Aerodynamics in Formula 1: A Literature Review on Design Strategies, Performance, and Regulatory Evolutions

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***Abstract*—Aerodynamics has for some time been at the base of what we do in Formula 1, which includes everything from how well a car turns a corner to fuel efficiency. In this work we look at in detail the aerodynamic forces and the design strategies which play with them which also looks at the growth of the regulatory structures which put a tie on their use. We begin with the basics of lift, drag, and downforce which are the forces we are playing with and which we engineer into components like the wings, diffusers and bargeboards to get that extra bit of performance. Also we look at drag reduction we go over the past use of the Drag Reduction System (DRS) and the part played by Computational Fluid Dynamics (CFD) in the simulation and fine tuning of air flow. A key section of the paper discusses the influence of aerodynamics on fuel use, picking out the increasing relevance of energy efficiency in motorsport. The regulatory timeline is followed from early developments to the 2022 ground effect renaissance, culminating in the 2026 switch to active aerodynamics. This change overcomes DRS with a dual-mode setup that enables drivers to dynamically change wing configurations, providing more strategic freedom and minimizing the need for artificial overtaking enhancers. Through the combination of technical analysis and regulatory perspective, this paper highlights the revolutionary potential of active aero systems in defining the next generation of Formula 1 where innovation, racecraft, and sustainability find common ground. et**

Keyword s— Formula 1 Aerodynamics, Drag Reduction System (DRS), Active Aero Technology, Downforce and Lift, Computational Fluid Dynamics (CFD), Fuel Consumption in Motorsport, Aerodynamic Optimization, 2026 FIA Regulations, Vehicle Dynamics, Motorsport Engineering words

I. INTRODUCTION

Aerodynamics is the secret behind Formula 1 car design and operation, with the car's speed, roadholding, and fuel efficiency being directly controlled by aerodynamics. Formula 1 cars are heavily reliant on aerodynamic forces such as downforce and drag to create more grip on the track and minimize air resistance to a point of maximizing straight-line speed. Downforce, generated by wings and the car underfloor, pushes the car onto the track surface, enhancing tire adhesion and cornering capacity. But downforce gain is typically at the expense of greater aerodynamic drag, and this results in higher fuel consumption due to greater engine load. This is a challenge for engineers to balance performance improvement without compromising fuel efficiency [2]. Technological advances like Computational Fluid Dynamics (CFD) and wind tunnel testing have revolutionized the process of aerodynamic design with precise simulation and optimization of airflow over complex car shapes. The use of technologies like the Drag Reduction System (DRS), reducing rear wing drag for short periods during straights, is a good example of minimizing aerodynamic drag to improve overtaking situations without sacrificing cornering downforce (LinkedIn, 2023)[1]. Concurrently, the sport is subjected to strict and ever-evolving regulations by the Fédération Internationale de l'Automobile (FIA) for the purpose of maximizing safety, fairness, and sustainability. Such regulations strictly dictate aerodynamic design strategies; for instance, the new 2026 regulations incorporate active aerodynamic devices, which promise added flexibility and potential additional reductions in drag and fuel usage. Furthermore, as Formula 1 targets net-zero carbon emissions, aerodynamic efficiency is integral to supporting fuel economy and sustainability aims in the sport [3]. The research discusses the fundamental aerodynamic principles that govern Formula 1, design methods employed to reduce drag and maximize fuel consumption, and the influence of technological and regulatory advancement on shaping the future of F1 aerodynamics. this document and are identified in italic type, within parentheses, following the example. Some components, such as multi-leveled equations, graphics, and tables are not prescribed, although the various table text styles are provided. The formatter will need to create these components, incorporating the applicable criteria that follow.

II. FUNDAMENTALS OF AERODYNAMIC FORCES IN FORMULA 1

A. Downforce

Downforce is the aerodynamic force pushing a Formula 1 car vertically downwards onto the race track. This force is important because it increases the grip that the tires have with the road surface by increasing the friction between the tires and road, which permits the car to corner much more quickly while maintaining control.”.

Lift on a plane is what allows the plane to rise in the air, whereas downforce is a kind of “negative lift,” pushing the car down. It is primarily produced by the car's front wing and rear wing but also the car's floor under the car using fluid dynamics via a bit of Bernoulli’s principle and Newton’s third law. Downforce grows with the square of the car’s speed; double the speed, get four times the downforce. Though while downforce works to corner harder and keep

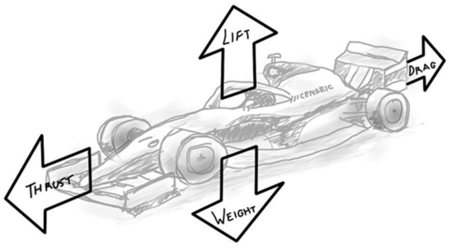

Fig. 1. Fundamental aerodynamic forces acting on a Formula 1 car — thrust, drag, lift (downforce in practice), and weight. Aerodynamic design in F1 seeks to maximize downforce for cornering grip while minimizing drag for straight-line speed. [Adapted from generic aerodynamics schematics].

the car stable, it creates more aerodynamic drag, which can slow the car down and cause it to use more fuel. As a result, achieving downforce with the least amount of drag is a key battle in F1 aerodynamic design

B. Lift

In Formula 1 lift is the aerodynamic force produced in the opposite direction to the aerodynamic forces keeping the car on the ground, the lift is created by the process of the car passing through the air, normal to the relative air flow. Such lift is sometimes a welcome phenomenon at the wing-tip of aircraft, where it is an upward force keeping the aeroplane airborne, but in the World of F1 racing and other forms of motorsport, lift is generally a negative force; reintroducing negative stability and threatening to put the car back into the air.

The designs of F1 cars, for example, are aimed at reducing lift from the air, and instead creating down force, the negative lift, something that pushes the car onto the track, which in turn enhances tire grip and cornering capacity. Lift is the product of pressure differentials on the surfaces of the car, created by the shape and orientation of the car, and controlling these pressures is essential to balancing speed, safety, and fuel efficiency.[5]

Formula of lift is

$$\text{lift} = CI \times r \times V\text{^}2/\ 2 \times A \quad (1)$$

CI= lift coefficient (contains all the complex dependencies and is usually determined experimentally)

V= velocity

A= Wing Area

The value of Lift is determined the parameters like density of the air, velocity squared, the air’s viscosity and compressibility, the surface area over which the air flows, the shape of the body, and the body’s inclination to the flow. Basically, it relies on the shape of the body, inclination, air viscosity and compressibility is very complex. [6]

C. Drag

Drag is the force of aerodynamics which acts to resist the movement of the Formula 1 car when it travels through the air. Drag is opposite to the direction of motion, more or less slowing the car down. Drag is created due to the fact that the car displaces air molecules out of its path (pressure drag) and due to air-friction between air and the surfaces of the car (skin friction drag). Reduction of drag is crucial to enhance the car's top speed and economy, but it needs to be balanced by the requirement for downforce, which actually increases drag at times. Technologies such as the Drag Reduction System (DRS) lower drag temporarily on straights to increase speed and overtaking possibilities.[7]

Drag Formula:

$$\text{Drag} = CI \times r \times V\text{^}2/\ 2 \times A \quad (2)$$

Where, D= Drag CI= drag coefficient (contains all the complex dependencies and is usually determined experimentally) V= velocity A= Reference Area Choice of reference area A affects the value of Cd [8]

$$D=CD0+(CL+CL0)2 \quad (3)$$

$$D= Drag\ Force/(\ 1/\ 2\ \rho ref Vref\text{^}\ 2\ Area) \quad (4)$$

For an airfoil, CD0 is defined as the parasite drag which is any dra that is not associated with lift generation. Note that the induced drag can be seen to correlate with the square of the coefficient of lift. In motorsport CD0 and CI0 would refer to the lift without some major components like the rear and front wing.

Where CD is the Total Drag Coefficient, CD0 is the Parasite Drag Coefficient, CL is the Lift coefficient, CL0 is the lift coefficient at 0 angle of attack, k is an experimentally determined coefficient that correlated lift and drag generation, ρref is the reference density, $Vref$ reference velocity, $Aref$ is the Reference Area Downforce will also increase the friction produced from the free wheels on the car, which are the front wheels in the case of a rear wheels-driven Formula 1 car, and a reduction in the friction coefficient this going to affect the driving wheel, which collectively will impede the speed of the car. It is then clear that lift generation is always coupled with drag generation. This would be significant penalty that has to be endured during straight sectors of the race track; however corners are where downforce is most useful.[9]

III. AERODYNAMIC COMPONENTS AND DESIGN STRATEGIES IN F1

A. Introduction of Aerodynamics in Formula one

Since 1960s, this was a revolutionary decade for F1, as it was a departure from basic designs to more emphasis on engineering and technology. One of the most pivotal developments was the arrival of aerodynamics as one of the key determinants of car performance. Perhaps the most important breakthroughs of this period were the introduction of wings and spoilers, which were fitted to the front and rear of the vehicles. Wings are able to create downforce and enhance the tires hold on the road more. The main function of the front wing is to create downforce on the front end of the car. Normally, the wing provides around 25-30% of the overall downforce [11]. Because the front wing and the rear wing need to be balanced, considering the stability of the car, which prevents the car from experiencing corner entry oversteering.

As Colin Chapman introduced wings and downforce to F1 vehicles, they received three times of world champions in 1960s [12]. When the inclusion of aerodynamic elements induced higher performance, it also introduced some new issues. Such early wings were generally installed in a hurry and poorly tested, resulting in numerous failures and accidents. Consequently, in 1968 highly mounted rear wings were prohibited by the Federation International de l'Automobile (FIA) due to their failure [13]. FIA imposed rules to make sure that aerodynamic devices were properly integrated into the car. Because the effect of aerodynamics became more obvious, teams began to spend more on research and development. This heightened the competition and gave birth to a wide range of innovative aerodynamic concepts. For instance, designing the car body itself to generate aerodynamic advantages started gaining traction. The late 1960s set the stage for subsequent aerodynamic technologies like ground effects and underbody aerodynamics, which became a reality in the 1970s and later. The sport began to feature fluid dynamics specialists, paving the way for even more advanced methods in the decades ahead.[10]

B. *Front Wing*

Being the most essential aerodynamic feature governing airflow to the brake ducts, radiators, diffusers, and engine intake, the front wing of a Formula One car holds much significance. It is designed with adjustable flaps and winglets that allow the adaptation of downforce distribution to suit handling needs. Its basic structure includes a main plane, aero-flaps, and end plates, whereby contemporary designs sport two- or three element aerofoils whose shapes are dictated by downstream flow constraints.

Aerodynamic downforce is developed due to both pressure differences straddling the wing and Venturi effects, where lessened ground clearance hikes the velocity of the flow of air and thus diminishes pressure underneath the wing. Both analytical and experimental means have proven the importance of maintaining the best lift-to-drag ratio, and load balancing on the front and rear wings for stability in conditions such as braking, cornering, and acceleration.

Although being subject to limitations, such as a purely central section with no downforce generation or a minimum ground clearance, cascades and flexible wing elements do provide engineers with opportunities to explore aerodynamics freedom. Flexible wings, generally speaking, contribute positively to handling by moving downward in a corner, thus increasing downforce by way of ground effect, all the while abiding by the FIA's regulations. Due to this, the front wing is the main aerodynamic feature, and this is why CFD plays such an important role as a tool in its design and performance evaluation.[14]

Fig. 2. Front Wing of Scuderia Ferrari Formula one team

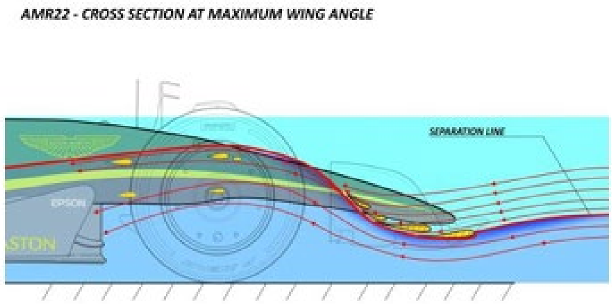

Fig. 3. Cross-sectional view of the Aston Martin AMR22 front wing at maximum angle of attack. The image illustrates the airflow interaction and load distribution across the wing elements under extreme aerodynamic settings, highlighting how Formula 1 teams balance downforce generation with drag penalties. [Adapted from RaceTeq]

C. *Rear Wing*

The rear wing of any Formula One car will almost certainly produce aerodynamic downforce, about a third of the total load in fact. Design and operation of these wings will be altered depending on the requirements of the various circuits: with high-speed circuits like Monza, teams lower the angle of attack of the rear wing to minimize drag and therefore maximize the top speed, whereas at tight low-speed circuits like Monaco, full wing angle is employed to yield maximum Fig.4: Rear Wing of Oracle Red Bull Racing Team downforce for cornering stability. The golf end plate upper multi-element aerofoil primarily generates downforce and is also the most altered element from the rear wing, while the lower one is smaller and works together with the diffuser to accelerate airflow beneath the car and promote ground effect. The endplates link the wing elements, blocking lateral flow of air to improve efficiency.

The design of an F1 wing is intended to press down on the car via downforce, contrasting an aircraft wing, which produces lift up into the air. Higher downforce means greater wing angle and drag, reducing vehicle speed in a straight line. To forge ahead between these competing requirements, the multi-element designs, endplate geometry, and drag reduction systems have been invented. Consequently, the rear wing is the last place where the chaotic number of combinations can be brought into relative order to obtain the required downforce-to-drag ratio, allowing for great cornering performance and efficient fuel consumption in diverse racing conditions.[15]

Fig. 4. Rear Wing of Oracle Red Bull Racing Team

D. Barge Boards

Bargeboards are essential aerodynamic components situated between the front wheels and the sidepods of a Formula One car. Their main role is to manage the turbulent airflow caused by the rotation of the front wheels; otherwise, this could hamper the car's aerodynamic efficiency. Bargeboards clean and redirect this disturbed air to establish a cleaner flow pattern around the car's bodywork. The airflow is generally subdivided into two distinct paths:

a. Toward the sidepods – Some of the air is taken through the inlet of the sidepods, where it cools vital components such as the engine, radiators, and other thermal management systems. Directed flow into these inlets is crucial to compete with the engine toward endurance and reliability during the race.

b. Around the outside of car – The leftover airflow is siphoned out to the area beyond the sidepods. This removes drag that is generated by turbulent air and wants to preserve the flow from getting into the car rear and being as clean and stable as possible, especially at the diffuser and rear wing. Further, bargeboards also work as generators for small vortices, which help energize the boundary layer of the induced airflow to delay separation and hence increase the effective performance of an aerodynamic device downstream. This generating of vortices also benefits the diffuser, which is a draw since the benefit to rear downforce comes without a complementary rise in drag. Hence, bargeboards act as a layer interleaving between front-end aerodynamics (front wing and wheels) and the rear-end devices (diffuser and rear wing), considered indispensable for achieving an optimized overall aerodynamic balance of an F1 car. [15]

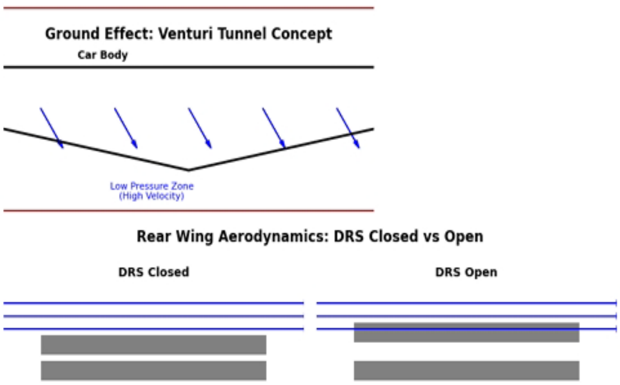

Fig. 5. Aerodynamic mechanisms in Formula 1. (Top) Ground effect generated by Venturi tunnels: as airflow accelerates through the narrowed underfloor channel, a low-pressure zone is created, producing suction and downforce. (Bottom) Rear wing aerodynamics with DRS closed (left) and open (right): opening the flap reduces drag by allowing smoother airflow, increasing straight-line speed.

E. Ground Effect

The ground effect, also known as the Venturi effect, is an aerodynamic phenomenon that occurs when airflow between a car's underbody and the track is accelerated through a narrowed channel, creating a low-pressure zone beneath the vehicle. According to Bernoulli's principle, this pressure difference, higher above the car and lower beneath, generates significant downforce, effectively "sucking" the car onto the track. This increased traction allows higher cornering speeds and improved stability.

The principle was initially used in Formula One in the late 1970s, with Colin Chapman's Lotus 78 being the first to use inverted aerofoil shapes inside the sidepods to create large Venturi tunnels. The game-changing technology was brought about by sliding skirts, which closed the gap between the sidepods and the road, keeping high-pressure air out of the tunnels and thus optimizing downforce at the expense of not much drag. But the technology had some inherent flaws. The vehicles became overly sensitive to changes in ride height, and brushing against bumps or kerbs could upset airflow under the vehicle, and downforce and grip could be lost with a sudden loss of stability. This led to a number of accidents and caused safety issues. The FIA put regulations in place in 1983 that prohibited sliding skirts and provided for flat underbodies, which in essence removed extreme ground-effect designs but ensured driver safety. [10]

F. Sidepods

Sidepods are important in controlling airflow around a Formula One vehicle, especially in containing radiators and the rest of the cooling systems. Without sidepods, adding radiators directly in the airflow would cause excessive resistance, generating increased aerodynamic drag. Sidepods make the process smooth by channeling airflow efficiently through the cooling ducts, reducing drag. Research has found that the inclusion of sidepods can decrease drag by a factor of 7 to 13 relative to non-sidepod configurations.

The majority of Formula One sidepods are shaped with a slight airfoil, which not only directs airflow but also creates a high-pressure area at the radiator entrance to provide optimal cooling. Yet, this shape can create slight lifting forces, something that engineers will need to balance out by way of detailed shaping and incorporation within the larger aerodynamic package. Contemporary sidepods are thus designed to balance drag reduction, cooling performance, and downforce creation, in turn making them an essential aspect in the aerodynamics of the car.

G. Diffuser

The diffuser, situated at the back of the floor of a Formula One car, is one of the most significant devices for creating underbody downforce. Through acceleration of air underneath the car, it generates a low-pressure area that, with the higher pressure on top, creates huge downforce.

As the diffuser flares upwards, it assists in the management of the transition from the high-velocity underfloor airflow and the slower ambient airflow at the rear of the car. This expansion minimizes turbulence and stabilises the wake, which improves efficiency and stability. The diffuser needs to be crafted carefully, though, so that flow separation is avoided since disturbed airflow can significantly reduce the overall efficiency of the entire floor. [17]

H. Undertray

The undertray is the biggest aerodynamic bodywork on a Formula One car and also one of the most effective, producing between four to nine times more downforce for a given drag than the rear wing. With the reduction in sizes of wings by the 2015 regulation, the undertray is now a focal point in aerodynamics, producing a significant amount of total downforce. Attached to the bottom of the chassis, the undertray takes advantage of ground effect, where the thin space between floor and track forces air to flow fast, generating a low-pressure area that actually "sucks" the car onto the ground.

The assembly consists of a flat central piece, outboard tunnels, side extensions, and the rear diffuser. The outboards and tunnels restrict airflow towards the center, avoiding pressure loss at the edges, while maximum downforce is realized at the back of the flat section, where pressure is minimum. Strakes are usually included to precondition airflow and improve diffuser efficiency. In the rear, the diffuser has an important function to deal with the transition between the lowpressure underfloor flow and the surrounding pressure. It prevents flow separation and high drag by progressively expanding the flow. In addition, the wake of the diffuser interacts favorably with the rear wing, enhancing the overall aerodynamic performance of the two parts together[19]

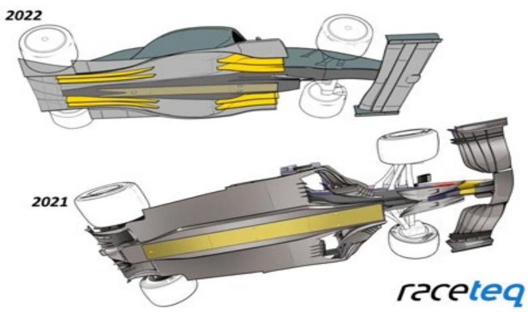

Fig. 6.

IV. DRAG REDUCTION TECHNIQUES IN F1

A. Drag Reduction System (DRS)

The Drag Reduction System (DRS) was implemented in Formula One in 2011 as an aid to overtaking. It enables the rear wing flap to deploy flat at predetermined zones of a track when one is one second behind the car in front, cutting aerodynamic drag by about 20% and boosting top speed. Experimental studies on multi-element wings have shown drag reductions of up to 83% for rear wings in free-flow conditions and around 70% for front wings underground-effect, resulting in an overall drag reduction of nearly 53%.

Similar applications in Formula Student (FST) vehicles demonstrated lap time reductions of approximately 1.5 seconds over 30 laps. Wing profiles used in motorsport are primarily borrowed from aircraft, and profiles like NACA, Eppler, Liebeck, and Wortmann profiles are used widely. High-lift aerofoils like Eppler 423, S1223, and FX74-CL5-140 are preferred because they have high lift coefficients when operating within low Reynolds number flows like those experienced by FST cars. The aerophysics of high-lift wings, outlined by A.M. Smith (1975) highlight quick pressure recovery methods such as Stratford or concave recovery, which are maximally lift-oriented but cause the boundary layer to be more susceptible to separation and stall at angles of attack greater than critical.

In multi-element wing design, the parameters of angle of attack, gap, and overlap are of utmost importance. Optimal values of 1–4% and 1–6% of chord length for gap and overlap, and recommended values of 4–6° for the AoA of the main element, 25–30° for the first flap, and 30– 70° for the second flap are recommended by McBeath. These settings provide maximum lift while postponing stall.

DRS needs to be operated by an actuator system, usually electric, to move the wing flaps. Linear and rotary actuators are used, but their location, casing, and structural mounting affect the aerodynamic performance. There is limited data in current literature on the aerodynamic costs of integrating actuators. Thus, this paper attempts to conceptually design and computationally analyze an active multi-element DRS system for an FST rear wing with the help of computational fluid dynamics (CFD) and finite element methods (FEM). The research includes:

a. Designing a multi-element wing profile under FST rules.

b. Aerodynamic performance analysis via FEM and CFD.

c. Designing a DRS mechanism from available technologies.

d. Development and analysis of a new linear actuator system for active DRS activation[21]

Fig. 7. DRS open of Mercedes- AMG PETRONAS Formula One Team

B. .Smooth and Streamlined Bodywork in Formula 1

Streamlined and smooth bodywork is essential to reducing aerodynamic drag and enhancing the overall aerodynamic performance of an F1 vehicle. The body is sculpted carefully with smooth surfaces and curves to enhance laminar flow and limit turbulence and flow separation, both of which increase drag. Key points are

- Sculpted Surfaces and Blunted Edges: The body panels of the car, such as sidepods, engine cover, and chassis, are sculpted with blunted edges and smooth surfaces to allow air to flow smoothly without sudden changes that introduce turbulence.

- Snug Packaging: Radiators, cooling ducts, and suspension units are packed snugly inside the body to minimize gaps and airflow interruptions, further decreasing drag. • Front and Rear Wing Design: The wings are mounted within the body with aerodynamic components that help manage airflow effectively while sustaining downforce to stabilize the car.

- Underbody and Ground Effect: The underfloor with its smooth shape utilizes the Venturi effect by accelerating the airflow beneath the vehicle, creating areas of low pressure that produce downforce without more drag than wings.
- Flow Management Devices: Small aero devices such as bargeboards, turning vanes, and vortex generators are utilized to direct airflow over the car, minimize vortices, and maintain the airflow attached to the body so as not to waste energy. • Balancing Drag and Performance: While reducing drag improves speed and fuel economy, designers have to provide enough downforce for grip and handling, resulting in compromises in bodywork shaping. [20]

Akshay Khot et al. (2021) conducted CFD analysis on front wings and body profiles to maximize airflow, minimize drag coefficients, and enhance lift-to-drag ratios, finding that streamlined shapes and smooth surfaces greatly increase aerodynamic efficiency. Research indicates that diffuser and sidepod shape must be carefully designed to affect both the quality of airflow and heat management, not only enabling performance improvement through wake turbulence reduction behind the car but also enhancing drag and cooling. 5.3. Vortex Generators Vortex generators (VGs) are minute aerodynamic instruments designed to create controlled vortices that energize the airflow close to the surface of the car, in particular, in areas where flow separation is expected. Flow separation actually results in reduced downforce and higher drag. Thus the forced flow is maintained over such surfaces as wings or body panels with vortex generators, which split the low-energy boundary layer from separating off of the surface.

In F1 cars, vortex generators work to subdue and delay flow separation especially around complex aerodynamic elements such as the front wing, bargeboards, and the edges of the diffuser. This addition of energy keeps the airflow attached longer, giving a finer reduction in pressure drag caused by turbulent wakes behind the car. Thus, these flow enhancements contribute to achieving improvements in aerodynamic efficiency, downforce, and subsequently cornering ability, with minimal drag penalty. Vortex generators, usually small fins or vanes arranged strategically on a surface on which flow separation is imminent, have found their origins in aerospace applications where they are extensively used on aircraft wings to aid in control at low speeds. [20]

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V. CFD ANALYSIS IN AERODYNAMIC OPTIMIZATION

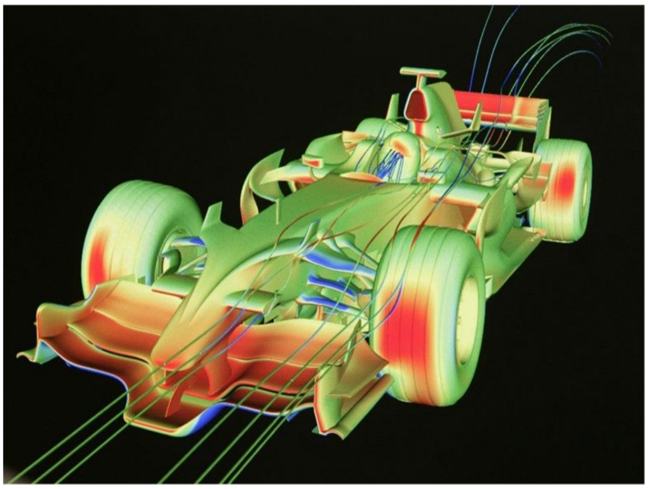

Fig. 8. Computational Fluid Dynamics (CFD) visualization of airflow around a Formula 1 car. Colored regions represent pressure distribution, while streamlines indicate airflow behavior over the front wing, sidepods, and diffuser. Such simulations are widely used in F1 to optimize aerodynamic efficiency, balance downforce, and minimize drag. [Adapted from CFD visualization sources].

Computational Fluid Dynamics (CFD) is now a bedrock of contemporary aircraft design and has tremendously decreased the dependence on expensive wind tunnel experimentation and testing. It serves as a "virtual wind tunnel" for accurate aerodynamic optimization by simulating the behavior of flow around intricate shapes. The process typically includes parametric shape modeling, grid generation, and flow-field analysis, with more-high-fidelity approaches like Euler solvers and Reynolds-averaged Navier–Stokes (RANS) equations being used extensively to model threedimensional effects in wing–body junctions, nacelles, and high-lift devices.

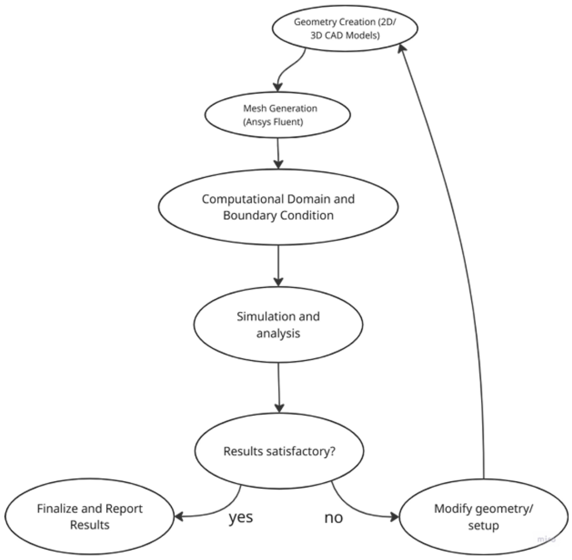

Fig. 9. Flowchart with the geometries

analyzed

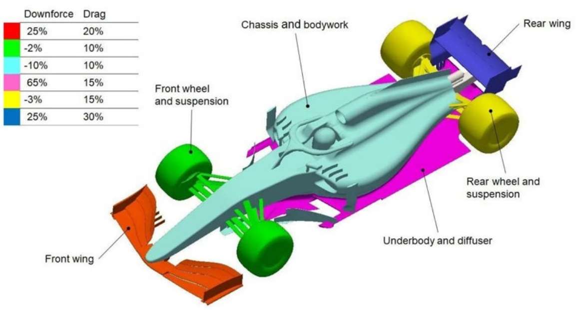

Fig. 10. Contribution of key aerodynamic components of a Formula 1 car to total downforce and drag. The front wing and rear wing generate significant downforce but also contribute to drag, while the underbody and diffuser provide the largest share of downforce with relatively lower drag. Percentages are indicative values based on computational studies. [Adapted from aerodynamic performance analyses of F1 cars].

Although CFD offers significant improvements in efficiency and precision, difficulties persist in the form of high computational expense and the intricacy of parameterizing 3D surfaces. This is overcome through the use of free-form parametric modeling in CAD, reducing variables while maintaining physical relevance. CFD-based optimization overall combines aerodynamics with digital design processes, allowing aircraft development to be more efficient, precise, and innovative. [18] The template is designed so that author affiliations are not repeated each time for multiple authors of the same affiliation. Please keep your affiliations as succinct as possible (for example, do not differentiate among departments of the same organization). This template was designed for two affiliations.

Computational Fluid Dynamics (CFD) is a pillar of aerodynamic optimization in motorsport and automotive engineering, especially high-performance vehicle design and tuning such as Formula One vehicles.

CFD allows engineers to test and predict airflow patterns surrounding intricate geometries, providing precise details on aerodynamic forces including lift, drag, and downforce parametric factors that determine speed, stability, and fuel economy. Core Steps in CFD Analysis:

a. Geometry and CAD Modeling The starting point is the precise development of 2D and 3D models of the automobile's aerodynamic parts by means of CAD software (e.g., SolidWorks). These models comprise features like front and rear wings, underbody diffusers, sidepods, and Drag Reduction System (DRS) mechanisms. Geometry precision is crucial since even small errors can drastically impact flow behavior and simulation accuracy.

b. Mesh Generation and Analysis The CAD geometry is discretized into a numerical mesh employing CFD solvers such as ANSYS Fluent or OpenFOAM. The mesh decomposes the domain into discrete cells where flow equations are approximated. High-quality meshing is used in areas of complex geometry or anticipated turbulent flow—like wing tips, vortex generators, and wake regions—to guarantee high accuracy. Mesh independence analyses are usually performed to confirm the accuracy of the mesh.

c. Computational Domain Configuration A simulation domain is established in order to mimic wind tunnel or actual track conditions. That entails defining the inlet and outlet boundaries, symmetry planes, and wall surfaces. The size of the domain should be sufficient enough to avoid artificial constraints on flow, and boundary conditions are established to represent realistic operating conditions, including vehicle speed, ambient pressure, and air direction.

d. Boundary Condition Specification Realistic boundary conditions are used, such as inlet velocity, outlet pressure, and wall treatments. Turbulence models such as the Transition SST or k-ω models are chosen according to the anticipated flow regime (laminar, transitional, or turbulent). These models assist in simulating phenomena such as boundary layer separation, vortex shedding, and flow reattachment, which are of central importance for aerodynamic performance.

e. Simulation and Solution Process The Navier-Stokes equations are solved numerically by the CFD solver throughout the mesh in order to simulate airflow behavior. Simulations are simulated for different configurations and speeds in order to assess performance in various race conditions. Iterative refinement is prevalent: half-way results are inspected, mesh density or boundary conditions are modified, and simulations are recrun until the required accuracy and performance measures—such as drag coefficient (Cd), lift coefficient (Cl), and downforce—are attained.

f. Result Analysis and Optimization Post-processing software is employed to visualize and analyze CFD results. Engineers look at pressure contours, velocity vectors, streamlines, and turbulence intensity to understand the location of flow separation, vortex creation, and aerodynamic inefficiency. Design parameters like wing angles, component locations, and surface curvature are optimized on the basis of these analyses. The objective is to reduce drag while increasing downforce, achieving speed and stability. Final outputs are frequently checked against wind tunnel measurements or on-track telemetry to verify simulation credibility.

CFD analysis not only speeds up the design process but also diminishes the use of expensive physical models. In Formula One, where aerodynamic efficiency may decide the winner, CFD is an essential tool for innovation, FIA regulation compliance, and the quest for sustainable engineering solutions. Formulae used

Lift coefficient: $l = Flift\ 1\ 2\rho U\infty\ 2A$

Drag Coefficient: $D = FDrag\ 1\ 2\rho U\infty\ 2$

Where,

Flift= lift force

Fdrag= drag force

ρ = Air density

U∞= Free- stream velocity

A= Reference Area

In establishing the computational configuration for our simulations, we used the methodology offered by [Loução, Duarte, & Mendes, 2022] who performed a CFD-aided aerodynamic investigation of a multi-element airfoil profile.

Their domain setup was in line with best practices in car aerodynamics, providing enough clearance upstream and downstream to record flow effects. In particular, a virtual wind tunnel of four upstream and eight downstream times the car reference length was created, dimensions that are practically in agreement with suggestions from Lanfrit [23].

TABLE I. BOUNDARY CONDITIONS

Type of Flow Turbulence	3D Steady State Flow
Turbulence model	Transition SST
Turbulence intensity	0.003%
Turbulent Viscosity Ratio	1%
Inlet velocity	14.7 m/s
Wall Treatment	Automatic wall treatment
Wall	Stationary wall, Specified Shear
Rear Wing Wall	Stationary wall, No slip

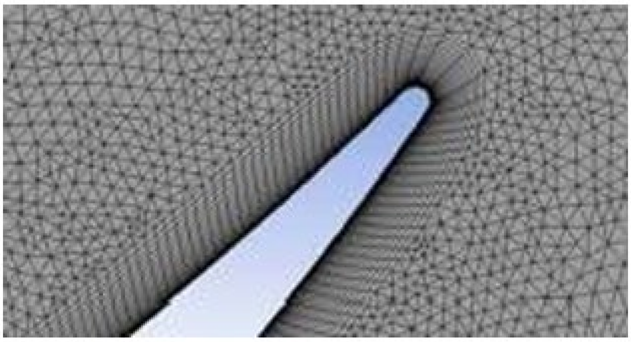

Fig. 11. Example of the mesh detail trailing edge of 2D profile

The selected turbulence model was Transition SST (γ–Reθ), which is well-suited to predict laminar–turbulent transition in low Reynolds number flows—a typical condition for Formula Student cars. The transport equation for the transition momentum-thickness Reynolds number, as used by them, is provided by Equation (1):

$$\frac{\partial(\rho\widetilde{Re_{\theta t}})}{\partial t}+\frac{\partial(\rho U_j\widetilde{Re_{\theta t}})}{\partial x_j}=P_{\theta t}+\frac{\partial y}{\partial x_j}\left[\sigma_{\theta t}\left(\mu+\frac{\mu_t}{\sigma_g}\right)\frac{\partial(\widetilde{Re_{\theta t}})}{\partial x_j}\right]$$

in which $(Re\theta t)$ +$\partial(\rho U_j Re\theta t)\tilde{}$ ∂xj =$P\theta t$ + ∂y ∂xj [$\sigma\theta t$ (μ + μt σg) $\partial(Re\theta t)\tilde{}$ ∂xj]̃ is transition onset momentum-thickness Reynolds number, Pθt is a source term, and ρ, μ, μt, Uj are density, dynamic viscosity, turbulent viscosity, and velocity components respectively [25]. For mesh generation, the research used an unstructured tetrahedral grid with inflation layers of prismatic types in the vicinity of the wall to provide sufficient boundary-layer resolution. Trailing edges were subjected to local refinement with element sizes of 0.8 mm and a volumetric growth.

The quality of mesh was ensured by the checks of asymmetry, orthogonally, and residual convergence. Following the methodology presented in [24], our research used the same turbulence model and meshing technique to ensure precision in simulating the aerodynamic performance of the rear wing during actual track conditions. The boundary conditions utilized in their work are tabulated in Table 1 and were used as a reference for our own adjustment in our setup.

These conditions represent the free-stream conditions of a Formula Student racing car lines for the second affiliation.

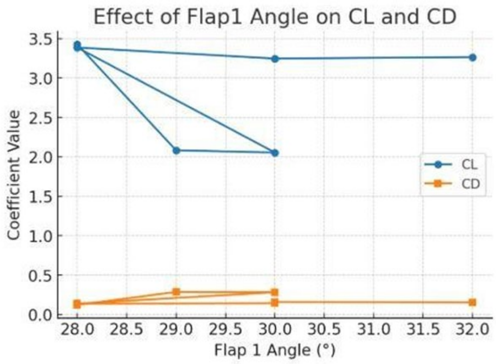

Fig. 12. Graph of Effect of Flap1 Angle and CL and CD Highlight author and affiliation lines of affiliation 1 and copy this selection

Effect of Flap1 Angle: The parametric study (Figure 2) indicates that increasing Flap1 angle generally decreases CL after a certain threshold, while CD tends to rise. For instance, increasing Flap1 from 28° to 30° at constant Flap2 = 60° reduced CL from 3.4254 to 2.0545, while CD increased from 0.1223 to 0.2835. This confirms the presence of an aerodynamic stall-like behavior at higher flap deflections

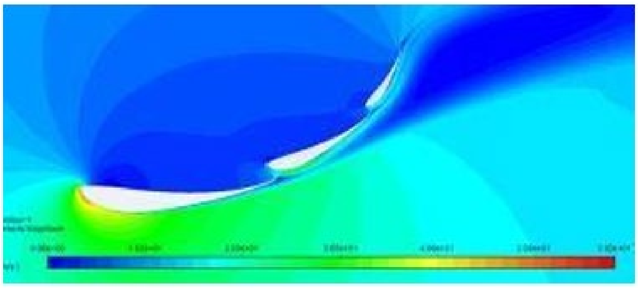

Fig. 13. Multi-Element profile speed contour graph

VI. THE EVOLUTION OF AERODYNAMIC REGULATIONS IN F1

Aerodynamics sometimes was virtually synonymous with performance in the realm of Formula 1, as regulation changes dictate the nature of technological development and competitive dynamics. Ever since the introduction of wings in the late 1960s, teams have tried to maximize airflow for downforce or to reduce drag. As aerodynamic development increased, so did concerns about safety, cost escalation, and reduced race quality as turbulent air is generated and overtaking becomes hard.

A solution to these problems has been found in the periodic approvals of FIA for the aerodynamic regulations. The one in 2009 was supposed to simplify front and rear wings and forbid appendages of different shapes and sizes that would cause wake turbulence so as to let cars race closer to one another [28]. The approach in 2017, on the contrary, allowed for wider cars and more aggressive aero profiles, giving priority to speed and thus inadvertently bringing back the greatly disliked overtaking problems.

The most transformative shift came with the 2022 regulations, which reintroduced ground effect aerodynamics through redesigned underfloors and simplified upper-body aero components. This change significantly reduced the aerodynamic wake, enabling cars to follow more closely and enhancing race spectacle [26]. Looking ahead, the FIA's proposed 2026 regulations continue this trajectory, emphasizing sustainability, cost control, and competitive parity through further aerodynamic simplification and standardization. According to statistical analyses, these shifts have brought about measurable effects on race dynamics, including in overtaking, in safety issues, and in convergence of team performances [27].

TABLE II. TIMELINE OF AERODYNAMIC REGULATIONS CHANGES AND THEIR IMPACT

Era	Major Aero Feature Change	FIA Regulation	Impact
1960s	First wings	Height/ Width limits	Increased cornering grip
1980's	Ground effect	Ban in 1983	reduced instability
2000's	Winglets, bargeboards	Outlawed 2009	Cleaner aero, cost control
2022	Ground effect return	Floor tunnels	Closer racing
2026	Active aero	Dual-mode wings	Efficiency + overtaking

VII. IMPACT OF AERODYNAMICS ON FUEL CONSUMPTION

Aerodynamic drag is also a major factor that governs fuel usage by a vehicle, especially at high speeds when the drag force is directly proportional to the square of velocity, according to Hucho (2013) and Kuti (2011). This square law makes it such that even tiny increments in velocity can lead to much greater energy requirements to overcome air resistance. Therefore, minimizing aerodynamic drag is an ultimate goal in vehicle design, especially in motorsports and highperformance automotive engineering. By precision aerodynamic tuning—such as the elaboration of body lines, incorporation of streamlined elements, and airflow management over the car—engineers can dramatically lower drag. This decrease directly results in better fuel economy, since less energy is needed to push the car forward against air friction.[21][30][31]

These gains not only serve to enhance performance but are also consistent with more general objectives of energy efficiency and emissions reduction. Yet to achieve maximum aerodynamic efficiency is more than just reducing drag. In competition situations such as Formula One, ensuring sufficient downforce is also paramount. Downforce provides increased tire grip and stability to the vehicle, particularly during cornering and braking. An optimal aerodynamic configuration thus needs to balance competing requirements of low drag and high downforce to provide both fuel economy and dynamic stability[29].This equilibrium lies at the heart of contemporary aerodynamic design practices, wherein computational technology and experimental testing are employed to calibrate vehicle performance under a variety of operational conditions.

VIII. TRANSITION FROM DRS TO ACTIVE AERO: THE 2026 F1 REGULATIONS

The shift in aerodynamic philosophy brought about by the 2026 Formula One regulations constitutes a significant one, and the DRS will now be replaced by an active aerodynamics system. Since its inauguration in 2011, the DRS has been a strategic overtaking aid, its provisions allowing drivers within one second of another to open a slot in the rear wing and cut down on drag on specified straights. While promulgating overtaking, the DRS has attracted accusations of being artificial and too proximity rule-dependent [33]

By contrast, the new active aero system grants the driver greater control over aero according to 2026 regulations configurations over the course of (a lap. Movable front and rear wings will permit cars to dynamically switch between low-drag and high- downforce modes throughout a lap, independently of their relative positions to other cars. This system eliminates the one-second activation rule and brings in a potential strategy-level situation in which drivers maximize their performance on straights and through corners [34]

Transitioning to these cars is aimed at improving race craft, diminishing aerodynamic wake, and fostering sustainability. 2026 cars will be smaller, lighter, and nimbler, with downforce cut down by 30% and drag down by 55% compared to 2022 cars. Such changes would hope to enhance energy efficiency and lend more raceability towards the long-term environmental goal of the sport [32].

Fig. 14. DRS in 2024 and MOM (Manual Override Mode) according to 2026 regulations

IX. CONCLUSION

The development of aerodynamic principles in Formula 1 has been continuously intermixed with engineering innovations and regulatory considerations. There has been a constant balancing of performance against safety and competitive committees with the evolution of wings, ground effect, DRS, and now the active aero conversion phases. This paper explores the fundamental aerodynamic forces governing F1 car behavior, the design concepts to manipulate airflow, and computational tools such as CFD used to optimize these designs. It also considers how aerodynamics affects fuel consumption and hence energy efficiency, which is becoming more important within the sport to keep it sustainable. The 2026 rules will be a major change.

The replacement of DRS by a driver-controlled active aero system pushes F1 into a more dynamic and strategic racing environment. This change brings greater overtaking opportunities, aligns with the goal to reduce drag, promote energy efficiency, and promote competitive racing. Being in a constant state of evolution, aerodynamics are at the core of technical innovation in Formula 1. The next set of developments will probably include AIbased simulations, adaptive materials, and most probably finer control systems. For active aero, unlike a mere technical upgrade, the shift has become the declaration of intent for a smarter, comprehensive, and fairer future in motorsports. Thus, while the tension between innovation and regulation remains, aerodynamic regulations have changed in Formula 1 to reflect the more general spirit of compromise between engineering excellence and sporting integrity.

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