



AERODYNAMICS ASPECTS OF FORMULA S RACING CAR

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1. Introduction

On the University of Maribor in Slovenia the new racing car is developed. This is already the second completely new car prepared by our university team for the world competition in Great Britain, by which we should the proof that the award for our tenth place on the competition in the year 2000 was not get by coincidence.

The restrictions on the car frame and engine are limited so that the knowledge, creativity and imagination of the constructors are really challenged. The car are build with a team afford over a period of about one year and are taken to the annually competition for judging and comparison with approximately 30 other vehicles from colleges and universities throughout the world.

In order to improve the properties of our car as much as possible the attention is dedicated to the chassis, to the engine, and to the aerodynamic also. This article is focused especially to the improvements that we achieved on the account of front and rear wings. In this approach the body of the car is not considered.

2. The general rules to be considered

In the continuation few general rule required by the competition organizer is pointed out in order to clarify the reasons why the racing vehicle looks out as it is. First of all the vehicle must be open-wheeled and open cockpit, a formula style body.

For the purpose of the competition, the students are to assume that a manufacturing firm has engaged them to produce a prototype car for evaluation as a production item. The intended sales marked is the nonprofessional weekend autocross racer. Therefore the car must have very high performance in terms of its accelerations, braking, and handling qualities. The car must be low in cost, easy to maintain, and reliable. In addition, the car's marketability is enhanced by other factors such as aesthetics, comfort and use of common parts. The manufacturing firm is planning to produce four cars per day for a limited production run and the prototype vehicle should actually cost bellow \$25,000. The challenge to the design team is to design and fabricate a prototype car that best meets these goals and intends.

The cars are judged in a series of static and dynamic events including: technical inspections, cost, presentation, and engineering design, solo performance trials, and high performance track endurance. These events are scored to determine how well the car performs.

The car must be conceived, designed, and fabricated by students without direct involvement from professional engineers, automotive engineers, racers, machinist, or related professionals. The students team may use any literature or knowledge related to the car design and information from the professionals or from academics as long as the information is given as a discussion of alternatives with their pros and cons. Professionals may not make design decisions or drawings and Faculty Advisor must sign a statement of compliance with this restriction.

3. The rules about aerodynamic

The purpose of the following rules is to minimize any likelihood of injury to spectators, officials, driver, etc. in the case of accidental contact with the wings and structure. The wing or wings must be located in a plan view with a quadrilateral defined by the outside of the tires on the sides, by a transverse line 460 mm in front of the fronts of the front tires, and by a transverse line between the rear of the rear tires. The driver egress from the vehicle within the 5 seconds shall not require any movement of the wing or wings or their mountings. The wing or wings must be mounted in such position, and sturdily enough, that any accident is unlikely to deform the wings or their mountings in such a way to block the drivers egress. All wings leading edges shall have a minimum radius 12,7 mm unless a wing projects in front of the front tires, in which case it must have a minimum radius of 19 mm. Wing leading edges must be as blunt or blunter than the required radii for an arc of plus or minus 45 degrees centered on a plane parallel to the ground or similar reference plane for all incidence angles which lie within the range of adjustment of the wing or wing element. All wing edges, end plates and wing accessories must have minimum edge radii of at least 3 mm i.e., this would mean at least 6 mm thick edge. No small radius edges may be included anywhere on the wings in such a way which would violate the safety intend of these rules, i.e. vortex generators with thin edges, sharp square corners on end plates, etc. No power device may be used to move or remove the air from under the race car except fans designed exclusively for cooling. No power ground effect are allowed.

4. The wings on racing car

There is, perhaps, no other aspects of competition car technology that has had a big an influence on performance ass the exploitation of downforce. In all the world's current major single seater championship, including Formula 1, Indycars, Formula 3000 and Formula 3, aerodynamic downforce is the most important single element in the performance of the cars. Downforce has become so significant that in most leading formulae the governing bodies have seen fit to regularly review the regulations concerning downforce-inducting devices in an effort to try to keep things in check. Described reasons lead the peoples that organize the Formula Student competition in the Great Britain to make the rules shown in previous chapters. Downforce plays such a large part in performance that devices to create it are expressly forbidden in some other junior training formulae so that drivers may learn in a gradual way how to handle it, and how to tune it to best advantage before progressing to the top level where it is so crucial.

It may seem that the loads created by the motion of air is unimportant, especially within the speed range encountered by automobiles. However, you only have to extend your hand out of a car's side window to feel the serious forces exerted by air. To understand how such aerodynamic forces can be crested, a typical cross section of a wing is shown on the Figure 1. It moves from right to the left. Because of the shape and angle of this airfoil section, the air will move faster on the lower surface than on the upper one. This speed difference creates a low pressure, suction, on the lower surface and a higher pressure on the upper one. The result of this pressure difference is the force that push an racing car to the ground.

Nothing in live comes free, and when the wings generate downforce they also create drag, which is the force that resists the motion. The drag is usually much smaller than the downforce. Of course any improvement in a vehicle's drag leads to potential improvements in fuel economy or in maximum speed.

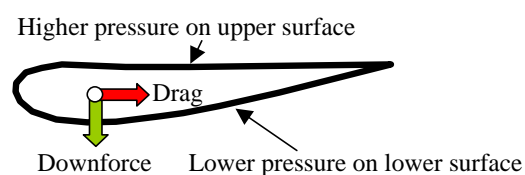


Figure 1. Typical cross section of a wing mounted on racing car

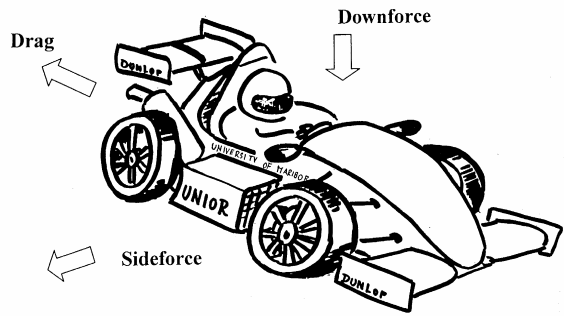


Figure 2. Three components of aerodynamic force

Instead of the downforce showed on the Figure 2 at very-high speed the experienced driver may have noticed the instability of the car caused by lift, which will usually be larger on the rear wheels than on the front ones. In race car design the creation of downforce by aerodynamic means is extremely important and leads to major improvements in race car performance, especially on tracks with numerous high-speed unbanked turns. Aerodynamic downforce increases the tires' cornering ability. It actually means that the car equipped by an aerodynamic device is able to sustain much greater sideforces. To demonstrate the positive wings influence on the car cornering speed, observe the two curves in Figure 3. The units compare the maximum cornering capability of race cars to a modern sports car [Katz 1995]. The gradual increase indicated by the solid line is a result of the continuous improvements in tire technology. This is the level of cornering available for production sport cars without aerodynamic downforce. The dotted line represents the trends in the performance of the most advanced vehicles, including F-1. The huge increase in the cornering capability in the 1970s seems to be a result of using wings. This trend accelerated towards the end of the 1970s with the introduction of ground effect principle. In addition to improved cornering speeds aerodynamics have dramatically improved vehicle stability and high-speed braking as well, which again lead to faster lap times. This is even more impressive when you consider that aerodynamic drag increase with addition of wings reducing straightway speeds.

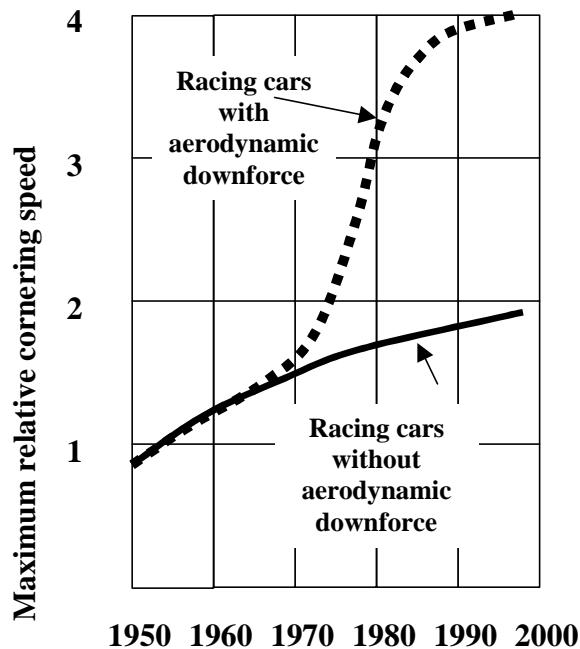


Figure 3. The increase of maximum cornering speed with aerodynamic downforce

5. How to select and design a wing set up

First thing the designer should know is that the front wings do not generate significant drag. The tests on the hillclimb single sitter in the full scale wind-tunnel demonstrated this fact [McBeath 1998], and even large changes to angle of attack did not alter the overall car drag by more than percentage point or so.

However, relatively small changes to the rear wing configuration not only altered the downforce but also made big differences to the car's drag figure. This situation is typical and representative of single seaters in general. In the continuation the eight point plan to a first approximation of wings set up is presented:

1. Calculate the theoretical top speed without wings.
2. Decide how much you are prepared to knock off that top speed by the addition of wings.
3. Calculate the difference in power absorption figures between the top speed without wings and the top speed you are prepared to accept with wings.
4. The difference between these two power absorption figures is what you are going to donate to rear wing in the quest for downforce.
5. Calculate the maximum wing C_D value that this represents.
6. Consult the wing catalogues to seek out first the basic configuration, then a specific profiles.
7. Calculate the theoretical downforce figure that the rear wings give, then calculate the downforce required at front to balance this value.
8. Consult the wing catalogues again to determine a suitable configuration, profile, and approximate angle of attack for the front wings.

Let us use these eight rules in our case. The race car Formula S has a frontal area without wings $A = 1.000 \text{ m}^2$ and the estimated wingless drag coefficient $C_D = 0.650$. The Honda 600 cm^3 engine power on the flywheel is supposed to be about 65.000 *bhp*. The transmission efficiency estimated on the basis of similarity should be over 88 percents (rolling resistance is also part of transmission losses). In this case the engine power that left to overcome air resistance is $P = 57.200 \text{ HP} = 42.059 \text{ kW}$. Under these conditions would be the maximum top speed calculated as follows (the air density is $\rho = 1.220 \text{ kg/m}^3$):

$$v = \sqrt[3]{\frac{2 \cdot P}{C_D \cdot \rho \cdot A}} = \sqrt[3]{\frac{2 \cdot 42059}{0.650 \cdot 1.220 \cdot 1.000}} = 47.300 \frac{\text{m}}{\text{s}} = 170.400 \frac{\text{km}}{\text{h}} \quad (1)$$

That would be the maximum speed, which could be reached on the ideal straight track. The fastest speed recorded at any Formula Student event the car has been driven on is 140 km/h. Therefore, for the sake of the example, let's assume that we decide that a maximum speed of, say, 155 km/h was going to be more than enough to leave some top end acceleration at the fastest part of the fastest course visited. In that case the needed power is much lower:

$$P_w = \frac{1}{2} \cdot C_D \cdot \rho \cdot A \cdot v^3 = \frac{1}{2} \cdot 0.650 \cdot 1.220 \cdot 1.000 \cdot \left(\frac{155}{3.6}\right)^3 = 31647 \text{ W} \approx 32 \text{ kW} \quad (2)$$

The power difference between the already calculated power and the power absorbed at the absolute top speed without wings, $\Delta P = P - P_w = 42 - 32 = 10 \text{ kW}$, is the value that we are going to donate to the rear wings in order to get the downforce. Now appears the question how the wings with appropriate drag coefficient, C_D , that would absorb the power difference, should look out. Let us suppose that the chord line of wing is about 265 mm that is presumably good compromise according to the design requirements. The span of the rear wing is 1000 mm. With this supposed data the frontal area of the rear wing is $A_{z_k} = 0.265 \times 1.000 = 0.265 \text{ m}^2$. Using the rearranged power absorption equation again, the highest possible drag coefficient of rear wings will be:

$$C_{D_{\max}} = \frac{2 \cdot \Delta P}{r \cdot A_{zk} \cdot v^3} = \frac{2 \cdot 10000}{1.220 \cdot 0.265 \cdot \left(\frac{155}{3.6}\right)^3} = 0.775 \quad (3)$$

So what kind of wing will have the aerodynamics drag $C_D = 0.775$? The diagram on the Figure 4 shows a tentative correlation based on published data points. In our example, a C_D of 0.775 should correspond to a C_L (this is actually downforce!) of about 2.450.

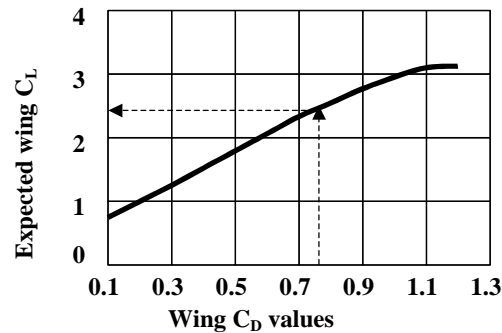


Figure 4. Wing C_D versus C_L

Consulting the few example wing data charts it can be seen that this would correspond to a two-element wing. Only two element wings can have high enough lift coefficients. Because of very hard rules that prescribed the radius of each leading edge, which should be at least 19 mm, the designer decided to use cambered single element wing. The cambered single element wings can not have lift coefficient higher than $C_L = 1.600$. This can be achieved at 14 degrees angle of attack. It is much less than calculated value 2.450! The decision to use single wings instead of recommended two elements wings means that due to the design rules we wont use aerodynamic downforce as it could be possible. It also means that the car is able to accelerate also by the speed 155 km/h and even over.

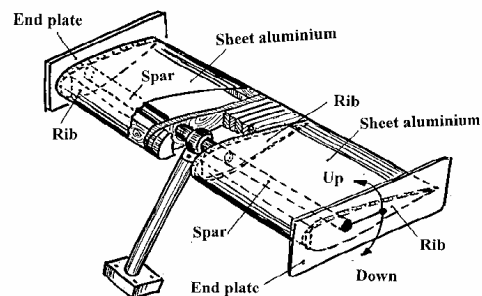


Figure 5. Front wing design

As with all amateur racers who do not have the luxury of a wind-tunnel to tray out these ideas o a scale model first, or even the measure the effects under controlled conditions, the only option for our team is to build the wing, fit it, and see if it helps the performance in absolute terms or relative terms. On the Figure 5 the concept and the final design of rear wing is shown. The angle of attack of a rear wing is a matter of adjusting and can not be prescribed in advance. The next step is to work out the front wing that should, theoretically balance this rear wing. The aerodynamic forces should be in proportional to the weight distribution, which, with the driver aboard, is about 50:50 front:rear.

Downforce of rear wing is $D_R = C_{L_{zk}} \times 1/2 \times r \times v^2 \times A_{zk} = 1.600 \times 0.5 \times 1.220 \times (155/3.6)^2 \times 0.265 = 479N$. The drag of rear wing is $DR_R = 120N$. Front wing area is about $A_{sk} = 0.265 m^2$ (the cord line is

0.265 m, the span is 1.000 m). It is presumed that the front wing profile is the same as it is on the rear wing. On that way the making procedure of the wings becomes more simple.

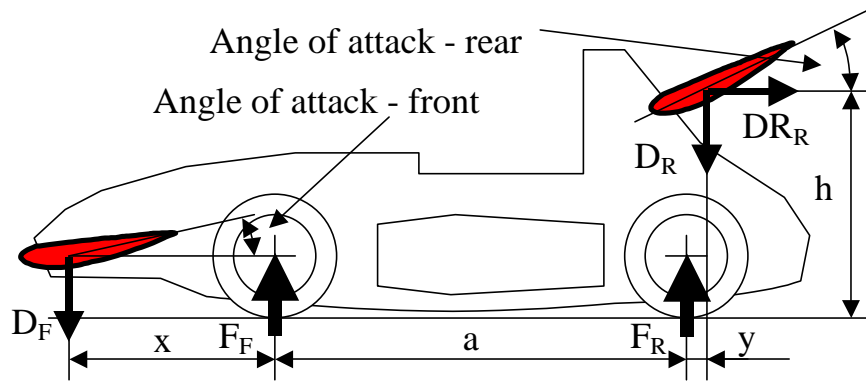


Figure 6. Sketch of the wing location

On the Figure 6 the location of the wings is shown. The rear wing is located at the position in that the downforce work through the axis of rear wheels. Considering the wing location the downforce of the front wing, D_F , can be calculated as follows:

$$D_F = \frac{D_R \cdot (a + 2 \cdot y) + 2 \cdot DR_R \cdot h}{a + 2 \cdot x} = \frac{479 \cdot (1.650 + 2 \cdot 0) + 2 \cdot 120 \cdot 0.800}{1.650 + 2 \cdot 0.500} = 370N \quad (4)$$

The theoretically lift coefficient (it actually means downforce!) of the front wing is to be:

$$C_{LFth} = \frac{2 \cdot D_F}{r \cdot A_{sk} \cdot v^2} = \frac{2 \cdot 370}{1.220 \cdot 0.265 \cdot (155 / 3.6)^2} = 1.230 \quad (5)$$

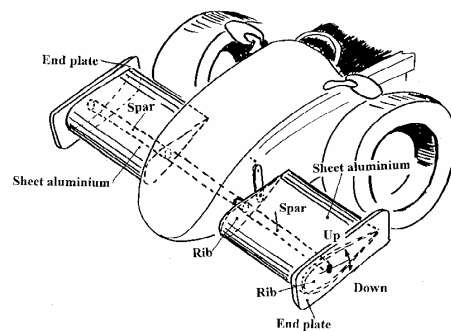


Figure 7. Front wing design

As it is seen on the Figure 7 the front wing is located very close to the ground. The distance between the lower surface of the front wing and the ground is only about 60 mm, it is 20% of cord line. Due to the ground effect the power of the front wing is rise for 80%. The actually needed lift coefficient of the front wing is than smaller, $C_{LF} = C_{LFth} / 1.800 = 1.230 / 1.800 = 0.690$. This correspond to simple one-element wing at very low angle of attack. The important thing is that we have determined that this Formula S car could run with a simple one-element rear wing, which would be balanced with a pair one-element front wings. Precise installation angles would have to be determined by testing. The wing profiles of rear and front wings are the same.



Figure 8. Front and rear wing on finished car

Due to the rules the minimum leading edge radius is 19 mm. To fulfil this very strong requirement we decided to use NACA 4422 wing profiles. To take this profile two other reasons exist: this profile is thick enough to put inside the steel spar, and such a great profile is easier to cover with the aluminium sheet. The ribs are made from 10 mm thick pressed wood. Aluminium sheet, which cover the wing, is fixed on ribs by screws. Endplates and additional plates with the basic wing profile are made from 6 mm thick forex, Figure 8.

6. The conclusion



Figure 9. On the left Formula S 2001/2002, on the right Formula S 1999/2000

In one year only the team Formula S on the University of Maribor were able to make the completely new car that differ a lot from previous one, Figure 9. The new car looks already much better out. The point of gravity is lower, the suspensions are dramatically improved. The engine is more powerful. The aerodynamic devices are added. We are completely aware that this described approach how to equip the vehicle with aerodynamic devices is the first step only.

The described approach of wing design enables the involved designers, i.e. students, to satisfactorily understand some happenings about aerodynamic what is in this investigation phase of decisional importance.

Probably much more scientific approach would be to involve the Computational fluid dynamics, or CFD. It is using the computer to solve the complex equations that have been developed to mathematically model what goes on fluid flows. If you consider that it would take quite a while with pen, paper, and calculator to solve the equation to define the airflow around a given point on a body, then it is clear that solving case for the whole surface of that body would be a very large task indeed. Solving the problems relating the laminar flow would appear to be not too troublesome, but where the flow is turbulent and separated, the mathematics become very complex and incredibly time consuming. And in essence, CFD is a complementary tool to the wind-tunnel, but it is possible to build and test models on computer rather faster than real solid models. But the computer predictions need validating and this can be only done using a real flow over solid models. The students and mentors involved in Formula S development are aware of all these things and we intend to use the powerful tools to solve the problems that appear. At this stage we are collecting the experiences about the racing car, after it we intend to use more sophisticated tools, such as CFD. But first we should get the basic fillings.

Next steep is to check the behaviour of the vehicle on the real track in order to investigate how these devices influence on the driving properties. Our vehicle is more or less finished, the spring is almost here, so we are able to drive it on the real track. This is the testing phase. The decisional data for set up the wing would be the lap time. The vehicle equipped with the wings must cornering much faster the car without it.

Maybe one should say that described approach how to design the wings on racing car is to primitive but let me to remember that first aerodynamics device on the racing car was successfully used few ten years ago, that happened in USA in the year 1966 when the racer Jim Hall first actually drive the car with the aerofoils fitted. But also today people are usually afraid of using the wings because they don't know how to calculate it. Frequently they think that it is very complicated to make such a calculations. Also on the Formula Student competition almost none have enough courage to put the wings on the car.

However, we, the Formula S team, are brave enough to design and also made the aerodynamics devices. We are convinced that all these improvements should help the team of Formula S to be competitive also in the year 2002.

Acknowledgement

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