

# ***Optimizing Rear Wing Angle of Attack: The Trade-Off Between Downforce and Drag***

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**Abstract.** Rear wings are generally fitted to sports cars to enhance the stability of the vehicle through production of a high-downforce aerodynamic effect. However, to increase downforce, more aerodynamic drag generally results, and thus both the performance and straight-line efficiency are reduced. A typical Design Parameter to change the performance of the rear wing is to alter its Angle of Attack and thus alter the airflow over the wing. This paper studies the connection between the rear wing angle of attack, downforce production, and drag generation. Through previous research on computational fluid dynamics (CFD) simulations, wind-tunnel experiments, and airfoil analyses, the changes in aerodynamic performance with an increase in wing angle have been investigated. Based on research by others, increasing the angle of attack will initially increase the downward force, but at high angles, flow separation will occur, expanding turbulent wake and increasing drag significantly. Therefore, it cannot be said that increased downforce is always desirable for a vehicle. A suitable range of the angle of attack has been identified that balances the demands of downforce and drags optimally. This paper shows that aerodynamics needs to be improved in Formula 1 design, and thus the shape of car has been modified.

**Keywords:** Angle of attack, rear wing, aerodynamic downforce, aerodynamic drag, flow separation

## **1. Introduction**

One might wonder why many sports cars have large rear wings and why Formula One teams invest a lot of money in developing aerodynamic parts. The above Design choices are all for improving the performance of aerodynamics. When the car moves through the air, air resistance acts on it and thus alters the speed, stability, and other characteristics of the vehicle. The two factor that causes this are Lift and Drag. Drag acts in the opposite direction of the car's motion, reducing efficiency; lift can reduce the grip of the tires and car stability [1].

In order to reduce lift and improve traction, some inverted airfoils have been added to the back of the vehicles. Aircraft wings are designed to produce an upward force, so the rear wings of race cars are reversed to generate a downward force, or negative lift. Downforce increases the normal force at the wheels and thus improves traction during turns, accelerations and braking. Downforce generation is accompanied by other problems. The same aerodynamic reasons for generating downforce also increase drag and reduce the car's maximum speed and fuel economy [2].

The first most important factor that affects rear wing performance is how much the angle of attack is. Although a relatively large angle of attack can produce a higher amount of downforce, an excessively large angle will cause flow separation at the leading edge of the wing, leading to turbulence and a considerable wake; thus, it will increase drag. This paper investigates the aerodynamic effects and changes in handling due to varying rear-wing-angle-of-attacks in a model car.

## 2. Background theory

Aerodynamics is the study of how fluids interact with moving objects. With an increase in the speed of a car, both lift and drag are proportional to the square of this speed and thus are also rising significantly. Therefore, relatively small aerodynamic changes can have significant effects on racing speeds.

The Aerodynamic lift for is described as [3]:

$$F_L = \frac{1}{2} \rho V^2 A C_L \quad (1)$$

Where:

$F_L$  = Lift force (N)

$\rho$  = Air density (Kg/  $m^3$  )

V = Velocity (m/s)

A = Reference Area (  $m^2$  )

$C_L$  = Lift Coefficient

Similarly, Aerodynamic Drag is described as:

$$F_D = \frac{1}{2} \rho V^2 A C_D \quad (2)$$

Where:

$F_D$  = Drag force (N)

$C_D$  = Drag Coefficient

These equations demonstrate that aerodynamic forces grow rapidly as speed increases because velocity is squared. Consequently, small aerodynamic improvements that alter the force can significantly affect a vehicle's racing speeds.

The above coefficients reflect how effectively a given shape generates lift or resists airflow. The angle of attack would alter both coefficients. Thus, it is one of the most important factors in aerodynamic designs.

A dimensionless parameter that can show the kind of flow of a fluid is called the Reynolds number. The Reynolds number determines whether the airflow at a point over a surface will be laminar or turbulent. Race cars operate at a relatively high Reynolds number, so flow separation and turbulent wake formation need to be considered in the design of aerodynamic parts.

The Reynolds number is described as:

$$Re = \frac{\rho VL}{\mu} \quad (3)$$

Where  $L$  is a characteristic length and  $\mu$  is the dynamic viscosity of air. Reynolds number can determine whether flow over the surface is attached or detached. Flow separation and wake formation are also important considerations for mechanics [4]. Automotive aerodynamic applications generally operate at high Reynolds numbers, and thus turbulent flow and flow separation are commonly observed in the formation of drag and wake.

### 3. Angle of attack and aerodynamic forces

Angle of attack is the angle between the chord line of a wing and the direction of the incoming airflow. A larger angle of attack reduces the pressure distribution over a wing. An Angle with a greater span will result in a larger pressure drop between the upper and lower ends, and thus more lift is generated.

Thin airfoil theory is used to predict that lift coefficient rises nearly linearly with the angle of attack before stalling [2]:

$$C_L \approx 2\pi\alpha \quad (4)$$

Where  $\alpha$  is the angle of attack (radians) [2].

Increase the angle of attack to deflect the airflow more steeply around the wing and thus create a larger pressure difference at the two surfaces. Therefore, there will be relatively stronger pressure differences aerodynamically. This force is called a lift for the aircraft. But for inverted motorsport wings, the same force acts downward as downforce.

Several CFD Studies support this connection. Kamas (2009) found that increasing the angle of attack of an inverted rear wing would increase downforce generation [5]. Khalid and others (2025) have determined that, at first, a large angle increases downforce because of a higher-pressure gradient over the wing [6].

Increase the grip allows the car to drive at a higher speed in a corner. This is why racing cars often have adjustable rear wings, and Formula One teams continuously optimize the wing system for different circuits and employ a Drag Reduction System (DRS) on their cars [7]. At a high angle of attack, a wing can produce a lower drag and is therefore suitable for flat-out, straight tracks. At the same time, at a corner, the wing will be set at a relatively high angle of attack to increase cornering speed.

Increasing the Angle of Attack will also increase Drag. The wing is more likely to reduce the speed of the air flowing over it; thus, a larger power input will be required by the engine. As a result, the advantages of the additional downforce need to balance the drawbacks of increased drag to optimize the performance of the car.

Other studies have reached the same conclusion via a genetic algorithm optimization study. Therefore, the angle of attack directly affects both the produced downforce and the drag in an adverse manner [8].

#### 4. Flow separation and wake formation

Although a larger angle of attack will generally increase downforce, this is not always the case. At a sufficiently large angle, the airflow can no longer follow the shape of the wing surface. It is called a division of flow.

Flow separation occurs when the boundary layer does not have enough momentum to overcome an adverse pressure gradient, and a turbulent wake is thus formed behind the wing. Separation of flow creates a region of turbulent wake and thus an increase in drag. With an enlarged wake, the airflows poorly. In the case of severe aerodynamic stall [5], an increase in the angle of attack will result in little additional downward force but a considerable rise in drag [4].

CFD studies of Formula SAE rear wings have shown that although downforce increases with an increasing angle of attack initially, too large of an angle leads to boundary-layer separation and reduced aerodynamic efficiency [6]. Wake formation behind vehicles is, in fact, the main source of pressure drags. Also, Research has shown that vehicle drag is highly sensitive to the flow behavior at the rear of the car, and a large wake forms due to separation [9].

Previous research has indicated that aerodynamic drag on road vehicles is largely caused by flow separation and wake formation at the rear end of the vehicle, thus wake control is necessary for good-aerodynamic automotive design [10]. And since excess drag will reduce both acceleration and top speed, the best rear wing may not be the one with the highest downforce but rather one that balances downforce and drag most optimally.

#### 5. Analysis

Some previous studies have shown that the angle of the rear wing is an aerodynamic quantity. The Airfoil Theory implies that increasing the angle of attack will increase the downforce generated by a wing initially. Airflow is still attached to the surface of the wing currently, and aerodynamic efficiency is relatively high.

Many other studies have also found that a large angle of attack is related to increased drag and flow separation. Research has shown that the angle of maximum downforce is not always the same as the angle of maximum aerodynamic efficiency. Vehicle performance is required to have a good grip and high speed; neither should be neglected.

Therefore, according to the above studies, aerodynamically favorable design aims to reconcile various forces in the system and not optimize a single performance variable. Although an increase in wing angle will enhance the downforce at the cornering position, an accompanying rise in drag is also likely, causing the top speed to be reduced. Therefore, the best rear wing angle will vary according to the specific purpose of the car and track conditions.

Therefore, to boost the performance of a car, the goal may not be increasing to the maximum downforce. Instead, mechanics would find an optimal range in which the aerodynamic efficiency is the highest, where an increase in downforce will not generate too much of a drag.

#### 6. Conclusion

Based on the above experiment, an increase in the angle of attack of the rear wing first strengthens the pressure difference across the wing and thus increases downforce. A large angle of attack also increases drag and may cause flow separation and wake turbulence simultaneously.

Previous studies have shown that the aerodynamic performance of an increasing angle of attack will not improve indefinitely. A particular operating range has been determined to be favorable for

the increase in downforce at this point, despite the corresponding drag increase. Beyond this range, there will be flow separation and an increased wake; thus, performance will drop.

Therefore, the best rear wing is not necessarily the one with the highest downforce. Instead, adjusting and modifying the configuration of the rear wing according to different circuit conditions is more important. At this time, engineers need to consider whether downforce and drag can be simultaneously reduced effectively for good performance. Recognize that there are a trade-off and study how to reduce drag through aerodynamics in the design of this vehicle is important for car performance.

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