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Aerodynamic Performance of F1 Racing Car Diffusers Based on the Venturi Effect: A Review and Future Perspectives

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Abstract. The aerodynamic performance of Formula 1 racing cars has been fiercely contested for decades, and the underbody diffuser—which generates ground-effect suction through the Venturi effect—is one of the most critical determinants of lap time. Compared to front wings and rear wings, the diffuser offers superior aerodynamic efficiency and exhibits lower sensitivity to turbulent wake from preceding vehicles, making its optimization essential for both qualifying and race performance. This review synthesizes findings reported in the literature from computational fluid dynamics (CFD) simulations and wind tunnel experiments, with a focus on the fundamental mechanisms of the Venturi effect in racing diffusers and the parametric influences of diffuser angle, ground clearance, and throat-to-exit area ratio. The analysis shows that diffuser performance hinges on a delicate balance between pressure recovery and flow separation. Optimal diffuser angles typically range between 5° and 12°, whereas ground clearance exhibits a nonlinear power-law relationship with downforce Key areas of consensus and persistent disagreements in the literature are identified, and future research directions—including dynamic ride-height effects, transient porpoising phenomena, and multi-component aerodynamic interactions—are discussed. This review provides a systematic reference for aerodynamicists and engineers engaged in the design and optimization of open-wheel racing car underbodies.

Keywords: Formula 1 diffuser, Venturi effect, ground effect, downforce

1. Introduction

The pursuit of aerodynamic excellence in Formula 1 racing has driven decades of research into devices that enhance cornering grip and straight-line stability without incurring an excessive drag penalty. Among these devices, the underbody diffuser—which exploits the Venturi effect to accelerate airflow beneath the car and generate suction—has emerged as a particularly efficient downforce generator. Unlike front wings and rear wings, which contribute approximately 60% of total downforce collectively, the diffuser alone can account for up to 40% of a racing car's total downforce [1]. Moreover, diffusers operate with minimal drag penalty and exhibit lower sensitivity to the turbulent wakes generated by preceding vehicles, making them indispensable in both qualifying and race conditions [2].

A substantial body of research has investigated the aerodynamic characteristics of diffusers using both CFD simulations and wind tunnel experiments [1, 3-5]. However, findings remain scattered

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across individual studies, as parametric effects often examined in isolation and under varying boundary conditions. This fragmentation limits the development of a unified understanding of diffuser performance and hinders the translation of research insights into practical design guidelines.

The present review addresses this gap by systematically synthesizing the existing literature on F1 racing car diffusers. The review is structured around three core questions: (1) What are the fundamental theoretical mechanisms by which the Venturi effect governs diffuser-generated downforce? (2) How do key geometric parameters—specifically diffuser angle, ground clearance, and throat-to-exit area ratio—individually influence downforce magnitude and aerodynamic stability? (3) On which issues have the research community reached consensus, and where do significant disagreements remain, thereby pointing toward future research directions? This review consolidates and critically evaluates the available evidence to fill a gap in the literature on the systematic documentation of diffuser aerodynamic performance, and provides a valuable reference for motorsport engineering applications.

2. Theoretical foundations of the Venturi effect in racing diffusers

The Venturi effect, stems from Bernoulli's principle, describes the inverse relationship between flow velocity and static pressure within a converging–diverging duct. In the context of a racing car diffuser, the underbody and the road surface form a convergent channel that accelerates airflow toward the throat—the narrowest cross-section—where static pressure reaches its minimum [6]. The diverging section downstream of the throat, i.e., the diffuser itself, then decelerates the flow and allows pressure recovery toward ambient conditions.

The key performance metric for a diffuser is the pressure recovery coefficient (PRC), defined as the fraction of dynamic pressure recovered in the form of static pressure rise between the diffuser inlet and outlet [7]. An ideal diffuser would recover all dynamic pressure, but in practice, viscous losses and flow separation reduce recovery efficiency. The PRC depends on the area ratio between the throat and the exit, as larger area ratios generally enable greater pressure recovery—provided that flow separation does not occur [6, 7].

For downforce generation, the diffuser serves two interconnected functions. First, it creates a low-pressure region beneath the car by accelerating underbody airflow, which increases the pressure differential between the upper and lower surfaces. Second, it manages the reintegration of underbody flow with the higher-pressure ambient air at the rear of the car, thereby reducing base drag and enhancing overall aerodynamic efficiency [8]. The diffuser's efficiency thus depends on its geometry, operating conditions, and the quality of the incoming flow.

3. Review of diffuser angle effects on diffuser performance

3.1. Diffuser angle and pressure recovery

The diffuser angle—the angle between the diffuser ramp and the horizontal plane—directly influences the expansion ratio and pressure recovery potential. As the diffuser angle increases, the expansion ratio increases, which in principle enhances pressure recovery and suction [7]. Experimental investigations on diffuser cones of 5°, 24°, and 60° demonstrated that the PRC decreases with increasing diffuser angle, with the 5° configuration exhibiting the lowest energy loss and the highest efficiency [7]. For full-scale FSAE applications, Tang et al. found that increasing the diffuser outlet angle from 3° to 15° steadily increased the vehicle's negative lift, whereas the inlet angle had an optimal value of 9°, beyond which downforce fell [1].

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3.2. Trade-off between pressure recovery and flow separation

However, beyond a critical angle, the adverse pressure gradient becomes too steep for the boundary layer to overcome, resulting in flow separation from the diffuser surface [4, 7]. Once separation occurs, the pressure recovery drops precipitously, and downforce decreases sharply while drag may increase. For a 2D diffuser section, Nan et al. reported that the drag coefficient increases monotonically with diffuser angle across different ground clearances, while the negative lift coefficient initially increases with angle up to approximately 8°-10° and then decreases due to stall [4]. The optimal diffuser angle is further influenced by diffuser length; longer ramps, while offering greater potential for pressure recovery, are more prone to boundary-layer separation at moderate angles because the cumulative adverse pressure gradient acts over a greater distance [4]. This interaction between angle and length means that optimal diffuser geometry requires case-specific determination.

4. Review of ground clearance effects on diffuser performance

4.1. Nonlinear relationship between ground clearance and downforce

Ground clearance—the minimum distance between the underbody and the road surface—directly modulates the strength of the ground effect. In general, reducing ground clearance increases the acceleration of underbody airflow, lowers static pressure, and thereby enhances downforce [4, 9]. However, this relationship is not strictly linear and exhibits important nonlinearities. Recent numerical studies report a nonlinear power-law scaling of downforce with ride height [2, 10]. For FSAE vehicles, Nan et al. demonstrated that at a fixed diffuser angle, lower ground clearance generally produces greater negative lift, but the benefit diminishes at very small clearances due to blockage effects from the merging of the underbody and ground boundary layers [4]. Similarly, Qiu et al. noted that for production passenger cars, reducing ground clearance from 140 mm to 100 mm increases aerodynamic downforce but also increases road load [9].

4.2. Flow instability risk at extremely low clearances

While lower ride heights offer greater peak downforce, they also introduce greater sensitivity to ride-height variations caused by braking, acceleration, or uneven track surfaces [2]. As ride height decreases toward a critical threshold, flow instabilities—most notably "porpoising"—can emerge as a self-sustained aerodynamic limit-cycle oscillation [2]. Porpoising, characterized by periodic vertical oscillations of the car, arises from the coupling between aerodynamic load and ride height: increased downforce reduces ride height, which further increases downforce, until the underbody grounds or the flow separates, causing a sudden loss of suction and subsequent rebound [2, 10]. This phenomenon has become a critical issue under current F1 regulations and necessitates careful integration of diffuser design with suspension kinematics and real-time ride-height control strategies [6].

5. Review of throat-to-exit area ratio effects on diffuser performance

5.1. Area ratio and throat flow velocity

The throat-to-exit area ratio is a fundamental design parameter that determines the diffuser's pressure recovery potential [6, 7]. In an ideal diffuser, a larger area ratio enables greater expansion

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and therefore higher-pressure recovery. According to the continuity equation, as the flow transitions from the throat to the larger exit, velocity decreases and static pressure rises. This pressure recovery is the primary mechanism by which the diffuser converts kinetic energy into useful suction beneath the car [6]. Yang et al. demonstrated that increasing the effective area ratio — by extending the diffuser length and raising the exit height — consistently reduced the vehicle's lift coefficient from 0.086 to -0.371 [5].

5.2. "Choking" problems induced by excessive area ratio

However, in practice, the area ratio is constrained by the onset of flow separation and "choking"—a condition in which the flow reaches sonic velocity at the throat, limiting the mass flow rate that can pass through the diffuser [2, 6]. Under choked conditions, downstream changes—such as variations in diffuser angle or exit pressure—no longer affect the upstream flow, effectively decoupling the diffuser from the underbody [10]. This represents a design limit beyond which further increases in expansion ratio yield no additional downforce and may even degrade performance due to increased drag from shock-induced separation [2]. Furthermore, an excessive area ratio promotes premature flow separation within the diffuser due to an overly steep adverse pressure gradient. As reported by Nan et al., this causes the negative lift coefficient to drop after it reaches a peak at specific expansion ratios [3].

6. Consensus, disagreements, and future directions

6.1. Main consensus

Several key findings are broadly agreed upon in the literature. First, the diffuser is consistently identified as the most aerodynamically efficient downforce-generating component on an open-wheel racing car, contributing 40%-55% of total downforce with minimal drag penalty [1, 3, 8]. Second, the diffuser angle exhibits a clear optimum—typically between 5° and 12°—beyond which flow separation causes a sharp decline in performance [1, 4, 7]. Third, the relationship between ground clearance and downforce is nonlinear: reducing clearance increases downforce until a critical stability threshold appears [2, 4, 9].

6.2. Persistent disagreements and open issues

Despite these areas of agreement, significant disagreements remain. The precise optimal diffuser angle varies considerably across studies, and reported values range from 7° to 14° depending on diffuser length, ground clearance, and Reynolds number [1, 4, 5]. This variability suggests that the optimal angle is context-dependent rather than a universal constant. Another area of disagreement concerns the relative importance of ground clearance versus throat-to-exit area ratio; some studies emphasize the dominant role of ground clearance, while others argue that the expansion ratio is equally or more influential [2, 3].

6.3. Future research directions

Several promising directions emerge from this review. First, the dynamic effects of ride-height variation during braking, acceleration, and cornering remain underexplored, as most existing studies assume steady-state conditions [2, 6]. Second, the porpoising phenomenon requires further investigation to develop reliable predictive models and effective mitigation strategies [2, 10]. Third,

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the interaction between the diffuser and other aerodynamic components, particularly the rear wing and rear wheels, warrants systematic study to enable holistic vehicle-level optimization [3, 8]. Finally, the application of active flow-control techniques—such as vortex generators and adaptive geometries—offers potential for extending the diffuser's performance envelope beyond passive-design limits [3, 6].

7. Conclusion

This review has systematically examined the aerodynamic performance of F1 racing car diffusers that operate via the Venturi effect. The analysis confirms that the diffuser is the most efficient downforce-generating device on an open-wheel racing car. The key geometric parameters—diffuser angle, ground clearance, and throat-to-exit area ratio—each exhibit optimal ranges beyond which performance degrades due to flow separation or choking. The diffuser angle must balance pressure recovery against flow separation, and optima typically range between 5° and 12°. Ground clearance follows a nonlinear relationship with downforce, and extremely low clearances introduce porpoising risks. The throat-to-exit area ratio determines pressure recovery potential, and excessive ratios lead to separation or choking.

Regarding limitations, this review primarily draws upon steady-state CFD and experimental data, with limited coverage of transient on-track conditions. Furthermore, most cited studies focus on isolated geometric parameters rather than coupled interactions. Future work should prioritize dynamic ride-height effects, porpoising dynamics, and multi-component optimization to advance both fundamental understanding and practical design. This review fills a gap in the systematic documentation of diffuser aerodynamics and provides a structured reference for motorsport engineers and researchers.

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