

Aerodynamic Designs of Front and Rear End Areas of Cars

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Abstract. With the conservation of energy becoming increasingly crucial, the efficiency of road vehicles requires an advance. The aerodynamic design of a road vehicle is responsible for its efficiency, especially the designs at the front and rear end areas. This paper focuses on the designs of the front and rear end areas, emphasizes the influences of these two areas on vehicle efficiency, and compares the improvements of optimizing parts in these areas. With alternations being made, the drag coefficient of the vehicle, which indicates the efficiency of that vehicle, can be reduced by at most 26%. In addition, the aerodynamic designs at the front and rear areas of classic vehicles and the current designs are introduced, followed by a description of the advantages of the new designs. Correspondingly, the drawbacks and limitations of nowadays designs are acknowledged, followed by the current challenges of the development of vehicle aerodynamics and the prediction of future designs.

Keywords: Aerodynamic drag reduction, vehicle aerodynamic, drag coefficient.

1. Introduction

In the automotive industry, the quest for improved fuel efficiency and reduced environmental impact has become increasingly critical. As consumers become more environmentally conscious, the demand for energy conservation and emission reduction is rising at the same time. Therefore, plenty of research are done to reduce the drag of road vehicles. For example, by adding a suction system to the rear window of fastback cars found that 17% of the aerodynamic drag is reduced [1]; Through the use of simulation software, relationships between different parts of cars and the drag coefficient are found, which is helpful when dealing with aerodynamic drag reduction situations [2].

Two of the most significant factors influencing a vehicle's overall aerodynamic performance are the drag experienced at the front end and the rear end [3]. The design and shape of a vehicle's front end and rear end play a crucial role in determining the amount of air resistance it encounters while in motion [3]. As vehicles travel, the air flowing over and around them creates drag, which directly affects fuel consumption and overall efficiency.

Reducing aerodynamic drag at the front and rear end is essential not only for enhancing fuel efficiency but also for improving vehicle stability and handling. A streamlined front end minimizes turbulence and allows for smoother airflow, which can lead to significant energy savings. What's more, with alternations to the front end, the ventilation, and air conditioning can be improved with the reduction of dirt and mud that attach to the vehicle, with wind noise also decreased through the modifications [3]. Modifications done to the rear end of a vehicle can also increase fuel efficiency, vehicle performance, and vehicle range. Moreover, emissions and noise can be reduced by altering the rear end area.

This paper aims to summarize the latest research progress in the field of vehicle front and rear-end area aerodynamic drag reduction design, focusing on key findings and new designs. Additionally, the practical applications of these advancements in modern vehicle design will be explored, showcasing how manufacturers are implementing aerodynamic improvements to satisfy regulations, standards, and consumer demands for more efficient, comfortable, and environmentally friendly vehicles in modern days. Moreover, the advantages and disadvantages of current technology will be discussed in this paper, followed by the main challenges faced when improving current technology, and the developing trend and direction in the future.

2. Aerodynamic influences of the front and rear end area

The front end and rear end area of a vehicle play a crucial role in its aerodynamic performance and are major contributors to the overall drag. Understanding and optimizing this area can lead to significant improvements in fuel efficiency, vehicle stability, and comfort. This section explores the aerodynamic influences of the front and rear end area, specifically examining how it affect drag and how improvements in design can enhance vehicle efficiency.

2.1. The influence of the front and rear end area on drags

The front-end area not only represents the initial surface encountering airflow but also significantly dictates the interaction between the vehicle and the surrounding air. Key components of the front end—such as the grille, headlights, bumper, and overall shape—collectively contribute to the drag force experienced by the vehicle. The relationship between drag force F_d and vehicle characteristics can be expressed using the following equation:

$$F_d = \frac{1}{2} C_d \cdot \rho \cdot A \cdot v^2$$

In this equation, F_d represents the drag force, C_d is the drag coefficient, ρ denotes the density of air (approximately 1.225 kg/m^3 at sea level), A is the frontal area of the vehicle, and v is the velocity of the vehicle relative to the air.

According to the equation, the frontal area A and the drag coefficient directly contribute to the overall drag force, hence, indicating that a larger frontal area typically results in greater drag, as it increases the amount of air that must be displaced. Also, while the density of the air, the frontal area, and the velocity of the vehicle relative to the air remains constant, the drag force increases as the coefficient of drag increases. For example, a vehicle with a frontal area of 2.5 m^2 and a drag coefficient of 0.30 travelling at 100 km/h (about 27.8 m/s) experiences a drag force of approximately 354 N. If the frontal area increases to 3.0 m^2 , the drag force rises to about 425 N, showing a roughly 20% increase in drag force. Similarly, an increase in the drag coefficient will also increase the drag force. Therefore, the importance of optimizing both the frontal area A and the drag coefficient C_d is revealed.

Research indicates that a vehicle's drag coefficient can be substantially influenced by the front-end design. For example, high-speed trains have head cars designed streamlined instead of having a shape trapezium to reduce their drag coefficient [4]. Since the head car of a high-speed train experiences no block to the airflow which the frontal area of a road vehicle does too, the coefficient of drag can also be influenced by altering the design of the frontal area.

Additionally, the rear-end design is equally essential in determining the overall drag force. Vehicles with flat or abruptly cut-off rear ends can experience base drag, primarily due to flow separation phenomena. The separation of airflow from the body of the vehicle creates a low-pressure wake region, increasing the drag coefficient [5]. At the same time, the turbulence at the rear of the vehicle contributes to the aerodynamic drag [6].

2.2. The Effect of Improving Front and Rear End Area Design on Increasing Vehicle Efficiency

The relationship between aerodynamic design improvements at the front and rear end and vehicle efficiency is well-documented. By focusing on reducing drag through innovative design, manufacturers can enhance the overall efficiency of vehicles, leading to better fuel economy, lower emissions, and improved performance.

According to research, almost 40% of the useful engine power is wasted against the aerodynamic drag [7]. Also, the drag coefficient is influenced by the modifications. The alternations made to reduce the drag coefficient, and their effect are given in Table 1.

Table 1. Effects of drag coefficient reduction design in front and rear end areas

Modifications	The percentage of the Drag coefficient was reduced and the reference
Vortex generator	4.2-10% [8], 12% [9]
Rear spoiler	-3% [10], 5% [11]
Diffuser	4% [12], 17% [13]
Vertical split plates	28% [14]
Flaps	19% [15], 25% [16]
Bumper	3.08% [17], 9% [18]
Rear screen	6.5% [19], 8.88% [20]
Rear fairing	26% [19]
Front-wheel deflector plate	7.28% [21]

3. Aerodynamic designs of vehicles' front and rear area

3.1. Design on classic vehicles' front and rear area to reduce their drag

Historically, the design of vehicles has evolved significantly, with aerodynamics gradually becoming a crucial factor in vehicle design as it can maximize the vehicle's performance and efficiency. Early road vehicle designs often featured boxy shapes with obvious edges, leading to increased drag and fuel consumption. The flat surfaces and sharp angles on those classic vehicles disrupt airflow and contribute to higher drag coefficients.

However, several classic models laid the groundwork for more aerodynamic designs. For instance, the Volkswagen Beetle (introduced in 1938) and the Chrysler Airflow (1934) were among the first group of designs which introduced rounded shapes to reduce the drag caused by the sharp shapes. The Beetle's distinctive shapes were engineered to reduce the aerodynamic drag, and the result coefficient of drag of the Beetle was 0.49, which was relatively low at that time [22]. Later in the 1960s and 1970s, VW had modifications called "detail optimization" to reduce the drag coefficient of their golf MK1. The modifications reduced the drag coefficient by approximately 19.6% [22].

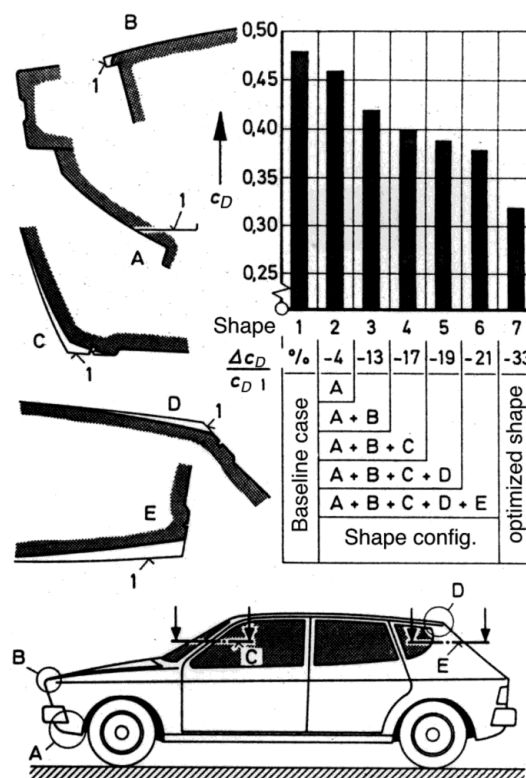


Fig. 1 Detail optimization of a hatchback car [22]

3.2. The design of nowadays vehicles' front and rear end area

Today's automotive designs are distinctly more sophisticated, with more advanced technologies and materials being used to enhance aerodynamic efficiency. Modern vehicles often employ computational fluid dynamics (CFD) and wind tunnel testing to refine their shapes, resulting in even lower drag coefficients. For example, a SUV, the BMW X3 introduced in 2017 has a drag coefficient of 0.29[23]. The decrease in drag coefficient significantly increases the fuel efficiency.

As the demand for conservation of energy becomes increasingly critical, more researches are done focusing on reducing the aerodynamic drag of road vehicles. The front end and rear end area are essential in decreasing the drag coefficient; hence many modifications are done to these areas to achieve the goal.

For the frontal area, the bumper and the front wheel deflector plate are focused on reducing drag coefficient. As for the rear end area, designs such as vortex generators, and spoilers are added, and parts such as the rear window are altered to reduce the drag coefficient. Shuai Yang used simulation software on the aerodynamic performance of the front bumper and the front wheel deflector plate and obtained a reduction in drag coefficient of approximately 7.28% [21]. Bansal R et al. used CFD simulation to find the effects of adding vortex generators and spoilers at the rear end of a road vehicle and obtained a drag coefficient reduction of 4.35% [24].

3.3. The advantages of new designs

Plenty of advantages are introduced by modern aerodynamic designs. Including increased vehicle performance, decreased fuel consumption, and environmental sustainability.

One primary advantage of the new designs is the significantly reduced drag coefficient, which results in a growth in fuel efficiency. For instance, the Tesla Model 3(2023) has a drag coefficient of 0.219, which contributes substantially to its approximately 450-mile driving range after one single charge [25].

Additionally, better aerodynamic designs contribute to improved handling and stability at higher speeds. Vehicles that effectively manage airflow experience reduced lift and better traction, enhancing overall driving dynamics.

Moreover, the integration of sustainable materials and technologies in aerodynamic designs is aligning with global trends towards eco-friendliness. Many manufacturers are now implementing lightweight materials, such as carbon fibre and advanced composites, that not only reduce vehicle weight but also enhance aerodynamic performance. This synergy between lightweight design and aerodynamics contributes significantly to improved energy efficiency and reduced emissions [26].

3.4. The limits and disadvantages of current designs

Despite the advancements in aerodynamic design, certain limitations and disadvantages remain prevalent. One significant challenge is the trade-off between aerodynamics and other vehicle attributes, such as safety and aesthetics. While streamlining shapes can lead to lower drag, it may compromise crash safety performance if not carefully designed.

Moreover, current aerodynamic designs often come with higher manufacturing costs. The intricate shapes and use of composite materials can lead to increased production and assembly complexity. Formula 1 race cars which are known for their complex aerodynamic designs require abundant money to design and produce. The front and rear wings together cost about \$200,000[27]. The high costs of complex aerodynamic designs not only increase the manufacturing of the parts but also limit the market accessibility as they cost much to repair.

Another drawback involves the limitations of dynamic systems, such as an active spoiler. These active aerodynamic parts can increase the weight as well as the complexity of the vehicle. These systems may also require additional maintenance, potentially affecting long-term reliability and overall vehicle performance. Along with the increased weight and higher frequency of maintenance is the increased energy usage, which objects the aim of conservation of energy.

3.5. Current challenges with future trend prediction

Various challenges are faced by manufacturers for different reasons. To begin with, the market share of SUVs in China increased from approximately 20% to 50% from 2010 to 2024[28, 29]. This indicates that consumer preferences shift towards larger vehicles such as SUVs. Manufacturers face the challenge of maintaining aerodynamic efficiency as these vehicle types tend to have higher drag coefficients due to their size and shape, which can counteract the aerodynamic designs.

What's more, the rise of electric vehicles (EVs) can cause challenges for manufacturers. EVs require designs that can maximize range and efficiency, which is related to aerodynamic designs. However, the integration of batteries and other components that only EVs have can disrupt airflow, leading to an increased drag coefficient. Manufacturers must adapt to these changes and create new designs to accommodate the new technologies.

In the future, as road vehicles become more intelligent and the materials become economical, the use of active aerodynamics may be increased since they can adapt to the surroundings leading to maximum efficiency. Also, more sustainable materials will be used in the production of vehicles. Lightweight materials reduce the weight of vehicles and hence increase both fuel efficiency and aerodynamic performance. Yet lightweight materials often come at a higher cost and may present challenges in terms of recyclability and environmental impact, so manufacturers must balance between the pros and cons.

4. Conclusion

In conclusion, the aerodynamic design of a vehicle's front and rear end plays a vital role in enhancing performance, fuel efficiency, and overall driving experience. This review has shown the evolution from classic designs of vehicles' front and rear end areas to modern designs, emphasizing the importance of streamlined shapes, active aerodynamic features, and lightweight materials.

While modern designs offer significant benefits, such as reduced drag and improved energy efficiency, they also face challenges. The integration of aesthetic considerations with functional aerodynamics presents a complex dilemma for manufacturers, as consumer preferences for visually appealing vehicles can sometimes clash with the principles of optimal aerodynamics.

Looking to the future, the rise of electric vehicles will further influence aerodynamic design, necessitating innovative approaches to meet performance standards while accommodating new technologies. Current research and development will be essential to address faced limitations and ensure that vehicles remain efficient, environmentally friendly, and aligned with consumer needs.

References

- [1] Rouméas M, Gilliéron P, Kourta A. Drag reduction by flow separation control on a car after body[J]. *International journal for numerical methods in fluids*, 2009, 60(11): 1222-1240.
- [2] Zhu X, Gao X. Research on simulation and optimization of automotive aerodynamic resistance based on ASO[J]. *Automotive Knowledge*, 2024, 24(07): 90-95.
- [3] Sivaraj G, Parammasivam K M, Suganya G. Reduction of aerodynamic drag force for reducing fuel consumption in road vehicle using basebleed[J]. *Journal of Applied Fluid Mechanics*, 2018, 11(6): 1489-1495.
- [4] Wu Z, Yang E, Ding W. Design of large-scale streamlined head cars of high-speed trains and aerodynamic drag calculation[J]. *Archives of Transport*, 2017, 44(4): 89-97.
- [5] Sparrow E M, Abraham J P, Minkowycz W J. Flow separation in a diverging conical duct: Effect of Reynolds number and divergence angle[J]. *International Journal of Heat and Mass Transfer*, 2009, 52(13-14): 3079-3083.
- [6] Sudin M N, Abdullah M A, Shamsuddin S A, et al. Review of research on vehicles aerodynamic drag reduction methods[J]. *International Journal of Mechanical and Mechatronics Engineering*, 2014, 14(02): 37-47.

- [7] Patidar A, Gupta U, Bansal A. Fuel Efficiency Improvement of Commercial Vehicle by Investigating Drag Resistance[R]. SAE Technical Paper, 2015.
- [8] Kim I, Chen H. Reduction of aerodynamic forces on a minivan by a pair of vortex generators of a pocket type[J]. International journal of vehicle design, 2010, 53(4): 300-316.
- [9] Aider J L, Beaudoin J F, Wesfreid J E. Drag and lift reduction of a 3D bluff-body using active vortex generators[J]. Experiments in fluids, 2010, 48: 771-789.
- [10] Kodali S P, Bezavada S. Numerical simulation of air flow over a passenger car and the Influence of rear spoiler using CFD[J]. International Journal of Advanced Transport Phenomena, 2012, 1(1): 6-13.
- [11] Kim I, Chen H, Shulze R C. A rear spoiler of a new type that reduces the aerodynamic forces on a minivan[R]. SAE Technical Paper, 2006.
- [12] Kang S O, Jun S O, Park H, et al. Actively translating a rear diffuser device for the aerodynamic drag reduction of a passenger car[J]. International Journal of Automotive Technology, 2012, 13: 583-592.
- [13] Peddie K M, Gonzalez L F. CFD Analysis of the Diffuser of a Formula 3 Racecar[J]. Orbit: University of Sydney Undergraduate Research Journal, 2009, 1(1).
- [14] Gilliéron P, Kourta A. Aerodynamic drag reduction by vertical splitter plates[J]. Experiments in fluids, 2010, 48(1): 1-16.
- [15] Kim D, Lee H, Yi W, et al. A bio-inspired device for drag reduction on a three-dimensional model vehicle[J]. Bioinspiration & biomimetics, 2016, 11(2): 026004.
- [16] Beaudoin J F, Aider J L. Drag and lift reduction of a 3D bluff body using flaps[J]. Experiments in fluids, 2008, 44(4): 491-501.
- [17] Shim H S, Lee Y N, Kim K Y. Optimization of bobsleigh bumper shape to reduce aerodynamic drag[J]. Journal of Wind Engineering and Industrial Aerodynamics, 2017, 164: 108-118.
- [18] Li, Z. Simulation and Optimization of Vehicle Aerodynamics Based on DrivAer Mode[D]. Shenyang University, 2022. DOI:10.27692/d.cnki.gsydx.2022.000288.
- [19] Sirenko V, Pavlovs' ky R, Rohatgi U S. Methods of reducing vehicle aerodynamic drag[C]//Fluids Engineering Division Summer Meeting. American Society of Mechanical Engineers, 2012, 44755: 97-102.
- [20] Elrawemi M, Aburawey I I. The effect of front and rear windscreen angles on the aerodynamic drag force of a simplified car model[J]. International Journal of Energy Applications and Technologies, 2019, 6(3): 83-88.
- [21] Yang S. Research on Active and Passive Drag Reduction in the Front Wheel Region of the DrivAer Model[D]. Jilin University, 2024. DOI:10.27162/d.cnki.gjlin.2024.001098.
- [22] Schuetz T C. Aerodynamics of road vehicles[M]. Sae International, 2015.
- [23] BMW Media Information. BMW at the IAA Cars 2017 in Frankfurt. Long Version.
- [24] Bansal R, Sharma R B. Drag Reduction of Passenger Car Using Add-On Devices[J]. Journal of Aerodynamics, 2014, 2014(1): 678518.
- [25] www.tesla.com
- [26] Haber D. Lightweight materials for automotive applications: a review[J]. 2015.
- [27] Jessner W. How much does a Formula 1 car cost and where can I buy one? www.redbull.com, 2023
- [28] www.cpcaauto.com/newslist.php?types=bgzl&id=420
- [29] www.cpcaauto.com/newslist.php?types=csjd&id=3588