Aerodynamics and aerodynamic research in Formula 1

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ABSTRACT

This paper will address the engineering performance differentiators for an F1 car and highlight the difference aerodynamics can make to that performance. It will also consider some basic aerodynamic challenges and the main tools used for aerodynamic exploration by teams.

NOMENCLATURE

ABS	Anti-lock Braking System
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
DES	Detached Eddy Simulation
DRS	Drag Reduction System (Driver adjustable bodywork used in F1)
ECU	Electronic/engine Control Unit
ESC	Electronic Stability Control
F1	Formula One
FIA	Fédération Internationale de l'Automobile (Governing Body of F1)
FOTA	Formula One Teams' Association
HPC	High-Performance Computing
KERS	Kinetic Energy Recovery System
PIV	Particle Image Velocimetry
RANS	Reynolds-Averaged Navier Stokes
SLA	Stereo Lithography
SLS	Selective Laser Sintering

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This is an adapted version of The 2012 RAeS Lanchester Lecture presented on 17 July 2012.
NB: This paper contains the views of the author, which are not necessarily those of his employer.

1.0 INTRODUCTION

This paper is based on the 2012 Lanchester Lecture. Most of the previous Lanchester Lectures have naturally dealt with Frederick Lanchester's links with aeroplanes. However, this paper will concentrate on cars – also an area in which he was very heavily involved. In 1896 he and his brother built one of the first petrol cars in England, a single cylinder 5hp internal combustion engine with chain drive. Bespoke engines were used and he experimented with fuel injection, turbochargers, added steering wheels, and invented the accelerator pedal. He was one of the first to use detachable wire wheels, stamped steel pistons, piston rings, hollow connecting rods and the torsional vibration damper. He was inventive – just the sort of person you need also in F1 in your engineering team.

I have links to two of the institutions where Lanchester studied: Hartley University College which is now the University of Southampton (where I am Visiting Professor of Aerodynamics) and Imperial College which I have used for wind-tunnel testing in the past.

If Lanchester were alive today, I am sure he would be delighted that his 1892 theory of aerodynamics[1] (which he was persuaded not to publish, for fear it would ruin his reputation as an engineer) has been largely vindicated.

2.0 MAIN PERFORMANCE FACTORS

An F1 car is an open-wheeled rear-wheel drive vehicle with the following current attributes:

- has a top speed of approximately 350kph or less depending on the circuit
- accelerates from 0 – 100kph in about 2·6 seconds
- decelerates from 200 – 0kph in about 2·0 seconds
- copes with loads of ≥ 5g braking and ≥ 4g in cornering (at higher speeds)
- nominally 'rigid' aerodynamic shape other than a specific movable DRS

There are a number of factors which affect the performance of an F1 car, such as: driver; grip (tyres, suspension, etc); vehicle mass and centre of gravity; engine and transmission; electronics, hydraulics, pneumatics and structures; aerodynamics. There are also outside factors which need to be taken into account once a race has started (e.g. weather, accidents) but these will not be dealt with here. The design of F1 cars is constantly being optimised for the circuits on which they race, especially with regard to aerodynamics and suspension.

As with most motorsport sectors, F1 design cycles are quite fast compared to other automotive sectors and significantly so compared to aircraft and aerospace. Normally a new car is designed every year and, at each race, cars are updated and tuned to improve performance. It is quite normal for an end-of-season car to be over a second faster over a lap of a typical track than it was at the start of the season. This makes life in F1 high pressure but also highly rewarding.

2.1 Driver

The driver makes a huge difference at all levels of motorsport. You only have to consider some extreme differences between team mates or think of the difference between a professional driver and a novice. The driver not only has to drive the car but also has to give feedback to his race engineer and activate/change/reset various settings on his steering wheel while fighting wheel to wheel with other drivers.

Today's drivers are in general fitter and better trained than in the past. It was a little easier in the past to have an edge through race fitness but the teams understand this far better now.

Consider the difference between completing a complex IQ test sitting quietly at a desk or trying to do so while riding at a high heart rate on an exercise bike… Practice also makes a big difference so it is not a surprise to learn that most modern champions started racing at an early age (e.g. in karts).

Most engineers will be unable to influence who will drive their cars, but they can train and educate them. This driver training and assessment is becoming ever more technical and focused as very little on-track testing is allowed in F1. As a result many F1 teams have invested in driving simulators of variable complexity. These primarily help drivers but also help engineers understand and tune the performance of the car. Race car driver simulators are still in an early stage of development compared to aircraft simulators, but the rate of development is very high. Some have no or very little movement of the cockpit part of the simulator in three dimensional space but others utilise extensive movement of position and attitude. Benefits range from simple cockpit familiarisation and learning a circuit to assessing and training a driver's precision and movement repeatability, as well as assessing different potentially available performance packages (e.g. an aerodynamics package with more downforce but more car attitude sensitivity).

Driver training and assessment can be very precise and scientific and may include details such as the control of atmospheric conditions and training for the use of the eyes. Ultimately driving an F1 car is a mental challenge so the mind also needs to be trained to achieve the best performance. Spatial awareness and the use of peripheral vision are extremely important.

2.2 Grip – tyres, suspension, etc

F1 cars are regulated to run on four 330mm (13inch) diameter rims with about 660mm diameter tyres. Overall complete wheel widths are about 330mm front and 375mm rear. Tyres are provided by a single supplier, Pirelli, which brings two different slick (no tread) dry-weather specifications (out of four specifications for the year) to each race meeting. Teams are limited to a total of eleven such sets split into 'prime' and 'option' (softer of the two types) tyres[2]. If it is a dry race, both specifications must be used, meaning drivers have to make at least one pit stop. Two wet tyres are also available at each race with differing tread patterns and compound and used for wet/intermediate and extreme wet tracks. Tyres are designed to work at high temperatures: hence the use of blankets to keep them warm until just before they are put on the car and the need for drivers to find ways to manage tyre temperature (and also thereby pressure) towards the end of any 'safety car' period.

As with all tyres, when the tyre contacts the ground it deforms due to the loads applied to it which change both the sidewall shape and the contact patch size/shape. Tyre shape is also influenced by tyre pressure, camber angle, and the horizontal forces the tyre exerts onto the road. Generally a larger contact patch offers more grip but there are compromises between grip, stability, wear and behaviour through the life of the tyre that are amongst the parameters Pirelli need to consider as they optimise the tyre's overall performance. For those working in aerodynamics, these many shape changes of the tyres are important considerations when making optimisations.

In 2012 tyre management has been critical. There were seven different winners in the first seven races, much of which came from how teams managed tyres during the race. Teams have to balance the time taken for pit stops (often less than three seconds total) plus pit lane time loss (there is a speed limit in the pit lane) against the amount of time lost through tyre performance evolution through chemical and surface quality changes or wear. Teams employ strategists and sophisticated software to constantly update their race tactics to achieve the best final race result.

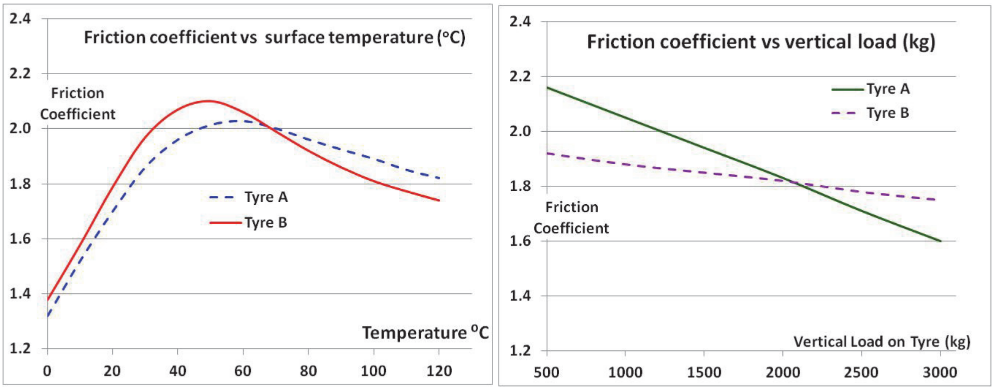


Figure 1. Conceptual indications of how tyre friction changes with temperature and vertical load.

It is particularly interesting to note that tyre friction changes with both bulk and surface temperature, with slip angle, tyre pressure, camber and also with vertical load. Friction reduction with increasing load also applies to road tyres, which is one reason why sportier cars use wider tyres. The trend reverses for snow and ice but that is not a concern for F1!

F1 tyres are specifically optimised for the task at hand and background development is being constantly undertaken. The optimisation is not the same as it would be during a 'tyre war' between rival manufacturers. The aim is to focus more on fairness, equality, safety and the show than on ultimate pace. Nonetheless the tyres have astonishing grip levels compared to road-car tyres (see Fig. 2). Both mechanical and chemical grip are at elevated levels.

Much improvement has been made (and continues to be made) on suspension systems. They are regulated to being passive and their action must be direct and caused by suspension motion[3]. This, in theory at least, limits F1 suspension systems to subsets of what is possible on road cars but it does limit the advantages that wealthier teams can obtain over teams that have less money to spend. Nonetheless suspension systems are complex from the shock absorbing and springing perspective. Some people were concerned when refuelling was banned because cars would qualify on low fuel (at the start of the race fuel contributes over

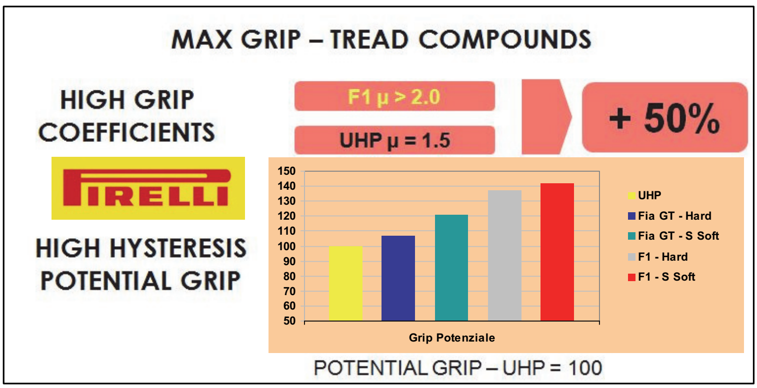


Figure 2. Comparing potential tyre grip for ultra high performance, FIA GT and F1 cars.
(courtesy of Pirelli Motorsport Services Ltd.)

20% to the weight of the car). There was no need for concern as, at high speed, aerodynamics contributes many times the total mass of the car. A suspension system already tuned to cope with huge aerodynamic forces can be adjusted and adapted to cope with additional mass. These high aero loads make suspension development a real challenge. The large tyre side walls effectively imposed by the rules mean the cars float on big (sophisticated) rubber balloons. Teams cannot 'pump' the tyres up at high speed (rules) or pump the suspension up (active suspension not legal) so inevitably ground clearance is lost at high speed and the suspension itself is quite stiff. This means losses in mechanical grip and ride comfort and these factors (mechanical grip at least) make a big difference to performance so the engineers work hard to find the best compromises.

For the development and assessment of suspension-related systems the teams use many tools. Sophisticated software simulations of course are widely used. In addition most larger teams own or have access to a seven-post rig. This looks like a road-car four-corner test rig with a hydraulic pad able to move tyres or uprights up and down in a realistic manner (a non-rotating tyre behaves differently to a rotating tyre). In addition aerodynamic and dynamic load can be applied in three places so that braking and cornering vertical loads can be simulated. Many teams have access to kinematic and compliance rigs which they use to help tune and select setups and possible geometries to track test.

2.3 Vehicle mass and centre of gravity

All F1 cars are limited in dimensions and mass by the regulations. In 2012 the minimum weight of the complete car without fuel but '…with the driver wearing his complete racing apparel…', must be no less than 640kg[(4)]. The weight applied on the front and rear wheels is prescribed to about 1% of a fixed distribution during the qualifying session[(5)]. This is to limit the advantage or disadvantage that a team will have if they either choose the right/wrong weight distribution and the disadvantage they would have if they are unable to produce a car that is light enough to move the weight distribution around.
It is an advantage to have a lower centre of gravity:

- reduces lateral weight transfer and thus keeps more weight on the inside wheels in cornering which allows the engineers more control over the mechanical balance of the car
- improves traction out of corners (all straights start that way) although it hurts straight-line traction

A minimum weight is imposed for reasons of safety and equality. A trend can be seen on road cars of the past 30 years where, for reasons of safety, cars have tended to become stronger and more crashworthy but also significantly heavier. For example, 'From 1980 to 2004 … the attributes of a Honda Accord have changed significantly. Weight has increased by over 50 percent, while horsepower has nearly tripled[(6)].' Between 1999 and 2005 the Accord's NHTSA Safety Rating also increased from four-star to five-star.

After years of optimisation for weight, the F1 teams have developed incredibly light-weight but effective safety structures including a protective monocoque and light energy-absorbing structures, which are needed to pass various crash tests. Of course, given the extreme nature of the sport, safety is also being evolved generally in F1, in the drive to keep human beings as safe as possible.

2.4 Engine and transmission of power

2.4.1 Engine

In 2006 the engine specification changed from a three-litre, ten-cylinder engine to the current specification which is valid until 2014[7]:

- eight-cylinder, four-stroke, naturally aspirated, with round reciprocating pistons
- maximum capacity of 2,400cc
- maximum rpm of 18,000 (from 2009; in 2008 was 19,000 and prior to this there was no limit, with even higher rpm being used)

The design of the present engines has been frozen now for many years but small modifications for reliability are permitted from time to time and certain freedoms exist with the mapping of, for example, fuel injection and ignition timing against rpm and throttle position. Engine features and accessories which impact the engine installation are permitted in a controlled way. Engine life has gradually been increased so that now a driver may currently use no more than eight engines in a season[8].

F1 cars run in atmospheric conditions where it is important to consider temperature, pressure and, because of elevated ambient temperatures, humidity is also a significant player. This applies too to the aerodynamics of the cars except that the impact of humidity for aerodynamicists is because of what it does to density only. For engine manufacturers, the reduction in oxygen content caused by the presence of humidity has an additional impact. Hopefully for aircraft it is only on takeoff and landing that humidity is as significant.

Engines are developed on specially adapted or purpose-built engine dynamometers. Dynamic testing in particular requires relatively low inertia so the engine can accelerate as quickly on the dynamometer as it does in the car. Engine dynamometers are in some cases fully dynamic so that realistic endurance testing can be done while simulating the duty cycle of a grand prix.

In 2014, a new more fuel-efficient engine formula and more energy recovery are planned. This will at least temporarily change the 'balance of power' between aerodynamics and engine.

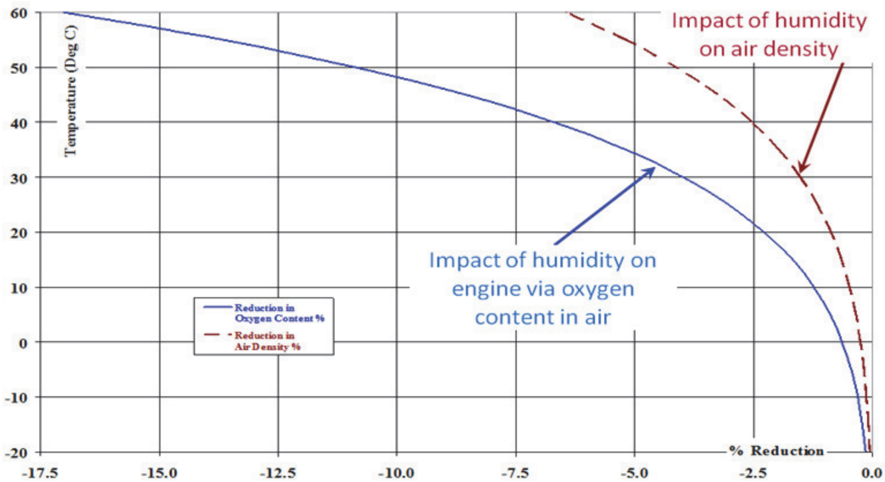


Figure 3. Effect of 100% humidity on air density and oxygen content in air as a percentage of density of dry air.

2.4.2 Gearbox

An F1 gearbox has a maximum number of seven forward gears and 30 gear ratio pairs per season[9]; and must now last for five consecutive events[10]. Gear change time is effectively zero and is followed by the momentary availability of additional torque created by slowing the rotational speed of the engine. Every up and down gearshift must be manually initiated by the driver[11].

Special gearbox dynamometers have been developed for F1. These allow torque to be applied in the appropriate manner with the appropriate rotation speed and the very low rotational inertia needed to mimic a F1 engine.

2.4.3 KERS

KERS was originally permitted and then used in 2009 by some teams but not used in 2010. It was readopted in 2011 partly because the car's minimum weight was increased making it far more attractive. This system stores some of the energy that would otherwise be dissipated under braking. The driver is then able to use this via a steering wheel mounted 'boost button'. Most systems use a battery 'pack' to store the power and the difficulty for F1 engineers is packaging the needed components efficiently. The maximum power, in or out, of any KERS must not exceed 60kW and the energy released may not exceed 400kJ in any one lap[12]. That is about six seconds at 60kW. The disadvantage of carrying KERS is a small centre of gravity height increase, but the advantage, once fitted, is more speed, faster lap times and a strategic edge in qualifying and when trying to defend a position or overtake another driver. It also adds to the challenge a driver has when trying to manage his race.

It is hoped that some of the safety features and some control technologies being developed for KERS can help with the improvement of such systems for normal road cars.

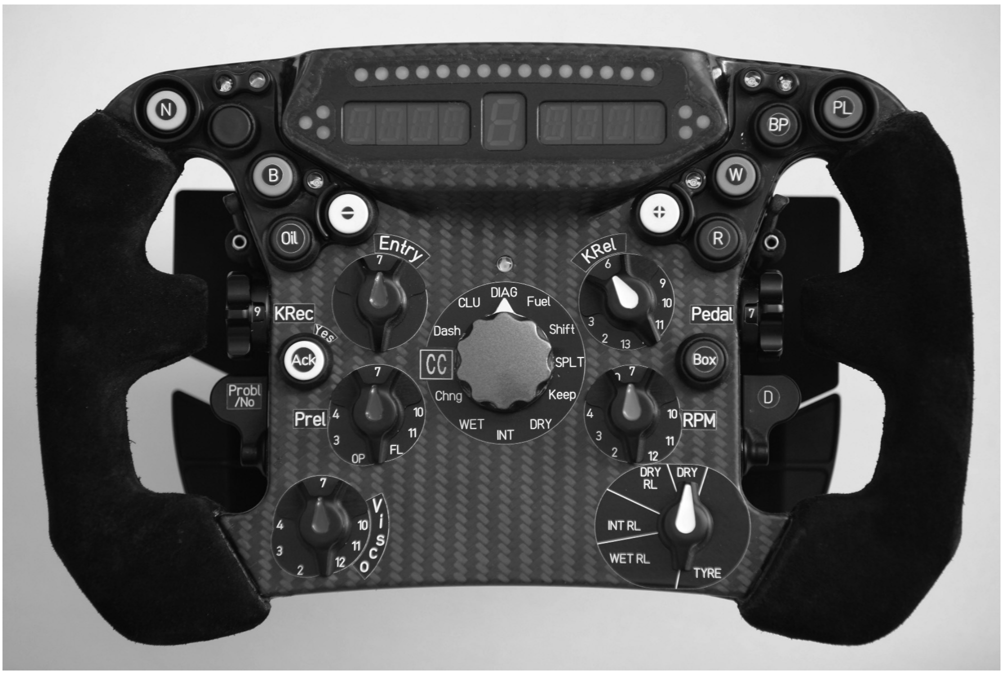


Figure 4. Sauber 2011 steering wheel.

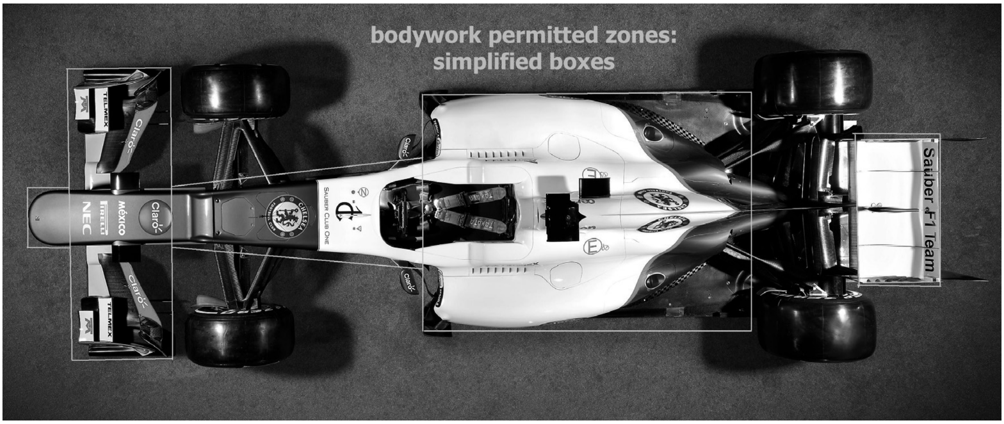


Figure 5. Plan view of car with bodywork exclusion zones.

2.5 Electronics, hydraulics and pneumatics

Electronics in F1 are all pervasive but driver 'help' is quite restricted compared to road cars. F1 drivers should be able to show their car-control skills as any electronic aids we give them will simply be used to go faster. Many now-common road car systems such as traction control, ABS and ESC are illegal in F1. Others areas of electronic control are limited and monitored via an FIA-specified ECU and a dedicated FIA data recorder[13].

Some years ago engineers were able to change settings on the car but such pit-to-car telemetry is now banned. This means that the driver is fully responsible for changing any electronic settings when the car is on track (e.g. KERS boost, DRS activation, brake balance, fuel richness, pit lane speed limiter). An idea of the number of systems controlled by the driver can be seen in Fig. 4. Obviously this is not as complex as the systems on many aircraft but there are no co-pilots or auto-pilots on an F1 car and you cannot 'look away' from the road for very long at all in an F1 car!

2.6 Aerodynamics

Aerodynamics allows literally tons of downforce to be created and so this has been the key performance differentiator in recent years. To a large extent this importance is created by the rules. However, aerodynamicists also face limits to the freedom they would love. F1 is governed by a strict set of regulations which include bodywork limitations. Some of these are designed to '…minimise the detrimental effect that the wake of a car may have on a following car'[14]. Bodywork, which is defined as: 'All entirely sprung parts of the car in contact with the external air stream, except...'[15] '… must be rigidly secured to the entirely sprung part of the car (rigidly secured means not having any degree of freedom). …must remain immobile in relation to the sprung part of the car.[16]' This may appear somewhat restrictive but there is still a lot teams can do!

Each F1 team will be organised slightly differently but, in general, aerodynamics departments are responsible not only for the external look of the car but any surface which comes into contact with air flow and a lot of fluid flow. This includes areas such as: airflow to the engine air box, including the effect of the driver; cooling for the brakes, radiators, electronics, etc; fuel slosh; and liquid flows used for cooling. Basically in F1 the aerodynamicists have a great deal of control over the design of the car.

Aircraft are mainly optimised for and rely on movable aerodynamic devices for manoeuvrability and operational efficiency over a range of conditions. Such devices were banned in motorsport by the FIA in 1969 after several serious accidents. In those days very few F1 people understood just how much load could be generated and how that would change the structure of a race car. Finally, after a brief experiment with adjustable front wings which started in 2009, from 2011 the FIA decided to allow specific and quite limited adjustment to rear wings under certain conditions. This drag reduction system (DRS) allows a driver to make an adjustment to the rear wing from the steering wheel. It can normally be used during practice and qualifying (unless the driver is on wet-weather tyres) but can only be used during a race at predetermined section(s) of the track when a driver is less than one second behind another car. This system has gone a long way towards overcoming some of the problems aerodynamics has caused in reducing overtaking. Overtaking a car that is only marginally slower has always been difficult but in F1 it was becoming excessively so.

Aerodynamics, exploited by teams to improve lap times, had resulted in huge losses of aerodynamic performance when behind another car. The basis for the present aerodynamic rules was a series of studies aimed at increasing the proportion of downforce retained when one car moves into the wake of another. This will also have helped but the concept of the DRS was the key to recent improvements in the ability of a faster car/driver combination to overtake one that is slower.

From lap-time simulation teams have learned that, very roughly, if they could change the previously mentioned performance parameters by a percentage, then they would have roughly the following effects on lap times. The starting point is a present generation of F1 car on an average present race track. If the race track or the start point changes, these values will change.

● Grip – from tyres, suspension, etc.	10% grip	=	3·2% lap time
● Vehicle mass and centre of gravity hgt.	10% mass	=	1·9% time
	10% cg	>	0·4%
● Engine and transmission of power	10% power	=	1·5% lap time
● Electronics, hydraulics, pneumatics	Difficult to measure but important		
	KERS	=	0·5%
● Aerodynamics	10% aerodynamics	=	1% lap time

So it is clear that aerodynamics is not on top of the ‘performance factors’ list considering what happens if you get an extra proportion of each parameter. But of course that is not the complete picture. It also depends on what you are permitted to change and on how much effort it takes to make the change.

3.0 IMPORTANCE OF AERODYNAMICS

Much of what the teams do is limited by the rules that govern the sport. These rules have evolved in part through collaboration between the teams’ technical representatives and the rule makers. It is only because of the rules that there are flat, stepped floors on race cars with no car-to-ground bridging devices, the teams run exposed rather than covered wheels, have an open cockpit of certain minimum dimensions, and virtually all bodywork is forced to be more or less rigid. The teams explored the flexibility to find ways around the rules on rigidity but each year these limits are tightened up. Tiny deflections in rear wing slot gaps was one relatively recent attempt to reduce drag at high speed, but this too has been limited by the addition of templates to the wing profiles. Suspension parts generally cannot be wing-shaped and have to be of neutral section, ie the same top and bottom shapes, and have to be fitted ‘horizontally’ with a tolerance of 5°. Rules also govern overhangs, heights, widths, etc. Despite the limitations of the rules, teams are able to work in many areas and continually increase aerodynamic efficiency. Due the nature of F1 cars the aerodynamics are quite different to that of road cars – with drag coefficients of many times a good modern road car – partly due to the exposed wheels and partly due to the benefits of downforce.

Downforce-generating wings working in 'ground effect', ie wings reasonably close to the ground, are in general more efficient (produce less drag for the same downforce) than those a long way from the ground. The wings are inverted with suction surfaces nearest to the ground; hence downforce is generated as against lift in the aeronautical sense. Increasing the angle of the wing slows down the air on the pressure surface of the wing and thus increases its static (surface) pressure, while speeding up the air flow along the suction surface, decreasing the static pressure there. The central part of the front wing of an F1 car is a fixed neutral section dictated by regulation. There is no limit to the angle-of-attack of the rest of the front wings as such other than aerodynamic stall but the rules limit wing position/size. The optimum front wing design is mainly dictated by the influence the front wing then has on the flow to the rest of the car rather than the direct need for front downforce. For global vehicle performance reasons all the front wing shapes used in F1 now are almost brutally three-dimensional in that the shape is different as you move along the span. These shape changes then create vortices at profile junctions which need to be managed as they move along and around the car.

F1 teams employ a number of aerodynamic devices which make virtually no direct contribution to downforce but which create or manage flow features around directly important downforce-generating surfaces thereby enhancing overall performance (see an example in Fig. 6). Boards running along the sides of the chassis which can easily be seen on cars from the mid 1990s to 2008 are a good example. These particular parts have been reduced in size and position due to the

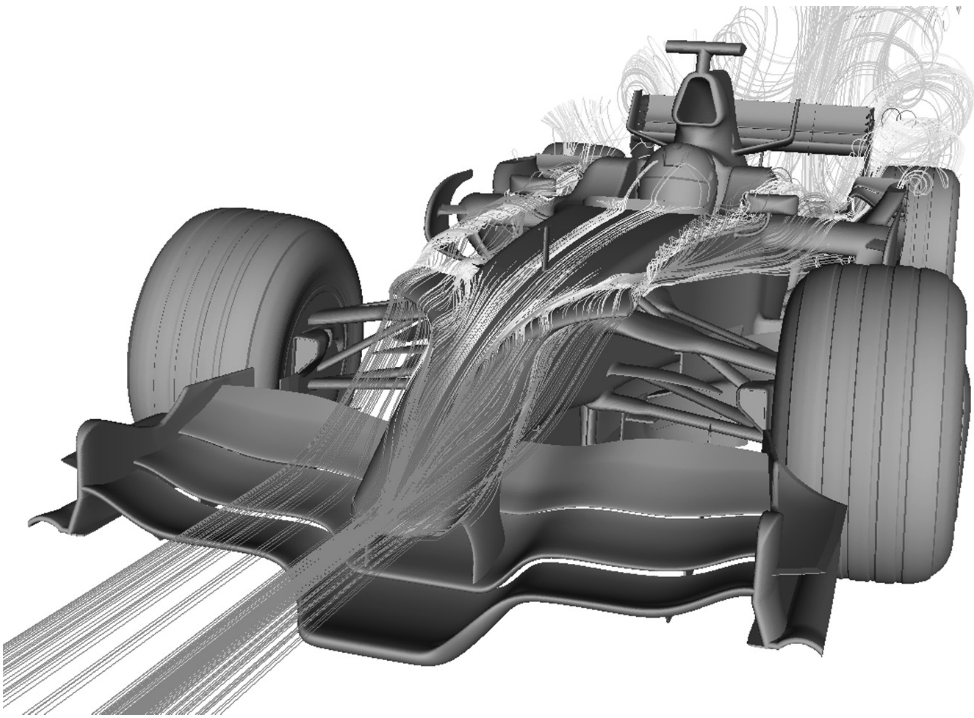


Figure 6. F1 car with indirect aerodynamic device.

regulations but are still used today and can make an overall contribution. Many of the rules followed are broken down into zones which have straight lines that limit what teams can and cannot do which explain most straight lines that still exist on F1 cars.

The aerodynamic set-up of a modern F1 racing car is unlikely to be the same at any two races in a year. Aerodynamic settings (such as the front and rear wings) and hence the drag of the car are optimised to suit individual circuits. In addition, bodywork and brake cooling ducts are changed to allow for the engine cooling requirements dictated by ambient conditions and circuit characteristics. The engineers can adjust the drag/downforce levels of the cars by adjusting or replacing components such as front and rear wings. This is used to select the optimum setting for the track – usually selected for minimum lap time but sometimes for the compromise between straight line speed and lap time. Then, as a result of aerodynamic development, regular bodywork updates are made that change some features of the car. There are of course other settings and updates (e.g. gear ratios, suspension settings and parts, electronics, engine), that are not directly aerodynamic, that ensure that the car is certainly never raced twice in the same configuration.

3.1 Force breakdown on a race car

Figure 7 shows the downforce and drag acting on an early 2009 car broken down into the direct contributions of some of the main groups of components. It can be seen that some parts create lift, not downforce. The front suspension, for example, creates lift but, if we redesign it to make it neutral in terms of downforce, then the total downforce of the car reduces. Parts are very interactive and work as a whole. This sort of breakdown of forces will vary for every car but alters most when teams dramatically change downforce level, such as for Monza (high speed track so lower drag level) or if regulations change. This force distribution is for a car that is still young in terms of aerodynamic development – later, better designs allowed a further increase in the percentage of downforce created by the floor. The rear wing, in this example, is directly responsible for 25% of the downforce and nearly 30% of the drag. However, if it is removed (or if it is lost in an accident), then the overall impact is bigger than the forces that normally act on the assembly directly – about 34% of the downforce of the car (and over 40% of the drag) is lost because the whole flow field around the car is changed. If the rear wing is removed front downforce is increased, most of which is a mechanical load transfer effect because the front wing is ahead of the front wheels. If a rear wing is 'lost' on the track, the result is almost certainly a dramatic spin and an accident due to this dramatic imbalance. Rules have been changed from time to time to reduce the risk of this happening. Teams are highly motivated to keep rear wings (in particular) on the car! On the other hand, the behaviour of the car without a front wing (understeer) is more likely to be predictable and controllable, and usually drivers are able to get the car back to the pits if that is the only damage. A nose change takes a typical F1 team less than 10 seconds.

3.2 Force breakdown on a rear wing

Breaking down forces further in subcomponents of the car also shows some interesting trends. In Fig. 8 from 2009, when the rules were slightly different to today, the mainplane of the rear wing (in green) makes the biggest single component contribution to downforce (this is normal as far as F1 cars are concerned) and a relatively modest contribution to the drag of the assembly but it requires the flow field created by the other elements around it to work well. From this base design if you wanted to reduce drag it would be tempting to reduce the size/height of the flap (in yellow) in order to improve efficiency. However, with most optimised designs this would not work as the airflow under

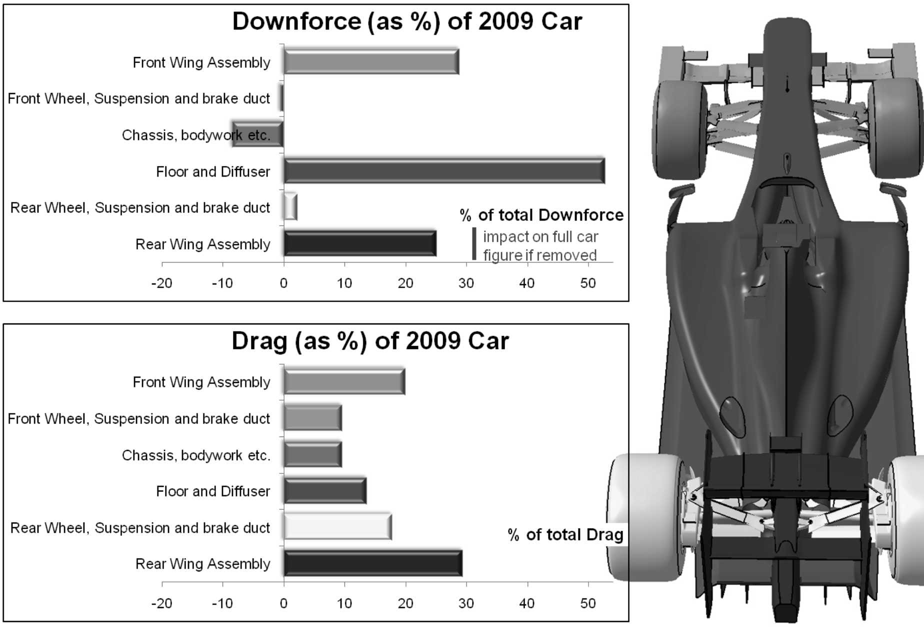


Figure 7. Insight into aerodynamics basics – downforce and drag breakdown into major components.

the mainplane is likely to become detached. The lower wing then relies on the upper for 'moral support' and it in turn helps to drive the flow that is exiting the diffuser of the car which is below it.

The two 'templates' around the upper rear wing assembly are there by regulation to hold the elements together and reduce passive deflection. The small mid rear wing uses a loophole in the rules that is now closed so you do not see these on rear wing assemblies now. Even the rear wing endplate, which is nominally flat, makes a direct (as well as an indirect) contribution to downforce.

3.3 How much faster does aerodynamics allow a car to go?

The forces exerted by aerodynamics increase with the square of speed – all other things being equal. On a race track it is also important to factor in the length of time the car spends in a corner. Figure 9 shows how downforce and drag can influence the limit speed of a car, over part of a lap of the Barcelona track – from normal to no downforce or normal to 25% of normal drag. Zero downforce is certainly achievable but getting the drag down to 25% of today's real car values is probably not possible for a legal F1 car but what we are trying to look at here is the limit of performance.

Figure 9. shows speed (vertical scale) against distance (horizontal scale) for the Sauber Ferrari F1 car along with several theoretical cars. The curves are created using lap-time simulation software, which is regularly validated and improved against real-car performance. It is assumed that other parameters such as suspension and tyres are at the same performance level, which is not strictly realistic but that is not that important as the focus is on aerodynamics. It is interesting to see that removing downforce increases lap time by more than 20%. Reducing the drag of the car to just 25% of its real value (a reduction that is beyond the limits one could achieve for an open-wheeled race car) gives much less than 5% of lap time gain. The gain also varies due to downforce level. This is fairly simple to explain. If you are at the cornering limit because you have no downforce, a drag reduction is not going to help much (until you get to a straight). Alternatively,

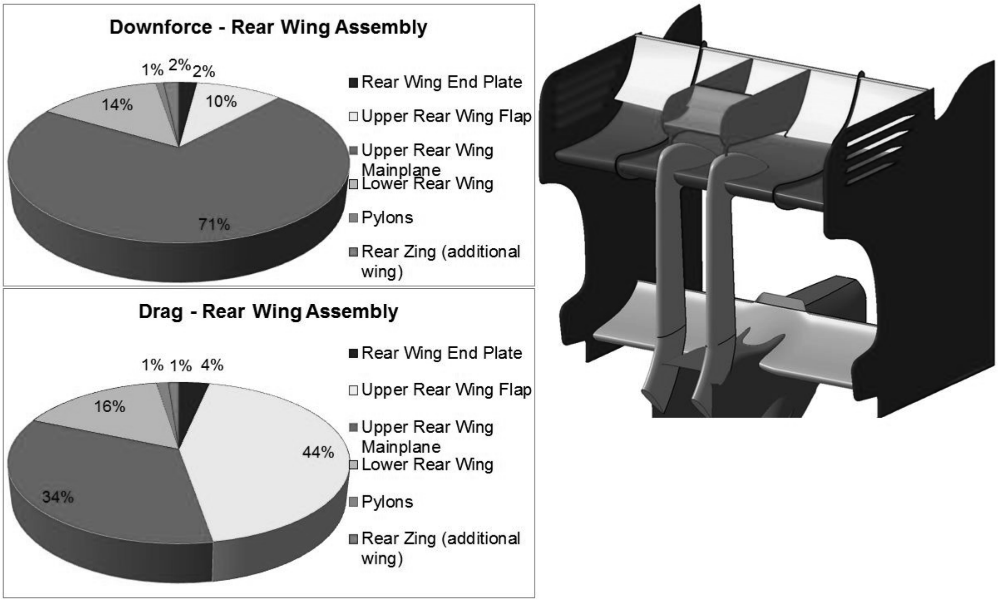


Figure 8. Insight into aerodynamics basics – downforce and drag on a rear wing assembly.

if you can fly around the corner because you have grip, your average speed is higher and you will have to 'fight' drag more using power – so a drag reduction will help you more. Applying power changes the 'balance' of a car because F1 cars are rear-wheel drive. So, if power is applied, the rear tyres have to cope with cornering forces as well as accelerative forces. There will also be some weight transfer caused by the acceleration which will tend towards reducing the apparent problem. In low-speed corners little power is needed to maintain speed so reducing the drag has almost no effect. In high-speed corners the influence of drag can become quite significant – going towards about 10% of the change that can be achieved with downforce in the example shown in the plot above and the table below. In extreme cases (e.g. when all cars are easy flat though a given (very high-speed) corner) then the situation changes and, practically speaking, only drag will be important.

One of the truly fascinating challenges of present F1 aerodynamics development is working out how to stay near the aerodynamic limit on every aerodynamically-important surface without causing significant detrimental flow state changes around too many parts of the car as it is driven around a complete lap. This includes changes of car attitude and speed but it is also useful to consider what happens when the car is in traffic, when it is hot or blowing a gale, or indeed when it is pouring with rain. Tyres flex and ripple under the extreme loads applied to them which changes an important part of the delicate aerodynamics package that is the car. Then, rain tyres are not only treaded but also, this year at least, come out of moulds of a different sidewall shape, so this adds to the matrix of tests a team needs to consider. Then, if you have not got your head full enough of performance parameters, remember the fact that cars are stone/rubber/insect blasted to varying degrees as they race around the track – design laminar flow devices at your peril! Do not forget which parts are most likely to be damaged in a racing situation – you cannot afford for the aerodynamics of the car to collapse when you lose small parts. Teams have found that the optimisation work is never finished, no matter how much work is done.

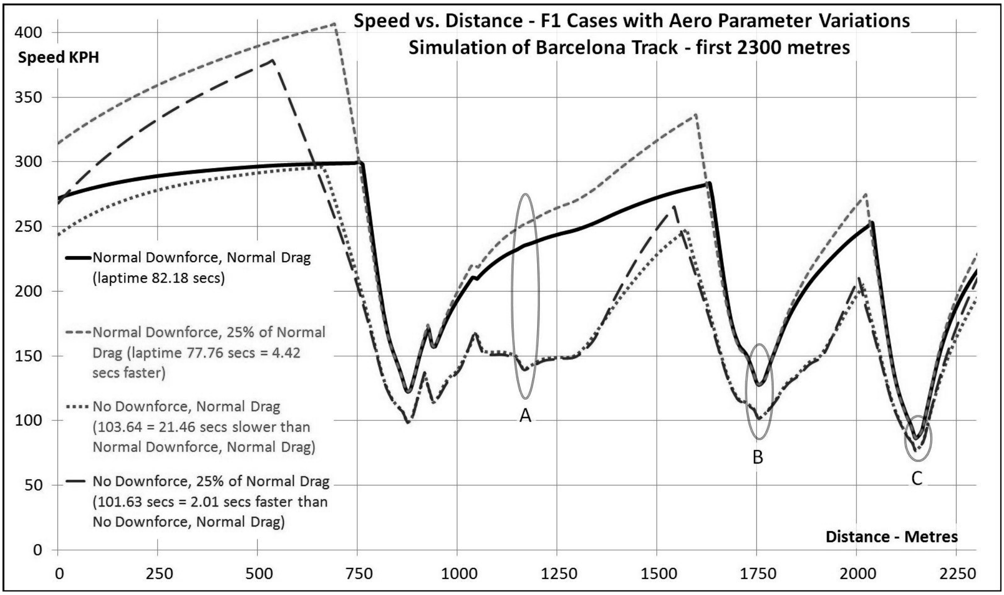


Figure 9. Influence of drag and downforce on the limit speed of an F1 car.

4.0 AERODYNAMIC TESTING

More than 100 years ago, Lanchester experimented with an aerodynamic balance[17] (see Fig. 10) to try to determine the coefficient of skin friction for cars. One can imagine both what actually happened and the frustration it must have caused:

'The aerodynamic balance consists of a horizontal arm or beam A, pivoted about a vertical axis B, the amplitude of motion permitted being regulated by the screws CC, which also form electrical contacts. For the determination of the coefficient of skin friction, a normal plane D is attached to one end of the beam and a friction plane E to the other, the areas of the two being adjusted until they exactly balance.

'… In spite of every precaution, when the instrument is mounted on a motor car the beam is found to be in a continual state of oscillation between its stops, probably due to slight rotational movements of the car body produced by the unevenness of the road. This difficulty was actually experienced to so great an extent that the employment of the instrument in its present form on a motor vehicle was abandoned.' (He added a footnote proposing that: 'The difficulty could be overcome by re-designing the apparatus with two beams having opposite rotary movement.')

Table 1
Speed variables depending on corner speed (as shown in Fig. 9)

	Corner type	Speed without downforce	Speed with normal downforce	Speed increase due to downforce	Speed increase possible in corners due to drag reduction to 25% of normal value
A	high-speed	139·5kph	235·5kph	69%	7·0%
B	medium-speed	101·4kph	127·6kph	25%	0·34%
C	low-speed	76·6kph	86·2kph	12%	0·2%

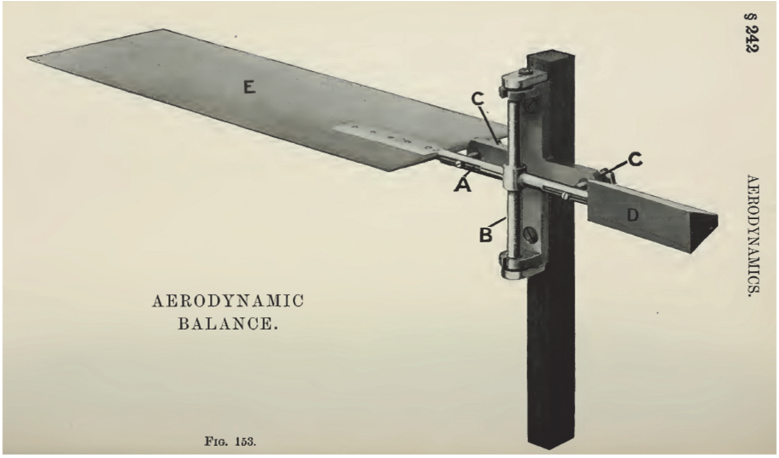


Figure 10. Lanchester's aerodynamic balance.

Table 2
Comparison of wind tunnels and CFD

	Wind tunnel	CFD
Fundamental understanding	Has been mainly shape change to performance change approach – don't need fundamental understanding. Flow visualisation possible. Modern laser visualisation techniques useful.	Excellent visualisation, reveals flow mechanisms and helps understanding of possible next steps. Has changed F1 design approach
Physical limitations	Certain scenarios cannot be tested (e.g. influence of heat, real cornering). Some details are harder to simulate. Models are expensive to create. Cannot automate shape evolution.	No limitations, any scenario can be simulated, although the time needed may be high. Mesh quality still influential.
Simulation of complete aero maps and optimisation of shapes	Fast and repeatable results within minutes and good sensitivity analysis (e.g. pitch, roll, height, yaw, etc.).	Slow, limitations for complete aero maps, but automated shape optimisation possible with parameterised shapes.

At first F1 teams experimenting with aerodynamic devices mainly tried them on the cars directly. Then a few tried wind tunnels with the real cars but soon learned that the lack of a moving ground simulation meant they could not rely on this to predict track performance. After some experiments with blowing and sucking boundary layers and a stationary ground plane, model testing over a simple moving belt started. Early F1 models were basic but since then the structure and the detail of F1 models have been transformed. Wood was the most common material for early (up to the 1980s) models, followed by metal inner structure, suspension and wings with wooden, fibreglass and vacuum-formed 'bodywork' parts. Carbon fibre was next for both structural and bodywork parts followed by (quite a revolution for F1 teams) rapid prototyping/manufacturing. Some teams have a large number of rapid prototyping machines of different technologies with some using materials developed for/by them in order to achieve the best combinations of properties. To achieve dimensional stability, stiffness and strength some parts are then metal coated. SLS and SLA technologies are the most common and, in the intervening time, the technology has progressed so far that rapid prototyped parts are now not only used for model wind-tunnel testing but are raced routinely on some F1 cars. Brake ducts and exhaust parts are two examples. Some rapid prototype materials can be re-used which makes the technology even more attractive.

Nowadays F1 teams have sophisticated tools with which they can conduct their aerodynamic examinations and explore the limits of aerodynamic downforce and stability. They use 50% or 60% scale models in the wind tunnel but many are also able to test full-size cars. Generally closed return wind tunnels with a mix of solid wall, slotted wall, ¾ open and adaptive wall configurations being used. Climatic wind tunnels are not used any more – they have a different function. Teams have fairly serious CFD capability and also go to special ‘straight line’ aerodynamic tests. Then of course there is real race track testing and racing itself, where the teams are constantly monitoring the cars and how they behave. The most important thing is to be confident in the correlation that can be achieved between the results obtained in the wind tunnel, with CFD and on the track – and understand that, at the moment, it is not possible to have perfect correlation. The challenge is improving race track performance despite the many issues that exist.

Despite their apparent affluence, F1 teams are regularly forced to find creative ways of assessing an idea without spending a great deal of resource (financial, time, wind tunnel – in the end they all amount to the same thing). The simpler the simulation, the more you can do … but the further you are from reality. Finding that balance is part of the regular process of development.

4.1 Wind-tunnel testing

In F1, the highest proportion of aerodynamic research resource and energy is spent on wind-tunnel testing of scale models of the car. The models are designed to simulate both the internal and external shape of the cars while enabling the teams to change the design of the model shape more simply than would be possible on a miniature replica of the real car. The model is usually suspended from above the working section of the tunnel and is packed full of motors, load cells, pressure-measuring equipment, computers and other electronics. Wheels can be run on the model just as on a race car, which is more accurate and more commonly used but has some issues. Wheels can also be held in place via special mounts from outside the model (from the floor of the wind tunnel outside the width of the moving ground simulation), which has been found to give better overall repeatability of force measurement but there is additional interference to the aerodynamic envelope around the car. Tests are conducted over a range of attitudes – e.g. ride height, pitch, roll, crosswind or yaw and steer while assessing model (as well as wheel) forces and scanning pressures plus extras such as the effect of exhaust gas (a typical example of another parameter to optimise).

It became a necessity for people in most teams to be on top of the design and development of wind-tunnel test facilities in all their delightful complexity, which was not the case 25 years ago. Pushing the facility to new levels means that everyone using it gets more or better results for the same effort. Hopefully, if teams know what they are doing these results are also track performance relevant. The teams have developed or aided in the funding of special sensors adapted to their needs such as laser ride height measurement systems that cope with rough ground and wheel lift measurement devices.

Moving ground systems started effectively as high-speed conveyers and as problems occurred they needed to be solved. Static killed lots of delicate sensors, which was countered by adding woven metal into the basically synthetic belts and using techniques such as ionisation and conductive brushes on the belt underside. Belt lift occurred under suction surfaces of the models so zoned suction systems were added. These of course were not perfect so additional power was needed and lots of heat was generated. This was countered with initially air and then liquid cooling systems. This technology took teams to over $50ms^{-1}$ test speeds with good reliability. Under belt load bearing and measurement systems were evolved to assess wheel lift forces and minimise sliding friction under the belt where the tyres run above. Belt surfaces still vary from glass like to quite rough and this makes a measurable difference to the results. Finally tyre testing technology and F1 wind-tunnel belt needs were combined by the American company MTS, which led to the high-speed steel belted moving ground simulations used by many teams today. These belts are supported by air bearings which virtually eliminate sliding friction and have made the moving ground systems much more robust, reliable, durable and able to run at high speed.

One can think of an F1 model as a robot. The model is nominally rigid but, during normal testing, most teams are able to change a major subset of heave, pitch, roll, yaw, road yaw, steer, radiator heat rejection, front wing angle, tyre load, exhaust velocity and other parameters. Heave, pitch and roll can be done with three motors but often a hexapod is used for these simple degrees of freedom. If tyre load measurement is used and the model is yawed relative to the road, the sensors under the tyre contact patches need to match tyre position. With eccentric systems this means three motors per wheel. Control systems are reasonably sophisticated and able to support fully synchronised motion.

As time has passed, F1 aerodynamicists have been forced to solve ever more complex optimisation problems which has kept the work challenging. They cannot for example think of just lift, drag and aerodynamic balance but need to consider how to optimise performance around a complete race weekend duration including taking into account aerodynamic stability because most electronic driver aids are not legal. Teams have worked in different ways to reduce the complexities of data from hundreds of sensors to a few relatively simple primary decision-making parameters, e.g. predicted lap time. To calculate simplified performance parameters though, there has to be data for the teams to use to correct every configuration tested for aerodynamic balance, drag, cooling level and some other relatively consistent adjustable features of the car. This is routinely done at most of the teams, thus allowing aerodynamicists to judge which run is beneficial for car performance seconds after the run is finished. When this rapid decision making is possible, design of experiments technologies allow the aerodynamicists to select the next part in a matrix of prepared components to be tested, without slowing the testing rhythm.

4.1.1 Cornering, steering and yaw

True cornering, which is quite different to yaw, is not, strictly speaking, possible unless one has a bent model and a different radius of curvature of model would be needed for each type of corner (not really practical). It would be possible to get closer with an extension of the adaptive wall technology already installed in some F1 wind tunnels to effectively bend the airflow, thereby approaching the aerodynamics of race car true cornering. Consider a car rolling slowly around a hairpin bend: the front wheels and tyres are turned into the corner at, let us say, 20°, and the rear wheels are square to the car. This means there is 20° of difference in angle of the road to the front wheel centreline and the angle of the road to the rear wheel centreline. The fact that the tyres slide slightly relative to the track makes it a little harder but does not change the problem with trying to simulate cornering. Yaw (model at an angle to the wind and road which remain in line) and something like crosswind (which can be approached by yawing both the model and the road relative to the wind tunnel = the wind) can be achieved. Most teams will experiment with some apparently 'strange' combinations of yaw and adverse yaw with steer and crosswind to try to get the most useful combination of factors to get as close to true cornering as possible. Wind-tunnel 'steer sensitivity' has limited meaning for a race car because the model in the wind tunnel does not 'react' mechanically to changes of steer. However, all these types of testing allow teams to understand certain aspects of stability and sensitivity. Many race car motions and conditions can be simulated quite well in a wind tunnel.

4.1.2 Bodywork deflections

On a wind-tunnel model, tested at either constant speed or over a small speed range, the deflection of shapes is limited (models are reasonably stiff if designed to be so). Achieving scale stiffness is in any case extremely difficult to achieve. Most model wind-tunnel testing is done at constant speed. Speed and scale are limited by regulation so teams go to the maximum. Testing at the highest speed permitted maximises forces on the model which helps with force measurement repeatability. On the model the forces acting on each component do not vary very much at all. On the race car, however, the dominant factor is the fact that forces generally scale with the square of speed and the speed range on the race car is high. Consequently teams normally do positional and shape sensitivity studies and target shapes that are likely to give the best overall performance. On some parts the race car deflections will be positive for performance (and will be purposely exploited). On others, deflection is negative and in these situations it may be that high stiffness for race car parts needs to be targeted. Normally aero elastic studies are done in software.

While on the subject of deflection it is also worth mentioning vibration. In F1 engines are bolted solidly to the chassis and not much importance is placed in making life comfortable for the driver – especially if it costs performance to do so. So we have quite violent vibrations in the cars – high frequency and low amplitude. A sign to the teams that this was the case was when we started to use aerospace specification electronics components. We found we had to find ways to protect them from the vibrations of the engine for them to survive. In extreme conditions this will also have an influence on aerodynamics but this is thought to be a relatively minor effect. Vibration of aerodynamic components can have a far more immediate effect. This can be induced by a car bouncing over a curb and will combine with the aerodynamic forces which act on the car. Imagine the tip of a front wing bouncing up and down at its own natural frequency – this is shown from time to time on TV. These vibrations can be quite complex but, for the purposes of discussion, only large vertical tip vibrations should be considered. In extreme combinations of conditions this can have a similar effect to cycling up and down the angle-of-attack of the (outer parts of) the front wing. If parts of the wing operate in areas of aerodynamic hysteresis, the average downforce of the wing will effectively be reduced by this vibration.

4.1.3 Different wind conditions

Crosswind, headwind and tailwind are real conditions that happen all the time, but simulating them correctly is difficult at best. In the wind tunnel the boundary-layer control system virtually eliminates the boundary layer and turning it off allows a ground-level boundary layer of, let us say, about 100mm or so to form – quite different to the real world. However, it is possible to vary road speed relative to wind speed to get some idea about head/tailwind and to simulate crosswind (model and road at an angle to the wind). This crosswind testing is probably an indication of the extreme limits of crosswind (of that angle) in the real world, because the flow angularity will happen all the way from top to (nearly) bottom. Put another way, the 'crosswind speed' in wind-tunnel testing is the same at the top of the rear wing to the bottom of the front wing. In the real world there is likely to be a significant gradient in crosswind speed top of car to bottom.

4.1.4 Boundary layer and Reynolds numbers

Reynolds numbers change with scale (size), fluid (or air) viscosity and speed. One way this influences aerodynamics is type and growth of a boundary layer on surfaces exposed to airflow. Normally a small scale model may have more of the surface with a laminar boundary layer and then once turbulence starts it builds more quickly relative to the model size than on a real car. It is possible to force turbulence with roughness which is a technique that is used from time to time on models but then you have a thick boundary layer further back on the model. In a race the real car is bombarded with sand, stones, insects, balls of rubber and other debris. This can change car performance notably during a race and needs to be considered.

The wind-tunnel model is normally run at the same speed for all tests (there are good reasons for this) and the Reynolds number for model testing is in the lower range of Reynolds numbers run by the race car. Areas of the greatest aerodynamic interest for the race car range from, let us say, 70kph to about 240kph above which speed most corners are flat out. Model testing with even a 50% model at $50ms^{-1}$ (180kph) is Reynolds number equivalent to testing with the real car at 90kph (a 60% model would equate to 108kph). For many reasons including cornering and the factors explained earlier, flow state changes happen then at different vehicle attitudes when compared to wind-tunnel model prediction. All this simply means you need to stay awake and expect some differences between what the wind tunnel tells you and what you measure on the race track.

4.1.5 Flow states

According to Schrauf[18], over half the drag of an aircraft is viscous with most of the rest being lift-induced. For an F1 car, only about 10% is viscous. The other 90% is form and lift/downforce (or pressure) induced. Forces are created such as positive pressure on the pressure surfaces of wings which face forward – that pressure is also drag. Suction is then created on the suction surface but, due to the fact that to create that suction low pressure is needed on rearward surfaces as well, we have drag. This is also true of aircraft wings but to a much lesser extent. There is very little aerodynamic surface area with which to generate many times the mass of the car in downforce so F1 cars use extreme angles to create that downforce and this hurts the lift to drag ratio.

The aerodynamics of open-wheeled racing cars involves complex fluid flow physics, which include[19]:

- separation as a normal feature, for example from the tyres
- surface roughness changes during an event lead to early transition
- suspension motion adding to levels of already unsteady flow
- highly complex physics: wall jet, shear layer instability, vortex meandering and breakdown, etc.
- force enhancing vortices
- turbulent wake and ground boundary-layer interaction
- compressibility (slot gaps at high speed – teams actively try to avoid this though)

One of the given challenges with all this optimisation is that aerodynamic hysteresis exists between certain states – each phase of the problem is non linear so, approaching it from one flow state, you switch to the next at a different point than approaching it the other way. As flow conditions change back and forth, the switches in flow state happen in different places/times/speeds, etc. So, for example, a floor stalling, as speed and downforce change the ride height of the car and consequently floor airflow is reduced, will re-attach at a different speed/height when the car slows down again. This hysteresis may also be significant simply because the flow structure is so dramatically different (it is not a microscopic change of flow

Figure 11(a). bluff body diffuser model in the wind tunnel; downforce regimes of a bluff body equipped with a rear diffuser[20].

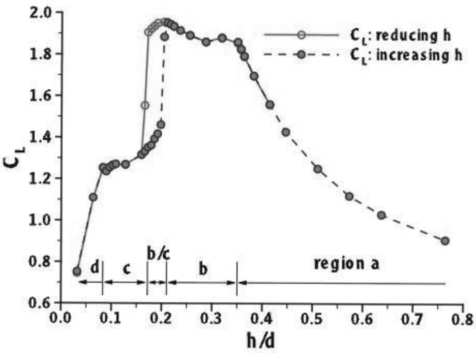
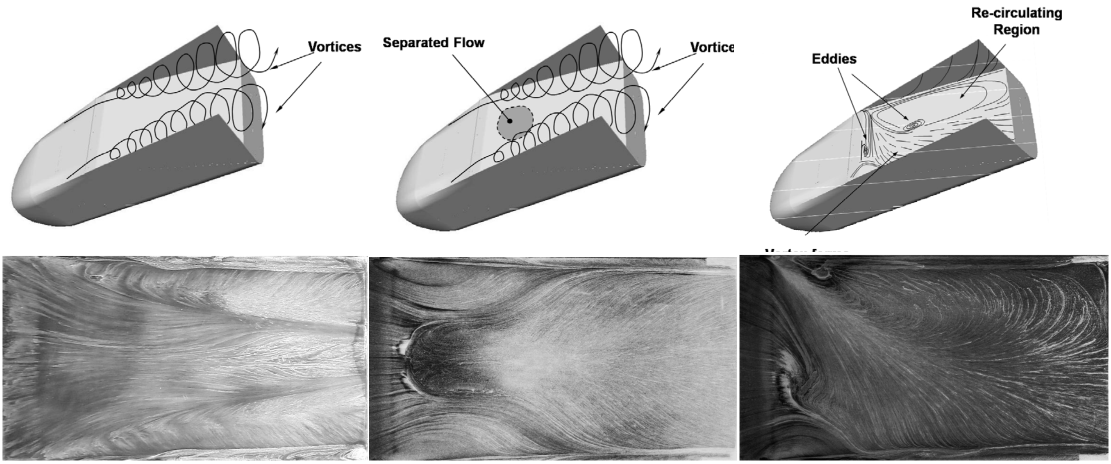


Figure 11(b). above shows the performance of a generic diffuser on a bluff body and highlights four main regions of flow type (performance regions).

so something has to trigger each change). For race cars, peak performance (aerodynamic power and efficiency) are directly next to a performance 'cliff'. For the aircraft industry optimisations are a little different – they can fold away their exposed wheels and dream about full laminar flow.

The (on-surface) flow visualisations below are good examples of some of these flow states. Figure 12(a) shows region 'a' where flow is largely attached to the diffuser surface and the impact of the two force enhancing edge vortices that roll up from the diffuser end plates can be seen. Flow at the end of a diffuser is nearly always slow and a bit unsteady which is not a surprise as the flow is diffusing. Figure 12(b) shows what is still basically symmetrical flow but there is a separation bubble just after the kick line of the diffuser; the highly turbulent flow generated by the separation on the ramp surface could potentially lead to the edge vortex breakdown, therefore leading to a loss of extra downforce due to the edge vortices. This is the mechanism that creates region 'b' in Fig. 11. Figure 12(c) shows that one of the vortices has burst although



(a) (b) (c)

Figure 12. (a),(b),(c) Surface flow visualisation on a diffusing ramp, showing streamlines, on three types of flow. Diffuser flow is from left to right. (courtesy of Southampton University)

flow is still clearly defined and there is a distinct and relatively stable flow pattern on the diffuser surface[21]. Figure 12(c) is associated with region 'c' in Fig. 11. The second large drop in C_L shown in Fig. 11(b) above (as *h/d* is reduced) is basically diffuser entry separation.

4.1.6 Blockage effects

In the real world the car pushes air around without restriction. This is clearly not the case in a wind tunnel and the impact becomes obvious with high levels of blockage. F1 teams used corrections from bluff body studies initially – but once a database of comparisons between the race car on the track to model in the tunnel is collected over a period of years, more representative corrections were made. After many years of research and with the aid of CFD, teams can apply quite complex corrections for wind-tunnel forces.

4.1.7 Tyre deformation

Before the 1980s there was little moving ground capability for wind-tunnel testing and model tyres were mainly solid or made of foam. Almost certainly the first F1 team to consistently use scale models over a moving ground plane were the Lotus team using a quarter-scale model in a wind tunnel at Imperial College[22]. When 'rolling roads' were introduced and improved, it became clear that the lack of representative rubber tyres was a major concern. Different teams worked around this problem in different ways but today teams get model scale tyres from Pirelli. Of course that is nothing like the whole story and tyre shape is important. Race car tyres have to last, for example, 200km (usually less). Model tyres are also limited by regulation and agreement and have to last at least a month of testing (on average more than two orders of magnitude extra mileage). So teams cannot do to model tyres what they do to race car tyres but are lucky enough to have model tyres developed by experts.

4.1.8 Dynamic motion

Race cars move dynamically. For example the early part of braking is a sudden change in acceleration of about 5g which causes a large weight transfer rear to front and consequently induces significant ride height changes. Dynamic motion to mimic these quite aggressive accelerations and vibrations of the race car has been tunnel tested. This presented limited benefits at the time but may present greater advantages when teams run out of performance gains with simpler research. Force measurement repeatability necessarily gets harder when you are trying to separate out aerodynamic and mechanical forces from a force measurement system which is strong enough to accept the full range of forces from both sources added together.

4.1.9 Routine model testing

Aerodynamicists working in F1 know when they have found an improvement for the car if the performance numbers improve in the wind tunnel. This is one of the reasons that this work in F1 is so satisfying. Improvements can be on the race track in weeks. Most teams test around the clock and many test seven days per week.

Teams need to optimise car performance with a number of currently agreed limitations. With scale-model wind-tunnel tests model scale and speed are limited. By agreement between the teams there is also a limit on the number of 'wind-on' hours (i.e. when the wind is running at more than a certain speed). This in turn has meant that teams need to have systems which can extract as much information as possible in the shortest time possible. It is important to find the right balance between

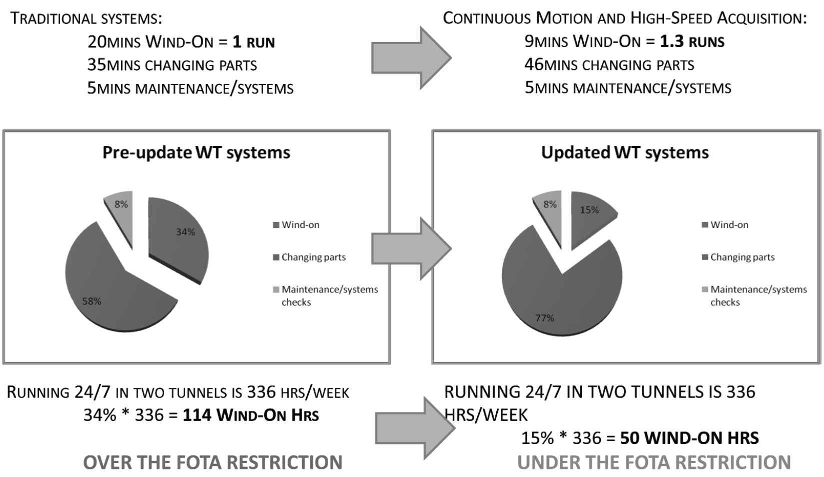


Figure 13. Comparison of Toyota's old and new tunnel test systems.
(courtesy of Toyota Motorsport GmbH and F1 Race Technology)

the duration of a wind-tunnel run and the amount of information needed from the wind-tunnel run. It is also fairly easy to understand that force measurement repeatability and the time taken to sample forces are related parameters.

Most teams hide what they do. Having withdrawn from F1, and in a bid to win F1 customers, Toyota Motorsport GmbH (TMG) updated its wind tunnels, by investing in an interlinked system combining continuous motion with high-speed data acquisition and fixed-installation PIV flow visualisation. They dramatically improved the effective testing throughput of their tunnel (see Fig. 13) while also allowing the experimental aerodynamicists working their facilities to have some of the advantages normally reserved for CFD aerodynamicists via well-integrated PIV systems.

'With a traditional quasi-static system, an average hour in the wind tunnel would consist of a single run covering a range of ride heights and yaw, steer and roll angles that would take 20 minutes. In addition, you need time to change parts and perform regular maintenance and system checks. So for one run you can expect to spend 34% of your time with the wind on, meaning 24/7 operation puts you significantly over the FOTA restriction.

'But with the continuous motion system, a single 'standard' run takes only seven minutes of wind-on time – just over a third of the time taken in quasi-static mode. Using this technology, we can complete 1·3 runs every hour – that's a 30% increase in completed tests compared to before. That means 30% more runs every day and 30% more opportunities to try out new concepts.'[23]

4.2 CFD

CFD has come into its own as far as racing car aerodynamics are concerned. Teams started to delve into the use of CFD in the late 1980s and early 1990s when CFD was already widely used in the aircraft industry. For the teams that experimented first with Navier-Stokes CFD codes, it was clear quite quickly that compute resources were going to limit what could be done with CFD for a long time. It was also evident that setting up cases was going to also occupy a lot of man time. In the early 1990s one way some teams put together enough compute power to solve cases was to link CAD work stations together at night when they were not being actively used for design work. The time needed to prepare cases was not such a drama then as crunch time was also limiting and teams were still working out how big the benefits of CFD would be.

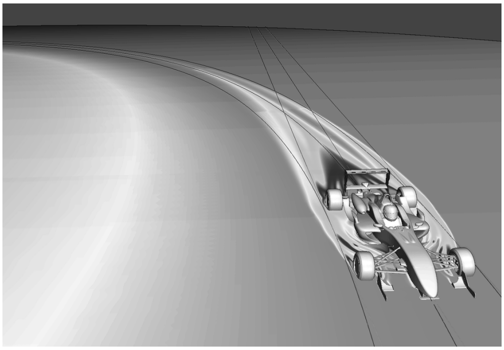


Figure 14. A formula car cornering simulation total pressure. (courtesy of TotalSim)

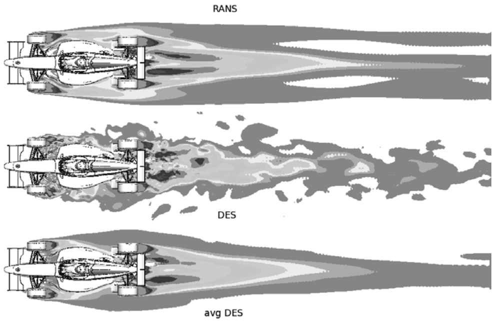


Figure 15. CFD solving techniques compared on a formula car. (courtesy of TotalSim)

Most teams also experimented with Panel Methods, Euler codes and 'meshless' CFD. Each of course brought temptations and limitations. In the early days of CFD most aerodynamicists were still thinking more about pressure distributions on surfaces than directly about managing flow structures so a real temptation of panel codes, apart from relative speed and simplicity, was the opportunity to use inverse aerofoil design techniques where an existing aerofoil and pressure distribution is used as a basis for a new design where the aerodynamicist simply draws the pressure distribution he wants and the code generates the shape needed to achieve it. While teams were learning about aerodynamics this was particularly useful but tools like these still have their place today.

In the past resources were limited because of a combination of global team finances and strategic decisions about where to invest in research tools where wind tunnels usually, and at the time correctly, won the battle for investment. But with increasing power per unit cost computers have continued to deliver more computational ability which has aligned well with improvements in CFD codes and in the ability of F1 teams to use CFD to understand and improve aerodynamic performance. Today though, agreements between the teams limit CFD computational power specifically so teams still need to consider exactly what they do in CFD and how they do it.

In the 20 plus years from the teams' initial use of CFD, a lot of work has been done. Commercial suppliers of codes such as Fluent and Star have taken motorsport, and particularly F1, seriously over the years and this has made these codes increasingly useful. Over most of this time trends were moving towards increasing case size with the main focus on improvements in correlation to reality. With an eye on efficiency and throughput it was never going to be possible though to focus exclusively on accuracy. Recent restrictions have sent the focus back in the direction of sensible correlation of trends and increased throughput. Each team focuses on its own ways to get the best out of the resources available. Naturally, meshing speed up techniques such as immersed boundary modelling and automatic shape optimisation routines such as Adjoint have been used or at least investigated by a number of teams.

Despite any internally imposed limitations modern HPC clusters allow the use of mathematical models which by now are quite sophisticated. Most teams keep quiet about their resources but in April 2007 the BMW Sauber team, partnered by Intel at the time, declared exactly what CFD cluster it was using. The cluster was ranked 1st in Europe and 3rd in the world for industrial use. Even though cell counts have not really gone up so much in recent years, correlation with track and wind tunnel keeps improving due to the effort that the teams (and software suppliers) are putting into pre-processing, code development and case setup.

Teams do not just focus CFD work on the aerodynamics of bodywork but also look at many other aspects of car design that could impact performance such as cooling for the electronics, engine, brakes; the driver-airbox interaction; air for the engine; fuel slosh, oil systems, etc. Given that aerodynamic forces load up structural parts of the car, teams have been using tools that allow them to investigate aero/structural interactions for many years.

Navier-Stokes codes predominate in F1 for CFD work. Some teams are combining the use of commercially available or open-source packages with in-house computer programs/enhancements to maximise the gains that can be made using computers. Parametric optimisation techniques are sometimes used for CFD performance enhancement just as can be done for wind-tunnel testing. Due to the complexity of aerodynamic interactions on F1 cars, these parametric techniques are usually used to assist an engineer rather than to fully dictate direction. Those teams able to write or influence CFD code writing work on this just as they have people working to improve the realism of wind-tunnel testing.

Even with today's decreasing cost of compute resources, developing in CFD using the limits of known CFD technology combined with the best practices available for the aircraft industry would be too slow. The teams tend to take a pragmatic approach and cut many corners to find what they believe to be the best compromise between accuracy and case throughput. Cornering flow can be quite well simulated (see Fig. 14) and is often used to help teams understand the difference between wind-tunnel testing and the track. The block mesh is modified by morphing it into a curve and the solution modified to include acceleration terms for the Coriolis Effect and centripetal acceleration to reflect the fact that the wake is no longer directly behind the car. RANS simulations are the most common used in F1 due to high throughput. However, it is interesting to study the differences and similarities between RANS and time-averaged DES. The simulation in Figure 15 was done with a fairly coarse grid compared to those used in aerospace, so naturally one could expect different comparisons with a finer grid. At present, most teams believe that they will find more track performance by running most cases using RANS rather than DES.

It will be some time before it is possible to dispense with wind-tunnel testing because wind tunnels allow hundreds of test conditions and vehicle attitude sensitivities to be assessed in minutes. Having said that, if you have a budget under a few million for your aerodynamic research, then CFD becomes a realistic option because the cost and complexity of wind-tunnel models, that can provide the sort of scale, measurement systems and accuracy that is needed, will mean you do not get much testing done in a wind tunnel the first time you invest your money.

4.3 Straight-line testing

Straight-line testing is mainly used for testing new concepts or for correlation purposes, to check that parts tested in the wind tunnel or developed using CFD work as expected in reality under more controlled conditions than are normally possible at a normal race track. In addition high constant speeds are possible at some facilities and certainly speeds well above the $50ms^{-1}$ limit imposed on wind-tunnel testing by regulation are possible. This type of testing costs a similar amount to going testing at a normal race track as it involves similar wear and tear on the car, engine, etc. but lots of tests can be performed in a short time if a team is organised. It is permitted in the regulations to swap aero track tests a team is permitted for a day of wind-tunnel testing with a full-size car. Each has advantages and disadvantages. Both are useful.

5.0 RESTRICTIONS

To avoid costs becoming prohibitive for the smaller teams, the FIA and F1 teams have agreed a number of testing restrictions. In addition the teams have agreed their own limitations for aerodynamic testing.

- scale model wind-tunnel tests – limited to 60% scale model with a maximum test speed of $50ms^{-1}$[(24)]
- full-size wind-tunnel tests – maximum test speed of $50ms^{-1}$ which can be exchanged for straight-line or constant-radius track testing
- aerodynamic straight-line or constant-radius track testing – almost the only possibility for testing during the F1 season but also limited by regulation to four days a year. A day's testing can be exchanged for four hours of full-scale wind-on wind-tunnel tests[(25)]
- real track tests both at normal circuits and at airfields for steady state testing – currently limited to a maximum of eight days (pre-season), three days (mid-season) and 15,000km[(26)]
- by agreement between teams we also limit both the amount of wind-tunnel testing we do and the size of the computer cluster we use for CFD calculations

There are currently no restrictions on other forms of testing, eg driver simulators, seven post test rigs, kinematic and compliance testing, tyre rig testing, etc.

6.0 CONCLUSION

All the research methods for improving car aerodynamics have their limitations. Testing everything engineers want to try on a real car is very expensive (engines, tyres, travel to the test tracks, personnel, etc) and has limited precision – plus this sort of activity is strictly limited. Real world condition changes such as wind, track temperature, tyre condition for example, mean that small (aerodynamic) steps cannot be reliably assessed. Wind-tunnel model testing works reasonably well in a straight line but realistic tyre shape changes are difficult to match to reality and important to F1 aerodynamics. Of course more aerodynamic downforce is only really needed when the driver is not able to drive at full throttle, such as when accelerating at low speed, cornering or braking. To simulate cornering in a wind tunnel is simply not practical although it is possible to steer the wheels and to yaw the model. More complex simulations such as real cornering, multiple cars and physically unrealistic shapes are possible using CFD but assessing sensitivity of forces to ride height, pitch, roll, yaw, steer and sliding through a corner are significantly slower than in a wind tunnel. CFD still provides the best insight into understanding airflow in 3 dimensions and helps the teams to understand why the cars behave as they do more quickly than with wind-tunnel testing.

As with many things in life, producing a race winning F1 car is a complex juggling act. A team's budget has to be spent effectively and efficiently and members of the team need to be able to solve problems quickly. Correlation between simulation and reality is rarely precise but it is still important to find track performance at a competitive rate. Using the tools the team has to put performance onto the car is important despite the many issues that exist is the ongoing challenge of the technical chiefs of the F1 teams.

Looking at Lanchester's skills and interests, I think he would have found F1 to be yet another stimulating part of the world of engineering. I am confident he would have honed a big niche in this field, if it was something he had found interesting!

One of the fascinating things about working in F1 aerodynamics over the years has been observing the way teams have been able to change their research methodology of aerodynamics 'on the edge'. Naturally, at first, teams were far behind the aircraft/aerospace industry. Now they are basically different – ahead in some areas, behind in others and focusing on different things. At first, in F1, the main focus was on improving the reality of aero testing to the point where teams ended up with real race cars running at real Reynolds numbers in wind tunnels equipped with boundary-layer control systems and moving ground simulations capable of running at high speed (high speed for a race car you understand!). This journey has funded the development of facilities capable of remarkable physical testing, but of course, in parallel, mathematical simulation has also made an increasing contribution. In the early days the focus was mainly on global forces. Then, as time passed and more was learned about theoretical aerodynamics, teams started to be able to use pressures and sub component forces to understand better how to optimise performance. It did not take long to work out that peak performance sat directly next to disaster. They experimented from time to time with pushing small parts of the car into the disaster area to help with ride height sensitivity but soon found this was particularly difficult to manage on the race track. With more common use of CFD and then with flow measurement techniques such as PIV in wind tunnels, teams have now been able to move more and more towards tracking and managing flow structures around the car. This is a departure from the use of simple 'rate of change of shape to rate of change of performance' ratios used successfully for performance tuning by some in the early years of F1 aero development. Today it is essential to manage the entire flow field around the car and not just to manage the performance of surfaces on the car. Happily the flow field is extremely complex so different solutions are able to be found by different teams – this is good because ultimately engineers would expect to all home in on a single family of solutions in the drive for efficiency.

It is worth stating that I have not been able to give away things I believe to be confidential in nature. So by implication the information in this article is some years behind the latest innovations and improvements to the methods the teams use.

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