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Review on Aerodynamic Optimization of Automotive Exterior Shapes

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Abstract. Driven by demands for energy efficiency, environmental protection and vehicle performance, aerodynamic optimization of automotive exterior shapes has become a core focus in the automotive industry. This review comprehensively summarizes its progress, methods and trends. It expounds basic aerodynamic characteristics, including fluid mechanics principles (Bernoulli's equation, boundary layer). main aerodynamic elements such as lift force, drag force, drag coefficient and their impacts on fuel economy. In aiming of handling stability and comfort. The paper outlines traditional methods such as streamline design evolution. Modern techno involves information technology such as CFD and Wind Tunnel simulation. Then development of algorithms makes new breakthrough. The new trends, by introducing advanced technologies like parametric modeling, machine learning and AI with neutral network(PINN, etc). Reviewing on evolution in fluid optimization tells future trends,challenges(EV design freedom, potential demands) and autonomous driving (sensor integration), as well as the need for multi-objective optimization. Continuous innovation in this field is essential to meet the industry's future requirements.

Keywords: Automotive aerodynamic optimization, Computational Fluid Dynamics (CFD), Machine learning, Electric vehicles (EVs), Artificial Intelligence

1. Introduction

With rapidly and regulation of green gases also the purpose of environment protection and low price. People now would rather choose battery energy vehicle. Also for these who chooses conventional engine vehicles But facing the challenge of long-distance driving, which imposes the greater demand for battery.

For those who chooses traditional conventional engine vehicle, increasing fuel price gives and requirement of avoiding global warming gives tremendous pressure on engines design. The two factors above enhances the designs of autos using concepts of aerodynamic to enhance the vehicle efficiency. Aerodynamics consists of two main component: skin fraction drag and the pressure drag. Pressure drag accounts for more than 80% of the total drag and it is highly dependent on vehicle geometry.

The factors which effect aerodynamic drag coefficient of auto are shapes and size. At high speed, the fuel consumption would contribute to 50% of total vehicle fuel consumption.when driving at speeds above 80 km/h [1]. Therefore, reducing aerodynamic drag Reducing the aerodynamic drag

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offers an inexpensive and solution to improve fuel efficiency and the shape of auto optimization for low drag become a general method applied by car industries designer. Through optimized exterior shapes is an effective way to improve fuel economy and reduce emissions.

Aerodynamic performance also has a significant impact on vehicle handling stability and driving comfort [2]. Unstable aerodynamic forces and moments also braking performance. Also directional stability, especially facing crosswind conditions. Aerodynamic noise generated by the air around the vehicle is an important source of noise [3], which directly affects the comfort of vehicle.

This review aims to provide a comprehensive overview of the aerodynamic optimization of automotive exterior shapes. It covers the basic aerodynamic principles, including traditional and advanced optimization methods especially with application of new AI technology. Neutral Network, Machine Learning are future trends in this field. With these new techno, designers will have new opinions on Automatic vehicle.

2. Basic aerodynamic characteristics of automotive shapes

2.1. Aerodynamic principles relevant to automotive design

Fluid mechanics gives the fundamental principles that drive the aerodynamic nature of a vehicle. The equation of Bernoulli and the idea of boundaries layer are what controls Main effects. The equation by Bernoulli explains the correlation between the external factors(velocity, air) of a fluid. In the case of an incompressible fluid (e.g. low-speed air), the equilibrium of the static pressure, dynamic pressure and gravitational potential energy density per unit volume is fixed [4].

The air flow passing around the vehicle, the closer to the surface of the vehicle in which the airflow is convex the higher the speed of the airflow; consequently, there is a reduction in the static pressure and the reverse. This is the pressure difference creating forces of aerodynamics on the vehicle.

Another concept of significance in automotive aerodynamics is the boundary layer. It is the layer, which is a thin sheet of fluid near the surface of the vehicle at which velocity of the fluid is zero (because of the viscous effects) to the free-stream velocity which is in the exterior of this layer. The layer sheet may be either laminar or turbulent. Laminar boundary layers possess less friction drag but will be more affected in terms of separation as compared to turbulent boundary layers, which possess more friction drag and resistance to separation, respectively. Boundary layer separation is associated with the loss of momentum of the airflow which ceases to follow the curved surface of the vehicle and a region of low pressure in the wake with turbulent flow is created. The wake is also a significant contributor of aerodynamic lift and drag.

2.2. Primary forces and moments of aerodynamics

Drag (F), lift (F) and side force (F) are the primary forces of aerodynamics on a vehicle. This is the yaw, pitch, and roll moment (M, M, and M, respectively).

Drag Force (F): The force against the direction of the motion of the vehicle is the drag force. It consists of pressure drag (form drag), friction drag and induced drag. Most vehicles have pressure drag which comprises 60-80 percent of all drag. It is occasioned by the pressure difference at the front and back of the car as a result of a separation in the movement of air. Friction drag is the drag associated with viscous interaction of an airflow and surface of a vehicle which makes up 10 -30 percent of all drag. Vortices induced in the back of the vehicle created induced drag particularly on high aspect ratio vehicle and is typically a minor fraction of the total drag.

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Lift Force (F): Lift force is the force that is at right angles to the direction of the motion of the vehicle. Positive lift (upward) decreases force of contact of the tire with the road which may impact the handling and braking characteristics of a vehicle. The force of the negative lift (downforce) increases the force with which the tire is in contact and enhances stability of the handling of the vehicle, especially high-performance vehicles. The difference in the pressure between the upper and lower surfaces of the vehicle is the principal cause of lift force.

Side Force (F): Side force is the force that is perpendicular to the direction motion and the vertical axis of the vehicle. It is primarily produced when the vehicle is under cross head wind or during cornering. Lateral force may make the vehicle out of the directed course and produce the yaw moment.

Yaw Moment (M): The moment about the vertical axis of the vehicle referred to as yaw moment, is known to cause rotation of the direction the vehicle heads. It arises when the aerodynamic forces experience skewed distribution on the left and right side of the vehicle as in under crosswind conditions.

Pitch Moment (M): Pitch moment refers to the moment around the lateral axis of a vehicle and it is inclined to lift the nose of the vehicle up and down. It occurs due to the disparity between the location of aerodynamic center and the center of gravity of the motor vehicle.

Roll Moment (M): Roll moment is that moment about the longitudinal axis of the vehicle, which has a tendency to lean the vehicle on one side. This is produced through the influence of a lateral force that is exerted at a height beyond the centre of gravity of the vehicle.

2.3. Effects of aerodynamic performance on vehicle performance

Aerodynamic performance has a significant impact on various aspects of vehicle performance, including fuel economy, handling stability, and driving comfort [5,6].

Fuel Economy: As mentioned above, aerodynamic drag is a major contributor to the total resistance of a vehicle. Reducing aerodynamic drag can significantly improve fuel economy. For example, a 10% reduction in aerodynamic drag can lead to a 3-5% improvement in fuel economy for a typical passenger car (SAE International, 2020). This is particularly important for electric vehicles (EVs), as reducing drag can increase their driving range, which is a key concern for EV users.

Handling Stability: Lift force and yaw moment have a direct impact on vehicle handling stability.Potential risk of accident due to the crosswinds.Especially at high speeds. The winds would make vehicle hard to control.

Driving Comfort: Aerodynamic noise is a major source of interior noise in vehicles. The noise is generated by the airflow passing over the vehicle's surface, especially around the side mirrors, windshield, and rear end. Reducing aerodynamic noise can significantly improve the quietness and comfort of the vehicle's interior.

3. Traditional aerodynamic optimization methods for automotive exterior shapes

3.1. Streamline design evolution

The streamline design of automotive exterior shapes has evolved significantly over the past century. In the early days of the automotive industry, vehicles had a boxy shape with poor aerodynamic performance. For example, the Ford Model T, produced in the early 20th century, had a drag coefficient Cd of around 0.7-0.8.

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Auto industry designers began to use wind tunnels to test and optimize vehicle shapes. The Audi 100 C3, in 1982, was a milestone in automotive aerodynamics optimization, with a drag coefficient of just 0.29, which is close to contemporary vehicle.

3.2. CFD technology

In recent decades, with the development of computer-aided design (CAD) and computational fluid dynamics (CFD) technologies, automotive aerodynamic design has become more precise and efficient. Modern passenger cars typically have drag coefficients between 0.22 and 0.30, with some high-efficiency models achieving even lower values. For example, the Tesla Model 3 has a drag coefficient of 0.21, making it one of the most aerodynamic production cars in the world. For example, the Tesla Model 3 has a drag coefficient of 0.21, making it one of the most aerodynamic production cars in the world. Computer fluid calculation code contains three main elements: (1) A pre-processor (2) A flow solve (3) A post-processor [4].

3.3. Optimization of key components

Design of the specific elements of the vehicle defining its aerodynamic performance depends greatly on the front bumper, the grille, the windshield, the roof, the side mirrors, and the rear end. These aspects can be optimized to eliminate numerous disturbances in the aerodynamic performance of the vehicle.

Front Bumper and Grille: This is the first section of a vehicle that makes contact with the airflow and is the front bumper and the grille. With a designed front bumper, it is possible to control the air flow in a smooth flow around the vehicle which reduces pressure drag. The grille is utilized to cool the engine as well as the other parts of the engine but generates aerodynamic drag. Actively closed grille shutters are common in vehicles to minimize the weight between cooling and drag, and may open or close according to cooling requirements. The active grille shutters close when needed and minimize the amount of air passing through the grille, and therefore it reduces drag.

Windshield and Roof: The upper part of the vehicle is made of the windshield and the roof. The windshield and roof can be designed in a sloping manner to minimize the difference between the airflow and thus minimise the drag. The rake of the windshield (windshield rake) is also a critical factor; a sharper rake is capable of reducing drag, but might add to wind noise. The roof is also required to be continuous and smooth in order to prevent a separation of the air flowing at the back of the roof.

Side Mirrors: Side mirrors are a significant contributor of aerodynamic drag and noise. The side mirrors that are traditionally used have a rectangular form and the frontal area is large leading to a lot of drag. Automobile makers have made the side mirrors of their vehicle more streamlined in order to minimize drag. There are also digital side mirrors that are made out of cameras in some current vehicles that have a significantly less frontal area, which further reduces drag and noise.

Rear End: This is the back part of the car and it is the part where the air moves away creating a wake area. There is a considerable effect of shape at the rear end on the size and strength of the wake, hence aerodynamic drag and lift. The size of the wake may be decreased with a tapered rear end (boat-tail shape) which will reduce the drag. Another component that is also significant in the optimization of rear-end aerodynamics is the rear spoiler. It could interfere with airflow separation, decrease the size of the wake and create downforce to enhance handling stability.

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4. State of art aerodynamic optimization technologies and applications

4.1. Parametric modelling and optimisation algorithms

Parametric modeling is a design approach whereby parameters are used in defining the geometry of a product [5]. Parametric modeling used in automotive aerodynamics means that the designer can easily edit the shape of the car by simply varying the values of the parameters, like the angle of the windshield, the height of the roof and the shape of the rear spoiler.

4.2. Shape optimization by machine learning

They are optimized to use a combination of parameters resulting in minimal drag in the aircraft design through optimization algorithms, taking into account other design parameters like size of the vehicle, styling, and structural strength among others [7].

The move to electric cars is causing a paradigm shift in the way cars were designed. Alterations in constraints allowed by the lack of a combustion engine provide new prospects of alteration of vehicle geometries. The present techniques in optimizing vehicle aerodynamics demand very many computational studies and physical experiments, through the analysis of a data set of industry level automobile geometries along with their respective aerodynamic performance that is available in experiment(Fig.1). The Aero design optimization of vehicle designs by utilizing the learnt aerodynamic relationship on the low-order space determined using the model. The aerodynamic tendencies of the geometries obtained due to the optimization process agree with validation simulations. Based on machine learning, the code of data-driven reduces the cost of conducting a real experiment and increases the accuracy of calculation results.

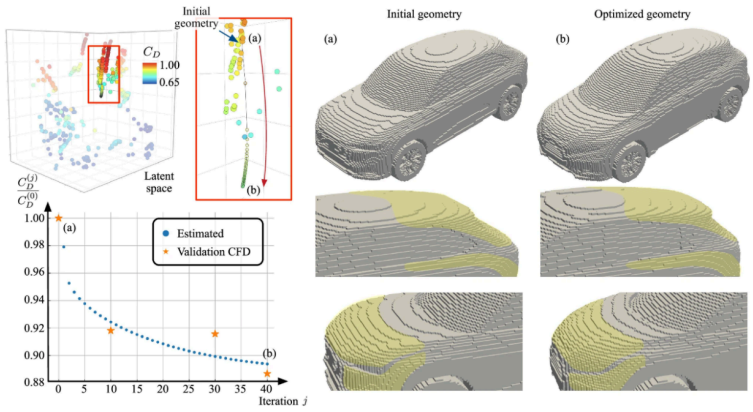

Figure 1. Data-based optimization of the vehicle shape in the latent space that has been found and colored by the normalized drag coefficient

4.3. AI in fluid optimization of aerodynamics

Nowadays the composition of Artificial Intelligence (AI) and multiphysics fluid dynamics modeling is a new drive in designing products at an engineering level [8]. With industries requiring more efficient and cost effective solutions that are also much faster, the traditional Computational Fluid Dynamics (CFD) approaches, though powerful, tend to be hampered by the high cost of computations, lengthy simulation times, and complexity of coupled multiple physics phenomenon solutions. To overcome these difficulties, AI-based optimization solutions help to improve predictive precision, speed up the simulation processes, and also provide the ability to design in real time. In

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comparison to single machine learning codes [9], AI AI utilizing physics-informed neural networks (PINNs) with CFD solvers. Embedding physical laws, and taking advantage of AI, with its pattern recognition capabilities, is to provide a new solution to solving the Navier-Stokes equation (N-S equation) and coupled partial differential equations in many physics landscapes. Applications AI-based optimization models to engineering represent an automatic geometry generation system, improve the quality of meshes, reduce the drag coefficient, handle many-phase flow systems finding optimal solutions in a short time, and respond to performance constraints. Moreover, uncertainty quantification and sensitivity analysis assisted with AI can lead to stronger and sturdier product development cycles.5. Future Trends and Challenges in Automotive Aerodynamic Optimization

5. Future trends and challenges in automotive aerodynamic optimization

5.1. Impact of electrification and autonomous driving

For electric vehicles (EVs), aerodynamic optimization is even more important than for internal combustion engine (ICE) vehicles, as reducing drag can significantly increase the driving range [10]. EVs have a different powertrain layout than ICE vehicles, with no engine under the hood, which provides more design freedom for the front end. This allows for a more streamlined front design, EVs often have a lower center of gravity due to the placement of the battery pack, which can affect the aerodynamic lift and handling.

Autonomous driving vehicles (ADVs) are equipped with a variety of sensors(cameras radars). These sensors may disrupt the air fluid around the vehicle, increasing aerodynamic drag coefficient and noise. Therefore, the integration of sensors into the vehicle's exterior shape while minimizing their impact on aerodynamic performance is a new challenge for aerodynamic engineering. In addition. ADVs may have more different driving patterns than human driven vehicles, like more frequent acceleration and deceleration which can affect the aerodynamic loads on the vehicle.

5.2. Challenges and future research directions

Despite the significant progress made in automotive exterior aerodynamic optimization, there are still many challenges and future research directions.

Multi-Objective Optimization: Currently, most aerodynamic optimization studies focus on reducing drag or increasing down force. However, in practical design, multiple objectives need to be considered, such as drag reduction, downforce generation, noise reduction, and styling requirements. Developing efficient multi-objective optimization algorithms that can balance these conflicting objectives is a major challenge.

Unsteady Aerodynamic Effects: Most aerodynamic studies focus on steady-state flow conditions (e.g., constant speed and no crosswind). However, in real-world driving, vehicles experience unsteady flow conditions, such as acceleration, deceleration, cornering, and crosswinds. Understanding and optimizing the unsteady aerodynamic effects is crucial for improving vehicle performance and safety.

Integration of Aerodynamic Design with Other Disciplines: Aerodynamic design is closely related to other disciplines, such as structural design, thermal management, and acoustics. Integrating aerodynamic design with these disciplines to achieve a holistic optimization of the vehicle is a complex task that requires interdisciplinary collaboration.

Validation of CFD Simulation for Complex Flow Phenomena: Although CFD simulation has improved significantly, there are still some complex flow phenomena, such as flow separation,

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vortex shedding, and turbulent flow, that are difficult to simulate accurately. Further research is needed to improve the accuracy and reliability of CFD simulation for these complex flow phenomena.

6. Conclusion

Aerodynamic optimization of automotive exterior shapes is a key research direction in the automotive industry, which plays a crucial role in improving fuel economy, handling stability, and driving comfort. This review has systematically summarized the research progress in this field, including the basic aerodynamic characteristics of automotive shapes, traditional and advanced optimization methods, and future trends and challenges.

The basic aerodynamic characteristics of automotive shapes are governed by fluid mechanics principles, and the main aerodynamic forces and moments have significant effects on vehicle performance. Traditional aerodynamic optimization methods, such as streamline design, optimization of key components, and passive aerodynamic devices, have been widely used and have achieved significant improvements in aerodynamic performance. Advanced technologies. The future of automotive exterior aerodynamic optimization will be influenced by the electrification and autonomous driving of vehicles, as well as the application of emerging technologies such as AI, additive manufacturing, and active aerodynamic devices.

In conclusion, aerodynamic optimization of automotive exterior shapes is a continuously evolving field. With the continuous development of technology and the increasing demand for energy efficiency and environmental protection, further research and innovation in this field are essential to meet the challenges of the future automotive industry.

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