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Wind Tunnel Investigation of Passive Spoiler Influence on Drag Characteristics of a 25° Ahmed Body

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Abstract. *Improving vehicle aerodynamic performance is a key strategy for reducing fuel consumption and carbon emissions in the transportation sector. Among various aerodynamic factors, pressure drag generated by flow separation behind bluff bodies plays a dominant role in total drag. This study experimentally investigates the effect of a small rear lip as a passive flow control device on the wake structure and drag coefficient (Cd) of a 0.2-scale 25° Ahmed body model under low to medium Reynolds number conditions. Wind tunnel experiments were conducted at free-stream velocities of 8 m/s, 10 m/s, and 12.5 m/s. Drag forces were directly measured using a load measurement system, while velocity distributions in the wake region were captured using hot-wire anemometry. The results show that increasing velocity intensifies the wake structure and strengthens longitudinal vortices without eliminating flow separation. The addition of the small rear lip modifies the shear layer development and redistributes momentum in the wake region. At higher velocities, the passive device produces a more stabilized downstream flow pattern and smoother velocity gradients, indicating potential improvements in base pressure recovery. However, wake size reduction is not always directly proportional to drag reduction. These findings demonstrate that simple geometric modifications can influence wake dynamics under laboratory-scale conditions and provide empirical insight into passive aerodynamic optimization for energy-efficient vehicle design.*

Keywords: *Ahmed body, passive spoiler, wake structure, drag coefficient, wind tunnel*

INTRODUCTION

The increase in global carbon emissions and the rise in fossil fuel consumption have made vehicle energy efficiency a strategic issue in the modern automotive industry. The transportation sector contributes significantly to total global CO_2 emissions, making fuel consumption reduction a top priority in the development of sustainable vehicles. One of the dominant factors affecting fuel consumption is aerodynamic drag, especially at medium to high speeds, where air resistance can contribute greatly to a vehicle's total resistance (Zhou et al., 2025). Therefore, reducing drag is an important strategy in improving vehicle energy efficiency while lowering emissions.

Theoretically, drag force consists of two main components, namely friction drag and pressure drag. In bluff body vehicles, such as passenger cars, pressure drag due to flow separation at the rear of the vehicle is the dominant component (Y. Wang et al., 2020). This separation phenomenon produces a wake region with low pressure that increases drag force. The grand theory in vehicle aerodynamics states that reducing the size of the wake and increasing base pressure recovery can significantly reduce the drag

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coefficient (Cd). As this theory has developed, various flow control methods have been developed, both active and passive.

Active flow control approaches such as synthetic jets and base blowing have demonstrated effectiveness in altering wake structures, but these methods require additional energy supply and complex control systems (Camacho-Sánchez et al., 2025). In contrast, passive flow control offers a simpler, more economical, and practical solution because it does not require external energy. Various passive devices such as vortex generators, deflectors, hemispherical protuberances, and linking tunnels have been tested on bluff body models to reduce drag through modification of flow separation patterns (Kemal & Özden, 2024; Mohammadikalakoo et al., 2020)

The most widely used reference model in vehicle aerodynamics studies is the Ahmed body, which was introduced as a simplified geometry of a real vehicle with a specific slant angle to represent complex wake phenomena (Z.-P. Wang et al., 2025). The Ahmed body with a slant angle of 25° is known to produce a stable three-dimensional wake structure that is sensitive to modifications in the rear geometry. Studies show that small changes in rear geometry can significantly affect pressure distribution and vortex patterns (Hung et al., 2022).

Recent numerical studies have shown that spoiler configurations can modify the longitudinal vortex structure and affect the pressure distribution in the base region, which ultimately impacts drag reduction (Zhou et al., 2025). However, most of these studies were conducted using Computational Fluid Dynamics (CFD) with limited experimental validation. In fact, the complexity of three-dimensional turbulent flow behind an Ahmed body is often difficult to predict accurately without experimental verification.

In addition, existing literature generally focuses on high speeds and large Reynolds numbers, while experimental research on low to medium Reynolds regimes, particularly in laboratory wind tunnels, is still relatively limited. In fact, wake characteristics at low Reynolds numbers can exhibit different behavior compared to full scale, so numerical results may not necessarily be representative of actual experimental conditions in 2024; (Kemal & Özden, 2024). This gap highlights the need for experimental studies that specifically evaluate the effect of passive spoilers on the drag coefficient in laboratory-scale wind tunnel conditions.

Based on this gap, this study utilized the wind tunnel facility at the Center for Automotive Research Laboratory, Gunadarma University, to conduct direct and measurable tests. The model used was an Ahmed body with a 25° angle of inclination and a scale of 0.2 of the original size, making it suitable for testing in low to medium Reynolds regimes in the laboratory. This scale was chosen considering the limitations of the wind tunnel dimensions while maintaining the similarity of flow characteristics to the reference model. Through direct drag force measurements, this study sought to obtain empirical data on the effect of passive spoiler installation on changes in the drag coefficient (Cd).

With this approach, this study is expected to contribute to two aspects at once. From an academic perspective, the experimental results can clarify how simple modifications to the rear of the model affect wake structure and pressure distribution at low Reynolds numbers. From a practical standpoint, the findings of this study can be used as a basis for designing simple and easy-to-apply passive spoilers to improve the aerodynamic efficiency of vehicles. Thus, this study not only fills the gap in experimental studies, which are still limited, but also supports the development of energy-efficient vehicle technology through realistic and applicable solutions.

METHODS

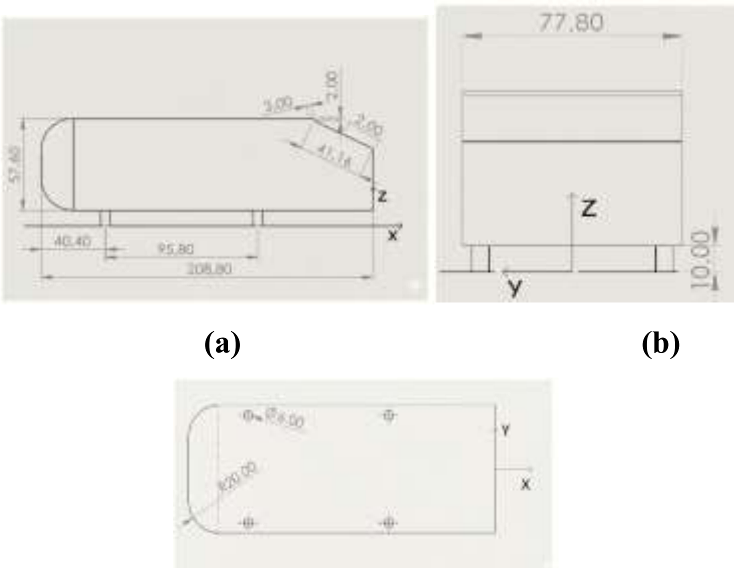
Research Design

This study uses a quantitative experimental design with a comparative approach to evaluate the effect of installing a small rear lip (passive spoiler) on wake reattachment characteristics and drag coefficient (Cd) on a 0.2 scale Ahmed body 25° model in low to medium Reynolds regimes. This design was chosen because direct measurement of drag forces in a wind tunnel provides higher empirical validity than numerical approaches alone, especially in three-dimensional turbulent flow in the base region (Fan et al., 2024). The experimental approach also allows for the observation of actual changes in velocity distribution and wake structure, as recommended in recent vehicle aerodynamics studies (Rijns et al., 2024). According to Wang et al. (2025), experimental verification remains the main reference in studies of Ahmed body geometry modifications, especially for spoiler configurations. Therefore, this study was designed to compare the baseline configuration (without spoiler) and the configuration with a small rear lip under the same flow velocity conditions.

The method used was the wind tunnel experimental method with drag force and flow velocity profile measurements using hot-wire anemometry. The testing was conducted in an open-circuit wind tunnel with a test section of 30 × 30 cm² and a maximum speed of 30 m/s. The Reynolds number was calculated based on the model height and free flow velocity to ensure compatibility with the regime commonly used in Ahmed body laboratory studies (Sagharichi, 2025). The drag coefficient was calculated using a standard non-dimensional equation based on the measured drag force, air density, frontal area, and flow velocity. This approach is in line with the experimental methodology used in studies of spoilers and base region modifications on model vehicles (Kheirkhah et al., 2025). In addition, the tests were repeated until statistical convergence was achieved, as recommended in modern bluff body experiments (Fan et al., 2024).

Ahmed Body

The research subject is a 0.2 scale 25° Ahmed body model made using a combination of acrylic (CNC machined) and Polylactic Acid (PLA) 3D printed material on the rear to facilitate variations in the installation of the small rear lip. The selection of a 25° angle was based on the characteristics of three-dimensional wake that is sensitive to rear geometry modifications, as reported in various recent experimental and numerical studies (Batay et al., 2024).



(a) **(b)**

(c)

Figure 1 Geometri Ahmed Body (a) side view, (b) Bottom view, (c) front view

A scale of 0.2 was chosen to adjust the dimensions of the test section while maintaining the similarity of the flow phenomenon to the reference model (Alam et al., 2025). The spoiler configuration was designed with a relatively small height relative to the model height to evaluate the effect of a simple lip on flow reattachment and base pressure recovery. Previous studies have shown that small modifications to the trailing edge can trigger significant changes in the longitudinal vortex structure and pressure distribution (Li et al., 2023).

The data sources in this study consist of primary and secondary data. Primary data was obtained through direct measurement of drag force using a load measurement system in a wind tunnel and real-time velocity data using a hot-wire anemometer. Velocity data was recorded at specific time intervals to obtain average values and turbulence fluctuations at the measurement point behind the model.

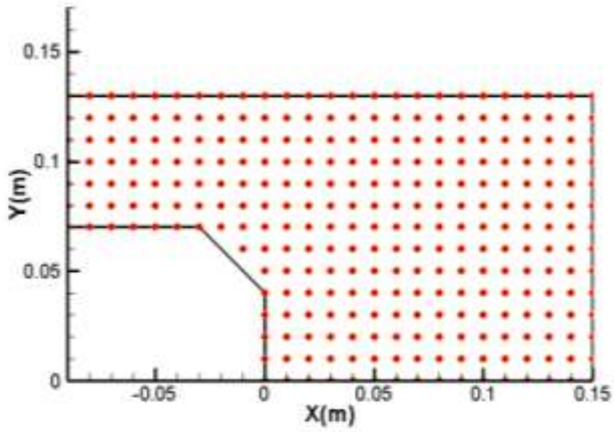


Figure 2 Measurements coordinate on plane (y,x) at z = 0 mm

This temporal data collection approach is important for capturing the characteristics of unsteady wakes at low Reynolds numbers (Solis et al., n.d.). Secondary data in the form of air density, temperature, and environmental pressure parameters were used to correct the drag coefficient calculations in accordance with vehicle aerodynamic testing standards (Ma et al., 2025).

Data analysis was performed using Tecplot 360 software to visualize the velocity distribution contours and identify recirculation zones and shear layer development. In addition, descriptive statistical analysis was used to evaluate the difference in Cd values between the baseline configuration and the configuration with a small rear lip. The results were validated by comparing the Cd change trends with previous experimental literature findings on spoiler and bluff body configurations (Hachimy et al., 2025). The interpretation of the results also considered the base pressure recovery and wake stabilization theories commonly used in modern vehicle aerodynamics studies (Zou et al., 2026). With a combination of force measurements, velocity profile analysis, and statistical approaches, this methodology is expected to provide a comprehensive overview of the flow reattachment mechanism and drag reduction on a laboratory-scale Ahmed body.

RESULTS

The upstream wind tunnel velocity was 8 m/s.

The figure below is the result of the reattachment length on the model in the upstream velocities 8 m/s. The length of reattachment of the flow through the Ahmed body has a length 0.15 m.

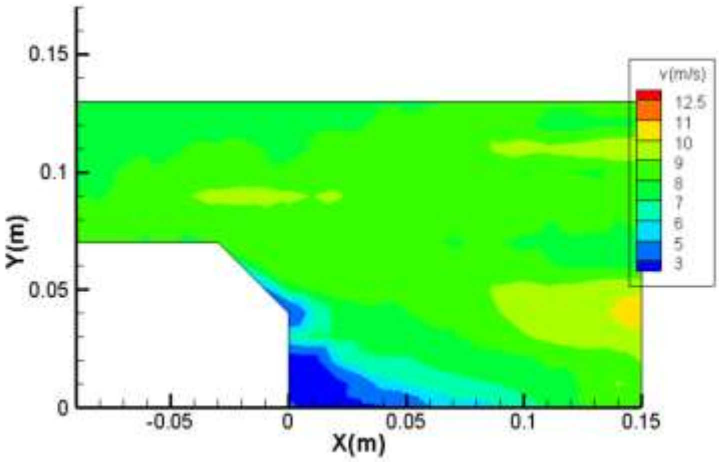


Figure 3 Experimental Measurement 8 m/s Without passive flow control

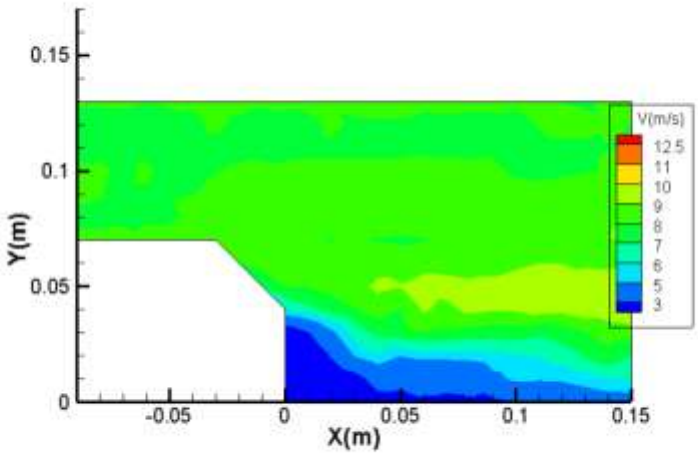


Figure 4 Experimental Measurement 8 m/s With passive flow control

Comparison of Figure 3 (without passive flow control) and Figure 4 (with passive flow control) at a speed of 8 m/s shows changes in the wake characteristics behind the 25° Ahmed body. In the basic configuration, the low-speed zone is localized directly behind the slant surface and forms a recirculation region with a reattachment length of approximately 0.15 m. This pattern indicates separation due to an adverse pressure gradient, which is characteristic of a 25° Ahmed body, where longitudinal vortices and three-dimensional wake structures are formed that affect the rear pressure distribution (Ahmed et al., 1984).

After installing the spoiler, the velocity distribution in the wake changes significantly. The low-velocity zone appears to be wider and longer, indicating changes in the development of the shear layer and the location of separation. Although spoilers as passive devices are capable of modifying the vortex structure and wake stability (Byrne, 1999; Hucho, 1995, 2013), the widening of the wake indicates that this configuration does not directly reduce the recirculation area but rather changes the distribution of flow energy behind the model. This confirms that the effect of spoilers on drag reduction needs to be further examined through quantitative analysis of the drag coefficient (Choi et al., 2008).

The upstream wind tunnel velocity was 10 m/s.

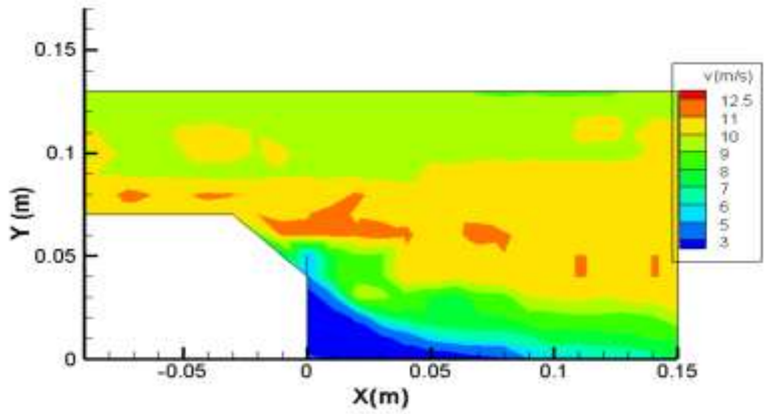


Figure 5 Experimental Measurement 10 m/s Without passive flow control

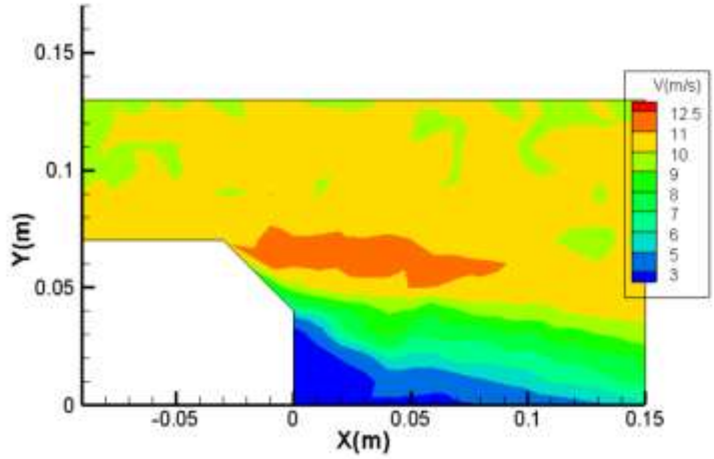


Figure 6 Experimental Measurement 10 m/s With passive flow control

At a free-stream velocity of 10 m/s, a comparison between the configuration without passive flow control (

Figure 5) and with passive flow control (Figure 6) shows a clear change in the wake structure behind the 25° Ahmed body. In the base model, the low-velocity zone is concentrated near the trailing edge and forms a fairly distinct recirculation region with a sharp velocity gradient between the shear layer and the free flow. The increase in flow velocity compared to the 8 m/s condition causes the vortex intensity in the rear region to become stronger, as indicated by the deeper blue color distribution at the bottom of the wake. This phenomenon is consistent with the characteristics of bluff bodies at higher Reynolds numbers, where the interaction between flow separation and longitudinal vortices becomes increasingly dominant (Ahmed et al., 1984).

After adding a spoiler as a passive flow control (Figure 6), the velocity distribution shows a more dispersed wake with a smoother gradient in the shear layer. A low-velocity zone still forms, but its distribution pattern becomes more regular and tends to shift downstream. This indicates that passive devices influence the development of the shear layer and modify the vortex structure behind the model. Aerodynamically, this change indicates a redistribution of flow momentum, which can affect base pressure and total drag characteristics. In line with the literature, the effectiveness of passive flow control is highly dependent on the interaction between the additional geometry and the wake dynamics formed at a slant angle of 25° (Choi et al., 2008; Hucho, 1995). Therefore, at a speed of 10 m/s, it can be concluded that the spoiler has a significant impact on the rear flow structure, although a quantitative evaluation of the drag coefficient is still needed to determine the overall aerodynamic effectiveness.

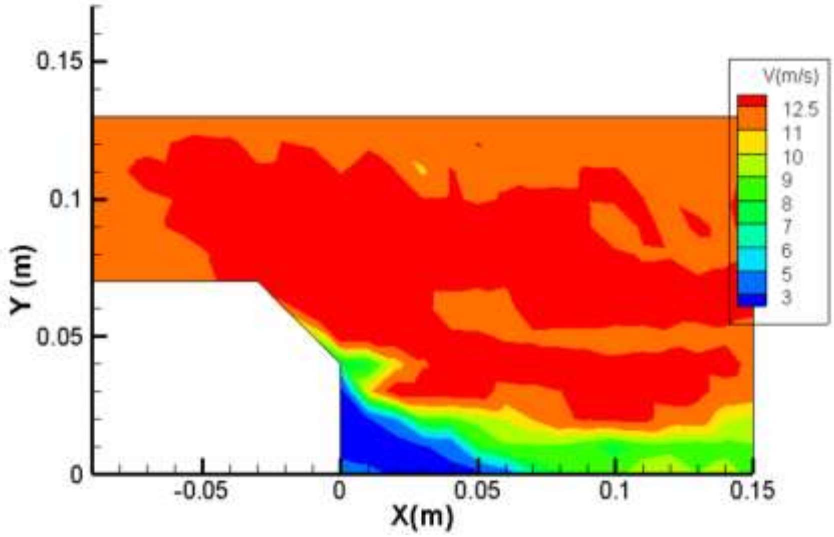


Figure 7 Experimental Measurement 12 m/s Without passive flow control

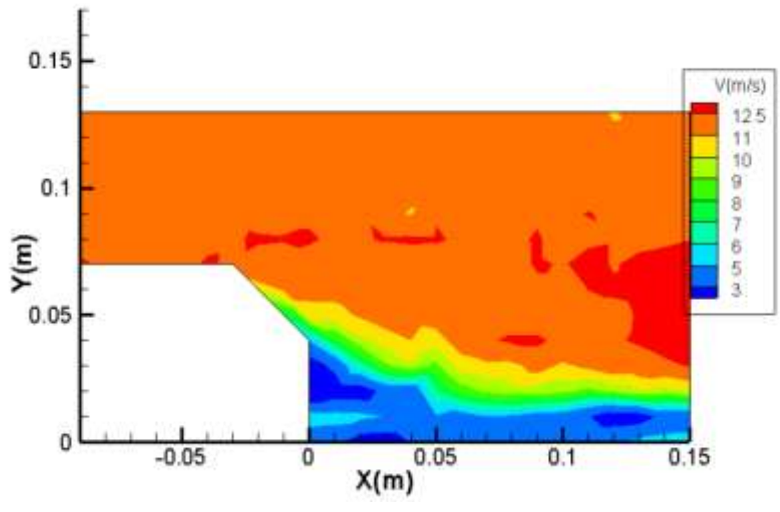


Figure 8 Experimental Measurement 12 m/s With passive flow control

At a speed of 12.5 m/s, the configuration without passive flow control (***Figure 1***) shows a more intense wake compared to lower speeds. The low-speed zone behind the model appears more clearly with a sharp velocity gradient, indicating a strengthening of the interaction between the shear layer and the longitudinal vortex due to an increase in the Reynolds number. Although the free flow momentum increases, separation still occurs significantly at an angle of 25°, so that the base pressure behind the model remains low and has the potential to increase pressure drag.

After the addition of passive flow control (**Figure 8**), the velocity distribution shows a more distributed wake and a more stable shear layer. A recirculation zone still forms, but its flow pattern is more controlled due to the redistribution of turbulent energy. These findings are in line with recent studies stating that passive devices work by modifying the wake structure and affecting base pressure, rather than completely eliminating separation (Kumar & Kim, 2021; Zhang et al., 2022). Thus, at 12.5 m/s, passive control was proven to alter wake characteristics, although quantitative drag analysis is still needed to assess its overall effectiveness.

DISCUSSION

Analysis of the velocity distribution at three variations of free flow velocity shows that an increase in velocity directly affects the wake structure behind the Ahmed body at an angle of 25°. At a velocity of 8 m/s, a recirculation zone is formed with a reattachment length of approximately 0.15 m and is characterized by a relatively localized low-velocity region behind the slant surface. When the velocity increases to 10 m/s, the wake intensity increases, as indicated by a sharper velocity gradient between the shear layer and the free flow. The longitudinal vortex structure becomes stronger due to the increase in the Reynolds number, so that the interaction between the shear layer and the base pressure becomes more dominant. At a velocity of 12.5 m/s, the momentum distribution in the rear region becomes more energetic, but separation still occurs significantly because the 25° geometry falls within the critical angle category that triggers stable separation. Thus, the increase in velocity does not eliminate separation but rather strengthens the vortex dynamics in the wake region.

When comparing the configurations with and without passive flow control at the three speed variations, a consistent pattern is observed in which the passive device modifies the development of the shear layer and the redistribution of momentum behind the model. At 8 m/s, the changes in the wake are still limited to the widening of the low-speed zone. At 10 m/s, the control effect becomes more apparent with a more dispersed wake distribution and a smoother gradient. Meanwhile, at 12.5 m/s, passive control shows a tendency to stabilize the downstream flow pattern even though the recirculation zone remains formed. This indicates that the effectiveness of passive control increases with the Reynolds number, but does not always correlate directly with the reduction in wake size. These findings are consistent with recent experimental and numerical studies stating that passive devices on Ahmed bodies work by rearranging vortex structures and affecting base pressure, rather than simply eliminating separation (Li et al., 2023; Zhang et al., 2022). Therefore, based on these comparative results, it can be concluded that increasing speed strengthens the wake structure, while passive flow control acts as a flow structure modification mechanism that potentially affects drag characteristics, although further quantitative analysis of the drag coefficient is needed to ensure overall aerodynamic effectiveness

CONCLUSION

I This study experimentally examined the effect of a small rear lip on the aerodynamic performance of a 0.2-scale 25° Ahmed body in a wind tunnel at low to medium Reynolds numbers. The results show that increasing free-stream velocity strengthens wake intensity and longitudinal vortices, while flow separation remains dominant due to the 25° slant geometry.

The addition of the passive rear lip modifies shear layer development and redistributes momentum in the wake region. At higher velocities, the device promotes a more stable downstream flow pattern and smoother velocity gradients, indicating potential improvement in base pressure behavior. However, changes in wake structure do not always directly correspond to proportional drag reduction.

Overall, the findings demonstrate that simple passive geometric modifications can influence wake dynamics and provide practical insight for aerodynamic optimization under laboratory-scale conditions.

LIMITATION

This study has several limitations that should be considered when interpreting the results. First, the experiments were conducted using a 0.2-scale Ahmed body model in a laboratory wind tunnel. Although geometric similarity was maintained, complete dynamic similarity with full-scale vehicles could not be fully achieved due to Reynolds number constraints. Consequently, the wake behavior and drag characteristics observed at low to medium Reynolds numbers may differ from those occurring under real driving conditions.

Second, the experiments were performed in an open-circuit wind tunnel with controlled and relatively uniform inflow conditions. Real on-road environments involve additional factors such as atmospheric turbulence, crosswinds, ground roughness, and vehicle yaw angles, which were not incorporated in this study. These factors may significantly influence wake dynamics and drag performance.

Third, the passive control device investigated was limited to a single small rear lip configuration. Variations in spoiler height, angle, shape, and placement were not systematically explored. Therefore, the results represent the aerodynamic response of only one geometric modification and cannot be generalized to all passive spoiler designs.

Fourth, the analysis focused primarily on drag coefficient and wake velocity distribution. Surface pressure distribution and detailed three-dimensional vortex measurements were not directly measured, which limits deeper understanding of base pressure recovery mechanisms.

Finally, the study relied solely on experimental measurements without complementary high-resolution numerical simulations, which could provide additional insight into detailed flow structures. Future research should integrate parametric geometric studies, higher Reynolds number testing, and combined experimental–CFD approaches to enhance the generalizability and robustness of the findings.

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