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Aerodynamics Design of Formula SAE Race Car

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ABSTRACT: *This paper describes the design of an aerodynamics package of a Formula SAE car. Formula SAE rules 2014 pertaining to aerodynamics is used to design the aerodynamic package which includes the front & rear wings and the diffuser. The aerodynamic package is designed to produce maximum downward force within the acceptable limits of increased drag and reduced top speed. Computational Fluid Dynamics (CFD) of this aerodynamics package is also described in this paper.*

An exoskeleton body structure and its respective ground effects is developed taking into account several factors to present an optimum body model as a final result. These factors include but are not limited to weight, cost, wind drag resistance, functionality and aesthetics.

Computational model of the vehicle body and diffuser was prepared using Solid works. Subsequently, several shapes & sizes were modelled and optimisation was done on the final design. Aerofoil selection was done from UIUC Aerofoil Database[1] to design the wings. Wings designed are analysed in XFLR[2] and Solid works to check the flow conditions. Diffuser is designed and analysed in Solid works.

I. INTRODUCTION

The design process starts with formulation of problem statement, which in this case is 2014 Formula SAE® Rules. The challenge is to develop a vehicle that can compete in all the events described in the 2014 Formula SAE Rules. All aerodynamic devices in Formula SAE [3] must satisfy the following rule requirements:

a) Location
   In plan view, no part of any aerodynamic device, wing, under tray or splitter can be:
   i) Further forward than 762 mm (30 inches) forward of the front of the front tyres.
   ii) Further rearward than 305 mm (12 inches) rearward of the rear of the rear tyres.
   iii) Wider than the outside of the front tires or rear tyres measured at the height of the hubs, whichever is wider.

b) Minimum Radii of Edges of Aerodynamic Devices
   All wing edges including wings, end plates, and undertray that could contact a pedestrian must have a minimum radius of 1.5 mm (0.060 inch).

c) Ground Effect Devices
   No power device may be used to move or remove air from under the vehicle except fans designed exclusively for cooling. Power ground effects are prohibited.

d) Driver Egress
   Egress from the vehicle within the time set in Rule T4.8 “Driver Egress,” must not require any movement of the wing or wings or their mountings. The wing or wings must be so mounted that any accident will not deform the wings or their mountings to block the driver’s egress.

Aerodynamics [4] is an important aspect in any automotive design. Commercial car manufacturers typically aim at increasing fuel efficiency by reducing aerodynamic drag. Thisis in contrast to race cars that focus on increasing cornering and braking ability by introducing aerodynamic devices.

Aerodynamic properties of an automobile are fundamental to its performance [5]. While the engine, suspension, transmission and tyres are the first structural components considered when automotive performance is assessed, the efficient performance of an automobile requires optimum aerodynamic performance.A racing car without aerodynamic consideration will not be able to attain high speed due to drag forces. This is not only a disadvantage for attaining better lap time but also has a risk of toppling.

II. THEORY OF AERODYNAMICS IN A FORMULA SAE RACE CAR

2.1 Aerofoils

Aerofoils are the most basic aerodynamic devices used on race cars. They can operate in free air and in confined flows and are used to enhance the pressure gradient of other body parts.

2.2 Inverted Aerofoils

Normally, aerofoils are used in aeroplanes to produce lift, but when used as an inverted aerofoil, they tend to produce downward force. An inverted aerofoil has a shape that allows more air to flow over its upper surface then that below it. This causes the air below the aerofoil to accelerate, creating differential pressure between its upper and lower surface, generating downward force. An inverted aerofoil indicating generation of downward force is shown in figure 1.

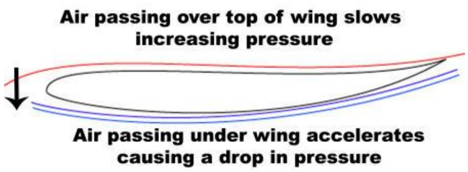

Figure 1: Inverted aerofoil

Inverted aerofoils on Formula SAE cars operate at a relatively low speed, requiring large degree of curvature. The pressure distribution around aerofoils is used to influence the performance of other aerodynamic components. The rear wing when placed low and very close to the rear of a carsucks air from below the car thus creating a pressure difference between the air flowing above and below the vehicle resulting in production of downward force. Without wing, the air behind the car would slow down leading to separation of air flow thus creating vortices resulting in increased drag. This concept has been used in designing multicomponent front and rear wings.

2.3 Multicomponent Wings

Multi component wings use the same principle as above. While the successive wings stacked with spacing of the order of their wingspan creates interference and produces less than twice the lift of a single wing, but wings placed successively can benefit from each other. The 1st element wing benefits from the low pressure zone created by the 2nd element wing behind it. The 2nd element wing experiences upwash [6] from the 1st element wing; the air coming off the 1st element wing will be turned up by some angle and this changes the angle of attack such that the 2nd element would see if it was in isolation. To utilize the upwash, the wing is placed at an appropriate angle of attack with respect to the upwash. The component of multicomponent wings with end plate is shown below in figure 2.

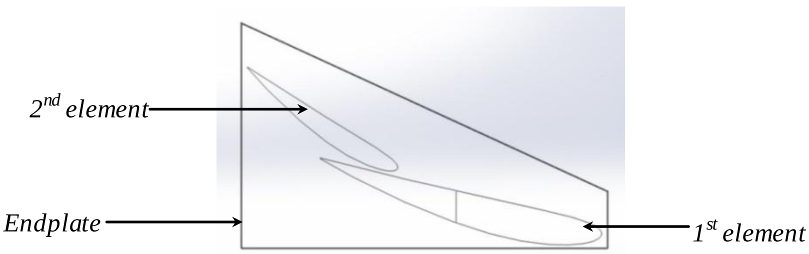

Figure 2: Multicomponent wings with endplate

2.4 Aerodynamic efficiency of a wing

The aerodynamic efficiency of the wing depends on aspect ratio and angle of attack[7]. Aspect Ratio is the ratio of the length of the wing to its width. The higher the aspect ratio, the more effective the wing is, which is evident from figure 3.

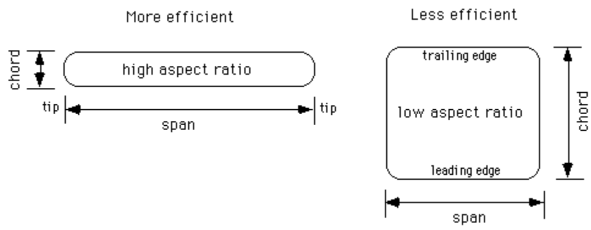

Figure 3: Efficiency of an aerofoil

The aerodynamic efficiency of the wing also depends on the angle of attack (α). It is the angle between the horizontal and the tangent to the camber line as shown in figure4. Increasing the angle between the wing and the ground will create more downward force, but at the same time it also creates more drag which is not desired. Hence an optimum angle must be found.The downward force achieved by the front and rear wings accounts for 50%. The remaining 50% downward force is achieved through under tray which works on the principle of venturi effect. [8]

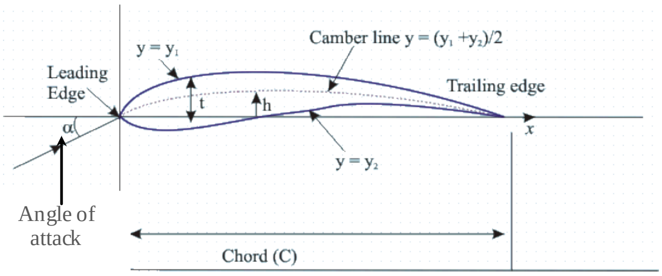

Figure 4: Nomenclature of an aerofoil

2.5 Venturi Effect

A venturi is a narrow tunnel that gets increasingly narrow towards one end. [9] The venturi (under tray) formed at the bottom of the car creates a low pressure zone between the car and the track, which helps in pulling the car down on the track as shown in figure 5.

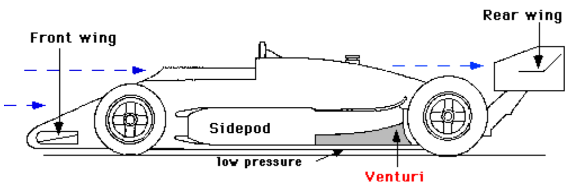

Figure 5: Venturi Effect in a Formula SAE Car

The last component of the car to come in contact with air is the rear wing. This wing is relatively bigger than the front wing but serves the same purpose. The rear wing is adjustable like the front wing and is set to a desired angle of attack to maximize its performance.

III. SPECIFICATION OF THE CAR

Net mass of the car in kg (without driver) : 204
Net mass of the car in kg (with 75 kg driver) : 279
Dimension of car in mm (L x W x H) : 2948 x 1388 x 1135
Wheel Base in mm : 1531
Track width in mm : 1216
All the dimensions are within stated rules by SAE Internationals

IV. METHODOLOGY

a. Body Panel Design
b. Aerofoil Selection for Front & Rear wings
c. Front & Rear wings Design with Endplates
d. Diffuser Design
e. Analysis of the Aerodynamic Devices
f. Downward force & Drag Calculations

4.1 Body Panel Design

[10] During design, the major concern was on increasing the aerodynamic efficiency of the car by design consideration of the wings and diffuser. The body panel design was followed by design of nose, wings and diffuser and their respective analysis.

While designing the body panel, turbulence caused due to air flow onto the wheels was considered. Accordingly the air flow through the side pods was channelled to the engine bay, for reducing turbulence in the tyres. This reduced vortex formation and finally the drag. Since the engine is air-cooled, channelling of air through the side pods also helped in engine cooling. The body panel design with side and top views are shown below in figure6&7 respectively.

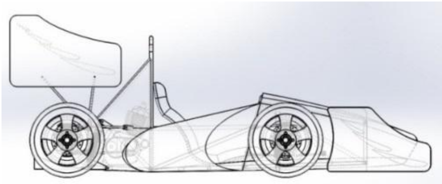

Figure 6: Side View of Car

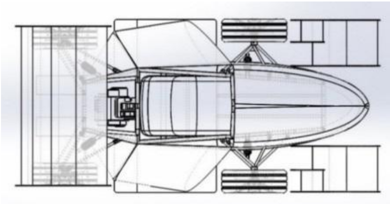

Figure 7: Top View of Car

4.1.1 Nose Design and Analysis

A shark snout is considered for nose to get a streamlined air flow to be channelledfor engine cooling through the side pods. The CAD model of nose is shown in figure 8.The flow analysis of nose was carried out using solid works. The results of the analysis obtained have been used to calculate aerodynamic balance. The objective of channelling air flow across the nose without creating vortices is apparent from the flow analysis shown in figure 9.

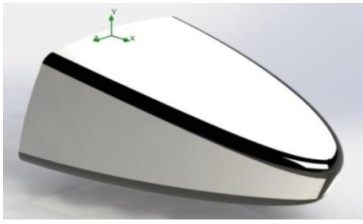

Figure 8. CAD Model of Nose

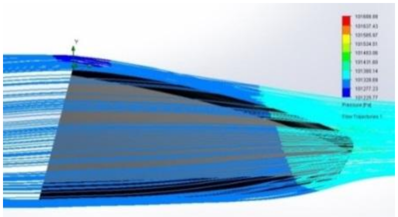

Figure 9. Flow Analysis in Nose using Solidworks

Table-2: Results of Flow Analysis of Nose using Solid works

Downward force produced by nose (F_{LN}) in Newton	7.031
Drag produced by nose (F_{DN}) in Newton	22.096

4.1.2 Front Wings Design and Analysis

The aerofoil NACA 6412 was selected for the front wings. A three element aerofoil for front wing assembly was considered in order to channel the air flow above the wheel, minimize turbulence and maximize downward force without any flow separation.The front wings with 3 element aerofoil are shown below in figure 10.

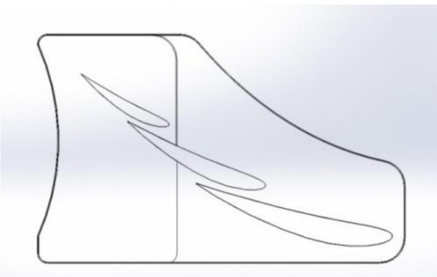

Figure 10: Front Wings with three elements Aerofoil

4.1.2.1 Analysis of Front Wings using XFLR

Table-3: Input Data for analysis of Front Wings with 3 element aerofoil

Wing Element-1	
Angle of Attack in degree	15
Chord Length(X) in mm	400
Span (L) in mm	365
Wing Element-2	
Angle of Attack in degree	20
Chord Length(X) in mm	300
Span(L) in mm	365
Wing Element-3	
Angle of Attack in degree	25
Chord Length(X) in mm	200
Span(L) in mm	365

The above data's are arrived after carrying a number of iterations

Figure 11: Wing Analysis in XFLR

Table-4: Results of Analysis of Front wingthrough XFLR

Coefficient of lift (C_L)	1.238
Coefficient of drag (C_D)	0.302
C_L/C_D	4.102
Area for downward force (A_L) in m^2	0.292
Drag Area (A_D) in m^2	0.2125

4.1.2.2 Downward & Drag Force Calculations

Assumptions

Velocity of car (v) : 14 m/s,

Density of air (ρ) : 1.225 kg/m^3

Drag Force (F_D) = $0.5\ \rho\ A_D\ C_D v^2$ (1)

Downward Force (F_L) = $0.5\ \rho\ A L\ C_L v^2$ (2)

Drag force produced by Front wings (F_{DF}) = 7.7042 N

Downward produced by Front wings (F_{LF})=43.397 N

The graphs generated from the analysis of front wings in XFLR are shown above in figure 12, 13, 14& 15 respectively. It indicates that increase in drag coefficient (C_D) does not increase the lift coefficient (C_L) appreciably for proportionate increase in drag coefficient hence the ratio C_L/C_D decreases. Also increase in angle of attack does not increase the coefficient of lift appreciably, but increases the drag coefficient, leading to a greater drag force which reduces the speed of the car which is undesirable.

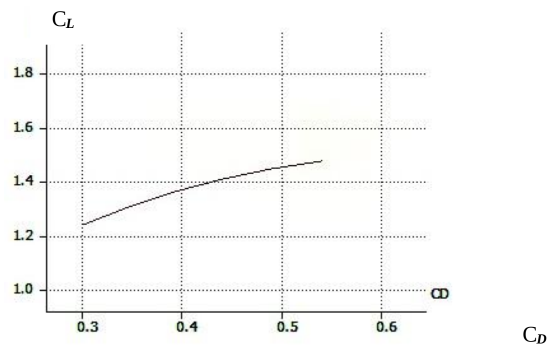

Figure 12: $C_L$vs C_D

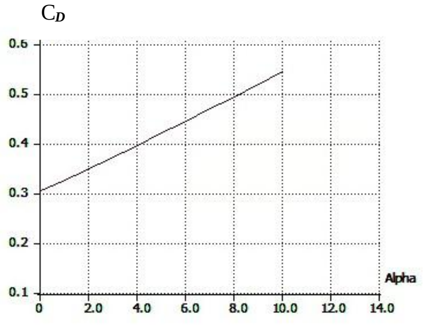

Figure 13: $C_D$vsα

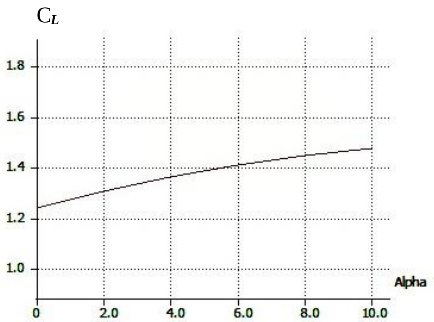

Figure 14: $C_L$vs α

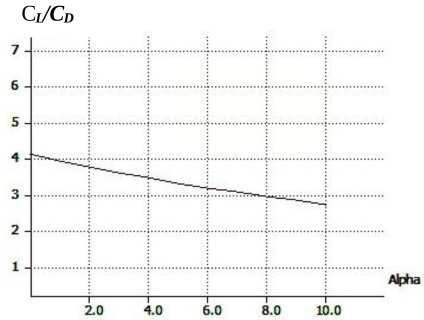

Figure 15: C_l/C_Dvs α

The results from the graphs have been used to optimize the angle of attack which is a variable parameter in design of wings. The angle of attack for the wing assembly isassumed as 15, 20 and 25 respectively. The behaviour of wings is then studied for an increment of 10 degrees which justifies the angle of attack assumed. Based on the iterations, a high value of C_L/C_D was finally achieved which indicates a high lift coefficient and low drag coefficient as desired.

4.1.2.3 Flow Analysis of Front Wings using Solidworks

The flow analysis of front wings using Solidworks in figure 16below shows that the flow lines are diverted above the wheels, thus reducing the turbulence on the wheels.

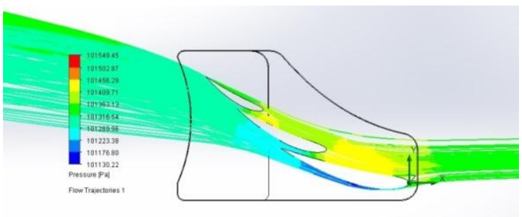

Figure 16: Flow Analysis

Table-5: Results of Analysis of Front Wings with 3 element Aerofoil using Solid works

Total drag force (F_{DF}) in Newton	19.0103
Total downward force (F_{LF})in Newton	51.7343

4.1.3 Rear Wings Design and Analysis

The aerofoil NACA 4412 was selected for the rear wings.A four element aerofoil instead of a single element aerofoil is considered to achieve maximum down force for a longer length without flow separation. The rear wings diagram is shown below in figure17.

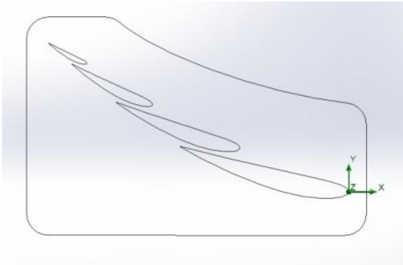

Figure 17: Rear wings with 4 Element Aerofoil

4.1.3.1 Analysis of Rear Wings using Solidworks

Table-6: Input Data for analysis of Rear Wings with 4 element aerofoil

Wing Element-1	
Angle of Attack in degree	15
Chord Length (X) in mm	400
Span(L) in mm	1372
Wing Element-2	
Angle of Attack in degree	20
Chord Length (X) in mm	300
Span(L) in mm	1372
Wing Element-3	
Angle of Attack in degree	25
Chord Length (X) in mm	200
Span(L) in mm	1372
Wing Element-4	
Angle of Attack in degree	30
Chord Length (X) in mm	100
Span(L) in mm	1372

The above datais arrived after carrying a number of iterations

4.1.3.2 Flow Analysis of Rear Wings using Solid works

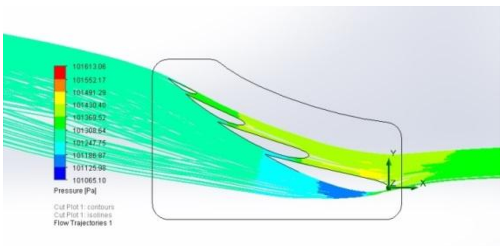

Figure 18: Flow Analysis

Table-7: Results of the Analysis of Rear Wings with 4 element aerofoil using Solidworks

Total drag force by rear wings (F_{DR}) in Newton	46.72
Total downward force by rear wings (F_{LR}) in Newton	110.921

Note: Analysis for rear wings in XFLR is not possible since XFLR can analyse for maximum of three elements at a time

V. AERODYNAMIC BALANCE

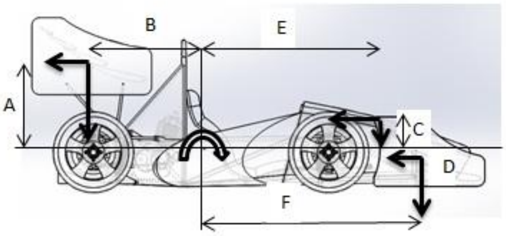

Figure 19: Forces acting on the car

M = Moment generated due to nose + Front wings + Rear wings

$$M = (F_{LN} \cdot E - F_{DN} \cdot C) + (F_{LF} \cdot F - F_{DF} \cdot D) - (F_{LR} \cdot B - F_{DR} \cdot A) \qquad (3)$$

$$M = 7.8619 \text{ N-m (clockwise)}$$

A low moment on the vehicle was achieved about its centre of gravity in the clockwise direction thus showing that no lift is generated about the centre of gravity of the car.

5.1 Diffuser Design and Analysis

[11] The role of a diffuser in a race car is to accelerate the flow of air under the body. The diffuser increases in volume along its length, creating a void that has to be filled by the air passing under the body. The venturi effect causes the flow to accelerate through the throat of the diffuser, creating the desired low pressure. Reduced pressure under the car leads to a downward force that contributes to a greater lateral force capability of the tyres. This increased lateral force capability is known as "aerodynamic grip".

Design Data for Diffuser

Inlet rake angle	: 2degrees
Ground clearance	: 1 inch
Exit rake angle	: 13degrees
Inlet velocity	: 14 m/s

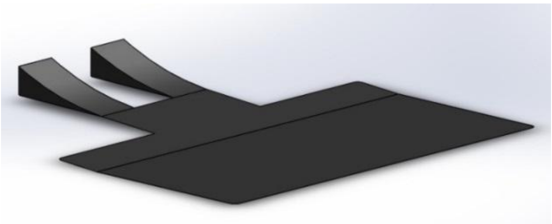

Figure 20: CAD Model of Diffuser

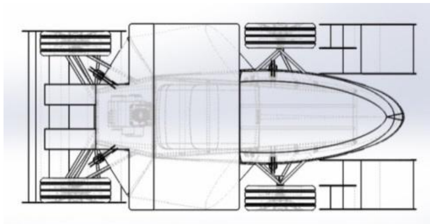

Figure 21: Under tray and Diffuser Mounted below the Car

5.1.1 Analysis of diffuser

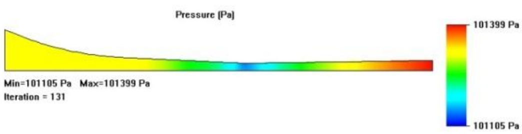

Figure 22: Pressure Variation

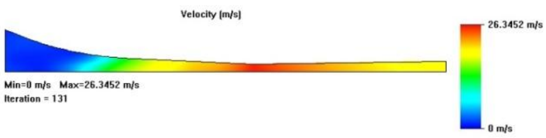

Figure 23: Velocity Variation

The Analysis of diffuser in figure22&23 shows maximum velocity and minimum pressure at the throat below the vehicle, which eventually leads to increase in the downward force. [12]

Table-8: Results of Analysis

Maximum velocity attained by air through diffuser in m/s	26.3452
Avg. pressure under the vehicle in Pascal	101252
Dynamic Pressure at throat of the vehicle (P_1) in Pascal	425.1
Pressure of air above the vehicle in Pascal	101399
Dynamic Pressure of air above the vehicle (P_2) in Pascal	177
Area of diffuser (A) in m^2	1.36215

Downward force produced due to diffuser(F_{LD}) : $(P_1-P_2) \times A$ (4)

: 337.937 N

VI. NET DOWNWARD FORCE PRODUCED BY THE AERODYNAMIC DEVICES

The net downward force produced by the aerodynamic devices is the summation of downward force produced by nose, front wings, rear wings & diffuser

Net Downward Force = $F_{LN} + F_{LF} + F_{LR} + F_{LD}$ (5)

Net Downward Force = 507.6233 N

The downward force of 507.6233 N generated due to the aerodynamic package was checked for its requirement. This was done by calculating the lift generated on the inner wheels during a sharp turn at a velocity of 14 m/s, so as to check whether the downward force created was more than the lift generated as desired.

Table-9: Lift generated during sharp turn (F)

Centre of gravity from ground (h) in mm	284
Minimum turning radius (r) in meter	7.5
Velocity of turn (v) in m/s	14
Weight of the car (with 75 kg driver) in kg	279
Track width of car (b) in mm	1216

Moment about O = $\frac{mv^2h}{r}$(6)

= 2070.7N-m

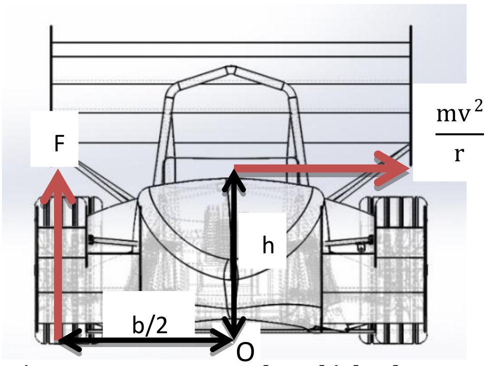

Figure26: Moment on the vehicle about O

Lift generated is calculated using equation, Moment about O = F x b/2 (7)

Therefore Lift Generated (F) = 3405.7578N

VII. BALANCING OF DOWNWARD FORCES

Total lift generated	:	3405.7578 N
Force absorbed by suspension for 1 inch travel	:	3000 N
Net downward force at 14m/s	:	507.6233 N

The net downward force of 507.6233 N created by the aerodynamic devices is more than the balance lift generated (405.7578 N), and hence the net force is in the down ward direction which maintains the dynamic stability of the car at 14 m/s during turn of radius 7.5 m. The aerodynamic package provided for the vehicle thus significantly benefits the dynamic performance of the car.

VIII. DRAG COEFFICIENT (C_D)

The net drag force on vehicle (F_D) is calculated by summing up the drag force due to nose (F_{DN}), front wings (F_{DF})&rear wings (F_{DR})
Net Drag Force (F_D) = 87.8263 N
Frontal impact area of the car (A_D) = 1.27348 m^2

Drag Coefficient (C_D) is calculated using the equation, $F_D = 0.5\ \rho\ A_D\ C_D\ v^2$(8)
Therefore C_D = 0.5744

IX. CONCLUSION

A net downward force of 507.6233 N due to the entire aerodynamic package is achieved at 14m/s. This has been verified against the lift generated at the inner wheels during a turn of radius 7.5m at 14m/s and proved to be effective in maintaining traction.The net drag coefficient calculated is0.5744, which allowed the vehicle to attain higher speed and better fuel efficiency due to low drag.

The selection of multicomponent wings element over single element for both front and rear produced a net resultant downward force of around 35%.The diffuser designed is responsible for 65% of the downward force produced and is proved to be effective at high speeds.

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