

# Fluid Mechanics Principles of Venturi Tunnels and Ground Effect Aerodynamics in Formula One Racing Cars

Zicheng Wang \*

The Experimental High School Attached to Beijing Normal University, Beijing, China

\* Corresponding Author Email: max.wang2030@gmail.com

**Abstract.** Ground effect aerodynamics has been central to the performance of Formula One (F1) racing cars. By shaping the underfloor as Venturi tunnels, engineers can accelerate airflow beneath the chassis, reduce static pressure, and generate strong downforce with limited drag penalties. This idea was first applied in F1 during the late 1970s, later restricted, and reintroduced in the 2022 regulations. This paper reviews the fluid mechanics principles of the Venturi effect using Bernoulli's equation and the continuity law, and summarizes how these principles are applied in modern racing. Wind tunnel experiments and computational fluid dynamics (CFD) models have shown that floor geometry, diffuser expansion angle, and ride height strongly influence downforce. Theoretical work further explains the physical mechanism of ground effect. Results from these studies indicate that Venturi tunnels can provide a large proportion of total downforce, while also introducing challenges such as "porpoising". This review highlights the continuing importance of ground effect in motorsport and its relevance for vehicle aerodynamics more broadly.

**Keywords:** Formula One; ground effect; Venturi tunnel; Diffuser; Computational fluid dynamics.

## 1. Introduction

### 1.1. Background

Aerodynamics has always been a key factor in Formula One racing. By generating downforce, cars achieve higher cornering speeds and better stability without adding weight. One of the most influential aerodynamic innovations is the ground effect, which makes use of the Venturi principle to accelerate airflow under the car, creating low pressure that pulls the car toward the track [1].

The concept was famously applied in the Lotus 78 and 79 during the late 1970s, using Venturi-shaped under floors and skirts to seal airflow [2]. Although highly effective, this design also created risks: if ride height changed suddenly, the downforce could collapse, leading to instability. As a result, the FIA banned movable skirts and imposed flat floors in 1983. However, underbody aerodynamics remained central, with diffusers becoming an important tool [1]. In 2022, the FIA reintroduced ground effect through new technical rules, reshaping car design and re-emphasizing Venturi tunnels [3].

The historical development of ground effect also shows how regulations shape engineering solutions. After skirts were banned in 1983, designers experimented with alternative diffuser geometries to regain lost performance. For instance, stepped floors and vortex generators were investigated as ways to energize the underfloor flow. These adjustments highlight that while rules limit certain concepts, the fundamental goal of enhancing underbody suction through Venturi mechanisms has remained consistent over decades.

### 1.2. Literature Review and Research Progress

Early studies concentrated on fundamental experiments. Zerihan and Zhang tested single-element wings close to the ground and showed that aerodynamic forces change non-linearly with ride height. Their results proved that ground clearance strongly affects lift and drag, with downforce rising as the wing approaches the surface, until separation occurs at very small gaps [4].

Zhang, Toet, and Zerihan provided a broad review of ground effect aerodynamics, summarizing how Venturi tunnels, diffusers, and boundary layer interactions determine pressure distribution and downforce generation. They emphasized that design effectiveness depends heavily on geometry and stability [1].

Diffusers have since been studied extensively. Saddington et al. reviewed diffuser research and concluded that expansion angle, length, and sealing are critical for maintaining attached flow [5]. Bhardwaj used CFD on simplified race car models, confirming that diffuser geometry directly influences both downforce and drag [6]. Minto applied CFD and wind tunnel methods to Formula SAE cars, further validating how underfloor tunnels enhance performance at different ride heights [7].

CFD methods have advanced the field. Buscariolo et al. applied spectral/hp element simulations to capture detailed flows past an F1 front wing in ground effect, showing that high-fidelity CFD can replicate complex vortical structures [8]. Krajnović and Basara studied Ahmed body configurations with simplified diffusers, demonstrating how geometry changes control pressure recovery and separation [9].

On the theoretical side, Tuck and Bentwich developed exact solutions for ground effect, clarifying the physical mechanism of pressure change when bodies move close to the ground [10]. Finally, recent work by Li and Wang traced the development of F1 aerodynamics, emphasizing the renewed role of ground effect under the 2022 regulations [2]. Hu analyzed the Venturi tunnels in modern F1, noting both their benefits and the challenge of “porpoising” [3].

In addition to aerodynamic measurements, theoretical approaches have also been applied. Tuck and Bentwich provided exact solutions to simplified ground effect problems, confirming that reduced pressure beneath a body near the ground can be derived directly from potential flow equations. Their results serve as a mathematical foundation that complements wind tunnel and CFD findings [10].

### **1.3. Motivation and Framework**

Although ground effect has been studied for decades, questions remain about the interaction between geometry, ride height, and flow separation. The return of Venturi tunnels in F1 has renewed academic and engineering interest. This review aims to summarize the theoretical principles, experimental and CFD approaches, and the engineering applications of ground effect using only recent and relevant literature. The structure is as follows: Section 2 outlines theoretical foundations; Section 3 discusses methods including CFD and wind tunnels; Sections 4 and 5 summarize results; Section 6 highlights limitations and outlooks; Section 7 concludes the paper.

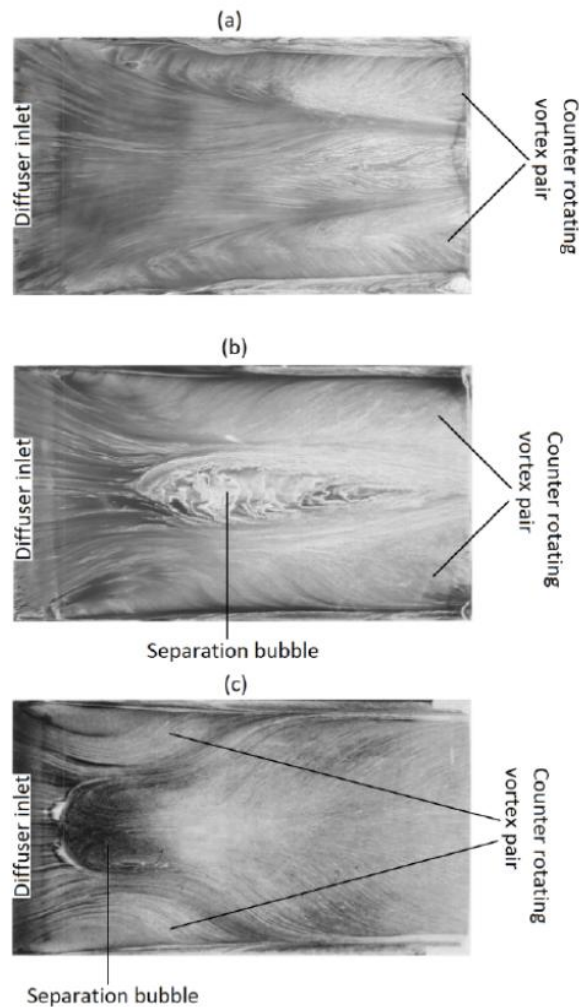
## **2. Theoretical Research**

### **2.1. Core Knowledge and Governing Equations**

The ground effect in Formula One cars is governed by Bernoulli’s principle and the continuity equation. When airflow is forced through a constricted throat in a Venturi tunnel, its velocity increases and static pressure decreases, creating suction. Zhang, Toet, and Zerihan emphasized that this mechanism explains much of the additional downforce in ground effect cars, and that diffuser geometry and ride height are the most sensitive design parameters [1].

### **2.2. Simplified Underfloor Geometry**

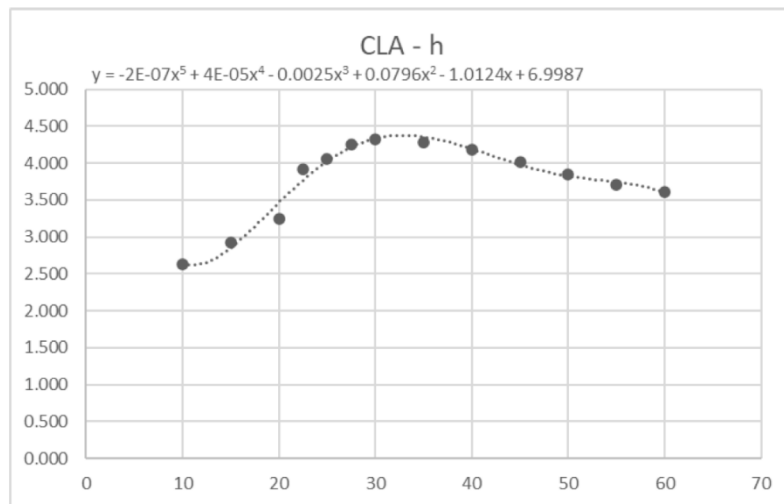
Researchers often analyze simplified underfloor models to quantify how diffuser angle and ride height affect aerodynamic forces. Saddington et al. reviewed numerous studies and concluded that diffuser expansion angles between  $5^\circ$  and  $10^\circ$  generally produce stable pressure recovery, while angles greater than  $12^\circ$ – $15^\circ$  increase the risk of separation [5]. Fig. 1 shows the flow visualization on the ramp surfaces for  $5^\circ$ ,  $10^\circ$ , and  $15^\circ$  expansion ramps, where counter-rotating vortex pairs can be clearly identified [5].



**Fig. 1** Flow visualization on the ramp surfaces of (a) 5, (b) 10 and (c) 15 diffusers at maximum-downforce ride height (flow from left to right) [5]

Bhardwaj applied CFD to race car geometries and confirmed that geometry changes directly influence both downforce and drag trends, even though the absolute values are dependent on the model scale [6].

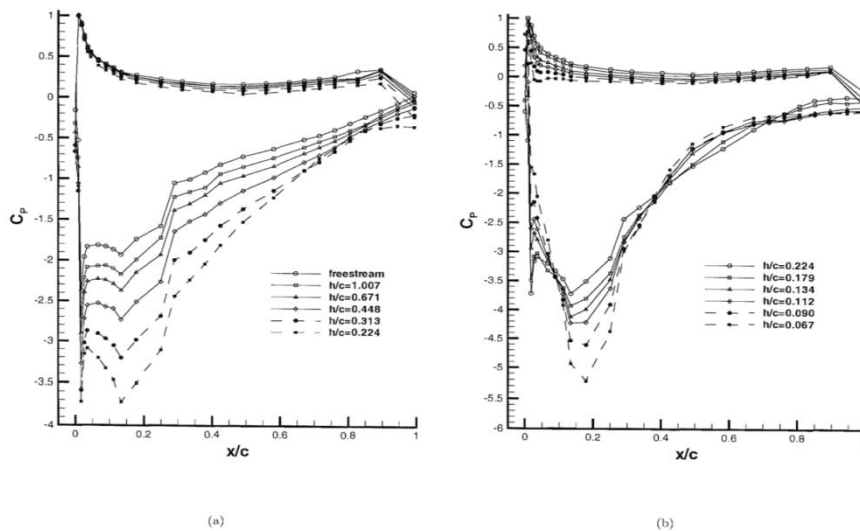
Minto, studying a Formula SAE car, provided experimental and CFD data showing how ride height influences diffuser contribution. At a ride height of 25 mm, the diffuser produced about 42% of the total downforce, while at 15 mm, this contribution rose to about 58%. However, further reduction in ride height caused unstable flow and a reduction in aerodynamic efficiency. These results confirm that diffuser performance is highly non-linear with respect to clearance [7]. Fig. 2 illustrates the variation of the lift coefficient with ride height for a Formula SAE diffuser, showing that downforce increases as clearance reduces to about 20–25 mm before falling at lower heights due to flow separation [7].



**Fig. 2** CLA – height [7]

### 2.3. Wind Tunnel Studies

Wind tunnel testing remains one of the most important tools for studying ground effect. Zerihan and Zhang tested single-element wings in a moving-ground tunnel and found that at a clearance of 0.1 chord length, the lift coefficient nearly doubled compared with freestream conditions. When the clearance was reduced to below 0.05 chord length, separation occurred and downforce decreased sharply. These findings illustrate the strong but limited effect of ground proximity [4]. Fig. 3 presents chordwise pressure distributions for wings at various ground clearances, indicating that as  $h/c$  decreases from 1.0 to 0.1 the suction peak grows, but at very low clearances separation occurs and downforce diminishes [4].



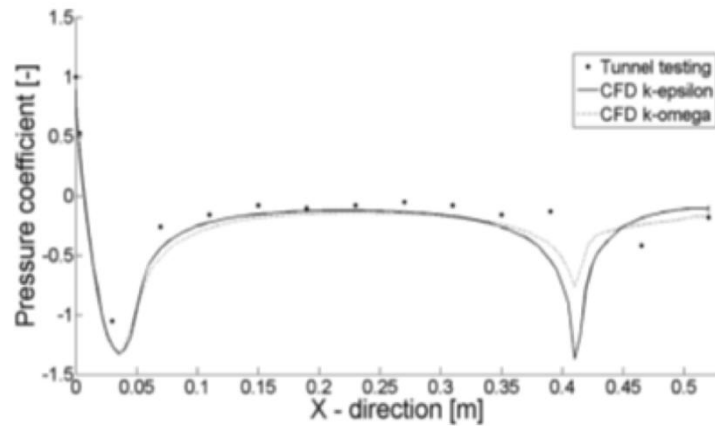
**Fig. 3** Chordwise surface pressures at wing center in ground effect at  $\alpha = 5^\circ$  (a) Moderate and large ground heights. (b) Small ground heights. [4]

Zhang et al. also noted that accurate simulation of the moving ground is essential in wind tunnel experiments. Without a rolling road system, a stationary ground plane introduces a boundary layer that weakens the suction effect and underestimates downforce [1].

### 2.4. Computational Fluid Dynamics (CFD) Studies

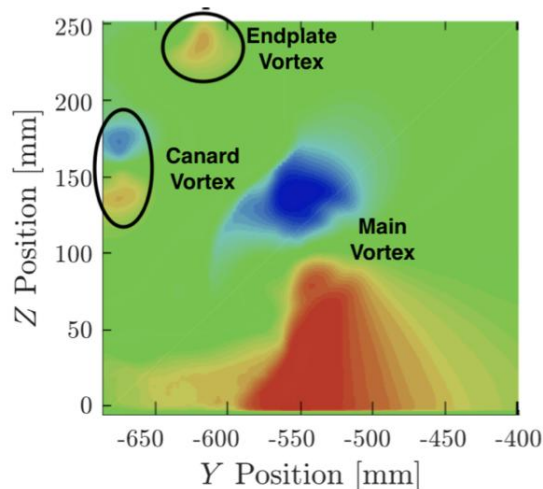
With increasing computational power, CFD has become a standard method for analyzing underbody aerodynamics. Bhardwaj showed how diffuser length and angle influenced pressure

distribution and aerodynamic coefficients, with CFD results validated against simplified experiments [6]. Fig. 4 shows the centerline pressure distribution from CFD simulations of an Ahmed body equipped with a diffuser, demonstrating strong sensitivity of pressure recovery to geometry [6].

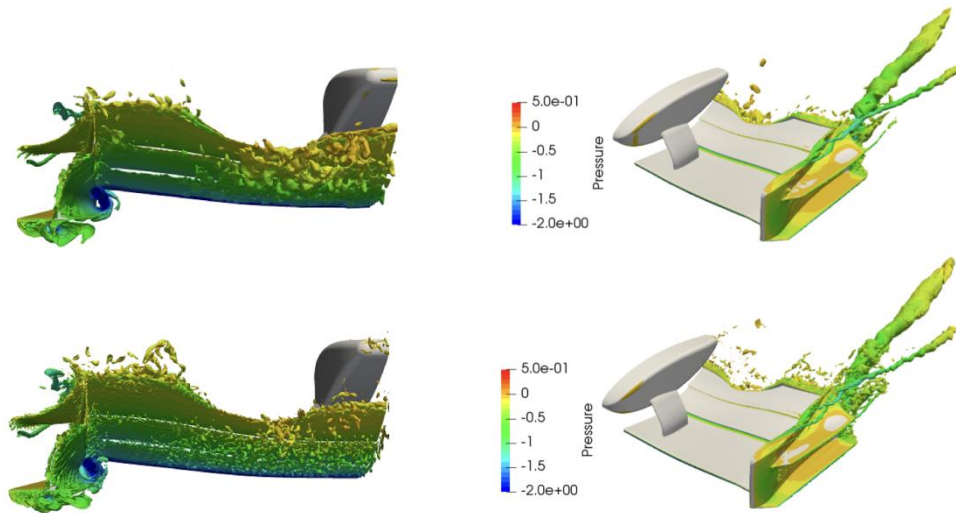


**Fig. 4** centerline pressure distribution of INVERTED AHMED BODY (Knight et al., 2018) [6]

Buscariolo et al. applied spectral/hp element CFD methods to simulate an F1 front wing close to the ground, capturing detailed vortical structures that are difficult to observe experimentally [8]. Fig. 5 illustrates the main vortex system generated by a front wing in ground effect, including the canard, endplate, and primary vortices [8]. Fig. 6 presents iso-contours of instantaneous vortical structures near the diffuser, highlighting unsteady shedding that influences flow stability [8].

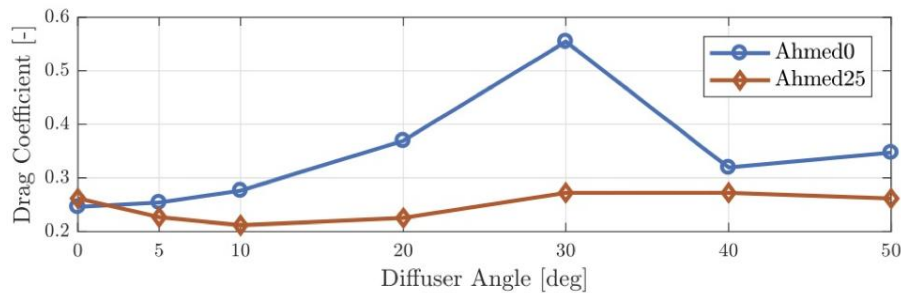


**Fig. 5** Imperial Front Wing vortices nomenclature definition. From top to bottom: endplate vortex (partially represented), canard vortex and main vortex. [8]



**Fig. 6** Comparison of instantaneous iso-contours of  $CP0 = 0$  colored by pressure, with instantaneous plane 1 (left) and instantaneous full (right) views, for both NM43(top) which have a polynomial order of 4 for velocity and 3 for pressure, and NM54 (bottom) simulations [8]

Krajnović and Basara investigated Ahmed-body models equipped with simplified diffusers and found that smoother expansion profiles delayed separation and improved pressure recovery [9]. Fig. 7 shows the drag coefficient comparison for Ahmed bodies with different diffuser expansion angles, indicating that moderate expansions reduce drag while excessive angles cause separation and drag rise [9].



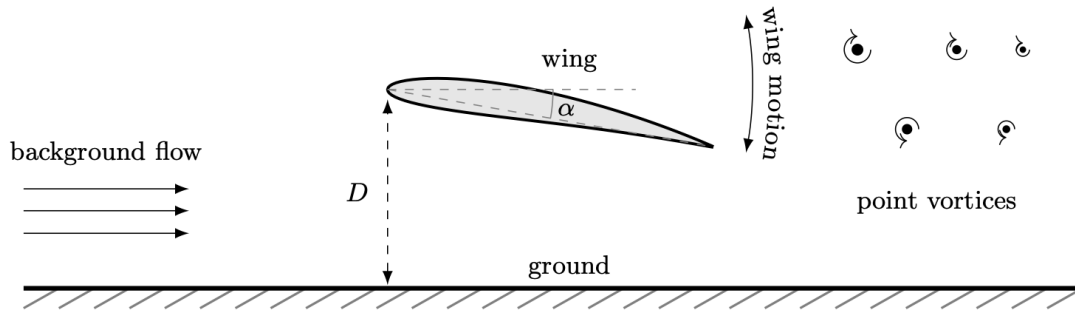
**Fig. 7** Drag coefficient comparison for Ahmed Body squared-back (blueline) and 25° slant inclination (orange line) considering standard configuration and evaluated diffuser angles: 5°, 10°, 20°, 30°, 40° and 50° [9]

Minto also validated CFD against wind tunnel measurements, reporting that differences in downforce coefficients were within 5%, showing good agreement between numerical and experimental results [7].

## 2.5. Analytical Solutions for Ground Effect

Another perspective on ground effect has been provided through analytical approaches. Tuck and Bentwich derived exact potential-flow solutions for simplified ground-effect problems, treating the flow as incompressible and inviscid. By applying complex-variable methods, they obtained closed-form expressions for velocity and pressure in the narrow channel between a lifting surface and the ground plane. Their results confirmed the classical Venturi principle: as clearance decreases, the local velocity increases and the static pressure drops, leading to stronger suction beneath the body. The pressure coefficient  $C_p$  was shown to become increasingly negative as the gap narrows, which is consistent with trends observed in wind tunnel and CFD studies. Although the model ignores viscous effects and flow separation, it provides a theoretical baseline for understanding ground effect in its idealized limit. This work demonstrates how mathematical solutions can complement experimental and computational approaches by clarifying the physical mechanism in its simplest form [10]. Fig 8

shows the scientific model of A wing which is in ground effect in a background flow. The chord length is nondimensionalized to unity, the angle of attack is  $\alpha$ , and the distance between the leading-edge and the ground is  $D$ . The origin is placed on the ground in-line with the leading-edge.



**Fig. 8** The mathematical model [10]

## 2.6. Factors Highlighted in Literature

Across the reviewed works, several recurring factors are consistently emphasized:

**Diffuser geometry:** Saddington et al. concluded that angles between  $5^\circ$ – $10^\circ$  are generally effective, while higher angles tend to separate [5].

**Ride height sensitivity:** Zerihan & Zhang observed that downforce doubled when clearance was reduced to 0.1 chord, while Minto found diffuser contribution increased from 42% at 25 mm to 58% at 15 mm [4,7].

**Sealing effects:** Zhang et al. pointed out that lateral sealing of the underfloor is important to reduce leakage and improve suction [1].

**Unsteady phenomena:** Hu described “porpoising” under the 2022 FIA regulations, where oscillations in ride height caused rapid variations in downforce [3].

**Flow structures:** Buscariolo et al. and Krajnović & Basara showed that diffuser-corner vortices and shear-layer reattachment strongly affect stability and separation [8-9].

## 2.7. Evaluation Metrics and Data Sources

The performance of ground effect systems is typically evaluated using aerodynamic coefficients. Bhardwaj and Saddington et al. reported that the lift coefficient ( $C_L$ ) and drag coefficient ( $C_D$ ) are standard measures, with the lift-to-drag ratio ( $L/D$ ) providing an efficiency metric. Pressure recovery and the onset of separation are also important indicators [5-6].

Because detailed F1 data are confidential, most studies rely on surrogate models. Zerihan & Zhang used single wings; Minto analyzed Formula SAE under floors; Krajnović & Basara studied Ahmed-body geometries; Buscariolo et al. used high-fidelity CFD for front wings. These open models provide reliable references for understanding the operation of Venturi tunnels in ground effect [4,7,8,9].

## 3. Results I – Geometry and Flow Mechanisms

The aerodynamic performance of Venturi tunnels in Formula One cars is strongly governed by the geometry of the underfloor and diffuser. Across the literature, geometric parameters such as diffuser expansion angle, throat height, and contouring of the tunnel have been identified as critical for generating stable downforce.

### 3.1. Diffuser Expansion Angle

Saddington et al. reviewed experimental and computational work and concluded that expansion angles between  $5^\circ$  and  $10^\circ$  generally maintain attached flow. Angles greater than  $12^\circ$ – $15^\circ$  increased the likelihood of separation and reduced pressure recovery [5]. Bhardwaj, using CFD, confirmed that

diffuser length and angle directly influenced both pressure distribution and aerodynamic coefficients [6].

### **3.2. Throat and Inlet Geometry**

Minto reported that in a Formula SAE car, the diffuser contributed about 42% of total downforce at 25 mm ride height and 58% at 15 mm [7]. Zerihan and Zhang tested single-element wings and found that at a clearance of 0.1 chord length, the lift coefficient nearly doubled compared with freestream; at  $<0.05$  chord, separation occurred [4]. These results show that throat clearance plays a critical role in downforce generation.

### **3.3. Flow Structures and Pressure Recovery**

Buscariolo et al. demonstrated through spectral/hp element CFD that pressure coefficients ( $C_p$ ) on the lower surface of a front wing decreased significantly in ground effect, creating strong suction [8]. Krajnović and Basara showed that smoother diffuser expansion delayed separation and improved pressure recovery in Ahmed-body studies [9].

Furthermore, Zhang, Toet, and Zerihan summarized that sealing devices along the underfloor edges reduce lateral leakage, thereby enhancing suction in the Venturi tunnels. Although modern F1 regulations prohibit sliding skirts, the principle remains relevant, as vortex structures along the floor edges can act as partial sealing mechanisms [1].

### **3.4. Summary**

Across studies, diffuser angle, throat geometry, and flow structures all strongly influence downforce. The optimal range is limited: moderate diffuser angles and controlled clearances produce the most stable results, while exceeding these limits leads to separation.

The historical development of ground effect also shows how regulations shape engineering solutions. After skirts were banned in 1983, designers experimented with alternative diffuser geometries to regain lost performance. For instance, stepped floors and vortex generators were investigated as ways to energize the underfloor flow. These adjustments highlight that while rules limit certain concepts, the fundamental goal of enhancing underbody suction through Venturi mechanisms has remained consistent over decades.

## **4. Results II – Ride Height, Stability, and Performance**

Ride height has consistently been shown to be one of the most critical variables for ground effect aerodynamics.

### **4.1. Ride Height Sensitivity**

Analytical studies also provide valuable insight into how ride height influences ground effect. Tuck and Bentwich derived exact potential-flow solutions for simplified configurations, showing that as clearance between the body and the ground decreases, the velocity in the gap increases while the static pressure falls. This produces stronger suction beneath the surface, creating additional downforce [10]. Although these analytical solutions do not account for viscous effects or flow separation, they establish a theoretical baseline that supports the trends observed in experiments and simulations.

Zerihan and Zhang observed that at  $h/c = 0.1$ , the lift coefficient almost doubled, but below  $0.05c$  the flow separated and downforce decreased [4]. Minto showed that lowering ride height from 25 mm to 15 mm increased the diffuser's share of total downforce from 42% to 58%, but stability declined as clearance decreased further [7].

## 4.2. Porpoising Phenomenon

Hu highlighted that the 2022 reintroduction of ground effect produced the porpoising problem, where oscillations in ride height caused fluctuations in downforce [3]. This effect arises because the aerodynamic force increases as clearance reduces, but a critical minimum leads to flow separation and sudden loss of suction. The repeating cycle creates instability, which teams had to mitigate through suspension design.

Buscariolo et al. noted that unsteady vortical structures generated near the diffuser exit can amplify these oscillations when coupled with vertical body motion [8]. This suggests that porpoising is not only a ride-height issue but also a flow-structure interaction problem.

## 4.3. Broader Trends

Li and Wang summarized that modern F1 cars rely more heavily on underfloor downforce than before, making precise ride height management central to performance [2]. Saddington et al. further noted that instability at low ride heights can cancel the benefits of high downforce [5].

Li and Wang also emphasized that the 2022 regulations intentionally shifted downforce generation toward the floor, reducing reliance on complex upper-body devices [2]. This change aimed not only to increase overtaking opportunities but also to reduce aerodynamic sensitivity in turbulent air. However, several teams reported that following another car still produced measurable losses in diffuser performance, showing that wake interactions remain an open challenge.

## 4.4. Summary

The evidence shows that ride height provides strong aerodynamic gains up to a point, but excessive reduction destabilizes flow. Modern F1 teams face the challenge of maximizing underfloor downforce while avoiding porpoising and separation.

In addition to ride height, lateral position relative to the track surface has also been discussed in the literature. Zhang, Toet, and Zerihan noted that asymmetric ground clearances, such as when a car corners with roll angle, can create uneven suction between the two sides of the floor. This imbalance not only affects total downforce but also generates yawing moments that influence handling stability. Although most academic studies focus on symmetric configurations, this lateral effect remains important in real racing conditions [1].

## 5. Limitations and Future Outlooks

Although many advances have been made, several limitations exist in the current literature:

Restricted access to F1 data – Exact floor geometries and performance metrics remain confidential, forcing researchers to rely on simplified models such as Ahmed bodies [9] or Formula SAE cars [7].

Scaling issues – Results from scaled experiments or student-level cars may not fully replicate the complexities of F1 aerodynamics.

CFD model sensitivity – Predictions depend strongly on turbulence models and grid resolution; small differences can alter separation behavior [6,8].

Computational resources are another practical limitation. While Buscariolo et al. demonstrated that spectral/hp element methods can capture vortical structures in detail, such simulations are computationally expensive and difficult to apply routinely in industry [8]. Krajnović and Basara used more conventional RANS methods, which are less costly but risk under-predicting unsteady separation. Future progress may therefore rely on hybrid methods that balance accuracy with efficiency, enabling more routine application of advanced CFD in motorsport [9].

Looking forward, several directions are emphasized. One important area is high-fidelity validation, where rolling-road wind tunnels are combined with advanced CFD to reproduce flow physics with greater accuracy. Another critical direction involves porpoising studies, aiming to improve the understanding of aero-suspension coupling under ground effect, particularly in the context of the 2022 regulations. Finally, researchers also highlight cross-application potential, extending the insights

gained from F1 racing to road cars and electric vehicles, where underbody flow management is increasingly important for efficiency.

## 6. Conclusion

This review has examined the fluid mechanics of Venturi tunnels and ground effect in Formula One cars. The literature shows that:

Geometry – Moderate diffuser angles ( $5^{\circ}$ – $10^{\circ}$ ) and controlled throat clearances maximize downforce.

Ride height – Strongly influences performance, with peaks at around 0.1 chord or 15–25 mm in scaled cars.

Flow structures – Vortices and pressure recovery determine stability, while poor geometries trigger separation.

Modern challenges – The reintroduction of ground effect has revived porpoising, making suspension and ride height control crucial.

The reviewed literature also shows that theoretical, experimental, and computational approaches complement each other: exact mathematical solutions clarify the pressure mechanism, wind tunnel tests provide physical validation, and CFD extends analysis to detailed flow structures. Only by combining these perspectives can a comprehensive understanding of ground effect be achieved.

Overall, Venturi tunnels remain a powerful mechanism for generating downforce in F1. Their study not only explains past and present racing performance but also provides insights relevant to wider vehicle aerodynamics.

## References

- [1] Zhang X, Toet W, Zerihan J. Ground effect aerodynamics of race cars. *Applied Mechanics Reviews*, 2006, 59(1): 33-49.
- [2] Li S, Wang Q. Study on aerodynamic development in Formula One racing. *Journal of Transportation and Vehicle Engineering*, 2023, 5(4): 112-118.
- [3] Hu T. Analysis of the Venturi tunnel and ground effect. *Proceedings of the 2023 International Conference on Hydraulics, Structural Engineering and Construction Technology (HSET)*, 2023.
- [4] Zerihan J, Zhang X. An investigation into the aerodynamics of wings in ground effect. *University of Southampton ePrints*, 2001.
- [5] Saddington A J, Knowles K, Knowles R D. A review of ground-effect diffuser aerodynamics. *Journal of Fluids Engineering*, 2019, 141(2): 020801.
- [6] Bhardwaj A. Analysis of ground effect diffuser on a race car to optimize aerodynamic performance. *International Journal of Innovative Science and Research Technology*, 2021, 6(5): 916-922.
- [7] Minto A. Ground effect analysis of a Formula SAE car. *University of Padua*, 2022.
- [8] Buscariolo F, Sherwin S, Peiró J, et al. Spectral/hp element simulation of flow past a Formula One front wing in ground effect. *arXiv preprint*, 2019.
- [9] Krajnović S, Basara B. Computational study on an Ahmed body equipped with simplified underbody diffuser. *arXiv preprint*, 2020.
- [10] Tuck E O, Bentwich J. Exact solutions for ground effect. *arXiv preprint*, 2019.