The Aerodynamic Optimization of New Energy Vehicles

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Abstract. In the field of new energy vehicle manufacturing, power batteries serve as fundamental components. However, they currently face challenges in terms of storage and discharge capacity, safety measures, service life, and cost-effectiveness. Furthermore, battery recycling poses environmental pollution risks while frequent replacements increase usage costs. Both factors hinder the development of new energy vehicles. Therefore, given limited advancements in battery technology, enhancing the overall kinetic energy of new energy vehicles through aerodynamic optimization has become a crucial issue that most manufacturers need to address. This paper aims to provide a concise introduction and discussion on external factors influencing the kinetic energy of new energy vehicles by reducing aerodynamic resistance during vehicle operation and improving vehicle body stability through adjustments made to its surface as well as front and rear sections. The objective is to minimize specific energy consumption and enhance kinetic energy in new energy vehicles. By integrating these research findings with relevant literature on this subject matter, this paper presents feasible schemes along with their limitations offering valuable references and inspiration for researchers exploring advancements in new energy vehicle technology.

Keywords: New energy vehicles; mechanical structure; aerodynamic optimization; kinetic energy improvement.

1. Introduction

In the context of the rapid global industrial development, air pollutants emitted from fossil fuel combustion, such as petroleum, coal, and natural gas, have gradually emerged as primary contributors to environmental pollution including greenhouse effect, acid rain, and ozone depletion. Simultaneously, the swift advancement of urbanization has positioned the transportation industry as the second largest consumer of fossil fuels after industrial production.

Among them, traditional fuel vehicles, as a prevalent mode of transportation, provide convenience for people's travel; however, they also emit CO, NOx, particulate matter and other air pollutants as well as greenhouse gases which have become the primary source of air pollution. Currently, new energy vehicles are gradually replacing traditional fuel vehicles in the transportation sector due to their distinctive power source characteristics. Power batteries serve as the vehicle's power generation source and constitute the core components with a cost accounting for 30% to 40% of the total vehicle cost. Among these batteries, lithium-ion batteries are extensively utilized in new energy vehicles owing to their attributes such as rapid charging and discharging capabilities, low self-discharge rate, absence of memory effect, high energy density along with safety and environmental friendliness [1].

Typically, lithium-ion batteries consist of a cathode, an anode, a separator, and an electrolyte. The capacity of these batteries is determined by the energy density at a given volume since it is the product of specific capacity and battery volume. The energy density of lithium batteries primarily depends on the choice of cathode materials. Currently known lithium battery cathode materials include lithium cobalt oxide, lithium manganese oxide, lithium nickel-cobalt-manganese oxide, lithium iron phosphate, and ternary metaerials (e.g. lithium nickel-cobalt-aluminum oxide, lithium nickel-cobalt-manganese oxide). Although lithium cobalt oxide is widely used as a cathode material in the new energy power battery industry, its specific capacity only reaches 138 mAh/g within a limited range which falls significantly short compared to the specific capacity of graphite material commonly used in negative electrode materials (4200 mAh/g). Presently, there seems to be little room for further improvement in terms of specific capacity for these cathode materials [2].

Lithium-ion batteries have made significant progress in addressing safety issues related to single-pack battery design and internal management systems, including the risks of battery overcharge, external thermal shock, extrusion, and short circuit. However, ensuring the overall safety of battery packs remains a major challenge for the development of new energy electric vehicles [3]. Additionally, the cycle life and shelf life of lithium-ion batteries are key factors that affect the performance of new energy vehicles. A reduction in battery lifespan would lead to an increased demand for battery replacements, significantly raising the operating costs of electric vehicles and hindering their development. Furthermore, new energy vehicles hold practical significance in reducing body resistance and improving energy utilization as demonstrated by structural transformations in conventional fuel-powered vehicles [4].

However, due to limitations in "battery development" for new energy vehicles, research on this issue is crucial for their advancement. This paper discusses and studies the aerodynamic methods to improve the performance of new energy vehicles by further optimizing the mechanical structure. Aerodynamics is used to analyze the causes of aerodynamic drag, and respectively from the surface of the car, the front, the rear design, three levels to improve the performance of the car. Specifically, these improvements include reducing the air resistance in the process of driving, reducing the turbulence and turbulence phenomenon caused by the drag coefficient around the body, improving the instability caused by the body weight, reducing the aerodynamic drag in the process of driving new energy vehicles, and reducing the energy consumption per unit time while improving the kinetic energy of the car.

2. The Method of Aerodynamic Optimization.

In the process of road driving, the vehicle generates a significant amount of air resistance. Overcoming this resistance is crucial for energy consumption and also affects vehicle stability. As a vital branch of fluid dynamics, aerodynamics studies the forces and moments generated when an object interacts with air during motion. It provides indicators such as velocity, pressure, density, and temperature changes over time in the flow field for various solid shapes.

Furthermore, it defines equations for controllable volume, mass, momentum, and energy conservation around the flow field to solve and analyze problems. Additionally, aerodynamics can be utilized for mathematical analysis and simulated wind tunnel experiments to better understand and address practical issues [5]. The body shape closely relates to driving speed; therefore, employing aerodynamics allows for a more comprehensive analysis of vehicle air resistance during exercise. With increasing popularity of vehicles worldwide, researchers have progressively applied Computational Fluid Dynamics (CFD) technology to analyze, calculate, and predict vehicle flow fields while utilizing aerodynamics to optimize and enhance vehicle bodies. This enables researchers to simulate and analyze fluid dynamics behavior around vehicles more accurately, resulting in more effective design improvements [6]. Airflow passing through vehicles forms complex external flow field structures characterized by phenomena like airflow separation/attachment and intricate vortex structures. These phenomena represent responses within automotive aerodynamics and fluid dynamic mechanisms/laws. The research on automotive aerodynamics holds significant practical importance in enhancing automotive performance metrics, with CFD playing a pivotal role in the realm of automotive research and development. It is imperative to employ stringent CFD aerodynamic benchmark models and tests for verification purposes, ensuring the accuracy of predictions.

Phan Anh Tuan et al. utilized the CFD method to simulate the external flow field surrounding the vehicle and evaluate the aerodynamic forces acting upon its body, thereby obtaining crucial parameters pertaining to aerodynamic characteristics as well as distribution of turbulent areas around the vehicle body. These findings hold immense significance in comprehending vehicle aerodynamics, optimizing vehicle design, and minimizing aerodynamic resistance [7].

The pressure coefficient cloud chart and streamline distribution in Fig. 1 [7] reveal that, while the vehicle is in motion and all other factors affecting resistance remain constant, the air resistance is

most pronounced at the vehicle's frontal area, roof surface, junction of the front hood and windshield, as well as its rear section.

Turbulent area around the vehicle body According to the equation (1), it can be clearly known that air resistance (F_d) is positively correlated with resistance coefficient (C_d), airflow velocity (V) and windward area (A). Therefore, when the windward area is reduced, air resistance will also decrease accordingly. At the same time, the square of airflow velocity of the vehicle body is linear with resistance, which means that the vehicle speed has a great influence on resistance. In the case that environmental factors such as air density are unchanged, simply reducing the driving speed will not have a substantial impact on reducing wind resistance. Therefore, the key to reducing wind resistance lies in how to reduce the resistance coefficient and further reduce the windward area.

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

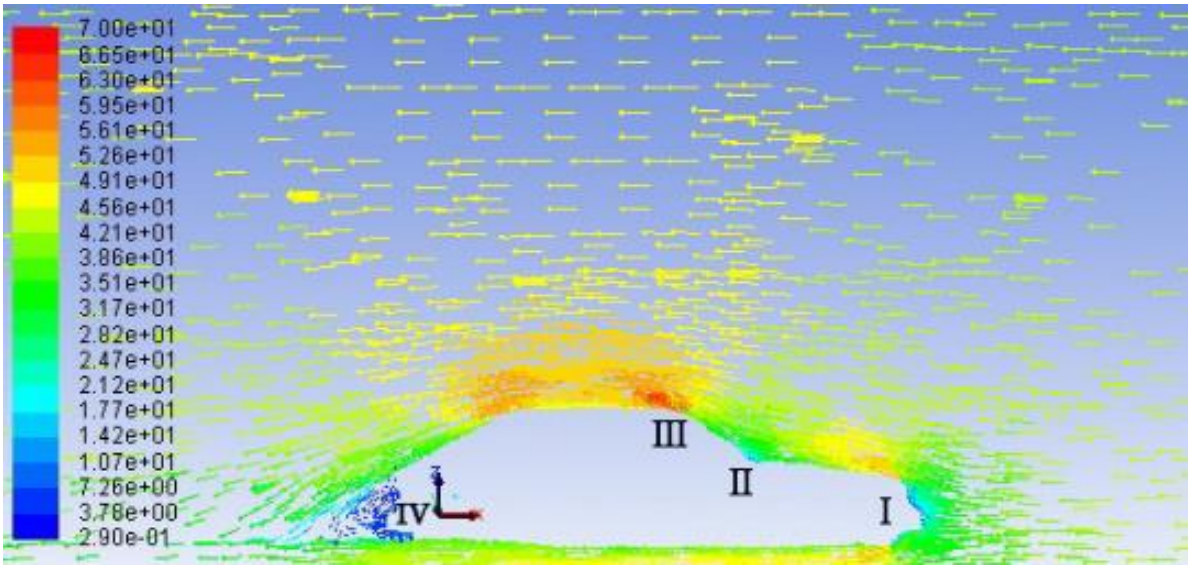


Fig. 1 The Turbulent Region Surrounding the Vehicle's Body [7]

2.1. Optimized Roof Design to Reduce Drag Coefficient

The design of automotive shapes necessitates a delicate balance between aesthetics and performance. While fluid simulation can assess aerodynamic performance, it incurs significant computational costs. Hence, an interactive system incorporating aerodynamic feedback for 2D vehicle contours is proposed to aid designers in crafting optimal aerodynamic profiles [8].

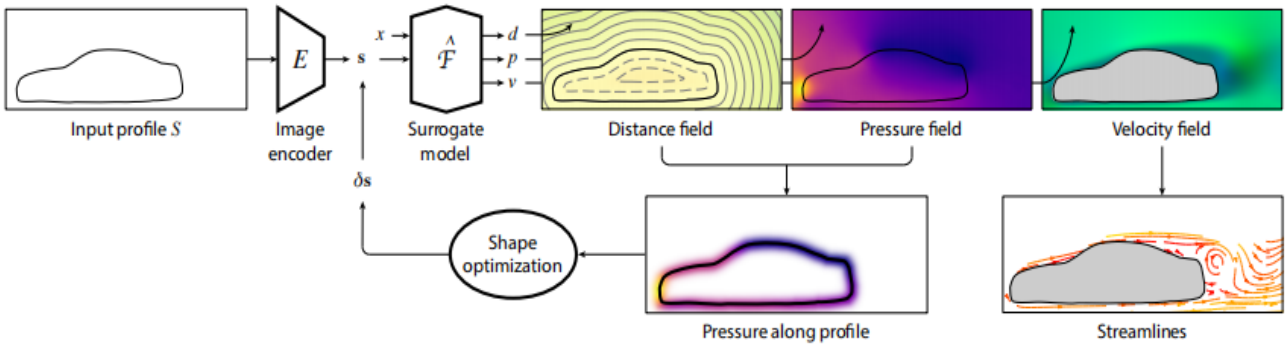


Fig. 2 Interactive Design of 2D Vehicle Profile with Aerodynamic Feedback [8]

The vehicle's profile S is initially input as a bitmap S, as depicted in Fig. 2 [8]. The encoder E calculates the low-dimensional latent descriptor of the model to predict fluid flow attributes at spatial coordinates “x” within the surrogate model. By querying the surrogate model “F (s,x)”, pressure “p” and velocity “v” changes can be predicted at query points. The model is trained to estimate the

distance “d” from each point to the shape contour, which is then utilized for various applications. For visualization purposes, the surrogate model is queried along particle trajectories moving through the velocity field to display streamlines. In terms of shape optimization, querying the surrogate model allows for prediction of pressure and distance fields around the vehicle, enabling deduction of drag coefficient by analyzing line pressure outputs. Additionally, querying the surrogate model behind the vehicle facilitates streamlined modeling aimed at detecting and attenuating vortices within the velocity field. Due to differentiability throughout calculations, small steps “δs” taken in latent space can enhance aerodynamic characteristics of sections effectively.

Considering that any slight change in resistance coefficient (C_d) will be amplified by speed according to the equation (2) increased energy consumption occurs; accordingly, wind resistance accounts for approximately 50%~60% of total power (W) exerted by a car. It becomes evident that air resistance has minimal impact on vehicles operating at low speeds but significantly affects those traveling at high speeds (V); thus, reducing air resistance through well-designed body shapes and corresponding parameter settings holds practical significance.

$$W = C_d \times V^2 \tag{2}$$

The airflow velocity at the rear column and rear end of a streamlined car is higher, resulting in an increased negative pressure. Conversely, a poorly streamlined car experiences forward shift of the airflow separation point, leading to high negative pressure at the rear windscreen and elevated air resistance. Due to the diverse shapes of car bodies, the resistance coefficients vary across different positions, as illustrated in Table 1.

Table 1. Statistics Table of Vehicle Surface Wind Resistance Coefficient [9]

Position	Resistance Coefficient (C_d)
Body C-pillar	-1.0～-0.3
Lower Rear Window	-0.3～0.1
Roof Rear End	-0.6～-0.3
Chassis	-0.1～0.1

Table 1 [9] illustrates the four key components of a vehicle that are influenced by the drag coefficient during the driving process. Consequently, optimizing vehicle performance, enhancing endurance, and reducing energy consumption can be achieved through minimizing the vehicle's air drag coefficient. It is important to note that the drag coefficient Cd serves as a reference value; however, variations may occur due to different wind tunnels and testing equipment. For instance, Mercedes-Benz G-Class has a Cd of 0.54, Maverick has a Cd of 0.45, Volkswagen CC has a Cd of 0.284, and the new Model S boasts an impressive Cd of 0.208. Presently, some domestic new energy vehicles have already surpassed 0.2 with light-year's solar car leading at an astonishingly low Cd value of only 0.175. Therefore, reducing the vehicle's drag coefficient should be pursued through adjustments in its internal and external structure as well as body design tailored to each specific vehicle's characteristics.

The removal of vehicle components is a straightforward technique employed by automotive designers. In contemporary low-drag models, the absence of roof racks or other attachments is notable due to their augmentation of the vehicle's frontal area. Smooth contours on the hood and windshield facilitate streamlined airflow over the vehicle; however, upon collision with these features, turbulence ensues, thereby increasing resistance during motion. Fig. 3 [10] illustrates various roof add-ons for different vehicles, including roof fins, racks, and trunks.



Fig. 3 Illustrations of Diverse Rooftop Luggage Arrangements [10]

The wind tunnel experiments conducted by Harun Chowdhury et al. in the RMIT industrial wind tunnel involved the use of various additional devices on top of the vehicle [11]. They determined the ratio between the resistance coefficient of the vehicle within a speed range of 40-120 km/h and the front projected area of these additional devices. Comparative analysis revealed that removing the roof additions is essential for enhancing vehicle performance.

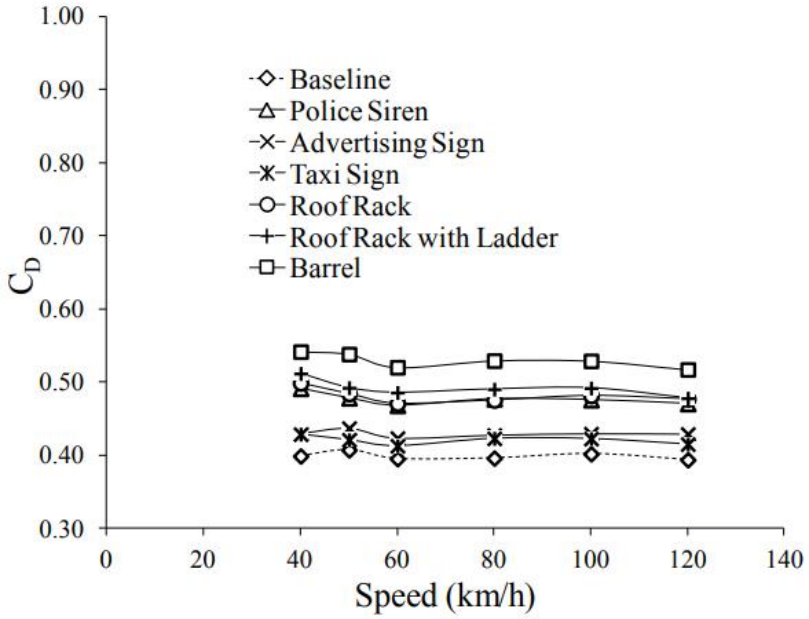


Fig. 4 The Relationship Between the Resistance Coefficients of Various Devices and the Velocity in the Wind Tunnel [11]

The baseline value of the vehicle without additional roof devices in Fig. 4 [11] is 0.4 in the wind tunnel test, which is compared with Table 2's statistical data on resistance coefficient and front wind impact projection area A for vehicles without roof devices. This comparison indicates that the vehicle without roof devices has the lowest air resistance coefficient. It should be noted that the wind resistance caused by the relatively small front area of a roof antenna can be disregarded [12]. Therefore, adding attachments to the roof will disrupt the airflow over it, resulting in increased top resistance and an increase in the resistance coefficient as the wind impact area of these attachments increases. This interference becomes more pronounced at higher speeds. Additionally, different attachments will alter the vehicle's center of gravity and affect its stability. Hence, removing these roof add-ons helps reduce bottom resistance, thereby improving fuel economy and driving stability.

Table 2. Percentage of influence of drag coefficient and projected area of front impact on roof of a vehicle without additional devices [11]

Devices	C_d	A
Siren	19.3%	0.9%
Billboard	7.2%	0.8%
Taxi Sign	5.1%	2.0%
Roof Rack	20.4%	1.2%
Roof Rack with Ladder	24.0%	2.5%

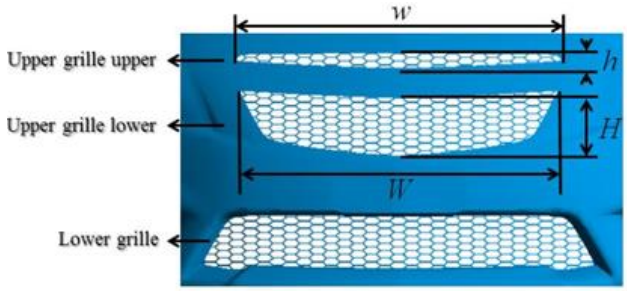
According to equation (2), p represents the surface pressure, p_o denotes the atmospheric pressure, V stands for the body airflow velocity, and ρ signifies the density of the fluid at standard atmospheric pressure. It is evident that each point in the fluid flow field exhibits a distinct pressure coefficient. The body surface resistance coefficient serves to illustrate the pressure distribution and determine air resistance at both the cab entrance and exit as well as engine cooling airflow. In addition to pursuing endurance, new energy vehicles themselves are also inclined towards achieving low wind resistance. From the formula for calculating wind resistance coefficient, it can be inferred that front wind resistance exerts a significant impact on said coefficient. Therefore, in order to reduce front wind resistance, an air inlet is typically positioned near both the front water tank mask and engine cover while adjusting their shape and number of grille openings to minimize air resistance for improved car head design.

$$C_d = \frac{p - p_0}{\frac{1}{2}\rho V^2} \tag{3}$$

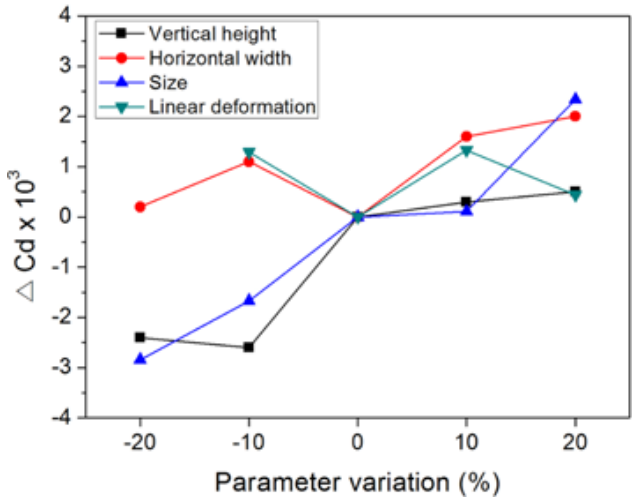
2.2. Front Grille Design

The front end module significantly impacts the vehicle's aerodynamic characteristics. Jack Williams et al. conducted a study on the vehicle's aerodynamic resistance under various moving conditions, and further divided the resistance of the front section into multiple components to analyze the main factors influencing each component's resistance. Additionally, they introduced the pressure loss coefficient caused by air explosion and discussed how inlet flow non-uniformity and module integration degree affect the resistance [13]. Fig. 5 (a) illustrates the design diagram of grille opening shape. They performed numerical design on a small vehicle's grille opening shape and examined changes in both aerodynamic performance and cooling efficiency based on six parameters related to grille opening size and shape: vertical height, horizontal width, size, linear deformation, and position. Among these parameters, blocking parameters are primarily applied to the lower grille and lower part of upper grille since only a minimal amount of airflow (approximately 4% of total intake flow through grilles) passes through the upper grille which can be disregarded compared to other airflows.

The variation of total resistance coefficient and parameters through numerical simulation is illustrated in Fig. 5 (b) [14]. A line graph depicts the relationship between four parameters, namely vertical height, horizontal width size, linear deformation, and the increase of resistance coefficient.



(a)



(b)

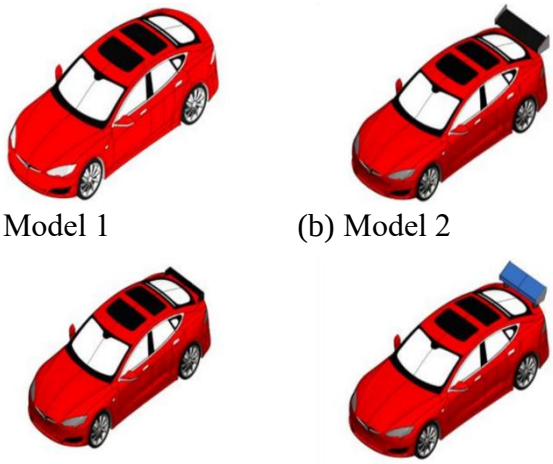
Fig. 5 Grid Analysis. (a) Grating Opening Shape Design [13], (b) Variation of Resistance Coefficient and Parameter [14]

The data analysis reveals that: for the vertical height parameter, it is recommended to maintain a range of 2.6×10^{-3}. Regarding the horizontal width parameter, the total drag coefficient is predominantly influenced by the mass flow through the grille inlet and radiator. If there is a high requirement for radiator mass flow, it is advisable to reduce the radiator's horizontal width to 10% of its original size. As for the size parameter, it is recommended not to exceed an increase of 20% compared to the basic model size. Concerning the linear deformation parameter, maintaining an unchanged grille opening area results in almost no change in grille mass flow. Given that the basic model exhibits optimal aerodynamic and cooling performance, it is no longer recommended to consider variations in linear deformation as a factor. In terms of position parameter adjustments, if there is high radiator mass flow, moving down the grille opening inlet by 10 mm would be beneficial. Lastly, with regards to blocking parameters, shifting the center of lower grille by 30 mm in its correct direction is advised.

2.3. Car Rear Design

The rear design of new energy vehicles typically considers multiple factors, including aerodynamics, energy efficiency, aesthetics, and functionality. The primary objective in considering aerodynamic factors is to minimize drag and prevent vehicle instability caused by lift forces at high speeds. Therefore, adding a rear device to generate additional downward pressure during driving is a viable design scheme. A rear spoiler is an installed device aimed at optimizing the vehicle's aerodynamic performance. It can be either fixed or adjustable. Its design controls airflow by altering flow direction and distribution of tail airflow, reducing air separation and turbulence, thereby decreasing tail resistance and increasing downward pressure on the vehicle [6]. This design enhances ground adhesion while improving handling and stability by reducing tail air pressure and minimizing lift forces generated. Muhammad Zakie Mohd Zin et al. constructed four different automotive

simulation models with varying rear spoiler designs [15]. By subjecting these models to explicit dynamic analysis at speeds of 140 km/h, 160 km/h, 180 km/h, and 200 km/h respectively (as shown in Fig. 6), they obtained the drag coefficient and lift coefficient for each design variant (Model 1-4).



(a) Model 1 (b) Model 2

(c) Model 3 (d) Model 4

Fig. 6 The Simulation Model of Four Distinct Rear Spoiler Designs [15]

According to the comparison in Table 3 and Fig. 7 [15] illustrating the drag coefficients of various models at different speeds, it can be observed that Model 3's spoiler design exhibits superior spoiler effectiveness and the lowest body drag coefficient at equivalent velocities. This outcome highlights how a well-designed spoiler aids in reducing air resistance, effectively streamlining airflow, mitigating turbulence at the rear of the vehicle, and consequently minimizing driving resistance. However, Model 4 with its rear spoiler design demonstrates a significantly higher body drag coefficient compared to Model 1, Model 2, and Model 3. The elevated drag coefficient implies that more energy is required for overcoming air resistance during driving, thereby impacting acceleration performance as well as overall vehicle capabilities. Additionally, this leads to accelerated battery energy consumption while diminishing the vehicle's range and energy utilization rate. In terms of aerodynamic effects on the vehicle's rear end, high drag coefficients increase risk levels when operating at high speeds.

Table 3. Wind Resistance Coefficient Data of Different Simulation Speeds and Different Simulation Car Models [15]

Velocity (km/h)	Coefficient Drag			
	Model 1	Model 2	Model 3	Model 4
120	0.2632	0.3524	0.2571	0.3891
140	0.2638	0.3527	0.2564	0.3911
160	0.2618	0.3530	0.2563	0.3911
180	0.2636	0.3540	0.2559	0.3924
200	0.2627	0.3511	0.2555	0.3901

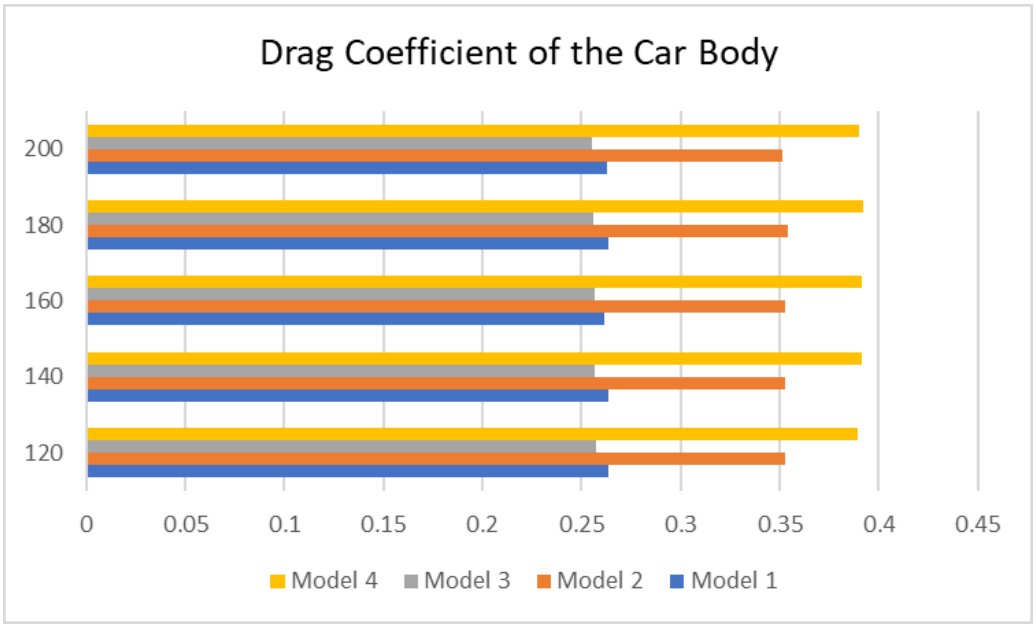


Fig. 7 Comparison of Body Wind Resistance Coefficients [15]

When a vehicle is traveling at high speeds, lift is generated due to the collision of airflow around the vehicle body. In general, the objective of vehicle design is to minimize lift impact in order to maintain optimal ground contact during driving and enhance stability and safety. Automobile designers often incorporate spoilers with additional weight to increase downforce by adding weight to the vehicle, thereby improving traction and reducing the likelihood of generating lift. Comparing the lift coefficient figures for different models at various speeds in Table 4 and Fig. 8 [15], it can be observed that Model 2 exhibits the lowest lift coefficient among Model 1, Model 3, and Model 4 when considering rear spoiler designs.

However, despite having the lowest drag coefficient at high speeds, Model 3's rear spoiler design has a less effective impact on reducing downforce compared to other models. Nevertheless, under normal driving conditions where vehicles typically do not generate lift, Model 3's rear spoiler design demonstrates superior disturbance effects. On the other hand, when combining its drag coefficient and lift coefficient together, it is recommended that automobile manufacturers consider adjusting their use of rear spoiler designs similar to that of Model 2 for vehicles requiring reduced lift such as racing cars [16]. Therefore, a rear spoiler design resembling that of Model 3 proves feasible and practical for aerodynamic drag reduction purposes as well as enhancing vehicle body stability in new energy vehicles.

Table 4. Lift Coefficient Data of Different Simulation Speeds and Different Simulation Car Models [15]

Velocity (km/h）	Coefficient Lift			
	Model 1	Model 2	Model 3	Model 4
120	-0.1198	-0.4066	-0.1133	-0.3950
140	-0.1231	-0.4071	-0.1144	-0.3967
160	-0.1283	-0.4084	-0.1192	-0.3958
180	-0.1235	-0.4072	-0.1134	-0.3954
200	-0.1246	-0.4102	-0.1152	-0.3963

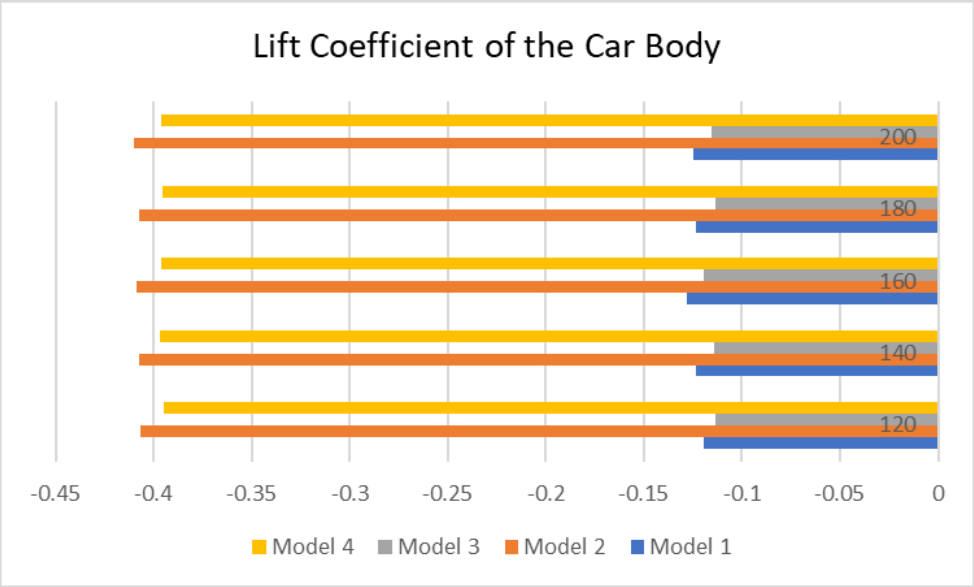


Fig. 8 Body Lift Coefficient Comparison [15]

3. Conclusion

The above methods have been employed to derive the following three primary conclusions. Removing the roof additional device is an effective method to improve the wind resistance. The front wind resistance of the front wind is positively correlated with the size of the drag coefficient, which can be achieved by designing the front grille. The more reasonable structure of the grille can be better used for flow diversion, thus reducing the front wind resistance. New energy vehicles usually adopt rear spoilers to improve aerodynamics and enhance vehicle efficiency. The design of parking spoilers is aimed at optimizing air flow and reducing air resistance, thus improving energy efficiency or range. The spoilers are usually designed for a specific speed range and may not be effective at low or high speeds, so a variety of designs are needed to adapt to different speeds.

At the same time, these analysis methods have certain limitations. For instance, removing the roof attachment may not be suitable for all models, such as taxis and ambulances. Additionally, different car brands often feature unique grille designs which, if excessively distinctive, can restrict brand flexibility and model differentiation. Moreover, Certain grille designs may impede airflow and consequently impact engine cooling efficiency and performance. Similarly, precise matching between rear spoiler design and vehicle shape as well as airflow is essential; otherwise it could lead to increased resistance or unstable air flow patterns.

The aerodynamic analysis mentioned in this article is just one key aspect of improving new energy vehicles. For the future development of new energy vehicles, there is still room for improvement in terms of batteries and materials, which will promote better development of new energy vehicles.

Author Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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