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How Underbody Geometric Parameters and Working Clearance Modulate Ground-Effect Flow and Aerodynamic Efficiency of Racing Cars

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Abstract. Ground effect aerodynamics plays a crucial role in the performance of modern racing cars, particularly in the interaction between the underbody geometry and the ground. This article reviews several key parameters related to the underbody and key working clearance that affect the ground effect flow field and aerodynamic efficiency, including ride height, the geometry of the underfloor inlet and Venturi channels, the geometry of the diffuser, and the sealing structures at the floor edges or sides. Special attention is paid to how these parameters affect the mass flow rate, pressure distribution, boundary layer development, flow separation, and the formation mechanism of vortex structures. Existing literature indicates that the most powerful and consistent evidence currently focuses on the coupling effect between ride height and the geometry of the diffuser. Changes in these parameters can trigger different force field patterns, separation states, vortex disintegration, and even lag phenomena in certain configurations. However, results from simplified bluff-body and diffuser models should primarily be interpreted as evidence for ground-effect mechanisms rather than as direct design rules for complete modern racing cars. Cross-research comparisons are also limited by differences in model configuration, Reynolds number, moving ground conditions, force definitions, and reference areas. Therefore, future research should focus more on multi-parameter coupling, consistent dimensionless comparisons, and aerodynamic robustness under dynamic riding heights, wheel wake, yaw, non-uniform intake conditions and other real operating disturbances.

Keywords: Ground effect aerodynamics, Underbody geometry, Diffuser, Ride height, Aerodynamic efficiency

1. Introduction

Ground effect aerodynamics is one of the important factors determining the performance of modern racing cars. One of the key engineering issues is how to achieve the desired aerodynamic performance by modifying the geometric parameters at the bottom of the car. The geometric parameters discussed in this article are limited to those that can directly alter the ground effect flow field at the bottom of the car, including the ground clearance at the bottom, the geometry of the

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bottom inlet and the Venturi channel, the length and angle of the diffuser, as well as the geometry related to the bottom plate edges or side skirts. Ride height is therefore treated here as a working clearance that directly changes the underbody flow channel, rather than as the shape of the underbody itself. These parameters will directly change the cross-sectional area of the flow channel at the bottom, the local flow velocity, the pressure distribution, the boundary layer development and the flow separation, and further affect the downforce, drag and aerodynamic efficiency generated by the car. In contrast, the wing attack angle, the ground clearance of the front wing, and the pitch and roll of the entire vehicle, which mainly affect the bottom flow indirectly by changing the incoming flow conditions, the tail flow structure or the vehicle posture, are not the core research objects of this article.

In the design of real racing cars, the optimisation of the geometric parameters at the bottom of the car is not merely about achieving the maximum downforce. A lower ground clearance, a more aggressive diffuser angle, or a stronger flow channel contraction may enhance the local low-pressure area, but they may also increase the risk of flow separation and aerodynamic sensitivity; in certain specific configurations and operating conditions, there may also be phenomena such as restricted inlet flow, boundary layer growth, local separation, or a decrease in downforce. Therefore, the ground effect design of racing cars usually requires a trade-off between downforce, drag, aerodynamic efficiency, and flow stability. Studying the functional laws of a single parameter and further analysing the coupling relationship between multiple bottom geometric parameters is an important foundation for understanding and optimising the ground effect system.

The development of ground effect technology in racing cars is influenced by both aerodynamic design and race regulations. In the 1970s, ground effect racing cars significantly enhanced the low-pressure area at the bottom of the car through Venturi-type underbody and side skirts, but their performance was highly sensitive to the ground clearance and sealing conditions. Subsequently, race regulations imposed restrictions on side skirts and underbody structures, leading to continuous changes in the implementation methods of the ground effect system. In 2022, the F1 technical regulations reintroduced a stronger emphasis on Venturi-type underbody channels and diffusers for vehicle downforce, making the underbody flow path and floor-edge design important engineering topics again [1-3]. At the same time, modern CFD and wind tunnel tests can more precisely analyse the impact of geometric changes on pressure distribution, flow separation, and vortex structures, providing conditions for the coupling study of different underbody parameters.

This paper systematically integrates existing numerical simulations, wind tunnel tests and experimental studies, focusing on analysing the underbody geometric parameters and key working clearance that directly control the flow of the ground effect under the car's underbody. It also explains how these parameters affect the pressure, drag and aerodynamic efficiency through mechanisms such as pressure distribution, boundary layer development, flow separation, vortex structure and diffuser pressure recovery. The paper first establishes a unified physical framework for the ground effect and aerodynamic efficiency of the car's underbody. Then it explains the functions of the main structures directly involved in the formation of the ground effect, such as the underbody, diffuser and edge of the base plate, in the complete underbody flow path. Subsequently, it compares the key geometric parameters and their coupling effects, while distinguishing literature-supported findings from mechanistic inference. Finally, it summarises the limitations of the existing research and points out the future research directions for real operating conditions.

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2. Ground effect and aerodynamic efficiency

2.1. Aerodynamic forces and efficiency

The aerodynamic performance of a racing car is typically described by two main aerodynamic forces: downforce and drag. Downforce is essentially the aerodynamic force that is perpendicular to the incoming flow direction and directed towards the ground, which can increase the normal load on the tyres and thereby enhance the available grip of the car during braking, steering, and acceleration. Drag, on the other hand, is opposite to the incoming flow direction and increases the driving force required to overcome air resistance. To facilitate the comparison of aerodynamic performance under different speeds and geometries, dimensionless lift coefficient and drag coefficient are usually used to represent it, namely $CL = L/(0.5\rho U^2A)$ and $CD = D/(0.5\rho U^2A)$. Since the lift in a racing car usually points towards the ground, some literature defines CL as negative. Therefore, in this paper, when discussing the magnitude of downforce and aerodynamic efficiency, the absolute value of CL is adopted. This paper uniformly defines aerodynamic efficiency as $|CL|/CD$, which is used to describe the level of downforce corresponding to the unit drag. This indicator can serve as a basis for comparison within compatible configurations, but it cannot alone represent the optimal state in car design. Actual racing cars need to balance the absolute downforce, drag, aerodynamic balance, and flow stability according to the characteristics of the track. Therefore, in the evaluation of geometric parameters later, changes in CL, CD, $|CL|/CD$, and flow stability will be considered, rather than solely focusing on the maximum aerodynamic efficiency as the design goal. However, absolute CL, CD and $|CL|/CD$ values from different studies should not be compared directly unless the reference area, force definition, model configuration and measurement conditions are compatible. The general downforce-drag trade-off in racing car aerodynamics is discussed by Katz [4, 5].

2.2. Formation of underbody ground effect

The core of the ground effect at the bottom of a racing car is a restricted, viscous and three-dimensional flow system formed by the vehicle's bottom surface and the moving ground. Continuity relations and Bernoulli relations can be used to explain the first-order connection between flow channel contraction, local acceleration and static pressure changes, but this idealised relationship cannot alone determine the downforce of the actual bottom of the racing car. The actual flow is also affected by factors such as inlet total pressure loss, boundary layer displacement thickness, ground motion, surface curvature, three-dimensional vortex structure, and diffuser outlet back pressure. Therefore, the pressure distribution at the bottom of the car should be understood as the result of the combined action of mass flow rate, viscous loss, boundary layer development and downstream pressure recovery [6]. As the airflow develops along the bottom of the car, the boundary layer will thicken under the action of adverse pressure gradients and may separate locally. The reduction in ground clearance usually enhances the flow constraint and suction at the bottom of the car, but the performance degradation mechanism that may occur at extremely low ground clearance depends on the specific configuration: classic near-ground wings and different Venturi bottoms may respectively exhibit inlet flow restriction, boundary layer blockage, local separation or vortex structure instability, so the statement that too low ground clearance will inevitably lead to stall cannot be regarded as a universal rule. In the following discussion of ground clearance, specific literature will be combined to explain the critical ride height and its corresponding mechanism under different configurations [7]. In addition to the longitudinal pressure gradient, lateral leakage at the bottom

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edge and vortex structure will also change the pressure field at the bottom of the car. Edge vortices may either restrict the lateral invasion of external high-pressure air into the bottom of the car or directly contribute to the downforce through their induced low pressure; when the position or intensity of the vortex changes significantly or even breaks down, it may instead worsen the downstream diffuser flow. Thus, the ground effect at the bottom of the car is not the result of a single geometric dimension or a simple Bernoulli relationship but is the result of the combined action of the pressure field, boundary layer, three-dimensional vortex structure, separation and pressure recovery. This unified physical framework will serve as the basis for the subsequent analysis of structural function and geometric parameters. The importance of moving ground simulation and Reynold number effects in ground vehicle aerodynamic testing has also been demonstrated experimentally by Sardou [8-10].

2.3. Race cars ground effect versus aircraft ground effect

Although the term ground effect is used in both racing cars and aircraft, their main relevant flow mechanisms are different. For an aircraft, proximity to the ground mainly modifies downwash, wingtip vortices and induced drag. For a racing car, the ground forms part of a restricted underbody flow channel that can accelerate the flow and establish low pressure beneath the vehicle. Therefore, the present review focuses specifically on the underbody-ground flow system and its influence on downforce and drag, rather than on aircraft near-ground flight. A recent review of experimental wings in ground effect studies is provided by Lee and Lin [7].

3. Aerodynamic structures involved in generating ground effect under the vehicle

3.1. Underfloor and venturi tunnels

The underside of the racing car and the Venturi channel form the main body of the complete underside flow path. Its main function is to provide a continuous and controlled geometric channel for the airflow entering the underside of the car, and to determine the distribution range of the main low-pressure areas along the longitudinal direction. The inlet, contraction section, throat, and rear expansion area jointly determine the channel shape of the airflow during the process from entering to leaving the underside of the car. Since the focus of this chapter is on the structural function rather than repeating the physical mechanism of Chapter 2, here only the following is emphasised: The Venturi-type underside is responsible for organising and maintaining the complete underside flow, while the specific contraction ratio, throat height, curvature, or ground clearance will change the pressure, boundary layer, and separation in Chapter 4.

3.2. Underfloor inlet and throat region

The bottom plate inlet and the throat region respectively perform the functions of establishing inlet conditions and forming key flow constraint positions. The inlet determines the mass flow rate distribution, total pressure level and flow uniformity when the external inflow enters the vehicle bottom and affects the working state of the downstream Venturi channel; the throat is a key area with a relatively small effective flow area in the vehicle bottom geometry, and its position and shape determine the way the main flow passes through the strongest constraint area of the vehicle bottom. These two components are not independent parts but functional divisions in the continuous vehicle bottom flow path. This chapter therefore defines their structural roles, while the effects of

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parameters such as inlet height, contraction ratio, throat height ratio and position are compared in Chapter 4.

3.3. Floor edge and side-sealing structures

The main function of the bottom plate edge and the lateral sealing structure is to control the lateral exchange between the low-pressure area at the bottom of the vehicle and the external flow field on the vehicle's side. In early racing cars, the physical side skirts could directly restrict lateral leakage, while modern racing cars rely more on the shape of the bottom plate edge and the resulting three-dimensional vortex structure to regulate this exchange. The edge structure should therefore be regarded as a functional component for controlling lateral flow and vortex formation, and the detailed effects of edge spacing, local height, sealing gaps, and vortex state are analysed in Chapter 4. Mahon, Zhang, and Gage experimentally observed that diffuser-edge vortices can enhance downforce as ride height is reduced, while vortex breakdown at low ride height is associated with downforce loss and increased drag [8].

3.4. Diffuser

The diffuser is located at the rear of the vehicle's underbody. Its main function in the complete flow path is to connect the low-pressure area under the vehicle's underbody with the external tail flow, and to provide appropriate outlets and pressure recovery conditions for the upstream underbody flow. It should therefore be regarded as a downstream control structure of the underbody system rather than an independent additional component. The effects of diffuser angle, length, area ratio, outlet height, and multi-channel configuration on separation, vortex structures, and aerodynamics are further analysed in Chapter 4.

3.5. Integrated function of the underbody system

The above structures do not operate independently of each other. The bottom plate inlet establishes the initial flow conditions for entering the vehicle bottom; the Venturi channel and the throat organise the main flow in the vehicle bottom and determine the main restricted areas; the edge structure of the bottom plate controls the lateral exchange and edge vortices; and the diffuser affects the entire vehicle bottom flow path through the downstream outlet and pressure recovery conditions. Therefore, the ground effect should be understood as a continuous and mutually coupled system, rather than being generated by a single component. This function provides the basis for the geometric parameter analysis in the next chapter: any change in a geometric parameter may affect other areas through mass flow rate, pressure gradient, boundary layer and vortex structure, so the single-parameter rule cannot simply be concatenated into a universal optimal design.

4. Direct controls of ground effect geometric parameters and flow mechanisms

4.1. Underbody ride height

Ride height, or ground clearance, is one of the parameters that directly affect the restricted flow channels at the bottom of the vehicle. It is not the geometric shape of the underbody itself, but its instantaneous value directly changes the operating geometry of the underbody-ground system. Existing studies have shown that its influence on the downforce cannot be simply summarised as the lower, the better. Senior and Zhang conducted research using a mobile ground wind tunnel on a

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simplified blunt body model with a 17° rear diffuser and side plates and observed four different aerodynamic states as the ground clearance changed: enhanced downforce at a higher ground clearance, maximum downforce at a moderate height, decreased downforce at a lower height, and a low downforce state at an extremely low height [11]. The decrease in downforce at the low ground clearance was related to the flow separation at the diffuser inlet and the suction loss in the front half of the diffuser. This result indicates that the so-called critical ride height should be understood as the position where the flow state changes for a specific vehicle underbody configuration, rather than a uniform numerical value applicable to all racing car underbodies. It should be noted that these results were obtained from a simplified diffuser-equipped bluff-body model rather than a complete modern racing car; they are therefore used here primarily to interpret ground-effect flow mechanisms rather than as direct design rules.

Ruhrmann and Zhang further changed the ground clearance at five diffuser angles of 5°, 10°, 15°, 17°, and 20°. The experiment showed that different diffuser angles would form different flow states, and the 15°, 17°, and 20° configurations exhibited significant hysteresis phenomena [9]. The decrease in downforce was also related to vortex rupture and three-dimensional flow separation. Therefore, the influence of ride height must be discussed together with the diffuser geometry. Zhang, Toet, and Zerihan also summarised the aerodynamic states in the vehicle ground effect as downforce enhancement, maximum downforce, and downforce reduction, and emphasised the role of edge vortices and three-dimensional viscous flow in these state transitions [12].

When comparing across documents, the ground clearance should not be limited to using millimetre values. Dimensionless forms such as h/L, h/c, or ratios related to throat height may reduce scale dependence, but these quantities are not automatically interchangeable because each uses a different characteristic length and therefore represents a different geometric relationship. A preferred comparison should use one clearly defined characteristic length where the available data permits it. Otherwise, the original study's dimensionless ratio should be retained and its definition stated explicitly.

4.2. Underfloor inlet and venturi-channel geometry

Compared with ride height and diffuser angle, in the seven core papers selected for this review, there is relatively limited public evidence for independent and systematic parameter sweeps on the shape of the vehicle bottom inlet, contraction rate, and throat geometry. Therefore, this review should not provide the best inlet shape or the best throat ratio based on the available direct evidence. Instead, the inlet and throat should be discussed primarily in terms of how their geometry changes downstream flow conditions and their coupling with the diffuser and ground clearance. Where the discussion below is derived from flow mechanisms rather than an independent parameter sweep, it is treated as a mechanistic inference rather than a directly established design rule.

Cooper et al. specifically introduced flow-area blockage when studying the vehicle bottom diffuser to describe the inhomogeneity of inlet velocity caused by the model vehicle bottom and ground boundary layer, and used area ratio, dimensionless diffuser length, and blocking degree to analyse the performance of the diffuser [1]. This indicates that even if the geometric cross-sectional area is the same, the effective flow area caused by the inlet boundary layer and the total pressure loss will change the downstream pressure recovery. Therefore, the geometric effect of the Venturi channel cannot be explained solely by the ideal continuity relationship but needs to consider the displacement thickness of the boundary layer and the inlet flow quality simultaneously.

Lasso-Parera, Granados-Ortiz and Ortega-Casanova's research provided an example of modern multi-parameter design: its two-dimensional parametric optimisation simultaneously uses up to

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seven to eight design parameters to control the leading edge and diffuser geometry of the vehicle bottom and then introduces the parametric optimal solution into the three-dimensional vehicle model and further optimises it using the adjoint method [6]. This study did not support a universally applicable single optimal value for the inlet, but it shows that the inlet/leading edge geometry and diffuser shape are more suitable to be regarded as a joint design space rather than completely independent single factors.

4.3. Diffuser geometry

The diffuser is one of the most well-evidenced direct geometric variables in the selected literature. Cooper et al. conducted experiments using a mobile ground wind tunnel on a single-plane diffuser and organised the experimental data using traditional diffuser parameters such as area ratio, non-dimensional length, and flow-area blockage [1]. The study showed that the underbody diffuser could significantly increase downforce, and under certain conditions where the ground clearance was not too small, it could also bring about a certain reduction in drag. At the same time, the optimal diffuser performance was affected by the boundary conditions of the moving ground and the fixed ground. This result indicates that the diffuser angle itself is not an adequate cross-document comparison indicator. At least, the length, area ratio, and inlet blockage conditions should also be explained simultaneously.

Ruhrmann and Zhang conducted five diffuser angle experiments and further demonstrated that the angle is strongly coupled with ride height. Hysteresis was observed in the larger 15°, 17°, and 20° diffusers, and the decrease in downforce was related to vortex rupture and separation [9]. This means that a larger diffuser angle generating stronger pressure recovery cannot be directly inferred as a larger angle performing better, because the enhancement of the inverse pressure gradient may change the vortex structure and separation state throughout the diffuser.

The lateral configuration of the diffuser is also important. Jowsey and Passmore divided a single-plane diffuser into multiple channels and conducted wind tunnel experiments [4]. Their results showed that the overall trend of the multi-channel design was similar to that of the single-channel design, but in the region slightly above the optimal angle of the single-plane diffuser, where flow had already experienced partial separation, the multi-channel configuration could significantly increase downforce with only a small increase in drag. The pressure distribution showed that this improvement was related to the diffuser pumping and pressure recovery of the inner and outer channels. Ehirim, Knowles, and Saddington further reviewed diffusers and pointed out that the longitudinal reverse-rotating vortex is one of the key flow characteristics of ground-effect diffusers, which can increase local velocity and suction, but vortex rupture may also lead to a loss of downforce [2]. Therefore, the analysis of diffuser geometry should cover angle, length, area ratio, channel configuration, and the corresponding vortex structure, rather than just comparing a single angle.

4.4. Floor-edge geometry and side-sealing arrangement

The functions of the bottom plate edge and lateral sealing structure are not only to prevent high-pressure external flow from leaking to the bottom of the vehicle. Zhang, Toet and Zerihan clearly emphasised the role of force-enhancing edge vortices in the review of racing car ground effect, stating that the edge vortices themselves can directly participate in the generation of aerodynamic force through their low-pressure vortex cores and changes in local flow velocity [12]. Ehirim et al. also pointed out in the review of ground-effect diffusers that the longitudinal vortices developing

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along the side of the diffuser would affect the velocity and pressure distribution within the diffuser, and vortex formation may be beneficial for maintaining adhesion and enhancing suction, while vortex breakdown would have adverse effects [2].

Therefore, changes in the sealing gap or floor-edge geometry may simultaneously alter the lateral leakage volume, the intensity of the edge vortices, the position of the vortices, and their stability in the diffuser. It is worth noting that this effect is not a simple rule of thumb: the stronger the sealing, the better. Ehirim et al. summarised the existing experiments and found that in some larger diffuser angle conditions, completely sealing the side skirt would cut off the favourable edge vortex suction, instead causing the diffuser to stall and reducing the downforce [2]. Thus, the parameters of the bottom plate edge need to be analysed according to the complete chain of geometry, lateral flow behaviour, pressure and separation, CL/CD, and cannot be described merely as reducing leakage.

4.5. Coupled geometric effects

The existing literature has most clearly demonstrated the coupling between ride height and diffuser geometry. Senior and Zhang showed that the same 17° diffuser would experience multiple aerodynamic and separation states as the ride height changed [11]. Ruhrmann and Zhang then explained that when the diffuser angle changed simultaneously, the force regime, vortex breakdown, and hysteresis also changed accordingly [9]. Cooper et al. further demonstrated that the performance of the diffuser should be described jointly by the area ratio, dimensionless length, flow blockage, and ground condition, rather than being determined solely by a single angle [1].

Jowsey and Passmore's multi-channel experiments added the dimension of configuration: in the angle region where the single-plane diffuser has partially separated, channel segmentation can be achieved by changing local pressure recovery and vortex structure expansion to extend the performance range [4]. Lasso-Parera et al. further extended this idea to multi-parameter optimisation, parameterising the leading edge and diffuser, and using surrogate-based optimisation and three-dimensional adjoint optimisation [6]. The final solution achieved a 7.98% improvement in the vehicle's lift-to-drag ratio compared to its baseline design, but this value is specific to its Formula Student geometry, objective function, and numerical method and should not be interpreted as a transferable design gain.

From these studies, it can be seen that the couplings that have been more clearly studied mainly focus on ride height with diffuser angle or area ratio, diffuser length with area ratio, and diffuser angle with channel configuration. In contrast, high-dimensional combinations such as inlet geometry with floor-edge geometry, floor-edge vortex with diffuser configuration, etc., have limited equivalent systematic quantitative evidence in the seven core papers selected in this review. Therefore, these combinations are more appropriately identified as evidence gaps in the selected literature, rather than being presented as a unified optimal design rule for the whole field.

5. Research gaps and future directions

5.1. Systematic quantification and optimisation of multi-parameter coupling

Existing classic experiments have demonstrated that there is a significant coupling between ride height, diffuser angle, area ratio, diffuser length and channel configuration. However, these studies usually cover only a limited number of variables at a time. In particular, the interaction between the inlet geometry and the edge vortices on the bottom plate, the influence of the bottom plate edge geometry on the downstream diffuser separation, and the regularity of multiple parameters jointly

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changing the critical ride height are still lacking a unified systematic quantification in the core literature selected in this paper. This should therefore be treated as a gap in the evidence reviewed here rather than a claim that no such studies exist in the wider field. Future research should more frequently employ Design of Experiments, surrogate models, adjoint optimisation, or other multivariable optimisation methods, while ensuring the physical interpretability of the flow, to establish the sensitivity and interaction between different parameters. Lasso-Parera et al.'s multi-parameter undertray optimisation has demonstrated the feasibility of this direction, but more validations under different vehicle models and under different constraints are still needed [6].

5.2. Comparability across models and ground-simulation conditions

Cooper et al. clearly demonstrated that moving-ground and fixed-ground simulations would alter the behaviour of the vehicle underbody diffuser [1]. The flow-area blockage caused by the boundary layer would change the effective area ratio and pressure recovery. Senior and Zhang, as well as Ruhrmann and Zhang, obtained critical ride-height behaviour based on the moving-ground conditions [9, 11]. Therefore, these results should not be directly equated with those obtained under fixed ground, different Reynolds numbers, or different vehicle underbody lengths. Future review and experimental studies should systematically report dimensionless geometry, Reynolds number, ground simulation, inlet boundary layer state, and measurement methods to reduce the seemingly contradictory but actually due to different boundary conditions issues among different studies.

5.3. External operating disturbances acting on a fixed geometry

The core scope of this article is still limited to underbody parameters and the key working clearance represented by ride height. Therefore, dynamic ground clearance height, suspension movement, track bumps, rotating wheels, wheel wake, yawing, and non-uniform incoming flow should not be redefined as new direct geometric variables. A more appropriate positioning would be that these factors act as external operating disturbances, causing the same fixed geometry to experience different instantaneous boundary conditions on a real vehicle. Since Chapter 4 has shown that ground-effect flow is highly sensitive to ride height, vortex state, and separation state, the actual operating attitude and incoming flow disturbances may cause the vehicle to transition between different force regimes.

Lasso-Parera et al. optimised the schemes after parameterising the two-dimensional vehicle underside and then placed them in a three-dimensional model including rotating wheels and other vehicle aerodynamic components for further optimisation [6]. This indicates that the migration from the simplified two-dimensional/fixed geometry model to the real vehicle environment introduces new three-dimensional couplings. Future work can study how these external disturbances change the pressure distribution, edge vortex stability, diffuser separation position, and transient CL, CD, and |CL|/CD of the established vehicle underside geometry without expanding the core parameter scope of this article.

5.4. From peak performance to aerodynamic robustness

Current ground-effect research often focuses on finding the ride height or diffuser configuration corresponding to the maximum downforce. However, the results of Senior and Zhang and Ruhrmann and Zhang indicate that near the maximum downforce, there may be simultaneous separation state transitions, asymmetric flow, or hysteresis. For real racing cars, a design that only achieves the

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highest |CL| under a single static condition may not have the best practical performance [9, 11]. Therefore, future research should not only compare peak CL and |CL|/CD, but also quantify the sensitivity near geometric parameters, hysteresis range, flow-state stability, and robustness to ride-height/yaw perturbation. Such an evaluation method can directly connect fixed-geometry studies with the stable aerodynamic performance of real racing cars.

Overall, the existing literature has clearly established the basic influence of ride height and diffuser geometry on the ground-effect flow. However, cross-parameter, cross-boundary condition, and migration to real dynamic conditions remain the main deficiencies. The focus of future research should not only continue to search for a single optimal parameter but also establish a unified framework that can describe the coupling of multiple parameters, flow-state transitions, and sensitivity to external disturbances.

6. Conclusion

This review study investigated how underbody geometric parameters and the key working clearance affect the ground effect flow and aerodynamic performance of the racing cars. The results show that the ground effect should not be explained merely through idealised continuity or Bernoulli relationships, as the actual underside flow has viscous, three-dimensional characteristics and is significantly influenced by boundary layer development, pressure recovery, flow separation, and vortex structures. Therefore, each geometric parameter must be understood through its aerodynamic effect within the complete underbody flow path, rather than being analysed in isolation.

Among the parameters considered, the underbody ride height and the geometric structure of the diffuser have received the most comprehensive experimental and numerical evidence support. The interaction between them can result in different aerodynamic states, changes in separation patterns, vortex disintegration, and lag effects that may occur under certain diffuser configurations. Therefore, the critical underbody ride height or the optimal diffuser angle cannot be regarded as universal design parameters. These values depend on the specific chassis geometry, diffuser configuration, ground simulation conditions, and the flow environment. In contrast, within the reviewed literature in this article, systematic evidence regarding the geometry of the inlet, the throat geometry, and the floor edge is relatively limited. Their effects are often inferred through coupled flow mechanisms rather than through separate parameter scanning analyses.

The review also points out that direct comparisons between different studies are difficult. Differences in model geometry, Reynolds number, moving ground conditions, force definitions, reference area and simulation conditions can significantly affect the reported lift coefficient (CL), drag coefficient (CD), and the ratio of lift to drag (|CL|/CD). Therefore, for different models, the trends and flow mechanisms in a single study are usually more reliable and suitable for comparison than the absolute aerodynamic coefficients across models.

Therefore, future research should go beyond the pursuit of isolated optimal parameter values and should instead focus more on the coupling of multiple parameters, consistent dimensionless representations, and aerodynamic robustness. Dynamic changes in riding height, suspension movement, rear flow of rotating wheels, yawing, and non-uniform inflow should be regarded as external disturbances acting on the fixed chassis geometry, so that subsequent research can evaluate whether a geometry optimised under static conditions can remain stable and effective in the actual racing environment. The present evidence therefore supports a clearer understanding of ride height but does not yet justify a universal optimal underbody geometry across racing-car configurations.

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