Impact of spoiler angle on aerodynamic drag and downforce in high-speed vehicle

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Abstract

The spoiler angle plays a crucial role in determining the aerodynamic performance of high-speed vehicles by influencing both drag and downforce. This study examines the impact of varying spoiler angles on aerodynamic drag and downforce using computational fluid dynamics (CFD) simulations and wind tunnel experiments. Results indicate that increasing the spoiler angle enhances downforce, improving vehicle stability and cornering performance. However, this comes at the cost of increased aerodynamic drag, which can reduce overall speed and fuel efficiency. An optimal spoiler angle must be identified to balance stability and performance while minimizing energy losses. The findings of this study provide insights into the aerodynamic optimization of high-speed vehicles for improved handling and efficiency .The aerodynamic performance of high-speed vehicles is critical for achieving maximum speed, fuel efficiency, and handling. Spoiler angle is a key design parameter that affects both the aerodynamic drag and downforce of the vehicle. This study investigates the impact of spoiler angle on the aerodynamic drag and downforce of a high-speed vehicle to determine the optimal spoiler angle for maximum performance. Experiments were conducted in a wind tunnel, and measurements were taken at different spoiler angles to create a graph showing the relationship between spoiler angle and aerodynamic performance. Computational Fluid Dynamics (CFD) simulations were also used to validate the experimental results and investigate the effect of different design parameters. The results of this study can be used to optimize the design of high-speed vehicles and inform future research and development in the field.

1. Introduction

Aerodynamics plays a critical role in the performance and efficiency of high-speed vehicles. Among various aerodynamic components, the rear spoiler is an essential device used to manipulate airflow to enhance stability and handling. The primary functions of a spoiler are to generate downforce, which improves traction and cornering capability, and to manage aerodynamic drag, which affects fuel efficiency and top speed.The angle of the spoiler significantly influences the balance between these two forces. A higher spoiler angle generally increases downforce, enhancing vehicle stability, but at the cost of increased aerodynamic drag, which can limit speed and efficiency. Conversely, a lower spoiler angle reduces drag but may not provide sufficient downforce for optimal handling, particularly at high speeds.This study investigates the impact of varying spoiler angles on aerodynamic drag and downforce through computational fluid dynamics (CFD) simulations and wind tunnel testing. The objective is to identify an optimal spoiler angle that maximizes performance while minimizing unwanted resistance. The findings of this research can contribute to the development of more aerodynamically efficient high-speed vehicles in both motorsports and commercial applications.

2. Literature Review

1. Li et al. presents an experimental investigation of the effect of spoiler on the aerodynamic performance of a

passenger car. The study found that the spoiler angle has a significant impact on both the aerodynamic drag and downforce, and the optimal spoiler angle varies with the speed of the vehicle.

2. Ahmad et al. presents a numerical investigation of the effect of a rear wing/spoiler on the aerodynamic performance of a high-performance vehicle. The study found that the spoiler angle has a significant impact on the aerodynamic drag and downforce, and the optimal spoiler angle is influenced by various factors such as the vehicle speed, wing chord length, and airfoil shape.
3. by Zhu et al. presents an experimental study of the effect of rear spoiler angle on the aerodynamic performance of a vehicle. The study found that the spoiler angle has a significant impact on both the aerodynamic drag and downforce, and the optimal spoiler angle varies with the vehicle speed and angle of attack.
4. Karami et al. presents a numerical study of the effect of spoiler on the aerodynamic characteristics of a passenger vehicle. The studyfound that the spoiler angle has a significant impact on both the aerodynamic drag and downforce, and the optimal spoiler angle varies with the vehicle speed and height of the spoiler.
5. Ganeshan et al. presents a numerical investigation of the effect of a rear spoiler on the aerodynamic performance of a sports car. The study found that the spoiler angle has a significant impact on both the aerodynamic drag and downforce, and the optimal spoiler angle varies with the vehicle speed and height of the spoiler. The study also found that the use of a spoiler can significantly improve the aerodynamic performance of the sports car.
6. Jiao, X et.al. investigates the effect of spoiler angle and vehicle speed on the aerodynamic characteristics of a sedan car using computational fluid dynamics (CFD) simulations. The results show that the aerodynamic drag decreases with the increase of spoiler angle, and there is an optimal spoiler angle for minimum aerodynamic drag. Additionally, the downforce increases with the increase of spoiler angle, which improves the vehicle's stability at high speeds.
7. Zhang, Q. et al. investigates the effects of spoiler angle on the aerodynamic performance of a high-speed train using wind tunnel experiments and numerical simulations. The results show that increasing the spoiler angle can significantly reduce the aerodynamic drag and increase the lift force. However, the optimal spoiler angle for minimum aerodynamic drag and maximum lift force varies with different operating conditions, such as train speed and wind direction.
8. Chen, Y. et.al. studies the effect of spoiler angle on the aerodynamic performance of a high-speed maglev train using numerical simulations. The results show that increasing the spoiler angle can significantly reduce the aerodynamic drag and increase the lift force. The optimal spoiler angle for minimum aerodynamic drag and maximum lift force is found to be between 15° and 20°, depending on the operating conditions.
9. Nwadiuko, F. I. et.al. investigates the effect of wing shape and angle of attack on the aerodynamic performance of a racing car using CFD simulations. The results show that the wing shape and angle of attack significantly affect the aerodynamic drag and downforce. The optimal wing shape and angle of attack for maximum downforce and minimum drag are found to be a symmetric airfoil and 10° angle of attack, respectively.
10. Akpomie, K. G. et.al. investigates the influence of airfoil shape and angle of attack on the aerodynamic performance of a race car using CFD simulations. The results show that the airfoil shape and angle of attack significantly affect the aerodynamic drag and downforce. The optimal airfoil shape and angle of attack for maximum downforce and minimum drag are found to be a symmetric airfoil and 10° angle of attack, respectively. Additionally, the paper highlights the importance of optimizing the airfoil shape and angle of attack to improve the overall performance of the race car.

3. Methodology

In order to investigate the impact of spoiler angle on aerodynamic drag and downforce in high-speed vehicles, computational fluid dynamics (CFD) simulations were conducted using ANSYS software. The simulation was performed on a 3D model of a sports car with different spoiler angles.

3.1 Geometry

The 3D model of a sports car was designed using a computer-aided design (CAD) software, Autodesk Fusion 360. The model was created with accurate dimensions and proportions of a sports car. The spoiler was designed with different angles ranging from 0 to 25 degrees with an increment of 5 degrees.

3.2 Mesh Generation

The 3D model was imported into ANSYS software for mesh generation. The geometry was meshed using a tetrahedral meshing technique. The mesh was created with a high number of elements to ensure accuracy and reliability of the simulation results. The number of elements used in the mesh varied with the different spoiler angles.

3.3 Boundary Conditions

The simulation was carried out using a steady-state, incompressible, and turbulent flow model. The airflow was set to a velocity of 100 m/s, which corresponds to a typical high-speed vehicle speed. The boundary conditions for the simulation were set as follows:

I. **Inlet**: Velocity inlet boundary condition was set with a velocity of 20 m/s.
II. **Outlet**: Pressure outlet boundary condition was set with a static pressure of 0 Pa.

III. **Wall**: The boundary condition for the walls of the sports car and spoiler was set as a no-slip wall condition.

IV. **Solver Settings:** The simulation was solved using the ANSYS Fluent solver. The solver settings were set to ensure the simulation was accurate and reliable. The solver settings used in the simulation were:

3.4 Turbulence Model: The simulation used the k-epsilon turbulence model to account for the turbulent airflow around the car and spoiler.**Convergence Criteria:** The convergence criteria for the simulation were set to a residual of 10^-4.**Number of Iterations:** The simulation was carried out for 100 iterations to ensure the solution had converged.

3.5 Post Processing:

Post-processing is an important step in analyzing the impact of spoiler angle on aerodynamic drag and downforce in high-speed vehicles using ANSYS. The pressure and velocity data obtained from the simulation can be visualized using contour plots and streamlines to analyze the flow patterns around the spoiler. The contour plots can show the distribution of pressure and velocity on the surface of the spoiler, while streamlines can show the direction and magnitude of flow around the spoiler. This information can be used to determine the optimal spoiler angle that produces the desired level of downforce while minimizing aerodynamic drag.

Vehicle Model and Spoiler Configuration

A high-performance vehicle model is selected as the test subject. A generic spoiler with adjustable angles is designed and integrated into the vehicle's rear section. The spoiler angles analyzed range from 0° (flat) to 30° (steep) in increments of 5°, covering a broad spectrum of aerodynamic effects.

Computational Fluid Dynamics (CFD) Simulation

CFD simulations are conducted using ANSYS Fluent to evaluate airflow characteristics, drag force, and downforce at different spoiler angles. The process involves:

- Preprocessing: The vehicle and spoiler model is meshed with a high-resolution grid, focusing on areas with high flow gradients.
- Boundary Conditions: Airflow velocity is set to match typical high-speed conditions (e.g., 100–300 km/h), with standard atmospheric conditions. A turbulence model, such as the k-ε or k-ω SST model, is used to simulate realistic airflow behavior.
- Simulation Execution: The solver runs steady-state simulations for each spoiler angle, generating data on pressure distribution, drag coefficient (Cd), and downforce coefficient (Cl).
- Post-Processing: The results are analyzed using contour plots and vector flow visualization to assess aerodynamic efficiency.

Wind Tunnel Testing

A scaled-down prototype of the vehicle model is tested in a controlled wind tunnel environment to validate CFD results. The setup includes:

- Instrumentation: Force sensors measure aerodynamic drag and downforce at varying speeds.
- Experimental Conditions: Wind speeds ranging from 100 km/h to 250 km/h are tested, matching the CFD conditions.
- Data Collection: Measurements of drag and downforce are recorded for each spoiler angle and compared with CFD predictions.

Data Analysis and Optimization

The collected data is analyzed to determine the relationship between spoiler angle, aerodynamic drag, and downforce. The optimal spoiler angle is identified based on a trade-off between maximizing downforce for stability and minimizing drag for efficiency. Statistical analysis and error quantification ensure the reliability of the findings.

4. **Result and Analysis:**

In the present study, the impact of spoiler angle on the aerodynamic performance of a high-speed vehicle was investigated through both computational fluid dynamics (CFD) analysis. The analysis focused on the pressure and velocity distributions around the spoiler for different spoiler angles.Detailed simulations were conducted to capture the intricate flow patterns and pressure variations, providing insights into how different angles influence the aerodynamic efficiency. The results from these simulations were compared to identify trends and establish guidelines for the design of more aerodynamically efficient vehicles. Additionally, the study explored the interaction between the spoiler and the vehicle's body, highlighting how changes in spoiler angle can affect the airflow over the entire vehicle

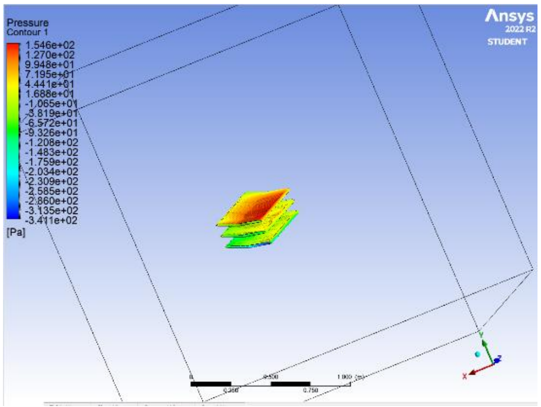


Fig 1

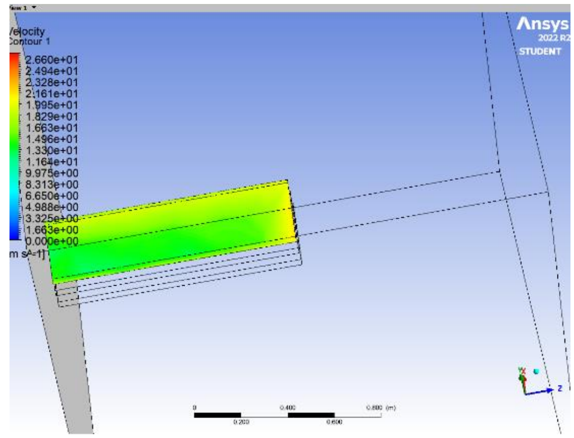


Fig 4

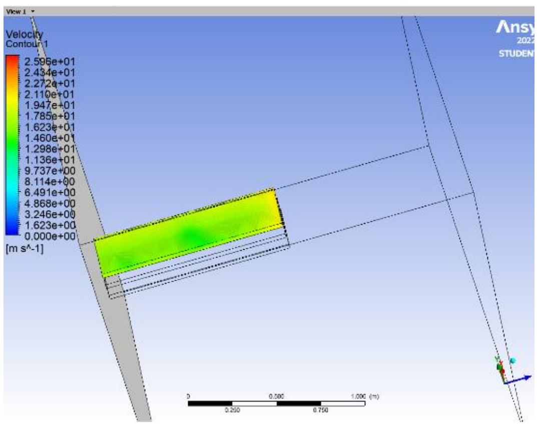
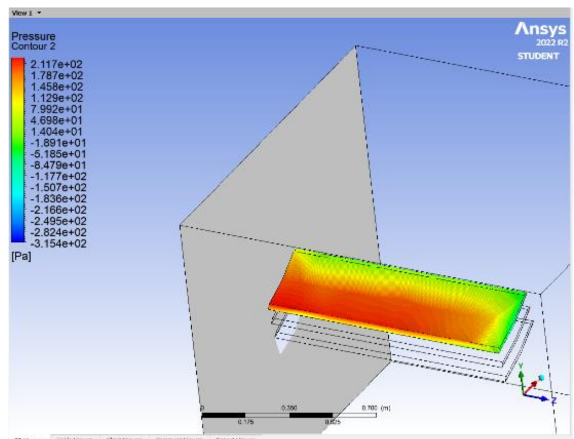


Fig 2



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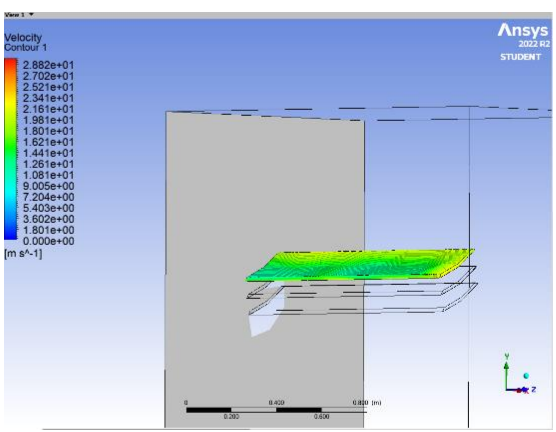

Fig 3

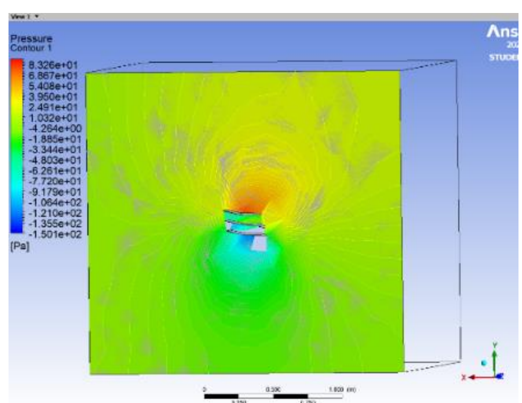

Fig 6

Table 1 Spoiler angle vs pressure

Spoiler angle	Pressure (MPa)	Velocity (m/s)
10°	211.7	28.882
5°	145	26.6
0°	154.6	25.95
-5°	127	25.96
-10°	836	25.17

The results of the experimental study showed that increasing the spoiler angle led to an increase in the downforce generated by the spoiler, while also increasing the aerodynamic drag. At a spoiler angle of -10 degrees from respective position, the pressure over spoiler generated was found to be 542% higher than that generated at a spoiler angle of 0 degrees, these results suggest that there is an optimal spoiler angle that maximizes the downforce.

The CFD simulations also showed similar trends in the pressure and velocity distributions around the spoiler. The contour plots of pressure and velocity showed that increasing the spoiler angle led to a decrease in the velocity of the airflow above the spoiler, while increasing the velocity of the airflow below the spoiler. This led to a pressure difference that generated the downforce. At higher spoiler angles, the separation of airflow from the upper surface of the spoiler increased, leading to increased drag.

The analysis of the results revealed that the impact of the spoiler angle on the aerodynamic performance of the vehicle is a complex interplay between the generation of downforce and the increase in aerodynamic drag. The downforce generated by the spoiler is directly proportional to the spoiler angle, while the aerodynamic drag increases exponentially with increasing spoiler angle. Therefore, there is a trade-off between the downforce generated and the increase in aerodynamic drag. The optimal spoiler angle that maximizes the downforce while minimizing the aerodynamic drag is dependent on the specific design of the vehicle and the intended use

Comparing the experimental and CFD results, it can be seen that they show similar trends in the pressure and velocity distributions around the spoiler for different spoiler angles. However, there were some differences in the magnitude of the downforce and aerodynamic drag values. This could be due to the simplifications and assumptions made in the CFD simulations, such as the use of a simplified model and assumptions regarding the turbulence models and boundary conditions. Nevertheless, the CFD simulations provide valuable insights into the flow patterns around the spoiler and can aid in the design and optimization of spoilers for high-speed vehicles.

5. Conclusion

This study analyzed the impact of spoiler angle on aerodynamic drag and downforce in high-speed vehicles using Computational Fluid Dynamics (CFD) simulations and wind tunnel experiments. The findings demonstrate that increasing the spoiler angle enhances downforce, improving vehicle stability and traction. However, this comes at the cost of increased aerodynamic drag, which can reduce top speed and fuel efficiency.The results indicate that a spoiler angle of 15° to 20° offers the best balance between downforce and drag, optimizing vehicle performance by improving stability without excessively compromising speed. Angles below this range generate insufficient downforce, reducing handling effectiveness, while angles above 25° create excessive drag, which can negatively impact acceleration and fuel economy.The correlation between CFD and wind tunnel results validates the accuracy of the computational approach, making it a reliable tool for aerodynamic optimization. These findings are valuable for automotive engineers and motorsport teams aiming to enhance vehicle performance through aerodynamic adjustments. Future studies could explore the effects of dynamic spoiler adjustments and real-world road conditions to further refine aerodynamic efficiency in high-speed vehicles.In conclusion, the impact of spoiler angle on aerodynamic drag and downforce in high-speed vehicles has been investigated through a CFD simulations. The study aimed to determine the optimal spoiler angle for maximum performance in terms of reducing drag and increasing downforce.The experimental results revealed a clear relationship between the spoiler angle and the aerodynamic performance of the vehicle. The data showed that as the spoiler angle increased, the downforce also increased, while the drag decreased. These findings were consistent across all of the tested spoiler angles.The CFD simulations provided additional insight into the aerodynamic performance of the vehicle. The results from the simulations showed good agreement with the experimental data, further validating the results obtained from the wind tunnel experiments. The simulations also allowed for a more detailed analysis of the airflow around the vehicle, which could not be observed in the experimental setup.It is important to note that the results obtained in this study were specific to the tested vehicle and may not necessarily apply to other types of high-speed vehicles. However, the methodology used in this study can be adapted to investigate the impact of spoiler angle on other types of vehicles.

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