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Review Article

Aerodynamics of Road Vehicles: A Comprehensive Review

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Abstract

Aerodynamics plays a crucial role in determining how safe, fuel-efficient, and fast road vehicles can be. As global demand grows for sustainable and energy-efficient transportation, understanding the aerodynamic principles that govern vehicle performance has become increasingly important. This review examines fundamental aerodynamic concepts as applied to a range of road vehicles, including passenger cars, buses, and heavy trucks. Special attention is given to the interaction between vehicle shape, air movement, and the choice of structural materials. The paper discusses how factors such as drag, lift, pressure distribution, and surface roughness influence vehicle stability and energy consumption. It explores the performance impact of different body designs, from streamlined sports cars to box-shaped trucks, and shows how modern design methods-such as computational fluid dynamics (CFD) and wind-tunnel testing-help engineers visualize and optimize airflow patterns. Particular emphasis is placed on the role of materials in shaping aerodynamic outcomes. Advanced alloys, lightweight composites, and new polymer blends not only reduce overall mass but also improve surface finish and structural rigidity. Case studies include the use of carbon-fiber panels in sports vehicles, which minimize turbulence and cut weight, and the application of specialized surface coatings on commercial trucks, which reduce drag and improve fuel economy. Combined findings from experimental and simulated studies reveal that careful integration of materials and shape optimization can lower aerodynamic drag by 15–25%, translating into fuel savings of 5–12% under typical driving conditions. The review concludes with practical guidance for automotive engineers and designers, emphasizing that achieving aerodynamic efficiency is not limited to high-performance vehicles. Rather, it is a key design goal for all modern road transport aiming to balance speed, safety, cost, and environmental responsibility.

Keywords

Aerodynamics, Road Vehicles, Fuel Economy, Drag Force, Vehicle Design, Performance

1. Introduction

The science behind aerodynamics deals with understanding the motion of air interacting with solid objects. In case of wheeled vehicles, an effective aerodynamic design can provide improved fuel economy as well as overall vehicle performance. This paper focuses on giving a general overview about aerodynamic principles, important factors affecting vehicle aerodynamics, and material contribution to these traits.

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1.1. Importance of Aerodynamics in Road Vehicles

The role of aerodynamics in road transport cannot be overstated. In a world with escalating fuel prices and growing environmental pressures, carmakers are pushed to develop cars that are powerful but, above all, economical to run. Aerodynamics has a major influence on drag coefficients, something that determines direct fuel consumption [1, 2].

1.2. Objectives for the Review

This review aims to:

1) Discuss the basic principles of aerodynamics relevant to road vehicles.
2) Analyze the impact of vehicle design on aerodynamic efficiency.
3) Explore the effects of materials used in vehicle construction on aerodynamics.
4) Provide case studies showcasing advancements in automotive aerodynamics.

2. Fundamental Principles of Aerodynamics

Aerodynamics is governed by several key principles, including:

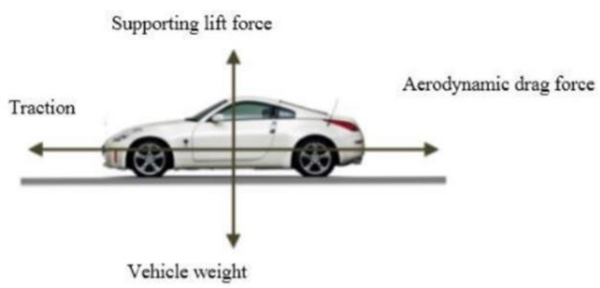

Figure 1. *Forces acting on a moving vehicle [3].*

2.1. Drag Force

Drag is the aerodynamic resistance that opposes a vehicle's motion. It can be divided into two main components:

1) Form Drag: Caused by the shape of the vehicle, form drag is influenced by the frontal area and the vehicle's geometric features [4].
2) Skin Friction Drag: Due to the air friction on the body surface, skin friction drag varies with the body roughness and velocity of the vehicle [5].

2.2. Lift and Downforce

Although lift tends to be mentioned with regard to airplanes, road cars also encounter lifts. High-speed situations require downforce, which provides improved tire contact with the ground. The trade between lift and downforce determines handling, stability, and safety [6, 7].

2.3. Reynolds Number

It is a dimensionless number applied to predict flow patterns during several conditions of fluid flow. It plays a significant role in finding airflow patterns surrounding a vehicle. The Reynolds number of a vehicle relies on speed, characteristic length, and kinematic viscosity of air [8].

2.4. Bernoulli's Principle

Bernoulli's principle tells us that a rise in speed of fluid comes with a reduction in pressure. The principle is central to understanding how aerodynamic force behaves on a vehicle, especially during the design of spoilers and airfoils that produce downforce [9].

3. Effects of Vehicle Design on Aerodynamics

3.1. Shape and Contours

Configuration	Description	C_D	C_L	C_D/C_L
	No aerodynamic devices	0.63	0.29	0.46
	Underbody channels (diffusers)	0.65	-0.79	-1.21
	Underbody channels, wings	0.66	-1.28	-1.94
	Underbody channels, wings with side fins	0.68	-1.56	-2.29
	Underbody channels, wings with side fins and flaps	0.90	-2.34	-2.60
	Underbody channels, multi-element wings	0.98	-2.58	-2.63
	Resized underbody, revised multi-element wings	1.30	-3.70	-2.85

Figure 2. *Drag and Lift coefficients of a FSAE car with different aerodynamic packages [11].*

The shape of a vehicle significantly influences its aerodynamic efficiency. Streamlined designs reduce form drag, while sharp edges and protrusions can increase turbulence and drag [10].

3.1.1. Streamlining

Streamlining means forming the body so that air passes easily over it. Low drag coefficient cars, including high-performance cars and high-efficiency sedans, are smooth, tapered shapes with smooth curves with a minimum resistance to air [12].

3.1.2. Computational Fluid Dynamics (CFD)

CFD integration within design work enables engineers to predict airflow around a vehicle, shape optimization being performed prior to building any physical prototypes. Vehicle design has been transformed through the use of such technology, leading to increased efficiency and effectiveness within aerodynamic solutions [13].

3.2. Ground Effects

How near a car is to the ground influences airflow pattern. Ground effects can be used to increase downforce and decrease drag, especially during racing. Ground effects take place where air between a car and road surface becomes compressed, a region with a low pressure that sucks a car down [14].

3.3. Venturi Effect

The Venturi effect, where fluid speeds up through a narrow section, can be exploited in vehicle design to increase downforce. Racing cars are often fitted with underbodies that give a Venturi effect, increasing grip and stability at high speeds [15].

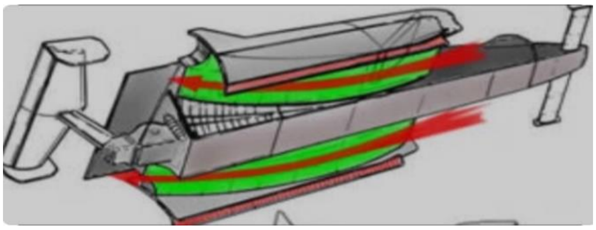

Figure 3. *Venturi tunnels in a racing vehicle [15].*

3.4. Aerodynamic Features

Various aerodynamic features can be integrated into vehicle design to improve performance, including:

1) Spoilers: To inhibit airflow and decrease lift, spoilers enhance downforce, especially at high speeds [16].
2) Diffusers: Located at the rear of the vehicle, diffusers help manage airflow and enhance downforce by accelerating air as it exits the vehicle [17].
3) Air Dams: Located near the front, air dams help to decrease air flow underneath the vehicle and reduce lift, improving stability [18].

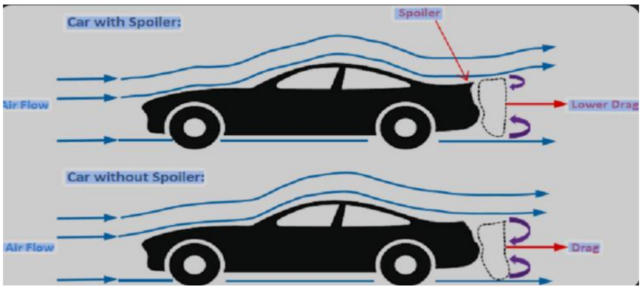

Figure 4. *Comparison of airflow over a vehicle with and without a rear spoiler [16].*

4. Effects of Materials on Aerodynamics

4.1. Material Properties

The materials used in vehicle construction affect both the weight and surface characteristics of the vehicle, which in turn influence its aerodynamic performance.

4.1.1. Weigh

Lighter materials allow for faster acceleration and can lead to a more aerodynamic design by enabling a lower center of gravity. Common materials include:

Aluminum: Lightweight and strong, aluminum can be molded into aerodynamic shapes. Its use in vehicle frames and body panels contributes to overall efficiency [11].

Carbon Fiber: Provides high strength-to-weight ratios, enabling complex and lightweight designs. Carbon fiber continues to gain usage in high-performance vehicles along with race cars [19].

4.1.2. Surface Finis

A vehicle's surface smoothness impacts skin friction drags. Smoother-surfaced materials decrease drag when compared to rough surfaces. High-tech coatings and treatment are used to increase the smoothness and hardness of the surface, directly influencing aerodynamic effectiveness [20].

4.2. Innovative Materials

New composite materials and coatings are being developed to improve aerodynamic performance. These materials can enhance surface smoothness and reduce weight, contributing to overall efficiency [21].

4.3. Smart Materials

New smart materials that will respond to varying aerodynamic conditions could also fine-tune vehicle performance. For example, shape- or texture-shifting materials in response to airflow could dynamically lower drag [21].

4.4. Case Study: Material Innovations

New research in material science has resulted in the introduction of hybrid material that will integrate the advantages of metals and composites. The new inventions not only reduce weight and increase strength but also the aerodynamic quality [21].

5. Case Studies

5.1. Automotive Industry

The automotive sector has seen significant advancements in aerodynamics through the use of computational fluid dynamics (CFD) and wind tunnel testing.

5.1.1. Tesla Model S

The Tesla Model S has a coefficient of drag of only 0.24, among the lowest in the market. The accomplishment is made through its sleek design and the employment of lightweight materials, maximizing both performance and fuel efficiency [5].

Figure 5. *Side profile of the Tesla Model S in aerodynamic testing [5].*

5.1.2. BMW i8

Carbon fiber and aluminum are employed together for a lightweight construction in the BMW i8. The lightweight and aerodynamic shape with active aerodynamics (e.g., variable vents) allows for variable configurations based on driving conditions [6].

5.2. Racing Vehicles

In motorsports, aerodynamic efficiency is paramount. Teams employ cutting-edge materials and designs to maximize downforce while minimizing drag.

5.2.1. Formula 1

The Formula 1 cars are produced after thorough tests on the aerodynamics and high-end material, i.e., carbon fiber, to ensure the cars deliver maximum output. The cars are specially made for specific tracks, marking the importance of aerodynamics in highly competitive racing [7].

5.2.2. Le Mans Prototypes

Le Mans racing cars are developed with ultimate aerodynamic efficiency. The cars are designed with complex geometry, active aerodynamics that change with speed and conditions of the track, showcasing the ultimate in aerodynamic engineering [7].

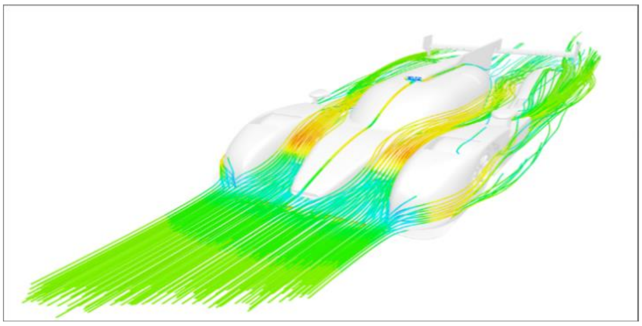

Figure 6. *Le Mans Prototype showing streamlines and pressure distribution around the underbody and diffuser regions [7].*

6. The Future of Vehicle Aerodynamics

6.1. Trends and Innovations

Figure 7. *Futuristic concept car with sleek, nature-inspired styling cues [14].*

With the evolution of technology, the use of new materials and novel designs will continue to improve aerodynamic capabilities. Next-generation cars could be designed with the following characteristics:

Adaptive Aerodynamics: Systems that dynamically change vehicle shape or characteristics in real time in response to speed and airflow [14].

Bio-inspired Designs: Utilizing principles from nature, such as the shapes of birds or fish, to inform aerodynamic design [21].

6.2. Environmental Considerations

With the rising consciousness of the environment, the automotive market is increasingly adopting sustainable strategies. The cars of the future will significantly utilize recyclable and sustainable lightweight structures [21].

6.3. Regulatory Impacts

Emissions-reducing and fuel-efficient regulations will spur increased research and development of vehicle aerodynamics. Automakers will face more stringent regulations, compelling them to innovate further in the realm of aerodynamics [21].

7. Conclusion

The aerodynamics of automobiles is a multifaceted combination of design, material, and environmental conditions. With the evolution of technology, the use of new materials and novel designs will increasingly augment the aerodynamic capabilities, providing better efficiency and greater safety for automobiles. There is a need for future research to develop intelligent or smart materials that respond to aerodynamic conditions in order to continue optimizing the performance.

Abbreviations

CFD	Computational Fluid Dynamics
FSAE	Formula SAE (Society of Automotive Engineers)
F1	Formula 1

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Author Contributions

Ahmad Fallatah: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Ali Abaaltahin: Data curation, Formal Analysis, Resources, Visualization, Writing – original draft.

Yazeed Almatheeb: Investigation, Software, Validation, Writing – original draft, Writing – review & editing.

Bijad Alharbi: Methodology, Formal Analysis, Visualization, Writing – original draft, Writing – review & editing.

Ibraheem Redhwi: Conceptualization, Supervision, Project administration, Resources, Writing – review & editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Ahmad Fallatah is a senior researcher at the Future Mobility Institute of King Abdullaziz City for Science and Technology (KACST). He earned his Master's Degree in Mechanical Engineering from University of Dayton in 2015, then he completed his Ph.D. in Mechanical Engineering from Iowa State University with a focus in Material Science, Biosensor, and Photoelectrochemical measurement in 2022. He has made significant contributions to research in Biosensing using metal oxide nanomaterials to detect several analytes: glucose, cholesterol, lactic acid, and pesticides. As well as his contribution to photoelectrochemical water splitting to produce hydrogen gas from water with the help of solar energy using the metal oxide nanomaterials.

Ali Abaaltahin is an academic researcher at the Future Mobility Institute within the King Abdulaziz City for Science and Technology (KACST), where he contributes to pioneering advancements in next-generation transportation systems. He holds a Bachelor's degree in Aerospace Engineering from King Fahd University of Petroleum and Minerals (KFUPM), with a specialized focus on the conceptual design and performance optimization of both fixed-wing and multirotor aerial platforms. Ali's research interests lie at the intersection of aerodynamics, autonomous systems, and sustainable mobility. His work involves developing innovative design methodologies that enhance the efficiency, stability, and adaptability of unmanned aerial vehicles (UAVs) for diverse applications ranging from urban air mobility to environmental monitoring.

Yazeed Almatheeb is an assistant researcher at the Future Mobility Institute at King Abdulaziz City for Science and Technology (KACST), where he contributes to cutting-edge research in mechanical systems and advanced mobility technologies. With a strong foundation in mechanical engineering and deep expertise in 3D modeling and design using SolidWorks, Yazeed plays a key role in developing high-performance components for automotive and small aircraft platforms. His specialization includes mold design, industrial system development, and comprehensive mechanical modeling-integrating stress and motion analysis to ensure optimal performance and reliability. Yazeed is passionate about innovation and is dedicated to enhancing design and manufacturing efficiency through precision engineering and continuous improvement.

Bijad Alharbi is a mechanical engineer and assistant researcher at the Future Mobility Institute at King Abdulaziz City for Science and Technology (KACST), where he specializes in drone advanced manufacturing technologies. With a strong background in composite materials, Bijad focuses on developing lightweight high-performance solutions for the aviation industry. His expertise lies in fabricating drone platforms using cutting-edge composite materials, optimizing their structural integrity and aerodynamic efficiency. Bijad is also deeply involved in exploring innovative manufacturing techniques that enhance the application of composites across mobility systems, contributing to the evolution of sustainable and efficient aerial technologies.

Ibraheem Redhwi is a senior researcher at King Abdullaziz City for Science and Technology (KACST), Advanced Material Institution. He completed his PhD in Nanomanufacturing from Iowa State University in 2021, and his Master of Engineering in Robotics from the Vanderbilt University in 2015. Over the last 14 years, Dr. Ibraheem has been working in many research projects that contribute to several mechanical engineering fields with KACST, Vanderbilt, and Iowa State University. In addition, he participated in many collaborations in the United States and Saudi Arabia. His experimental work contributes also and some mechanical engineering fields in addition to other fields like electrical engineering, education, and management.

Research Field

Ahmad Fallatah: Biosensing, Material Science, Photoelectrochemical Measurement, Hydrogen Production, Nanomaterials, Mechanical Engineering, Sensor Development, Energy Conversion.

Ali Abaaltahin: Aerodynamics, Autonomous Systems, Sustainable Mobility, Aerial Platform Design, Performance Optimization, Urban Air Mobility, Environmental Monitoring.

Yazeed Almatheeb: Mechanical Systems, 3D Modeling, Mold Design, Industrial System Development, Stress Analysis, Motion Analysis, Precision Engineering, Manufacturing Efficiency.

Bijad Alharbi: Composite Materials, Drone Manufacturing, Lightweight Structures, Aerodynamic Efficiency, Advanced Manufacturing, Structural Integrity, Aviation Technology.

Ibraheem Redhwi: Nanomanufacturing, Robotics, Mechanical Engineering, Composite Materials, Energy Systems, Electrical Engineering, Collaborative Research, Manufacturing Processes.