

Car Aerodynamics Part 1

This is a difficult subject to cover, even briefly, in one article so I propose to do 3 parts

Part One Introduction and some history

Part Two Basic concepts

Part Three Aerodynamics of 60's sports cars

Part One

Introduction

With the wisdom of hindsight, it is amazing that in the period when flight aerodynamics progressed from the first efforts of Lilienthal and the Wright Bros., to the Phantom, Boeing 707 and the Comet, there was almost zero progress in the subject as applied to cars. As we will see later, moving any object but especially a low drag car shape quickly and close to the ground inevitably brings aerodynamics into play, but very few thought of it, and even fewer tried any practical implementation of the ideas.

Perhaps a representative view was that expressed by Enzo Ferrari, "that worrying about aerodynamics was for people who couldn't build powerful engines"!

As we all know, aerodynamics in the form of downforce etc, is now a dominant and decisive factor in modern motorsport but is still not as well understood as it might be, witness the revised rules for F1 in 1998. It just so happens that the cars we are interested in are from the exact era when the role of lift and downforce was just beginning to be understood and applied. For example, it was the very high speeds achieved by the GT40 at Le Mans, which clearly showed that lift was a critical issue. This led to the "Bread van" (J) version of the 40, and the Lola T 70 to try to deal with the problem.

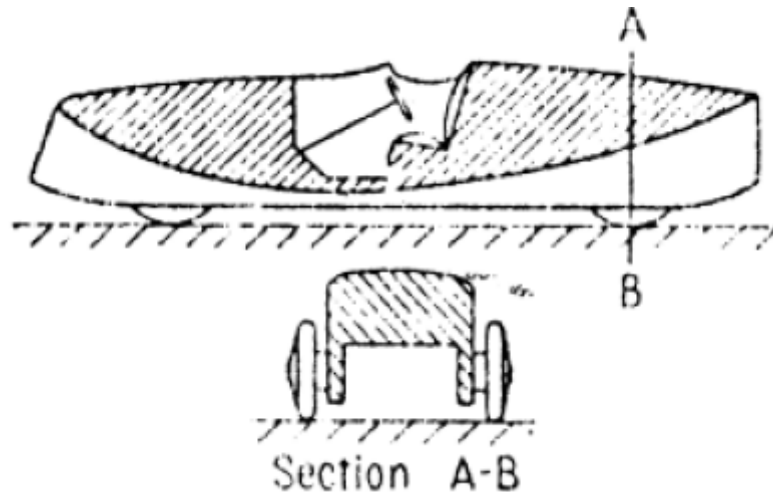
Early Days

As one might hope, bearing in mind the fact that the basics of most aspects of car technology were established by the First World War, and that aircraft design was also progressing rapidly, someone did have the idea of applying some aircraft thinking to car aerodynamics at this early stage. An early example of this was the Tropfenwagen, which had a Cd of .28, even though it had 4 open wheels!

In fact it was in 1928 that the whole concept of ground effect cars was laid out in an article by a Mr. R. Prevost in the September issue of "The Automobile Engineer". He was concerned with the technical aspects of a car intended to attack the Land Speed record.

He wrote "I endeavoured to find a form (of car shape) offering the minimum resistance to advance in the air (drag) while at the same time giving the

machine the maximum stability and power of keeping on the track" (downforce), and " the underside is nothing more than a venturi", and " I have endeavoured to allow the air to flow with the minimum loss of pressure, while at the same time utilising the depression resulting from this flow to increase adhesion to the ground"!



When I came across this article I was gobsmacked! Fifty years before any serious attempt to use these effects, the concept and basic principles had been clearly and correctly identified. Why did it take so long?, it's not as if high power and high speed did not appear until the 60s? The supercharged V12 Auto Unions and Mercedes in the 30's would have benefited greatly from some help in the adhesion department,(whether the tyres would have stood it is another question).

A long gap

After this article we have to wait until the mid 50's for Michael May to turn up at the Nurburgring with an inverted wing above his Porsche, it was promptly banned! probably because it was quick! This was a different approach to Prevost, it was a straightforward aircraft type aerofoil section wing, upside down so that the force generated was down. There seems to be an unwillingness at the time to accept the idea that extra downforce over and above the cars weight gave extra grip with no corresponding inertia penalty, the idea was dropped in the face of the usual hostile response to anything not understood.

However, gradually people began to think in terms of ways to reduce lift, for example the Ginther spoiler and the roll bar of the 250P Ferrari. Wind tunnel testing became more widely used, mostly in an effort to reduce drag. Where spoilers etc were used it was to eliminate lift rather than introduce downforce, low drag was the be all and end all and no thought was given to the potential benefits of trading speed on the straights for speed in the corners.

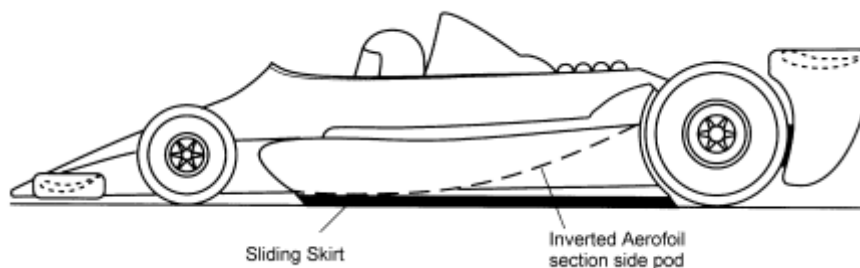
For example, Ford used a wind tunnel to test early versions of the mid engined coupe which eventually led to the GT 40. Initially it had approx. 220 kg of drag, and similar lift at 200 mph!

Downforce at last!

When attempts were made to generate downforce, the route taken tended to be rather direct. The 1965 Chaparral 2C was a pretty conventional looking spyder sports racing car apart from the variable incidence wing over the rear wheels. This led to the 2E version, which refined the application of the downforce. Then there was the 2J version which had large fans pulling air out from under the box like rear body to generate low pressure under the car and hence downforce with less drag than a wing.

None of these approaches actually used the method of generating downforce, which is now universal in modern sports racing cars, the straightforward venturi.

The Lotus type 78 was at the time, (1978) probably one of the most sophisticated applications of under body flow, to generate downforce, it used inverted wing section side pods in almost exactly the same way as proposed by Prevost 50 years earlier. These were very effective, despite being open sided because of the use of side skirts, without these, long since illegal, it would have generated far smaller forces.



The modern era

When skirts became illegal, the Lotus 78 approach could not generate large enough forces and led to the first attempts to make the flat underbody of a car generate downforce. The Porsche 956 of the early 80's was a good example. The Group C regulations defined a large flat area (1m by .8m) of floor under the monocoque, and the under wing as it became called, was designed to feed air into this area, and extract it in such a way as to generate large downforces. Since we are talking about a large acreage under a Group C car, a tiny pressure drop of 0.1 psi adds up to a force of 1000 lbs. and more.

The 956/962 car was based on an aluminium monocoque and had some slightly quirky ideas about what the air was supposed to do under the car, it was an early application of underwing design and did well until a later and better implementation arrived. The flat 6 boxer engine, and the fact that they used a fixed floor wind tunnel did not help. As a result, most of the downforce was on the rear of the car, and the lift to drag ratio was of the order of 2 ½.

The Group C Jaguars designed by Tony Southgate (who used to work with Eric Broadley!) used a composite monocoque, with a fully developed design using the full range of possibilities, front & rear wings as well as underwing to generate competitive drag and downforce figures. Ultimately the Jaguar would have lift to drag ratio of roughly twice that of the Porsche.

That pretty well gets us up to date. There has been an intensive programme of refinement since the Jaguars, but no major new principles developed. Aerodynamics is now a critical part of racing car design, once it was enough to generate bit of downforce, now the lift to drag ratio of a car design has to be optimised to several decimal places, with minute changes being tried all the time (try reading the technical bits in Autosport F1 coverage) to find a slightly better way of reducing drag and lift or a give bit more downforce.

That's a brief canter through the history of the application of aerodynamic ideas to cars, next time, I'll try to introduce the basic concepts.

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Car Aerodynamics Part 2

Stephen Hawking's publisher said that each equation in his book would halve the sales, I will therefore endeavour to keep to the approach I've used

before, to concentrate on concepts and examples rather than maths to get the subject across (assuming it worked the last time?) We must however start with some basics, starting with how air behaves.

Air

The key properties of air that concern us are:-

- 1) Mass, which means that air has momentum, and kinetic energy when moving .
- 2) Elasticity, which means that it can compress or expand,(i.e. pressure goes up or comes down storing or releasing potential energy as it does so.
- 3) Viscosity, which means it does not like to be sheared and will thus tend to "stick" to surfaces to form a so called boundary layer.

It is these properties, and the interrelationships between them that affects what air does when it is assaulted by a ton of steel and fibreglass going at high speed!

Since we are concerned mostly with drag and lift/downforce, lets look at how the properties of air bring about various sorts of drag. Aerodynamicists break drag down into three main types, i.e., form drag, induced drag and skin drag. There are other names used, but these will do for our purposes. There is a certain amount of interdependence/interrelationship between them but it is helpful to discuss them separately initially as they each are caused by a different mechanism. We'll start with skin drag as it is easiest.

Skin Drag

This is basically caused by the viscosity of air. You may not think of air as being viscous but it is, especially at the speeds we are concerned with, or at least hope to be! Air has a viscosity which is approximately 1/100th of that of water, which might not seem much but it adds up as we will see.

If we look at what happens at the front of a car at speed, we have the air standing still roughly and the car travelling quickly. The mass (inertia) of the air means that it would prefer to stand still, but the layer of air molecules next to the surface of the car has no option but to accelerate very fast to the speed of the car. This is another way of saying that there is an attached boundary layer. Of course nothing accelerates without a force being involved (anyone remember Newton's third law, $F=m.a$?), so this force comes from the car and is seen as a force opposing the motion of the car. So we have a very thin boundary layer, the layer next to the car is moving quickly, but only a short distance away from the skin, the air is standing still. This is where viscosity comes in, this large difference in speed means that the air is being sheared

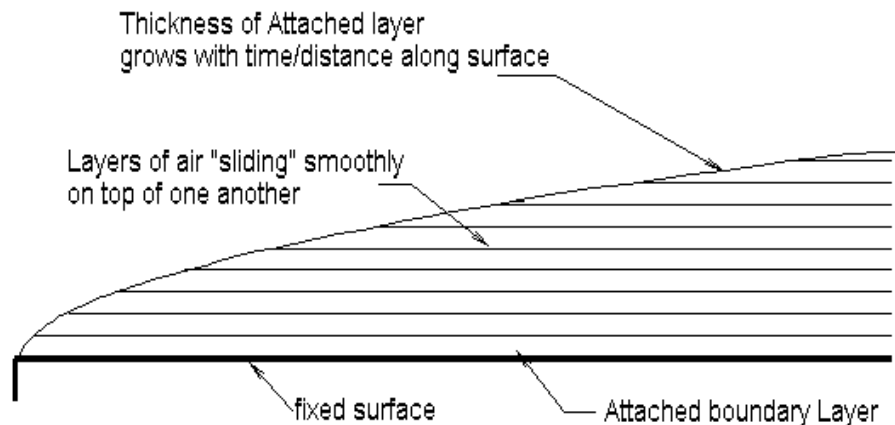


figure 1

at high speed, which generates large shear forces, which are seen by the car as drag, but also have the effect that given time, the next layer of air away from the car starts to accelerate, and so on. Given time means that as the air flows along the length of the car, the boundary layer gets thicker and thicker, and a greater and greater volume (mass) of air is being accelerated to near car speed, which requires more and more force and hence more and more drag. The layer may be typically a few millimetres thick near the front of a car, and several centimetres thick near the rear. If you think about the acreage of our cars, this is a significant volume of air to accelerate, so skin drag is a significant component in the overall drag of a high speed car.

Eventually, as the layer get thicker and more air is accelerated to high speed, the boundary layer may become turbulent, the nicely organised situation of layers of air sliding smoothly over one another breaks down into chaotic vortices which do an even better job of mixing in more and more air from outside the layer, and the vortices themselves absorb energy resulting in yet more drag.

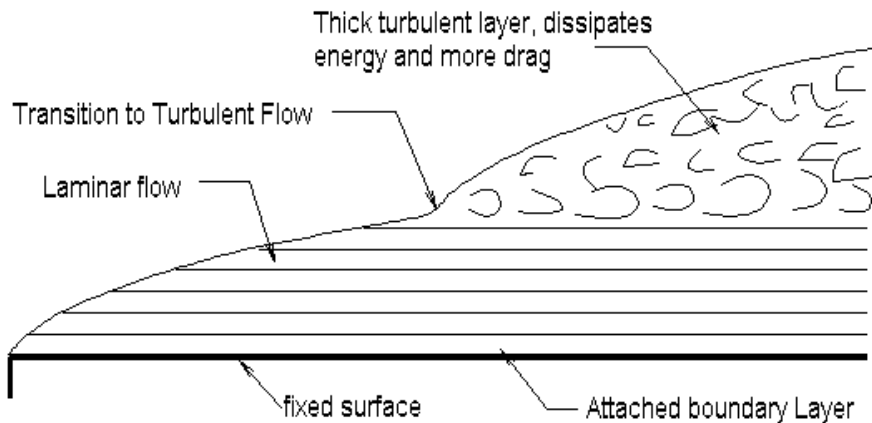


figure 2

There is little you can do about skin drag as it comes about because of the physics of the situation. All you can do is have a smooth highly polished surface with as few projections as possible into the boundary layer. Dead insects stuck to the front will "catch " more air than a smooth surface resulting in a thicker boundary layer, accelerating more air to near car speed and therefore more drag. Because it is all about sliding layers of air along the surface, skin drag is about forces acting parallel to the surface of the car and is primarily related to the viscosity of air interacting with its inertia.

Form drag

However, the other properties of air also get in on the act. If we look at a car with the aerodynamic sophistication of a house brick, say, a "7" clone, travelling at speed, it can be seen that since it is not easy for air to flow around the car (which would result in skin drag) it tends to "pile up" in front of the car, which it can do as air compresses readily. But what happens when you compress a gas, the pressure goes up! If we look at the rear end of a 7, it is as sophisticated from an air flow point of view as the front. As a result It is as difficult for the air to follow the shape at the rear as it was at the front, and the air gives up and becomes separated from the car. Good, you might think, less skin drag, and you would be right, but it also results in a large "hole" in the air behind the car i.e., low pressure because air can expand just as readily as it will compress.

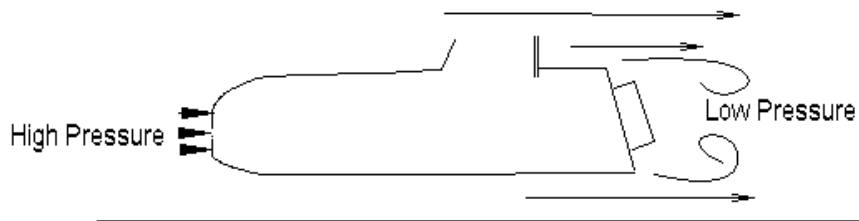


figure 3

So we have high pressure in front of the car, and low pressure behind it, if you multiply this pressure difference by the cross section area of the car you have an estimate of the force which the air is exerting against the motion of the car, multiply again by the speed in question and you have the power required simply to maintain the pressure difference between the front and rear of the car.

This in a nutshell is why a 1300 crossflow "7" will do 110 mph and a 4.6 litre Rover V8 powered "7" will only go another 30 mph or so faster, much of the extra power goes into overcoming this drag, which goes up as the square of the speed.

This drag force which is concerned with pressures acting on the car, is called form drag. Pressures act at right angles to a surface, skin drag acts parallel to the surface, so you can (and will!) have both.

This is a very basic view of form drag, it is of course much more complex than this, we will get into more of that later!

Induced drag

This type of drag is particularly important in the context of lift and drag.

The ideal shape would move through the air in such a way that the air separated smoothly and easily in front of the car, flowed smoothly over the body and merged seamlessly again behind the car, there is a shape that does this, it is called a low drag body, its shape may surprise you as not being intuitive, but air likes it. You have seen a similar shape before, this is why nuclear submarines have blunt bows and tapering tails. The drag factor (coefficient) of a flat plate of a certain area is approximately 1, the drag factor of a low drag body of the same area is 0.04 would you believe!

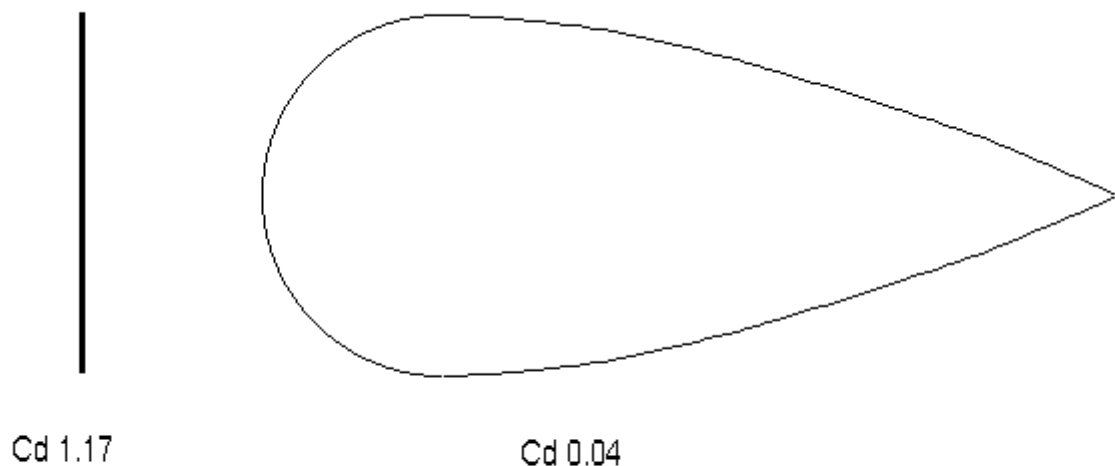


figure 4

The drag is so low with this shape because it does pretty much what I just described and leaves the air behind it much as it found it (nearly anyway). Obviously there is some form drag, and some skin drag, both being unavoidable, so what makes the drag higher of any other shape. The answer is of course, induced drag.

The key factor is the "leave air much as it found it" bit. As soon as the shape of a car deviates from that of the low drag body (not a very practical shape), it is unable to allow the air to merge together smoothly, as a minimum due to the fact that cars tend to be flat on the underside, because roads are roughly flat! This is of great significance when we come to discuss lift.

The less than optimal shape results in a certain amount of turmoil in the air behind the car due to lack of "tidying up" of the flow because of the shape. This turmoil carries and therefore requires energy, which comes from the engine of course. Induced drag is a very efficient way of slowing you down, the drag of a flat plate is high partly because the form drag (pressure difference between front and back) is high but also because the flow is chaotic as air tries to make its way round the edge of the plate, skin drag is low however!

You can think of induced drag as being like the wake of a boat, but in three dimensions. You have probably seen it in action!. You may have noticed in Formula 1 that there is a small plume of condensed water vapour trailing from the top outer corners of the rear wing, or something similar from the corner of the trailing edge of the flaps of a large aircraft. That is because in each case we are talking about wings, and wings generate lift by deliberately creating asymmetries between the flow over and under the wing, so when the two flows meet at the corners of the wing/flap, they are doing very different things and don't get on well together creating powerful vortices which consume large amounts of energy.

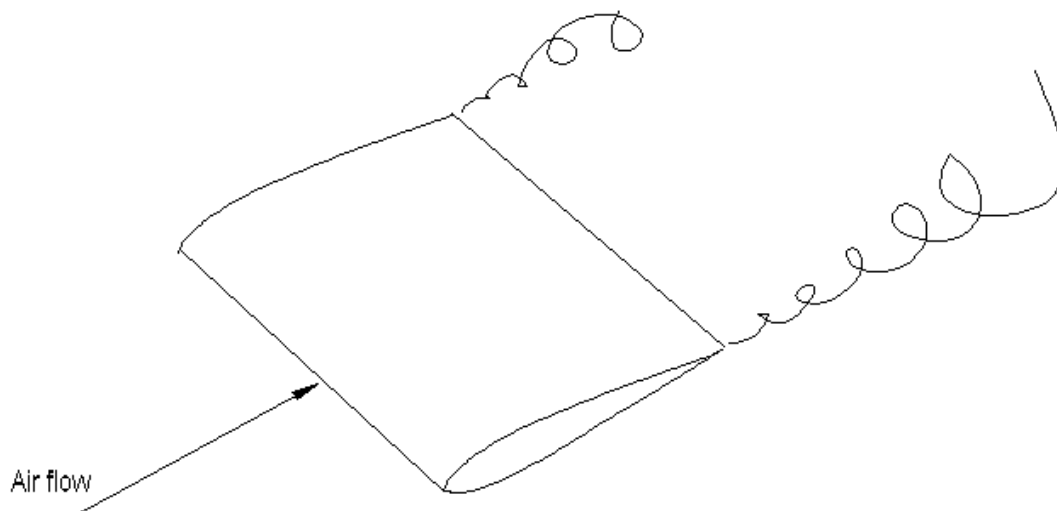


figure 5

By now you should be getting the idea that flows that consume energy are a bad idea from the point of view of going quickly, and you're right, because the only source of energy is the engine.

You can see these vortices sometimes if the air is moist enough, as the vortex has a low pressure at its centre, where the relative humidity of the air reaches saturation and the water vapour condenses. If you haven't noticed this, it does happen, keep an eye out for it the next time you watch a race or practice on the box.

Total drag

The drag coefficient quoted for cars is a summation of the above three types of drag. Frequently the drag quoted for a type of car is measured using the base model, no spoilers and skinny tyres as these "stick out" into the passing air and cause extra drag! The "sporty" versions almost always have the worst drag!

Lift and downforce

As I have already implied, in order to generate forces at right angles to the direction of travel there has to be a difference in the flow around the object in question, in the plane that you want the force. If there isn't a difference, the air will flow round the shape and merge painlessly after the body has gone. How does this difference in flow generate forces at right angles to the flow, to answer this question we have to involve Msr. Bernoulli (here comes an equation folks)

The Bernoulli equation

As we have said, air has mass and elasticity. Mass means that when air is moving, it must have kinetic energy and momentum. Elasticity (really compressibility) means that at a certain atmospheric pressure, the air has a certain potential energy, like a ball at the top of a slope, or like a compressed

spring. The Bernoulli equation defines a relationship between these two parameters that is crucial for several aspects of the operation of a fast car.

You are familiar with the ideal that fluid molecules flowing in a laminar flow follow flow lines, you must have seen smoke trails being used to make these lines visible in a wind tunnel. I hope you can imagine that if you were a gas molecule in this flow, following along a flow line, that you don't have much time to relate to what is going on either side of as things are moving briskly, a bit like those rare occasion when 4 lanes on the M25 are moving smoothly but at different speeds (it does happen I'm told). If the flow line you are following decelerates because it is approaching a hold up, the molecules behind tend to keep going, because of their momentum they "bunch up", but end up having to settle down to the same speed as you (some M25 drivers it seems have yet to realise that you can't drive through/over the car in front). This simple analogy has some profound consequences, and is the basis of the Bernoulli equation. The velocity of the molecules defines their kinetic energy, so when the flow decelerates, kinetic energy is lost. But as the molecules bunch up, the local pressure goes up. Guess what, the total of the two energies along a flow line is constant, in other word, energy is conserved.

$\text{Kinetic energy} + \text{Potential energy} = \text{constant}$

If we assume that air at different heights above the ground has similar energy levels before the car arrives, then we can look at the effects of the car on the air above and below the car.

Typically the air flow divides in front of the car at some height above the ground, some goes over and some under the car. It is a bit of a squeeze to get under the car and friction between the air and the car and the ground means that velocity is reduced, kinetic energy is reduced so pressure goes up.

Over the top of the car, the air is also initially decelerated and again at the foot of the windscreen which means that pressure is tending to increase (that's why so many car heaters draw the air in at the bottom of the windscreen, and why it comes in even with the fan not running). But once over the highest point of the car, the favourable pressure gradient accelerates the air, so the pressure drops.

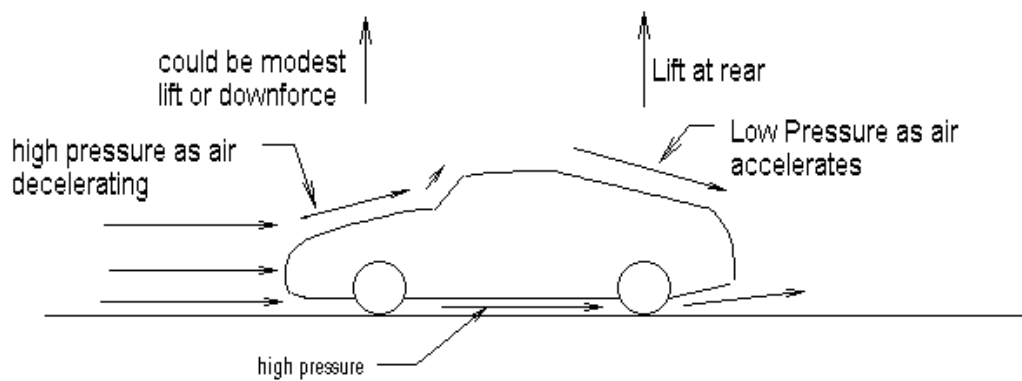


figure 6

Lift and downforce

So we have a pressure increase under the car, an increase over the front of the car and a decrease over the rear. Whether there is any lift over the front depends on which pressure is higher, that above or below the car, but there will almost certainly be lift over the rear because most cars have the highest point in the middle, and then slope down at the back.

To generate downforce we have to reverse this situation as far as we can, and/or generate downforce separately to offset the existing lift by using wings etc.

In the next exciting episode? we will look at the venturi, and the underwing, and then review some real car aerodynamics to see how these problems were addressed.

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Car Aerodynamics Part 3

Before we look at some specific cars, we need to discuss the venturi effect and its application to the underwing.

The venturi

The venturi is relatively straightforward to understand once you have grasped the Bernoulli equation (remember that ?).

A venturi is a device through which a fluid flows, which starts with a certain cross section, which then reduces to a smaller , and then increases to a large cross section.

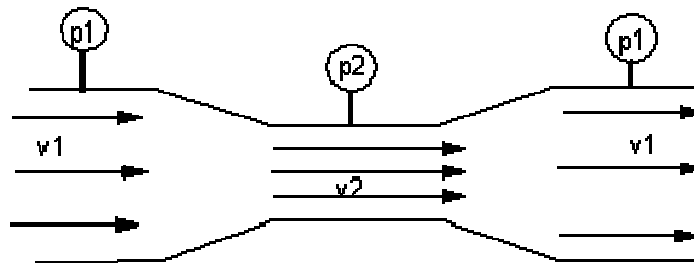


Fig 1 Venturi flow

The Bernoulli equation says that the total energy (kinetic and potential, i.e. speed and pressure) is constant, so when the fluid accelerates in order that the same mass flow rate can get through the smaller cross section, the pressure drops

$$(p_1 + \rho \cdot v_1^2) = (p_2 + \rho \cdot v_2^2)$$

This may seem counterintuitive, you might think that there would be a higher pressure because of the “squeeze” to get through the narrow section. This would in fact happen, but only at very high speeds, like, the order of the speed of sound, at the speeds we are interested, Bernoulli’s equation holds.

So what, you may say, very clever, but what use is this trick? There are two important applications of the venturi in cars.

The Carburettor

A carburettor has to meter fuel so that it provides the correct air fuel mixture over a range of operating speeds and throttle openings. It therefore needs to detect the amount of air flowing through it and use this to control the flow of fuel. Nearly all carbs (including Holley and Carter) use the venturi to do this, as the pressure drop between P_1 and P_2 is related to the flow rate (velocity). That’s the good news. The bad news is that the pressure drop is related to the square of the velocity.

Why is this a problem? In a basically simple carb. such as the Holley, the fuel is introduced into the throat of the venturi, using the lower pressure here as the means of “sucking” fuel from the float chamber, (the difference between P_1 & P_2). The flow rate of a liquid through a pipe at modest rates is linearly proportional to the pressure.

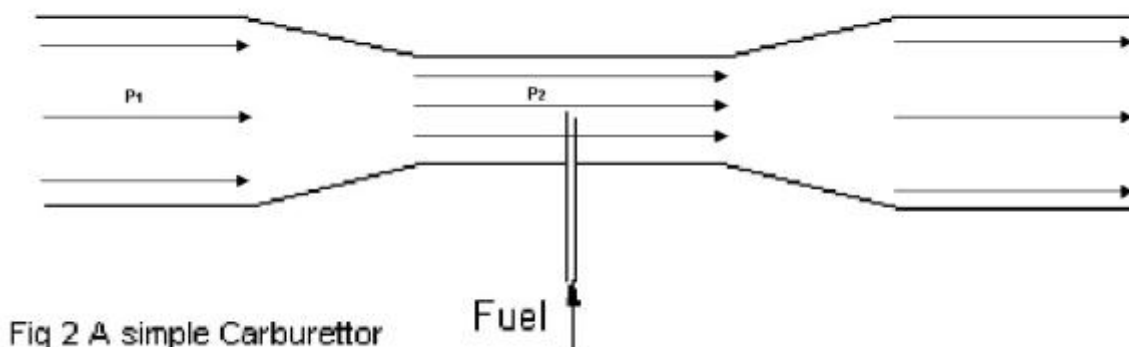


Fig 2 A simple Carburettor

This is the problem, air delivery is a square law behaviour with pressure, fuel is linear. This is why carbs are so complex, because they try to approximate to the square law with what is in effect, a number of different fuel metering mechanisms, with for example, separate systems for idle, full power system, and intermediate operation.

Directly relevant to the topic of aerodynamics, is the application of the venturi to the design of the car underwing

Racing car Underwing

I find the term underwing a bit misleading, expecting to see a separate aerodynamic device under the car, in fact the term is used to describe the underside of any car which has been designed with aerodynamics in mind.

If we apply the venturi idea to the underside of a car, we end up with something like this.

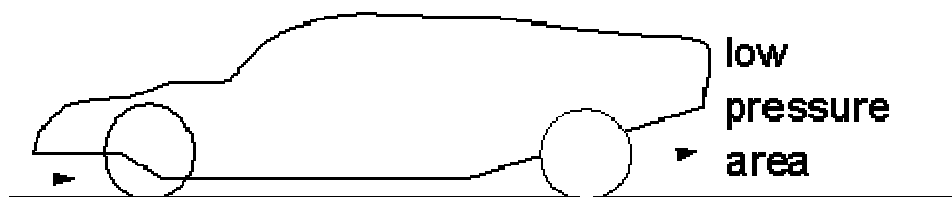


Fig 3 A basic underwing venturi

This is not how it would really be done, but it illustrates the idea.

It's really very simple, air accelerates as it goes under the lowest part of the car, and its pressure drops as a result. Not very much, maybe a fraction of a psi, but as it is acting over a large area, it adds up to hundreds of pounds very quickly. But this crude venturi is not operating on its own, and the fact that it is part of a moving car has some effects. Firstly, in practice, getting enough air under the car to operate the

underwing is not a problem, so the lead in or front part of the venturi is not necessary, and universal practice on track cars is to have a splitter as low to the ground as possible to avoid any high pressure areas under the front of car. On the other hand, there is a low pressure behind the car which can be used to facilitate the flow of air under the lowest part of the car and extract it as efficiently as possible. So you can think of the underwing as operating as partly venturi, and partly by giving the low pressure area behind the car, access to the underside of the car

Aerofoils & Wings

Of course the aerodynamic device that everybody know about is the wing, and this was one of the first devices used to generate downforce. For example, Michel May in the 50's, and Chaparral in the 60s. In each case, this was a straightforward wing upside down to generate grip, applied to a car with no other pretension to aerodynamic design. Just sticking a wing on a car will generate downforce, but at a higher drag penalty than the underwing.

How the aerofoil generates lift is quite simple.

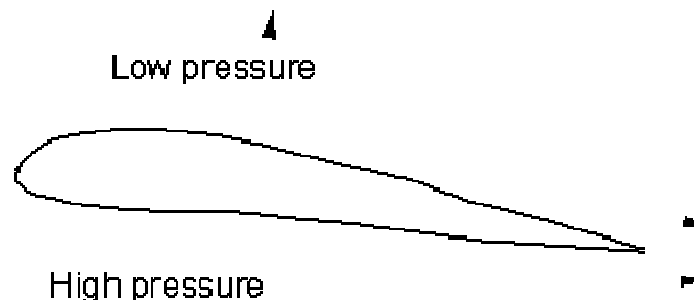


Fig 4 Aerofoil section

Just in front of the wing, the air has a defined energy (pressure & velocity) as per the dreaded "B" equation. The air that goes under the wing is forced to change direction as it piles up under the leading edge, and continues to be slowed by friction of the layers nearest the wing, so the kinetic energy is reduced, so the potential energy is increase, & the pressure goes up.

On the upper surface, the air is accelerated vertically to find its way round the leading edge resulting in a localised high pressure area at the leading edge (called the stagnation point), and then finds the top surface of the wing dropping away from it due to its curvature, so the pressure drops over the top surface, and the velocity increases. The pressure difference between the top and bottom gives the lift.

A wing can be positioned anywhere there is clean air flow to operate in, and being an external device, can be easily changed and adjusted. So they can be used on single seaters where the rules limit downforce generation by underwings, as well as in addition to underwings to adjust front and rear downforce balance. For example, a Le Mans car with a powerful underwing optimised for high speed may find it has an understeer problem due to lack of front downforce on low speed circuits, an add on adjustable front wing is a lot easier to implement than to change the underwing which will require a new tub!

A further refinement of this idea is the use of a full width rear wing positioned just behind and above the main body. The wing (upside down of course) generates downforce by causing a higher pressure above it than below it, this pressure difference pushes the wing down, but also increases the low pressure area behind the car and hence its ability to take air away from under the car. The wing, and the form drag resulting from the “vacuum” behind the car will increase overall drag, but if done properly, will give an increase in grip which will result in a better overall lap speed.

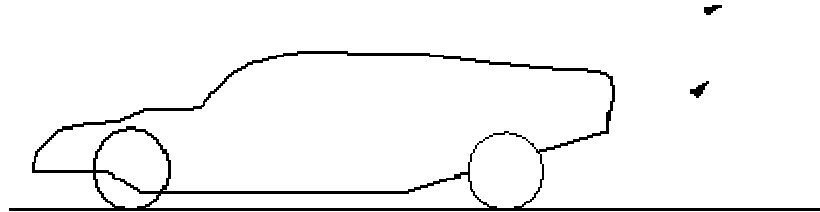


Fig 5 Combined use of wing and venturi

This raises an interesting point about drag and downforce, and car power. To a certain extent, Ferrari got it completely backwards, it requires downforce to make the best use of power.

If you have a small highly tuned engine in a small car, the overall limit in lap time is most likely to be maximum speed, as small cars tend to be nimble in corners anyway. In this case, you need to minimise drag as this will limit top speed, and this means that drag increasing downforce devices are a luxury you cannot afford from a power point of view.

On the other hand, with cars more like ours, we seldom if ever reach terminal velocity on the track so speed is not the limiting factor, it is grip to increase speed in the corners and getting the power down as early as possible.

In this case, powerful cars can afford to “use” power to operate drag inducing downforce devices, as they are still quicker overall, as they still have enough power for outright speed, but are now much quicker in the corners.

Lets have look at some real cars at different points during the evolution of aerodynamic design.

D type Jaguar

Having just talked about the trade off between drag, downforce and outright speed, the D type was probably right on the power borderline at Le Mans where terminal speed was of crucial importance on the Mulsanne straight.

The 3 litre straight 6 needed all the help it could get and the car was a typical tradition low drag design. It had low drag “bullet” shape with no thought to downforce. Fortunately it was fairly high off the ground by modern standards so probably modest lift only would have been generated under the car (since they were apparently quite stable at high speed)

GT 40

The GT 40 was quite definitely over that borderline, achieving very high terminal speeds at Le Mans, and awareness of the importance of lift was just beginning. Hence lift as well as drag figures were measured in wind tunnel testing. The shape of the Mark 1 was however a conventional low drag shape, designed as it was for maximum straight line speed at Le Mans, and not as a circuit racer.

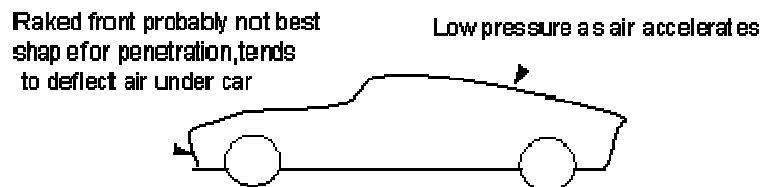


fig 6 GT 40

The front where airflow separates is rather high, tending to give a high pressure area in front of the car, with plenty of air going underneath to give some lift. The radiator air intake will seem almost like a solid surface to air at high speed, any vanes in the intake will have little effect as the speed and mass of air involved is small. Also the rear body shape tends to generate lift as air accelerates to fill the void behind the highest point of the car.

T 70

The T70 was the very next step, its design trying to eliminate lift, actually did this to such good effect that downforce was actually generated, but with the inevitable drag penalty. Hence it was not optimum for Le Mans where it could not match the GT 40s' for straight line speed, but ideal for Spa with its sweeping high speed curves, which the Lola could take fast enough for the downforce to still be working.

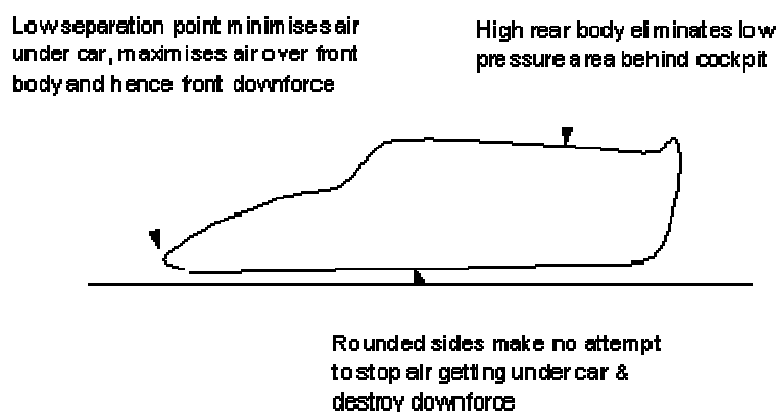
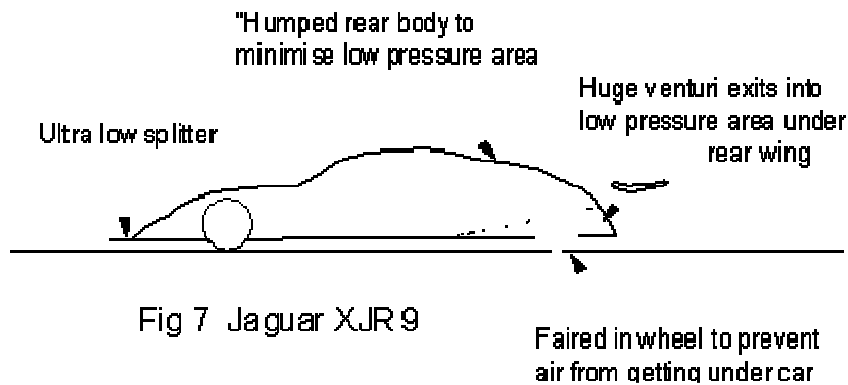


Fig 7 T 70

Jag XJR9

The Le Mans winning XJR9 represents a fully developed downforce based sports car. After this, the principles involved were pretty much known and most of the cars since have optimised various aspects of the design rather than breaking new ground.



This sort of car can generate downforce of the order of 2 or 3 times its own weight , with a downforce to drag ratio of 3 or so, and a drag coefficient of would you believe, 0.7! That drag coefficient, twice that of a road car, is literally the price paid for the downforce.

Conclusion

In the end, this turned out to be a bigger topic than I thought even at the most basic level, I've enjoyed the research and straightening out my own thoughts. I hope I have been able to convey an appreciation of what is now a fundamental technical aspect of modern racing cars.

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