The State-Of-Art Aerodynamic Designs On The Open Wheel Race Cars

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Abstract. The F1 race car industry is forever innovating and overcoming difficulties as there are so many variables and uncertainties on an object moving at over 360kpm. This paper will discuss the different designs' effectiveness and variables that affect the performance of such designs. Computational Fluid Dynamics (CFD) simulations will be examined, along with physical tests to achieve the best results, and to form an accurate conclusion. The paper concluded the relationship between proximity to ground, wing incidence with downforce, including the cause of force reduction phenomenon. Individual study and interactions of front wing and wheel is also discussed with several CFD figures. Overall, these results shed light on guiding further exploration of aerodynamic design for open wheel race cars.

Keywords: Aerodynamics, F1, open wheel, ground effect, downforce, drag, vortices, wake, CFD.

1. Introduction

With 20 Grand Prix hosted every year across the globe, F1 is no doubt one of the most popular sports in the world. Not only popular but they are also one of the most expensive sports due to their innovative nature, costing over $450 million per year to maintain a F1 team. Being one of the most technological advanced pieces of gear, F1 cars are able to accelerate from 0 to 100kpm in merely 2.6 seconds, reaching a top speed of over 372.6kpm [1]. In order to achieve and maintain this incredible speed, the secrets lie in the different aerodynamics designs of it.

Specifically, the downforce creation, drag reduction and vortex management relies on the aerodynamic designs. According to the computational simulation of a F1 race car by Ravelli and Savini, the front and the rear wing contributes to a total of 53.8% and the underbody creates 44.5% of the total downforce [2]. Although downforce is beneficial, the cost it comes with is the immense drag and induced drag it produces, to combat this, engineers had often sacrifice one in pursuit of the other. Knapik, et al. have done an in-depth simulations and comparisons of multiple shapes of the front wing, where the paper concluded that Eppler E420 front wing was the most efficient in regard to maximizing downforce and minimizing drag [3]. Zhou also made a rather unique shape in an attempt to optimize lift to drag ratio, but on the rear wing foil design, to maximize lift to drag ratio at 62 [4]. It is all in a straight track however, center of pressure is crucial when cornering [5]. In an ideal situation, center of gravity should be at the same region as center of pressure. On this basis, if more downforce is created in the front, it will cause oversteer, and understeer if excessive at the back. In situations of an overtake, the car behind will suffer from "dirty air" which is turbulent air as a result of the preceding car, leading to loss of downforce [6]. Guerrero and Castilla used Computational Fluid Dynamics (CFD) and found that the following car experiences a low kinetic energy wake region produced by the preceding car, at about 0 to 10 m/s. As a result, a crucial aerodynamic device, the diffuser's performance is reduced by a maximum of 70%, and the overall aerodynamic load varies from 23% to 62%, depending on the proximity to the preceding car.

In races, the FIA (Fédération Internationale de l'Automobile) set rules of dimensions, weight, and other aspects for a safe and fair competition. Consequently, engineers are always changing up the designs of the car, two of the major competitors Ferrari and Mercedes in a race for the championship title in 2019 had opposite designs of front wing, "outboard-loaded" and "inboard-loaded" each with a different theory to help the lap time of their cars [7].

This paper will introduce the concept of downforce, highlighting its importance to the performance of a F1 vehicle. The rest part of the paper is organized as follows. The Sec. 3 will discuss the relationship between proximity to ground. Subsequently, the Sec. 3 will discuss the different factors associated with the designs of inverted wings of downforce in the front wing. Afterwards, the Sec. 4 discusses the significance of wheel in both drag and ground effect. Following that, the Sec. 4 talks about the wing and wheel as one system, and how they interact aerodynamically with each other. Sec. 5 will discuss the shortcomings, future outlook, and further study. Eventually, the Sec. 7 will conclude all the information presented in the paper.

2. Downforce

Engineers of F1 cars aim to achieve the highest speed possible during straight paths and turns. However, at top speed on a straight path, F1 can create enough lift to take off. On this basis, engineers make use of multiple designs, e.g., inverted wings, diffusers, and the wheels to create downforce. Downforce is negative lift, which maintains the wheels intact with the ground, unlocking higher speeds. F1 cars are able to generate 750kg of downforce, this allows light modern F1 cars to have enough downforce to drive upside down on the ceiling. Though seems ideal, it comes with the consequence of drag, which is unavoidable with the creation of downforce. As a consequence, finding the right balance between speed and downforce is crucial. Capable of speeds over 300kpm, any flaws in the aerodynamic design will be exaggerated, like the Mercedes CLR in 1999, owing to a large rear overhang, not providing enough downforce to counteract the lift in the front, especially that it was suffering from the "dirty air" or low-pressure zone due to the preceding car. Thus, it caused a catastrophic flip. Apparently, the significance of downforce in racing scenarios, if not executed perfectly, events as such might occur. An equation defining downforce can be written as:

$$D = \frac{1}{2} W c C_L \rho v^2 \tag{1}$$

where D is downforce, W is wingspan, c is wing chord C_L is lift coefficient, ρ is air density, and v is velocity.

3. Inverted Wing Design

3.1. Proximity To Ground

Zerihan designed an experiment on the effect of downforce produced by a single element wing using a wind tunnel [8]. The wing was a scale (80%) model of the 1998 Tyrrell 026 F1 car rear wing with 223.4mm Wing Chord, paired with a generic endplate with dimension of 250×100×4mm, enabling the wing to be tested at proximity to the ground.

The test results from Zerihan have revealed an inverse relationship between the Lift Coefficient C_L and proximity to ground shown in Figure 1. It could be explained by the fact that the ground acts as a barrier, forcing air through a smaller cross-sectional area below the wing, accelerating the flow, thereby lowering the pressure, to help with further downforce. The maximum lift coefficient of 1.72 was achieved at the distance of 0.082c from ground. As expected, there is an inverse relationship between height and downforce created, but a phenomenon called force reduction occurs after the downforce reaches its maximum, i.e., the downforce decreases as the wing gets closer to the ground.

An earlier study conducted by Ranzenback and Barlow concluded that the force reduction phenomena is attributed to the boundary layers of the suction surface of the wing and ground merging ascribed to being too close to the ground. The explanation was that the existence of the boundary layers hindered flow between the wing and the ground, thus increasing the pressure, causing a decrease in the downforce produced. Nevertheless, Zerihan suggests that flows are less able to accelerate bi this means on account of excessive separation of the boundary layers instead of boundary layers merging, thereby lowering velocity, decreasing downforce.

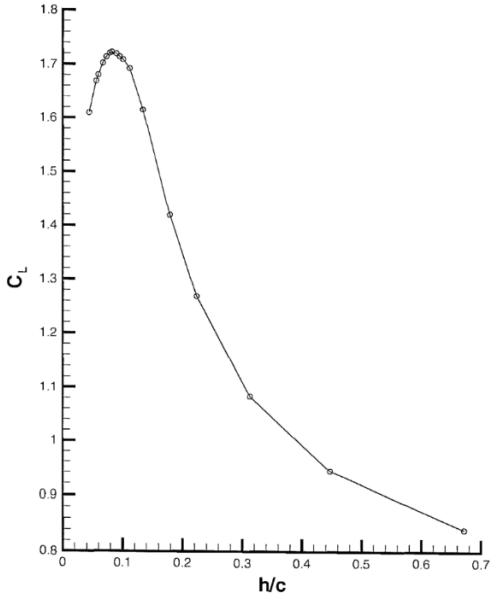


Figure 1. Relationship between Lift Coefficient and proximity to ground [8].

3.2. Angles of Incidence:

Angle of incidence of the wing has a positive relationship with the lift coefficient. The main takeaway from this is that the angle of incidence affects the sensitivity of the lift coefficient. Between 0.134c to 0.179c, the slope at 1° is 4.3 and at 3° it is 2.9. The same trend can be seen on the rest. Additionally, the peak at which the wing reaches maximum downforce is shifted left as the angle of incidence decrease. It is noted that due to physical limitations of the endplate design, at angles of -3° and -1°, force reduction phenomenon cannot be observed.

Reviewing the new theory of force reduction, the force reduction phenomena can be explained as a stall similar to an airplane. The incidence is too high and velocity being too low, causing separation of flow and vortexes at the trailing edge, ultimately decreases lift. These further concretes the theory as it is consistent with conventional wings, suggested by Diasinos. In this casem one can conclude that the angle of incidence of an inverted wing has an inverse relationship with stalling height and the angle of incidence has a positive relationship with maximum downforce

1) Angle of incidence has an inverse relationship with stalling height
2) Angle of incidence has a positive relationship with maximum downforce

4. The effect of wheels on ground effect production:

The wheels while not a component designed to improve the aerodynamic performance of a car, but for open wheel cars especially, where mostly the two front wheels will be encountered with headwind, and according to Zhang, it contributes to as much as 40% of the total drag of those cars.

4.1. Vortices

Vortices can have advantageous effect in which it prevents boundary layer separation by pulling separated layers back into the air foil, or the vortices are able to redirect the wheel wake from the front tire out of the bodywork of the car. On the other hand, it can increase the induced drag of the car which is a form of drag produced due to the difference in pressure in the front and rear end of the body.

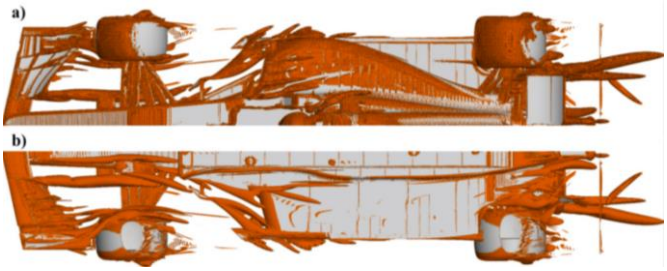


Figure 2. An iso-contour display of F1 (a) top view (b) bottom view [2].

In Figure 2, an iso-contour display is shown from different perspectives of the F1, wakes can be observed at the wheels, and vortices created by multiple components. It shows vortexes generated by the front wing, wing tip vortex generated from the rear wing, two counter rotating vortices generated from the bargeboard, and a vortex developed at the diffuser.

To investigate the wake development further, Diasinos setup an experiment to verify the reason in wake development at different regions of the wheel when stationery and rotating. Diasinos replaced the ground with a slip condition to prevent boundary layer to occur and used simulation to observe the top and bottom potion of the wheel separately. It was found that in a non-rotating wheel, the wide vortices would form in a lower region on the wheel, while for a rotating wheel, narrow vortices would form in the centre and above the wheel. The separation point is moved more to the front as the wheel rotates faster simply due to the wheel rotating against the direction of flow. Because of the separation point being more forward, there are less flow following the top potion of the wheel, the flow goes to the sides of the wheel, consequently losing downwash in the wake. Thereby, it explains the reason that the position of the wake is higher and more central, and why stationary wheels have wider and lower wake. A useful relationship has also been found shown in Figure 3, as the separation point on the tyre increases in height, drag and lift decreases subsequently.

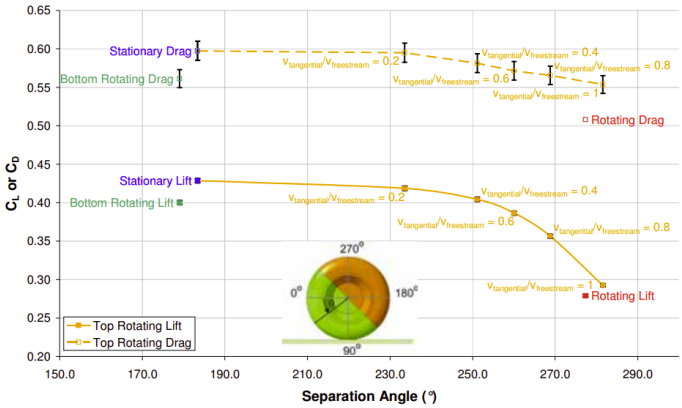


Figure 3. Relationship between the angle where the separation occurs and the lift with the drag [9].

5. Wing And Wheel as A System

The previous discussion was focused on isolated aerodynamic components of an open wheel race car, but in reality, they do not work in isolation, the combination of bodies will cause uncertainties and other effects (e.g., vortices, dirty air). In order to investigate the interactions of the wheels and the wing, 3 different scenarios are developed to be investigated. The first where both wing vortices travelling outboard of wheel, the second where Main wing vortex travelling inboard while secondary vortex travels outboard of wheel, and the third where both wing cortices travelling inboard of wheel

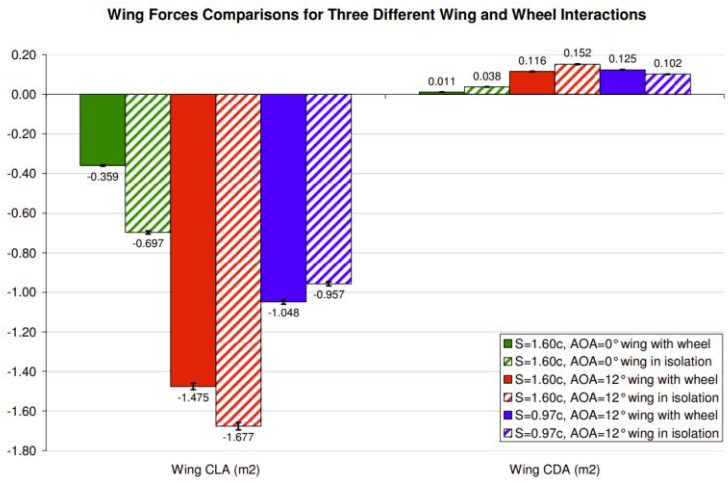


Figure 4. Downforce and downforce variations between the 3 scenarios

Seen from Figure 4, in the first scenario with 1.6c and incidence of 0, there is a decrease in downforce when in combination of the components from -0.687 to -0.359 and a decrease in the drag from 0.038 to 0.011. The second scenario with the same setup as scenario 1 but with incidence of 12, there is also a decrease in downforce when in combination of the components from -1.677 to -1.475 and a decrease in the drag from 0.152 to 0.116. Lastly, the third scenario, with 0.97c and incidence of 12, there is an increase in downforce when in combination of the components from -0.957 to –1.048 and a decrease in the drag from 0.102 to 0.125.

To expand on this aspect, Martins, Correia, and Silva conducted a CFD simulation to observe the changes in the vortices formed by the front wing and wake from the front wheels at different cross-sections of the car by altering second flap angle of attack [10]. The model of which is replicated from a prototype by the FIA for the new regulations of 2022. It is said that the new regulations will allow narrower wakes to ease overtaking. As shown in the left panel of Figure 5, at z = -0.8, no vortex breakdown was observed. At z = -0.9 lower edge vortex breakdowns below the wing were observed, creating a recirculation zone, this separation of flow from the body also creates a higher amount of drag than if it was attached to the body. A vortex that suffers from breakdown also cannot serve the purpose of containing and redirecting the wheel wake since the vortex's energy is too low. Regarding the wheel wake, at plane z = -2.1 at 30° and 32° of the second flap, the wake shape and characteristics were similar, however, at 34°, a wider and shorter wake was formed illustrated in the right panel of Figure 5 (blue area means low energy flow, red area means high energy flow). It also indicated that large amount of energy was lost, this was largely due to increase downwash in the central region of the front wheels, thus more drag was produced. When analyzing the forces on the front wing, high drag force fluctuations was observed, which due to the proximity to the vortex breakdown, to minimize that, the best way is to reduce the low-pressure wake's size.

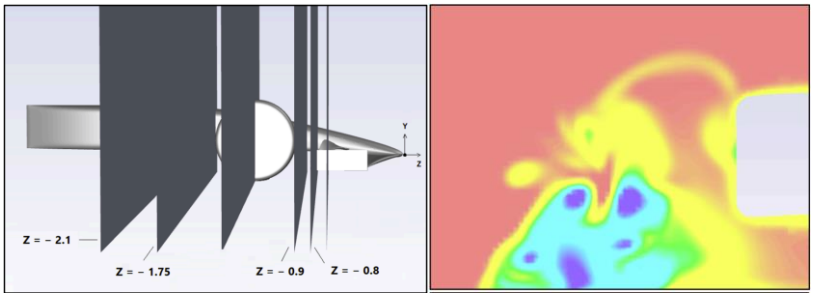


Figure 5. Four CFD Model Cross-Sections That Was Analyzed (left panel) and Total Pressure Coefficient Plot at z = -2.1 and 34° (right panel).

6. Gaps and Future outlooks

One of the most difficult aspects of aerodynamics of components is testing out theory experimentally and obtaining reliable results. Previous predictions and estimations from Zhang and Zerihan about positions of vortices of wheels were proven wrong with computational modeling, but there still remains necessities for it to be proven experimentally. Diasinos was only able to isolate variables and gain a theory of vortices formed by a wheel using an unorthodox way of separating the top and bottom portions, it will be difficult to prove experimentally using conventional methods like wind tunnel testing.

The majority of papers published are focused on an isolated component. Nevertheless, as discussed above, the results of components combined deviates significantly from results of an isolated component. Besides, vortices and wake development can change characteristics of certain aerodynamic designs which should be considered for future research. The paper only touched on a few of the many aerodynamic designs on a modern F1 race car, designs (e.g., diffusers, bargeboard, cockpit optimization) also acts as a crucial part in maximizing downforce and minimizing drag. Additionally, limitations on CFDs should be considered, it does not replicate real life perfectly. With this in mind researches testing for errors of real life F1 race cars and simulations will be very valuable for more accurate results.

7. Conclusions

In summary, this paper discusses the state-of-art applications designs on the open wheel race cars in terms of aerodynamic principles. Specifically, the significance of downforce, along with the theories and different factors are analyzed including proximity to ground, angle of incidence is taken into consideration on the effect of inverted wings in producing the ground effect. Several relevant experimental and computational produced data are presented to support theories given. The focus then shifts to how wheels, specifically the vortices and wake it produces affect the overall performance of the race car, as well as the effect of having the two components interacting with one another in difference scenarios and designs. This paper hopes to give insight on aerodynamic designs of an open wheel race car and encourage research on multi-component interactions on open wheel race cars. Overall, these results offer a guideline for future research on the topic and phenomenon and interactions on aerodynamic bodies at a high velocity.

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