SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Comparative Analysis of Aerodynamic Drag Between Long Tail and Short Tail Aero Helmets Through Wind Tunnel Testing

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ARTICLE INFO

Article history:
Received 19 August 2024
Received in revised form 13 November 2024
Accepted 24 November 2024
Available online 10 December 2024

Keywords:
Aerodynamic drag; aero helmet; wind tunnel; drag coefficient

ABSTRACT

Aerodynamic drag is a critical factor influencing the performance of competitive cyclists, particularly in time-trial events, where reducing drag can significantly improve speed and efficiency. Helmets are an essential component of aerodynamic gear, and their design plays a vital role in minimizing air resistance. However, the effect of different helmet shapes and head positions on aerodynamic performance has not been thoroughly examined. This study aims to investigate and compare the aerodynamic performance of long-tail (LT) and short-tail (ST) aero helmets, along with the Kabuto Aero SL, under varying pitch angles and speeds. Wind tunnel testing was conducted using an adult-sized mannequin head, with helmets evaluated at pitch angles ranging from 15° to 45° and wind speeds of 5 to 15 m/s. The results showed that the LT Aero helmet achieved the best performance at lower pitch angles (15°), while the ST Aero helmet performed optimally at a 25° pitch angle. The Kabuto Aero SL helmet demonstrated superior performance at low pitch positions, particularly at 15°. These findings highlight the importance of helmet design and head positioning in optimizing aerodynamic efficiency for cyclists in competitive conditions.

1. Introduction

Aerodynamics plays a crucial role in competitive cycling, particularly in time-trial competitions, where maintaining high speed with minimal energy output is important [1,2]. Aerodynamic drag accounts for up to 90% of the total resistance encountered by cyclists, particularly at high speeds, such as those observed during time-trial events [3,4]. Research has consistently demonstrated the critical influence of aerodynamic factors on cycling performance, and much of the recent focus has been on optimizing the equipment used by cyclists, including helmets, to minimize this drag [5]. Helmets, in particular, contribute between 2% and 8% of the total aerodynamic drag experienced by cyclists traveling at speeds over 30 km/h [6,7].

The introduction of aerodynamic helmets has provided cyclists with a notable performance advantage. Early research by Sidelko [8] highlighted the impact of helmet design on drag reduction,

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https://doi.org/10.37934/arfmts.125.1.127138

showing that aerodynamic helmets could reduce drag by 3% to 6%. Additionally, Crouch *et al.,* [4] reported that helmets designed with aerodynamic shapes, offer an exceptional ratio of aerodynamic benefits to cost, making them highly valuable equipment for riders. The primary focus in designing aerodynamic helmets is to ensure a smooth airflow around the cyclist's head and back, reducing turbulence and enabling them to move more efficiently through the air [9]. These findings underscore the importance of helmet design in improving cycling performance, especially for time-trial events, where aerodynamically efficient equipment can be the determining factor in race outcomes. The benefits are not limited to elite cyclists, even amateur riders can experience significant energy savings which equivalent to reducing power output by 8 to 13 watts by using aerodynamic helmets [8].

In the current market, two primary designs of aerodynamic helmets are available which are the long-tail (LT) and short-tail (ST) options. LT helmets, typically referred to as time-trial helmets, are characterized by their elongated, streamlined shape, which is designed to guide airflow smoothly over the cyclist's back, minimizing turbulence and drag [10]. Studies such as those by Beaumont *et al.,* [11] and Alam *et al.,* [12] have shown that LT helmets can reduce drag significantly when used in optimal head positions, particularly when the tail aligns with the rider's back. This positioning allows the helmet to function as an aerodynamic extension of the cyclist's body, enhancing airflow attachment and reducing flow separation at high speeds [13]. On the other hand, ST helmets offer a more compact design that is often preferred for its versatility across various riding positions. While they may not provide the same level of drag reduction as LT helmets in a time-trial scenario, ST helmets are designed to offer a balance between aerodynamic efficiency and practicality in dynamic riding situations. For instance, Fintelman *et al.,* [13] observed that ST helmets perform better at intermediate pitch angles, such as 25°, where airflow attachment is optimized, reducing turbulence around the head. However, the overall aerodynamic benefit of ST helmets depends heavily on the specific head position adopted by the rider, with minor adjustments in head posture having a measurable impact on drag.

Several studies have investigated the effect of cyclist posture on aerodynamic performance, with particular attention paid to head position and its interaction with helmet design. A cyclist's posture, particularly the angle of their head relative to the rest of their body, is a critical factor in determining the aerodynamic drag they encounter. Research has shown that even small changes in a cyclist's pitch angle can lead to substantial variations in the drag coefficient. For instance, in the study by Chowdhury and Alam [14], it was observed that cyclists who maintained a lower head position, effectively reducing the exposed frontal surface area, experienced noticeably lower drag forces compared to those who adopted a more upright head posture. By lowering the head, cyclists are able to streamline their body profile, allowing airflow to move more smoothly over the helmet and down the rider's back, thus minimizing the air resistance.

Similarly, Barry *et al.,* [6] demonstrated that the aerodynamic advantages offered by helmets could be optimized by adjusting the cyclist's head pitch angle to align with the helmet's aerodynamic profile. This study highlighted that helmets are not universally efficient across all head positions but rather, their design is intended to perform optimally at specific angles that minimize drag. This suggests that both helmet design and rider position must work in tandem for maximum aerodynamic efficiency. For example, long-tail (LT) helmets are designed to provide optimal aerodynamic performance when the rider's head is tilted slightly forward, allowing the helmet's tail to lie flat against the rider's back. However, if the rider raises their head too much, the tail of the helmet becomes a source of drag, increasing resistance and negating the aerodynamic benefits. On the other hand, short-tail (ST) helmets offer more flexibility across a range of head positions but may not achieve the same level of drag reduction as long-tail helmets in the most favorable aerodynamic conditions.

The use of wind tunnel testing has become a standard method for evaluating helmet aerodynamics, offering precise measurements of drag forces under controlled conditions. In pursuit of aerodynamic advantages, cyclists should undergo wind tunnel training to find the optimal position as a slight degree of tilt in the helmet can cause significant changes in wind resistance [15]. Previous studies utilizing wind tunnels have highlighted the importance of helmet shape, surface smoothness, and frontal area in influencing drag coefficients [15-18]. However, many of these studies have focused either on LT helmets or specific configurations of ST helmets, leaving a gap in the literature regarding direct comparisons between the two helmet types across different head positions and pitch angles. Addressing this gap is essential for providing comprehensive insights into helmet design optimization. Given the critical role that helmet design plays in reducing aerodynamic drag, this study seeks to build on the existing body of literature by providing a detailed comparison of LT and ST helmets through wind tunnel testing. By examining the performance of these helmets across a range of pitch angles, this research aims to offer new insights into the optimal design and usage of aerodynamic helmets in competitive cycling. The findings from this study will contribute to the broader understanding of how helmet shape, cyclist head position, and aerodynamic drag interact to influence overall performance.

2. Methodology

2.1 Wind Tunnel Test Setup

The wind tunnel test setup in this study closely simulates the conditions experienced by a professional cyclist, with varying wind speeds and angles to accurately measure the drag forces acting on the helmet. This method allows for a precise evaluation of the helmet's aerodynamic performance, which is crucial in a sport like road cycling, where reducing air resistance can significantly improve speed and efficiency. The wind tunnel testing was conducted at the Faculty of Engineering, Universiti Putra Malaysia, using an open-loop wind tunnel, the OLWT-1000. The test section of the open-loop wind tunnel measures 1 x 1 m with a length of 2.5 m. The wind tunnel tests were conducted at speeds ranging from 5 to 15 m/s, closely resembling the apparent wind velocity encountered by cyclists during time trials. The dimensionless representation of drag, called the drag coefficient (Cd), can be calculated using the following equation:

$$C_d = \frac{(Df+Dp)}{\frac{1}{2}\rho v^2 A} \tag{1}$$

where ρ is the fluid density, v is the velocity of the object relative to the fluid, and A is the reference area of the object.

Helmets were fixed to an adult-sized mannequin head and attached via an aerodynamic strut to the wind tunnel balance. To accurately measure the drag on the mannequin head and helmet, a six-component balance with fully integrated automatic control, Balance Data Acquisition (BADAQ), was used to collect drag force measurements at a rate of 10Hz for 30 seconds. The overall wind tunnel test process is shown in Figure 1.

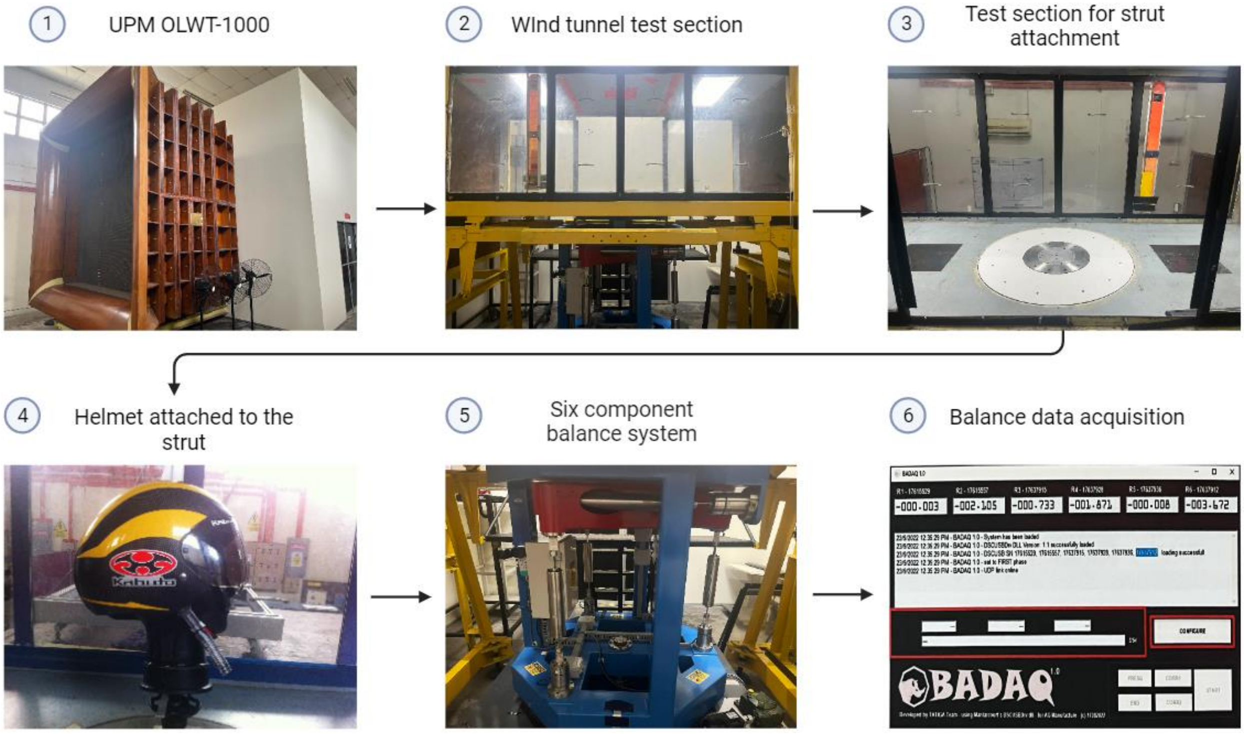


Fig. 1. UPM wind tunnel testing process

The helmets were tested at various pitch angles ranging from 15^{o} to 45^{o}, in 5^{o} increments. The pitch angles of the head position are shown in Figure 2. These angles simulate the head positions adopted by professional cyclists during the tucked position in time-trial events.

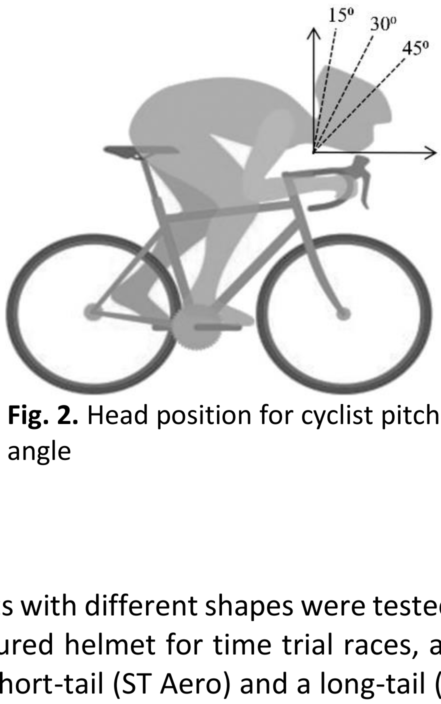


Fig. 2. Head position for cyclist pitch angle

2.2 Description of Helmets

In this research, three helmets with different shapes were tested. One of the helmets, the Kabuto Aero SL, is a standard manufactured helmet for time trial races, as shown in Figure 3. Meanwhile, two newly designed helmets, a short-tail (ST Aero) and a long-tail (LT Aero), were fabricated using a 3D printer. The main purpose of this test was to compare the aerodynamic drag data between the short-tail and long-tail aero helmets.

Fig. 3. Kabuto Aero SL helmet

The newly designed short-tailed helmet is an improvement of the Kabuto Aero SL model. The frontal area was reduced, and sharp edges were introduced on the top and back of the helmet to help shed small vortexes, as shown in Figure 4. By combining aerodynamic design with the advantages of a standard road helmet, this new design allows cyclists to gain valuable seconds during their rides while maintaining optimal comfort throughout a race. A key benefit of the ST Aero helmet is its reduced weight at the cyclist's neck, achieved by eliminating the long-tail design, which helps reduce strain commonly experienced when cycling in a tucked position. Additionally, its streamlined shape enables riders to keep the helmet securely positioned out of wind resistance for extended periods, without losing energy or compromising overall comfort. As a result, this helmet is particularly advantageous for events such as sprints, Keirin races, and time trials.

Fig. 4. ST Aero helmet

The LT Aero helmet was designed with a streamlined body shape, as shown in Figure 5. This low-drag design enables cyclists to experience significantly reduced aerodynamic drag at higher speeds, resulting in energy savings of up to 13% [19]. The helmet's design emphasizes the use of a vertebrae posture shape in the "Tail Down" position. When the tail of the helmet rests against the cyclist's back and the rider looks ahead, turbulence caused by the front air vents is minimized, thereby reducing drag.

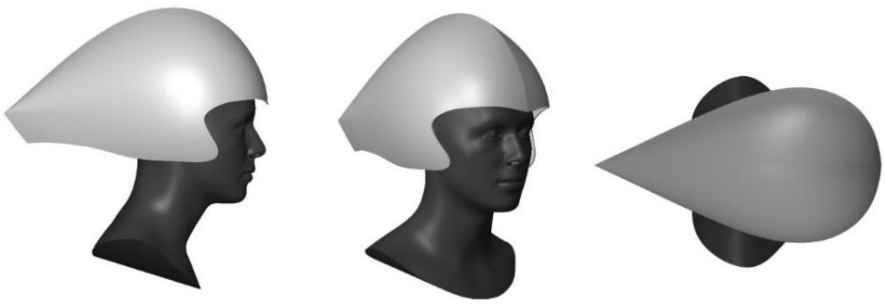


Fig. 5. LT Aero helmet

The design emphasizes the importance of the vertebrae posture shape for the "Tail Down" position. When the tail is positioned against the back and the rider looks straight ahead, air vents can create turbulence and increase drag. By eliminating these vents and optimizing the helmet for the vertebrae posture, airflow is better streamlined to match the cyclist's posture, significantly reducing drag. Table 1 shows the specifications and frontal area at the 0° pitch position for the three helmets tested in this experiment.

Table 1
Helmets specifications

Model	Kabuto Aero SL	ST Aero	LT Aero
Total Mass (kg)	0.345	0.335	0.394
Length (cm)	27.50	28.00	39.00
Height (cm)	19.00	22.70	22.70
Width (cm)	18.00	21.00	21.00
Frontal Area (cm^2)	692.00	658.00	658.00

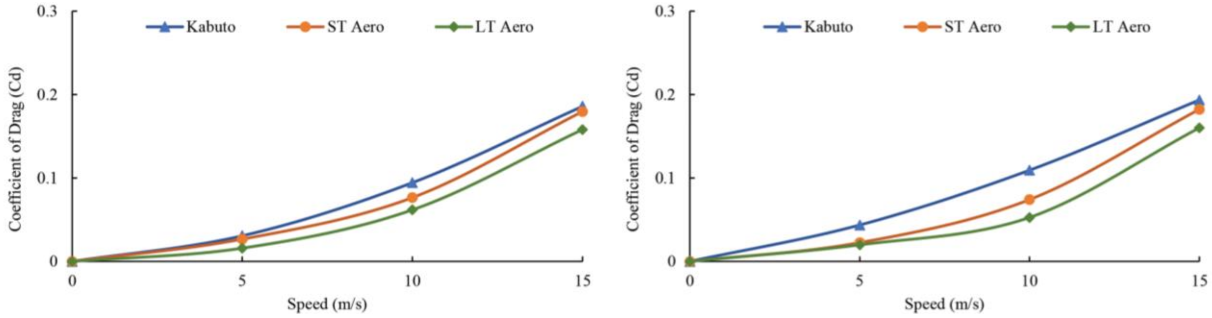
3. Results

3.1 Aerodynamic Testing Results for Pitch Position

This section presents the findings for the aerodynamic results across different pitch positions. Analysis from Figure 6(a) and Figure 6(b) shows a significant increase in drag coefficient at pitch positions of 15° and 20° for the Kabuto Aero SL helmet. Both the ST Aero and LT Aero helmets exhibited a consistent upward trend in drag coefficient. However, once the speed reached 5 m/s, the LT Aero helmet outperformed the ST Aero helmet. The highest drag coefficients recorded were 0.1859 and 0.1935 at 15° and 20° pitch positions, respectively, for the Kabuto Aero SL. In contrast, the LT Aero helmet recorded the lowest drag coefficients, with values of 0.1581 (a 17.66% reduction) and 0.1601 (a 20.86% reduction) compared to the Kabuto Aero SL at 15° and 20°, respectively. The performance of the ST Aero helmet was also superior to that of the Kabuto Aero SL, with reductions of 3.33% and 6.14% at 15° and 20°, respectively.

The difference in drag coefficients observed between the Kabuto Aero SL and the LT Aero helmet aligns with previous research by Beaumont *et al.,* [11] using computational fluid dynamics, which found a similar trend in drag variations between different helmet designs. The helmet's frontal area and length play a critical role in influencing drag coefficient performance. The results indicated a maximum 6% difference in drag coefficient reduction between the long-tail and short-tail helmets.

Debraux *et al.,* [20] also highlighted that drag is primarily affected by the effective frontal area. As discussed earlier, the frontal area of the newly designed helmets was reduced by 34 cm^2. This minimized frontal area design effectively reduced the helmet's drag coefficient. Wind tunnel test results confirmed this, with the ST Aero helmet reducing its drag coefficient by 3.33%, and the LT Aero helmet by 17.66%, compared to the Kabuto Aero SL. Furthermore, it was observed that the reduction percentage for the LT Aero helmet increased by 3.2%, and by 2.81% for the ST Aero helmet, as the pitch position increased from 15° to 20°.

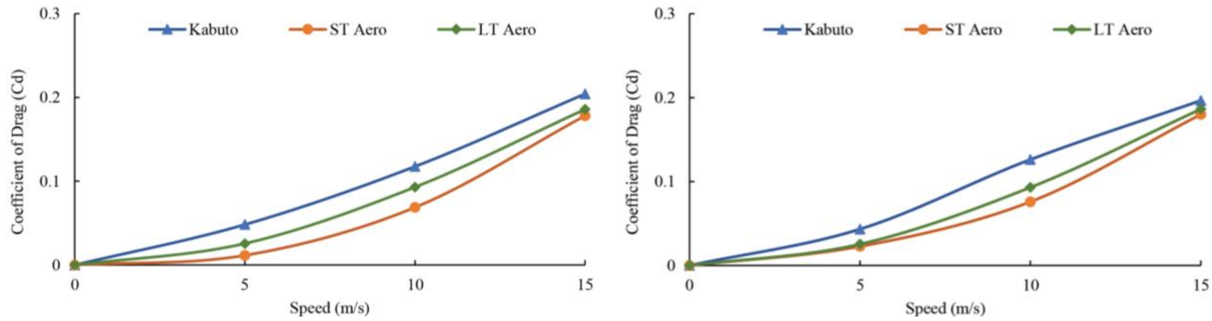


(a) (b)

Fig. 6. Helmet drag coefficient result at (a) 15^o and (b) 20^o pitch angle

In certain situations, the use of a long-tailed aero helmet may not be advantageous. This can occur when the helmet is not specifically designed for particular head positions or is excessively optimized for a single position, potentially increasing drag. As shown in Figure 7(a) and Figure 7(b), there is a rapid increase in drag at pitch angles of 25^o and 30^o for the long-tailed helmet. This may be attributed to flow separation at the back of the helmet, leading to turbulence. It is important to acknowledge that this study had limitations, as the helmet was fixed onto a mannequin head and attached using an aerodynamic strut in the wind tunnel. Consequently, the increased drag coefficient was likely caused by flow separation at the back of the helmet, where no body posture was present to maintain airflow attachment. According to Crouch *et al.,* [4], the tail of an aero helmet helps keep airflow attached to the cyclist's body for as long as possible, but when the airflow separates, it creates low pressure and drag, which slows the cyclist down.

Although the performance of the LT Aero helmet decreased at these pitch positions compared to the Kabuto Aero SL helmet, the LT Aero still demonstrated a better drag coefficient overall. The drag coefficient for the Kabuto Aero SL was the highest at 25^o and 30^o pitch positions, with values of 0.2042 and 0.1965, respectively. Notably, at the 30^o pitch position, the Kabuto Aero SL drag coefficient decreased by 3.92% compared to the 25^o position. In contrast, the ST Aero helmet performed the best at both pitch positions, recording drag coefficients of 0.1781 and 0.1802.



(a) (b)

Fig. 7. Helmet drag coefficient result at (a) 25^o and (b) 30^o pitch angle

In contrast, the results show notable differences at pitch angles of 35^o, 40^o, and 45^o, as illustrated in Figure 8(a), Figure 8(b), and Figure 8(c). The LT Aero helmet outperformed both the Kabuto Aero SL and ST Aero helmets at these angles, with drag coefficients of 0.1833, 0.1922, and 0.1957, respectively. Although the ST and LT Aero helmets share the same frontal area, it is evident that variations in overall length and tail shape played a significant role as the pitch angle increased. According to Foguenne [21], aero helmets are more aerodynamic when the tail is elevated in the air and the cyclist is looking downward, compared to when the tail rests against the cyclist's back. When the cyclist positions the helmet with the tail against their back and looks straight ahead, increased turbulence is generated due to airflow passing through the front air vents, leading to higher drag. However, when the cyclist looks downward, lifting the tail, smoother airflow occurs around the helmet as it avoids direct exposure of the vents to the wind.

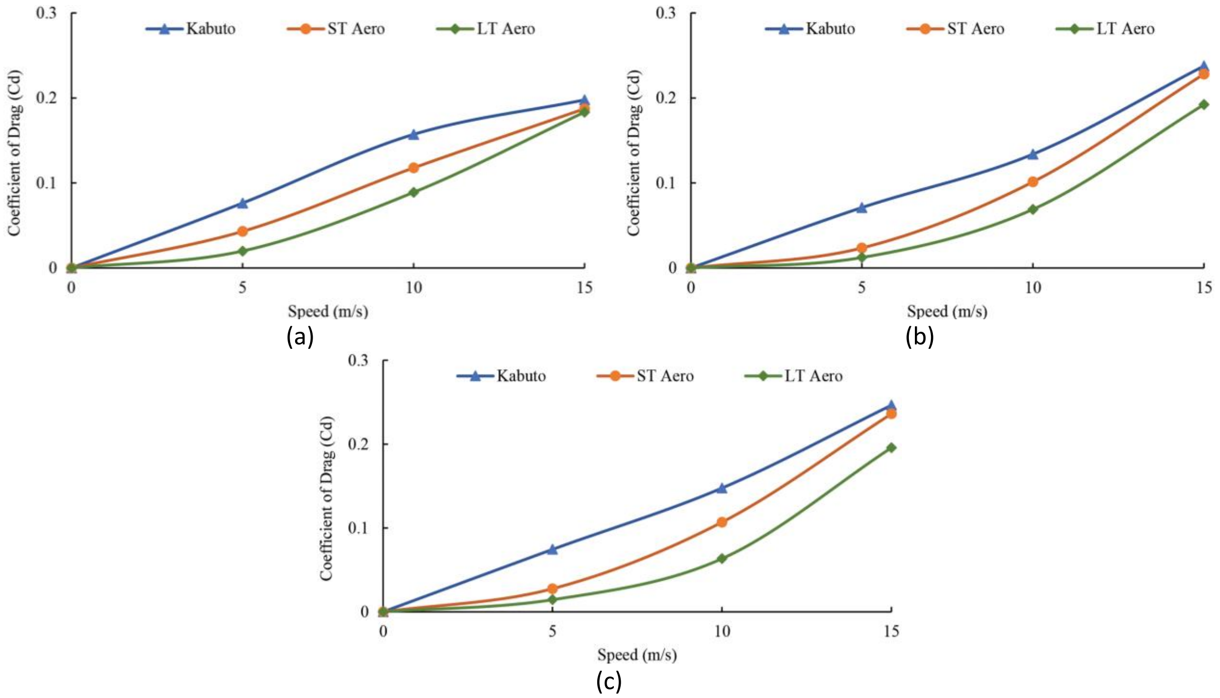


Fig. 8. Helmet drag coefficient result at (a) 35^{o}, (b) 40^{o} and (c) 45^{o} pitch angle

The data in Figure 8 indicates that both the Kabuto Aero SL and ST Aero helmets experienced a similar increase in drag coefficient as the pitch position increased from 35^{o} to 45^{o}. The drag coefficient values for the Kabuto Aero SL helmet were 0.1977, 0.2377, and 0.2464 at pitch positions of 30^{o}, 35^{o}, and 45^{o}, respectively. In comparison, the ST Aero helmet recorded drag coefficient values of 0.1873 (a reduction of approximately 5.55%), 0.2281 (a reduction of approximately 4.04%), and 0.2361 (a reduction of approximately 4.18%) at the same pitch positions.

3.2 Optimal Angles and Speeds for Helmet Aerodynamic Performance

The Kabuto Aero SL, ST Aero, and LT Aero helmets were tested in a wind tunnel to determine their optimal pitch positions. An analysis of each helmet's performance at different pitch angles is shown in Figure 9, Figure 10, and Figure 11. Based on the data in Figure 9, it can be concluded that the Kabuto Aero SL performs most effectively at a low pitch position, particularly at a 15° pitch angle. This is consistent with the findings of Barry *et al.,* [6], who demonstrated that minimizing the frontal surface area of the rider through lower head positioning significantly reduces aerodynamic drag. As the pitch angles increase beyond 15°, a corresponding rise in the drag coefficient is observed, which can be attributed to increased air resistance from a larger frontal area being exposed to airflow. Thus, Kabuto Aero SL is best suited for low pitch positions, where aerodynamic efficiency is maximized.

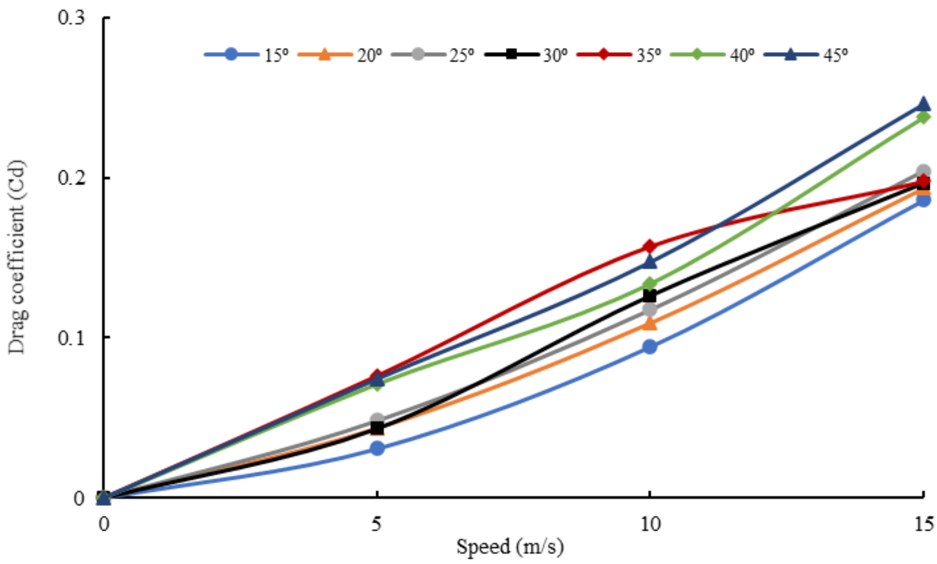


Fig. 9. Kabuto Aero SL helmet drag coefficient result at all pitch position

In contrast, the performance pattern of the ST Aero helmet, as shown in Figure 10, differs from the Kabuto Aero SL. The optimal pitch angle for the ST Aero helmet was found to be 25°, where it achieved a lower drag coefficient, in line with research by Debraux *et al.,* [20], which emphasized that small variations in head position could have a significant impact on drag due to the helmet's shape. Beyond 25°, the drag coefficient rises again, reaching its highest point at a pitch angle of 45°. At 10 m/s and a pitch angle of 35°, both the Kabuto Aero SL and ST Aero helmets showed suboptimal performance, but as the speed increased, their drag coefficients improved at higher pitch angles (40° and 45°). This result aligns with findings by Crouch *et al.,* [4], who identified that at higher speeds, aerodynamic performance improves as helmet design begins to compensate for the increased turbulence, particularly in time-trial conditions where airflow stabilization becomes critical. This highlights the importance of matching helmet design with riding conditions and pitch angle to achieve optimal aerodynamic performance.

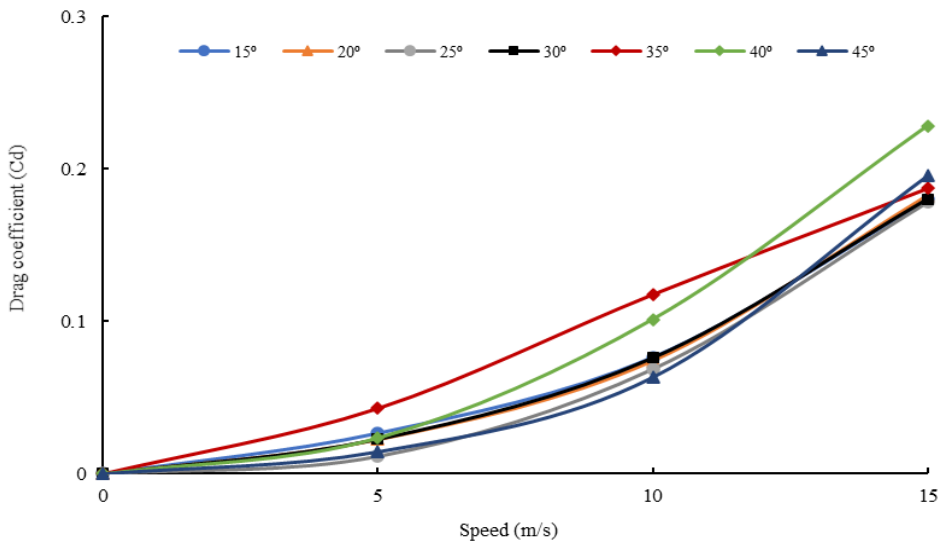


Fig. 10. ST Aero helmet drag coefficient result at all pitch position

The LT Aero helmet's drag coefficient shows a consistent increase, as demonstrated in Figure 11, but it performs best at a pitch angle of 15°. This result is in accordance to Beaumont *et al.,* [11], who highlighted the effectiveness of long-tail helmets at lower pitch angles due to their streamlined design, which helps maintain airflow attachment to the rider's body, reducing turbulence. Notably, at pitch angles of 25°, 30°, and 35°, the LT Aero helmet exhibits less significant increases in drag coefficient compared to the other helmets, suggesting better aerodynamic performance over a wider range of angles. This is likely due to its elongated tail design, which helps channel airflow more efficiently at moderate pitch angles, as indicated by previous studies on long-tail aero helmet designs [11].

Results clearly demonstrates that helmet design plays a critical role in aerodynamic performance, with the optimal helmet choice depending on specific pitch angles and riding conditions. The findings confirm that both the LT Aero and ST Aero helmets deliver superior aerodynamic performance when used with the appropriate head position, while the Kabuto Aero SL excels at lower pitch positions, where its design effectively minimizes drag.

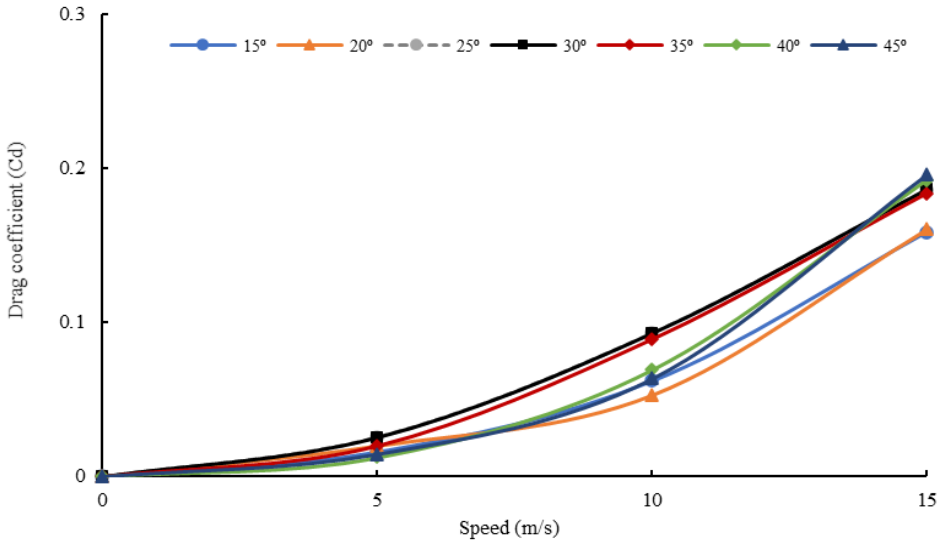


Fig. 11. LT Aero helmet drag coefficient result at all pitch position

4. Conclusions

The primary objective of this study was to evaluate the impact of long-tail and short-tail aero helmets on aerodynamic drag through wind tunnel testing. The results revealed a significant increase in drag coefficient at pitch angles of 25^{0} and 30^{0} for the long-tail helmet, indicating that its use may be suboptimal in certain conditions, particularly when not aligned with specific head positions or when excessively optimized for a single posture. This effect is likely driven by flow separation at the rear of the helmet, resulting in increased turbulence. In contrast, the Kabuto Aero SL demonstrated optimal aerodynamic performance at a 15^{0} pitch angle, effectively minimizing drag at lower head positions. However, as the head position changed, the helmet's frontal surface area increased, leading to a notable rise in drag, exacerbated by turbulence at the back of its spherical design. These findings provide critical insights into the relationship between helmet design, head position, and aerodynamic performance. The study underscores the importance of selecting helmets that are not only well-suited to a cyclist's posture but also optimized for specific riding conditions to maximize aerodynamic efficiency.

Acknowledgement
The authors would like to thank the Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia and LANL-JBNU Engineering Institute-Korea, Jeonbuk National University for the close collaboration in this research. This research was not funded by any grant.

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