Experimental Analysis of Formula 1 Cars Moving Under Wake Conditions

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Publication Date: 2025/07/21

Abstract: The aerodynamic wake effect in Formula 1 continues to be a critical barrier to close racing and overtaking, particularly through corners. Despite years of regulatory developments, the aerodynamic turbulence generated by a leading car still severely compromises the downforce and performance of a following car. While this phenomenon is widely acknowledged in the motorsport community, experimental data that quantifies the loss of aerodynamic performance under wake conditions remains limited, especially at small scale. This study aims to analyze and quantify the downforce loss experienced by a Formula 1 car due to wake turbulence using a cost-efficient, scaled wind tunnel setup. An official 1:18 scale diecast model of a 2021 F1 car was mounted on a load cell within a custom-built wind tunnel, and raw downforce values were measured under clean air conditions and various wake conditions simulated using upstream obstructions. The experimental setup focused on within-subject comparisons, varying the distance and lateral offset between the test model and the simulated wake source. Findings revealed a maximum downforce loss of approximately 53% at 5 cm behind the obstruction with no lateral offset, with recovery observed at increased distances and small offsets. These results affirm the hypothesis that wake turbulence significantly affects aerodynamic performance and provide a tangible demonstration of how proximity and alignment influence downforce retention. By offering a simplified, replicable approach to studying wake effects, this research contributes valuable experimental insight into a widely discussed yet under-tested aerodynamic challenge in Formula 1 racing.

Keywords: *Wake Turbulence, Formula 1 Aerodynamics, Downforce Loss.*

How to Cite: Neev Menon (2025) Experimental Analysis of Formula 1 Cars Moving Under Wake Conditions. *International Journal of Innovative Science and Research Technology*, 10(7), 1357-1362.
https://doi.org/10.38124/ijisrt/25jul932

I. INTRODUCTION

Formula One was, and always will be, one of the fastest and gruelling motorsports in the world. With cars touching speeds of 330 km/h on straights, the aerodynamic study of these cars remains the most crucial aspect of Formula One.

The biggest issue faced by F1 teams for many years has been the wake effect experienced when one car follows another closely, especially in corners. By definition, wake effect is the way in which a vehicle disturbs the air it passes through, which heavily impacts the amount of downforce a following car can generate, in turn affecting its overtaking potential. Wake effect is commonly known as 'dirty air' or 'turbulent air'. It reduces the car's downforce while turning into corners, resulting in a loss of stability and balance. This makes it difficult for drivers to overtake. Throughout the years, the Federation Internationale de I'Automobile (FIA) has been introducing new regulations with the primary aim of reducing the downforce loss experienced by the cars while overtaking. Despite the efforts, wake effects still play a huge role in the difficulty of passing another car.

The main goal and contribution of this paper is to evaluate and approximately quantify the loss of downforce experienced due to wake, by comparing downforce values under free stream conditions and when following another car. The experiments have been performed in a scaled-down model of a wind tunnel, with the aim of replicating the on-track conditions as closely as possible.

II. MATERIALS AND METHODS

The purpose of this study was to investigate the aerodynamic behaviour of a Formula 1 car model under varying wake conditions, with a specific focus on the wake effect generated by an upstream object on downforce. A single 1:18 scale official diecast model of a 2021 Formula 1 car was tested in various aerodynamic conditions inside a closed wind tunnel as part of a within-subjects design experiment. This method allowed for a clear comparison of the aerodynamic effects of disturbed airflow versus clean air conditions because the same model, mounting platform, and measurement equipment were used for all test cases, ensuring consistency across trials.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25jul932

In order to replicate on-track conditions as closely as possible, the wind tunnel was specially designed and constructed. A rectangular steel frame with acrylic windows to monitor the airflow supported the entire structure, which included a diffuser, a transparent acrylic test section, and a contraction section. The contraction section helped accelerate the air uniformly using a flow straightener made of honeycomb mesh, while the diffuser slowed the airflow and stabilized it before exiting. Airflow was generated by a 'Digismart' 12-inch exhaust fan operating on a suction principle, mounted at the exit end of the tunnel. The test section—where all measurements were taken—was constructed from transparent acrylic for optimal visibility and access. It measured 30 cm × 30 cm in cross-section and housed the model car mounted on a steel platform placed above a single bar-type load cell. The load cell was fixed underneath the platform using screws and was configured to measure vertical forces exerted on the model (i.e., downforce) during wind-on and wind-off conditions.

An Arduino Uno microcontroller interfaced with a HX711 analogue-to-digital amplifier module, was electronically connected to the load cell. The HX711's data and clock lines were connected to digital pins on the Arduino, and the excitation and signal lines of the load cell were connected to the HX711's input terminals using jumper wires. A laptop running the Arduino IDE was connected to the Arduino via USB to power and monitor the Arduino. The load cell was not calibrated for this experiment; instead, raw output values from the HX711 module were recorded directly. These values, though not converted to Newtons, were used to calculate relative changes in downforce under different wake conditions. By recording the baseline raw value of downforce in clean air and comparing it to the raw value in the presence of a wake (created by placing another model car upstream of the F1 car), the percentage loss in downforce was calculated.

The experimental procedure involved first taring the load cell in the absence of any external airflow or force to establish a stable baseline. Once airflow was initiated via the fan, raw downforce values were recorded under "clean air" conditions with no upstream obstruction. The wake effect was then simulated by placing a car model at different distances (5 cm and 10 cm) and lateral offsets (0 cm and 2 cm) in front of the F1 car to represent a leading car's aerodynamic wake. After positioning the obstruction and allowing the airflow to stabilize, the new downforce readings were collected. All readings were taken through the Arduino serial monitor using an averaging function for better consistency and to reduce noise.

For data analysis, the raw downforce values under wake conditions were compared against the baseline clean air values. The primary metric computed was the percentage loss in downforce, calculated as the relative difference between the two conditions. Since the emphasis was on the comparative trend rather than on determining exact physical force values in Newtons, neither statistical software nor calibration constants were used. Instead of measuring precise aerodynamic coefficients, the research goal was to observe how turbulent airflow impacts aerodynamic load on a Formula 1 car model, and this approach was ideally suited to that goal. Although the quantitative precision is limited when using uncalibrated load cell readings, the accuracy of relative changes—which were the main focus—is unaffected. An additional limitation includes the use of a fixed pre-made model with no active components (such as DRS or adjustable wing angles). However, these were acceptable within the scope of a focused educational experiment and were addressed by maintaining strict consistency across all testing conditions.

Fig 1 Wind Tunnel Used in the Experiment

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25jul932

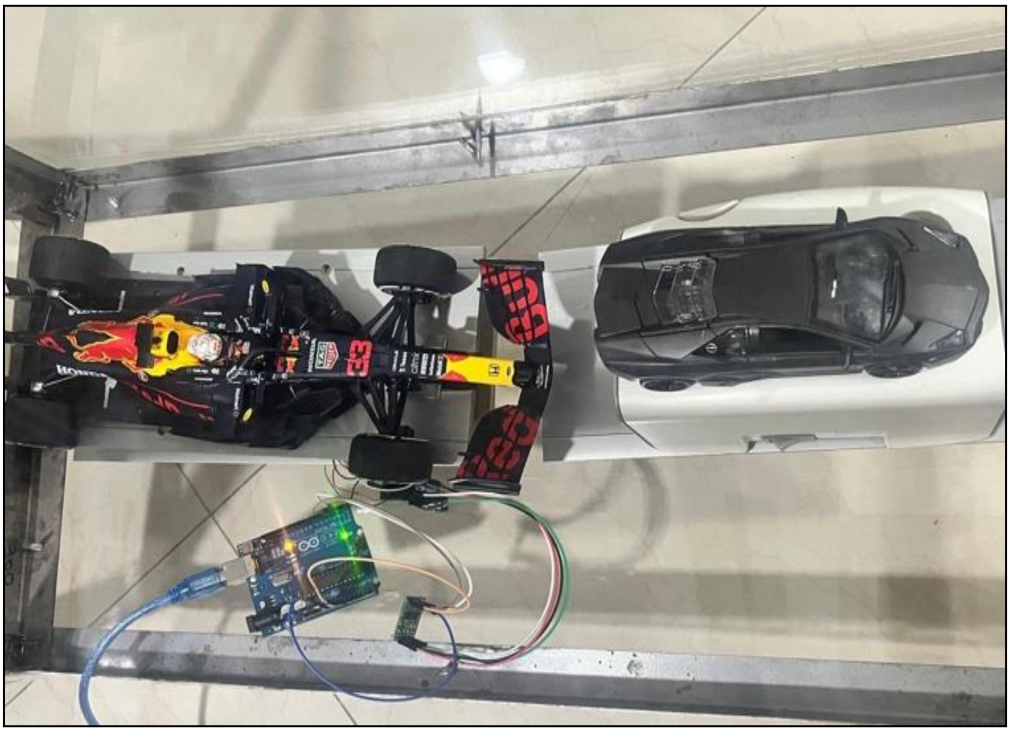

Fig 2 F1 Car Placed Behind Another Model Car to Demonstrate Wake

III. RESULTS

The aerodynamic performance of the scale model Formula 1 car was tested in the wind tunnel by keeping the rear wing angle constant and DRS flap closed. The downforce values in free stream conditions and under wake conditions were found and tabulated. The table below shows the downforce values and percentage loss of downforce in different wake conditions.

Table 1 Downforce Values Under Different Wake Conditions

Downforce Values Under Different Wake Conditions		
Wake Condition	**Downforce (Raw Value)**	**Downforce Loss (%)**
Clean Air	17047.3	0
5cm behind, 0cm offset	8013.9	52.99
5cm behind, 2cm offset	10194.2	40.2
10cm behind, 0 offset	13006.6	23.7

In clean air, the car generated 17047.3 raw units of downforce, which is the maximum downforce possible at the generated wind speed. When placed directly behind (i.e., at an offset of 0cm) another model car, the downforce sharply decreased by 52.99%, with the F1 car generating 8013.9 units of downforce. Introducing an offset of 2cm at the same distance reduced the downforce loss to 40.2%, increasing the downforce to 10194.2 units, thus improving aerodynamic performance. At a further distance of 10cm behind the leading car, the downforce value further increased to 13006.6 units, thus reducing the loss to just 23.7% of the original value.

The data clearly shows how pursuing another car leads to a notable loss in downforce, especially in corners. This supports the hypothesis that wake turbulence has a detrimental effect on the aerodynamic efficiency of a following car, and demonstrates that even small changes in position can have a significant impact on aerodynamic performance.

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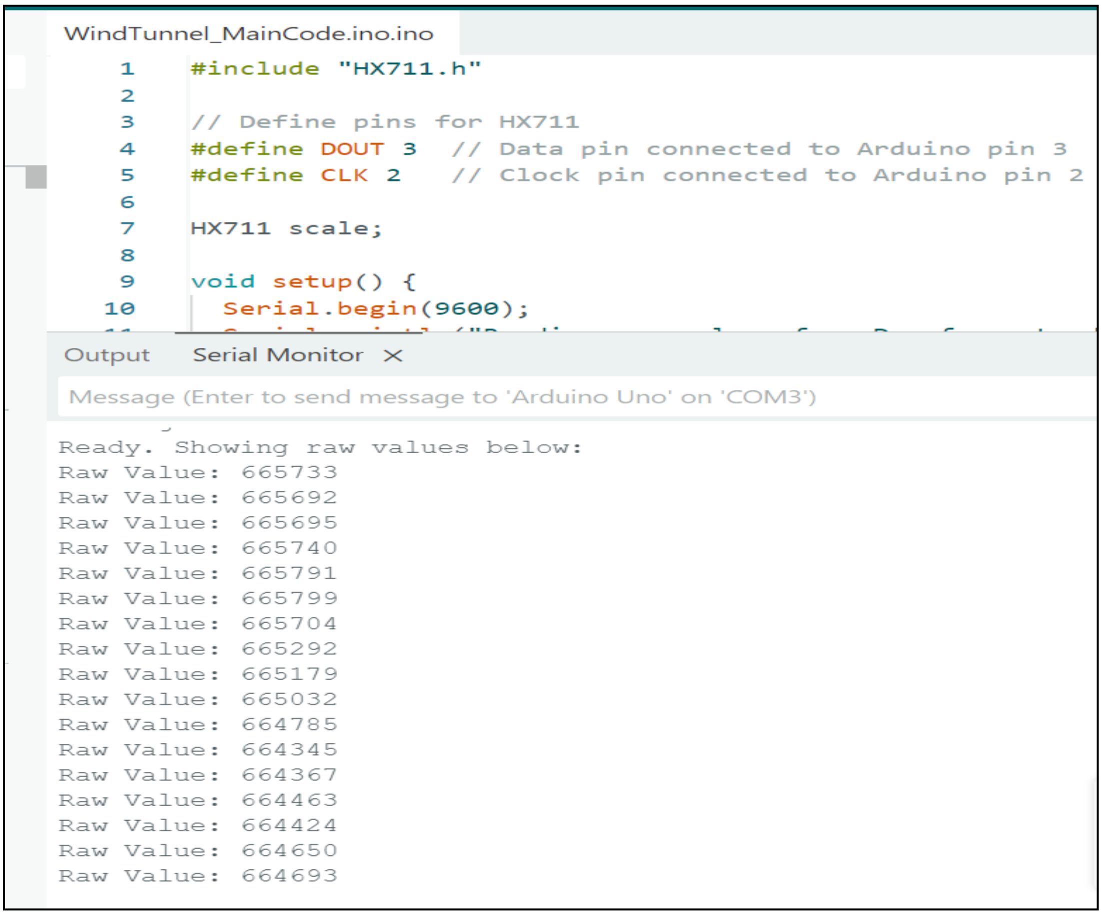

Fig 3 Some Raw Values Displayed on the Arduino IDE

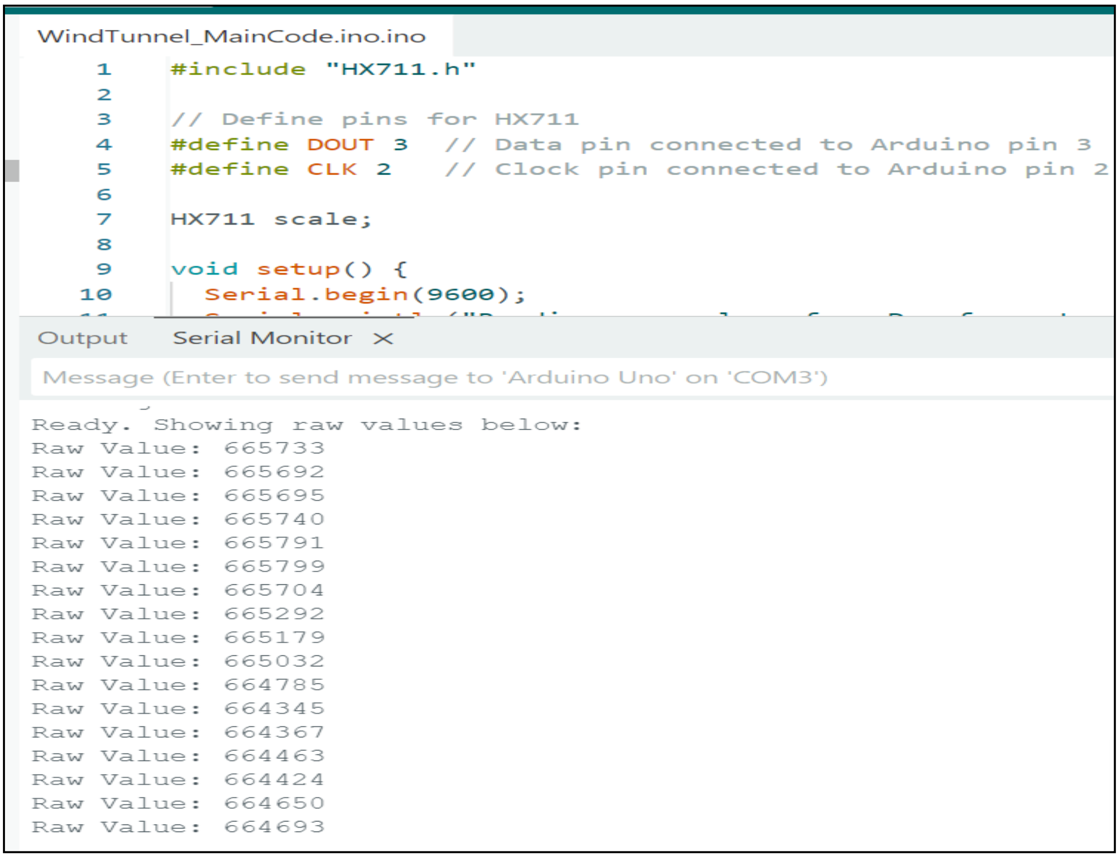

Fig 4 Some Raw Values Displayed on the Arduino IDE

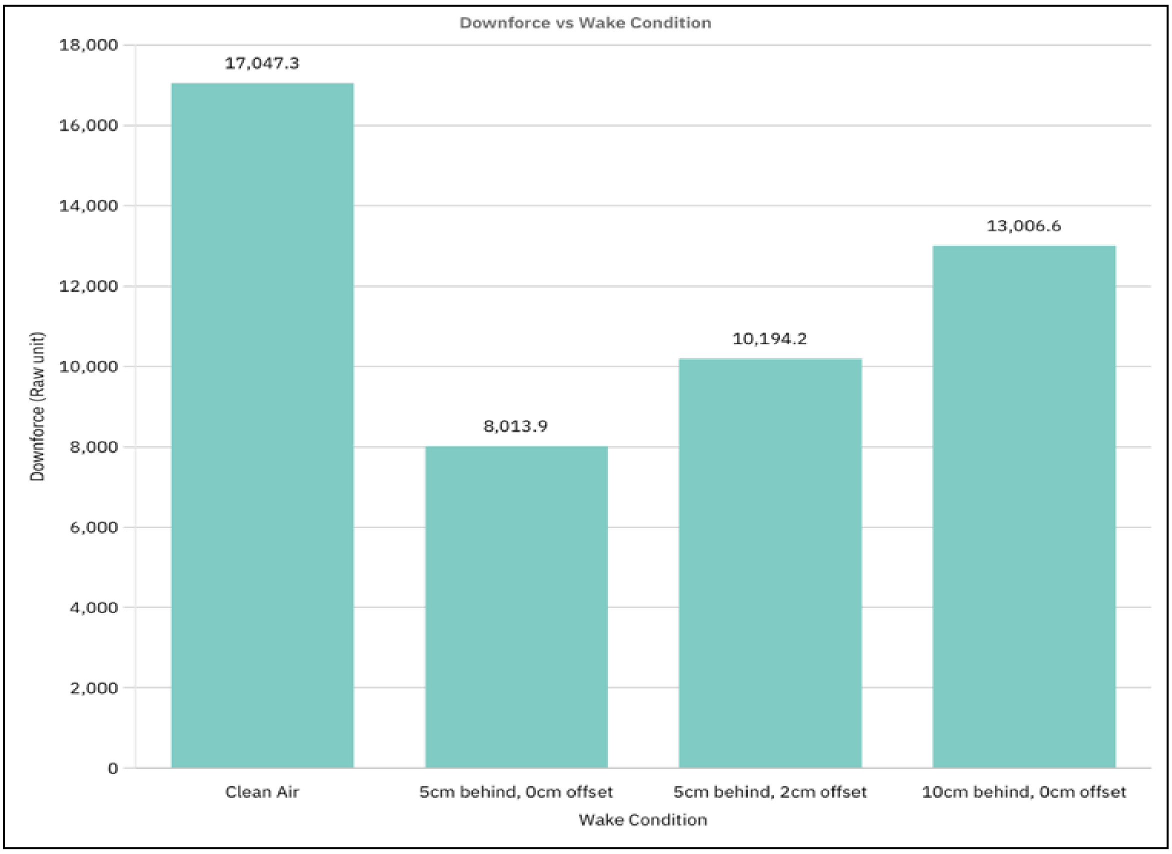

Fig 5 Bar Graph Representing Downforce Values in Different Wake Conditions

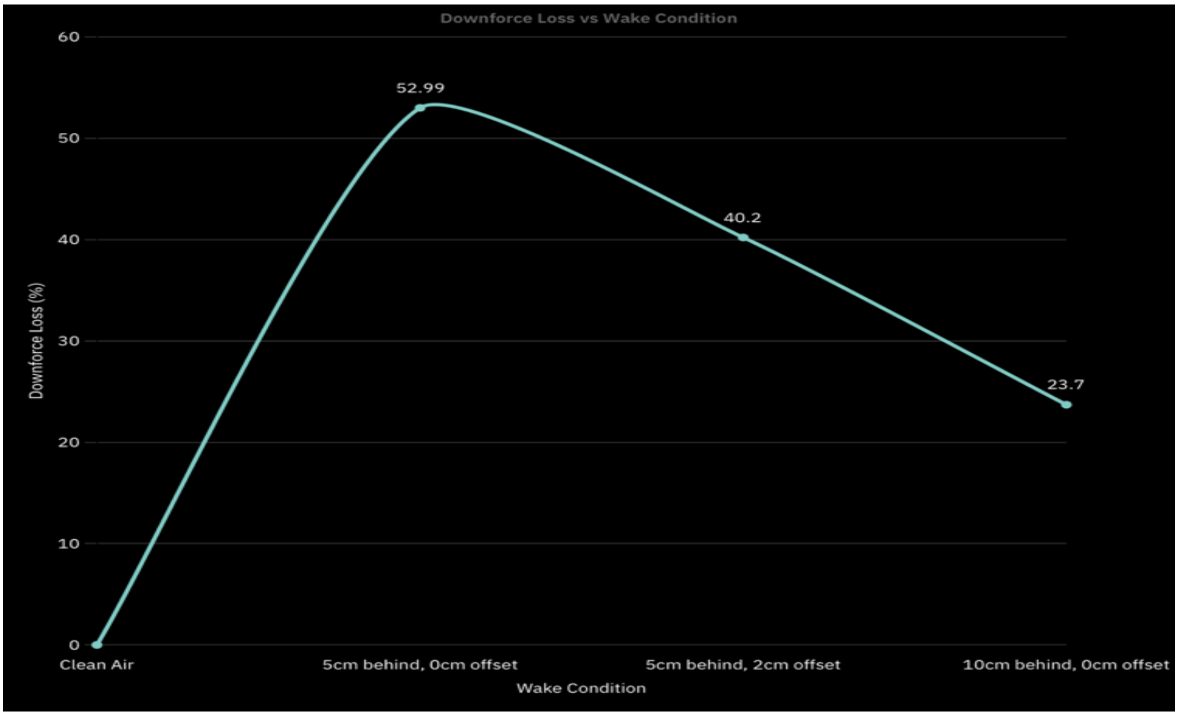

Fig 6 Line Graph Showing the Trend of Downforce Loss Due to Wake

IV. DISCUSSION

The results of this study provide clear experimental confirmation of the aerodynamic challenge brought about by wake effects in Formula 1 racing. In line with the hypothesis, chasing another car when directly behind significantly hindered the aerodynamic performance of the rear vehicle by diminishing the downforce that it could generate. This is in line with the conventional explanation of turbulent wake or dirty air, wherein the flow behind a leading car is significantly disturbed and severely impacts the downforce experienced by the car behind.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25jul932

The results indicate a discernible trend: with increase in distance from the front car or introduction of a lateral offset, the adverse impacts of the wake decrease. Specifically, a downforce loss of 52.99% was recorded when the model car was placed just 5 cm behind the front car without an offset, thus establishing the ferocity of the wake turbulence. The loss, however, reduced to 40.2% when a 2 cm lateral offset was introduced at the same distance. This demonstrates the fact that even a small lateral offset can result in a significant aerodynamic gain. At a farther distance of 10 cm directly behind, the downforce loss reduced to 23.7%, thus establishing that increased separation helps in re-laminarization of the flow to a more stable and beneficial condition. This test, although performed with raw load cell readings rather than newton-scale calibrated forces, was still capable of measuring relative aerodynamic development in different wake conditions accurately. Because focus was on comparative downforce loss and not necessarily on accurate measurement of forces, the use of raw readings did not invalidate the results.

One limitation of the experiment is that it was conducted using a pre-fabricated, scale model that lacked key aerodynamic features of an F1 car like an adjustable rear wing and Drag Reduction System (DRS). Although this setup facilitated a simplified test, it also limited the experiment from studying how aerodynamic adjustments—such as adjusting wing angles or the activation of DRS—would affect downforce loss under wake conditions. In addition, the lack of load cell calibration adds some degree of uncertainty to the absolute force measurements; however, this limitation doesn't affect the comparative analysis that is the focus of this experiment. Subsequent experiments can improve this design by adding a calibrated sensor system and testing different aerodynamic setups, thus achieving a better understanding of how teams can counter wake turbulence.

In summary, this research confirms the significance of wake turbulence in Formula 1 racing and provides quantifiable evidence to justify ongoing regulatory intervention against it. It places into context how slight variations in following position are able to achieve staggering improvements in aerodynamic performance and overtaking ability—crucial knowledge for motorsport engineers, designers, and strategists for calculating optimal driver lines around the circuit to ensure maximum possible aerodynamic efficiency and stability.

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