashion applies to a Formula SAE race cars also. Aerodynamic package of a Formula

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SAE race car involves a front wing, rear wing and an underbody diffuser which operate in tandem to increase the downforce of the car. In the design of an open-wheel race car, one is faced with numerous instances of complex geometries such as rotating wheels, A-arms and the cockpit with a driver etc. This nature of the vehicle makes it certainly difficult if not impossible to approach the problem of aerodynamic design of the entire car analytically. It is due to these difficulties that methods of simulation such as computational fluid dynamics (CFD) have been employed in the design of aerodynamic package of a race car. Along with the aerodynamic package vehicle dynamics is equally is really important for the performance of an FSAE car. The vehicle dynamics of the car determines the vehicle handling and how the vehicle behaves in straights and corners when the input is given to it by the driver. The aerodynamic package works to improve the vehicle handling. The suspension and steering determine the turning radius of the car, how the wheel is oriented to the car, how the vehicle behaves about the 3 axes, about the X axis which is the Roll motion, about the Y axis which is the pitch motion and about the Z axis which is the yaw motion. This paper seeks to establish correlation between the vehicle dynamics aspect and the aerodynamic aspect of the car and how they collectively work together to make a better performing car. The primary object of this paper is to design and develop an Aerodynamic package for a FSAE race car which will increase the performance of the car in terms of lap times and acceleration.

To design the Aero package such that it is in accordance with the FSAE Rule book. To optimize the front and rear wing designs along with entire car assembly to achieve good aerodynamic efficiency (high lift and low drag characteristics) and balance with the help of various CFD simulations. To design a vehicle dynamics package involving Suspension system, Steering system and Braking system to achieve good vehicle handling and stability which will indirectly aid the performance of the car.

To perform lap time simulations of the designed car with and without aero package around various FSAE racing tracks to help quantify the outcome of this project.

Aerodynamic grip of a car was explored to increase the acceleration, cornering and braking speed. The aerodynamic lift on a prototype rear spoiler was investigated through wind tunnel testing and computational fluid dynamics (CFD) simulation (Brandon, et. al., 2015). Juxtaposition of experimental and numerical data for various angles of attack was satisfactory. A prototype rear spoiler for the race car was sized from the data that was generated in the study. (Scott and Jeff, 2005) provided reference and guidance. Design for front and rear inverted Airfoils, or 'wings' package and details of the simulations performed is explained in this paper. This wing package is designed to produce maximum down force within the stated acceptable limits of increased drag and reduced top speed. Values from experimental measurements were used and quantitative estimation on dynamic Event Performance was done for 2003 Monash Formula SAE. The analysis predicted that the 'wing' package described would significantly benefit the car's dynamic event performance. (Girish, 2015) sheds light on basic vehicle Aerodynamics and then later dives into the analysis of an under-tray diffuser for an FSAE race car. 2D model construction of diffuser is done, which is subjected to various CFD Simulations. The limitations of the 2D construction are discussed after which the 3-Dimensional construction is made with an in-Depth mesh Study. The conclusion of the 3D analysis is that the downforce for the new Under-tray was increased by 33% as compared to the old diffuser design in free stream. A thesis gave an idea about the overall Aero Package for an FSAE race car (Oxyzoglou, 2017). The results obtained from the simulations are co-related to the ones that are obtained from the lap time simulation approach. Components like front and rear wings and under tray diffuser to name a few were presented, that should be added to the car to increase its downforce because the car. This paper has also laid a path to follow with respect to the CFD analysis and demonstrated methods to obtain performance enhancing methods to increase downforce and to keep drag as low as possible. In the thesis of Henrick, Aerodynamic of a vehicle was investigated and the results obtained from simulations were correlated with that obtained from the wind-Tunnel testing of the same components with ground proximity (Henrik, 2014). The competition rules were kept in mind and the Aero Package was developed using Computational Fluid Dynamics. The Aero Package included in this front wing, rear wing and under tray diffuser. Samant et al have provided invaluable information about the suspension for the car (Samant, et. Al, 2016). In this paper design procedure of the front double A-arm push rod suspension system for a formula student race car has been described. The design procedure is carried out in Solid Works software and the vibrational and dynamic analysis was done on ANSYS Workbench. A general overview of various Suspension geometries was also mentioned in this paper. In all, it outlined the various aspects to observe about the suspension design for FSAE Race car. Leonard, et. al, have provided much needed insight on the design of chassis (Leonard, et al, 2013). The authors have illustrated the important factors needed to be considered before and while designing the chassis. It has mentioned the various changes that can be done to achieve the best strength characteristics while modelling the monocoque in the subsequent iterations. FSAE rules require that the monocoque frame have strength equal to or greater than the traditional steel space frames that they replace. Based on the results of the tests, a sandwich construction using composite skins fabricated from carbon/epoxy prepreg and aluminium honeycomb core was selected in this paper. Jannis & Van have given another excellent source for Chassis Design (Jannis & Van, 2008). In this report an approach is presented on designing a lightweight hybrid race car chassis consisting of a fiber reinforced composite cockpit. Main emphasis was on reducing the weight of the car. High strength and stiffness for a very low overall weight is achieved. Mitchell has explained the Design of a Carbon Fiber Composite Monocoque Chassis for a Formula Style Vehicle (Hiller, 2020). This report again outlines the procedures that were followed whilst a Carbon monocoque chassis was designed. Proprietary software like Solidworks and Ansys was used for Design and Analysis purposes. Geometrical, Suspension and powertrain constraints were met. The Chassis was verified by a Quasi-static load frame test and three-point load bend test.

2.0 Theory and Methodology

FSAE race cars primarily have two types of limitations that hinder their performance in terms of lap times and accelerations namely, power limitation and traction limitation. To explain these limitations, the forces acting on the CG of a race car are considered as shown in the figure, the forces acting are frictional force in the direction of motion of the car, which is also called as Traction.

Drag in the direction opposite to the motion of the car. Downforce acting in a vertically downwards direction.

Now the net force acting on the car is,

$$F_{net} = F_{trac} - F_{drag}$$

Where,

$$F_{net} = \mu N$$

Now the Normal force N is the sum of vehicle weight and the downforce acting on the vehicle

$$N = mg + F_{downforce}$$

From Bernoulli's principle we know that,

$$F_{downforce} = \frac{1}{2}\mu A_f C_l v^2$$

$$F_{drag} = \frac{1}{2}\mu A_f C_d v^2$$

Then the net force equation is given by,

$$F_{net} = \mu\left(mg + \frac{1}{2}\mu A_f C_l v^2\right) - \left(\frac{1}{2}\mu A_f C_d v^2\right) = ma$$

And the acceleration of car,

$$a = \mu g + \frac{\frac{1}{2}\mu A_f(\mu C_l - C_d)v^2}{m}$$

The expression obtained for acceleration clearly shows that it depends on the mass of the vehicle and the traction available at the tyre contact patch. From the above equation it can be said that acceleration varies inversely with the mass of the vehicle. The limitation when the mass of the vehicle is very high compared to the power available such that no matter the amount of traction present at the tyre contact patch, the vehicle will not reach higher values of acceleration due to the lack of power available is called Power Limitation.

Also, from the equation it can be said that acceleration of the vehicle is directly proportional of the traction force generated at the tyre contact patch. Traction limitation occurs when the mass of the vehicle is low and the power available is sufficient, but due to the low mass of the vehicle the normal force acting on the tyres is also low, which reduces the traction force generated at the contact patch which cause the vehicle to not completely utilize the power available and reach higher accelerations.

This paper deals with the case of a traction limited FSAE race car, where the performance limitation as seen from the equations can be overcome by either increasing the downforce acting on the car by employing various aerodynamic devices to increase the normal force acting on the tyres or by increasing the coefficient of friction between the tyre and the road surface.

3.0 Results and Discussions

The aerodynamic devices such as the front wing, rear wing designed were added to the whole car body as a whole and was simulated to verify the improvements.

The front wing and rear wing were placed in the appropriate location values as specified by the formula SAE rule book. Both the car without the aero package and with aero package were simulated to display the improvement in car performance and also substantiate the use of an aerodynamic set up. The ground clearance of the nose of the vehicle was taken as 30mm accommodating for the 25mm maximum suspension travel in the downward direction. The wings were placed in their prescribed location volumes in accordance with the formula SAE rule book as described in previous sections. The two vehicle set ups with and without aerodynamics package are as shown (Fig.1).

Figure 1: Vehicle Set up with Aero Package

3.1 Simulation Procedure

3.1.1 Preparation of geometry

The car geometry was modified in Space Claim in order to simplify the body and remove unwanted elements that might disrupt the mesh. A fictional model of Percy (the driver) was added to the model too as the driver is a key component of drag in a formula vehicle. The cockpit was sealed and certain complex sections simplified. The control volume was of a cross section of 6000mm by 6000mm with the wake being 9000mm to simplify the simulation further we cut the control volume along the symmetry plane to save computational time and effort. Two bodies of influence were added, one to refine the mesh further and the other to create the wake. While generating the mesh for the car with aero package meshing interference was noted and miniscule modifications made to improve mesh quality.

3.1.2 Meshing of geometry

Meshing is the most important part of any simulation as the accuracy of the model depends on the nature of the mesh. The mesh also influences computing power and time. A perfect balance of refinement needs to be met to generate not only yields accurate results but also saves time and computing effort. There were various local sizing's applied to better refine the mesh at certain key and complex geometries. The mesh surface mesh generated for simulation is as shown in Figure 2.

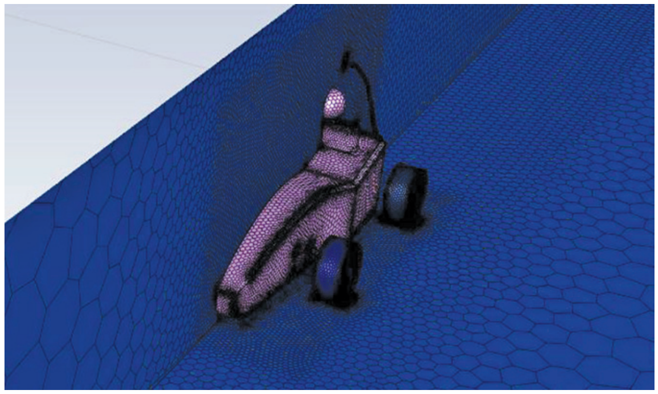

Figure 2: Surface Mesh for Vehicle with Aero Package

3.1.3 Simulation set up parameters

The simulation was initialized taking a k-omega SST turbulence model with curvature correction. The relative velocity of the air was taken as 27m/s. In case of this simulation the body is stationary and all other components such as the air and the ground are moving relative the car body. Rotational motion of 116 rad/s was added to the wheel mesh along with translational motion of 27m/s to the ground mesh.

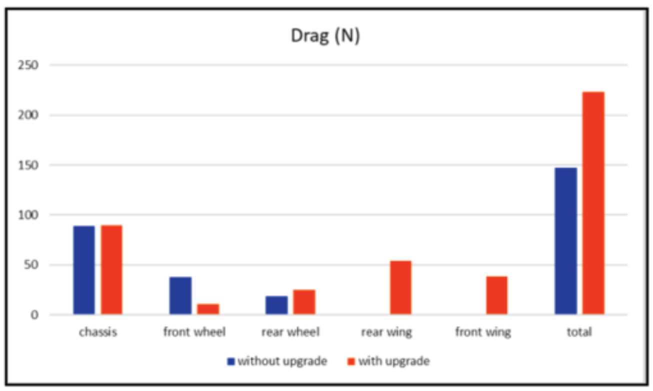

Figure 3: Drag acting on the various components of the vehicle with and without aero attachments

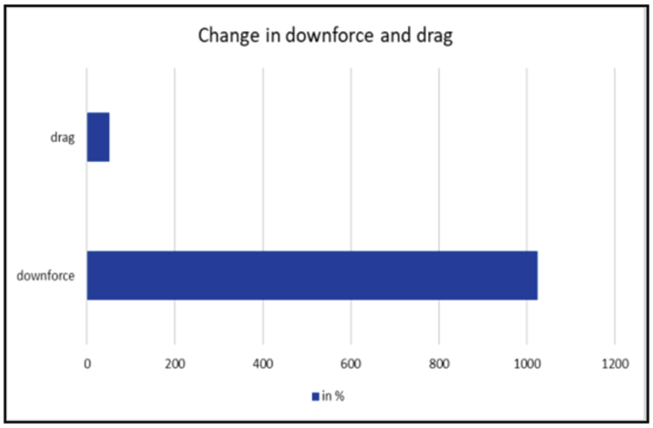

Figure 4: Percentage change in downforce and drag acting on the vehicle due to aero upgrades

3.1.4 Simulation results

The simulation results were successfully obtained and we can infer those various beneficial gains in performance had been made. The lift coefficient, drag coefficient, lift force, drag force of the total vehicle set up and off individual components was obtained to support this conclusion.

3.2 Lap Time Simulations

Lap time simulations are performed to analyze the effect of the designed aero package on the performance of the car in terms of lap times and accelerations around a particular racing track.

3.2.1 Software

The software used for all lap time simulations in this project is Optimum Lap. It is an open-source software developed by Optimum G, a company founded by one of the most reputed FSAE judge Mr. Claude Rouelle in the year 1978.

Optimum Lap is a simplified vehicle simulation tool that estimates a vehicles performance on a given racing track. In this software the vehicle is reduced to its most fundamental components such that the vehicle can be defined with only 10 parameter and each parameter represents a specific aspect of the car such as engine, tires, and aerodynamics which makes it easy to see how each parameter impacts the vehicles performance.

The vehicle model used in Optimum Lap is a point mass, quasi-steady state model.

Mathematically, this is overly simplistic, but in reality, this model is very powerful at analyzing the global performance trends of a vehicle and comparing the performance between different configurations of the vehicle without having to capture or model more detailed effects. Its tools allow researchers to study the effects of aerodynamics package, tires and suspension, and mass.

3.2.2 Simulation Procedure

STEP 1: To model the vehicle by entering various aerodynamic, vehicle dynamic and power unit parameters, such as mass, wheels driven, radius of the tyre, aerodynamic coefficients (lift and drag coefficients) and power unit torque-rpm data.

STEP 2: This involves track modelling, here track modelling can be done in 2 ways that is either by directly importing a pre-existing track from the Optimum Lap database or by modelling a custom track by entering the straight-line section lengths and corner radii, the latter method is a complex process and is required only when a custom track has to be modelled and hence the former method is used in the current simulation process.

STEP 3: To run the simulation by selecting the respective vehicle and track models and extracting required data after the simulation is complete.

3.2.3 Simulation input parameters

As explained previously the simulation is performed for 2 configurations/set ups of the car that is for car without aero package and for car with aero package, and hence there will be two sets of vehicle models and input parameters. However, since both the cars employ same power train, the power train input parameter will remain same for both.

The aerodynamic parameters such as lift and drag coefficients, frontal area and air density are obtained from the CFD simulations explained in the previous chapters. The vehicle dynamic and power train parameters such as vehicle mass, tyre radius, frictional coefficients and motor torque-rpm data are obtained from the initial design considerations as mentioned in the methodology and from results obtained through suspension design and analysis.

Configuration 2: With Aerodynamic package (Table 2).

3.2.4 Power unit parameters

As mentioned in the methodology the motor used in the power train is an axial flux motor named as Emrax-188. The motor's torque, power and rpm (speed) data which have been used to model the vehicle for the current simulation are shown in Figure 5.

Table 1: Input Parameters of configuration 2

Vehicle Type	FSAE - Aero
Mass	239 kg
Driven wheels	2 Wheel drive
Drag coefficient	0.490
Downforce coefficient	0.951
Frontal area	1.120 m^2
Air density	1.225 kg/m^3
Tyre radius	0.231 m
Rolling resistance	0.002
Longitudinal friction	1.8

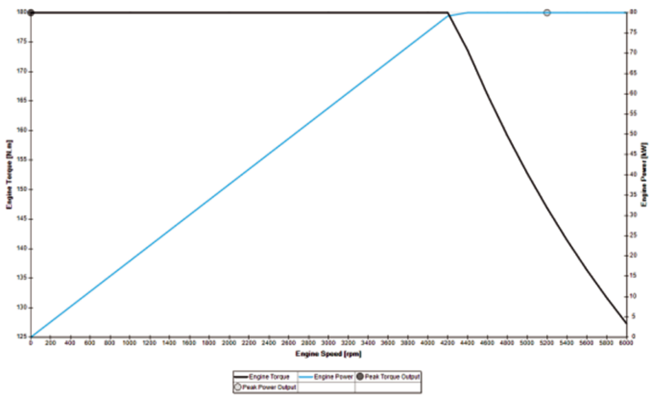

Figure 5: Power v/s Torque curve of the motor

3.2.5 Simulation results

To begin with the traction model for both the configurations of the car obtained from the simulations is compared and analysed, then the lap times, lateral and longitudinal accelarations, speed plots and various other data which was generated by the simulations is tabulated and analysed with respect to each track.

3.3 Traction Model

The simulated traction model for configuration 1, that is for the car without aerodynamic package is shown in the Figure 6. Here the the black line represents the driving force acting on the wheel (torque generated by the motor) or in other words tractive force acting on the wheels. The green line represents traction limit or the maximum traction force supported by the tire depending on the available

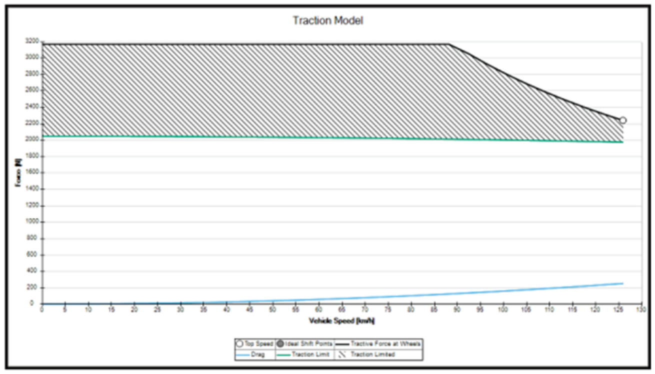

Figure 6: Traction Model of Configuration-1

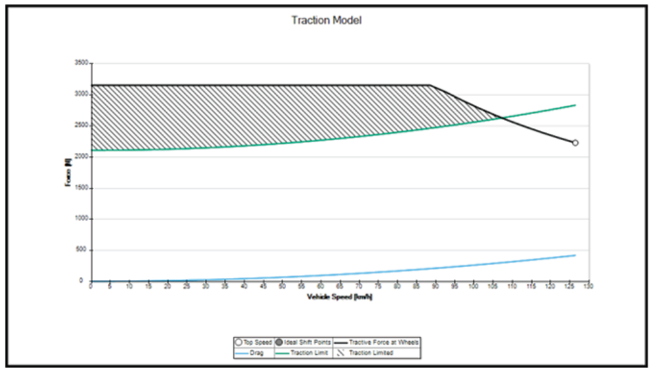

Figure 7: Traction Model of Configuration-2

frictional grip which in turn depends on the normal load (Aerodynamic downforce) acting on the vehicle and the tires. The shaded region is known as traction limited region, it is a region where the car is not able to completely utilise the driving force generated by the power unit (motor) due to insufficient frictional grip/

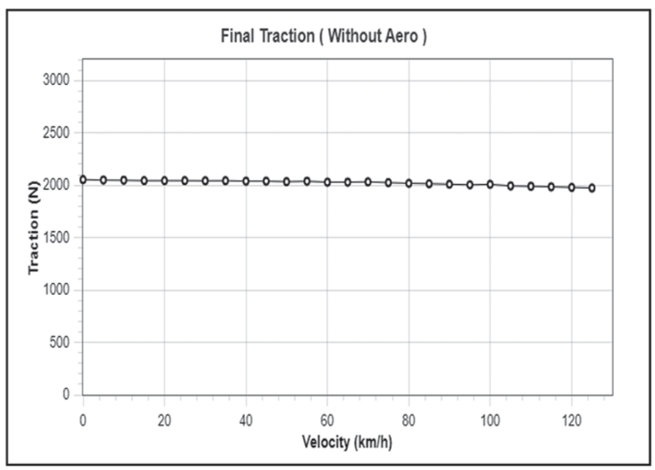

Figure 8: Final Traction curve of Configuration-1

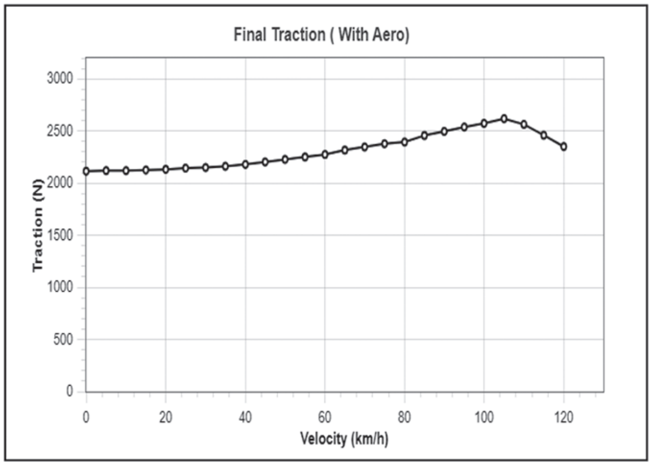

Figure 9: Final Traction curve of Configuration-2

traction at the tire-road contact patch and hence from the above graph/data we can say that the configuration 1 of the car is traction limited.

From the aforementioned traction model data of configuration 2, it is clear that the traction force in all aspects i.e. maximum tractive force, minimum tractive force and average tractive force has increased with the employment of aerodynamic package.

4. Conclusions

- For configuration 1 (without aero package) 294.7 N of drag and 91.82 N of lift was obtained at a velocity of 97.2 km/h.
- For configuration 2 (with aero package) 446.38 N of drag and -848.9576 N of lift (down force) was obtained at a velocity of 97.2 km/h.
- The aerodynamic devices added such as the front and rear wing and underbody diffuser showed considerable improvement in downforce levels of the vehicle. These gains would lead to better traction capabilities and higher cornering speeds of the vehicle. This can be inferred with the lap time simulations carried out on various auto cross and endurance tracks.
- By implementing aerodynamics package to an FSAE race car, the following trends were observed in the traction model: Average traction was increased by 328.883 Newton. Highest available traction was increased by 761.468 Newton. Traction at average speed of 60 km/h was increased by 237.697 Newton.
- The final traction available at contact patch for both the configurations of the car is graphically represented in the below images.

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