Determination of Critical Downforce Coefficient of a Vehicle for Optimum Aerodynamic Performance

Brightson George[1], Jairesh J. V.[2], Chithraiselvan G.[3], Gokul Nath S.[4]

[1]*B.E. Student, Mechanical Engineering, Bannari Amman Institute of Technology, Erode-638401*
[2]*B.E. Student, Mechanical Engineering, Vins Christian College of Engineering, Kanyakumari-629502*
[3]*B.E. Student, Mechanical Engineering, Bannari Amman Institute of Technology, Erode-638401*
[4]*B.E. Student, Mechanical Engineering, Bannari Amman Institute of Technology, Erode-638401*

Abstract - *- The ultimate aim of every race car designer is to improve the lap time, without compromising safety and other aspects. In order to achieve this objective, the most predominant factor is cornering ability at high speed. During cornering, the cars have to reduce its longitudinal acceleration to compensate for the lateral acceleration i.e., it has to slow down while cornering to avoid sliding or deviating from the desired path, as the traction provided by tyre is limited for a given load. One such way to improve the cornering ability, ultimately improving lap time, is by improving the traction of the tyres by increasing the load acting on it. The effective way to increase load on tyres while cornering is by increasing aerodynamic downforce coefficient of a car to a certain limit, that is, up to critical downforce coefficient. The critical downforce coefficient is the value after which the drag nullifies the positive effect on the lap time caused by downforce. This paper provides the methodology to determine critical downforce coefficient of a car for a given track. The critical downforce coefficient is determined by series of analytical calculations and simulations carried out using OptimumLap software.*

Key Words: Cornering, Critical downforce coefficient, Downforce, Drag, Lap time.

1. INTRODUCTION

From a distance, any automobile racing appears to be a sport which have a strong penchant for popularity and commercial media coverage. But, despite the false facade the highly popular sport seems to hold, on its root, it act as a place where new technologies are tested and proved before being incorporated into the commercial automobiles. In this technology race, several factors contribute to the win like chassis design, engine, tyres and so on. The best race car on a track is undoubtedly the fastest car on the track, the one with the best lap time, at least as long as only single lap is considered. Since over a race distance several factors come into play, sometimes it is not the fastest that wins. The time taken for a race car to complete a lap depends on how fast a car can accelerate, brake(decelerate), corner ability, aerodynamics, top speed and so on, of which improving one compromises another. Of these, aerodynamics is a field which has attracted a lot of focus over the recent years. Aerodynamics is the reason why we see more streamlined cars, and several attachments ranging from small flaps to large spoilers.

1.1 Significance of Aerodynamics

The importance of building aerodynamically efficient car is well understood when the effect of aerodynamic forces on a moving object is analyzed.

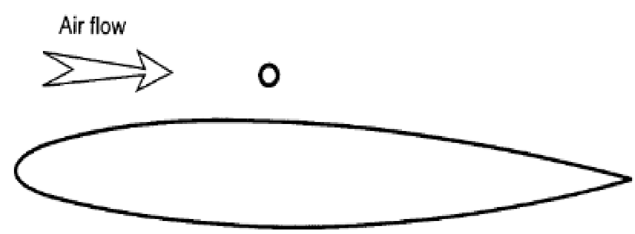

Fig - 1 : The cross sections of rod and airfoil with same drag

In [1], comparison of two cross section shows that a cross section of a circular rod has the same drag as the thicker (up to 10 times) and larger airfoil. Thus the important step for any race car is to reduce the drag and thereby increase the speed and acceleration. However with constrained rules in the body design of any race car it is almost impossible to reduce drag below a certain limit. Nevertheless, the drag reduction is only secondary. The most primary concern of any race car designer is to produce more downforce as it would improve the cornering ability of a car by increasing the load acting on it.

1.2 Downforce to lap time relation

When increasing the aerodynamic downforce coefficient of the car, which is done by adding aerodynamic elements, it is important to note the relatively smaller increase in drag force or drag coefficient of the car according to [2]. This drag force upon reaching certain value decreases the speed along a straight line significantly enough to nullify the positive effect of increased downforce. Therefore, for very high downforce coefficient the effect on the lap time due to enhanced cornering is nullified by the reduction in straight line performance due to increased drag coefficient. So, for every vehicle depending on the track an optimum aerodynamic setting exists and it is marked by critical downforce coefficient(value above which drag nullifies the effect on the lap time due to downforce). Throughout this paper the effect of side winds is not considered. This paper will provide the methodology to determine the critical downforce coefficient of a certain vehicle for a given track (the value varies with different track layouts) using a few analytical calculations and a series of simulation on the OptimumLap software.

2. METHODOLOGY

2.1 Selection of Vehicle

Formula SAE-no aero car is chosen for the determination of critical downforce coefficient as it is widely known, also, the downforce and drag coefficient and other parameters(both performance and dimensional) of a standard FSAE - no aero car are available in the online database of the OptimumLap software. The term no-aero means the car does not have any aerodynamic add-ons like wings, diffuser, flaps and so on. Formula SAE is a student design competition in which students are challenged with the task of designing, manufacturing and testing a formula styled race car(open cockpit, open wheel), organized by SAE International [3]. The competition is all about selecting the best combination of racing aspects like braking, acceleration and cornering stability.

Table - 1 : Vehicle configuration of FSAE - no aero car

Vehicle Configuration

Parameter	Value
Total Mass	250 kg
Max Torque	63.4 N.m @ 10549 rpm
Type of Fuel	Gasoline
Type of Transmission	Sequential Gearbox
Max Power	97.24 hp @ 11351 rpm
Power Mass Ratio	0.39 hp/kg
Downforce @ 100 km/h	-6.17 N
Drag @ 100 km/h	443.53 N

The 'built' race car is tested for its performance in a series of events like Autocross, Skip pad, Fuel economy, Endurance events. In such competition maintaining a balance between certain performance parameters is the key. The real potential of the students is displayed when they improve a parameter without compromising another parameter.

Table - 2: Performance metrics of FSAE - no aero car

Performance Metrics

Metric	Value
Top Speed	148.57 km/h
Time for 0 to 100 km/h	3.35 s
Time for 100 to 0 km/h	1.96 s
Lateral Acceleration - Skidpad 50 m	14.68 m/s^2

2.2 Selection of Track for simulation

The Buddh International Circuit is chosen for the determination of critical downforce coefficient of the FSAE car for this paper as the track data, performance parameters are available in the online database of the software. The Buddh International Circuit is an Indian motor racing circuit in Greater Noida, Uttar Pradesh, India, 40 km from Delhi. It is a very challenging track characterised by quick change of directions and fast flowing corners.

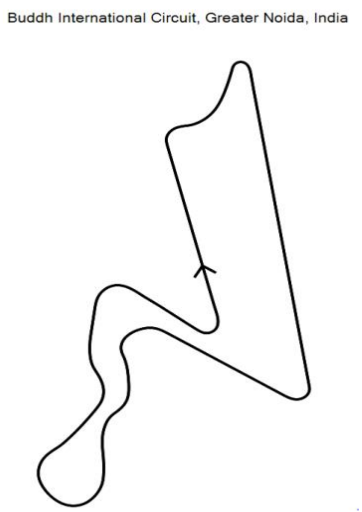

Fig - 2 : Buddh International track layout

2.3 Calculation and Simulation:

Initially the data of the Buddh International Circuit is downloaded from the track database and loaded into the software from the OptimumLap website. Next load the parameters of the standard FSAE car with no aero in the OptimumLap software and the simulation is carried out to find the lap time. Then the simulation is carried out for increasing values of downforce coefficient and the corresponding lap times are noted.

In real world this increase in downforce would correspond to the incorporation of aerodynamic add-ons like wings, diffuser, flaps and so on. As a result, the coefficient of drag increases with that of downforce, with other values remaining constant throughout the simulation [4].

The lap time for the FSAE - no aero car with the initial setup (no aerodynamics add-ons) on the Buddh International circuit is found to be 139.54 seconds. The initial coefficient of drag (C_{do}) and coefficient of downforce (C_{dfo}) are 0.6 and -0.01 respectively. The C_{dfo} is negative which implies that vehicle experiences lift. In order to carry out the rest of the simulations we require drag coefficient for every downforce coefficient we assign.

Relationship between the drag and downforce coefficients are provided by the equation denoted in [1], which, to be precise draws the relationship between the coefficients of lift and drag. Downforce is the negative of lift. Therefore it is important to note that C_l and C_{lo} are negative for downforce.

$$C_d=k*(C_l - C_{lo})^{2}+C_{do}$$

C_d - Coefficient of drag (after aerodynamic add-ons)

C_l - Coefficient of lift (after aerodynamic add-ons)

C_{lo} - Coefficient of lift (before aerodynamic add-ons)= 0.01

C_{do} - Coefficient of drag (before aerodynamic add-ons)= 0.6

C_{dfo}- Coefficient of downforce (before aerodynamic add-ons) =($-C_{lo}$) =-0.01

C_{df} - Coefficient of downforce (after aerodynamic add-ons) =($-C_l$)

k - Polar coefficient (ranges from 0.03 - 0.04)=0.04

The equation is solved for increasing values of C_{df} from 0.1 to 2.5 with the C_{df0} and C_{lo} values being -0.01 and 0.6(remains *unchanged throughout) and C_d is tabulated in the Table - 3.

The value for P is chosen to be 0.04 according to [1] which accounts for the added drag due to added downforce. The C_{dfo} and C_{df} are the negatives of C_{lo} and C_l and hence the sign change.

Table - 3: C_{df} to C_d iteration

C_{dfo}	C_{lo}	C_{df}	C_l	C_{do}	C_d
-0.01	0.01	0.1	-0.1	0.6	0.600
-0.01	0.01	0.5	-0.5	0.6	0.610
-0.01	0.01	1	-1	0.6	0.632
-0.01	0.01	1.5	-1.5	0.6	0.689
-0.01	0.01	2	-2	0.6	0.758
-0.01	0.01	2.1	-2.1	0.6	0.775
-0.01	0.01	2.2	-2.2	0.6	0.792
-0.01	0.01	2.3	-2.3	0.6	0.810
-0.01	0.01	2.4	-2.4	0.6	0.829
-0.01	0.01	2.5	-2.5	0.6	0.848

3. RESULTS

Now for every individual set of C_l and (its corresponding) C_d, the lap time simulation is done on the software and the respective lap time(s) are calculated. At a certain C_l value the lap time reverses its order and starts increasing, which is Critical Lift coefficient. The lap time is plotted against downforce coefficient in the graph below. The slope of the relationship is negative in the beginning and after the critical downforce coefficient it experiences a positive slope.

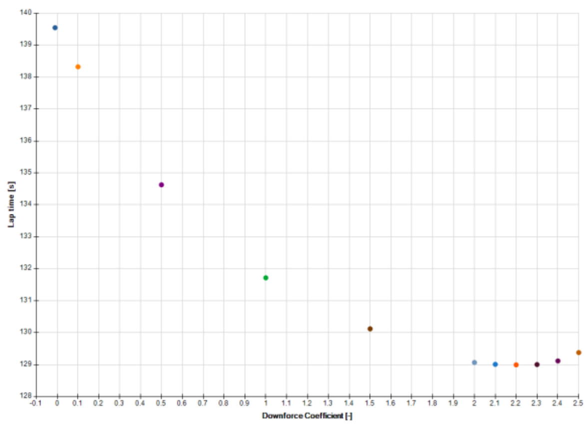

Chart - 1 : Effect of downforce coefficient in lap time(i)

From the Chart - 1 and Chart - 2, the critical coefficient of downforce for the FSAE- no aero car on the Buddh International circuit is found to be 2.2 and the corresponding lap time is 128.950 which is about 10 seconds clear from the lap time by the initial setup without any aerodynamic downforce. Going further the critical coefficient, the lap time increases which is undesirable. So the aerodynamic add-ons should be designed to reach the downforce coefficient 2.2.

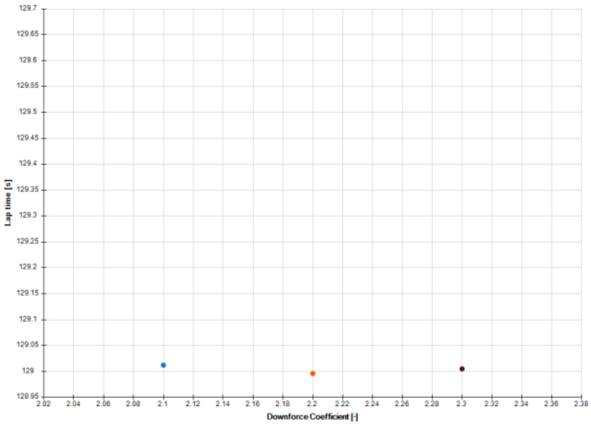

Chart - 2: Effect of downforce coefficient in lap time(ii)

4. CONCLUSION

To summarize, the initial coefficients of drag and downforce of the car before any aerodynamic add-ons, which are usually determined by fluid simulation or wind tunnel testing, in this case, already present in the database of the software, are noted. Then for increasing values of the downforce coefficient the corresponding drag coefficients are found. For the individual sets of the drag and downforce coefficients the lap time simulation is carried out. Initially the lap time decreases but at a certain point it reverses the direction and increases, the value of the downforce coefficient after which this increasing trend is shown is the critical downforce coefficient. In our case, the critical downforce coefficient is found to be 2.2 and the lap time is 128.950 which is 10 seconds clear from the initial lap time of the car without any aerodynamic downforce. The difference at first might seem insignificant but in a race which consists of the about 20 laps, the difference would become 200 seconds which is enormous and a great advantage over the others, one that guaranties victory.

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