Dean&Francis

ISSN 2959-6157

An Analysis of the Differences in Aerodynamic Drag among Bullet-shaped, Canted Nose at Subsonic Velocities

Xiao Wang[1, *]

[1]No.80 High School, Beijing, China
*Corresponding author: oscarwxa@icloud.com

Abstract:
Drag force is very important for high-speed rail' s energy efficiency and operating speed. This study compares bullet-nosed and canted-nosed train designs through meta-analysis of existing experimental data and verifies the validity of the possible explanations through existing simulations. The result shows that the bullet-nose train can reduce 29.2% of drag force in 41.66 m/s and 35.6% in 79.1667 m/s, which primarily because of a better pressure management and the reduction of flow separation. Although it is superior in aerodynamics, the durability of the canted-nose design reflects necessary compromises on crosswise stability and space requirements. These findings provide a quantitative guidance for the superiority of bullet-nose in reducing drag force compares to canted-nose. Moreover, this paper analyzes the cause and the physical principle behind the phenomenon by dividing the composition of drag force. Also, this study reveals the balancing between aerodynamic performance with other critical design considerations in current and future train development.

Keywords: Drag force; Nose shape; Pressure drag force.

1. Introduction

High-speed rail (HSR) has now become a vital transportation medium for its efficiency, capacity, and environmental benefits [1]. However, aerodynamic drag is a main contributor in the total resistance force, which limits the economic and service efficiency of HSR. Thus, the reduction in aerodynamic drag can save a large amount of expenses in energy and operational costs, contribute to higher possible service speeds ensuring safety, and reduce environmental noise pollution. Furthermore, in the global context of carbon neutrality initiatives, minimizing aerodynamic drag is a direct pathway to reducing the carbon emission for high-speed transportation systems.

Train aerodynamic Design is a complex multi-objective optimization problem, involving drag reduction, noise reduction, crosswinds resistance, tunnel trafficability etc. Among them, Nose Shape Design is one of the most critical factors affecting aerodynamic performance, since it is responsible for the majority of the drag force. Therefore, the design of the shape of the noses of HSR trains plays a vital role in the overall aerodynamic drag reduction of HSR trains.

Currently, many studies like the study conducted

ISSN 2959-6157

by Amol Radhakisan Dhumal et al have conducted the effect of different shapes of noses on the aerodynamic drag of trains [2]. Also, from the designs of typical HSR trains around the world, previous studies done including Shinkansen in Japan and Shanghai Maglev in China, the aerodynamic characteristics are specified in the reduction of drag force to ensure safety, speed, and the reduction of noise [3]. Trains such as Shinkansen uses highly streamlined bullet-shaped design to reach a higher service speed, and Shanghai Maglev uses canted nose to ensure the crosswind stability.

Although the superiority of streamlined shapes is well-established empirically, a detailed quantitative analysis dissecting how the drag force differs for classical nose shapes such as bullet and canted, presents a clear gap in the literature. Furthermore, it also indicates that there are few studies that provide clear physical explanations and examples for the reasons why certain shapes perform better than others through detailed flow field analysis.

This study aims to conduct a numerical comparative analysis of two representative head types: bullet-nose and canted-nose, which includes real-life example trains, their aerodynamic performance differences, their basic flow mechanisms, and conclude a preferred nose.

The primary contributions of this work are in two aspects. First, it establishes a quantitative breakdown of the drag composition between two selected head shapes, which clearly demonstrates the important role played by pressure drag. Existing studies have obtained detailed flow field visualizations through CFD simulations, further supporting this numerical pattern, which experimentally explain the observed drag force differences by revealing the flow mechanisms behind the data. Overall, these numerical data and chart analyses provide valuable insights and a solid foundation for the future aerodynamic design of drag reduction for high-speed train design.

2. Methodology

2.1 Theoretical Basis

The analysis is grounded in the fundamental principles of fluid dynamics, particularly the Reynolds-averaged Navier-Stokes equations used in CFD simulation. The drag force decomposition theory provides the framework for understanding pressure and friction components. The similarity principles ensure valid comparison of data across different experimental conditions and scales. These theoretical foundations enable meaningful interpretation of the aerodynamic performance differences between various nose shape configurations.

The pressure drag induces because the head, tail, and other parts of the train can cause drastic changes in the flow field [4]. Especially when the airflow separates at the tail, a large and low-pressure vortex area, also called wake area, will be formed. The front of the train is under high pressure, while the rear is in a low-pressure area. This huge pressure difference between the front and rear pulls the train backward, forming a pressure difference resistance. As investigated by previous studies, the pressure drag is responsible for a considerable portion of the total drag of the train and thus should be taken as the main consideration. Therefore, the most effective way to reduce the total resistance is to focus on reducing the pressure difference resistance [5].

As the nose shape becoming increasingly flat toward streamlines, the airflow no longer separates at the front end of the vehicle but can flow a longer distance along the surface of the front. This causes the originally huge and chaotic low-pressure Wake Region to rapidly shrink in volume and become relatively orderly. The pressure difference between the high-pressure area at the front end of the vehicle and the low-pressure area at the rear suddenly decreases, so the pressure difference resistance drops sharply [6].

While the density of air, reference area, and velocity range is assured, the drag coefficient that has been conducted was based on different reference area. Thus, drag coefficient itself cannot explain and support the drag variance directly. Thus, difference in area should be included and recalculate the actual drag force of each model at different speed. When calculating drag force, the drag force equation is used.

$$F_d = \frac{1}{2}\rho V^2 A C_d \tag{1}$$

2.2 Data Collection Strategy

As a common, detailed, and reliable method for simulating aerodynamic characteristics, High-fidelity Computational Fluid Dynamics (CFD) simulations are employed to calculate the total, pressure, and friction drag coefficients. CFD will also provide a visualized diagram of aerodynamic characteristics of each nose. This approach allows for detailed examination of flow characteristics that are difficult to measure experimentally [7]. Although CFD may introduce inaccuracies, especially when predicting phenomena such as flow separation and turbulent wake structure with ideal mathematical model, it provides a complete, high-resolution flow field data. In contrast, wind tunnels are typically limited to point measurements from pressure taps or probes, which may cause more serious accuracy problems and need a strictly controlled experimental environment. Thus, only studies that are conducted by CFD is selected into this research.

The data for this comparative analysis was primarily extracted from academic journal articles. Additional sources included official technical reports from railway operators like JR Pass, SNCF, Deutsche Bahn and publicly available patent documents that provide detailed geometrical information. The primary academic databases searched were Web of Science, Scopus, ASME Digital Collection, and Google Scholar. The search was conducted using a combination of keywords including: "high-speed train", "HSR", "aerodynamic drag", "drag coefficient", "nose shape", "head geometry", "CFD simulation" , along with specific model names, such as Shinkansen "N700S", "Shanghai Maglev", and "CR400AF".

2.3 Screening and Classification Criteria

Studies were included only if they reported a quantitative drag coefficient (C_d) value for a full-scale or scaled train model, reference area, and data that varies with given velocity range. The reference area used for calculating drag coefficient must be clearly stated. Studies that only presented qualitative flow visuals or did not specify testing or computational conditions were excluded in the data selection. But the flow charts can provide visual evidence that can further prove and better explain the founding in the collected and calculated data. To ensure a fair comparison, the data comes from one study and collected in a same condition, with the same air density, Reynolds number, and temperature. In other words, these variables are controlled to ensure an only difference caused by different nose shapes, which would affect reference area and the drag coefficient. In the calculation of drag force, with different reference area A and drag coefficient C_d the air density ρ of 1.225 kg/m^3 and V of 41.66 m/s to 79.1667 m/s stays the same.

The two selected train models were classified into different types of noses based on their primary geometric characteristics. Bullet-type is characterized by a high length-to-height ratio or aspect ratio, long and continuously curved nose. Shinkansen n700s is accord with these categorical characteristics. On the other hand, canted-nose is characterized by a flattened, wedge-like profile with distinct lateral surfaces, like Shanghai Maglev. Canted nose usually has a lower aspect ratio comparing to bullet nose or streamline nose.

2.4 Data Extraction and Processing

Data extracted from the selected sources included the train model, its head type classification, and the reported drag coefficient. The reference cross-sectional area used for calculating C_d was also recorded. Key test conditions including Reynolds number, wind or train speed, and temperature were documented to contextualize the results. The same speed range is selected for the comparing trains' data to ensure the fairness of comparison.

2.5 Comparative Analysis

The primary method of analysis is the quantitative comparison of the drag force calculated by drag coefficients (C_d) across the bullet nose shape and the canted nose shape categories.

The data is presented in line chart in the literature, showing the values of drag coefficient for each train. The speed range selection will be conducted within the same speed range for a fair comparison. The data used in calculations are estimated by the line chart in the cited literature.

The flow charts in the literature shows a clear flow of passing air. Only the obvious pattern and shapes will be analyzed instead of specific numerical calculations.

It is acknowledged that this meta-analysis has inherent limitations. Variations in computational setups and experimental conditions between different sources introduce uncertainty into the direct comparison. Therefore, the analysis focuses on identifying clear and significant trends rather than absolute differences and specific conclusion of a given type of train. The findings will be discussed in the context of these methodological variations.

3. Result

R To illustrate this trend with specific examples, the Japanese Shinkansen n700s series and the French Shanghai Maglev were selected for a detailed comparison, as both are well-documented and represent pinnacle implementations of their respective design philosophies.

ISSN 2959-6157

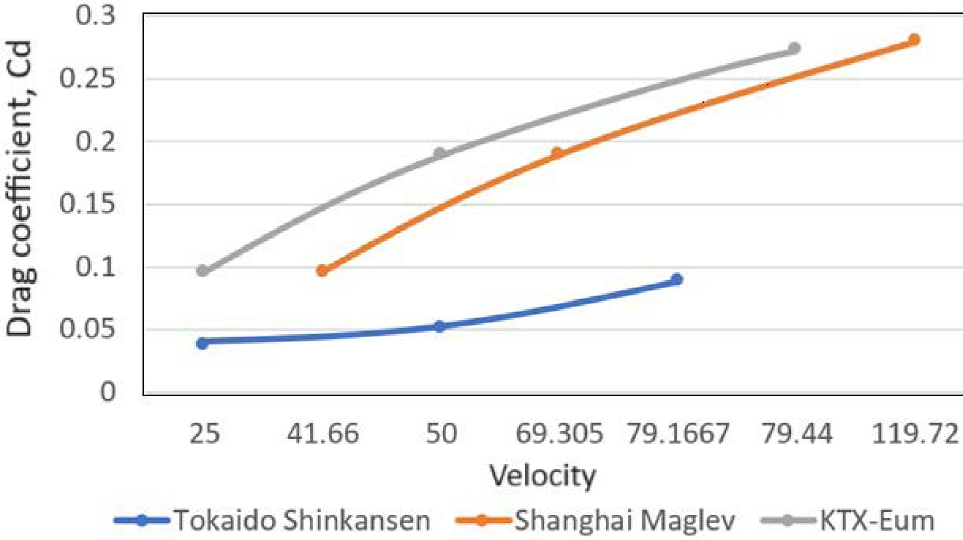

Fig. 1 Drag coefficient data extracted in the study [3]

As data and plot by sources, shown as Figure 1, in speed range of 41.66 m/s to 79.1667 m/s, the reported C_d for the Shinkansen n700s ranges from 0.045 to 0.09, while values for the Shanghai Maglev typically range from 0.1 to 0.22. The calculated drag force for Shinkansen n700s ranges between 294.6 N to 2127.90 N. In comparison, the values for the Shanghai Maglev range from 415.99 N to 3304.89 N. This places the drag force of the bullet-type n700s approximately 29.2% in 41.66 m/s and 35.6% in 79.1667 m/s less than the Shanghai Maglev under comparable conditions.

The data in the simulation conducted by Muhammad Syafiq Shaiful Anuar et al. shows the Shinkansen with a streamlined nose cone has the lowest drag coefficient, which is congruent with the analyze that with the nose shape sharper and flatter toward streamlined, though it may increase the friction drag by the increasing surface area, the pressure drag reduces in a considerable amount, which far exceeds the effect caused by friction drag force [3].

For showing and interpreting the delay of separation point and the reduction of the tail vortex area, the study conducted by Z. Wu et al provides clear flow field charts and intensity graph of wake and vortex for different noses [8].

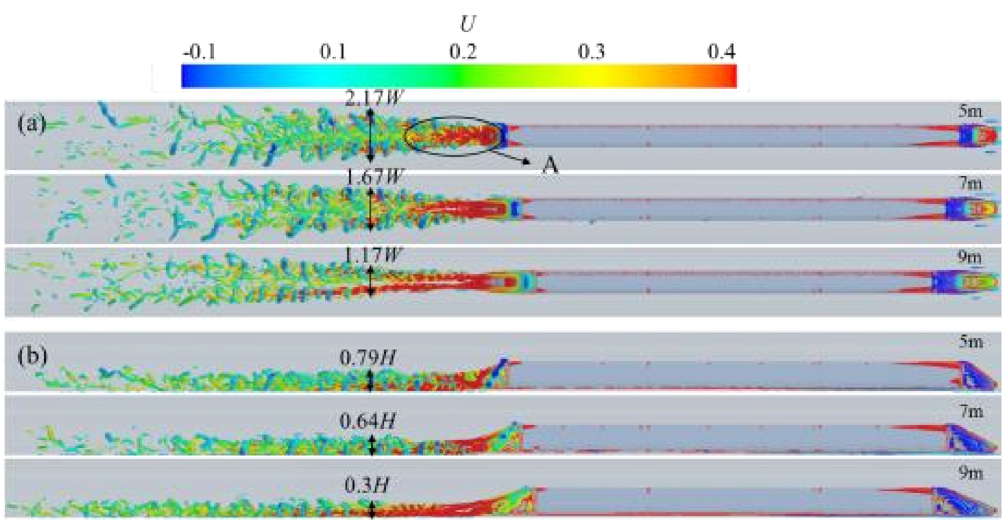

Fig. 2 Instantaneous Q contour map (Q = 50,000) around the train for different stream-lined lengths at t = 0.25 s: (a) top view and (b) front view [8]

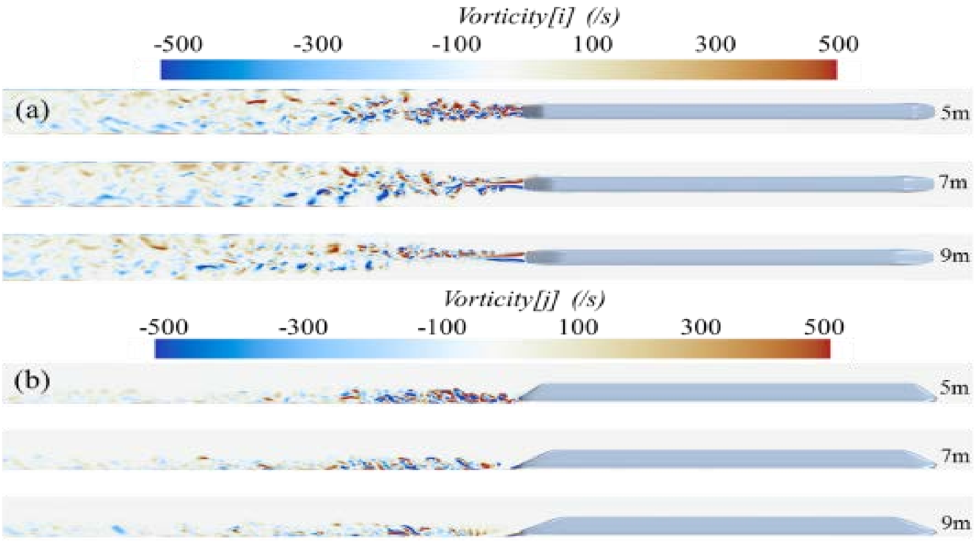

Fig. 3 Comparison of instantaneous vorticity for different streamlined lengths: (a) instantaneous x-vorticity (w_x) in the horizontal plane 0.2 m from the rail surface, and (b) instantaneous y- vorticity (w_y) in the longitudinal section y = 0 m [8]

Figures 2 and 3 clearly demonstrate the influence mechanism of the increase in the length of the streamlined head on the wake structure and aerodynamic drag of the train. Analysis shows that a longer streamlined head can effectively delay flow separation and reduce pressure difference resistance by optimizing the wake pattern.

For the five-meter short-head train, the vortex structure in Figure 2 is in a fragmented and disordered state. The two main vortex structures mixed with each other and rapidly broke into small-scale vortices, indicating that the airflow experiences early flow separation on the rear surface of the vehicle. This flow separation leads to the formation of a large-scale turbulent structure in the wake region, which is manifested as a high-intensity vorticity area in the vorticity field shown in Figure 3, reflecting the existence of intense rotational motion and energy dissipation in the wake region. This flow state leads to a significant pressure difference between the high-pressure area at the front of the vehicle and the low-pressure area at the rear, thereby generating considerable pressure difference resistance.

For the nine-meter-long train, Figure 2 shows that two clear and stable main vortex structures are formed in the wake area. The vortex shape is complete and orderly, and the number of small-scale vortices has significantly decreased, indicating that the flow separation point has moved backward, and the airflow remains attached to the rear surface for a longer time. This delayed separation effect significantly improves the wake characteristics. The range of the high-intensity vorticity region corresponding to Figure 3 is significantly reduced, and the vorticity intensity is significantly decreased. It proves that the turbulent kinetic energy in the wake is significantly reduced. The optimization of the wake structure effectively increases the pressure at the rear of the vehicle, thereby reducing the pressure difference between the front and rear and achieving a decrease in pressure difference resistance.

4. Discussion

The present analysis unequivocally demonstrates a measurable aerodynamic advantage of the streamlined bullet nose over the canted nose design, with a calculated drag reduction of approximately 29.2% in 41.66 m/s and 35.6% in 79.1667 m/s. This difference in drag force performance is not static but exhibits a slight increase with velocity in the range collected.

This phenomenon can be primarily attributed to the superior management of pressure drag by the bullet nose. Its elongated and continuously curved geometry facilitates a more gradual pressure gradient and delays flow separation, resulting in a significantly constricted and less energetic wake region compared to the canted nose. This means a smaller difference in air pressure from the nose to the rear, reducing the pressure drag.

These findings are in strong agreement with the work of Amol Radhakisan Dhumal et al., who reported a 38.6% to 57.9% drag reduction for similar streamlined head shapes in their CFD simulations [2]. The consistency between independent studies reinforces the robustness of this conclusion.

However, for the design of trains, extreme drag reduction is not the only factor to be considered. Other considerations are also very important, such as crosswind, gap lengths, noise pollution, and so on [4, 9, 10]. Therefore,

ISSN 2959-6157

this study is not an evaluation of vehicle models, but merely an analysis of the impact of the shape of the front of the vehicle on drag reduction.

This article's classification of the shape of the vehicle head is rather vague, lacking detailed standards. Moreover, the data consideration is insufficient, and there is a lack of universal risks. The speed was only taken within a valid small range, which can only specifically prove the general rules that occur in this speed interval.

5. Conclusion

This study conducted a systematic analysis of existing aerodynamic data for bullet-nose and canted-nose high-speed trains. The analysis reveals a consistent performance hierarchy where bullet-nose designs demonstrate approximately 29.2% in 41.66 m/s and 35.6% in 79.1667 m/s lower drag coefficients (C_d) compared to canted-nose configurations across operational speed ranges. Compared with the canted noses with a lower length-to-height ratio, the noses with a streamlined body and the ones with a large length-to-height ratio and a shape similar to a streamlined body, like the bullet noses, can make the wake adhere to the rear of the vehicle, prolongs the separation time of the wake at the rear of the vehicle. In addition, this nose can also reduce the generation of a large number of vortices at the rear to dissipate energy, create a smaller pressure difference with the front of the vehicle body, and thereby achieve the purpose of reducing pressure difference resistance. This further elaborates the authenticity and reason for the low drag of the bullet nose.

The research mainly contributes to synthesizing simulation data from the source to provide quantitative evidence for a better nose type in reducing the drag force in a considerable speed. Also, this research investigates the aerodynamic trade-off, providing potential causes and reasons of the drag induction. Furthermore, the flow charts are analyzed to further elaborate and verify the Authenticity and feasibility of the proposed causes. This research would offer valuable insights for train designers and researchers focusing on drag reduction and energy efficiency optimization. The data comparison serves as a valuable reference for future comparative studies and research on unified integration of the drag optimization with data and experiments.

For future research, experimental and computational parameters is suggested to be reported more standardly. Moreover, the models of different noses should be collected more comprehensively. In this way, it enables more precise and universal comparisons, which leads to a more detailed and authentic results and conclusions. In addition, future research will investigate and consider specific other factors, including higher operating speeds or resistance when passing through tunnels. In addition, the advantages and disadvantages of each nose design will also be analyzed, which will further enhance the precise prediction of trends and practical

References

[1] De Rus G, Nombela G. Is Investment in High Speed Rail Socially Profitable?[J]. Journal of Transport Economics and Policy, 2007, 41(1): 3-23.

[2] Dhumal A, Ambhore N, Tamkhade P, et al. Numerical Optimization for Aerodynamic Performance of Nose Cone of FSAE Vehicle through CFD. CFD Lett, 2024, 16: 161-171.

[3] Shaiful Anuar, M. S., Kariem Shater, S., & Sapit, A. Aerodynamic Study of High-Speed Train's Drag Coefficient by Computational Fluid Dynamics. Journal of Complex Flow, 2024, 6(1): 16–22.

[4] Tian Li, Dai Zhiyuan, Yu Mengge, et al. Numerical Investigation on the Aerodynamic Resistances of Double-unit Trains with Different Gap Lengths. Engineering Applications of Computational Fluid Mechanics, 2021, 15(1): 549-560.

[5] Dunlop, J. Slipstream Control for High-Speed Trains. Doctoral dissertation: Monash University, 2021.

[6] Sun Zhenxu, Yao Shuangbao, Wei Lianyi, et al. Numerical Investigation on the Influence of the Streamlined Structures of the High-speed Train's Nose on Aerodynamic Performances. Applied Sciences, 2021, 11(2): 784.

[7] Silvestri L. CFD modeling in Industry 4.0: New Perspectives for Smart Factories. Procedia computer science, 2021, 180: 381-387.

[8] Wu Z, Zhou D, Li S, et al. Numerical Analysis of the Effect of Streamlined Nose Length on Slipstream of High-speed Train Passing through a Tunnel. Journal of Applied Fluid Mechanics, 2022, 15(6): 1933-1945.

[9] M Baker C, Cheli F, Orellano A, et al. Cross-wind Effects on Road and Rail Vehicles. Vehicle system dynamics, 2009, 47(8): 983-1022.

[10] Jasim S A, Iswanto A H, Jalil A T, et al. Noise Pollution in Rail Transport. Case Study: Baghdad Subway. Noise Mapping, 2022, 9(1): 113-119.