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# The Influence of F1 “porpoising” Phenomenon and Venturi Floor Design on the Performance of Racing Cars

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**Abstract:**

Aerodynamics is the decisive factor for the performance of modern Formula 1 (F1) cars. Unlike ordinary cars which rely on mechanical grip, F1 racing cars achieve significant downforce through the coordinated operation of the floor, front wings and diffusers, thereby significantly increasing the speed of cornering.In 2022, the Fédération Internationale de l’Automobile (FIA) regulations underwent reform, reintroducing the concept of ground effect, which made the Venturi underbody the core of aerodynamic design. However, this extreme geometric design also leads to the “ porpoising “ phenomenon, where the racing car experiences periodic up-and-down vibrations due to the interruption of air flow at high speeds. This paper systematically analyzes the application of the Venturi effect in the base plate of F1 racing cars and its impact on downforce and drag through literature review, wind tunnel experiments and Computational Fluid Dynamics (CFD) simulation data. At the same time, it also explores the formation mechanism of the porpoising and its comprehensive influence on the stability of the racing car, the physical condition of the driver and the competition results. Case studies show that the Mercedes W13 frequently exhibits dolphin leaps due to the design of its base plate. In contrast, the Red Bull RB18 effectively mitigated this phenomenon through geometric optimization and material reinforcement. The conclusion of this study emphasizes that in the future development of F1 aerodynamics, a balance needs to be struck between pursuing extreme performance and maintaining stability.

**Keywords:** Aerodynamics; Venturi effect; Ground effect; CFD; Formula 1.

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# 1. Introduction

This article introduces the "porpoising" phenomenon and the Venturi plate, as well as the background of its re-emergence in the 2022 season due to the new regulations. In 2022, the FIA modified the Formula 1 technical regulations, aiming to reduce the downforce sensitivity to drafting in order to make overtaking easier. Therefore, the FIA changed the shape of the car body, as well as the proportion and design of the wings [1]. After the modification, most of the downforce was generated through the ground effect, resulting from the very large Venturi ducts with Venturi plates. the first season following the implementation of the new regulations, such incidents represented a step towards the unknown. Almost all racing cars will experience severe bouncing incidents on the track. This is known as the " porpoising" phenomenon. This is caused by the unstable airflow between the aerodynamic floor and the ground. This will result in a decline in the overall performance of the racing car, damage to the body, and health problems for the driver. This phenomenon not only may affect the competition results, but also may endanger the physical conditions of the racing drivers. In conclusion, the research on the aerodynamics of F1 racing cars has shifted from simply increasing downforce to achieving a balance between downforce and the stability of the car's aerodynamics. The Venturi plate, while offering significant performance potential, also introduces unprecedented engineering risks. Therefore, studying the relationship between the Venturi effect and the dolphin jump phenomenon is of great significance for understanding the development trend of F1 aerodynamics and guiding the engineering practices of the teams. This paper will, through literature analysis, experimental data and case studies, explore the aerodynamic mechanism of the Venturi plate design and its impact on the performance of racing cars. It will also systematically analyze the formation mechanism and influence range of the dolphin jump phenomenon, and finally propose potential improvement measures and future research directions.

# 2. The fundamentals of aerodynamics in F1 racing cars

## 2.1 The role of aerodynamics in F1

The Aerodynamic optimization is central to modern F1 cars design, driving performance through two primary objectives: minimizing air resistance to maximize straight-line speed and generating substantial downforce to enhance grip and cornering ability without sacrificing velocity. Unlike conventional vehicles that depend on mechanical grip from tires, F1 cars rely on aerodynamics to produce the majority of their traction, enabling cornering forces exceeding 5g [1]. At speeds above 250 km/h, downforce can surpass the car's weight, effectively anchoring it to the track. This allows for elevated cornering speeds, reduced braking distances, and improved lap times, critical for competitive performance.

Historically, downforce was primarily generated by upper-body components like wings and bargeboards. However, these elements produce significant vortices and turbulent airflow, disrupting trailing cars and reducing their aerodynamic efficiency by up to 50% in certain conditions [1]. In 2022, the FIA's regulations focused on ground effect aerodynamics, emphasizing the synergy of the front wing, floor, and diffuser to generate high downforce and reduce wake interference [2]. This approach enhanced grip in corners, enabling F1 cars to outpace other racing categories through corners. For instance, the Venturi tunnels in the floor accelerate airflow to create low-pressure zones, significantly boosting downforce while maintaining cleaner air for following cars, thus facilitating closer racing and overtaking opportunities.

Fundamental Principles of Formula 1 Aerodynamic Design

The aerodynamic optimization of racing cars is mainly achieved through three aspects: reducing air resistance, increasing downforce and enhancing the stability of the racing car. First of all, air resistance is the main obstacle to the performance of the racing car when it passes through a long straight section. According to the resistance formula:

$$D = 1/2\rho v^2 Cd \tag{1}$$

where ρ is air density, v is velocity, Cd is the drag coefficient, and A is frontal area. In F1 racing, the main way to significantly reduce the frontal area and thus decrease air resistance is by narrowing the cross-sectional area, optimizing the body shape, and concealing the suspension components. At the same time, increasing downforce is also a key aspect of the aerodynamics design in F1. According to the lift formula:

$$L = \frac{1}{2\rho v^2 Cl} \tag{2}$$

If Cl < 0, a negative lift—or downforce—is generated. The front wing, rear wing, diffuser, and particularly the underfloor are designed to maximize this effect.

In 2022, the FIA modified the Formula 1 technical regulations, aiming to reduce the downforce sensitivity to drafting in order to make overtaking easier. Therefore, the FIA changed the shape of the car body.

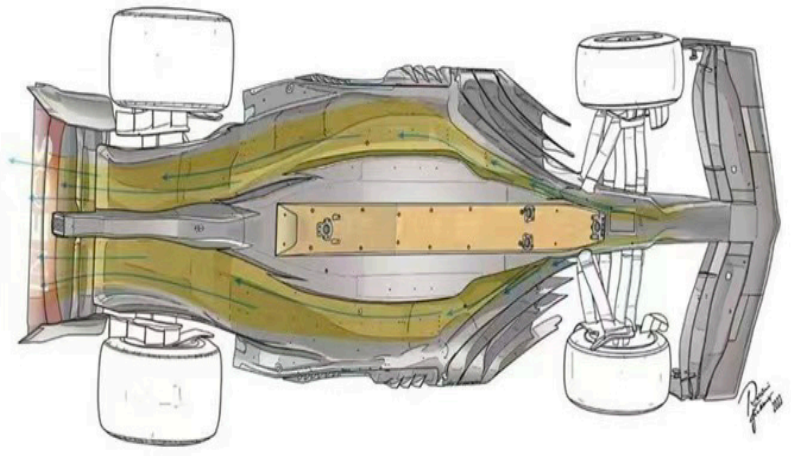

**Fig. 1 The underfloor of the Formula 1 car**

Key changes included:

• Elimination of complex bargeboards and vortex generators.

• Standardization of front and rear wing profiles.

• Introduction of sealed floor edges and defined Venturi tunnels extending from the front of the floor to the diffuser.

As detailed in the Figure 1, shows the Venturi tunnel of a Formula 1 car. These tunnels are designed to accelerate airflow beneath the car, creating a low-pressure region that generates suction. Because this force is centered and produces less wake, it was expected to improve following performance as detailed in the Figure 2. However, the underfloor became extremely sensitive to ride height, suspension travel, and track surface irregularities—conditions that vary constantly during a race. The Venturi effect describes how fluid velocity increases and pressure decreases in a constricted flow path. In F1, the underfloor acts as an inverted Venturi tube, with the track forming the lower boundary. According to Bernoulli's principle:

$$P + 1/2\rho v^2 + \rho gh = constant \quad (3)$$

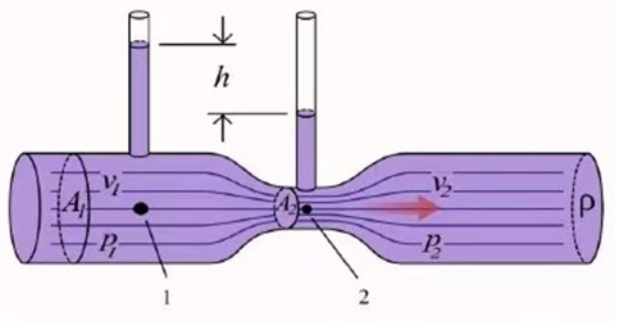


**Fig. 2 Venturi tunnel**

The ground-effect aerodynamics central to modern Formula 1 cars rely on the Venturi effect, where airflow accelerates through the narrow throat of the underfloor tunnel, reducing static pressure and generating significant downforce to enhance grip [1]. This system, however, operates within a tightly constrained ride height window. When the gap between the car's floor and the track falls below a critical threshold—typically 15–20 mm—airflow risks separating or choking, causing a sudden loss of suction and destabilizing the car [2].

T This instability is the main cause of the "dolphin jump" phenomenon, that is, due to the interaction between the constantly changing aerodynamics and the suspension dynamics, the racing car will vertically bounce up and down. CFD studies and wind tunnel tests consistently demonstrate that even minor ride height variations, as small as 1–2 mm, can lead to substantial downforce fluctuations, particularly in cars with aggressive underfloor designs optimized for maximum suction [2]. The expansion angle of the diffuser further enhances this sensitivity: a steeper angle increases downforce by accelerating the airflow, but in dynamic conditions (such as during track bumps or high-speed turns), it increases the possibility of airflow separation, thereby exacerbating instability and the risk of "swaying" [2].

These findings indicate that the F1 teams must strike a delicate balance between maximizing aerodynamic performance and maintaining stability in various racing conditions.

## 2.2 The Mechanism of Porpoising

Porpoising phenomenon was first observed during the preseason tests in 2022. High-speed footage showed that, especially for the Mercedes W13 racing car, it was experiencing violent up-and-down swaying on the straight sections. This movement has a rhythmic quality, and the frequency of its vertical motion is between 8 and 12 hertz -

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this range coincides with the natural resonant frequency of the human spine [3]. Drivers reported severe discomfort. As detailed in Figure 3, Lewis Hamilton described the 2022 Azerbaijan Grand Prix as one of the most physically demanding races of his career, citing back pain caused by repeated vertical loading [4]. George Russell also confirmed the physical toll, noting that the oscillations made it difficult to maintain concentration over race distance.


**Fig. 3 Lewis Hamilton troubled by back pain after the race due to the car's porpoising phenomenon.**

Telemetry data revealed that the oscillations were self-sustaining, persisting as long as the car remained at high speed.

Porpoising is not random bouncing—it is a self-excited oscillation driven by a feedback loop between aerodynamics and suspension dynamics:

1. At high speed, airflow accelerates under the car, generating strong downforce.
2. The car is pushed downward, compressing the suspension and reducing ride height.
3. As the underfloor gap narrows, airflow begins to separate or choke.
4. Downforce collapses suddenly, releasing the downward load.
5. The suspension rebounds, lifting the car and restoring the gap.
6. Airflow reattaches, downforce rebuilds—and the cycle repeats.

This process creates a limit cycle oscillation. If the frequency of the aerodynamic pulses aligns with the natural frequency of the suspension or chassis, resonance can amplify the motion.Unsteady CFD simulations have demonstrated that even sub-millimeter changes in underfloor clearance can trigger significant pressure fluctuations, confirming the sensitivity of the system [3]. Porpoising is thus a classic example of fluid-structure interaction (FSI)—a challenge well-known in aerospace and civil engineering, but newly critical in modern F1. And it also causes some human consequences

The impact extends beyond driver comfort:

• Performance loss: Drivers must lift off the throttle to dampen oscillations, sacrificing top speed.
• Braking instability: Oscillations disrupt weight transfer, increasing stopping distances.
• Tire degradation: Irregular vertical loads accelerate wear and reduce grip consistency.

More critically, the physiological impact is significant. Exposure to 8–12 Hz vibrations over 90+ minutes can lead to spinal fatigue, muscle strain, and long-term musculoskeletal issues [5]. This raises ethical and regulatory questions about driver safety.

## 3. Case Study: Contrasting Design Philosophies

The Mercedes W13 featured an aggressive aerodynamic

concept: ultra-narrow sidepods, a deep underfloor, and a focus on maximizing airflow under the car. The design aimed to enhance the "coke-bottle" effect, improving airflow conditioning into the Venturi tunnels, as shown in Figure 4.

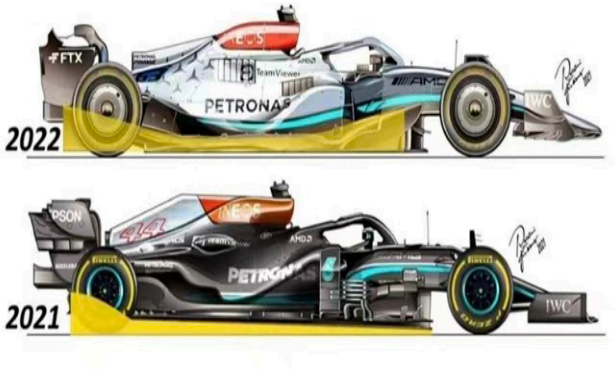


**Fig. 4 The different concept of the floor design of the Mercedes-AMG F1 car between the 2021 and 2022 seasons.**

However, this aggressive design came with significant drawbacks. The underfloor proved extremely sensitive to changes in ride height, operating effectively only within a very narrow window. Even small vertical movements from the suspension—such as those caused by track undulations or aerodynamic loading—could disrupt the airflow beneath the car, leading to premature flow separation. This instability was further worsened by structural deformation; reports and technical analyses indicated that the floor itself experienced measurable flex under high aerodynamic loads, which altered the intended geometry and disrupted the low-pressure seal essential for ground effect [6]. As a result, the W13 began exhibiting porpoising at relatively low speeds, often as early as 260 km/h, well within the range of many circuits' straights. To manage the issue, the team had to make substantial setup compromises. These included raising the ride height to increase clearance, reinforcing the floor structure to reduce flex, and adjusting suspension damping characteristics to suppress oscillations. Although these measures do help reduce the jolts of the vehicle, they also cause the vehicle to deviate from the optimal aerodynamic operating state. As a result, the peak downforce significantly decreases, and the mechanical grip in high-speed turns also weakens. By the middle of the season, it became clear that the design of the W13 model prioritized theoretical aerodynamic efficiency over actual dynamic stability, which ultimately limited its performance potential, despite its innovative design concept. To some extent, this phenomenon weakened the competitiveness of the Mercedes team. As a result, the team only scored 575 points - only 14 points less than the 589 points of the Red Bull team - and failed to win the championship.

In contrast, the Red Bull RB18 adopted a more pragmatic and balanced approach in terms of its aerodynamic layout. Although it strictly followed the 2022 regulations and mainly relied on the ground effect generated by the ventilated tubular chassis to provide downforce, His design prioritizes consistency and stability over the pursuit of peak values in the wind tunnel. The key elements of this design concept include moderately widened side skirts, which help to improve the flow of air entering and surrounding the chassis, thereby enhancing the stability of the airflow. The structure of this chassis is more gentle compared to those of competitors such as Mercedes. This reduces its sensitivity to changes in driving height and lowers the probability of faults caused by sudden airflow detachment. Additionally, Red Bull focused on structural rigidity, reinforcing the floor to minimize flex under load—a known trigger for porpoising. This strict control over mechanical performance ensures that this aerodynamic platform can maintain stable performance under various track conditions and fuel loadings. Therefore, in the 2022 season, the RB18 model hardly experienced any jolts up and down, even on those rough tracks that other racing cars struggled to handle. CFD simulations and race telemetry consistently showed a flatter downforce curve across varying ride heights, indicating a much wider operating window [6]. This stability gave Max Verstappen the confidence to drive at his full potential, allowing him to remain undisturbed by violent vibrations, thus maintaining a stable lap time and better managing the tires. This car is not only fast but also highly practical. The speed, reliability and driving comfort advantages he demonstrated played a crucial role in the dominance of the Red Bull team in 2022 and 2023. This proves that long-term success often stems

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from strong engineering technology rather than minor improvements at the control margins.

The McLaren MCL36 performed exceptionally well during the 2022 preseason tests. The reason for this was that it adopted a robust aerodynamic design, which successfully eliminated the up-and-down movement of the vehicle body [7]. Its relatively shallow Venturi tube and moderate diffuser angle reduce the sensitivity to vehicle height, keeping the downforce within a range of 20 to 25 millimeters, with a fluctuation amplitude of less than 10%. For changes of 1 to 2 millimeters, the fluctuation amplitude does not exceed 10%. The streamlined side skirt design ensures smooth airflow and reduces wind resistance, thereby enhancing the straight-line driving performance and tire lifespan on low-resistance circuits like Monza. Driver Landor Norris and Daniel Ricciardo stated that during high-speed driving, the vibration amplitude decreased, allowing them to adopt aggressive suspension settings without experiencing significant discomfort. This stability enabled the team to secure the third place in the Australian race as recorded in the 2022 race report, but this conservative design sacrificed a certain degree of peak downforce on a high-pressure track like Monaco [8].Mid-season upgrades to floor strakes further reduced oscillations, securing a fourth-place constructors' finish McLaren's strategy focuses on controlling performance. It has successfully combined aerodynamic design with suspension tuning to effectively reduce the interaction between fluids and the structure.

In the 2022 season, Ferrari's F1-75 racing car maximized downforce through a deep Venturi channel. The generated downforce even surpassed that of McLaren's MCL36 car. However, this design caused a serious "swinging" phenomenon when the speed exceeded 260 kilometers per hour. CFD simulation results show that a slight reduction in the vehicle body height would significantly decrease the downforce and trigger low-frequency oscillations similar to the "swinging tail" phenomenon, which led to the driver discomfort described by Charles Leclerc and Carlos Sainz. To mitigate this, Ferrari initially raised the ride height , which stabilized the car but reduced downforce by approximately , adding 0.2–0.3 seconds to lap times. By the Spanish Grand Prix, Ferrari introduced upgrades, including revised floor strakes and a diffuser angle adjustment which notably reduced the severity of "porpoising" [9]. Due to the flexibility regulations of the FIA, stronger carbon fiber reinforcements were adopted, further enhancing the structural stability [2]. At Silverstone Circuit, Leclerc noticed that the vibration amplitude decreased by 70%, which enabled the F1-75 racing car to achieve five victories in the early stages of the season. However, the initial performance decline caused by the frequent "dive" maneuvers cost Ferrari approximately 50 championship points. This highlights the risks associated with the aggressive design, as such designs require a significant amount of resources for correction [8]. Despite these challenges, Ferrari's rapid adaptations highlighted their engineering resilience, though at the expense of development resources diverted from other areas, such as power unit reliability. The widespread "frequent jumping" phenomenon in the 2022 season prompted the FIA to introduce stricter rules to ensure the safety and fairness of the races. The mandatory installed vehicle height sensor is designed to ensure the minimum ground clearance to avoid excessive interference from air flow. The improved floor deformation test has solved the problem of excessive bending, which exacerbated the vibration phenomenon. The strict review of the compliance of the lower part of the floor has limited the flexible body parts that might violate the aerodynamic rules. These measures are aimed at creating a fair competitive environment and protecting the health of the drivers by reducing harmful vibrations. By 2023, all teams had largely adapted to these restrictions. Mercedes learned from the difficulties of the W13 and launched the W14 racing car, which had its chassis redesigned and its suspension dynamics improved, significantly reducing the "porpoising" phenomenon. Red Bull, building on their stable RB18 platform, further refined their design, widening their performance advantage. The 2022 season demonstrated a significant shift in the F1 design philosophy, moving from an aerodynamic design focused on peak performance to a more robust and adaptable system that can balance speed, stability, and driver safety under dynamic racing conditions.

## 4. Conclusion

The 2022 F1 technical regulations aim to enhance the quality of the races by reintroducing ground effect aerodynamics. The focus is on increasing downforce and reducing rear flow turbulence, which is beneficial for overtaking. However, this shift exposed a fundamental engineering challenge: ensuring the stability of ground-effect systems under dynamic conditions, such as varying track surfaces and speeds. The "porpoising" exhibits a regular vertical oscillation characteristic. Its occurrence is not due to a design flaw, but rather is caused by some radical design choices that ignore the interaction between the fluid and the structure. This phenomenon occurs when the airflow beneath the vehicle loses its stability, thereby triggering a feedback loop with the suspension dynamics. It has an impact on vehicle performance and the health of the driver. Mercedes' experience with the W13 exemplifies the pitfalls of over-optimization. Its pursuit of maxi-

mum downforce through a deep Venturi floor led to severe porpoising, compromising lap times and driver comfort due to excessive vibrations. Conversely, Red Bull's RB18 showcased the advantages of a balanced, systems-level approach. By prioritizing aerodynamic strength and structural integrity, the Red Bull team achieved stable driving performance, a shorter development cycle, and reduced the physical burden on the drivers, thereby achieving dominance in 2022 and 2023. This contrast highlights the need to design solutions that can both achieve aerodynamic efficiency and ensure actual stability. To address the swaying issue, the team must adopt targeted strategies: design a vehicle base structure with lower sensitivity to changes in driving height, enhance the structural stiffness to reduce dynamic deformation, take the biomechanical characteristics of the driver as the core constraint condition to reduce health risks, and utilize real-time CFD simulations to predict and prevent the instability threshold. These measures ensure performance gains without compromising safety. Regulators may also need to intervene by introducing rules, such as vibration limits or mandatory ride height sensors, to safeguard drivers if porpoising persists as a health concern. Ultimately, the innovations in F1 should enhance the competitive performance of the races, while prioritizing the safety of the drivers and the stability of the races. It is essential to ensure that the advancements in engineering technology align with the overall goals of this sport.

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