

The Aerodynamic Characteristics of a Fully Deformable Formula One Wind Tunnel Tyre

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ABSTRACT

Competitive aerodynamic performance of a Formula One car relies upon total understanding of the downstream wake of exposed rotating wheels. Sensitivities to the downstream vortices and low stagnation-pressure regions lead to subtle design decisions in bargeboards, side-pods and the leading edge of the highly sensitive floor region. A significant proportion of an F1 aerodynamicist's time is spent dealing with front wheel wake structures and indeed much of the front wing is developed to provide pressure gradients and vortex structures to control this wake.

Wind tunnel testing of scaled deformable tyres has become a common occurrence in F1 in recent years although there is a significant lack of available literature, academic or otherwise. Due to high vertical loads experienced by a grand prix car and the relatively high levels of camber used for mechanical advantage, the use of a rigid tyre is no longer considered suitable for the accurate simulation of an F1 wheel wake. This investigation has studied in detail the aerodynamic consequences born from sidewall bulge and contact patch parameters through the use of an innovative rotating sidewall scanning technique, static contact patch measurements, five-hole pressure-probe wake measurements, Particle Image Velocimetry (PIV) and load-cell drag measurements. A table of three-dimensional coordinates for the maximum and minimum deformation levels has been included in this paper to enable further CFD studies to be undertaken.

For longevity of tyre and moving ground plane, deformation levels are often fairly conservative in industrial and race team applications. The work presented here includes a full range of on-track axle heights, which far exceed those usually tested in the aforementioned settings and the aerodynamic consequences of under-deforming have been identified. It has been concluded that insufficient deformation of the tyre sidewalls leads to a significant overestimate in the width of the wake as well as the aerodynamic loads associated with it. As a result of this study, the most sensitive parameters of a deformable tyre relating to aerodynamic testing have been identified and summarised. For development of an F1 car, a compromise in tyre pressure is considered less detrimental to the downstream wake compared to providing insufficient deformation with an incorrect axle height.

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INTRODUCTION

The aerodynamic performance of a Formula One (F1) car depends heavily upon a highly complex system of pressure gradients and vortex structures in order to generate negative lift, known more commonly as downforce. This highly sensitive combination of features must be controllable in order to develop further and as such, they require precise understanding. As well as downforce considerations, the aerodynamic drag of an F1 car is an important feature. F1 cars often run extremely high levels of drag due to the highly aggressive aerodynamic devices on the car. In addition, it has been reported that the exposed rotating wheels of a grand prix car contribute between thirty-five and fifty percent of the overall drag of the vehicle (Dominy [1]). Whilst it may

appear that downforce is more significant than drag, reducing the drag has a practical application in F1 car design. By reducing the drag of components, which do not produce useful vertical load, such as the wheels, devices such as the rear wing can become even more aggressive in order to produce more downforce for the same target drag penalty.

Aside from the forces at work, the flow structures of an F1 front wheel assembly are extremely complex. Fackrell and Harvey [2,3] and in more detail in Fackrell [4], performed the first significant comprehensive aerodynamic study of an exposed race car wheel in isolation. Their work showed the characteristic positive lift generated by a wheel and also showed that when rotating, both the lift and drag of the wheel are reduced due to the forward movement of the upper

separation point. Because of this sensitivity, it is clear that the wheels of a grand prix car have significant contributions to the overall aerodynamic performance of the car.

A significant proportion of the downforce of an F1 car is produced under the large flat floor in close proximity to the ground. Regulations of the sport, which are also responsible for the exposed wheel nature of the formula, heavily restrict the size and location of the floor. The leading edge, in particular, is an area in which a large proportion of downforce is developed and this propagates down to the rear of the car where the expansion from the diffuser encourages further load. Because the leading edge of the floor is in close proximity to the downstream wake of the front wheel assembly, its performance can be enhanced or hindered by subtle changes to the front wheel wake.

Measuring the lift of a rotating wheel is a complex and contentious procedure. It is not considered reliable due to the varying reaction force with the ground as separating the mechanical and aerodynamic forces of any experiment becomes problematic in this situation. Morelli [5] attempted to overcome this by breaking the contact of the wheel with the floor. In doing so, the results of his experiments showed significant changes to the flow-field. The force measurements showed negative lift from a rotating wheel. This was explained due to the gap under the wheel causing acceleration and therefore low pressure pulling the wheel down. Stapleford and Carr [6] performed the same experiment with a sealed gap using strips of paper with much more conventional positive lift and drag results.

Saddlington et al. [7] combined published work of the flow-field combined with their own LDA measurements to produce a comprehensive description of the downstream flow-field. Their description comprises two large counter-rotating vortices generated by large central downwash and two upper counter-rotating vortices generated from the tyre's shoulder. Knowles' conclusion from this work was that the sidewall of the tyre formed these features. Fackrell and Harvey's work, as above [2], showed the sidewall profile as well as the aspect ratio have significant effects on the aerodynamic characteristics of the wheel.

Mears et al. [8, 9, 10] showed the forces at work on a rotating wheel by using a radio telemetry system. By measuring the static pressure distribution at several points on the tread in different rotational positions, they confirmed the previous studies of exposed wheel aerodynamics as well as showing experimental proof of Fackrell's 'jetting' phenomenon. Jetting is the process of air being squeezed out of the frontal contact patch and is responsible for an area of low pressure around the contact patch. This effect is sometimes referred to as 'tyre squirt' and can be a detrimental contribution to the delicate F1 aerodynamic system. More detail on this can be found in Mears [11].

Sprot et al. [12] showed for a front wheel assembly including brake cooling ducts, higher levels of through-hub flow were of a significant drag benefit due to preventing the dominant low hub-flow related spillage drag. This also had

the benefit of moving the dominant counter-rotating vortices toward the outboard of the car. This prevents the inboard feature impacting upon the sensitive floor area as well as the sidepods and cooling ducts. The counter-rotating features downstream of the wheel can also assist the floor pressure distribution. Under normal circumstances, the low pressure under the floor results in an inwash from the low quality (low stagnation pressure) air in the tyre's wake. This is not good for diffuser performance and also means that this particular mass-flow is only acting on part of the floor. By sealing the outside of the floor, or providing outwash at the floor level, this encourages much higher energy flow to enter from the front of the floor and therefore act upon the whole surface of the floor, giving more load and more diffuser potential. The inboard vortex of an isolated wheel, as described by Saddlington et al. [7] would provide the opposite, detrimental inwash. Moving the whole structure outboard or disturbing the inboard feature entirely, whilst minimising stagnation pressure losses is something aerodynamicists strive to achieve.

F1 tyres have characteristically high sidewalls. Due to this, it is often the case that these are considered as part of the suspension geometry. Because of vortex features, the jetting phenomenon, through-hub flow and wake-breathing, the shape of the tyre is significant to its aerodynamic performance. As an F1 car drives at varying speeds, it generates varying levels of downforce. For example, higher speed corners will provide more compression of the suspension springs and the sidewall whereas lower speed corners will provide relatively little deflection. There is also the question of steering angle and slip in the system. Due to these parameters, the sidewall and contact patch of a tyre changes significantly many times per lap. This provides another element of unpredictability to the already complicated flow structure.

Traditionally, scale wind tunnel tests are performed with rigid tyres with a fixed sidewall shape. Only three known studies are reported to include an element of deformation in race car wheels. These were by Purvis [13], Axerio et al. [14] and Mears [11], as above. However, the latter case used a pneumatic tyre but it was treated as rigid with a high inflation pressure and negligible vertical load. Pneumatic tyres are also used in full scale testing but there is a significant lack of published work on the characteristics of setup parameters such as vertical load or tyre pressure. The advantages of using a deformable tyre include the ability to have a full and consistent contact patch as opposed to contact line, hence more suitable to a real world simulation. A tyre under load also creates a sidewall bulge and the effect of camber can be effectively modelled without making the wheel conical. Purvis' wheel only considered the former point by having a tread made from deformable foam. Despite this, an important conclusion was achieved which showed that the width of the wake changes linearly with the width of the contact patch. Therefore it is more desirable to perform flow-field studies

on a fully deformable tyre as intricacies can be identified which would be otherwise overlooked.

The work of Axerio et al. comprised a comparison of Particle Image Velocimetry (PIV) techniques against two Computational Fluid Dynamics (CFD) methodologies. This work concluded by illustrating how the wake structure of the wheel, particularly the vortex centres of the two lower lobes, oscillate in time. To this date, there has not been a reported study describing the subtleties of deformable tyre flow structures. In order to use these as a tool for aerodynamic development, their performance and characteristics should be fully understood in isolation.

EXPERIMENTAL CONFIGURATION AND TECHNIQUES

WIND TUNNEL CONFIGURATION

The Durham University 2m² open-jet open-return wind tunnel (as reported by Sims-Williams et al. [15, 16]) was used in this investigation. The wheel model being used generated an average jet blockage (average due to the deformable nature of the tyre changing the projected frontal area) of 3.4% including the sting arm and brake scoop and the tests were performed at a Reynolds number (based upon wheel diameter) of $Re = 4.80 \times 10^5$ (in the supercritical regime, the importance of operating in this region was emphasised by Fackrell [4]). The tests were performed with a moving ground plane synchronised with the free stream. These configurations are consistent with accepted values for accurate wind tunnel testing of a rotating, exposed wheel.

THE DEFORMABLE TYRE

A fully deformable pneumatic tyre designed specifically for wind tunnel operation was used in this experiment. The tyre was typical of those used by the teams for wind tunnel testing during a recent F1 season. It was 50% scale with an aspect ratio of 0.53 (based on tyre diameter and maximum width) compliant with the current regulations of the sport. The sidewall construction had been carefully designed by the manufacturer in order to match the exact deformations seen on-track under varying loads.

There are many parameters that can be used to set deformation on a pneumatic tyre. Vertical load, tyre pressure and axle height are all valid variables. In this case, axle height was used as the primary control variable as this was considered the most repeatable condition. A set of axle heights was chosen to match F1 cars under straight-line conditions over a range of speeds from slow corner exits up to end-of-straight conditions. These can be seen in [Table 1](#). Essentially the axle heights correspond to a linear deflection with force due to the spring approximation of the tyre sidewall combined with the velocity-squared characteristic of downforce.

Table 1. Axle height conditions used to simulate varying deformation levels.

Vehicle Speed (kph)	Mid-Rim Axle Height (mm – Model Scale)
80	159.0
120	158.0
180	155.9
250	153.3
310	150.0

The axle heights in [Table 1](#) were set using a Baumer laser distance sensor placed on the support sting as a reference. Before testing could begin, particularly for PIV measurements, the tyre had to be balanced to a high precision. This was achieved by utilising the inbuilt load-cell normally used for drag measurements. By synchronising an optical sensor to provide a datum point with the force trace from the load-cell it was possible to see where the mass offset was on the tyre and hence where mass could be added to balance the wheel. This allowed, among other benefits, for perfectly stable PIV images to be taken while an inadequately balanced wheel would produce wheel geometry movements between image pairs that would corrupt near-wheel measurements.

APPLICATION OF DEFORMATION

The tyre required some form of vertical load in order to deflect and deform to the correct contact patch shape. It is very difficult to apply a large vertical force in a wind tunnel environment without damaging either the tyre or the belt for the moving ground plane. This usually results in a compromise in tyre pressure and axle height in order to minimise the vertical force. It could be argued that, if the tyre axle height and pressure are incorrect then an incorrect tyre profile and contact patch are being simulated which could be as bad as not simulating deformation at all. The philosophy of this experiment was to test beyond these usual compromises to obtain a detailed relationship between vertical load, tyre pressure and aerodynamic performance. Three tyre pressures were tested for this investigation. These were 0.5psi (3.4kPa), 2.0psi (13.8kPa) and 3.0psi (20.7kPa).

Deformation was applied by setting the tyre inflation pressure and axle height through the use of a 'wheels off' sting mounted to the inboard side of the wheel. This was extended beyond its pivot point and placed on the tip of a pneumatic cylinder mounted to the floor of the tunnel. See [Figure 1](#) for the experimental layout. [Table 2](#) shows the range of conditions tested and also displays the axle rise due to the centripetal reaction force caused through wheel rotation. The latter was taken into account when the wheel height was defined, as the axle height would change by up to 3.3mm depending on the level of vertical load. The measured air pressure at the pneumatic cylinder determined the vertical load. These values are therefore a maximum theoretical load

value and are intended as a reference to relative forces required for differing levels of deformation. Typically, F1 wind tunnel tests of deformable tyres do not exceed the order of 50-100N by using the rim's weight alone as the method of applying vertical load. As the table shows, this only approaches the slow-medium cornering speed conditions outlined in [Table 1](#).

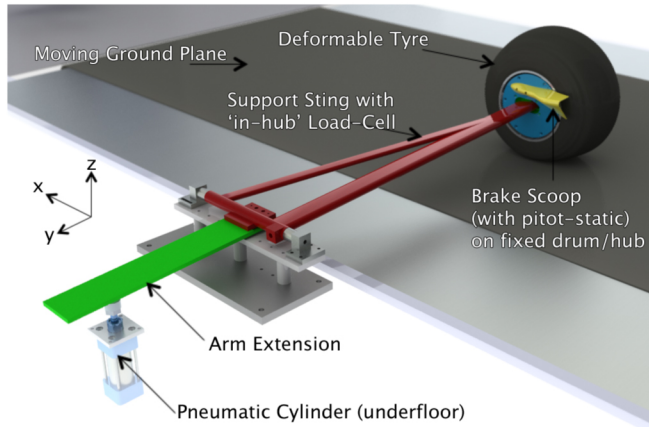


Figure 1. The experimental layout of the deformation rig in the wind tunnel.

Table 2. Vertical loads applied to meet the 50% scale axle height conditions (including centripetal axle rise).

Tyre Pressure [psi,(kPa)]	Rotating Height (mm)	Nominal Vertical Load (N)	Rotational Axle Rise (mm)
0.5, (3.4)	159	46	2.8
	156	127	2.1
	153	191	3.3
	150	240	2.9
2.0, (13.8)	159	127	1.6
	155	191	1.5
	153	240	2.0
	150	280	2.0
3.0, (20.7)	159	175	1.7
	155	240	1.8
	153	289	1.8
	150	334	2.6

The wheel was run at a typical on-track camber angle of between 3.20° and 3.45° depending on deformation levels. This is known to be a significant change from a mechanical perspective but since there is no published work on the aerodynamic effect of camber on a wheel using a deformable tyre, the significance of this cannot be quantified. The most likely significance of changing camber angles will be due to the reduction in contact patch size, emphasising inboard tread contact. This will allow air to pass underneath the tread on the outboard side for low levels of deformation (slow-speed corners) generating a similar effect to that measured by

Morelli [5]. In terms of geometry changes, the deformation level and axle height will dominate this so it can be assumed that this small change in camber angle is negligible for this study.

CONTACT PATCH MEASUREMENTS

The size and shape of the contact patch of a rotating tyre are both very difficult measurements to take. As already presented, the sidewall of the tyre stretches and straightens as the wheel rotates leading to an axle height rise. This effect causes a change in sidewall shape that in turn creates a change in contact patch size. For this experiment, static measurements of the contact patch were made with axle heights set to match those of the rotating condition. By placing a transferrable ink cross on the tread of the tyre and then placing it on a piece of paper before applying the deformation, an imprint of the contact patch length and width was measured. This method did not achieve the exact contact patch shape (which is non-rectangular and assumed elliptical for area calculations) but did give useful information relating to the proportion of the tyre's width which is sealed and that which allows low-pressure air to pass underneath.

SIDEWALL PROFILE MEASUREMENTS

As the focus of this paper is on the behaviour and performance of a deformable tyre, a significant proportion of the research effort was on measuring quantitatively the subtleties of the sidewall profiles. A Baumer laser sensor was used in this process. It was calibrated against a highly reflective surface at varying distances over its 30-130mm range. The calibration was then checked with the dull matt black curved surface of the sidewall of the tyre when stationary. It was found that the average delta of the sensor on the angled and curved matt black surface relative to the highly reflective perpendicular surface was 0.8mm. This was on top of the inherent 0.3mm laser repeatability from the reflective surface test. The above delta was taken for a static section of the sidewall and due to the characteristic hysteresis of a deformable tyre, this delta is smaller than typical circumferential changes in the shape of the tyre as it rotates.

In order for the tyre to be measured in a controlled manner whilst rotating, the three-axis wind tunnel probe traverse system was used. By mounting the laser distance sensor to the end of the sting, which normally holds a five-hole pressure-probe, the laser could be traversed around the tyre in order to measure the profile. [Figure 2](#) shows the details of this setup. In order to eliminate vibrations and other discrepancies in the measurement technique, a second laser was placed on the same mount, which measured a flat plate mounted firmly to the inboard side of the hub. This reference was subtracted from the first laser measurement in order to account for any movements of the whole wheel assembly relative to the measurement tip.

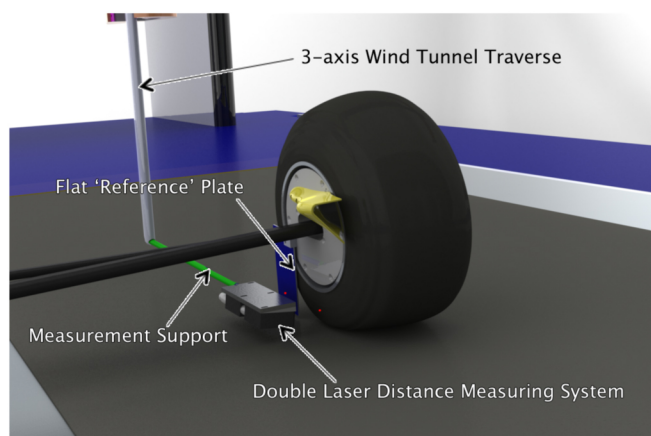


Figure 2. The sidewall profile measurement technique utilising two laser distance sensors and the wind tunnel three-axis traverse.

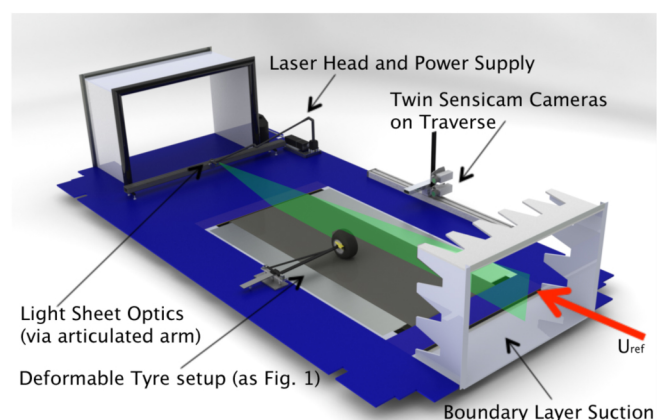


Figure 3. The PIV experimental layout.

5-HOLE PRESSURE-PROBE MEASUREMENTS

As well as traversing a laser distance-measuring device around the wheel, the wind tunnel's three-axis traverse system was used for pressure-probe measurements in the downstream wake. Based upon an average wheel diameter of 0.32m, the planes measured were 0.5D, 1.0D, 1.5D and 2.0D from the axle in the crossplane orientation (y-z plane). The probe used was one of Durham University's in-house designed five-hole probes manufactured with a rapid prototyping machine. The probe was independently calibrated at velocities typically observed in the downstream wake of a tyre. The angular resolution of the probe was $\pm 50^\circ$ in both pitch and yaw. Although the probe is capable of measuring turbulence levels, it was used as a steady-state probe to obtain the average flow-field for comparison with other test conditions.

PARTICLE IMAGE VELOCIMETRY (PIV)

In order to measure the subtler flow physics such as recirculation and in order to interrogate regions that would be out of range for the above probe, PIV was used. A 120mJ dual head pulsed Nd:YAG system with twin high-resolution Sensicam cameras was used. Figure 3 shows the layout in detail. The laser beam was delivered to the test section via an articulated arm and was placed in the flow far downstream of the model (2.5m from the furthest rear part of the model). A longitudinal orientation was applied (x-z plane) in order to view the regions of the flow related to jetting and upper surface separation. Only the valid vectors from the two hundred image pairs per configuration were averaged to produce the vector fields presented in this paper.

The two cameras were placed one above the other and both synchronised to allow a 340mm total image height (1.1D) to be achieved. They were traversed downstream to allow multiple positions to be stitched together in order to provide the overall field. Each pulse was separated by 20 μ s which allowed a good separation of particles between images but short enough to prevent signal drop-out between image pairs. The flow was seeded using DEHS oil distributed via a compressed air fed ILATEC 40 nozzle seeder, which produces particle sizes of the order of 1 μ m. These particles were subsequently distributed into the air stream via a purpose built smoke delivery rake mounted upstream of the nozzle contraction of the wind tunnel.

DRAW MEASUREMENTS

As well as the above flow-field measurements, conventional load-cell measurements were made in order to measure the aerodynamic force contributions to the wheel. The load-cell was located inside the hub as mentioned in Figure 1.

Traditionally, a low-speed tare is subtracted from rotating wheel measurements in order to extract the aerodynamic forces. This is justified by a constant bearing drag. As the speed of the wheel increases, the rotation of the wheel induces airflow over and through the wheel. This is characterised by a velocity-squared relationship becoming apparent at the upper velocities. Figure 4 displays the wind-off rolling drag measurements for a mid-range deformation level (155mm axle height) with tyre pressure of 2.0psi (13.8kPa). This displays an always-increasing level of drag likely due to the rolling resistance of the deformable rubber. A slight velocity-squared relationship is apparent at the very top of the scale. Due to this variation, it was decided to use a full speed wind-off tare to obtain the most reliable aerodynamic forces. Due to this, the forces presented are likely to be slight underestimates of the absolute aerodynamic forces. It has been suggested that the velocity-squared relationship present at the higher velocities may be due to secondary rolling resistance effects of the tyre, however the