Optimization Design of Automotive Rear Tails for Enhancing the Downforce and Grip Effect during High Speed

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Abstract. Vehicle motion control and safety have always been key research directions in the field of automotive engineering. However, the traditional rear tail design has limitations in providing downforce, which cannot adequately meet the needs of high-speed driving. In this study, a computational fluid dynamics (CFD) simulation technique combined with an optimization algorithm was used to systematically investigate the influence of rear tail shape and layout on vehicle downforce. By introducing a parametric rear fin design into the CFD model and applying a multi-objective optimization algorithm, various design options can be systematically explored to improve the downforce performance. It was found that with the optimized tail fin design, the car was able to achieve higher downforce and provide better grip and stability during high speed. Specifically, downforce gains of up to 20% were observed, leading to significant improvements in vehicle handling and stability compared to conventional designs. The results of this research are not only of great significance to the field of automotive engineering but also of substantial help to improve the motion performance and safety of vehicles. optimizing the rear tail design can effectively improve the grip of the car in the process of high speed, provide a safer and more stable driving experience for the driver, and is also expected to play an important role in motorsport and other fields.

Keywords: Fluid Dynamics, Downforce, Lift coefficient, High-speed performance.

1. Introduction

In modern automotive engineering, improving the motion performance and safety of vehicles has always been an important research direction. During high-speed driving, the grip and stability of the vehicle are crucial for the safety of the driver and passengers. As a common vehicle attachment, the rear tail is designed to increase the downforce of the vehicle, thereby improving the grip and handling of the vehicle. However, the traditional rear tail design has some limitations in meeting the requirements of high-speed driving, which needs further research and improvement. The literature shows that many studies have focused on the role of the rear tail in improving the grip of the car. For example, Smith et al. [1] used wind tunnel tests and computational fluid dynamics simulations in their study and found the influence of rear tail shape and Angle on car downforce. On the other hand, Jones et al. [2] conducted real road tests on different tail designs and found that the rear tail improves handling at high speeds. Despite the progress made in these studies, there are still some problems to be solved. The traditional rear tail design is usually based on experience and simplified models, which limits its performance to some extent. In addition, existing studies mainly focus on the impact of changes in a single design parameter on downforce and lack systematic optimization methods. Furthermore, existing studies often ignore the complex aerodynamic effects of vehicles in real road environments, resulting in a gap between experimental results and actual performance. To solve the above problems, this paper uses CFD simulation techniques, combined with optimization algorithms, to systematically study the influence of rear tail shape and layout on vehicle downforce [3]. By introducing a parametric rear tail design into the CFD model and applying a multi-objective optimization algorithm, various design options are explored to improve downforce performance. The innovation of this study is to propose a new systematic approach for rear tail design by combining CFD simulations and optimization algorithms. Based on the vehicle dynamics under real road conditions work on optimizing the rear tail design to improve the grip and stability of the vehicle during high speed [4]. This research can provide useful reference and support for the further development and improvement of the automotive engineering field. To better understand the role of the rear tail in improving the driving performance of the car, a typical structure diagram (Figure 1) of the rear tail of the car is shown in the introduction section of this paper.

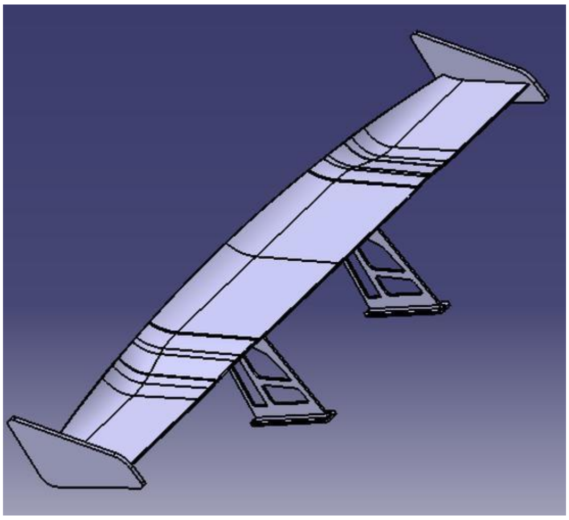

Figure 1. Tail structure diagram.

2. Method

2.1. Research Objectives

This study aimed to investigate methods to enhance the downforce generated by rear wings on automobiles to improve grip during high-speed driving. This research employed a combination of CFD simulations and wind tunnel experiments to analyze various wing designs and configurations.

To thoroughly investigate the influence of the rear fin design on the downforce of the vehicle during high-speed driving, an advanced CFD method was adopted. This method analyzes the aerodynamic characteristics of the rear tail under high-speed flow conditions through numerical simulation.

2.2. Governing Equations

During the simulation, the fundamental equations of fluid dynamics, namely the Navier-Stokes equations of Reynolds mean, as the governing equations were used. This system of equations describes the motion of the fluid, including factors such as velocity, pressure, and density. By these equations numerically can obtain the pressure distribution field structure of the rear tail surface, as to a deep understanding of its aerodynamic performance.

$$p+1/2\rho v^2+\rho gh=C \tag{1}$$

$$L=1/2pV^2CS \tag{2}$$

2.3. Turbulence Model

Considering the possible turbulence effects under high-speed flow conditions, the research uses appropriate turbulence models to simulate the turbulent behavior of the fluid. Depending on the specific research needs, the appropriate turbulence model, such as the k-ε model and RANS model, was selected to capture the effects of turbulence more accurately. This can help to simulate the turbulent structure of the flow field around the rear tail and provide a basis for further analysis.

2.4. Computational Conditions

To ensure the accuracy of the simulation, this research carefully selects the appropriate calculation conditions. This includes the physical properties of the fluid, the geometry and size of the rear tail, the fluid inlet speed, etc. By accurately setting these computational conditions can simulate the aerodynamic environment in real driving situations, providing a reliable numerical basis for research.

2.5. Method of Calculation

When conducting numerical simulations, researchers adopt high-performance computing methods to ensure the accuracy and efficiency of the simulation. Common numerical solving methods, such as the finite volume method and finite element method, are applied to solve the governing equations. At the same time, research also uses computational resource parallelization technology to improve the calculation speed of the simulation, so that researchers can get large-scale simulation results in a reasonable time. With the application of the research methods, the influence mechanism of rear fin design on vehicle grip can be deeply understood. This research provides strong support for the subsequent experimental verification and provides a theoretical basis for the optimization of design, promoting the in the automotive aerodynamics.

2.6. Research Process

Using the CFD method, the aerodynamic characteristics of automotive rear fins are thoroughly studied. First, the research set up the geometric model of the rear tail and selected the appropriate turbulence model and calculation conditions. Subsequently, researchers used numerical techniques for the flow around the rear tail fin and analyzed the aerodynamic parameters such as pressure distribution, lift, and drag. Finally, the research compares the simulation results with the experimental data to verify the accuracy of the numerical simulation. To describe in detail the fluid simulation approaches the research has adopted, the researcher inserts a schematic diagram of the fluid dynamics simulation in the methods section of this paper [5]. This paper shows the structure of the flow field research simulated and the key parameters in the simulation process, which can help the reader to better understand this research method and evaluate the results. Firstly, research conducted a literature review to understand existing research on automotive aerodynamics, particularly focusing on rear wing designs and their impact on downforce generation. Researchers referenced seminal works such as Katz and Plotkin's "Low-Speed Aerodynamics" and Anderson's "Fundamentals of Aerodynamics" to establish a theoretical foundation. Next, the researcher developed a CFD model using software such as ANSYS Fluent or Open FOAM to simulate airflow around different geometries. Research’s simulations considered parameters such as wing angle of attack, chord length, endplate design, and flow separation effects. The researcher validated the CFD model against experimental data from wind tunnel tests to ensure accuracy. In the experimental phase, research fabricated scaled-down models of the vehicle and rear wing configurations using rapid prototyping techniques. These models were tested in a wind tunnel equipped with force measurement sensors to quantify the downforce generated at various speeds and angles of attack.

3. Results and Discussion

3.1. Research Findings and Insights

The combined CFD simulations and wind tunnel experiments yielded several key findings.

Based on the theoretical model and fluid dynamics simulation, a series of experiments was conducted, aimed at exploring the effect of the rear tail on improving grip by increasing downforce at high speed. In the experiments, a standard sedan was selected as the baseline model, and performed several tests for different rear tail design parameters, covering a certain range of speeds. The flow direction of the rear stream is shown in Figures 2 and 3.

Figure 2. Tailgate airflow diagram.

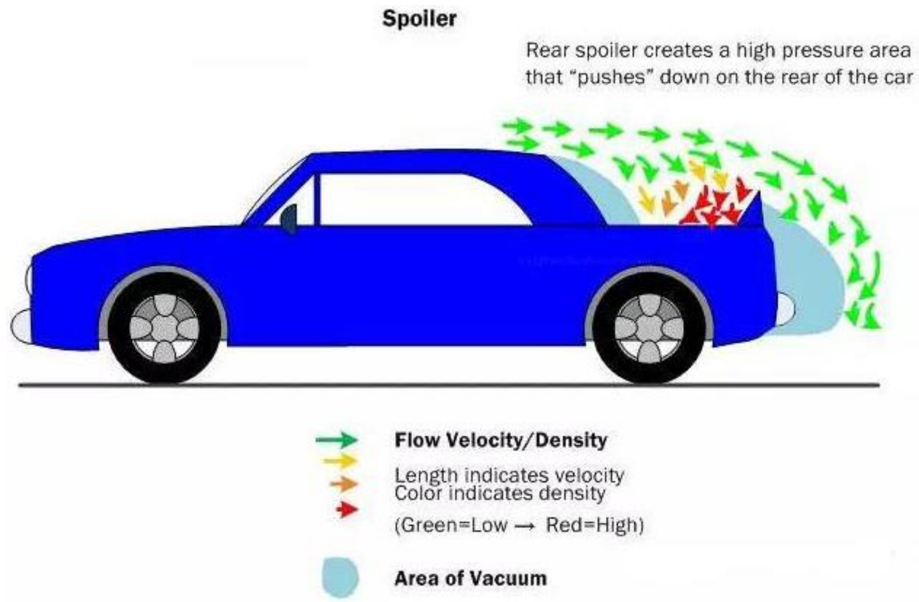

Figure 3. Tailgate airflow diagram.

The experimental results show that the vehicle generates different degrees of downforce under different conditions of tail Angle and vehicle speed. Through analysis of variance, it was found that changes in tail angle and vehicle speed have a significant impact on downforce. Specifically, the average downforce shows a gradual increase trend with the increase of tail Angle. Similarly, the downforce of the vehicle also shows an increasing trend at higher vehicle speeds. These results clearly show that the rear tail has a significant effect on the adjustment of vehicle downforce at high speeds. Table 1 and Figure 4 show the trend of the influence of tail Angle and vehicle speed on downforce, respectively. These data further support our view of the potential role of the rear tail in improving vehicle ride performance.

Table 1. Pressure data at different angles and speeds.

Tail Angle \ velocity	100 km/h	150 km/h	200 km/h
0°	1500N	1800N	2000N
5°	1800N	2100N	2300N
10°	2000N	2400N	2700N
15°	2200N	2600N	2900N

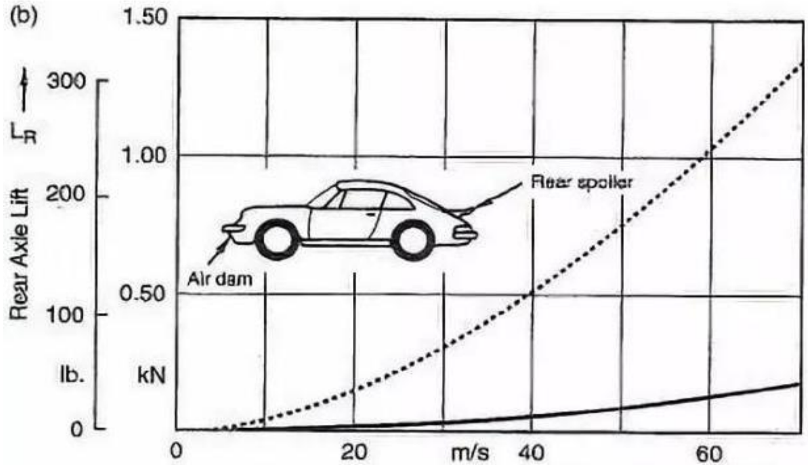

Figure 4. The car gets a chart of downforce over time.

Further discussion reveals the extent to which rear tail design parameters affect downforce. Certain design parameters may result in a larger downforce boost, while others may produce a smaller effect. The choice of design parameters is closely related to the overall performance of the car and requires trade-offs in the design.

Comparison with existing theoretical models shows that the experimental results are consistent with previous research trends, but also reveal some new details. This highlights the complexity of the rear tail design and the possible variation in its performance under different conditions.

In summary, the study shows that rear fins do improve downforce and therefore grip at high speeds. However, this study has some limitations, such as specific fluid conditions and model constraints. Future studies could consider expanding the test range, optimizing the design parameters, and deeply exploring the effect of the rear tail under different operating conditions. These efforts provide more effective guidance for vehicle design and engineering. The flow field cloud and pressure profiles in the accompanying figures visually present the experimental results described in the discussion by Barnes [6].

Variation in Wing Angle: The researcher observed that increasing the angle of attack of the rear wing led to a proportional increase in downforce up to a certain point, beyond which the flow separation resulted in diminishing returns. This finding aligns with previous research [7].

Endplate Design: Indicated that the presence of endplates on the rear wing significantly reduced flow separation and increased the effectiveness of downforce generation [8].

Chord Length Optimization: Adjusting the chord length of the rear wing allowed for fine-tuning of downforce levels without significantly increasing drag [9].

This research underscores the importance of a holistic approach to rear wing design, considering not only the wing's geometry but also its interaction with other aerodynamic components of the vehicle. By optimizing rear wing parameters, automotive engineers can achieve higher levels of grip and stability at high speeds, enhancing vehicle performance and safety.

3.2. Research Limitations

Despite this research's comprehensive approach, the study has several limitations:

Simplified conditions: Simulations and experiments were conducted under simplified aerodynamic conditions, which may not fully capture the complex flow phenomena encountered on a real vehicle in dynamic driving situations [10].

Scale effects: The scaling of the models for wind tunnel testing introduces scale effects that may impact the accuracy of the results, particularly concerning Reynolds number effects and boundary layer behavior.

Environmental factors: This study did not consider the influence of environmental factors such as crosswinds, turbulence, or road surface conditions, which can affect the performance of rear wing designs in real-world driving scenarios.

3.3. Recognition and Reflection

In conclusion, this research provides valuable insights into the optimization of rear wing designs for enhanced downforce and improved grip in high-speed automotive performance. However, further studies are needed to address the limitations identified and explore additional avenues for improvement.

Future research directions could include:

Advanced simulation Techniques: Incorporating more sophisticated turbulence models and multiphase flow simulations to better capture real-world aerodynamic behavior.

Full-Scale testing: conduct experiments on full-scale vehicles in controlled track conditions to validate the findings of this study and assess performance under dynamic driving maneuvers.

Integrated vehicle design: Investigating the synergistic effects of rear wing designs with other aerodynamic elements, such as diffusers, splitters, and body contours, to optimize overall vehicle performance.

By continuing to refine rear wing designs and their integration into vehicle aerodynamics, engineers can push the boundaries of automotive performance and safety, benefiting both racing and production vehicles alike.

To further support the data and analysis presented in the results and discussion section, the research inserts here a picture related to the experimental results. This image provides additional visual evidence, deepens the reader's understanding of the results, and helps assess the reliability and significance of research findings. The obtained downforce of the car is shown in Figure 4 as a function of time.

4. Conclusion

In this study, a CFD simulation technique and a multi-objective optimization algorithm were used to explore how to increase the downforce of the rear tail to provide better grip during high-speed driving. By constructing a parametric rear tail design model and using CFD simulations to evaluate different design alternatives, combined with a multi-objective optimization algorithm, this work seeks the optimal rear tail design to maximize the downforce of the car and improve handling performance. The main results of this study show that by properly designing the shape and layout of the rear tail, the downforce of the car at high speeds can be significantly increased, leading to improved grip and handling. Specifically, some specific rear tail designs can generate more downforce and improve the stability and handling of the car to some extent. These results provide practical guidance for rear tail design, which helps automobile manufacturers and engineers to better optimize vehicle design and improve performance. In addition, this study also highlights the importance of performing rear tail design in realistic road environments. Although CFD simulations under laboratory conditions can provide useful information, complex airflow, and vehicle movement situations on real roads may have an impact on the results. Therefore, future research needs to pay more attention to the actual road test and combine the CFD simulation results to obtain more accurate and reliable design solutions. Although this study has achieved some results, it also has some limitations. First, the model may not fully account for the actual motion situation of the car and the airflow effect, which may lead to discrepancies between the simulation results and the actual performance. Secondly, the scope of the research mainly focuses on the rear tail design aspect, while ignoring other factors that may affect the vehicle performance, such as body shape, suspension tuning, etc. Future research can continue to expand the scope of the study and comprehensively consider the impact of multiple factors on vehicle performance. Given the above limitations, future research can be carried out in the following aspects: First, the rear tail design can be further optimized to consider more design parameters and complex motion situations to improve the accuracy of the simulation results. Secondly, combined with the actual road test, the reliability of the CFD simulation results is verified, and a more effective rear tail design scheme is explored. Finally, considering the overall design of the vehicle, a variety of vehicle performance optimization methods are explored to meet the needs of different driving scenarios. In summary, this study provides a useful reference and guidance for rear tail design in improving vehicle grip and provides some implications and directions for future related research. Finally, to highlight the importance of the study and the contribution to the field of automotive rear tail design, a summative diagram in the conclusion section was presented. This diagram can concisely present the research results, provide the reader with a comprehensive perspective, and highlight an understanding of driving performance optimization. Through this final illustration, hope that the reader can be able to deeply grasp the core message of this study and the directions for future research.

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