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Racing Technology Optimisation: Drag Control and Downforce

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Abstract. This paper explores the aerodynamic optimisation of racing vehicles, with a specific focus on drag reduction and downforce generation. The study outlines fundamental aerodynamic principles affecting racing performance, such as drag coefficient, wake turbulence, ground effect, and pressure distribution. Optimisation methods, including CFD simulations, wind tunnel testing, and machine learning applications, are discussed in detail. Each method's advantages and limitations are analysed in the context of practical implementation. The paper highlights the importance of balancing aerodynamic efficiency with handling stability, especially in high-speed environments where marginal improvements can significantly influence performance. Case studies from Formula 1, Formula E, and hypercar design are examined, illustrating the application of technologies like DRS systems, active rear wings, and energy recovery integration. These examples demonstrate how manufacturers optimise airflow to reduce drag while maintaining or enhancing downforce for improved control. While significant progress has been made, challenges remain in developing cost-effective, adaptive, and efficient aerodynamic systems. The paper concludes with a discussion on the future of racing aerodynamics, emphasising the role of intelligent systems and real-time optimisation in shaping the next generation of racing vehicle design.

Keywords: Aerodynamic optimisation, Drag reduction, Downforce generation, Computational Fluid Dynamics (CFD), Active aerodynamics

1. Introduction

The evolution of racing car technology has been closely tied to advances in aerodynamic design. In the early stages of automotive development, aerodynamics was not a significant consideration. However, as competition intensified and vehicle speeds increased, engineers began to recognise the critical influence of airflow behaviour on performance. Modern racing cars are now finely tuned aerodynamic machines, designed to minimise drag and maximise downforce under dynamic track conditions [1].

Racing aerodynamics focuses on two primary goals: reducing drag to improve top speed and fuel efficiency, and increasing downforce to enhance traction, stability, and cornering capability. Achieving a balance between these two opposing forces is one of the key challenges in vehicle design [2,3]. Aerodynamic components such as front and rear diffusers, side skirts, splitters, and

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active rear wings all play essential roles in managing airflow. The use of ground-effect techniques, airflow channelling, and pressure control mechanisms is increasingly integrated into racing design strategies [4].

Despite notable advancements, engineers still face difficulties in managing turbulent wake effects, ensuring stability during yaw, and balancing airflow distribution for cooling and control. Traditional tools such as wind tunnel testing and CFD simulation provide critical insights, yet each has limitations—wind tunnels are costly and scale-limited, while CFD simulations require extensive computational resources and must be validated through experimentation [5].

To address these challenges, emerging technologies like AI-driven aerodynamic modelling and active aero components are becoming more prominent. These allow for real-time adjustment of aerodynamic elements based on vehicle speed, track segment, and driving input, which can improve efficiency across varying conditions. Additionally, the integration of machine learning accelerates the design iteration process, reducing development time and cost [6].

This paper aims to systematically explore aerodynamic optimisation in modern racing, focusing on drag reduction and downforce strategies. It begins by outlining fundamental aerodynamic principles relevant to racing. It then introduces key optimisation techniques, including CFD, wind tunnel testing, and AI-assisted design. Practical application cases from Formula 1, Formula E, and hypercars are examined to illustrate real-world outcomes. Finally, the paper evaluates current challenges and discusses future directions for aerodynamic research, offering both technical insights and engineering guidance.

2. Fundamental principles of racing aerodynamics

The main fundamental principle concerning racing aerodynamics is optimising the vehicle's performance under racing conditions. These principles include downforce generation, drag reduction, airflow management, the ground effect, cooling and ventilation, yaw control, and aerodynamic stability.

2.1. Vehicle aerodynamic characteristics

Drag coefficient (Cd) and streamlining optimisation. The drag coefficient (Cd) represents a number that represents any object's (shape’s) resistance to fluids (air in automotive engineering). A lower Cd would represent less drag, which means the vehicle would be able to travel through the air with less resistance from the medium. When vehicles travel at high speeds, the vehicle moves through air at the speed air resists it. If a Porsche was driving through air that is static at 50 mph, it can be thought of as air molecules pushing the Porsche at 50 mph, and if the vehicle had a higher Cd, it would mean that moving at speeds would be difficult for the vehicle, and there would be more resistance in comparison with a vehicle with a lower Cd [7]. A lower Cd would also mean better fuel efficiency (longer distance covered with the same amount of fuel, weight, road, and engine, internal friction, etc). Cd could also affect the car’s acceleration, which means that the car would be slower if it had a higher Cd in some cases. A typical race car, such as the Formula 1 race car category, normally has a 0.7 to 1.0 Cd. It can also be seen that Tesla and other newer electric cars have lower drag coefficients than sports cars; this does not mean that they are more optimised for racing; downforce is another aspect that will be explored further on in this research paper [8-10].

Turbulence, wake, and their impact on vehicle stability. Turbulence is defined as an instability in airflow, which can be seen as spirals that occur because of pressure differences (caused by sudden changes in surface geometry), the non-slip effect, and flow separation [11].

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Turbulence increases the drag coefficient and could mean aerodynamic instability in most cases. Turbulence is most often seen in production cars at the back of the vehicle, where there is negative pressure, which causes the airflow to separate or circle back to the vehicle. This would cause the rear to be more unstable, and is also known as wake turbulence [11].

2.2. Key components affecting aerodynamic performance

Optimisation of front diffuser and air channels. The front diffuser is a component that is part of some production cars (can be added via body kits), and most race cars which is crucial for maximizing downforce through the use of Bernoulli's principle, by increasing the amount of airflow under the car through the use of the front diffuser, the speed increases as the volume increases as the front diffuser is lower than the underside of the car, which speeds up the airflow, according to Bernoulli's equation, pressure decreases as velocity increases, as the pressure difference increases (underside less than uperside of the vehicle), the downforce increases.

The aerodynamic functions of side skirts and diffusers. The main function of side skirts is to maintain the low pressure under the car by preventing the airflow from the side of the vehicle from getting underneath the vehicle, to the vehicle's low-pressure area.

The use of side skirts also increases the downforce on the sides of the vehicle. By increasing the skirt angle, the air pressure increases as the flow moves towards the back of the side skirt [12].

The rear diffuser affects how the airflow at the rear of the vehicle acts. As the pressure decreases, the rear diffuser allows the airflow to slowly expand into a lesser pressure than the pressure under the vehicle, which can prevent flow separation and wake turbulence.

3. Racing aerodynamic optimisation methods

3.1. CFD simulation optimisation

Applications of RANS, LES, and DNS in racing aerodynamic analysis. When simulating the overall downforce of a car, RANS (Reynolds-Averaged Navier-Stokes) is used for quick, steady-state simulations. For analysing wake and vortex behaviour, more dynamic, unsteady flow features are captured during LES (Large Eddy Simulation), and turbulence is better represented. All scale of turbulence is solved using DNS (Direct Numerical Simulation). Due to its high computational requirements, it's suited for research and small-scale experimentation.

A hybrid optimisation strategy combining computational fluid dynamics and wind tunnel testing

3.2. Wind tunnel testing techniques

Application of PIV (Particle Image Velocimetry) in racing flow field testing. The application of particle image velocimetry is to visually present and statistically show the airflow patterns around vehicles in wind tunnels. PIV works by adding lightweight particles (smoke, oil, or microspheres) into the airflow of wind tunnels and using lasers to capture the motion of these particles and turn them into graphs that can be visualised. As a result, PIV presents a detailed velocity map, which can be used to analyse the overall aerodynamics of the car.

Comparison between 1:1 wind tunnel testing and scaled-down model testing. A 1:1 scale offers high-accuracy results and also gives real geometry and flow conditions. However, the 1:1 wind tunnel requires huge facilities to house these tests and requires huge amounts of financial effort in comparison to a scaled-down model test. A scaled-down model is more affordable, but it trades off

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for inaccurate flow behaviour, such as different Reynolds numbers than the actual 1:1 tests, since air particles can't be sized down [13].

3.3. AI-driven racing aerodynamic optimisation

The role of machine learning in racing fluid dynamics optimisation. The use of AI in aerodynamic optimisation can accelerate the process with less cost. Through the use of AI machine learning in optimisation, the analysis of the CFD and predicting flow behaviour becomes easier and faster. Also, it takes out the need for simulations that cost huge amounts of money.

AI-driven strategies for predicting drag reduction. AI can optimise drag reduction through analysing CFD data and wind tunnel results. AI can be designed to pinpoint aerodynamic trends in the model and analyse shape changes. As a result, AI can produce low-drag designs, and this process is significantly faster than the traditional methods.

4. Practical application cases of racing aerodynamics

4.1. F1 Racing aerodynamic optimisation

Application of DRS (Drag Reduction System) technology in aerodynamic optimisation. In F1, race cars use spoilers to increase downforce by increasing the pressure above the spoiler. However, these spoilers cause a lot of drag, and the excessive drag and downforce are not needed during parts of the race track where the race car needs to accelerate to high speeds (straights) [14]. And during these parts of the race track, teams will implement the DRS system to change the angle of the spoiler, such that the air is allowed to flow through the spoiler without creating much drag.

The resurgence and optimisation of ground-effect racing cars. The resurgence of the use of the ground-effect on racing cars has been caused by the realisation that the ground effect can increase the downforce without increasing excessive drag as the wings do (through increasing high-pressure zones). Instead of high-pressure zones that create excessive drag, low-pressure zones can increase downforce without the excessive downside. The current optimisation methods include CFD, wind tunnel testing, and AI machine learning to optimise the ground-effect [14].

4.2. Electric racing cars (formula E) aerodynamic optimisation

Trade-off between low drag and high efficiency in aerodynamics. The main goal in the trade-off is to have a balance between downforce and energy saving (energy saving and top speed). When you increase the downforce in Formula E through increasing high pressure, the result leads to more drag and lower top speeds. If you have too much of an energy-efficient design with lower drag, you lose crucial cornering efficiency that high down-force designs have. The main goal is to balance the trade-off between these two aspects to produce a car that would be able to do both, without one being significantly less [15].

Integration of Energy Recovery Systems (ERS) with aerodynamic optimisation. The ERS is a batch of units that are integrated in not only Formula E but also Formula 1 to recover energy [16]. In FE, the ERS consists of recovering energy during braking, and F1 consists of braking and energy recovery from exhaust heat (MGU-K and MGU-H). These units can increase the amount of energy in the car and prolong the energy use in Formula E.

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4.3. Hypercars and high-performance racing car aerodynamic design

Active aerodynamics technologies in hypercars (e.g., variable rear wings, dynamic diffusers). Active aerodynamics are commonly used in hypercars and high-performance race car aerodynamic designs. Active aerodynamics are used to shift the geometry of the car to adapt to different speeds, which results in different natures of airflow. These can be seen in rear wings and diffusers [17]. A rear case of active aerodynamics also includes changes in geometry or airflow during cornering, to differentiate the downforce and drag on the two sides (outer side and inner side of the turn) of the vehicle [18].

Case studies of aerodynamic optimisation in mass-produced high-performance vehicles. The Porsche Taycan reduces drag for a better range without sacrificing the performance of cornering. The Taycan includes active aerodynamics in its cooling flaps and rear spoiler. It includes a smooth rear diffuser and underbody. This results in a drag coefficient of around 0.22 [19].

The Corvette C8 includes active aerodynamics in its front splitter, rear spoiler and flow channels under the car, which can optimise its downforce and performance without excessive drag.

5. Conclusion

This study offers a comprehensive examination of aerodynamic optimisation techniques in racing vehicles, particularly emphasising the importance of drag control and downforce enhancement. Through a combination of theoretical principles and applied case studies, the paper evaluates how components such as diffusers, side skirts, and rear wings influence airflow behaviour and vehicle stability. Key tools such as Computational Fluid Dynamics (CFD), wind tunnel testing, and Particle Image Velocimetry (PIV) are analysed for their effectiveness in simulating and visualising aerodynamic phenomena. The integration of machine learning and AI technologies into aerodynamic modelling also reveals a promising direction for cost-effective, data-driven optimisation.

Case studies from Formula 1, Formula E, and high-performance hypercars illustrate real-world applications. In Formula 1, technologies like Drag Reduction Systems (DRS) and ground-effect designs have significantly impacted vehicle performance. Formula E highlights the trade-off between energy efficiency and aerodynamic load, while hypercars demonstrate the potential of active aerodynamics to adapt to changing driving conditions and speed ranges.

Despite these advancements, several challenges remain. Accurately managing turbulent wake, achieving aerodynamic adaptability in real time, and balancing energy consumption with performance remain active areas of research. High testing costs, the complexity of integrating active systems, and regulatory constraints also pose barriers to widespread adoption.

Future development will likely involve smarter, more responsive aerodynamic systems that can adapt dynamically to track conditions. Advances in materials, such as shape-memory alloys and active composites, may allow for further refinement of adaptive aero components. The use of AI-driven simulations is expected to accelerate innovation while reducing reliance on expensive wind tunnel testing. As racing continues to serve as a testing ground for next-generation vehicle technology, the optimisation of aerodynamics will remain essential to achieving greater performance, safety, and efficiency on and off the track.

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