# Racing Car Technology Optimisation: Aerodynamic Refinement Through Wind Resistance Control and Downforce Enhancement

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**Abstract.** The ultimate pursuit of modern racing car performance relies on the optimisation of aerodynamics, the core of which lies in balancing the contradictory demands of reducing wind resistance and increasing downforce. Excessive resistance limits acceleration and top speed, while insufficient downforce leads to a decrease in grip, affecting handling safety. With the rise of electric racing cars (such as Formula E), aerodynamics still needs to be coordinated and optimised with battery cooling and energy recovery systems. Traditional wind tunnels and trial-and-error methods can no longer meet the demands. CFD simulation, AI-driven optimization, and hybrid methods have become key technologies, significantly enhancing the efficiency and accuracy of R&D.This article systematically explores the fundamental principles of car aerodynamics (such as Bernoulli's law, turbulence and wake effects), the role of key components (front wing, tail wing, diffuser), and optimization methods (wind tunnels, CFD, AI models). The case studies include the DRS variable rear wing, the ERS energy recovery system, and the mass production vehicle design of the Xiaomi SU7 Ultra, demonstrating the integration of theory and practice. In the future, the synergy between computing innovation and track performance will further promote the development of aerodynamics.

**Keywords:** Aerodynamic Optimisation, Downforce Optimisation, Cfd Simulation, Wind Tunnel Experiment, Ground Effect

## 1 Introduction

The essence of modern racing cars is the ultimate pursuit of speed, efficiency, and stability. The technology of engines and electric motors, which provide power for the racing cars, has been highly mature. Thus, aerodynamic optimisation plays a significant role in enhancing the performance, fuel efficiency, and handling of the racing cars, especially in reducing drag and increasing downforce. Excessive air resistance will limit the acceleration capability and maximum speed of the racing car, and this phenomenon always occurs in events such as F1 and endurance races. On the contrary, if the air resistance is not enough, which means the downforce is not enough will cause

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the grip of the tires to decline tremendously. And it will reduce steering ability, resulting in skidding, increasing the lap time, and the risk of accidents. Besides, the rise of electric racing cars (such as Formula E) has brought about new constraints, where aerodynamic efficiency must be optimised in conjunction with battery cooling and energy recovery systems. However, the traditional trial-and-error approach and isolated wind tunnel tests can no longer meet the demands of modern racing cars. Today's competitions require real-time adaptability, computational accuracy, and compliance with regulations. To further improve the performance of the racing car, it is necessary to find the best balance between reducing wind resistance to increase straight-line speed and increasing downforce to enhance stability.

With the development of technology, more and more novel technologies like CFD and wind tunnel experiments can be employed to address these challenges. Automotive engineers have been able to optimise the aerodynamic components on racing cars, such as the front wing, diffuser, and adjustable rear wing (DRS), with an unprecedented level of precision.

The development of racing car aerodynamics has experienced remarkable technological transformations. Early research and development work was entirely dependent on scale model wind tunnels and the experience and judgment of engineers. This approach was time-consuming and labour-intensive, with limited accuracy. With the progress of computing technology, high-precision CFD simulation technology has revolutionised this scenario, enabling more precise and efficient flow field analysis. More notably, the integration of machine learning technology has led to a qualitative enhancement in the prediction accuracy of flow fields. Additionally, the hybrid approach that combines digital simulation with physical testing has substantially improved the efficiency of the research and development process.

This paper will systematically investigate the latest progress in the optimisation of racing car aerodynamics, encompassing its basic principles: the generation mechanisms of wind resistance and downforce, various optimisation methods and their applications, as well as the diverse aerodynamic designs in high-performance sports cars such as F1 and Formula E. This paper intends to summarise the current trends and envision the future directions, highlighting the synergy between computational innovation and track performance enhancement.

## 2 Basic Principles of Racing Car Aerodynamics

The study of racing car aerodynamics focuses on optimising vehicle performance through airflow characteristics. Its core challenge lies in balancing downforce and drag. Additionally, controlling airflow stability enhances the racing car's grip and speed.

The downforce generation mechanism utilises aerodynamic components, including front wings, rear wings, and diffusers, to press the vehicle firmly onto the track surface. This configuration enhances cornering grip and driving stability through aerodynamic effects. The principle operates according to Bernoulli's law governing pressure-velocity relationships: when airflow speed under the wing surface exceeds that above, a low-pressure zone creates vertically downward aerodynamic force.

Race cars primarily reduce aerodynamic drag through three technical approaches: aerodynamic body shaping, active/passive drag reduction systems, and chassis optimisation. Specifically, designing smooth, low-profile body structures minimises frontal areas and prevents airflow separation. Drag reduction systems effectively lower the vehicle's drag coefficient (Cd). The aerodynamic drag force is calculated as $F = ½\rho v^2CdA$, where $\rho$ represents air density, v denotes velocity, and A indicates frontal area. These engineering measures collectively decrease wind resistance, thereby enhancing both vehicle performance and fuel efficiency.

## 2.1 Vehicle Body Aerodynamic Characteristics

**The Influence of Streamlined Body on Coefficient of Aerodynamic Drag**. The coefficient of drag is a key parameter for evaluating the aerodynamic performance of racing cars, and its value directly reflects the extent to which the body shape affects aerodynamic drag.

Through research, it has been found that the optimisation of streamlined body design can significantly reduce the Cd value. The main principles include: The adoption of a teardrop-shaped front face design can effectively reduce the stagnation pressure of the airflow. The side profile design, with the waistline curvature gradient controlled within 0.03mm to 0.05mm, can effectively delay airflow separation and reduce turbulence intensity. Installing a fully enclosed underbody shield on the chassis eliminates the turbulence sources from the underbody components (exhaust pipe, suspension) to lower the Cd value.

**Turbulence, Wake Flow, and Their Effects on Vehicle Stability**. When airflow passes over the car body, sudden changes in surface curvature cause the laminar boundary layer to separate, creating turbulent vortices. This increases both skin friction drag and pressure drag, raising the drag coefficient (Cd). It may also induce body vibrations.

The separation of airflow behind a racing car forms a low-pressure zone, generating alternating shedding vortices. The structure of the wake directly influences pressure drag and high-speed crosswind stability. Additionally, an asymmetric wake may lead to directional instability under crosswinds, particularly noticeable in high-centre-of-gravity vehicles like SUVs. The periodic shedding of wake vortices can induce vertical oscillations in the vehicle body, compromising traction.

## 2.2 Key Components Affecting Aerodynamic Performance

**Significant Influence of Racing Rear Wings on Downforce**. Downforce is influenced by multiple factors, including ground effect, air density, and the influence of additional aerodynamic components. Among these, the rear wing of a racing vehicle typically demonstrates a remarkable effect in enhancing downforce. Figure 1 shows two distinct aerodynamic behaviours: When the rear wing is retracted, high-speed airflow passes over the vehicle body and continues moving diagonally downward, generating significant downward momentum along the Z-axis. In contrast, when the rear wing is deployed, the airflow becomes predominantly horizontal after passing the wing surface, resulting in a substantial reduction of downward momentum in the Z-axis direction. This comparison demonstrates the rear wing's crucial role in modifying the vehicle's vertical aerodynamic forces [1].

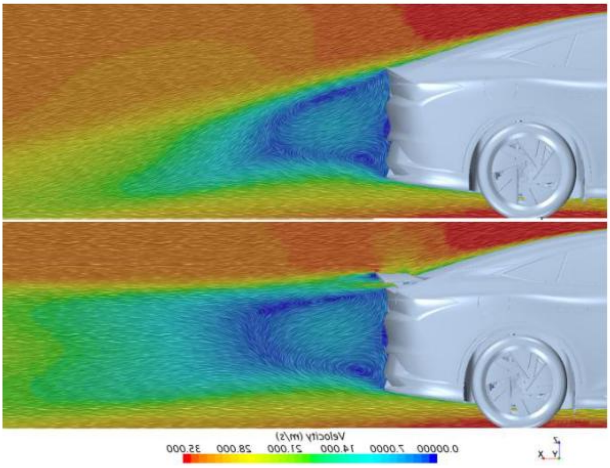

**Fig. 1.** Two distinct aerodynamic behaviours [1]

**Components for Wake Flow Optimisation**. When a race car moves forward, a low-pressure zone forms at its rear. The pressure difference between the front and rear of the car generates a backwards force opposing the direction of motion, resulting in a drag force. During driving, vortices are generated behind the car, which is the result of fluid separation, causing the formation of a low-pressure area. As shown in Figure 2(a), by cutting the lower rear body at a certain angle, some of the fluid that would otherwise flow to the low-pressure area can be guided, thereby reducing this pulling effect.

Another popular method to reduce rear-end separation is to use a diffuser (Figure 2(b)), which can enhance the car's aesthetics to some extent. However, since the lower rear body is not fully cut, its drag reduction effect is not as good as that of a similar degree of rear lower body cutting [2].

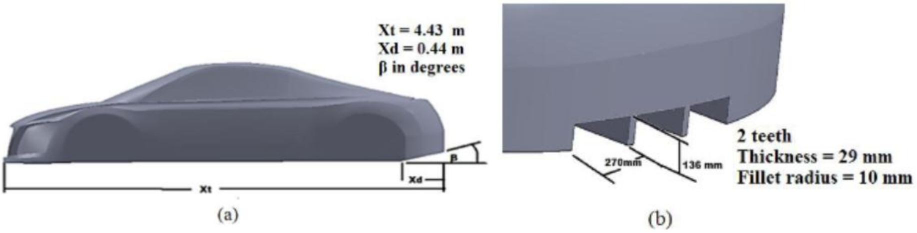

**Fig. 2.** (a) By cutting the lower rear body at a certain angle, (b) Reduce rear-end separation is to using a diffuser [2]

# 3 Optimisation Methods for Racing Car Aerodynamics

## 3.1 Application of Wind Tunnel Technology and CFD Technology

Wind tunnel technology (WT) and computational fluid dynamics (CFD) numerical simulation are the most commonly used techniques for studying the aerodynamic performance of vehicles. Although the application of CFD in aerodynamic research has only been widely adopted by scholars and engineers in recent decades, it has significant advantages - it can provide detailed information on flow field variables throughout the entire computational domain (such as wind speed, concentration, temperature, etc.).Compared with wind tunnel (WT) tests, the latter is limited by measurement technology, cost, and efficiency, and usually can only obtain data at limited measurement points. It should be noted that the accuracy of CFD simulation is always an important consideration, and its calculation results must be strictly verified by experimental data [3].

The CFD technology mainly employs three turbulence simulation approaches: RANS, LES, and DNS. RANS processes turbulence through statistical methods and only resolves the average flow. It has high computational efficiency but is difficult to capture transient vortex structures, and applies to the aerodynamic performance evaluation of the entire vehicle and the analysis of the cooling system. LES directly resolves large-scale eddies and utilises sub-grid models to handle small-scale turbulence. It can predict transient flows and aerodynamic noise relatively well and is commonly used to verify the results of RANS. DNS directly solves the Navier-Stokes equations with the highest accuracy, but involves an extremely large amount of computation. It is mainly used for validating turbulence models and studying small-scale flows. In the development of racing cars, a hybrid strategy of "RANS as the main approach with LES as local supplementation" is usually adopted, and the wind tunnel test data is combined for verification to balance the computational efficiency and simulation accuracy. Besides, piv is a key means of measurement in wind tunnel technology. It is a non-contact optical flow measurement technique that determines velocity fields by tracking the motion of tracer particles. The core principle involves seeding the flow with high-scattering microparticles (e.g., oil droplets or fluorescent tracers), illuminating a 2D plane with a dual-pulse laser sheet, and capturing two consecutive images at a fixed time interval ($\Delta t$) using a high-speed CCD camera. Cross-correlation algorithms then compute particle displacements (dx, dy), while sub-pixel interpolation (e.g., Gaussian fitting) enhances resolution, ultimately yielding 2D velocity fields (v_x = dx/Δt, v_y = dy/Δt). Key technical considerations include particle selection (micron-sized, high flow-following capability), optimisation of $\Delta t$ (ensuring displacement $\leq 1/4$ interrogation window size), and algorithm refinement (multi-grid iteration, image deformation) to achieve high-precision measurements (error $< 1\%$).

Wind tunnel technology simulates the motion state of objects by manipulating airflow. Its principle is founded on Galilean relativity: the motion of an object in static air is equivalent to the flow of air over a stationary object. A wind tunnel constitutes a closed-loop system consisting of a power system, a stabilization section (containing honeycombs and damping nets), a contraction section, a test section, a diffusion section, and a recirculation channel (including guide vanes), and aerodynamic forces and pressure fields are measured through strain balances and pressure holes. This technology constitutes the core of the research and development of racing car aerodynamics, and is employed to optimise the vehicle body design, enhance downforce, reduce drag, and strengthen high-speed stability [4].

Besides, piv is a key means of measurement in wind tunnel technology. It is a non-contact optical flow measurement technique that determines velocity fields by tracking the motion of tracer particles. The core principle involves seeding the flow with high-scattering microparticles (e.g., oil droplets or fluorescent tracers), illuminating a 2D plane with a dual-pulse laser sheet, and capturing two consecutive images at a fixed time interval (Δt) using a high-speed CCD camera. Cross-correlation algorithms then compute particle displacements (dx, dy), while sub-pixel interpolation (e.g., Gaussian fitting) enhances resolution, ultimately yielding 2D velocity fields (v_x = dx/Δt, v_y = dy/Δt). Key technical considerations include particle selection (micron-sized, high flow-following capability), optimisation of Δt (ensuring displacement ≤ 1/4 interrogation window size), and algorithm refinement (multi-grid iteration, image deformation) to achieve high-precision measurements (error < 1%).PIV plays a pivotal role in optimising race car aerodynamics by enabling detailed flow field analysis. For instance, it measures wake vortex structures (e.g., vortex core position, reattachment length) to refine rear-wing designs for reduced drag and enhanced downforce. It also analyses flow separation under crosswind conditions to improve side-skirt aerodynamics and visualises tire wake turbulence and cooling airflow in engine bays for thermal management. Compared to traditional point-based methods (e.g., hot-wire anemometry), PIV offers full-field measurement, dynamic tracking (kHz-level high-speed PIV resolves transient vortices), and non-intrusiveness (avoiding probe-induced flow disturbances). However, high-speed flows (>50 m/s in racing) require shorter Δt or high-repetition-rate lasers/cameras, while complex 3D flows (e.g., underbody aerodynamics) demand advanced techniques like stereoscopic PIV (SPIV) or tomographic PIV for accurate reconstruction. These applications provide critical experimental data for aerodynamic performance enhancement in motorsports [5].

### 3.2 Aerodynamic Optimisation for Racing Cars Enabled by AI

AI technology is profoundly revolutionising the paradigm of aerodynamic optimisation for racing cars. Through the establishment of an innovative methodological system that integrates traditional CFD with artificial intelligence, a leapfrog improvement in R&D efficiency has been achieved. Regarding flow field prediction, large-scale models based on architectures such as Transformer or Fourier Neural Operators can simulate the complex flow field characteristics around racing cars quickly and accurately, including crucial flow phenomena such as turbulence and separation vortices. Compared with traditional CFD simulation methods, this can save a considerable amount of time. For example, the "Oriental·Yifeng" large-scale model enables rapid prediction of the wing flow field via an encoder-decoder structure. Similar technologies can be directly applied to the flow field analysis of key components like the rear wing and diffuser of racing cars [6].

In the aspect of aerodynamic performance prediction, AI models are capable of establishing the mapping relationship between the geometrical shape of racing cars and aerodynamic forces, rapidly assessing key performance indicators such as downforce and drag for different design schemes. The three-dimensional shape aerodynamic coefficient prediction framework based on point cloud representation and Transformer architecture can be adapted to the geometry of racing cars and provide immediate feedback for design iterations. Furthermore, AI has also exhibited superiority in the aspect of turbulence modelling. For example, the "Qinling Soaring" large-scale model, trained with large-scale flow field data, is capable of simulating high Reynolds number turbulence effects more accurately. This is particularly significant for the airflow management at the bottom of racing cars and the design for drag reduction [6].

In addition, the Lamborghini Huracán Performante is equipped with the ALA (Aerodynamica Lamborghini Attiva) active aerodynamics system, which utilises intelligent algorithms to dynamically manage airflow distribution and downforce control. This system consists of front and rear electric valves and a hollow rear wing, with independently controllable left- and right-wing valves that respond in just 0.2 seconds. During high-speed cornering, the system automatically closes the inner-side valve to increase downforce while keeping the outer-side valve open to reduce drag, based on real-time sensor data including steering input and lateral acceleration (refreshed every 500 milliseconds). This asymmetric adjustment can boost cornering downforce by 750%. For straight-line acceleration, all valves are fully open to minimise drag, while emergency braking triggers full closure for maximum downforce. Compared to traditional hydraulic systems, ALA employs forged carbon fibre materials that reduce weight by 80% and seamlessly integrates with the ESC and all-wheel-drive system. This technological synergy ultimately enabled the Huracán Performante to conquer the Nürburgring with a record-breaking lap time of 6 minutes and 52.01 seconds.

## 4 Practical Application Cases of Racing Car Aerodynamics

### 4.1 The Application of DRS (Deployable Rear Wing) Technology in Aerodynamic Optimisation

In aerodynamic optimisation, DRS mainly plays a role through its dynamic adjustment ability. It can flexibly adjust the state of the rear wing according to different driving conditions to optimise the vehicle's performance. When cornering at high speed or braking, increasing the attack angle or expansion angle of the rear wing can significantly enhance the downforce, strengthening the vehicle's grip and stability. The fan-shaped expanded rear wing can provide 357.85 kg of downforce at a top speed of 300 km/h. During straight-line driving, reducing the attack angle or folding the rear wing can effectively reduce wind resistance, increase the top speed, and improve fuel economy. The folding fan expansion mechanism of the rear wing imitates the movement of a peacock spreading its tail, achieving a balance between compact folding and multi-angle expansion [7].

### 4.2 Energy Recovery System (ERS) Combined with Aerodynamic Optimisation

The ERS significantly enhances energy utilisation efficiency by recovering kinetic energy during braking and converting it into electrical energy for storage. In the context of racing, frequent acceleration and braking result in substantial energy loss, but the ERS can recover this energy and provide additional power for subsequent acceleration, thereby extending the vehicle's range and reducing the frequency of pit stops for charging or battery replacement. In dynamic braking force distribution strategies, the ERS can interact with aerodynamic components for coordinated adjustment. For instance, during high-speed driving, the active rear wing can be deployed to increase downforce, and at this time, the ERS can prioritise the recovery of energy generated by wind resistance-assisted deceleration. Conversely, at low speeds, the proportion of hydraulic braking force can be dynamically adjusted to compensate for the reduced effect of wind resistance and ensure smooth braking [8].

### 4.3 Tire-body aerodynamic interaction: Reduce the influence of hub vortices on downforce

The influence of the aerodynamic interaction between the tires and the vehicle body on the downforce of the entire vehicle is mainly reflected in the coupling effect between the wheel wake and the flow field at the back of the vehicle body. Studies show that when the airflow velocity near the wall at the middle and rear of the vehicle body is relatively high, a low-resistance state (symmetrical wake state) with symmetrical upper and lower vortices is formed. At this time, the upper vortex is farther from the vehicle body and its intensity is weakened, causing the pressure in the middle and upper areas of the back to rise significantly, thereby increasing the downforce. Rotating the wheels can promote the formation of this state by weakening the wake separation. For example, ground movement combined with wheel rotation can increase the pressure in the mid-upper area of the back by 0.033. However, if the hub design is poor, resulting in asymmetrical vortices (such as stationary wheels or overly large rim openings), it will enhance the upper vortices and bring them closer to the vehicle body, causing a decrease in pressure in the mid-upper area of the rear. For instance, if a certain operating condition indicates a 0.0324 reduction in pressure in this area, it will lead to a loss of downforce. The optimization directions include: precisely simulating the rotation effect by using the sliding mesh method to control the flow in the hub area, reducing turbulence by reducing the spoke opening area (for example, reducing from 300 degrees to 100 degrees can reduce ventilation resistance by 33%) and optimizing the tread design (giving priority to longitudinal tread); Meanwhile, the depth of the wheel arch cover and the track need to be designed collaboratively. If the track is appropriately increased, the interference of the wake on both sides of the back can be weakened. These measures need to be verified in combination with the IDDES Model and wind tunnel tests to maximise the downforce while controlling the ventilation resistance (such as the optimisation case of Tesla Model S) [9].

### 4.4 Optimisation and Application of Ground Effects in Racing Car Aerodynamics

The regression and optimisation of ground effects in racing car aerodynamics have significantly enhanced performance by reducing ground clearance and optimising the design of the front wing. Studies show that when the front wing of a racing car is close to the ground, the airflow forms a high-speed and low-pressure zone between the wing surface and the ground, which can generate lift 60% to 80% higher than that in free space, while the drag only increases by 30%. This principle is perfectly demonstrated in the Red Bull RB18 racing car: it adopts a tunnel floor design, and by precisely controlling the ground clearance of 30-50mm, the ground effect contributes 55% of the downforce of the entire vehicle. The optimised 8° sweepback Angle front wing, in combination with the end plate design, not only sustains the lateral roll of the airflow (avoiding more than 20% of lift loss) but also increases the lift-to-drag ratio by 15%. Meanwhile, the carbon fibre base plate ensures structural rigidity under a pressure of 3000kg, while the optimised diffuser curvature enables the undercarriage airflow velocity to reach 240km/h, ultimately achieving an outstanding performance of a 1.2-second reduction in lap time at the Monaco Grand Prix. In the future, by integrating dynamic control with new material technologies, the application potential of ground effects in the field of racing will be further explored [10].

### 4.5 Aerodynamic Optimisation Cases of Mass-produced High-performance Automobiles

The Track-level Aerodynamic Design of Xiaomi SU7 Ultra. As a mass-produced sedan that can directly enter the racetrack, it achieves a maximum vehicle downforce of 285 kg through the aerodynamic kit tuned on the Nürburgring Nordschleife. The key technologies include Front optimisation: The oversized front splitter, U-shaped air knife, and expanded intake grille increase the downforce on the front axle by 452 kg. Rear design: The active diffuser (adjustable from 0° to 16°) and 1560mm full carbon fibre rear wing generate downforce by utilising the Bernoulli principle. Bottom treatment: The front/rear spoilers increase the downforce by 19 kg while maintaining an ultra-low drag coefficient of 0.195 Cd.

## 5 Conclusion

Modern racing aerodynamics presents a complex optimisation challenge that requires balancing fundamentally competing aerodynamic requirements while operating within stringent technical regulations. The primary technical challenges include achieving optimal trade-offs between drag reduction and downforce generation across varying speed regimes; integrating aerodynamic systems with emerging electric powertrain thermal management requirements; overcoming computational limitations in modelling transient flow phenomena and turbulence interactions at racing speeds; and developing responsive active aerodynamic systems capable of real-time adaptation to dynamic track conditions. Current technological constraints are particularly evident in the limited effectiveness of existing solutions like DRS (Drag Reduction Systems), which operate within narrow, regulatory-defined parameters and exhibit mechanical response limitations.

Future research directions should prioritise several key areas of investigation. First, the development of machine learning-enhanced CFD methodologies shows significant potential for accelerating simulation workflows while improving predictive accuracy of complex flow interactions. Second, advanced materials research focusing on adaptive structures and smart surfaces could enable continuous aerodynamic optimisation through controlled morphing capabilities. Third, the implementation of integrated sensor networks coupled with digital twin technology may facilitate real-time aerodynamic adjustments based on comprehensive vehicle state monitoring. Additionally, the translation of racing-derived aerodynamic innovations to production electric vehicles represents an important cross-domain application, particularly for range optimisation through active airflow management systems.

From a computational perspective, ongoing research efforts should address critical gaps in turbulence modelling, particularly in developing hybrid RANS-LES approaches that can accurately capture flow separation and vortex dynamics while remaining computationally tractable. Furthermore, systematic studies are needed to evaluate the performance trade-offs associated with various active aerodynamic implementations under different racing conditions. These research initiatives must be conducted within the framework of evolving technical regulations and sustainability requirements, which increasingly influence aerodynamic development strategies in both motorsport and automotive industries. The successful resolution of these challenges will require multidisciplinary collaboration across aerodynamics, materials science, control systems, and computational physics domains, potentially yielding innovations that could transform vehicle efficiency paradigms beyond motorsport applications.

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