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A NUMERICAL STUDY ON THE IMPACT OF SPOILER ORIENTATION AND GEOMETRY ON SALOON CAR AERODYNAMICS

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Abstract. *According to data from the Ministry of Energy and Mineral Resources (ESDM), energy consumption in Indonesia has exhibited a consistent upward trend. In 2023, it increased by 6.29% compared to the previous year. The transportation sector accounted for 37% of total energy consumption in 2023, which is considered very high. Therefore, it is essential to improve energy efficiency in this sector. One effective way to achieve this is by using vehicle designs that are more energy-efficient, particularly those with aerodynamic shapes. Vehicles with lower drag force can reduce fuel consumption significantly. Several studies have proposed the integration of external aerodynamic devices—such as vortex generators, rear spoilers, rear fairings, and fenders—aimed at actively manipulating airflow around the vehicle to reduce aerodynamic resistance The objective of this study is to investigate the effect of spoilers on the aerodynamic performance of a car. The research employs a numerical method using ANSYS Fluent software to analyze the resulting drag force, pressure contours, velocity contours, and flow patterns around the vehicle. The model used in this study is a sedan car with four different configurations: without a spoiler, with a flat spoiler and with an upward-tilted spoiler. The results indicate that Spoiler model 2 achieves an average drag coefficient reduction of approximately 19.8% compared to non-spoiler 1 across the tested speed range (5–25 m/s), Among all configurations, Non-Spoiler 2 produced the highest lift coefficient (1.19), suggesting the least favorable aerodynamic stability. In contrast, Spoiler 1 exhibited the lowest lift coefficient (0.22), highlighting its superior ability to minimize lift and improve overall stability performance*

Keywords: *Vehicle aerodynamics, Spoiler position, Spoiler geometry, Drag reduction, Numerical simulation*

1. INTRODUCTION

According to data from the Ministry of Energy and Mineral Resources (ESDM), energy consumption in Indonesia has shown a steady upward trend. In 2023 alone, national energy consumption increased by 6.29% compared to the previous year. The transportation sector is a major contributor to this increase, accounting for approximately 37% of total energy consumption in 2023, a figure considered remarkably high (Kementrian ESDM et al. 2024). This situation underscores the urgent need to improve energy efficiency within the transportation sector.

The increasing demand for energy-efficient and environmentally friendly vehicles has driven automotive manufacturers to prioritize aerodynamic optimization in their design processes. Aerodynamic drag contributes significantly to a vehicle's overall energy consumption, particularly at higher speeds, and directly influences fuel economy and carbon dioxide (CO_2) emissions (Chowdhury et al. 2012). Even minor improvements in aerodynamic design can lead to considerable reductions in fuel consumption and enhance vehicle stability, offering both economic and environmental benefits (Fernandez, Shofiah, and Nampira 2025).

Saloon cars, widely favored for their balance of comfort, practicality, and affordability, constitute a substantial portion of global passenger vehicle fleets. However, their aerodynamic performance often lags behind that of more streamlined vehicle categories, such as sports cars and hatchbacks (Fabian et al. 2022). Improving the aerodynamic characteristics of saloon cars is therefore crucial not only for reducing fuel consumption but also for enhancing safety and ride quality under diverse driving conditions.

Among various aerodynamic devices, rear spoilers play a crucial role in controlling airflow patterns around the vehicle body. Properly designed spoilers can mitigate lift forces, thereby enhancing tire-road contact, improving cornering performance, and increasing high-speed stability (Ayyagari and He 2017; Abood, Hussain, and Ali 2025). In addition, spoilers can alter wake structures behind the vehicle, helping to reduce drag and suppress turbulent vortices that negatively affect fuel efficiency (Eftekhari, Al-Obaidi, and Eftekhari 2020).

Although significant research has been conducted on the aerodynamic optimization of high-performance and racing vehicles, studies focusing specifically on saloon cars remain limited (Koitrand, Gaylard, and Orso Fiet 2015; Piratla 2023; Zakher, El-Hadary, and Aziz 2019) . Unlike sports or racing cars, saloon cars require a delicate balance between minimizing drag and generating sufficient downforce to ensure safe handling and passenger comfort. This balance is particularly challenging due to the typically larger and less aerodynamically refined body shapes of saloon vehicles.

Moreover, most previous studies have concentrated on fixed spoiler configurations and have largely overlooked the potential advantages offered by varying the spoiler orientation or utilizing adaptive spoiler systems. Recent advances in active aerodynamic technologies suggest that adjusting spoiler angles based on driving conditions can offer further improvements in aerodynamic efficiency without significantly increasing drag (Eftekhari, Al-Obaidi, and Eftekhari 2020).

Despite advancements in Computational Fluid Dynamics (CFD) modeling, there is still a lack of comprehensive studies systematically examining the combined effects of spoiler geometry and orientation on the aerodynamic behavior of saloon cars. Addressing this gap is essential to guide the development of more efficient and safer vehicle designs that comply with increasingly stringent environmental regulations.

Therefore, this study aims to conduct a numerical investigation into the effects of different spoiler geometries and orientations on a typical saloon car using CFD simulations. The analysis focuses on quantifying changes in drag coefficient (Cd), lift coefficient (Cl), and wake flow characteristics resulting from these design variations. The findings are expected to provide practical insights that can support future aerodynamic optimization strategies for saloon vehicles.

2. LITERATURE REVIEW

Aerodynamic forces play a pivotal role in determining the performance, fuel efficiency, and stability of road vehicles. The two main aerodynamic coefficients—drag coefficient (Cd) and lift coefficient (Cl)—are central to evaluating how effectively a vehicle can minimize resistance and maintain stability at various speeds. According to fundamental aerodynamic theory, the drag force acting on a vehicle is directly related to the air density, frontal area, square of the relative velocity, and Cd value. Likewise, lift force depends on similar parameters and is responsible for affecting the vertical loading on tires, directly influencing vehicle handling and safety (Ferrari, Rossi, and Di Bernardino 2022) (Howell 2013).

The application of aerodynamic devices, particularly rear spoilers, has been widely recognized as an effective approach to improve flow behavior around the vehicle body. Spoilers can suppress lift forces that reduce tire contact, thereby enhancing handling performance and increasing driving safety, especially at highway speeds (Abedin and Mukut 2019; Katz 2021; Shao 2025). In addition, they help control wake structures behind the vehicle, minimizing flow separation and reducing turbulent vortices that contribute to aerodynamic drag ("Review of Effects the Rear Spoiler Aerodynamic Analysis on.Pdf," n.d.).

Recent numerical studies have demonstrated that spoiler design significantly influences both drag and lift characteristics. Valencia et al. (Valencia and Lepin 2024) performed a computational analysis of sedan-type vehicles equipped with various spoiler geometries and showed that optimized designs could reduce lift forces while causing only a marginal drag increase. Similarly, Hesam Eftekhari et al. (Eftekhari, Al-Obaidi, and Eftekhari 2020) emphasized the role of inclination angles, noting that moderate spoiler angles (10°–15°) strike a balance between drag reduction and downforce generation.

Further research has explored active and adaptive aerodynamic components, including variable geometry spoilers, as a means of dynamically improving aerodynamic performance. Tarun Venkatesh (Allah and Mulyanto 2025) investigated an adaptive rear spoiler system and reported enhanced cornering stability and improved straight-line performance without a significant drag penalty. See-Yuan Cheng et al. (Cheng et al. 2019) supported these findings, demonstrating that angle-adjustable spoilers can effectively adapt to different driving conditions to maintain optimal aerodynamic efficiency.

Despite these advances, most existing work has focused primarily on sports or racing vehicles, where maximizing downforce is prioritized even at the expense of higher drag (Xia and Huang 2024; Abedin and Mukut 2019; Shao 2025). In contrast, saloon cars require careful trade-offs to maintain low drag for fuel efficiency while providing sufficient downforce to ensure stability and safety under daily driving conditions (Konwar Roy and Sharma 2021).

Moreover, comprehensive investigations integrating both spoiler geometry and orientation are still limited for saloon cars. Zhaowen Deng et al. (Deng et al. 2020) highlighted that simultaneous optimization of spoiler shape and angle can lead to significant improvements in aerodynamic coefficients and wake behavior, but further studies tailored specifically to typical saloon vehicles remain scarce.

The advancement of Computational Fluid Dynamics (CFD) techniques has enabled detailed examination of complex flow structures and surface pressure distributions. Recent works using high-fidelity simulations have successfully revealed critical insights into wake dynamics and separation behavior behind vehicles equipped with different spoiler configurations. However, a systematic study combining shape and orientation variations in saloon cars is still lacking.

Addressing this gap can provide valuable guidance for future design strategies, supporting the development of energy-efficient, stable, and safer passenger vehicles that comply with stringent environmental standards and evolving market expectations.

3. RESEARCH METHODS

3.1 Research Object

In this study, four model variations were investigated, as illustrated in Figure 1.

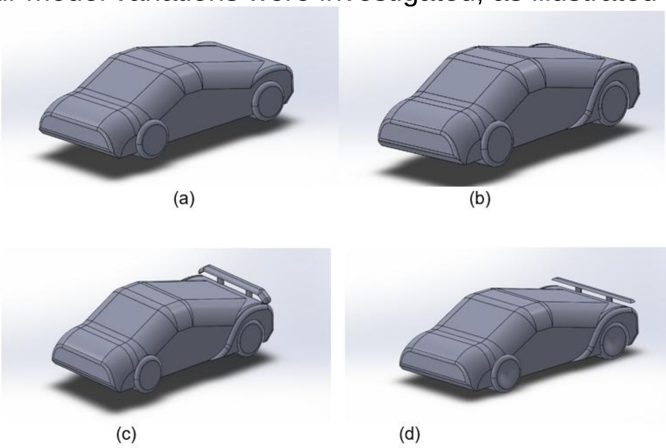


Figure 1. Variation of Spoiler (a) non-spoiler 1,
(b) non-spoiler 2 (c) Spoiler Model 1, (d) Spoiler Model 2

3.2 Step of the research

Aerodynamic performance is crucial for optimizing stability and efficiency in sedan cars. Computational Fluid Dynamics (CFD) has become a reliable tool to predict aerodynamic behaviors, reducing the need for extensive wind tunnel testing and providing detailed flow insights. This study presents a numerical CFD analysis on four configurations. The numerical study was conducted using CFD simulations to evaluate the lift coefficient (Cl) and drag coefficient (Cd) at different velocities: 5 m/s, 10 m/s, 15 m/s, 20 m/s, and 25 m/s with the step (figure 2).

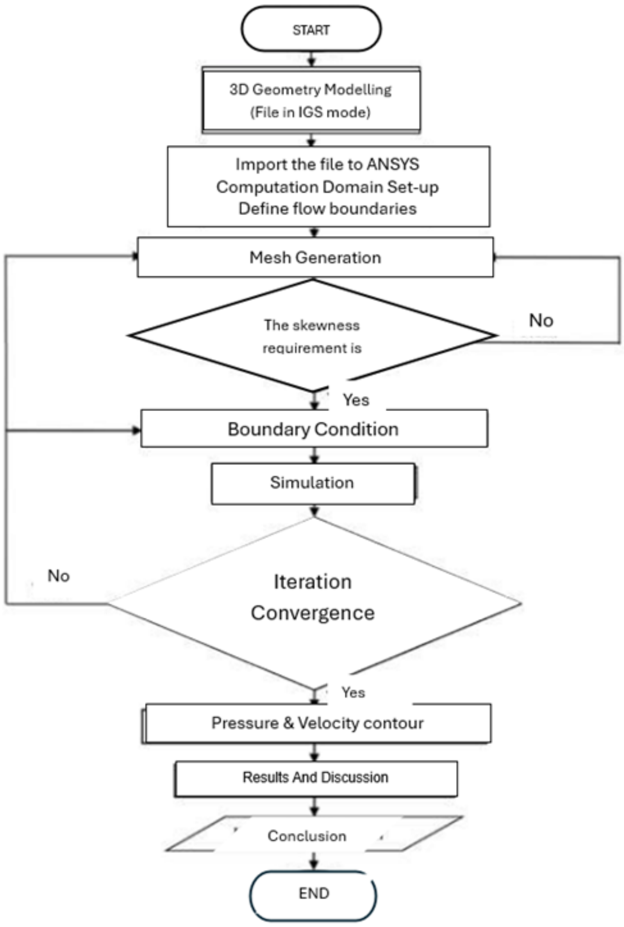


Figure 2. Flow Chart

The three-dimensional computational domain was discretized with an unstructured triangular grid to capture complex geometric features effectively. Mesh refinement was applied to critical regions, including the vehicle surface, underbody, and wake area, to improve solution accuracy. The Reynolds-Averaged Navier–Stokes (RANS) equations with the realizable k–ε turbulence model were adopted to predict turbulent flow behavior accurately. This model is widely validated for external vehicle aerodynamics due to its robustness in capturing large-scale separations and wake dynamics. Simulations were conducted using ANSYS Fluent (2023 R1). A second-order upwind discretization scheme was used for all transport equations to improve numerical accuracy. Convergence was monitored by checking residual reductions below 10^{-5} and stabilization of integral quantities such as drag and lift coefficients within ±1% over several hundred iterations.

Post-processing was carried out to visualize and analyze flow structures, surface pressure distributions, and velocity fields around the vehicle. Important aerodynamic parameters, including drag coefficient (Cd), lift coefficient (Cl), and pressure contour, were extracted and compared among different spoiler configurations and angles.

Streamline and wake flow analyses were also performed to investigate separation zones and vortex behavior.

4. RESULTS AND DISCUSSION

The aerodynamic testing data obtained from the saloon car models reveal the significant influence of different spoiler configurations on both drag and lift performance. The study analyzed four configurations: non-spoiler1 non-spoiler 2, Spoiler Model 1, and Spoiler Model 2, evaluated across speeds ranging from 5 m/s to 25 m/s

4.1 Lift Coefficient (Cl) Analysis

Table 1 presents the simulation results for four vehicle models evaluated at various inlet velocities ranging from 5 to 25 m/s. The analysis focuses on the aerodynamic performance in terms of lift coefficients, providing a comprehensive comparison of each configuration under different speed conditions

Table 1. Lift Coefficient

Velocity (m/s)	Non-Spoiler 1	Non-Spoiler 2	Spoiler 1	Spoiler 2
5	0.95	0.96	0.22	0.28
10	1.10	1.11	0.23	0.34
15	1.08	1.17	0.25	0.34
20	1.09	1.19	0.26	0.35
25	1.10	1.12	0.27	0.38

As summarized in Table 2, Non-Spoiler 1 and Non-Spoiler 2 show high Cl values, exceeding 1.0 at higher velocities. The elevated lift indicates substantial upward aerodynamic forces, which can reduce tire traction, deteriorate vehicle handling, and increase rollover risk during sudden maneuvers.

Spoiler 1 displays the most significant reduction in lift, maintaining Cl values from 0.22 at 5 m/s to 0.27 at 25 m/s. The low Cl reflects superior downforce generation, contributing to enhanced stability and improved high-speed cornering capability. This finding supports the principle that well-designed rear spoilers can reduce lift by modifying rear pressure distribution and controlling wake separation (et al. 2024).

Spoiler 2 demonstrates moderate Cl values, between 0.28 and 0.38. While these values are higher than Spoiler 1, they still represent a clear improvement over both non-spoiler configurations. The moderate lift suggests that Spoiler 2 prioritizes drag reduction, possibly at the expense of some downforce generation, which may be acceptable in scenarios where fuel efficiency is prioritized over maximum lateral stability.

4.2 Drag Coefficient

Table 2 presents the simulation results for four vehicle models evaluated at various inlet velocities ranging from 5 to 25 m/s. The analysis focuses on the aerodynamic performance in terms of drag coefficients,

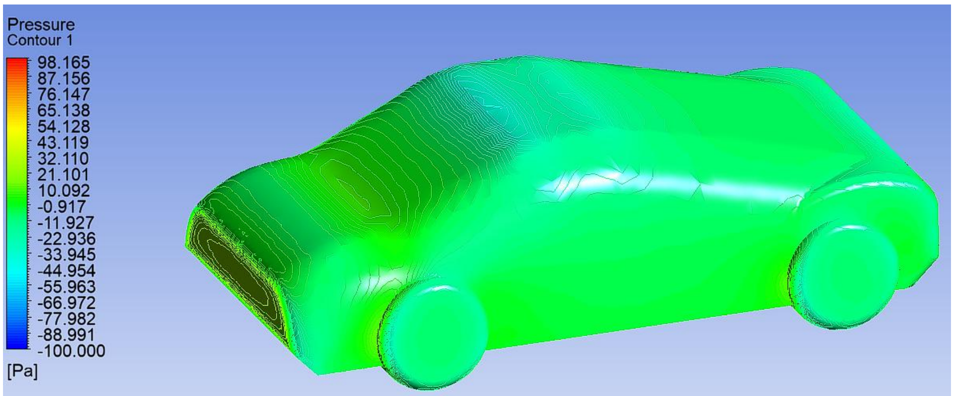
Table 2. Drag Coefficient

Velocity (m/s)	Non-Spoiler 1	Non-Spoiler 2	Spoiler 1	Spoiler 2
5	0.64	0.68	0.68	0.5357
10	0.65	0.69	0.68	0.51
15	0.65	0.70	0.68	0.51
20	0.65	0.70	0.68	0.519
25	0.65	0.70	0.67	0.52

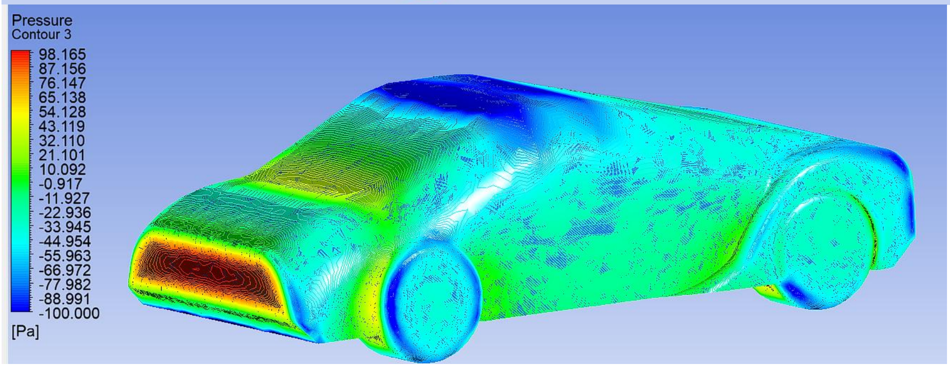
According to Table 2, the drag coefficients for all configurations. Non-Spoiler 1 maintains relatively stable Cd values, approximately 0.64 to 0.65, across all velocities. This configuration serves as the baseline, representing typical flow behavior without any aerodynamic aids. Non-Spoiler 2 demonstrates higher drag, with Cd values ranging from 0.68 to 0.70. The increased drag suggests greater flow separation and larger wake regions, which can negatively impact fuel efficiency and increase overall resistance (Katz 2021). Spoiler 1 shows comparable drag values to non-spoiler 2, with Cd remaining around 0.68 to 0.67 at higher speeds. The consistent drag indicates that although Spoiler 1 effectively modifies the flow field for lift control, it does not contribute to drag reduction, possibly due to additional frontal area and wake turbulence.

In contrast, Spoiler 2 records the lowest drag coefficients among all configurations, ranging from 0.51 to 0.54. The significant reduction in drag highlights an effective suppression of wake vortices and a streamlined flow reattachment behind the vehicle. This result is crucial for improving fuel economy, as lower drag directly reduces the propulsion energy requirement at higher speeds (Connolly, Ivankovic, and O'Rourke 2024).

No spoiler 1



No Spoler 2



Spoiler 1

Spoiler 2

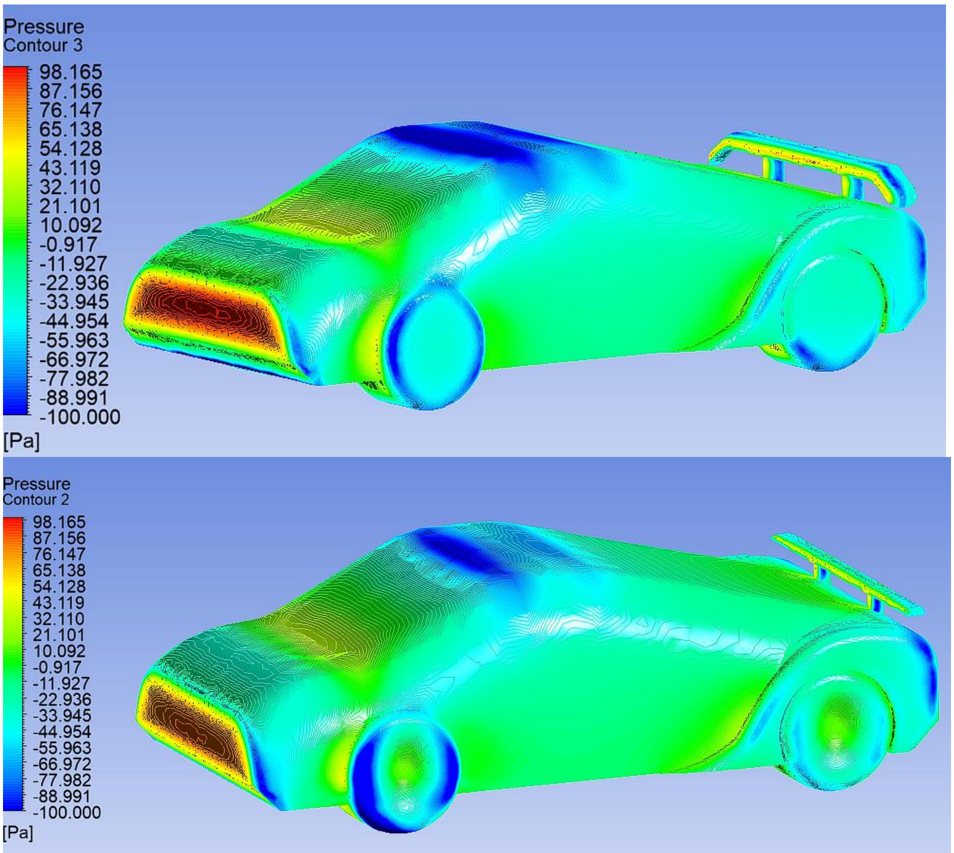


Figure 3. Pressure Contour

Pressure contours highlight surface pressure distribution and help interpret lift characteristics. Non-Spoiler 1 and Non-Spoiler 2 exhibit large low-pressure zones on the upper rear surface and trunk, which are responsible for generating strong lift forces. This effect reduces tire-ground contact and compromises vehicle stability, especially during high-speed maneuvers or sudden lane changes. Spoiler 1 successfully reduces the low-pressure area at the rear, resulting in lower lift coefficients. The spoiler induces a downward force by redirecting airflow and increasing rear deck pressure, thereby enhancing vehicle stability and safety [8]. Spoiler 2 also shows a reduction in rear low-pressure zones, though not as significant as Spoiler 1. This pattern aligns with its moderate lift coefficient, indicating that while it reduces lift, its primary design focus is on drag reduction rather than maximizing downforce.

4.4 Velocity Streamline

Figure 4 presents the velocity streamlines around the investigated saloon car model. This visualization illustrates the flow patterns and streamlines trajectories, providing critical insights into flow attachment, separation regions, and wake formation. The analysis of these streamlines is essential for understanding the aerodynamic effectiveness of different spoiler configurations and their impact on vehicle stability and drag reduction.

No spoiler 1

No Spoiler 2

Spoiler 1

Spoiler 2

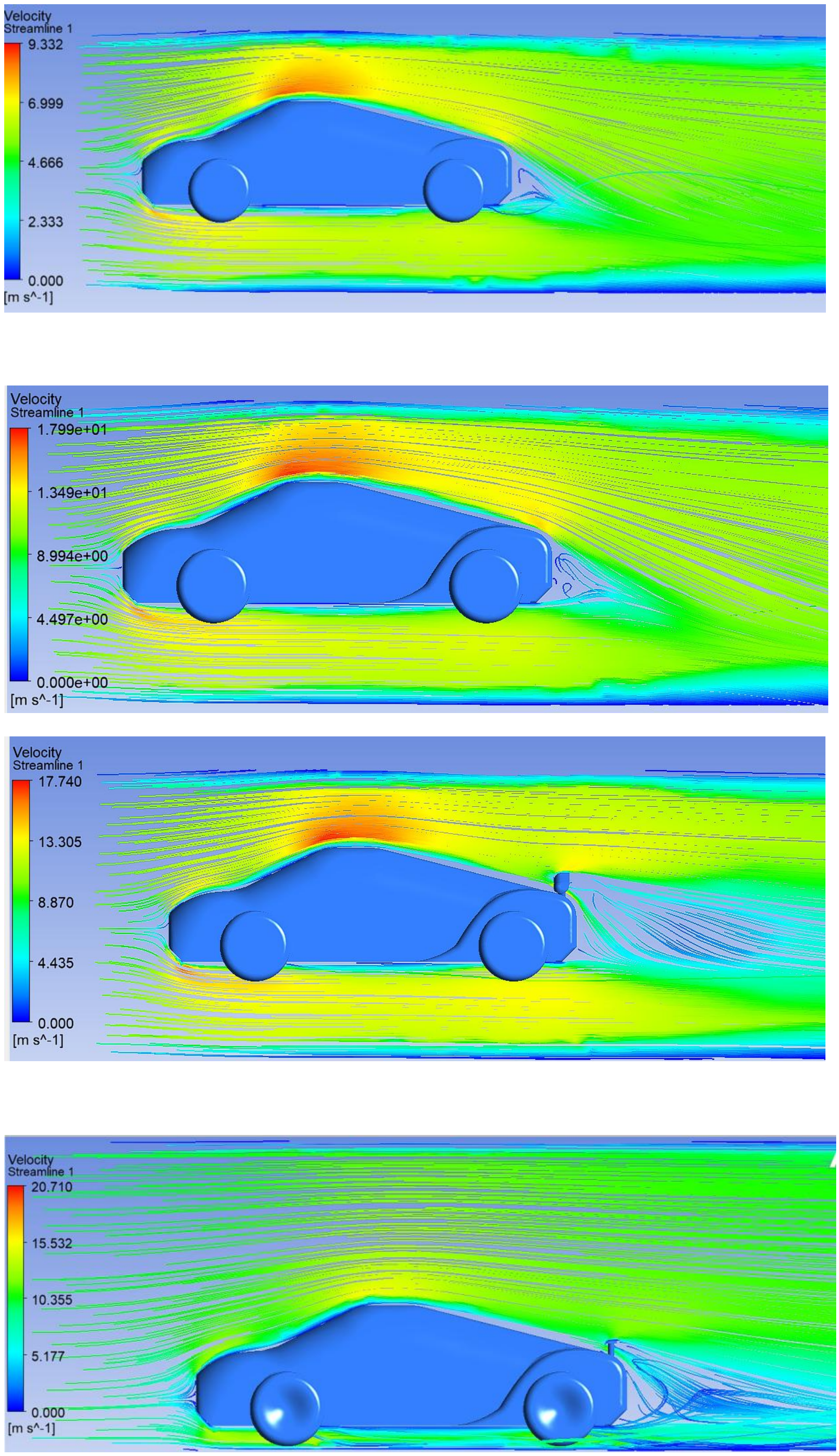


Figure 4. Velocity Streamline

The velocity contour plots demonstrate the flow acceleration and deceleration regions around the vehicle body. Non-Spoiler 1 and Non-Spoiler 2 exhibit large wake regions characterized by low-velocity recirculation behind the rear end. The broad wake indicates significant flow separation and high drag generation, which is consistent with the relatively high drag coefficients observed in these configurations. Spoiler 1 shows improved flow attachment near the rear deck, with reduced low-velocity zones. This suggests that Spoiler 1 effectively guides airflow downward, promoting wake contraction and reducing rear-end turbulence. However, some residual separation is still visible, indicating potential for further optimization. Spoiler 2 demonstrates the smallest wake region among all configurations, with a clear high-velocity core extending behind the vehicle. This streamlined flow indicates effective suppression of recirculation and enhanced base pressure recovery, directly contributing to its lowest drag coefficient and supporting improved fuel efficiency.

CONCLUSION

The aerodynamic analysis performed on four sedan configurations — two without spoilers, one with spoiler model 1, and one with spoiler model 2 — clearly demonstrates the significant influence of spoiler design on both drag and lift performance.

For drag characteristics, spoiler model 2 consistently achieved the lowest drag coefficient values across all tested speeds, resulting in an average reduction of approximately 19.8% compared to non-spoiler 1. This substantial decrease indicates enhanced aerodynamic efficiency, potentially contributing to improved fuel economy and higher maximum speeds.

In terms of lift behavior, spoiler model 1 recorded the lowest lift coefficient, with a minimum value of 0.22, effectively reducing lift force and thereby enhancing vehicle stability. Conversely, non-spoiler 2 exhibited the highest lift coefficient, reaching up to 1.19, which may compromise stability at high velocities.

Overall, the results confirm that spoiler model 2 is optimal for minimizing aerodynamic drag, while spoiler model 1 is most effective for reducing lift and improving ground adhesion. The selection of a spoiler should therefore be based on whether priority is given to reducing aerodynamic resistance or maximizing stability.

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