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A Fluid Dynamics Analysis of Automotive Aerodynamic Kits: Effects on Flow Separation, Wake Structure, and Drag Reduction

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Abstract. Aerodynamics Add-ons, which include Front Splitters, Diffusers, Spoilers & Wings that are a multi-million dollar industry as they are being sold to car enthusiasts everywhere with little evidence that they actually create an aerodynamic advantage. The focus of this research will be to study the effects that all the above named add-ons have on Flow Separation, Wake Topology, Pressure Distribution & Drag Reduction in Bluff Body Vehicles. This research will review existing literature about each of the four types of add-ons mentioned in the abstract. Each of the reviewed pieces of literature will use experimental validation to establish the mechanisms involved in achieving good aerodynamic performance in Complex Vehicle Systems. The literature-derived tables will contain data for the Drag Coefficient (Cd), Lift Coefficient (Cl) Base Pressure and Wake Dimensions at varying configurations. The results of this research show that Aero Kits can be effective at creating additional Down Force but that they work through changing where Flow Separates, Re-Energizing the Boundary Layer and Improving Base Pressure. The results also show that there are many variables that affect the Performance of Aero Kits including Reynolds Number, Ground Effect, Ride Height and Geometric Interactions Between Components.

Keywords: aerodynamics, ahmed body, drag reduction, flow separation, wake structure

1. Introduction

Aerodynamics is a crucial factor influencing vehicle stability, fuel economy, and high speed driving dynamics. Many manufacturers and aftermarket suppliers are touting aerodynamic kits as cost effectively ways to create down force and reduce drag. Unfortunately, most of the claims made about the effectiveness of these products are based on little to no understanding of fluid mechanics and do not take into consideration the nature of bluff body flow (i.e., flow over an object with very steep geometric discontinuities and a sharp trailing edge) that occurs when flow passes over a road car. As such, bluff bodies develop their boundary layer almost immediately after the leading edge, they produce a low pressure wake, and they experience significant amounts of pressure drag [1]. One example of a bluff body is the "Ahmed Body" which has been extensively used as a model to study many aspects of bluff body flow. For instance, it can be shown that the major portion of the flow around the Ahmed Body occurs as follows; Flow separates at the back of the slanted surface,

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and two counter-rotating vortices form above and below the flat surface called the c-pillar, and finally there is a large recirculating bubble behind the vertical base [2]. Other researchers have since studied how changes to slant angles, height above ground level, and add-on parts affect the size and shape of the wake produced by a vehicle [3]. This paper will address this gap in knowledge by collecting together and validating results from previous research to demonstrate how front splitters, diffusers, and wings/spoilers work through physical flow principles [4].

2. Methodology

2.1. Literature-based analytical approach

The study utilizes a literature-based methodology to analyze the results from experimental validations of peer reviewed research into automotive aerodynamics. Rather than create novel computational or wind tunnel data the study synthesized the available literature results using fundamental principles of fluid mechanics (such as boundary layer theory, pressure gradient effect, wake dynamics). This was done to ensure that each conclusion is based upon physical evidence (i.e., actual measurements) rather than uncertain simulation methods. By utilizing the literature this method also allows for comparison of different studies and provide generalized insight to readers. The literature review process focused on studies that had sufficient detail of their experimental setup, validated computational fluid dynamic (CFD) model(s), and transparently reported the various aerodynamic metrics. Ensuring that all analyses were consistent, scientifically rigorous, and relevant to the topic at hand.

2.2. Reference geometry: Ahmed body

The Ahmed body provides the baseline model for all geometries tested in this study due to its ability to capture critical aerodynamics properties of typical automotive configurations. These include the characteristics within the frontal stagnation area (i.e., air deceleration and subsequent formation of an associated high pressure region), boundary layer growth on the roof with influence from both surface roughness and pressure gradient effects, controlled flow separation at the rear slant which determines wake structure and drag force, and the formation of large scale wakes such as counter rotating vortex pairs or recirculation bubbles.

A particular importance is given to the standard 25° slant Ahmed body because of its special position in the transition zone from attached to separated flow; therefore, it is very susceptible for all kind of aerodynamic changes. Due to similarities with the rear shape of many hatchback cars (e.g., Opel Astra) and sedans (e.g., Ford Mondeo), the drag characteristics of the 25° slant Ahmed body have been extensively documented in the literature. Therefore, we test at high Reynolds numbers:

$$Re = \frac{UL}{v} \tag{1}$$

where U is freestream velocity, L is the characteristic length of the body, and ν is kinematic viscosity. Experimental studies consistently report a drag coefficient of approximately 0.29–0.33 for this configuration [2, 5], with variations attributed to differences in Reynolds number, ground clearance, and experimental setup.

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2.3. Data sources

The research is based on a number of academic peer-reviewed articles grouped by category. Each category provides additional information for understanding vehicle aerodynamics.

Wind tunnel testing serves as a reference point for measuring baseline flow patterns and aerodynamic coefficients [2, 6]. Experimental results can be compared to those from computational fluid dynamics (CFD) simulations [3, 7], which also include additional details about the flow field and the pressure distribution. In addition to providing overall aerodynamic performance characteristics, component specific investigations examine the effects of individual aerodynamic devices such as splitters, diffusers, and wings [8, 9].

Ground effect describes how being close to the ground affects the air flowing beneath the car and the amount of down force that will be generated [10].

2.4. Evaluation metrics

The aerodynamic performance of an object is evaluated based on a number of standard metrics that represent the amount of drag or lift experienced by the object, in addition to how the airflow behaves around it.

Drag coefficient (C_d), a dimensionless measure of aerodynamic resistance, calculated as:

$$C_d = \frac{F_d}{\frac{1}{2}\rho U^2 A} \tag{2}$$

Lift coefficient (C_l), which quantifies the net vertical aerodynamic force, with negative values indicating downforce:

$$C_l = \frac{F_l}{\frac{1}{2}\rho U^2 A} \tag{3}$$

Base pressure coefficient, which reflects the pressure in the wake region and directly impacts pressure drag

Wake size and structure, including the extent of the recirculation bubble and the strength of trailing vortices

Vortex intensity and coherence, measured through vorticity fields and flow visualization data

These metrics provide a comprehensive description of aerodynamic behavior, allowing for objective comparisons between baseline and modified configurations.

2.5. Physical interpretation framework

The authors interpret their findings by employing foundational fluid mechanics principles that frame their understanding of how aerodynamic changes occur (i.e., via a) Boundary layer growth - how velocity increases as you move from the surface of the vehicle toward its centerline, b) Separation due to an adverse pressure gradient - a significant contributor to wake generation and increased drag, c) Wake behavior and vortex shedding - a primary mechanism for determining the dynamic behavior and organization of the flow behind the vehicle and d) Momentum transfer between different flow regions - e.g., interaction between flows beneath the vehicle and in the wake).

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3. Aerodynamic impact analysis and performance metrics

3.1. Baseline flow structure

Beginning with the blunt, or bluff body shape of the Ahmed body model, this represents a typical type of passenger vehicle. Upon entry to the front of the model, the incoming airflow strikes the stagnation area (high pressure) and thus causes the airflow to be pushed across the roof of the model and under it. As the boundary layer develops from the front to back along the roof, as it passes the rear sloping edge, an adverse pressure gradient is encountered which results in flow separation. Flow separation creates a pair of counter rotating vortices trailing behind the vehicle known as C-pillar vortices which draw fast moving air into the separated flow behind the vehicle increasing its drag. A large recirculating flow zone exists directly behind the vertical base of the model due to very low pressures present there and slow flowing velocities, as shown in table 1.

Table 1. Baseline drag coefficient of ahmed body [1]

Study	Drag Coefficient (C_d)	Ref
Ahmed et al.	0.29–0.33	[2]
Guilmineau	~0.31	[7]

These wakes are responsible for most of the aerodynamic drag, which accounts for about 70% of all pressure drag on bluff body designs [1]. The baseline flow will provide a benchmark that is used to compare the effectiveness of various aerodynamic modifications. Any modification to this baseline flow structure (such as altering separation point location, vortex strength or the size of the wake) has an effect on both the drag and lift characteristics of a vehicle.

3.2. Front splitters

The Ahmed body's front flow and under-body aerodynamic characteristics are modified significantly as a result of the presence of front splitters; this has an effect on both the lift and drag of the body. The results of Choi & Lee [8], which were obtained from their wind tunnel testing, indicated that based upon the level of splitter placement (height) and clearance to the ground, front lift may be decreased by anywhere from 10-30%. Additionally, the flow through the underbody was found to have been increased such that the pressure beneath the body was lower, while the down force created at the bottom of the vehicle was greater. Finally, a small amount of additional drag (0.01) occurred as a result of the increased frontal area and local pressure drag produced by the addition of the splitter.

The underlying mechanism is described by the Bernoulli principle:

$$P + \frac{1}{2}\rho U^2 = constant \tag{4}$$

The splitter divides the airflow to decrease the front of the vehicle's stagnation point and create additional acceleration underneath the vehicle. A higher air speed (velocity) in this area is associated with lower static pressure; conversely, the higher static pressure above the splitter produces an upward force called downforce. In addition to creating downforce, the splitter prevents the entrance of turbulent airflow into the undercarriage or wheel wells; therefore, it assists in maintaining front end stability.

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The effects mentioned above are amplified at increased speeds since the drag force is proportional to the square of the speed. As such, while the small increases in drag illustrate a consistent trade-off for production aerodynamic kits between downforce and aerodynamic performance, they indicate a consistent trade-off.

3.3. Effect of diffusers

Well-designed diffusers have been reported to be able to reduce drag by as much as 8%, recover the base pressure coefficient, and maintain attached flow as long as the diffuser angle does not exceed 12-14 degrees. The relationship between diffuser angle and flow attachment is summarized in Table 2.

Table 2. Diffuser performance [6]

Diffuser Angle	Flow Condition	Aerodynamic Result
< 12°	Attached flow	Drag reduction
> 14°	Flow separation	Drag increase

3.4. Effect of rear wings and spoilers

Wings and spoilers primarily influence the wake flow's direction of propagation and circulation. Hossain et al. [9], as indicated in Figure 1, have also shown that angle is directly proportional to the increase in down force and drag. The quantitative data for these parameters are given in the table provided as Table 3.

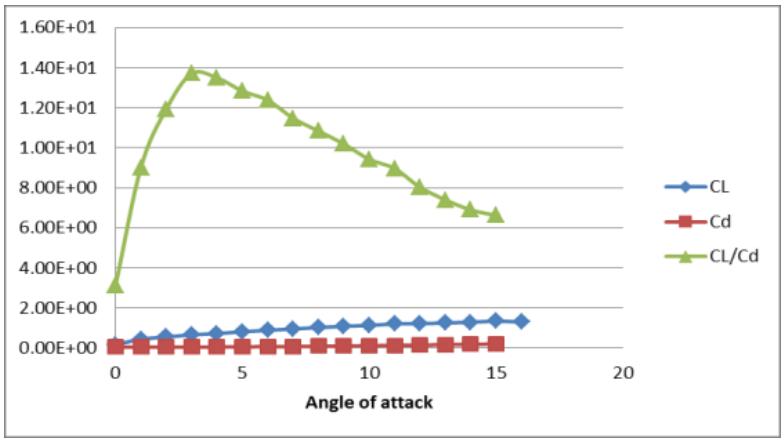


Figure 1. Variation of C_l and C_d with spoiler angle [9]

Table 3. Spoiler angle effects [9]

Spoiler Angle Change	Lift Coefficient Change	Drag Coefficient Change
+5°	$\Delta C_l \approx -0.02$	$\Delta C_d \approx +0.01$

Zerihan, J., and Zhang, X [10]. further showed that ground-effect wings significantly enhance downforce efficiency but are highly sensitive to ride height.

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3.5. Combined effects

Studies have shown that there are significant non-linear effects as individual component interact with each other. Adding a splitter to a diffuser will generally improve underbody flow, however adding a diffuser to a wing may cause some level of flow interference which can significantly affect how well it works. Whether these components work together effectively depends upon how close they are to each other [4]. Components that do not fit together properly tend to add turbulence or drag.

4. Discussion

4.1. Flow-control mechanisms

The results confirm that aerodynamic kits function through three primary mechanisms:

1: Separation control: Devices delay or redirect flow separation, reducing wake size.

2: Pressure redistribution: Diffusers and splitters modify pressure gradients to influence drag and lift.

3: Wake manipulation: Spoilers and wings alter vortex structures and flow direction.

4.2. Dependence on reynolds number

Low speed means that you are traveling below 60km/h. Dynamic pressure is very low so it will not take much energy for the air to move around your car. If you increase in speed then as mentioned above the effects will grow like. So, it would be easier to get an advantage by fitting a body kit if you can travel faster.

4.3. Engineering significance

The key to these research findings is that they are useful to automotive engineers and aftermarket designers. Optimized splitters, diffusers and spoilers will provide actual measurable improvements in the three areas most important for road vehicle performance (drag reduction, high speed stability and pressure recovery) with no "looks" involved [11]. A modest 3-8 percent reduction in drag can lead to improved fuel economy for gas powered automobiles and an extended drive range for electric vehicles by reducing aerodynamic drag. These results will also allow automotive engineers to correct many common mistakes made when designing aerodynamic kits. Examples include using a diffuser angle that is too extreme and poorly integrating components that result in flow separation and therefore additional drag. This research has provided a realistic, physics based model that can be used by automotive engineers and aftermarket designers to create functional, safe and road worthy aerodynamic kits.

4.4. Limitations of current studies

Existing work has many obstacles to overcome. The major obstacles are that each study may have used different test vehicle designs (thus potentially affecting results), different Reynolds numbers, and a variety of simplified body shapes (such as the Ahmed model) when they could be using actual production vehicles.

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5. Conclusion

The present research used fluid dynamics and validation of the literature to analyze how well designed automotive aerodynamic kits were capable of modifying flow separation, wake characteristics and pressure distributions as they relate to improved overall vehicle aerodynamics. It has been shown through this research that diffusers and front splitters are consistently able to produce drag reductions at stable conditions while the rear wing is able to generate high levels of downforce with an accompanying drag penalty. Thus, the success of an aerodynamic kit will depend heavily upon the design of each component, operational conditions and the total system design. Therefore, when evaluating or enhancing aerodynamic capabilities for production vehicles, it is recommended that each part be examined within the context of the entire system.

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