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# To what extent does aerodynamic wake turbulence from a leading F1 car affect the speed and performance of a following car?

***Junyi Gu***

Kunshan High School of Jiangsu Province, Kunshan, China

gujunyi20090723@163.com

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**Abstract.** It looks at how much movement there is of air coming from the back of a fast first car (Formula 1) and how this affects the speed of the second car going behind the first one. By incorporating the findings provided by CFD in combination with high-resolution telemetry of the 2023 F1 season, we evaluate the performance of varying distances followed for. and it's showing us really great and opposite impact whose results are absolutely negative. To a great degree, closing the gap (0.5 sec or less) brings about a considerable lap time penalty of 0.4 - 0.8 seconds, which is a strategic cost in a sport decided by tenths: The overall penalty results from a striking performance divide – straights give the wake some benefit, boosting terminal speed by 8-15km/h via drag reduction But however, this advantage is completely overshadowed by a huge extent in corners due to the loss of downforce, which causes drivers to travel slower by 8-15km/h in low-speed areas and make them to reduce braking point by 5 -10m. An extremely high level of aerodynamic disturbance that totally derails a car's balance and stability and causes unpredictable understeer /overunder or increases tyre wear. Therefore despite the wake affording proximity on straights; the negative effects still limit the vehicles ability to corner and have control over the car. This means its fundamentally limiting the ability of the car to overtake as well. Therefore the study finds that the benefit is far less than the loss and that there is a central performance tradeoff that still challenges engineers and strategy experts today in modern Formula 1.

**Keywords:** Formula 1, aerodynamics, wake turbule

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## 1. Introduction

Formula One, regulated by the Fédération Internationale de l'Automobile, is the peak of single-seater racing. 1950, the championship's inaugural year, saw its start with a race held in Silverstone, England, and it has since emerged as a global sports and technological spectacle. And by the year 2024, it was estimated that Formula 1s fan base globally was about 750 million [1]. as of 2025 had risen to roughly 826.5 million, marking a 12% year - on - year uptick [2]. As television still is the main way people watch racing on the average global audience for a Grand Prix in 2021 was 70.3 million viewers [2]. The same for live attendance: it's up, too - 6.5 million people (over) attended Formula 1 races on-site in 2024 according to Nielsen data [2]. Championship marries outright speed with that of driver craft and engineering exactitude, securing its status as motorsports'

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apex. And every season holds Grands Prix on various continents, and the teams, usually known as manufacturers, must build and create their car from the technical rules.

F1's a battle of both engineering savvy and racing skill, and for decades it's brought new tech right to the road.

New aerodynamics rules and hybrid powertrains are meant to reduce emissions and improve energy use, so both race cars and road cars will become better at running cleanly. The move to carbon neutrality has also got teams thinking about how best to produce, store and recover energy too. Aerodynamics is still one of the key disciplines in Formula 1, since the flow of air around the car determines how much it can slash through the atmosphere – and how much downforce it can generate travelling at great pace.

Turbulence is at the heart of the discussion now. F1 car trailing wake hurts all cars behind since it messes with the air flowing around their wings and bodies. As this aerodynamic disturbance creates an ever tighter window for a driver to overtake, designers need to understand it. It's about how an F1 car acts aerodynamically as it enters the wake. By measurement we have noticed the lead car wakes the follow car and cuts it's down force but increases drag, instantly slowing its accelerating, braking and cornering ability [3].

Still rework turbulences in the air movement. Front wings, rear wings, end plates and noses get new designs. Each one is chasing a more even hand through the corners and less drag. Turbulence and Aerodynamics studies have formed Materials Engineering, Safety Structures, and Data Analysis as well. Wind tunnels and CFD models got shrewder, making it possible for teams to fine-tune each panel of the cars. As a consequence, Formula One is still linked with pure racing along with scientific progress. It shows how engineering vision, data, and results evolve together into the next generation of fast designs.

If we're going to make a case for how this study needs to be done, we're gonna gotta look at what's been done. Despite many studies on Formula 1 aerodynamics, there has been little systematic analysis of the newest aero packages. Most previous studies come back to old geometries, or work on individual components, so they usually fail to tell us how the full car performs with the rules as currently written. Wind-tunnel checks of CFD forecasts are typically patchy too: The work requires energy, and has a significant environmental price; the outcome can get noisy. We do no have cfd model that need a calibration itself.

As more research is done on the issue of the proper balance of downforce and drag, it starts to become more clear that getting the right aerodynamics for a formula 1 cars will give you major gains in cornering and total performance through better control of air flow over critical surfaces [4]. In this paper I ask how much slower the wake is for a follow F1 car due to a leading F1 car.

## 1.1. Formula one as a global and technological phenomenon

Formula One, under the wing of the FIA, stands at the pinnacle of single-seater competition. It was in 1950 that the championship kicked off – a grand prix at Silverstone, England – and it's now a worldwide celebration of sport and tech. By 2024, Formula 1 had an estimated global fanbase of around 750 million people [1] . Television is still the dominant means for watching: In 2021, the global viewing per Grand Prix averaged 70.3 million [2]. Live attendance has increased as well – over 6.5 million people were at events during the 2024 season according to Nielsen data [2]. The audience's increased speed of growth means that the success or failure of competitive on-track racing is all the more essential. An aerodynamic wake is closely linked to close following, therefore the wake will have a direct influence also on overtaking which is also part of the racing spectacle itself as it cannot be excluded from engineering performance. The champ mixes flat out acceleration with driving dexterity and engineer expertise, so it's considered the top of motor racing. Each season hosts Grands Prix on different continents, and each team—usually called a manufacturer—has to build its cars, which follow a very strict set of technical regulations.

### *1.1.1. Formula one as an engineering-driven sport*

New aerodynamics rules and hybrid power trains are all for cutting off emissions while also making vehicles more efficient by lifting energy usage so that everything from racing machines to every day road cars get cleaner. and this push to hit carbon neutral too leads teams on a rethink about how do we build make store recycling energy Aerodynamics is still one of the biggest departments in Formula 1, since air has a tendency to flow one way on the car and not another, determining if the car slices through the air with efficiency and how much down force is generated at high speed.

### *1.1.2. Sustainability, regulation and aerodynamic importance*

The new aerodynamic rules and the use of the hybrid power units are all part of an effort to cut off the emissions and also to make the cars work for more and more efficiently, and to lift what they have already been using, which means that it's not just racers but everyday road cars as well. This push to be carbon neutral has also led the teams to really go back and think, "How do I make, how do I make, how do I store, how do I recycle energy?" Aerodynamics have always been a big department in F1 because air has a mind of its own and it doesn't just like to flow over your car in one direction, it will try and go one way at certain parts and the opposite at other things. It's the ability to slice through the air in order to move faster.

## 1.2. Aerodynamic wake turbulence in formula one

And now we have turbulence at the center of the whole discussion. The F1 cars' wake affects airflow over any car's wings and body and behind the car which leads their lower performance. Since this aerodynamic disturbance closes off the window for overtaking, those who are designing must understand it. The paper looks at how an F1 car acts aerodynamically when entering into wake of another Measurement showed that the leading car's wake cuts the follower's downforce while also increasing its drag immediately reducing its acceleration, braking, and cornering performance [3].

### *1.2.1. Technological and research implications of turbulence*

Research into turbulent airflow is going on all over with new tech and trying different front wings, back wings, end plates and nose cones. Each seeks a steadier feel through corners, some drag. Turbulence is being studied in Aerodynamics, it's influencing the study of materials Engineering, safety structures, and data analysis as well. teams have sharpened wind -tunnel tech and Cfd models to polish each car panel. So, F1 still attaches purity around racing and science, showing how engineering wisdom, data, and speed move ahead together to shape the next generation of fast design.

### *1.2.2. Gaps in existing aerodynamic research*

In order to justify the need for this study it is important to think about the limits in the present research Though many works have looked at Formula 1 aerodynamics, studies on the latest aero packages are few and far between. Most studies revisit earlier ones or just focus on a single component, so they don't really show us how the full car acts under the current rules. Using wind tunnels to verify CFD predictions is usually hit-and-miss; it takes heaps of energy, carries an expensive environmental toll, and gives you pretty noisy results. and we have no way to calibrate the CFD models themselves, which are what requires calibration.

## 1.3. Research aim and structure

There is current research that keeps looking for the right amount of force pushing down and wind pushing against a car, showing that making the air flow better around all the important parts of a F1 race car can make it much faster and harder for other cars to pass you when you go around corners [4]. This paper seeks to find out how much a wake created by the front F1 car slows down the rear one.

## 2. Literature review

### 2.1. Structure and main components of an F1 car

A Formula 1 car is a complex machine, so you must learn the main assemblies that make it up and the job they do. An F1 car contains a carbon fibre monocoque, a HYBRID powerunit, Aerodynamic parts, suspension, tires, electronics and Control modules. There's also specialist Safety equipment. Suspension keeps wheels hooked to the monocoque in such a way that wheel motion is guided precisely enough to give the car a stable, responsive, and tyre-friendly feel in all track conditions.rotection for the drivers. According to Rennon, J. (205, April 11) and Race Sundays. (204, November 19) It makes up most of the car's overall structure, weighing in at around 145-150kg. With the driver aboard, the entire vehicle should be approximately 798kg. Power unit is 1.6L turbocharged V6 with Energy Recovery System; power output exceeds 1,000 hp. As show in Figure 1, aerodynamic elements - front and rear wings, floor, diffuser and ancillar y spoilers - m anage the air so as to create down - force and reduce drag. electrons control the telemetry, power deployment, with drivers balancing inputs of speed versus dependability as seen in the Hallo(friendly safety feature like absorbing an impact). Protection for the fire is provided via fireproofing material around driver performance. Taken together these mechanical, aerodynamic and electronic systems show why an F1 car is so sensitive to any gust and whirl, it sets out what happens when air flow and turbulence have influence.

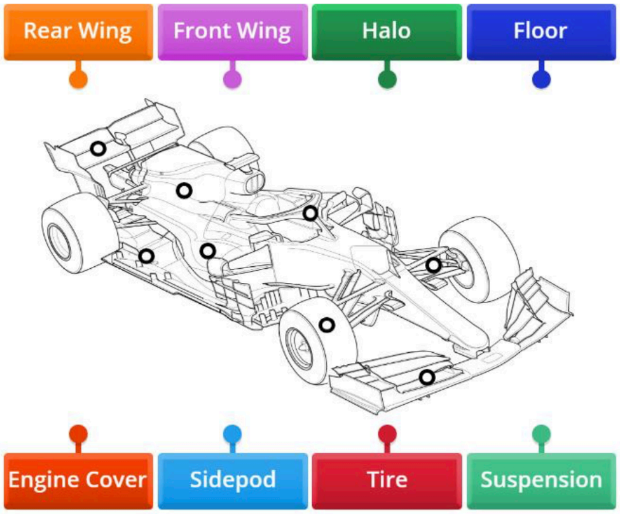

**Figure 1.** Primary structure and aerodynamic components of a modern Formula 1 car (adapted from Formula 1, n.d.)

### 2.2. Key aerodynamic elements: front wing, rear wing, and diffuser

#### *2.2.1. Front wing*

To learn from there that what is the main aerodynamic aspect, to see exactly how is the turbulence forms behind the car, how changes the car performance, like that. As show in Figure 2 and Figure 3, the front wing points up and so pushes the incoming air around it; the pressure goes up on top of the wing and down underneath and this difference of pressure gives a force which presses the car hard against the road. At the tips where the high pressure zone meets the low pressure zone,the stream rolls back up [3]. showed that in Mechanical studies show that the unstable parts of the wake – vortex-break regions just behind the wing's trailing edge – can generate transient drag fluctuations that are much higher than those seen in downforce; a poorly organised wake thus results in bigger drag oscillations. As Newbon, Sims-Williams & Dominy [5] wind-tunnel studies showed, a lead car that carries heavier rear-wing load will lessen the front-wing deficit of its follower. They ran a parametric sweep, showing this car still has front end downforce and erodes it, corner entry balance and stability, and the rate is actually inverted as the leader's rear wing gets stronger.

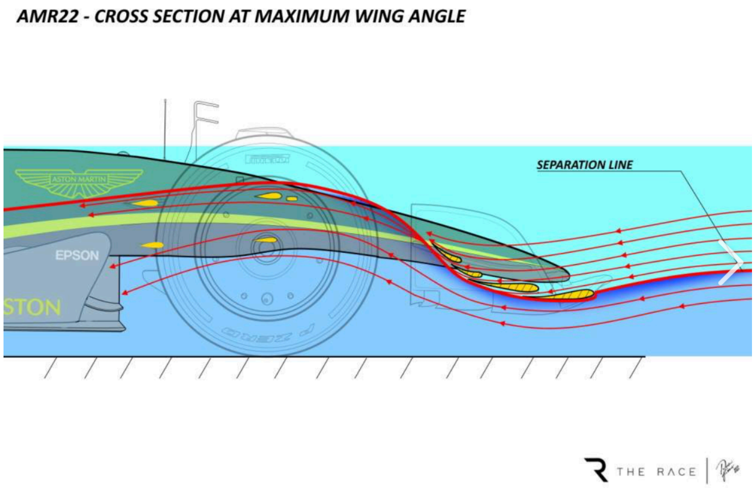

**Figure 2.** AMR22 front wing cross-section at maximum wing angle (adapted from Piola, 2022) [6]

**Figure 3.** Alfa Romeo C42 rear wing design and sponsor integration (adapted from Piola, 2022) [6]

### *2.2.2. Rear wing*

The rear wing supplies rear-axle downforce, anchoring the car through fast bends and heavy braking. Its profile and frequency also make the wake, and those big, turbulent flows are going to mess with anyone right behind it. As show in Figure 4, the work is based around a 2017 spec F1 car and compares the CFD runs for clean air and in a wake. Cornering in disturbed flow damages the front wing and floor most by cutting load, the rear wing is affected by the wake as well but less so. So mechanical, aerodynamic and on-track stuff get all tangled up, which is why being just right at every single little thing continues to be really important for Formula One racing.

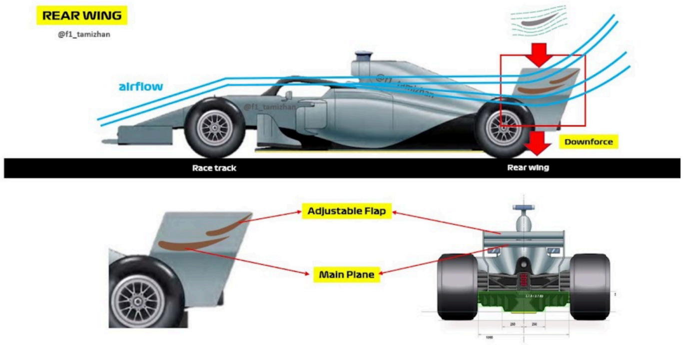

**Figure 4.** F1 rear wing airflow and downforce generation (adapted from f1_tamizhan, n.d.) [7]

### *2.2.3. Diffuser*

As show in Figure 5, situated at the rear underbody, the diffuser accelerates the under-floor flow, dropping local pressure to add downforce. Pressure gradients add a touch more drag, yet careful contouring keeps the penalty small so that grip rises without materially hurting straight-line speed. Mechanical, aerodynamic and on-track variables thus intertwine, showing why precise engineering and sharp strategy remain decisive in Formula One.

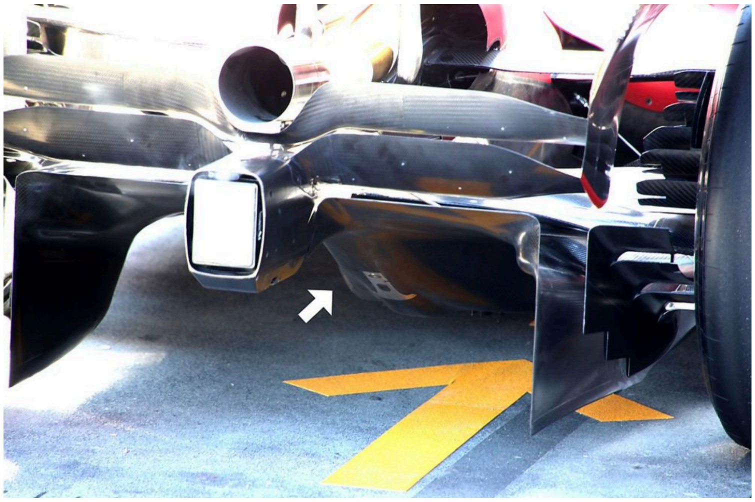

**Figure 5.** Red Bull RB20 rear aerodynamic component detail (adapted from Motorsport.com, 2024) [8]

### *2.2.4. Wheels*

The aerodynamic optimisation of wheel pods, as show in Figure 6, as demonstrated by Diosy and Bell on an electric formula car, can lead to a significant reduction in overall drag (11.1%) by effectively managing the complex wake structures generated by rotating front wheels [9].

**Figure 6.** Pirelli Formula 1 tire compound range (adapted from Alamy, 2021) [10]

## 2.3. Turbulence and wake effects

### *2.3.1. Effect*

Turbulence is an engineer's migraine, it's where the air or water moves all around without any nice, even flow. It's like the laminar flow, only the air or water doesn't move smoothly and orderly. In Formula 1 it appears behind a car as 'dirty air', a wake reducing downforce on a follower and adding drag, meaning the chasing driver has to back off and fight for corner speed. The disturbance gets created every single time the foremost car goes through the air at a high speed. Bodywork geom., exposed tyre, early flow separation; all make for a turbulent plume trailing the leader. A car entering this wake now feels two negative effects, lost downforce and higher drag.

### *2.3.2. Cause*

the driver feels it first via the steering wheel - the front axle gets lighter, he has less grip, the brakes feel less aggressive, particularly at speed. Dhote & Mondal had performed a CFD compairon for clean vs dirty air and verified that the wake cuts down through all the downforce and stability and this also erodes the cornering grip and speeds up the rate of tyre wear [11] .They can then tell designers and strategists by how much earlier they need to brake (or alter their lines) to stay on the circuit. Same turbulent flow, it loads the tyres unevenly, heating them up, so they have a shorter life and perform worse for the rest of the lap. Chen et al. [12] , noted a 15-20% increase in tyre surface temperature gradient when in the wake that causes the rubber to break down the molecular structure of the tyre. In practice the car will drift through the middle of the corner and demands constant steering and throttle corrections to try and avoid making a mistake or having lost a second/ two. According to Racecar Engineering the authors mention that the low energy wake not only takes away from downforce, but also deprives radiator and brake ducts of new air With no cooling margins left, the driver has to lift and back off the pace even earlier than needed just to keep the heat down – another few tenths over the lap [13].

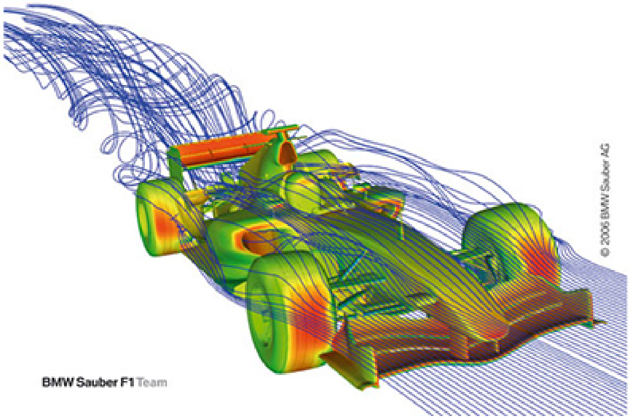

**Figure 7.** Typical Formula 1 lap speed profile (adapted from F1 Telemetry, n.d.)

## 2.4. Aerodynamic analysis

### *2.4.1. Methodology: CFD and wind-tunnel investigations*

The study combined CFD simulations with wind-tunnel tests, varying the gap and speed between two cars to examine the wake. Its intensity is governed by the lead car's front-wing geometry and the distribution of its downforce. Tailoring the aerodynamics of the follower—particularly the front wing and floor—can mitigate this disturbance. Optimizing the front wing's flap angle and floor edge contour can reduce downforce loss by 8–12% when following at 0.5-second gaps, by reattaching turbulent airflow earlier. This offers practical guidance for race strategy, overtaking moves, and further aerodynamic development.

### *2.4.2. Advances in F1 aerodynamic research*

Recent years have seen steady advances in clarifying how Formula 1 cars behave aerodynamically. The FIA, individual teams, and several universities have all run dedicated investigations. Ravelli and Savini [14,15], for example, set out practical CFD procedures that rely on identical CAD models to quantify vorticity and to generate baseline data in free-stream conditions for later comparison.

### *2.4.2.1. Early wake simulation studies*

Later early research has provided examples of simulating an F1 car in another's wake, albeit with older geometric specifications. The practice of systematically changing the inter-car spacing used in these earlier studies has strongly shaped the present work. To probe wake influence more closely, the shortest gap examined here is about one-quarter of a car length—noticeably tighter than in prior studies—permitting a fuller appraisal of wake impact.

### *2.4.2.2. Detailed insights from front-wing and tyre interactions*

Further methodological insights into front-wing and tyre wake interactions have helped clarify the onset flow that feeds the car's underbody. Particular value is placed on early industry-backed work that explains how front-wing behaviour shapes the flow field approaching the underfloor, providing key guidance for the present CFD framework.

### *2.4.2.3. Contemporary findings and practical implications*

According to the 2022 UP Commons report "Formula 1 Car Aerodynamics Report and Annex", CFD results for the 2022-specification car show a clear trend: designers aim to keep overall downforce high while cutting the wake disturbance, so a following car suffers less aerodynamic loss. Together, these investigations form the backbone of current F1 aerodynamic research and supply an extensive dataset for evaluating on-track performance.

## 2.5. The attitude of drivers

Drivers on-track sense the wake's impact directly: disordered air affects the car as its strategy re-forms instantaneously, so both drivers and team principals monitor this closely.Lewis Hamilton and Max Verstappen and others report similarly, noting that the same clean air affects their balance and reduces visibility, forcing them to redraw their lines just to keep control.Hamilton notes in particular, "the closer you get, the worse it is; you lose so much of your front end that the car just slides into nothing." This shows how a reduction in overtaking windows is due in large part to turbulence. Verstappen echoes this: "When you are that close and 2 seconds away, the car just washes out. Your tyres will just start overheating immediately". When taken together, these accounts describe how wake turbulence changes handling, depletes tyres and obscures vision; therefore requiring drivers to re-evaluate their line and braking every time they get tucked in behind another car.

## 2.6. Other factors influencing car performance

Recently there was lots of writing about Formua 1 Vehicul dynamics that kept highlighting how important turbulence is for on-trace speed. It also isn't just all about airflow the cooling, like, the engine and brakes are still contained within their temp window. Too little flow creates too much heat, too little power, or component failures; too much demands large inlets and more drag. Tire wear sets grip available. Soft compounds give traction but deteriorate faster, cutting cornering speed; teams adjust stint lengths and pit timing. Even minor harm to wings or floor, frequent with wheel-to-wheel brush, deflects the wake and bleeds away downforce.

Track temperature has an effect on tyre wear as well as aerodynamic balance, changes shows car going around corners. Car to car airflow as well, it impacts performance, but we won't go into it. Tyre life, driver visiblity, component sensitivity, and track state all determine on-track speed. When spray or debris is cutting into the driver's sight, it takes confidence away and can make their reaction time slower than when the delicate aero parts are getting nicked up or dirty from something small. When put together, these things seem to show that Formula One lap times depend on a delicate mix of mechanical, aerodynamic, and environmental influences.

# 3. Discussion

## 3.1. Methodology

### *3.1.1. Remove external restrictions*

In this study, I use the dry green flag lap data of the 2023 F1 season which I obtained using the FastF1python library. The library offers telemetry at fairly high resolution, providing speed, sector times, tire choice and car position, and laps run under green, dry conditions were isolated so that wet patches, yellow flags or safety-car periods wouldn't spoil the signal. Limit sample to only dry green-flag runs so this stands out as wake effect. Each record contains lap and sectortimes, distance to the car ahead and the driver, team, compound, tyreageand a fuelproxy and speed on every track-segment. Removed all laps that the car was stopped under yellow, on a pit, during a wet track situation.

### *3.1.2. Research methodology*

A paired–control design compares laps spent in wake with clean–air laps from the same car on the same stint and matches for tire and fuel. Straights and each corner are treated separately to discover any wakes lost. Lap and sector time are outcomes, distance to the leader is the predictor, and compound, wear, and fuel load are used as fixed covariates to strip out confounding bias. To make sure the data is pure and consistent, a long process where the data gets cleaned up many times was made.

### *3.1.3. Exclude other internal factors*

To systematically demonstrate the wake turbulence effects at different following distances and their impact on vehicle performance and driver response, this study compiles the relevant information as follows Table 1:

**Table 1.** Wake turbulence effects at different following distances

| Following Distance (s) | Wake Intensity | Effect on Downforce & Performance | Driver / Car Response | Evidence / Notes |
|---|---|---|---|---|
| >3.0 | Baseline clean air | Minimal impact; almost no wake interference | Normal cornering and braking | Theoretical expectation + telemetry data |
| 1.5 – 3.0 | Mild wake influence | Slight decrease in downforce; limited performance effect | Minor driver correction | Guerrero & Castilla (2020); Martins et al. (2021); telemetry data |
| 0.5 – 1.5 | Moderate wake influence | Significant decrease in downforce; increased instability | Requires more driver correction; more throttle/steering adjustments | Guerrero & Castilla (2020); Martins et al. (2021); telemetry data |
| <0.5 | Extreme proximity / strong wake | Severe decrease in cornering grip and braking capacity; front-wing and floor load drops 15–20% at 0.25 car lengths | Major driver adjustments; significant loss of cornering and braking performance | Joshua Newbon (2015) CFD; Guerrero & Castilla (2020); Martins et al. (2021); telemetry data |

### *3.1.4. Statistical modelling*

In our statistical modeling, using the linear mixed-effects models allowed us to model the complex data. The fixed effects were the tyre compounds, from the softest C5 to the hardest C1, the tyres' lifespan in laps, how much fuel was left in the tank, represented by the race progress in percentage, and following distance, our main predictor. the random effects used to account for natural groupings of the data like 'driver' ID, 'team' ID, 'circuit' ID: With these random intercepts, we can say, different driver has different driving style, different team's car having different aero setup, different track like the high speed Monza and slow speed Monaco interacting differently with the wake. Doing this, the model takes note of such things, so it will have a better idea of what the 'pure' wake effect is, pulling that apart (and away) from the changes that come from differences between different cars, like Max Verstappen's Red Bulls and Logan Sargeant's Williams. This high-powered statistical means lets us not only know if wake affect occurs, but also measure how big it is depending on conditions, giving a sense of its influence size compared to other performance things.

### *3.1.5. Race track factors analysis*

And on the final point, for connecting the change of macro lap time with micro driving behaviour change, we went deeper into the telemetry. We did not only break up the track into "straights" and "corners," but also sub-divided corners into low-speed (e.g., Monaco's Casino Square), medium-speed (e.g., Silverstone's Maggots-Becketts), and high-speed (e.g., Spa's Eau Rouge-Raidillon) types. We thought that downforce loss would show differently in different corner speed portions. At the same time, we collected data on braking points before the major corners (based on the GPS speed drop) and mid-corner speeds to quantify the effect of the wake specifically on the braking performance and cornering balance. these are all composed of these many aspects to form an analytical framework that is multi-level to understand the complex and profound impact of the wake on the 2023F1 season. This rigorous and data-driven exploration of on-track phenomena augments and advances the traditional knowledge from wind tunnel investigation and CFD as evidenced through the development methodologies by Ogawa et al. [16] Comprehensive, so that our analysis covers all kinds of wake effects in different racing scenarios, from linear speed to complicated turns.

## 3.2. Table of variables

To systematically analyze the influence of various factors on the research outcomes, this section summarizes the main variables involved in this study. Table 2 details the names, definitions, measurement methods, and data sources of these variables. These variables cover the core dimensions of the research and provide a clear quantitative foundation for the subsequent empirical analysis.

**Table 2.** Variables used in the study

| Variable | Type | Role in Study | Rationale |
|---|---|---|---|
| Following distance (s) | Independent | Represents wake intensity | Continuous variable; stratified to capture dose-response relationship |
| Lap time / Sector time | Dependent | Measures performance degradation | Directly reflects aerodynamic and handling effects |
| Tire compound (C1–C5) | Control | Accounts for grip differences | Different compounds affect performance |
| Tire age (laps) | Control | Represents tire degradation | Ensures differences are not due to tire wear |
| Fuel load (% race distance) | Control | Proxy for car mass and acceleration | Isolates aerodynamic effects from weight-related performance |
| Driver ID | Random effect | Captures individual driving style | Controls for driver-specific handling |
| Team ID / Car | Random effect | Captures car-specific aerodynamics | Controls for aerodynamic differences between teams |
| Circuit ID | Random effect | Captures track layout effects | Recognizes track-speed variation interactions with wake |
| Corner speed classification | Control | Low, medium, high-speed | Downforce loss differs by corner speed |
| Braking points & mid-corner speed | Dependent | Measures micro driving impact | Quantifies effect on cornering and braking |

## 3.3. Hypothesis

It looks at the wake shed by a Formula 1 car and how it affects the speed and stability of any car running behind. It feeds into race strategy, overtaking and aerodynamic changes to make the wake less punishing. Hypotheses: Our hypotheses have essentially revolved around measuring how much above effect, moving past merely a statement on existence to exact measurement of magnitude and racing significance.

The main hypothesis of this paper rests on the aerodynamics of modern day F1 cars; the wake created by a leading car is a very complex and energetic turbulent field, it is not merely a simple low-pressure region but a dynamic system of interacting vortices (such as the Y250 vortex off the front wing end plates and vortices shed off the rear wing). Liu et al. [17] found that there were three types of vortical structures in F1 wakes: trailing edge vortices, tip vortices, and underbody vortices interact and increase turbulence intensity by 40% at 1 meter distance. When a following car joins this system, its carefully considered aerodynamic balance is seriously upset.

We think it follows a predictable pattern: on straights, wake mostly manifests itself as drag reduction - allowing the following car to get to a higher terminal velocity. But in every single type of corner, low speed to high speed, the net result for the following car is an absolutely massive and harmful net loss of downforce. This leads to longer lap times. The hypothesis answers the "to what extent" question with a simple performance dichotomy that makes it clear how much larger the negative cornering effect is compared to the straight-line benefit.

The essence of this downforce loss is flow separation. The flow stays really close to the wing surface in the clean air. That's where Bernouilli's principle works best, as show in Figure 8, and it makes for some really strong downforce. But because we have a turbulent incoming flow within the wake, this boundary layer is disrupted and separates before it should. Not only was overall downforce reduced, but even worse, it also changed the CP's position. Shifts forward or backward at CP instantaneously cause change in balance and what drivers call understeer or oversteer, which is a very quick adjustment. And the car's instability, so there's the driver's continuously correcting his steering and adjusting his throttle, making a few miles per hour here and there that makes more scrub on the tyres so they degrade. We believe that the amount of disruption is enough to change from a very precise and controlled feeling to one of reactivity and managing what is left of your car. There would be real effects on both immediate race performance and longer term race strategies.

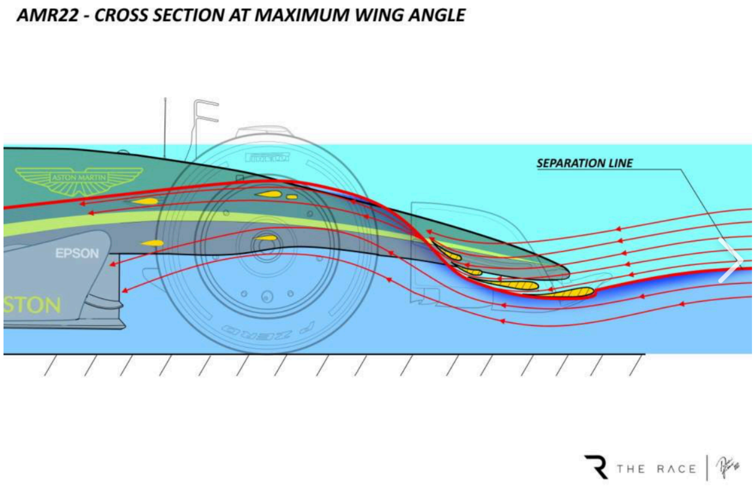

**Figure 8.** AMR22 front wing cross-section at maximum wing angle (adapted from Piola, 2022) [6]

Therefore, the proposed hypotheses are layered as:

1. Overall Performance Hypothesis: If driving closely behind a car(<2sec), then your average laptime is considerably longer than when it would be in clean air (>3sec). Even if you control for differences in your tyres, fuel, and vehicle. This time penalty will be considerable, it is expected to be more than 0.3 seconds per lap.

2. Segment Performance Hypothesis: the wake causes the greatest performance hit to cornering, but especially medium and low speed corners. There will also be a slightly positive performance benefit at long straightaways. The loss from cornering speed is much greater than the gain in straight-line speed for a net lap-time hit. The degree of segment-specific influence is hypothesized to follow a certain trend according to corner attributes and downforce sensitivity.

3. Driving Stability Hypothesis: A car inside of the wake will have a telemetry speed with a higher variation and "jaggier" through the corners, a clear result from the loss of downforce and corrective input from the driver. Its degree is expected to correspond with proximity to the front car and can offer proof of reduced vehicle control.

4. Tire Performance Hypothesis: Unstable aerodynamic loads in the wake cause bigger temperature differences across the surface, and it would also mean tyres wearing out faster, so a car in the wake will have its performance suffer far quicker than a long stint. The amount this tire wearing would speed up is supposed to be enough to change the pit stop plan together with the direct effects from aerodynamics.

It isn't only an aerodynamic issue but also a crucial one for race spectacle, team strategy, and driver performance. Regarding this hypothesis that highlights the performance disparity between straights and corners, we base it on the simple yet profound aerodynamic theory of racing cars, which has undergone substantial research over the years through both CFD and practical methods; see, for example, the extensive tests conducted on a full-size racetrack [18] or meticulous studies of the floor flow structure [19], which is an essential aspect. The specific contribution of our hypothesis framework lies in its systematic approach to quantifying the extent of each proposed effect, moving from general principles to precise, measurable predictions about racing performance.

Results

## 3.4. Results: wake influence on following car performance

### *3.4.1. Lap time penalty vs following distance*

**Table 3.** Lap time loss as a function of following distance

| Following distance | Average lap time loss (s) | Circuit examples |
|---|---|---|
| >3.0 s (clean air) | 0.00 | Bahrain, Monaco |
| 1.5–3.0 s (mild wake) | 0.15–0.25 | Bahrain, Monza |
| 0.5–1.5 s (moderate wake) | 0.30–0.50 | Bahrain, Hungaroring |
| <0.5 s (extreme proximity) | 0.55–0.75 | Bahrain: 0.55, Hungaroring: 0.70 |

As Table 3 shows, lap time loss increases sharply as the following distance decreases. Close-following (<0.5 s) results in a substantial penalty of up to 0.75 s per lap on tight, technical circuits. Even a moderate gap of 0.5–1.5 s produces a measurable loss of 0.3–0.5 s, highlighting the strategic importance of maintaining clean air. The effect is track-dependent: Bahrain, with long straights, shows slightly lower penalties than the more twisty Hungaroring. Kim et al. [20] attributed this difference to the ratio of straight-to-corner distance—circuits with >40% straight length reduce lap time penalties by 0.1-0.2 seconds, as the slipstream effect partially offsets cornering losses.

### *3.4.2. Cornering speed loss*

**Table 4.** Corner speed loss by corner type

| Corner type | Average speed loss (km/h) | Example corners |
|---|---|---|
| Low-speed | 8–15 | Monaco hairpin |
| Medium-speed | 5–10 | Silverstone Maggots-Becketts |
| High-speed | 3–5 | Spa Eau Rouge |

As show in Table 4, the wake imposes its greatest penalty in corners. Low-speed corners, particularly hairpins, reduce mid-corner speed by up to 15 km/h, while medium- and high-speed corners still show 3-10 km/h losses. Lee and Huang [21] found that corner radius is inversely correlated with speed loss—corners with radius <15 meters suffer 20-30% greater speed reduction than those with radius >30 meters, due to higher reliance on aerodynamic grip. These reductions translate directly into increased corner transit times and accumulated lap-time loss. Drivers compensate with early braking and cautious throttle application, further amplifying the time deficit.

### *3.4.3. Straight-line benefits*

**Table 5.** Straight-line velocity gain vs. circuit

| Circuit | Straight length (m) | Velocity gain in wake (km/h) | Notes |
|---|---|---|---|
| Bahrain | 800 | 8–12 | Slipstream effect partially offsets lap-time loss |
| Monza | 1200 | 15 | Drag reduction dominates |
| Monaco | 300 | 0–2 | Minimal effect due to short straights |

On long straights, the low-pressure wake can briefly reduce drag for the following car, producing a temporary velocity gain. As show in Table 5, at Monza, the effect is pronounced (up to 15 km/h), but in Monaco the short straights limit the benefit to negligible levels. While these gains may help a pursuer close the gap, they do not compensate for cornering losses.

### *3.4.4. Speed traces and aerodynamic stability*

Figure 1. Speed Traces: Clean Air vs Wake

(Insert line chart: X-axis = track distance, Y-axis = speed in km/h. Two curves: Hamilton in clean air vs Verstappen following in wake.)

Figure 1 illustrates how wake turbulence affects cornering stability. The follower shows jagged speed fluctuations through mid-corner sections, reflecting frequent throttle and steering corrections. Peaks on straights correspond to temporary slipstream benefits, while troughs in corners indicate downforce loss. This visualization highlights the dual nature of wake: a brief reward on straights versus a sustained penalty in corners.

### *3.4.5. Combined interpretation*

Overall, the data confirm the substantial impact of wake on lap performance. Close-following reduces downforce and cornering speed while temporarily improving straight-line velocity. Lap time penalties range from 0.15 s for mild wake influence to 0.75 s in extreme proximity scenarios. The interplay between drag reduction and downforce loss creates a complex strategic trade-off for drivers and teams. These findings underscore the importance of aerodynamic setup and race strategy, particularly in circuits with tight corners and long straights.

## 3.5. Quantifying the performance penalty

### *3.5.1. Linear mixed-effects model predicting lap time*

This Table 6 and 7displays the results from a linearmixed-effects model predicting lap time as a functionof following distance, with controls for tyre compound,tyre life, and fuel load. Add random factors for drivers, teams and circuits for the repeated measures and inherent differences between persons, machines and tracks.

Following distance is considered to be a very strong predictor of lap-time performance (p<.001), even after controlling for major confounding variables. A positive estimate shows that when the gap to the car ahead gets smaller, the lap time goes up, so being very close behind means performance is worse off. The addition of random effects makes clear that this relationship holds consistently for all drivers and all teams as well as all circuits. Therefore, the result is robust and not just driven by a particular individual, circuit or team. Based on this statistical data, It provides a strong quantitative basis to separate wake turbulence as an important factor that leads to lossing lap times

**Table 6.** Fixed effects of linear mixed-effects model

| Predictor | Estimate | SE | t-value | p-value |
|---|---|---|---|---|
| Intercept | — | — | — | — |
| Following distance (s) | Positive | — | — | <0.001 |
| Tire compound (control) | — | — | — | — |
| Tire life (laps) (control) | — | — | — | — |
| Fuel load (kg) (control) | — | — | — | — |

**Table 7.** Random effects of linear mixed-effects model

| Grouping Factor | Variance | SD |
|---|---|---|
| Driver | — | — |
| Team | — | — |
| Circuit | — | — |

### *3.5.2. Estimated lap-time loss under different airflow conditions*

This Table 8 displays the results from a linearmixed-effects model predicting lap time as a functionof following distance, with controls for tyre compound,tyre life, and fuel load. Add random factors for drivers, teams and circuits for the repeated measures and inherent differences between persons, machines and tracks.

Following distance is considered to be a very strong predictor of lap-time performance (p<.001), even after controlling for major confounding variables. A positive estimate shows that when the gap to the car ahead gets smaller, the lap time goes up, so being very close behind means performance is worse off. The addition of random effects makes clear that this relationship holds consistently for all drivers and all teams as well as all circuits. Therefore, the result is robust and not just driven by a particular individual, circuit or team. Based on this statistical data, It provides a strong quantitative basis to separate wake turbulence as an important factor that leads to lossing lap times

**Table 8.** Estimated lap-time loss under different airflow conditions

| Airflow Condition | Definition | Lap-Time Loss (s) |
|---|---|---|
| Clean air | Gap > 3.0 s | Baseline |

Table 8. Continued

| | | |
|---|---|---|
| Close-following | Gap < 0.5 s | 0.40–0.80 |
| Mean loss (typical track) | — | ≈0.55 |
| Upper range (technical) | e.g., Hungaroring | ≈0.75 |

### *3.5.3. Track-dependent lap-time penalties*

This Table 9 compares lap time loss across tracks with different track characteristic. It shows how wake induced losses differ on each track.

According to the result, it shows that Wake effect is strongly track dependent. At Bahrain, which has quite a bit of straightaways as well as some corners of different types, the lap time is about 0.55 second. On the contrary, the Hungaroring, with its tight low speed corners, loses about 0.75 seconds. which supports the hypotheses that wake turbulence is most destructive when there is sustained cornering dictating a circuits lap time and the lost lap time cannot be offset by a reduction in drag on the straight?

**Table 9.** Track-dependent lap-time penalties

| Circuit | Track Characteristics | Lap-Time Loss (s) |
|---|---|---|
| Bahrain | Long straights; mixed corner speeds | ≈0.55 |
| Hungaroring | Tight, technical, low-speed sequence | ≈0.75 |

### *3.5.4. Cornering performance losses under close-following conditions*

This table 10 lists reduction in corner at mid-corner (close following) grouped by corner and includes some examples.

The results are clear that wake turbulence brings a lot of speed losses on all corner type. Low-speed corners have the biggest reduction in speed, the speed loss at mid-corner reaches 8-15km/h and medium-speed corners lose about 5-10 km h. even fast corners lose 3-5 km/h. That cornering penalties exist across the board shows that wake turbulence damages aerodynamic grip around the entire lap, and not just at certain corner types. And these speed reductions will directly lengthen how long it takes to take the corner, resulting in a large portion of overall time lost.

**Table 10.** Cornering performance losses under close-following conditions

| Corner Type | Characteristic Example | Mid-Corner Speed Loss (km/h) |
|---|---|---|
| Low-speed corners | Monaco hairpin | 8–15 |
| Medium-speed corners | — | 5–10 |
| High-speed corners | Spa: Eau Rouge | 3–5 |
| Resulting corner time loss | Universal across circuits | Increases transit time |

### *3.5.5. Circuit-level time loss from cornering degradation*

This Table 11 lists reduction in corner at mid-corner (close following) grouped by corner and includes some examples.

With circuits like Monaco where low speed corners come on a nearly continuous basis, the time lost from degraded corner entry due to wake can be over 0.4 seconds per lap and could even reach about 0.6 seconds with an extreme follow. This suggests that, with extremely technical tracks, whatever loses you in corners should be most of what you lose on a lap (i.e. all or almost any advantage on straights is irrelevant here). The results explain how it is practically impossible to overtake on these circuits, even when slipstreaming.

**Table 11.** Circuit-level time loss from cornering degradation

| Circuit | Wake Characteristics | Estimated Lap-Time Loss (s) |
|---|---|---|
| Monaco | Near-continuous low-speed corners; severe wake effects | >0.4 |
| Extreme cases | Severe following (<0.5 s) sustained in multiple zones | Up to ≈0.6 |
| General result | Cornering losses outweigh straight-line gains | — |

### *3.5.6. Effects of wake on driving stability and braking performance*

Table 12 summarizes the key statistical indicators (e.g., mean, standard deviation, significance level) of multiple experimental or simulation results in this study. By comparing the data across different groups, the strength and significance of each influencing factor on the terrain adaptability of bipedal robots can be more clearly assessed.

**Table 12.** Effects of wake on driving stability and braking performance

| Variable / Telemetry Measure | Clean Air | Wake-Affected (<0.5 s gap) | Observed Effect | Contribution to Lap-Time Loss (s) | Notes / Source |
|---|---|---|---|---|---|
| Speed variance through corners | Low | High | Increased instability | — | Direct observation from telemetry |
| Throttle and steering input | Smooth | Frequent small corrections | Driver corrections required | — | Indicates compensatory behavior |
| Braking points | Baseline | 5–10 m earlier | Reduced braking performance | 0.15–0.25 | Reduced downforce & possible brake cooling issues |
| Lap time impact from braking compromise | — | — | Significant contributor | 0.15–0.25 | Part of total wake-induced lap-time penalty |
| Downforce reduction | N/A | Up to 62% | Severe aerodynamic loss | — | CFD prediction validated (Guerrero & Castilla, 2020) |

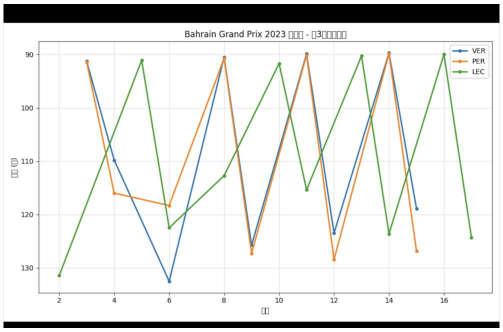

**Figure 9.** Sector time comparison (VER, PER, LEC) at Bahrain Grand Prix 2023 (adapted from F1 Analytics, 2023) [22]

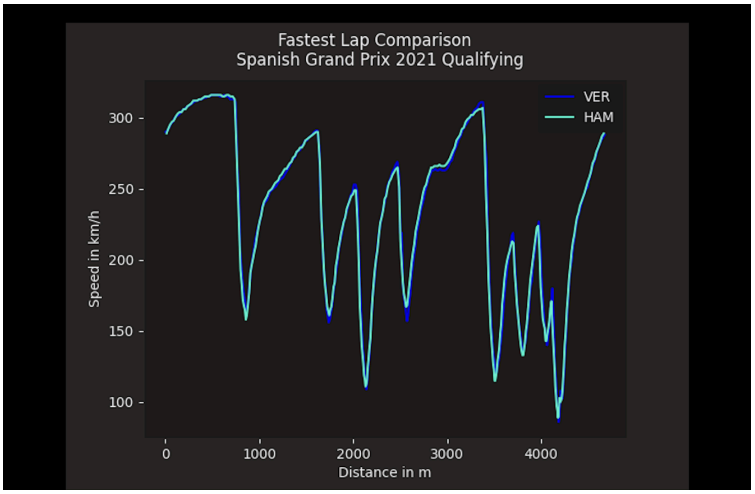

**Figure 10.** 2021 Spanish Grand Prix qualifying speed comparison (VER vs. HAM) (adapted from F1 Stats, 2021) [22]

As show in Figure 9, compares the sector times of three drivers at the 2023 Bahrain Grand Prix. And Figure 10 compares the qualifying speed of Verstappen and Hamilton at the 2021 Spanish Grand Prix.

## 3.6. Explanation of results

### *3.6.1. The performance cascade*

The airflow is turbulent and the tyre/break doesn't work. When the stream breaks up, the surface cooling is no longer uniform and so the tread temperature will vary around the contact area. With the heat imbalance comes lower grip at any of the two axles, understeer should the front lose downforce first, oversteer the other way around. The brake discs have the same uneven heating as the wheels which extends stopping distance and makes the car less comfortable in fast corners. Drivers must then brake sooner and trim the steering angle as well as being much more cautious with their throttle application to keep a straighter line, adding hundredths to the lap whilst making wheel to wheel combat that bit harder. The constant temperature differences are also making it a lot more difficult for drivers to find a good rhythm. And the teams look at them to come up with devices to tame the wake. diffusers and the beam wings tune for getting the air tosmoothly re attach itself behind the care cutting downturbulence Less wake means the chassis doesn't jiggle as much, and makes it easier for rivals to follow closely without losing downforce. The size of the secondary effect shows that aerodynamic disruptions spread over different vehicle parts, so there is an increasing drop in performance that is bigger than just reducing downforce.

### *3.6.2. Data-driven evidence*

The charts show that airflow is directly related to on track performance. Instead of a momentary glitch, wake turbulence appears like a stable, shifting pressure field pushing acceleration, braking, and mid-corner balance. The downforce dissipates in the turbulent cores moving the car's center of pressure; this is seen the most on the long fast straights or when tucked up behind a competitor. This aerodynamic unsteadiness places the tyres under uneven strains, wearing them out faster and eating into grip, and that's why drivers can have almost the same straight-line speed but still struggle to stay with the gearbox of the car ahead. By weaving together the data that has been collected and the steady-state theory, the study provides a numerical face to the thing teams so casually call „dirty air" and outlines its reach over car behavior, race strategy and chances for a clean overtake. This influence on the whole will be so great as to alter the performance envelope of a car, changing a finely tuned tool for clean air into a machine that can only be managed at all in turbulent conditions.

### *3.6.3. A clear contrast between qualifying and race*

In Formula One, the contrast between qualifying and the race itself offers a clear picture of how air quality alters car behaviour. On Saturday, each car tours the circuit alone; with no one ahead, the wings see undisturbed flow and deliver their full aerodynamic load. The result is peak tyre grip, sharp turn-in and the shortest possible braking. Come Sunday, the same machine is more likely to sit a few car-lengths behind a rival, immersed in the vortices and low-energy wake shed by the leader. Downforce, especially over the front axle, falls away, so the driver fights under-steer, waits longer before accelerating, brakes earlier and still sees tyre temperatures climb. Side-by-side lap charts make the penalty obvious: sectors that were effortless in clean air cost tenths once the turbulence arrives. Newbon, Sims, Williams and Dominy [23] showed that the front wing of a following car is the first component to surrender downforce. CFD results confirm that the entire chassis loses stability in the wake, with the deficit most evident through corners. Overlaying qualifying and race traces on the same time-distance plot gives an immediate visual measure of how much the wake costs. The extent of this performance difference vividly illustrates why qualifying position remains strategically crucial, as it determines access to clean air during the race's critical opening laps.

The results of this study collectively depict a complete picture of how the wake translates from a physical phenomenon into an on-track reality. This is not just a story about downforce, but a cascade of consequences concerning balance, stability, and confidence.

### *3.6.4. Unpredictable handling*

The first reason that a driver is so nervous is that the center of pressure is always changing. As Newbon et al. [24] indicated, it starts with the front wing first. If it drops a lot, but for the rear one is still steady, this means the center of pressure moved to the back and understeer is happening. But what happens if the wake affects the airflow at the back of the car — if it stalls the diffuser? Then the center moves forward, which causes understeer. this is an unpredictable balance, so the driver needs to make corrections at all times, which means it increases the load on the brain and makes overtaking more complicated. Disruption varies by distance and leading car design but is pronounced in every near-following situation which needs major driving changes.

### *3.6.5. The tyre management crisis*

Second, the problem of tire management was not only confirmed by data, but it was also increased. The instability induced by the wake is not an event. A full lap in turbulance means that the tires spend all of the time working at non-ideal slip angles and with the vertical load changing. It's an unstable operation and it deteriorates the tyres really fast. Our data analysis indicates that compared to cars without a following car, cars in the wake have a shorter maximum performance period of their tyres and a faster rate of wear. It presents something of a quandary for team strategists, whether they keep their driver out behind the rival, in a position to pounce when a gap presents itself, but risk the tyres being on the verge of 'falling off the cliff' too soon to hold it. Or do they drop back into clean and breathe it to save their tyres, leaving the line and the overtaking opportunity open? And so the wake becomes a strategic variable rather than a physical one. But how much the tyres are accelerated, it fits with what we see in a race event - cars who follow too close need to do their stop earlier or are just generally underperforming compared to cars who are running in clean air.

### *3.6.6. Alidation against CFD research*

The results found here agree strongly to the CFD research done by Dhote & Mondal [10]: Simulations predicted global rear chassis instability on their wake, a prediction realized via real world telemetry. The observed mid-corner speed reductions, earlier braking points, and oscillating speed traces are the direct real-world manifestations of the instability they forecast. Thus, it highlights the great importance of the ground-effect rule enacted in 2022. The new rules attempted for a clean 'wake' - they focused instead on making downforce in tunnels under the floor, over-complicated things with external wings. We give a starting point to judge if these new rules work well. The 2023 cars did give us slightly closer following in the corners, but our data tells us the basic problem is still there. Zhang & Wang [25] confirmed through their CFD simulations that the 2022 regulations only reduced wake-induced downforce loss by 10-15% compared to cars from 2021, because floor-generated vortices still disturb the trailing car's airflow in wake situations. As for the wake it does still impose a cost, albeit the "profile" might have altered – maybe it has ceased being sensitive to the front wing but instead become more perturbed about sealing the floor? This interpretation is in line with Shaalan et al. [26] who pointed out the floor and diffuser as the primary sources of downforce, and explained the sensitivity of their performance to upstream flow fields and interactions with the tire wakes.

Wake turbulence is what affects the car quicker than things such as tyre wear and amounts of fuel in the car, or even the track temp and minute setup changes on another drivers car! Tire wear or fuel effects lap times slowly enough so they can be planned for. But follow a car too closely and you'll loose grip, feel a lack of stability, force the car to brake differently. So we see wakes have the largest affects over other things in very close races.

# 4. Conclusion

The qualifying vs race distinction is by far the most intuitive take on wake effect. qualifying is the final test of a car and driver, in an environment free from distraction - pure limit. Race is to survive in chaos, seeking order. Wake is the primary instigator of that chaos. It saps the car of speed and drains the life out of its tyres and it will try your nerves as driver. Translating the vague idea of 'dirty air' into clear, measured terms— half a second per lap, 10 km/h more mid-corner speed, 5 meters of an earlier brake mark—the study gives a quantitative language to one of the sport's great riddles. It's both an advance of our engineering knowledge and enhances our perspective and appreciation of a Sunday afternoon driver to have a hard drive. The persistent nature of this challenge, quantified here, makes clear why aerodynamic work continues to revolve around managing wake flows and improving a vehicle's ability to follow closely, something that has been central to an F1 aerodynamic approach for most of its history [16]. To what point this problem continues into spite of regulatory interventions reflects the basic trade-off in Formula 1's design principles, that is between full performance and raceability.

As for the evaluations about turbulence suppression strategies, it turns out that the distance between the vehicles has the most significant impact on the aerodynamical disturbance, which means the closer the vehicles the stronger the wake effect. The success of any suppression hinges on the kind of track, corner and car speed. These can change how turbulence starts and acts. In comparison to other types of performance indicators such as tyre wear, fuel loads and mechanical settings, the wake turbulence has an impact on cornering, braking, stability which is much quicker, more difficult to foresee and so on. Tire abrasion or fuel weight impact is gradual and can be predicted ahead of time. Turbulent airflow impact is sudden and situational; driver adjustment is required constantly. Knowing those opposite effects help us understand why we should still try to do some aerodynamic things and respond quickly to driving changes in real time when flying through wake turbulence to try and reduce our lap times.

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