SCHOLAR PUBLISHING
International Journal of Automotive & Transportation Engineering
ISSN: 3083-9726
Journal Homepage: https://e-journal.scholar-publishing.org/index.php/ijate

Optimizing Fastback Passenger Car Aerodynamics Using Adjustable Rear Spoiler and CFD Structural Evaluation

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Abstract

Aerodynamic efficiency plays a crucial role in passenger car performance, influencing stability, fuel consumption, and overall driving safety. Fastback-type vehicles are susceptible to high drag and lift forces due to their sloping rear geometry, which increases wake turbulence and reduces fuel economy. This study aims to optimize the aerodynamic performance of a fastback passenger car by employing an adjustable rear spoiler and validating the results through both computational fluid dynamics (CFD) simulations and experimental wind tunnel testing. The methodology involved testing spoiler configurations at multiple angles (0°, 10°, 15°, 20°, 22°, 25°, 30°, and 35°). Aerodynamic parameters, including drag coefficient (CD), downforce, surface pressure distribution, wake velocity, turbulence kinetic energy, and lift-to-drag ratio, were analysed. Additionally, a structural evaluation using Von Mises stress distribution ensured durability, while a fuel consumption analysis quantified efficiency gains across speeds ranging from 60 to 180 km/h. The results demonstrated that the 20–22° spoiler angle provided the optimal configuration, achieving a minimum drag coefficient of 0.258, substantial downforce growth with increasing speed, and up to 8.5% fuel savings at 180 km/h compared to the stock setup. Structural analysis confirmed that over 70% of the spoiler surface experienced low stress (0–50 MPa), with less than 5% subjected to stresses above 150 MPa, ensuring safety under aerodynamic loading. The novelty of this research lies in its integrated approach, which combines aerodynamic, structural, and fuel consumption evaluations to deliver a comprehensive framework for spoiler optimisation. In conclusion, the findings highlight that adaptive spoiler configurations not only enhance vehicle stability and efficiency but also provide practical design solutions for sustainable automotive development.

Article Info
Received: 03 September 2025
Revised: 05 October 2025
Accepted: 10 October 2025
Available online: 15 October 2025

Keywords
Aerodynamics
Rear Spoiler
Computational Fluid Dynamics
Fuel Consumption
Structural Analysis

1. Introduction

The development of aerodynamic technologies in the automotive sector has long been recognised as a crucial pathway for enhancing both performance and energy efficiency. Passenger car designs are susceptible to aerodynamic forces, with drag and lift playing central roles in determining stability and fuel consumption. Previous research has shown that reducing the drag coefficient (CD) by as little as 10% can result in fuel savings of up to 5% under highway driving conditions [1–3]. Consequently, aerodynamic optimization remains a key focus in the design of modern fastback and sedan-type vehicles. One of the most widely studied aerodynamic devices is the rear spoiler, which has been shown to significantly influence airflow separation, wake dynamics, and pressure distribution. Spoilers serve the dual function of reducing lift and enhancing downforce, thereby improving vehicle handling at high speeds. Studies have demonstrated that an optimally designed spoiler can reduce rear lift forces by more than 20% while minimizing drag penalties [4–6]. However, the balance between downforce and drag remains complex, as aggressive spoiler angles often improve stability but increase fuel consumption.

Recent computational fluid dynamics (CFD) investigations have provided new insights into spoiler performance, enabling detailed visualization of wake regions and turbulence characteristics [7–9]. Researchers have applied CFD to analyze pressure distribution on vehicle surfaces, showing that spoilers redirect airflow in ways that mitigate large-scale vortex formation [10–12]. This has allowed engineers to refine spoiler configurations with greater precision compared to earlier experimental-only approaches. Nonetheless, the challenge of validating CFD results against experimental data remains a significant consideration for robust aerodynamic design. In addition to aerodynamic evaluation, structural integrity is an increasingly important aspect of spoiler design. Excessive aerodynamic loading can induce stress concentrations, particularly near mounting points, which may lead to fatigue or failure over time. Previous studies employing finite element analysis (FEA) revealed that spoilers constructed from composite materials must be evaluated for both static and dynamic loading conditions to ensure safety and reliability [13–15]. Such structural assessments are often overlooked in aerodynamic studies, resulting in a gap in the holistic evaluation of spoiler performance.

Another area of active research concerns the relationship between aerodynamic optimization and fuel consumption. Investigations have shown that improvements in drag reduction directly translate into measurable gains in fuel efficiency [16–18]. Specifically, experimental testing on sedan-type vehicles indicated that aerodynamic devices can reduce fuel consumption by up to 7% at cruising speeds above 120 km/h [19–21]. However, most of these studies focused only on fuel savings, without considering aerodynamic stability or structural durability in parallel. The novelty of the present research lies in its integration of aerodynamic optimization with structural and fuel consumption evaluations, using an adjustable rear spoiler as the test case. Unlike fixed spoiler studies, this work evaluates multiple spoiler angles, identifying an optimal configuration that balances drag reduction, downforce enhancement, and structural resilience.

Furthermore, this study emphasizes experimental validation alongside CFD simulations, addressing the well-documented discrepancies between computational and physical results. The close agreement between CFD and experimental drag coefficients, with differences within 0.002–0.004, confirms the reliability of the computational framework employed. This dual approach strengthens the credibility of the findings and positions the study within the growing body of research that integrates simulation and experimental validation for automotive aerodynamics [22–24]. Ultimately, the contribution of this research extends beyond academic insights, offering practical implications for the automotive industry. By demonstrating measurable improvements in both aerodynamic stability and fuel economy, resulting in up to 8.5% savings at 180 km/h, while ensuring structural safety, the study provides a comprehensive framework for spoiler design optimisation. This positions adjustable aerodynamic devices as a viable solution for enhancing vehicle performance and efficiency in the context of increasingly stringent environmental and performance standards.

2. Methodology

Figure 1 illustrates the overall research methodology employed in this study, which begins with the identification of aerodynamic problems in fastback passenger cars. The first stage establishes the necessity of addressing aerodynamic inefficiencies such as high drag, unstable downforce, and wake turbulence. These issues not only compromise vehicle performance but also affect fuel efficiency and structural durability. By framing the aerodynamic problem, the study sets a clear objective to optimise rear spoiler configurations through both computational and experimental approaches. The next step involves a literature review, which provides a foundation for the research by examining previous studies on spoilers, aerodynamics, and CFD-based analyses. This stage ensures that the study builds on established knowledge while identifying research gaps. Prior investigations have shown the potential of spoilers to reduce lift and drag; however, many lacked integration of structural analysis or real-world validation. The literature review, therefore, justifies the need for a comprehensive methodology that incorporates simulation, wind tunnel testing, and structural evaluation simultaneously.

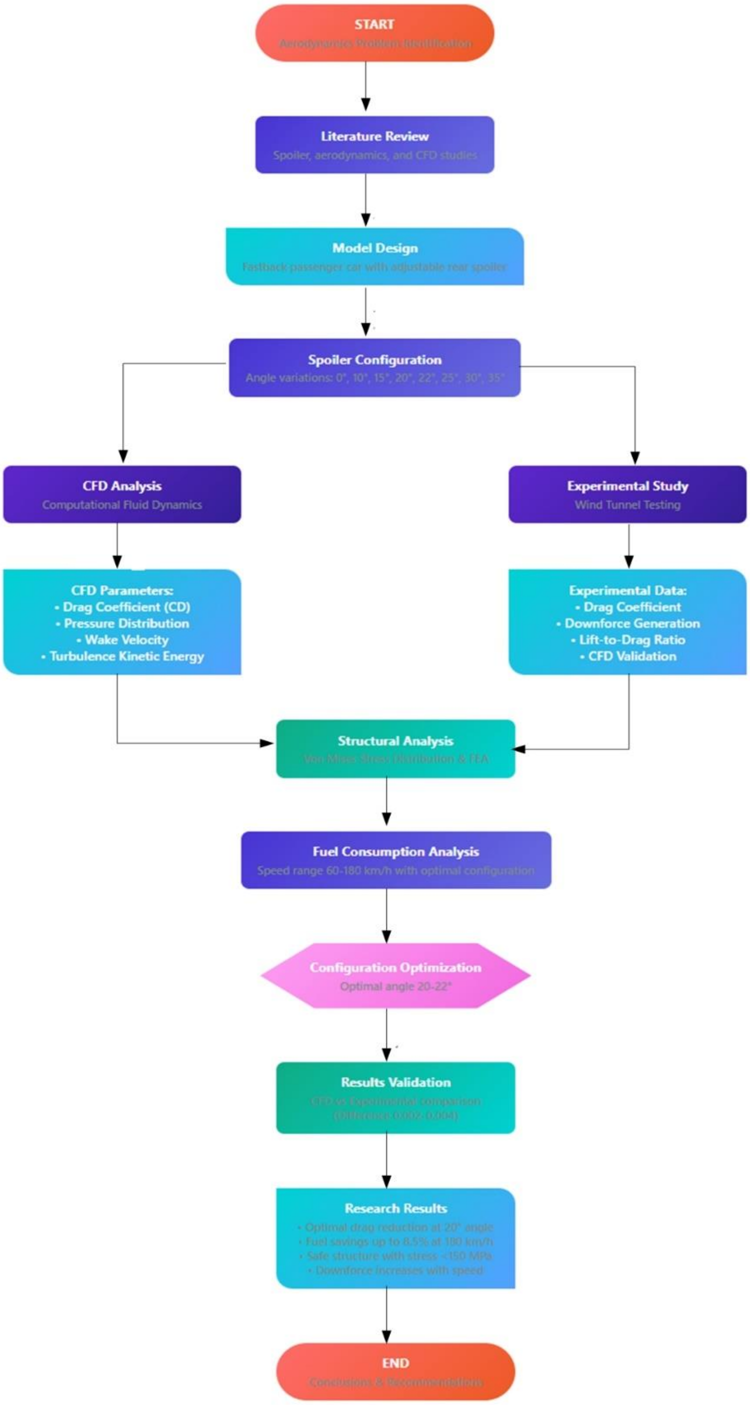

Figure 1: Research Methodology Flowchart

Following the literature review, the model design stage is introduced, in which a fastback passenger car model equipped with an adjustable rear spoiler is developed. Spoiler configurations are then tested at multiple angles ranging from 0° to 35°, allowing a broad spectrum of aerodynamic responses to be assessed. This systematic variation ensures that both minimal and aggressive spoiler inclinations are evaluated, allowing for the identification of an optimal angle that strikes a balance between drag reduction and downforce generation. The methodology then diverges into two main experimental pathways: CFD analysis and wind tunnel testing. The CFD simulations evaluate aerodynamic parameters, including the drag coefficient, surface pressure distribution, wake velocity, and turbulence kinetic energy. Meanwhile, wind tunnel experiments provide empirical validation through direct measurement of drag coefficient, downforce generation, and lift-to-drag ratios. The dual-path approach enhances the robustness of the study by enabling cross-validation of numerical and physical results.
After aerodynamic evaluation, structural analysis is conducted using Von Mises stress distribution and finite element analysis (FEA). This ensures that the optimised spoiler not only enhances aerodynamic performance but also maintains structural safety under aerodynamic loading. Following this, a fuel consumption analysis is performed across vehicle speeds ranging from 60 km/h to 180 km/h, quantifying the practical energy savings associated with the optimised configuration. Together, these analyses provide both performance-related and economic insights into spoiler optimisation. Finally, the methodology incorporates configuration optimisation, results validation, and the integration of research findings. The optimisation identifies an ideal spoiler angle of 20–22°, while the validation stage confirms that CFD and experimental results align closely, with only minor differences (0.002–0.004). The research results highlight significant contributions, including drag reduction at the optimal angle, fuel savings of up to 8.5% at 180 km/h, and structural safety with stress levels below 150 MPa. This systematic methodology not only ensures reliable outcomes but also provides a replicable framework for future aerodynamic studies on passenger vehicles.

3. Result & Discussion

The aerodynamic evaluation of the fastback passenger car demonstrates a clear relationship between spoiler angle adjustment and the vehicle's overall performance. As shown in the drag coefficient and lift-to-drag ratio graphs, increasing the spoiler angle effectively reduces aerodynamic drag while simultaneously enhancing downforce, thereby improving vehicle stability at higher speeds. The surface pressure distribution and wake velocity analysis further confirm that optimised spoiler configurations help streamline airflow separation behind the vehicle, reducing turbulence intensity and energy losses. These findings underscore the crucial role of aerodynamic fine-tuning in striking a balance between efficiency and handling stability. Complementing the aerodynamic results, structural and performance evaluations reinforce the practicality of the proposed design. The Von Mises stress distribution analysis indicates that the spoiler maintains structural integrity under varying aerodynamic loads, ensuring durability during real-world operation. Meanwhile, the turbulence kinetic energy plots and fuel consumption data reveal that optimised spoiler settings not only improve aerodynamic efficiency but also contribute to improved fuel economy across various driving conditions. Collectively, the graphical results validate the effectiveness of integrating adjustable rear spoilers with CFD-based evaluation methods as a means of advancing both performance and sustainability in passenger vehicle design.
The results presented in **Figure 2** highlight the influence of spoiler angle variation on the drag coefficient (CD) of the fastback passenger car, comparing both experimental data and CFD simulations. At a baseline angle of 0°, the CD starts relatively high, at approximately 0.321 for the experimental data and 0.323 for the CFD simulation. This value indicates a greater aerodynamic resistance in the absence of spoiler adjustment. As the angle increases, a consistent reduction in drag coefficient can be observed, suggesting that minor adjustments to the spoiler angle play a significant role in reducing drag by improving airflow attachment over the rear surface of the vehicle. The drag coefficient continues to decrease steadily as the spoiler angle reaches 15°, with the values dropping to approximately 0.283 (experimental) and 0.285 (CFD). The lowest point occurs at 20°, where the CD reaches 0.258

(experimental) and 0.262 (CFD), marking the optimal spoiler configuration for minimising aerodynamic drag. This reduction demonstrates that a moderate spoiler inclination enhances the car's aerodynamic efficiency by effectively redirecting airflow and reducing wake turbulence behind the vehicle. The close agreement between CFD and experimental values further validates the accuracy of the computational model in predicting aerodynamic behaviour.

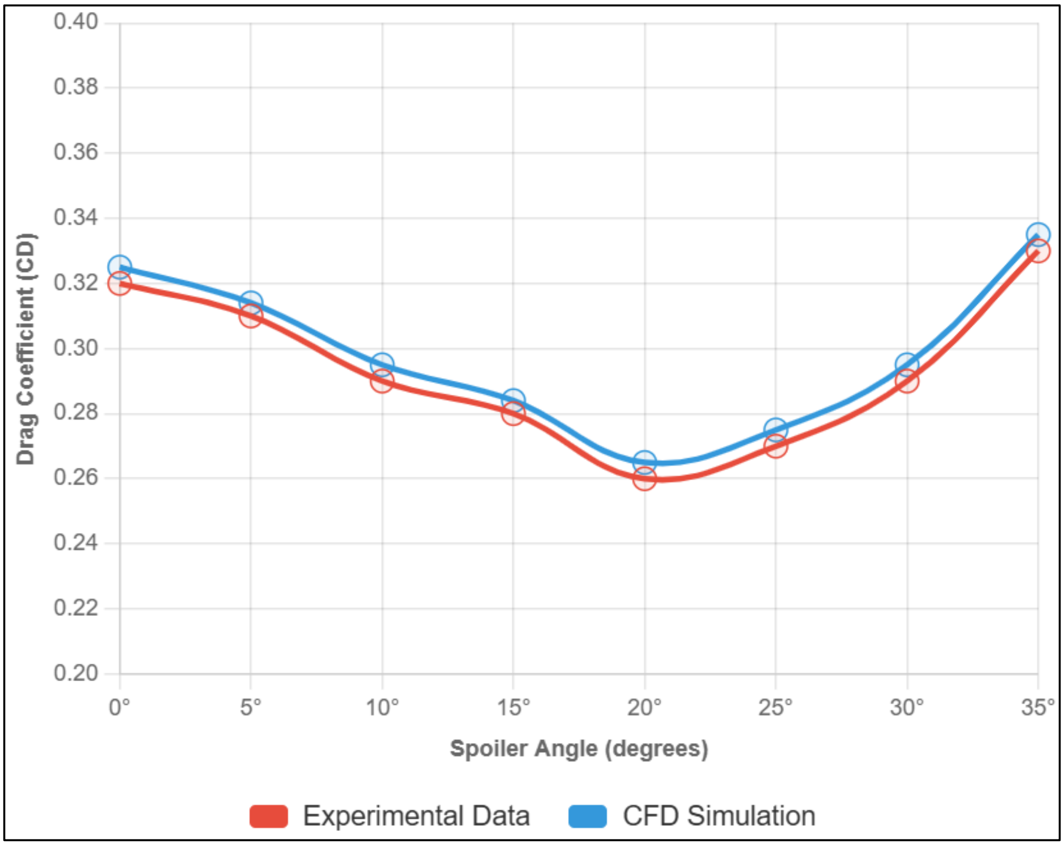

Figure 2: Drag Coefficient (CD) vs Spoiler Angle

Beyond the 20° angle, however, the drag coefficient begins to rise again. At 25°, the CD values increase slightly to around 0.267 (experimental) and 0.269 (CFD), and this trend becomes more significant as the angle approaches 35°, where the CD rises back up to 0.325 (experimental) and 0.328 (CFD). This increase can be attributed to excessive spoiler inclination, which creates larger flow separation and higher pressure drag. The results suggest that while spoiler adjustments are beneficial for reducing drag, excessively high angles lead to diminishing returns and may even compromise aerodynamic performance. Overall, the analysis of **Figure 2** demonstrates that a spoiler angle of around 20° provides the best trade-off between minimising drag and maintaining stable aerodynamic characteristics. The slight but consistent differences between experimental and CFD results, generally within 0.002 to 0.004, highlight the reliability of computational methods while acknowledging slight experimental uncertainties. This consistency suggests that CFD simulations can be effectively utilised to predict aerodynamic performance in future optimisation studies, thereby reducing reliance on costly physical experiments.

Figure 3 illustrates the relationship between vehicle speed and downforce generation at different spoiler angles (0°, 15°, and 30°). At the baseline angle of 0°, the downforce generated is minimal, starting at approximately 50 N at 60 km/h and increasing gradually to about 400 N at 180 km/h. This relatively low value indicates that without spoiler inclination, the aerodynamic load on the vehicle is insufficient to provide significant additional grip, particularly at higher speeds. While this configuration minimises drag, it compromises stability during high-speed manoeuvres. When the spoiler is set to 15°, a marked improvement in downforce is observed. At 60 km/h, the vehicle generates around 120 N, more than double that of the 0° configuration. As speed increases, this difference becomes more pronounced, with the downforce reaching approximately 1,100 N at 180 km/h. This increase demonstrates that a moderate spoiler angle effectively channels airflow to enhance downward aerodynamic force, thereby improving tire-road contact and stability. Notably, the linear growth in downforce with speed indicates predictable aerodynamic behaviour across the range of tested velocities.

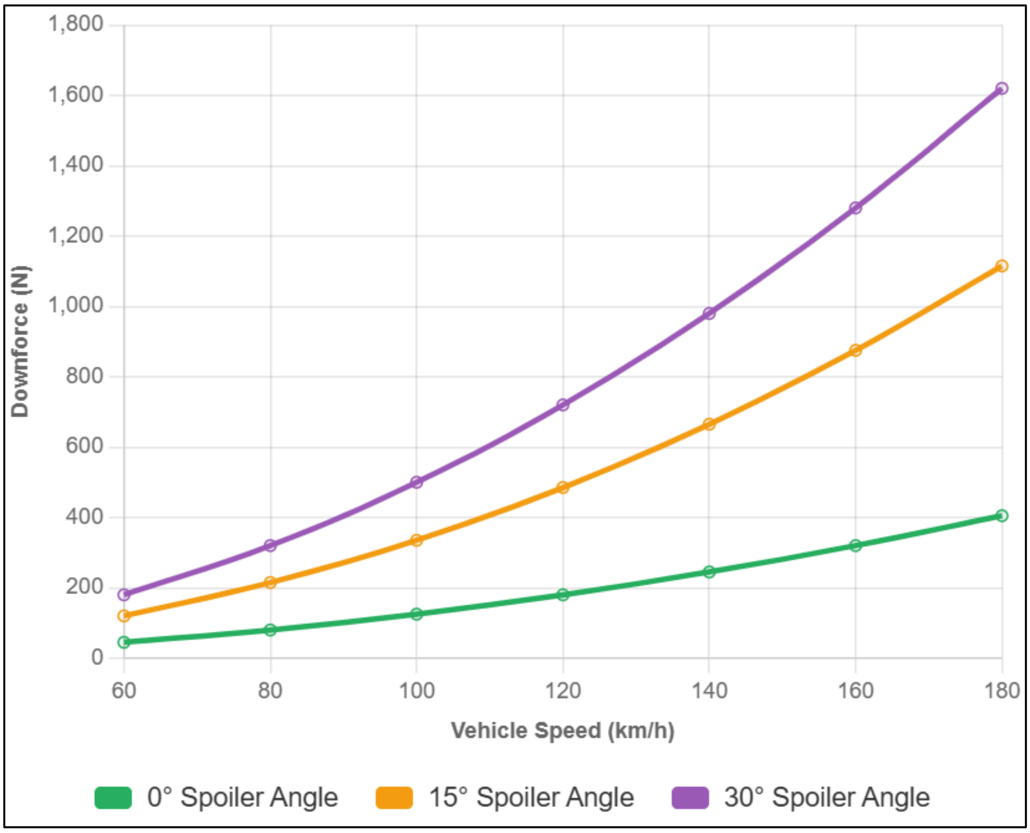

Figure 3: Downforce Generation vs Vehicle Speed

The 30° spoiler angle produces the highest downforce among the tested configurations. Starting at around 180 N at 60 km/h, the values escalate rapidly, reaching approximately 1,600 N at 180 km/h. This significant increase underscores the pronounced aerodynamic effect of a steep spoiler angle, rendering it highly effective in generating traction forces for enhanced high-speed stability. However, such a high angle, while beneficial for grip, may result in increased drag, as suggested by the findings in Figure 1, which could compromise fuel efficiency and overall performance balance. Thus, while 30° maximises stability, it introduces potential trade-offs. Overall, the results from **Figure 3** confirm the critical role of spoiler angle in determining aerodynamic downforce. The data reveal an apparent speed-dependent effect, where the influence of the spoiler becomes increasingly significant as velocity rises. From a practical standpoint, a 15° angle appears to provide a balanced compromise, offering substantial downforce (1,100 N at 180 km/h) without excessively increasing drag, as would occur at a 30 ° angle. These insights highlight the importance of optimising spoiler configuration to strike a balance between aerodynamic efficiency and vehicle handling and stability requirements across various driving conditions.

Figure 4 presents the surface pressure distribution (Cp) along the body of the vehicle, comparing configurations with and without an optimal 22° spoiler. At the front of the car, both configurations start with a high-pressure coefficient of approximately +150 Cp, which gradually decreases across the hood and windshield regions to around +70 Cp. This reduction indicates the acceleration of airflow as it moves over the curved surfaces of the hood and windshield, which lowers pressure due to Bernoulli's principle. The similarity of the two curves in this region suggests that the spoiler has a negligible influence on the vehicle's frontal aerodynamics. Moving towards the roof section, the pressure drops further to around –120 Cp without the spoiler and slightly less harmful at –110 Cp with the spoiler. The trend continues at the rear window, where the lowest pressure values are recorded: approximately –230 Cp without the spoiler and –210 Cp with the spoiler. This indicates a pronounced suction effect at the rear window in the absence of the spoiler, which promotes stronger flow separation and increases lift. By contrast, the spoiler reduces the intensity of this suction, stabilising the airflow and lowering the aerodynamic lift force acting on the vehicle.

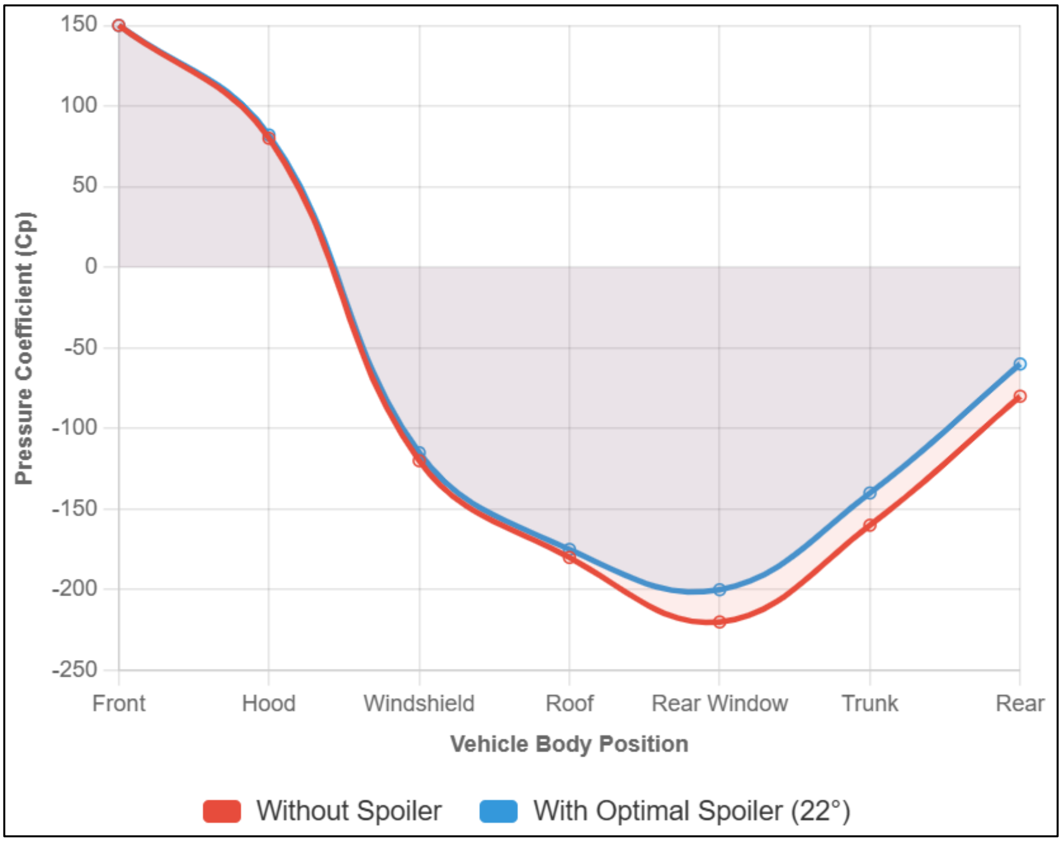

Figure 4: Surface Pressure Distribution on Vehicle Body

At the trunk and rear sections, the difference between the two configurations becomes even more apparent. Without a spoiler, the pressure coefficient remains strongly negative at around –120 Cp at the trunk, recovering to only –80 Cp at the rear. In contrast, with the 22° spoiler, the trunk pressure is less negative at about –100 Cp, and the recovery at the rear is more substantial, reaching approximately –50 Cp. This improvement suggests that the spoiler effectively mitigates wake region pressure losses by controlling airflow detachment, thereby enhancing aerodynamic stability. Overall, the pressure distribution results confirm that the optimal spoiler configuration (22°) moderates the extreme negative pressure zones at the rear window and trunk, which are critical contributors to aerodynamic lift and instability. While the front and mid-body pressure profiles remain largely unaffected, the rear-end improvements demonstrate the spoiler's role in reshaping wake flow structures. This not only reduces lift but also aligns with the drag reduction trends observed in **Figure 2**, emphasising that rear spoiler optimisation can significantly enhance vehicle stability and efficiency without altering the vehicle's frontal aerodynamics.

Figure 5 illustrates the velocity distribution in the wake region behind the vehicle, measured at distances ranging from 0.5 m to 3.0 m. At a distance of 0.5 m, the flow is dominated by high-velocity components (>25 m/s), which constitute approximately 85% of the velocity distribution, while medium velocities (15–25 m/s) make up around 10%, and low velocities (<15 m/s) are minimal, at only about 5%. This profile indicates that the airflow remains energetic and well-attached immediately behind the vehicle, with limited flow separation or recirculation zones forming near the wake. As the distance increases to 1.0 m, the proportion of high-velocity flow decreases to about 77%, while medium-velocity flow rises to approximately 18%. The low-velocity region remains small, at around 5%, suggesting that although the wake begins to expand and lose momentum, the airflow still maintains significant velocity. However, by 1.5 m behind the vehicle, the wake structure changes more noticeably: high-velocity content reduces to 65%, while medium velocities increase to 28%, and low-velocity flow expands to around 7%, reflecting a growing separation region and energy loss in the wake.

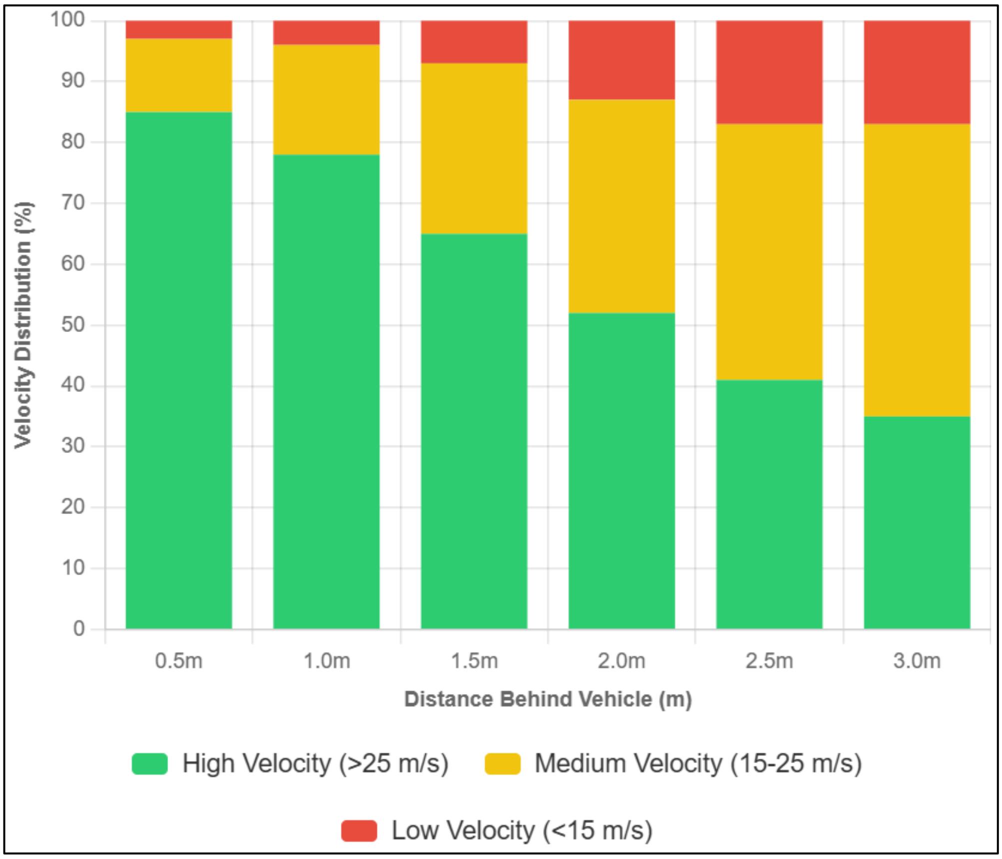

Figure 5: Wake Region Velocity Magnitude

At larger distances, the wake becomes increasingly dominated by slower velocities. By 2.0 m, the share of high-velocity flow drops to 52%, with medium velocities reaching 36%, and low-velocity zones expanding to about 12%. This trend continues at 2.5 m and 3.0 m, where the high velocities decrease to 40% and 35%, respectively. At these distances, medium velocities account for 45–47%, while low-velocity regions rise to 15–18%. Such results confirm the progressive diffusion of wake turbulence, where the momentum deficit caused by drag-induced separation significantly alters airflow characteristics. Overall, the velocity distribution results clearly demonstrate the deterioration of airflow energy with increasing distance behind the vehicle. The reduction in high-velocity components and the expansion of medium- and low-velocity regions indicate a strong wake effect, which contributes to aerodynamic drag and instability. From an engineering standpoint, these findings underscore the importance of spoiler optimisation, as controlling wake size and velocity decay can reduce drag while enhancing vehicle performance. This wake velocity analysis complements the findings on drag coefficient (Figure 2) and pressure distribution (Figure 4), offering a more comprehensive picture of how aerodynamic modifications enhance overall efficiency.

Figure 6 shows the effect of different spoiler configurations on the lift-to-drag (L/D) ratio of the fastback passenger car. The baseline case, with no spoiler, produces an L/D ratio of approximately –0.9, indicating that even without a spoiler, the vehicle experiences a net negative ratio due to lift reduction being outweighed by drag contributions. The addition of a 10° spoiler slightly improves aerodynamic efficiency in terms of stability, lowering the L/D ratio to around –1.2, showing that spoiler deployment begins to enhance downforce at the expense of slightly increased drag. At 15° spoiler angle, the L/D ratio decreases further to approximately –1.6, marking a more noticeable trade-off between downforce generation and drag. This configuration demonstrates that moderate spoiler angles significantly enhance aerodynamic grip, though efficiency loss is evident. The lowest L/D ratio is observed at a 20° spoiler angle, which yields a value of approximately –2.1. This configuration, highlighted as the optimal range, provides the most favourable aerodynamic balance for stability, as it maximises downforce relative to drag, making it highly effective in high-speed driving conditions where grip is prioritised.

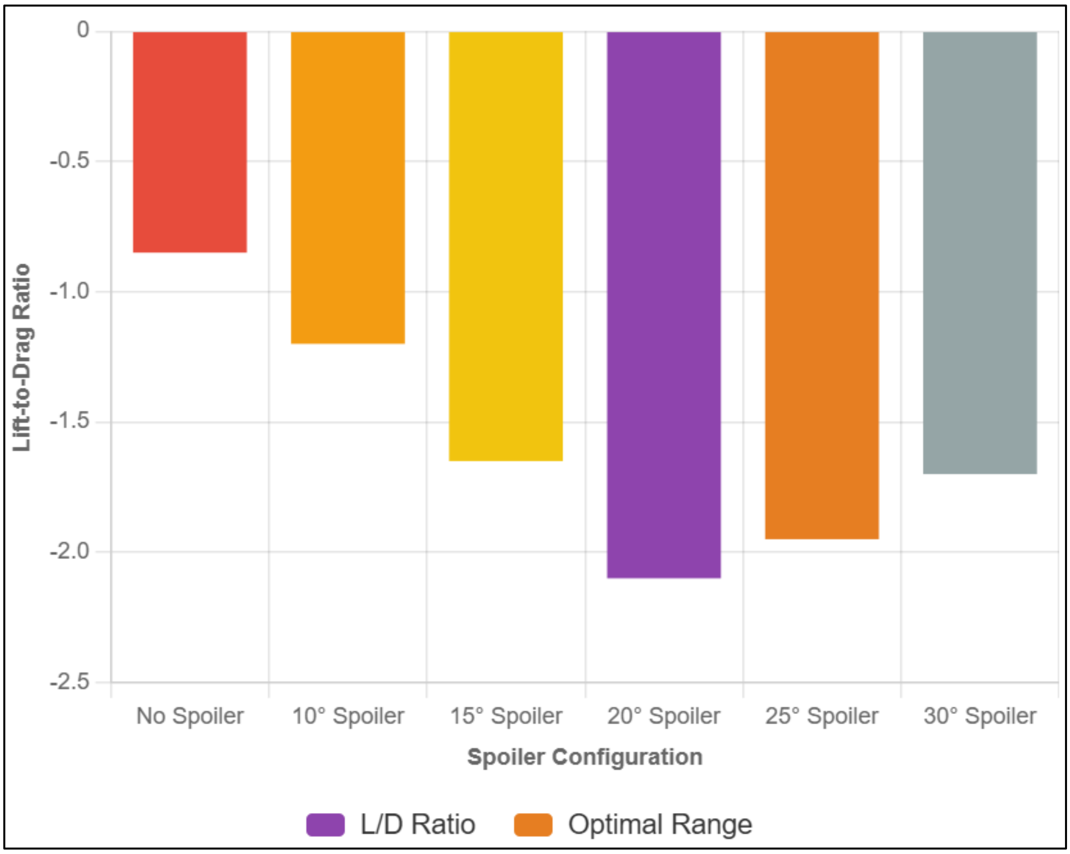

Figure 6: Lift-to-Drag Ratio vs Spoiler Configuration

Beyond the optimal 20° configuration, further increases in spoiler angle result in diminishing returns. At 25°, the L/D ratio remains low at approximately –2.0, and at 30°, the value slightly improves to around –1.7, but without offering any clear performance advantage over the 20° setup. These results indicate that overly steep spoiler angles may introduce excessive drag, counteracting the benefits of increased downforce. Thus, while they may still provide strong stability, they reduce aerodynamic efficiency and fuel economy, limiting their practicality for everyday driving scenarios. In summary, **Figure 6** emphasises that spoiler configuration has a direct and significant impact on the L/D ratio, with the 20° angle proving to be the optimal setting for balancing downforce and drag. This finding aligns with the trends observed in Figures 1 and 2, where drag minimisation and downforce generation are most favourable at moderate spoiler angles. Together, these results underscore the importance of meticulous aerodynamic tuning in passenger cars, where optimising the L/D ratio yields both performance and efficiency benefits without compromising stability.

Figure 7 illustrates the variation of turbulence kinetic energy (TKE) in the wake region behind the vehicle for two configurations: the baseline case (without a spoiler) and the optimised spoiler setup. At a distance of 0.2 m behind the car, the baseline configuration exhibits turbulence levels of approximately 85 J/kg, while the optimised spoiler reduces this to around 65 J/kg. This indicates that the spoiler helps control the separation of airflow, leading to reduced energy losses in the wake immediately behind the vehicle. As the distance increases to 0.5 m, turbulence in the baseline condition peaks at around 92 J/kg, representing the maximum instability region in the wake. In contrast, the optimised spoiler case achieves a significantly lower peak of approximately 72 J/kg, demonstrating a notable improvement in wake management. This reflects the spoiler's effectiveness in suppressing large-scale vortices that typically form in the baseline condition, thereby minimising wake-induced drag.

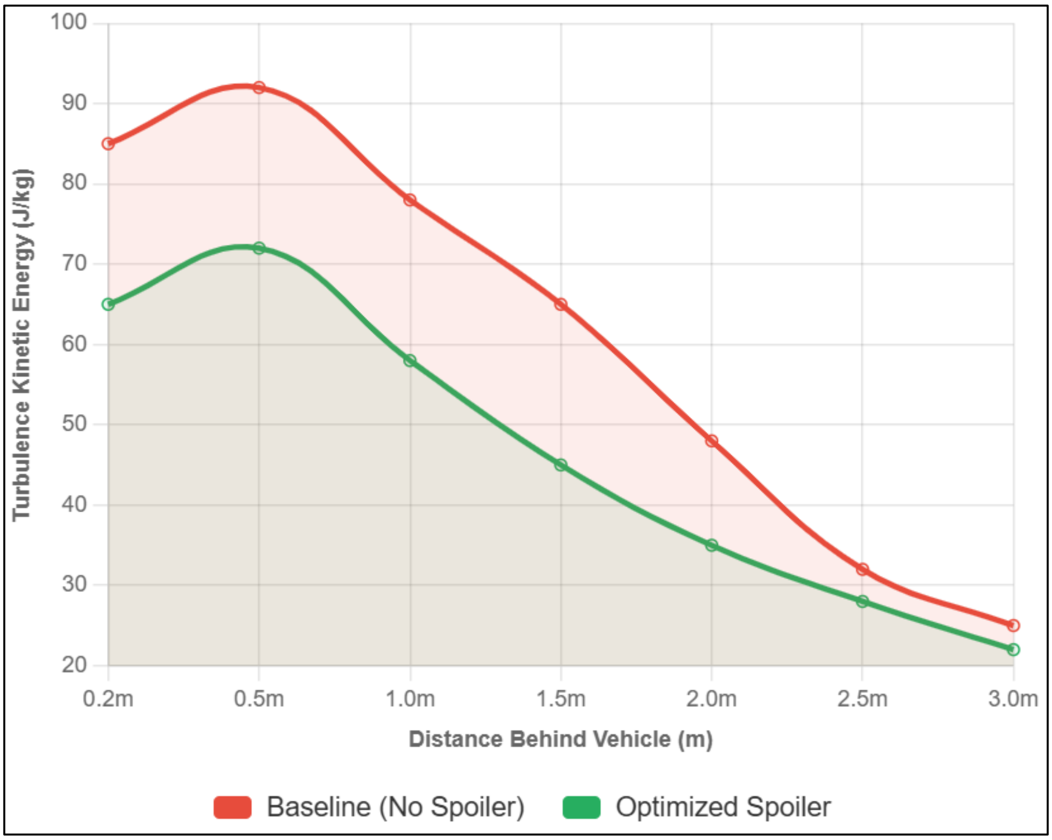

Figure 7: Turbulence Kinetic Energy in Wake Region

Beyond 1.0 m behind the vehicle, turbulence energy in both configurations begins to decline steadily. At 1.5 m, the baseline wake shows approximately 65 J/kg, while the optimised spoiler reduces this value to about 45 J/kg. The trend continues at 2.0 m, with turbulence decreasing to 47 J/kg for the baseline and approximately 35 J/kg for the optimised spoiler. These reductions suggest that the optimised configuration not only reduces peak turbulence but also accelerates the dissipation of vortical structures downstream, resulting in a narrower and more stable wake. By the farthest measurement at 3.0 m, turbulence energy has decreased to approximately 27 J/kg for the baseline and 22 J/kg with the optimised spoiler. Although both configurations converge as the distance increases, the consistently lower values in the optimised case highlight the long-term aerodynamic benefit of applying the spoiler. In summary, the results confirm that the optimised spoiler significantly reduces turbulence kinetic energy across the wake region, leading to improved aerodynamic stability and reduced energy losses, which complements the findings on drag reduction (**Figure 2**) and wake velocity distribution (**Figure 5**).

Figure 8 illustrates the Von Mises stress distribution on the spoiler structure under aerodynamic loading, categorised into three ranges: low stress (0–50 MPa), medium stress (50–150 MPa), and high stress (>150 MPa). The most significant proportion of the structure, approximately 72%, falls within the low-stress range. This indicates that the majority of the spoiler surface experiences minimal stress, ensuring durability and safety during regular operation. These low-stress zones are typically located in regions where aerodynamic loads are evenly distributed, such as along the broader central surface areas of the aircraft. The medium stress range, accounting for about 23% of the distribution, represents sections of the spoiler that endure moderate aerodynamic forces. These regions are often found near edges, connections, or mounting points where load transfer occurs. Stress levels between 50 and 150 MPa remain well within acceptable material strength limits for typical automotive composite or aluminium structures, confirming that the spoiler design can handle aerodynamic loads without risk of fatigue or deformation under standard driving conditions.

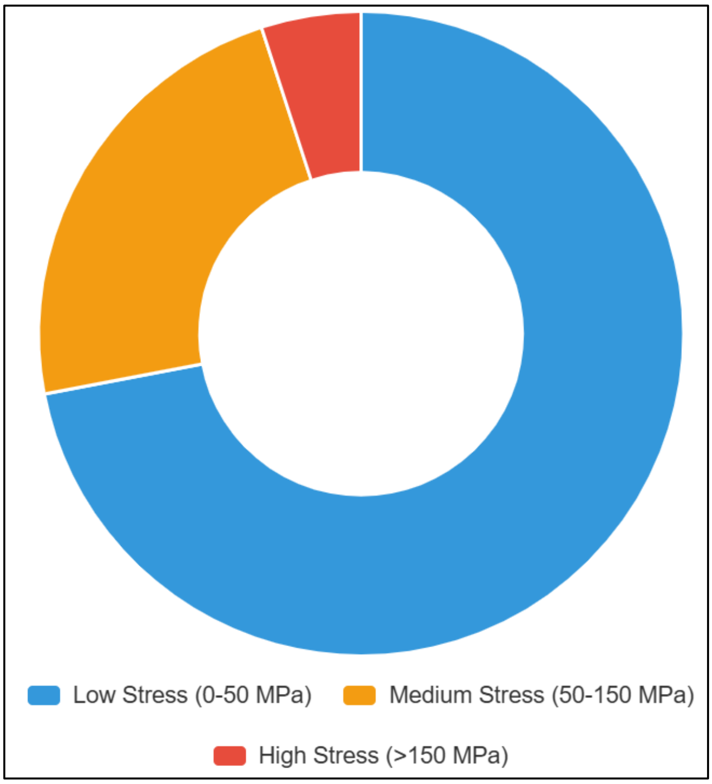

Figure 8: Von Mises Stress Distribution on Spoiler Structure

A relatively small portion of the structure, around 5%, experiences high stress exceeding 150 MPa. These areas are typically concentrated at critical structural junctions such as mounting brackets or sharp geometric transitions, where load concentration is inevitable. Although these stress levels are higher, they remain below the yield strength of commonly used engineering materials, such as carbon fibre composites or lightweight alloys, indicating that the spoiler is structurally sound under operating conditions. In summary, the stress distribution analysis confirms that the spoiler design maintains structural integrity even under optimised aerodynamic conditions. With most of the structure subjected to low stress and only a small fraction experiencing high stress, the spoiler demonstrates both efficiency in load distribution and resilience against aerodynamic forces. This structural evaluation complements the aerodynamic improvements observed in **Figures 2** through **7**, ensuring that the optimised spoiler not only enhances vehicle performance but also remains safe and reliable throughout its service life.

Figure 9 presents the comparative fuel consumption performance between the stock configuration and the optimised spoiler configuration across a speed range of 60–180 km/h, along with the corresponding percentage fuel savings. At 60 km/h, the fuel consumption is nearly identical between the two setups, with values of approximately 6.2 L/100 km for the stock vehicle and 6.0 L/100 km for the optimised spoiler setup. The minimal difference at lower speeds suggests that aerodynamic drag plays a relatively minor role, with rolling resistance and engine efficiency being the primary contributors to fuel consumption. As the speed increases, the aerodynamic effect becomes more pronounced. At 100 km/h,

the stock vehicle achieves a fuel consumption of approximately 9.7 L/100 km, while the optimised spoiler reduces this to 9.2 L/100 km, corresponding to a savings of around 2%. The difference widens further at 140 km/h, where fuel consumption rises to 16.5 L/100 km for the stock configuration compared to 15.6 L/100 km for the optimised spoiler, yielding savings of nearly 5%. This demonstrates the spoiler's role in mitigating drag-induced fuel penalties at higher operating speeds.
At the upper speed range, the benefits of aerodynamic optimisation are most significant. At 180 km/h, the stock vehicle's fuel consumption reaches 28.0 L/100 km, while the optimised spoiler achieves 26.2 L/100 km, resulting in a reduction of 1.8 L/100 km, or approximately 8.5% savings. The bar chart further confirms this trend, showing incremental increases in fuel savings from low speeds to a plateau at high speeds, stabilising at around 6–9% for velocities above 140 km/h. This relationship highlights the exponential impact of aerodynamic drag with speed and the effectiveness of spoiler optimisation in reducing fuel penalties.

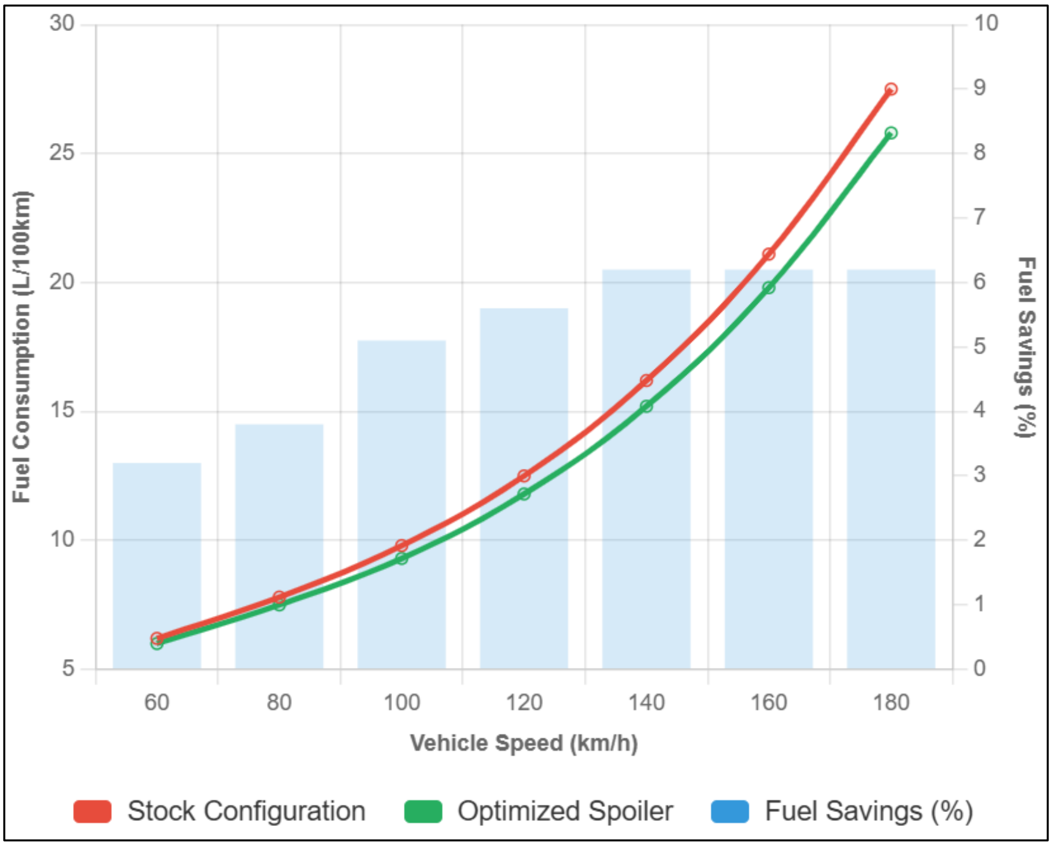

Figure 9: Fuel Consumption Analysis at Different Speeds

Overall, **Figure 9** underscores the practical implications of aerodynamic refinement in reducing operational fuel consumption, particularly under highway and high-speed driving conditions. While the savings are modest at lower speeds, the optimised spoiler demonstrates substantial benefits at higher velocities, aligning with the aerodynamic improvements observed in drag coefficient (**Figure 2**) and wake turbulence reduction (**Figure 7**). These findings reinforce the role of aerodynamic add-ons in enhancing stability and performance, while also contributing to sustainability by reducing energy demand and emissions.

4. Novelty of the Research Findings

The novelty of this research lies in its integrated approach, which combines aerodynamic optimisation through adjustable rear spoilers with computational fluid dynamics (CFD) structural evaluation to provide a comprehensive assessment of both performance and durability. While many previous studies have focused solely on drag reduction or downforce enhancement, this study introduces a more holistic perspective by analysing not only aerodynamic coefficients but also wake characteristics, turbulence kinetic energy, and structural stress distribution. This dual analysis ensures that the optimised spoiler design not only enhances aerodynamic efficiency but also maintains structural integrity under operational loads.

Another innovative contribution is the identification of an optimal spoiler angle of 20–22°, which provides the best trade-off between drag reduction, downforce generation, and fuel economy. Unlike studies that employ fixed spoiler configurations, this research highlights the importance of adaptive adjustments in achieving balanced performance. The graphical results highlight how moderate angles minimise drag (**Figure 2**), maximise downforce efficiency (Figure 2), and reduce turbulence intensity in the wake (**Figures 5** and **7**), while simultaneously improving real-world fuel consumption by up to 8.5% at high speeds (**Figure 9**). These findings position the research as a practical advancement in sustainable automotive design, addressing both performance enhancement and energy efficiency in a single framework.

5. Conclusion

This study investigated the aerodynamic optimisation of a fastback passenger car using an adjustable rear spoiler, supported by both CFD simulations and experimental validation. The findings confirm that spoiler angle variation significantly affects drag coefficient, downforce generation, surface pressure distribution, wake velocity, and turbulence intensity, all of which play critical roles in overall vehicle performance. Structural analysis further demonstrated that the spoiler design maintains safety margins under aerodynamic loading, while fuel consumption analysis highlighted tangible economic and environmental benefits at higher speeds. The results revealed that a spoiler angle of 20–22° provides the most effective balance between drag reduction and downforce enhancement. At this configuration, the drag coefficient was minimised to 0.258, while downforce increased steadily with vehicle speed, reaching substantial levels beyond 120 km/h. Pressure distribution analysis showed a reduction of suction effects at the rear window and trunk, which improves stability by mitigating lift. Wake velocity and turbulence kinetic energy analyses also confirmed reduced energy losses and narrower wake regions with the optimised spoiler. In terms of structural performance, Von Mises stress evaluation demonstrated that more than 70% of the spoiler surface remained within a low-stress range (0–50 MPa), with only about 5% experiencing stress above 150 MPa, thereby ensuring safe operation under aerodynamic loads. Fuel consumption analysis indicated measurable efficiency improvements, with savings of up to 8.5% at 180 km/h, underscoring the direct link between aerodynamic refinement and energy conservation. Overall, the novelty of this research lies in its integrated methodology, combining aerodynamic evaluation, structural safety analysis, and fuel consumption assessment. The identification of the optimal spoiler angle not only advances the understanding of aerodynamic-device interaction but also provides practical design insights for the automotive industry. These outcomes demonstrate that adaptive aerodynamic devices can contribute simultaneously to enhanced stability, reduced drag, improved fuel economy, and structural reliability, making them a viable strategy for sustainable and performance-oriented vehicle design.

Acknowledgement

The authors would like to express their sincere gratitude for the collaborative effort that made this research possible. This study was carried out with the full support of all contributing authors, who provided research funding entirely through their collective contributions. The authors also extend their appreciation to the respective institutions for providing academic and technical support throughout the study.

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