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AERODYNAMICS: HOW AIRFLOW AFFECTS BICYCLES, RACE CARS, AND AIRCRAFT

Nitya Varun Pancholi *

St Christopher's school, Bahrain.

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ABSTRACT

Aerodynamics is the study of the forces and motion experienced by objects through the air (NASA Glenn Research Center, 2023b). This article examines boundary layers, drag, lift, separation, Reynolds number scaling, and the design tools that engineers use to optimize aerodynamic performance. By focusing on these topics, this article argues that a set of physical principles governs low-speed airflow over a cyclist's helmet, an F1 car's floor, and a Boeing 787's wings. In other words, this article shows practical problems posed by aerodynamic performance such as "how do I go faster?" or "how do I stay planted through a corner?" ultimately are questions about generalized fluid dynamics.

Keywords: Aerodynamics; Boundary Layer; Drag and Lift; Flow Separation; Reynolds Number; CFD

1 INTRODUCTION

Aerodynamics is the study of how gases, particularly air, interact with moving objects and the forces that arise from this interaction (EBSCO, n.d.). As an object moves through a fluid, or as a fluid moves past an object, the molecules of the fluid near the object are disturbed and move around the object, generating aerodynamic forces (NASA Glenn Research Center, n.d.).

Aerodynamics is important because air is not a passive backdrop to motion; it actively resists, redirects, and sometimes assists it. Every vehicle that moves through air must contend with these aerodynamic forces that airflow produces. A cyclist fighting a headwind, a baseball player throwing a curveball, and an airliner's ability to stay aloft are all governed by the same underlying principles of aerodynamics. Even though scale, speed, and type of vehicle differ enormously, they all are acted upon by the same fundamental forces of aerodynamics - drag and lift.

This universality is precisely what makes aerodynamics one of the most prominent fields of study. Whether it is the airflow around a bicycle helmet or the airflow around the wing of a Boeing 787, the same underlying principles apply. What changes is simply the scale, speed, and geometry of the objects involved.

The purpose of this article is to build a conceptual and structural bridge between everyday knowledge about air resistance and the engineering principles used to design real vehicles. This article dives into the fundamentals of airflow and boundary layers, the forces of drag and lift and the phenomenon of flow separation. It further introduces the

Reynolds number as a tool for comparing flows at different scales and goes through the different tools engineers use to optimise designs. This article covers three case studies: bicycles, Formula 1 cars, and aircraft, showing how the same theory can be applied to different machines.

The framework in this article applies to low-speed, effectively incompressible flow, which covers cyclists, race cars, and aircraft during takeoff and landing. At cruise, airliners also experience compressibility effects such as shock waves and wave drag, which are beyond the scope of this article.

2 UNDERSTANDING AIRFLOW

2.1 What Happens When Air Meets an Object?

Air is a viscous fluid, which means that there is internal friction (viscosity) resulting in air molecules sticking along the surface of the aircraft rather than sliding along it. At any point in time, an object moving through air will displace the air around its shape.

Depending on the object's shape, speed, and orientation to the flow, different flow patterns can form. Air can remain closely attached to the surface, producing smooth, predictable behavior. Alternatively, the flow can break away from the surface, producing swirling, disorganized wakes that increase resistance and reduce control over the object. The transition between these is central to aerodynamic design, and it depends heavily on a thin region of air next to the surface known as the boundary layer (Schlichting, 1949).

2.2 Boundary Layers

A boundary layer is a thin layer, often just millimeters thick, near the surface of the object which changes the effective shape the flow experiences (NASA Glenn Research Center, n.d.).

The molecules next to the surface stick to it (the no-slip condition), so the air has zero velocity at the wall. Viscous interactions slow the adjacent layers, and this effect weakens with distance, so the velocity rises gradually to the free-stream value (NASA Glenn Research Center, n.d.). Although thin, the boundary layer has a large influence on aerodynamic performance since it determines how the flow eventually separates or stays attached, and it is directly responsible for a significant portion of total drag.

The boundary layer can be broken up into two main categories: laminar or turbulent. Laminar flow occurs when air particles move parallel to the surface - air moves in smooth, orderly layers that slide past one another. On the other hand, a turbulent boundary layer is filled with vortices featuring velocity variations in all directions. Here, the flow becomes chaotic with a constant mixing of air between layers. A turbulent layer, while it creates more surface friction, is more resistant to separating from the surface than a laminar one, helping the flow "hang on" longer before breaking away (Remmerie, 2018).

The point where a boundary layer changes character from laminar to turbulent is known as transition, which directly affects drag and the risk of separation. Due to this, predicting where and when transition occurs is one of the most consequential tasks in aerodynamics (Atlas of Engineering, 2026).

3 DRAG AND LIFT

3.1 Drag: The Force That Slows Things Down

Drag is the aerodynamic force that acts opposite to an object's direction of motion, resisting its motion through the air (NASA Glenn Research Center, 2023a). Drag is a mechanical force generated by the difference in velocity between the solid object and the fluid. Every vehicle moving through air experiences drag, and overcoming it consumes energy, whether that energy comes from a car's engine or a cyclist's legs.

$$D = \frac{1}{2}\rho V^2 C_D A$$

Drag is calculated using the above equation (NASA Glenn Research Center, 2025), where ρ is air density, V is the speed of the object relative to the air, C_D is the dimensionless drag coefficient and A is the reference area. The C_D captures how much drag the object's shape actually experiences. A streamlined shape has a low coefficient while a blunt one has a

high coefficient. A key point here is that drag depends on the square of the speed, and so doubling the speed quadruples drag.

There are three distinct sources of drag: skin-friction drag, form or pressure drag, and induced drag. Skin-friction drag is caused by the viscous interaction between molecules of the air and the object's surface within the boundary layer. The magnitude of skin friction, therefore, depends on surface texture, flow conditions, and fluid properties. Form (or pressure) drag is caused by patterns of high and low pressure created by the object's shape. The magnitude of form drag depends on the shape of the object. Induced drag arises specifically as a byproduct of generating lift. The magnitude of induced drag depends on the amount of lift being generated by the wing and on the wing geometry (Leishman, 2022a).

A cyclist riding into a headwind must work far harder than one riding with a tailwind, because drag increases sharply as velocity rises. At high speeds, drag can account for the majority of the resistance a cyclist must overcome. Similarly, a car cruising on the highway spends a large proportion of its engine output against air resistance rather than rolling resistance, so the power required rises quickly as speed increases.

Since drag grows quickly with speed - specifically with the square of speed - even a small reduction in an object's drag coefficient saves energy at high velocities (Lumen Learning, n.d.). This is why reducing drag is one of the first priorities in the design of any vehicle.

3.2 Lift: The Force That Helps Things Rise

Lift is a mechanical aerodynamic force generated perpendicular to the direction of airflow (IVAO, n.d.).

$$L = \frac{1}{2}\rho V^2 S C_L$$

Lift is calculated using the above equation where ρ is air density, V is the speed of the object relative to the air, S is the wing planform area and C_L is the dimensionless lift coefficient. Lift has the same structure as drag: dynamic pressure times an area and a coefficient. The difference is in the direction, since lift acts perpendicular to the flow. C_L depends on the wing's shape and the angle of attack.

In aircraft, many parts of the aircraft contribute to lift, but the wings generate most of it. Lift is produced because the wing's shape and its angle to the oncoming air force the flow to turn downward, which lowers the pressure over the upper surface and raises it under the lower surface; the net pressure force acts upward and supports the aircraft's weight (Study Flight, 2025).

Formula 1 cars use the same underlying physics but instead of producing an upward force, they are shaped to produce a downforce. Downforce increases the vertical load on the tires, which in turn increases the grip available for braking and accelerating. Modern F1 cars generate a large proportion of their downforce from the floor and diffuser rather than from the wings, since underbody aerodynamics can produce substantial downward force with relatively little drag, making it one of the most efficient ways to generate aerodynamic grip (RacingNews365, 2023).

Lift and drag are interdependent forces and the ratio between the two - known as the lift-to-drag ratio - is an efficiency metric used across aerodynamics. An airplane has a high L/D ratio if it produces a large amount of lift relative to its drag. Aircraft designers strive for a high L/D ratio to maximise range and fuel efficiency (NASA Glenn Research Center, 2024a).

4 FLOW SEPARATION

4.1 What Is Flow Separation?

Flow separation is when the boundary layer of air loses enough energy that it can no longer follow the contours of an object's surface, detaching from the surface of the object. Once separation occurs, the air breaks away, leaving a region of disturbed, low-energy flow behind the point of the detachment. This separation changes the effective shape the air "sees" compared to the physical shape of the object (Fiveable, 2026).

Separation tends to occur where the surface curves away from the flow direction too sharply, causing a reversed flow, or where the pressure increases in the direction of flow - known as an adverse pressure gradient. The boundary layer, having already lost energy to friction, cannot push through this rising pressure and so peels away from the surface.

4.2 Why It Matters

Flow separation is one of the most consequential occurrences in aerodynamics due to its dual effect: it creates a turbulent wake that increases form drag, and it removes the pressure difference responsible for generating lift or downforce (Wyatt, 2024). On an aircraft wing, separation at high angle of attack can cause a sudden loss of lift. This is known as a stall, a condition that is highly dangerous because it can occur quickly if pilots exceed the wing's critical angle of attack. Once separation spreads across a wing, control becomes difficult because the airflow detaches from the lifting surface. Recovery requires reducing the angle of attack to allow the flow to reattach to the wings (Leishman, 2022b).

Real-world examples of managing flow separation span all three vehicles discussed in this article. A cyclist's body position strongly influences where and how flow separates around their body; a more streamlined position delays the separation and reduces the size of the turbulent flow behind the rider, lowering drag (Crouch et al., 2017). When designing a car, the shape of the rear of the vehicle is carefully designed with diffuser strakes to manage where and how airflow separates. This is important because the sudden loss of downforce causes instability and height changes (Fluid Jobs, n.d.). In aircraft, leading-edge devices are employed to delay separation and push the stall to a higher angle of attack, improving safety margins.

5 REYNOLDS NUMBER

5.1 What is Reynolds number?

The Reynolds number is a dimensionless quantity used to characterize and compare different airflow situations.

$$Re = \frac{\rho v L}{\mu}$$

The above equation is used to calculate Reynolds number, where ρ is air density, v is the speed of the object relative to the air, L is the characteristic length and μ is the dynamic viscosity of air. It represents the ratio between inertial forces, which keep the fluid moving and generate turbulence, and viscous forces, which tend to damp out motion and keep flow laminar. A low Reynolds number indicates that the viscous effect dominates, producing smooth, laminar flow. A high Reynolds number indicates that the inertial effect dominates, producing chaotic, turbulent flow (Bushnell et al., 1993).

The Reynolds number allows engineers to compare flows that look completely different, with different speeds and sizes, given that the shapes are geometrically similar. This is because the Reynolds number combines an object's size, the speed of the flow, and the properties of the fluid (its density and viscosity) into a single number (NASA Glenn Research Center, 2024b).

5.2 Why Engineers Use It

Engineers cannot always test on full sized vehicles directly, because it is too expensive to build or too large to test on. Instead, they test smaller-scale models in wind tunnels or simulations. For the results to be meaningful and representative, the model's Reynolds number must be as close as possible to that of the full-sized vehicle, because flow behaviour depends strongly on Reynolds number, not just on shape.

This creates an engineering challenge: achieving the same Reynolds number on a small-scale model requires either very high wind speeds or pressurised wind tunnels, since simply shrinking the model reduces the characteristic length and therefore the Reynolds number for a given speed. Engineers across aircraft, cars, and cyclists wrestle with the same scaling problems. This is why a shape that performs well at one Reynolds number cannot always be assumed to perform the same way when scaled up at a Reynolds number orders of magnitude higher.

6 HOW ENGINEERS IMPROVE AERODYNAMIC PERFORMANCE

6.1 Wind Tunnels

Wind tunnels are one of the oldest tools used for aerodynamic development and testing. A wind tunnel is a controlled testing environment in which air is artificially driven past a stationary object to recreate real-world aerodynamic conditions. This allows engineers to precisely measure how airflow interacts with the design being tested and the different forces and pressures the structure would experience in real flight (Llopis, 2026). Drag and lift are measured using sensitive balances placed beneath or around the model.

Wind tunnel testing has been used for many generations - the Wright brothers themselves built a wind tunnel to measure the lift and drag of wing shapes before ever attempting powered flight. The same basic principles remain central to aircraft and race car development today; Formula 1 teams, for example, still rely heavily on scale-model wind tunnel testing to validate and refine floor, diffuser, and wing designs (Fluid Jobs, n.d.).

6.2 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) uses numerical methods and computer processing power to simulate airflow around an object by solving the equations of fluid motion. It solves the Navier-Stokes equations over a computational mesh that represents the vehicle's shape and the surrounding air. Rather than building a physical model, engineers can evaluate a design entirely through software, examining pressure distribution, velocity fields, and separation patterns in detail (Chowdhury, 2024).

CFD is widely used across aerospace and motor sport design because it allows many design variations to be evaluated quickly and relatively cheaply, as compared to building and testing physical prototypes. Moreover, it can reveal flow details that are difficult to measure directly in a physical test. However, it is not a replacement for physical testing: CFD results depend on the accuracy of the models used to approximate complex and chaotic flow behavior, and are generally validated against experimental data from wind tunnel or water tunnel tests (Mamou & Cooper, 2008; Mikołajczyk et al., 2023).

6.3 Reduced-Order Models

CFD simulations, while powerful, can be computationally expensive, sometimes requiring hours or days of supercomputer time for a single configuration. Since aerodynamic design and optimization requires evaluating thousands of shapes and designs, engineers have developed reduced-order models (ROMs). ROMs are simplified mathematical representations that capture the essential behaviour of a full CFD simulation for a fraction of the cost (Li & He, 2022).

The most common approach to build a ROM is through the use of proper orthogonal decomposition (POD). This is a technique that analyses the full CFD solutions across a range of design variations and extracts a set of dominant flow patterns that can be recombined to approximate new designs without rerunning the full simulation (Iuliano, 2011). These models are then used as fast stand-ins for the expensive CFD solver, allowing engineers to search a large design space efficiently before returning to expensive CFD or wind tunnel testing to confirm the promising designs. This layered approach - ROMs for broad exploration, full CFD and wind tunnel testing for final validation - has become a standard strategy used in aerodynamic design (Chowdhury, 2024).

7 APPLICATIONS IN THE REAL WORLD

7.1 Bicycles

At very high speeds, aerodynamic drag dominates over other forms of resistance for a cyclist, making up a much greater proportion than rolling resistance. Because of this, racing is an aerodynamically dominated sport; participants adopt low, tucked positions and use triathlon bikes to reduce frontal area and hence drag; equipment such as aerodynamic helmets, skinsuits, and deep-section wheels are all used to reduce drag; and teams are relying more and more on wind tunnel testing and on-bike aerodynamic sensors to measure the rider's drag area (Hopker et al., 2025). Riders who ride close together in a peloton also reduce drag significantly by drafting; CFD simulation and wind tunnel experiments show that cyclists riding in the center of a big peloton experience only a small fraction of the drag of an isolated rider (Blocken et al., 2018).

7.2 Formula 1 Cars

Aircraft wings generate upward lift; Formula 1 cars invert this to generate downforce, which increases tire grip and therefore cornering speed. Much of this downforce is generated by the floor and diffuser rather than the visible front and rear wings. The underbody - the floor and diffuser - can generate a large share of an F1 car's total downforce while adding comparatively little drag, making it one of the most aerodynamically efficient parts of the car. This underbody-dominant approach was reintroduced through Venturi-tunnel floor designs in 2022 and achieves very high downforce by accelerating air through the narrow gap beneath the car. However, it is highly sensitive to ride height, and if the airflow beneath the floor separates or 'stalls', downforce can be lost suddenly (Giuliana, 2024). Balancing maximum downforce against acceptable drag, and against the everyday reality of following another car through disturbed, turbulent air remains one of the prominent engineering challenges in motorsports, currently being addressed by new regulations aimed at reducing wake turbulence (Fluid Jobs, n.d.).

7.3 Aircraft

Aircraft design centers on maximising the lift-to-drag ratio: generating enough lift to support the aircraft's weight while minimising the drag that must be overcome by engine thrust, since fuel burn and operating cost are directly tied to aerodynamic efficiency. Wing shape, aspect ratio, and surface smoothness are all optimised with this trade-off in mind. For instance, long, slender wings with a high aspect ratio reduce induced drag compared to short, stubby wings of the same area. This explains why glider and long-range airliner wings tend to be long and narrow. At the same time, aircraft must be designed with adequate stall margins, since low-speed flight regimes - such as during takeoff and landing - push wings closer to their critical angle of attack, where flow separation and loss of lift become a safety concern. Devices such as flaps and slats temporarily reshape the wing to generate extra lift at low speeds without triggering separation. Since full-scale flight testing is expensive and difficult in early design stages, aircraft manufacturers rely on a combination of wind tunnel testing, CFD, and reduced-order surrogate models (Iuliano, 2011; Li & He, 2022) to explore and refine wing and fuselage shapes before committing to a final, flight-tested design (NASA Glenn Research Center, 2023b).

8 CONCLUSION

Aerodynamics relies on a compact set of ideas - boundary layers, drag, lift, flow separation, and Reynolds-number scaling - that recur, mostly unchanged, across every scale of vehicle discussed in this article. A thin boundary layer of air decides friction and separation whether it forms on a cyclist's helmet or an airliner's wing. Drag opposes motion and grows sharply with speed. Lift and downforce both arise from pressure differences caused by geometry and the angle of attack. Flow separation degrades performance and, in extreme cases, can cause a wing to stall or a race car's floor to lose grip. Finally, the Reynolds number indicates which flow regime (laminar, transitional, or turbulent) a vehicle operates in, and it allows a small-scale wind tunnel model to represent a full-size aircraft of the same shape, provided the Reynolds numbers are matched or the differences are accounted for.

What differs across bicycles, race cars, and aircraft is not the aerodynamic forces but the engineering objective. A cyclist and an aircraft designer both want to minimise drag; however an aircraft designer also wants to generate lift to fly, while a Formula 1 engineer deliberately generates downforce to maximise grip. These differing goals are achieved using the same methods of testing and refining. Wind tunnels provide direct physical measurement and comparison; computational fluid dynamics allows rapid, detailed exploration without building physical models; and reduced-order models make large scale design feasible by approximating expensive high-fidelity simulations with cheaper versions.

Ultimately, aerodynamics illustrates how practical everyday questions - such as how to make a plane more efficient or how to make a bike faster - can all be understood and expressed using the same underlying theory. Understanding this theory of aerodynamics is what allows engineers to move fluidly between problems that may look different but share the same physical foundation.

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