

# Numerical Analysis and Wind Tunnel Validation of Aerodynamic Efficiency with Engine Variations for a Subscale Commercial Aircraft Model

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## Abstract

WITH nacelles, the locations of engines in aircraft can be a significant factor in aerodynamic performance during the aircraft design process, as they are mainly placed on the wing, impacting drag (D) and lift (L). Nacelles, the outer structure of engines, and pylons, which serve as connectors to the wing, are expected to be aerodynamically designed to deliver efficiency and minimize induced drag (D) during flight. While most research on engine-induced effects on performance focuses on the nacelle, the span directional engine locations are often overlooked, and they can be particularly critical for designing new configurations, such as Electric Vertical Take-Off and Landing (eVTOL) and electrified small-scale passenger aircraft. At the same time, the aero-structural aspects are relatively overlooked. Typically, for design and analysis, the aerodynamic performance metrics of aircraft can be estimated using computational methods, such as ANSYS Fluent. However, those computational methods are not fully guaranteed when the aircraft interacts with flow separation, shock waves, and wake that may occur during the flight due to aero-propulsion interactions, especially for new configurations. For performance and design validations, span directional engine locations and their aerodynamic effects are significant in this paper. The authors of this paper investigate aerodynamics using computational methods and wind tunnel testing for validation purposes. Variations are considered, particularly in terms of the wingspan's directional changes, the number, and the size of the engines. When more than a single engine is considered at each wing, proportionally distributed propulsion characteristics, such as size, power, and thrust, have been applied. As an approach to investigating associated aerodynamics, a low-fidelity computational tool based on the lifting-line theory has been selected due to its rapid computational time. Furthermore, corresponding wind tunnel testing has been conducted to validate its results. This study systematically investigates the effects of engine variances along the wingspan using simulation to determine their impact on lift (L), drag (D), and overall aerodynamic efficiency (AE). Then, wind tunnel testing will serve as a validation tool to ensure the accuracy of the simulation results. Findings reveal that engine placement has a significant impact on aerodynamic efficiency (AE), with configurations closer to the fuselage resulting in improved aerodynamic efficiency (AE). For a single engine per wing, an aerodynamic efficiency (AE) of 16.2 was found, which is best when placed near the wing root. The introduction of proportionally distributed propulsion systems featuring smaller engines distributed across the wingspan resolves ground clearance challenges posed by larger nacelles while maintaining acceptable aerodynamic performance. The same trend has been observed; in single engines, the engines closer to the wing roots provide a better aerodynamic efficiency (AE) of 15, 12.84, and 9.75 for 2, 3, and 4 proportionally distributed engines per wing, respectively. The outcome of this work contributes to further study of more efficient aerodynamic designs for enhanced efficiency. As a result, the directional variations of the engines are critical to the aircraft's performance, ensuring that computational and wind tunnel testing results are well-matched.

## Introduction

High demand for eco-friendly and carbon-neutral commercial airlines has increased in the aerospace and aviation industries. Commercial airlines are estimated to produce 12% of all carbon emissions [1] and the US government plans to diminish toxic emissions by 40% by 2050 [2]; therefore, developing zero-emission commercial aircraft is unavoidable [3]. One of the most common regional passenger jets, the Boeing 737 was initially launched in 1967, and since then, it has been one of the most successful fleets in the aviation industry [4, 5]. The current design convention features a tube-shaped fuselage and sweep-angled, tapered wings, particularly for mid-to-large commercial airliners.

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Aircraft design is a complex and lengthy process that encompasses aerodynamics, aerostructures, propulsion, manufacturing, and testing, among other aspects. It is a complex and iterative process to find an optimal or near-optimal condition considering all aspects above. The tube-shaped fuselage and tapered wing designs are among the most cost effective in terms of manufacturing and operation. However, unconventional designs, such as blended wing bodies (BWB) and truss-braced and morphing wings, can also be considered when only aerodynamic performance is a primary concern [6-14]. Many researchers have studied and demonstrated the advantages of unconventional wings and body shapes, which offer significantly higher performance than conventional ones. Meanwhile, most of the new configurations are “paper” designs, not considering the characteristics of propulsion systems or full-path operations such as ascending and descending.

Furthermore, new designs for the mass production line are another enormous challenge for manufacturers, including maintenance, repair, and overhaul (MRO) costs. As a result, only a few design modifications, such as the use of advanced materials, mechanisms, and manufacturing processes [15-21], have been recently implemented in actual assembly and production lines to outperform the aircraft by reducing weight, lowering manufacturing costs, and decreasing time. However, these modifications have had a minimal impact on substantially improving aircraft performance.

Therefore, the authors in this paper adopt a distinct approach to achieving our goal of transitioning to carbonless aviation with minimal alterations to aircraft design, including the retention of the same fuselage, wing shapes, and operational conditions. We maintain the same baseline, the Boeing 737, but replace the engine with an internal combustion engine (ICE) with a solid oxide fuel cell (SOFC)-based electrified propulsion system. However, when carbonless aircraft are considered, adopting new propulsion systems to decrease aviation carbon emissions is complex due to degraded performance. To identify the new aircraft design metrics while matching the total weight of two versions of aircraft and calculating their performance, the carbonless aircraft is far beyond its performance, about half of the desired range [22, 23]. Still, with the same configuration but a new engine, it is interesting to investigate how engine variations, aerodynamics, or aero-propulsion interactions could improve aerodynamic performance, especially nacelle aerodynamics.

Nacelles are the housing for the aircraft engines, as they protect the turbines and blades from any unexpected external disturbances. Nacelles are aerodynamically designed to deliver efficiency and minimize induced drag during flight. Therefore, the optimal design of the nacelles is critical, particularly when the aircraft interacts with flow separation, shock waves, and wakes that may occur during flight. Several parameters in aerodynamics relate to the aircraft's nacelles, including locations in wingspan directions, chord directions, vertical directions, and toe angles [11, 24-30]. As the first step, the authors of this paper investigate the aerodynamic effects of various engine locations in the baseline Boeing 737 Max aircraft. Variations are considered, particularly the span directional changes, the number, and the size of engines. When more than a single engine is considered at each wing, proportionally distributed propulsion characteristics, such as size, power, and thrust, have been applied. As an approach to investigating nacelle aerodynamics, a low-fidelity computational tool based on the lifting-line theory has been selected due to its rapid computational time, and corresponding wind tunnel testing has been conducted to validate its results.

## **Problem Statement**

Wings in aircraft are the primary source of aerodynamic force that enables flight. Engines attached to the underside of wings are the thrust and power generators and a large portion of the drag (D)'s source. Therefore, engines, nacelles, and aerodynamic effects during flight are particularly significant in this paper for enhancing performance, informing new aircraft designs, and validating potential new aircraft designs. Therefore, it is imperative to study the effect of variation on the engine using existing methodologies. Among many tools, these computational methods are not fully guaranteed to be accurate when the aircraft is in an unsteady flow, interacting with flow separation, shock waves, and wakes that may occur during flight due to aero-propulsion interactions. Additionally, it requires a significant amount of computational time to model, simulate, and validate the results. So, the authors of this paper investigated aerodynamics with engine variations using a rapid computational tool and wind tunnel testing for validation. The main objective of this paper is summarized below.

### **A. Expanding the design envelope from aero-propulsion interaction**

Understanding aero-propulsion interaction enables a transformative approach to aircraft design. This interaction reveals how engine positioning, thrust distribution, and nacelle configurations affect aerodynamic forces, including lift (L) and drag (D), as well as the overall aerodynamic efficiency (AE). By incorporating these insights into the design process, engineers can optimize nacelle placement and engine alignment to reduce drag and enhance aerodynamic efficiency. For instance, proportionally distributed propulsion systems enable smaller engines, reducing

weight and mitigating ground clearance constraints, which is crucial for regulatory compliance, such as Federal Aviation Administration (FAA) guidelines. Additionally, this knowledge supports the development of novel wing configurations, such as using multiple engines per wing strategically spaced to balance aerodynamic performance and structural loads. Furthermore, integrating low-carbon propulsion systems, such as solid oxide fuel cell (SOFC)-based engines, with optimized aero-propulsion coupling can reduce emissions while maintaining efficiency. In essence, leveraging aero-propulsion interaction fosters sustainable aviation by enabling configurations that minimize environmental impact while improving operational performance.

## **B. Validating aero-propulsion interaction**

Understanding the aero-propulsion interaction on an aircraft requires a complex, iterative approach. This study aims to establish a methodological approach to understanding this complex phenomenon. This study proposes investigating the effect of aerodynamics from an aero-propulsion perspective, focusing on engine locations by combining computational fluid dynamics (CFD) simulation and wind tunnel validation. The approach proposed in this research addresses some of the most crucial problems of aerodynamic studies, i.e., 1) understanding the effect of nacelle and engine-induced aerodynamics on overall performance, 2) minimizing the need for complex design for computational fluid dynamics (CFD) simulation, and 3) minimizing the need for complex dynamic or aerodynamic scaling for wind tunnel testing.

### *1. Understanding the effect of aero-propulsion interaction on overall performance*

Aero-propulsion interaction refers to the complex relationship between an aircraft's aerodynamic forces and its propulsion system. This interaction influences the aircraft's overall performance and efficiency. It is imperative to understand the effects of variations in nacelle geometry, nacelle-pylon-wing configuration, and the impact of engine position on the aircraft's overall performance. It is even more critical while designing new aircraft. This is often overlooked in most of the research. The authors in this study aim to determine the optimal engine location by varying the engine's position along the wingspan. This study also examines the possibility of using one or multiple engines per wing and investigates the effect of different engine locations along the span.

### *2. Minimizing the need for complex design for CFD simulation*

Computational studies require a significant amount of time and resources to complete, especially for unsteady flows. The problem intensifies when a model requires multiple iterations to illustrate the ideal scenario. It is more critical when computational fluid dynamics (CFD) simulation is the only tool used for such a study. Wind tunnel validation has been employed in this research as a validation tool to eliminate the need for a complex design and to reduce computational time. This enables simple engine designs, pylons, and other components, as well as a low-fidelity computational fluid dynamics (CFD) tool, to accelerate the process.

### *3. Minimizing the need for complex dynamic or aerodynamic scaling for wind tunnel testing*

Simply scaling an aircraft or an airfoil is insufficient for ensuring similitude in wind tunnel testing. However, meeting all the similitude parameters is impossible, depending on the wind tunnel setup and other environmental constraints. As this wind tunnel test aims to validate the findings from prior computational fluid dynamics (CFD) analyses, it is essential to match the trend of aerodynamic parameters. This makes it easier to test the subscale models in the wind tunnel by following dynamic scaling parameters to a viable range. By combining computational fluid dynamics (CFD) simulation with wind tunnel testing, the effect of nacelle aerodynamics can be observed from an aero-propulsion perspective. This leads to improved aircraft efficiency and performance, eliminating the need for a complex design process involving computational fluid dynamics (CFD) simulation and a subscale model for wind tunnel testing.

## **Approaches**

This study utilizes aerodynamic simulation and wind tunnel validation to assess the effect of varying engine characteristics. The authors of this paper utilize a rapid yet low-fidelity tool, MachUp [31], for computational analysis. CAD-modeled aircraft configurations, particularly wings, are analyzed using the lifting-line theory for quick response. Variations are considered, particularly in terms of the wingspan's directional changes, the number, and the size of the engines. Similarly, wind tunnel tests are performed on the same cases to validate the nacelle aerodynamics. In this case, rather than comparing the matching values, the trend in lift (L) and drag (D) is of importance. The following details describe each approach. When more than a single engine is considered at each wing, proportionally distributed propulsion characteristics, such as size, power, and thrust, are applied. In the case of a proportionally distributed

propulsion system, the total thrust produced by multiple engines remains the same as that produced by a single engine. The Boeing 737 Max 800 features one Leap-1B engine per wing, producing approximately 120 kN of nominal thrust at sea level [32]. To proportionally distribute this thrust, we utilize two engines per wing, each capable of producing approximately 60 kN of nominal thrust. This system enables the use of smaller but multiple engines, thereby addressing the issue of ground clearance [33, 34]. The optimal diameter for generating proportionally distributed propulsion is shown in Table 1.

**Table 1. Dimensions engines considering proportionally distributed propulsion system.**

Engine Number Per wing	Outer Diameter (m)	Inner Diameter (m)	Length (m)
1	2.803	2.349	3.514
2	2.075	1.63	2.445
3	1.965	1.318	1.977
4	2.003	1.137	1.705

### A. Computational analysis of engine-induced aerodynamics

Understanding the impact of using multiple engines and the change in their relative position is essential. The authors in this study utilize low-fidelity tools, such as MachUp5 and MachUpX, for this purpose. Each software analyzes the lift (L) and drag (D) of wings and other aerodynamic surfaces. Though MachUp has several versions, MachUp5 and MachUpX are mainly used for their more reliable and efficient aerodynamic modeling. Considering the overall aerodynamic performance, these simulation tools help find the optimum engine location and inter-distance. The approaches for computational aerodynamic analysis are summarized as follows:

1. Simulate the effect of using multiple engines per wing by placing them together and changing their position as a group.
2. Analyze the optimum number of engines per wing within the variations.
3. Simulate the effect of adjusting the engine position along the span to achieve the optimal engine configuration.
4. Analyze the optimal location for the engines, considering the optimal number within the variations.

### B. Validating the engine-induced aerodynamics using wind tunnel testing

For the precise assessment of nacelle aerodynamics on a subscale commercial aircraft, it is essential to examine how aircraft performance changes with variations in engine configuration and position under different conditions. Therefore, the authors of this paper first evaluate the nacelle aerodynamics for the mentioned conditions using computational analysis. Then, wind tunnel experiments are designed and performed in similar situations. Furthermore, the findings from wind tunnel experiments are compared with the numerical simulation results to identify the effects of engine-induced aerodynamics on aircraft performance. The authors of this research considered the Boeing 737 Max 800 as the base aircraft. The approaches for wind tunnel validations are summarized as follows:

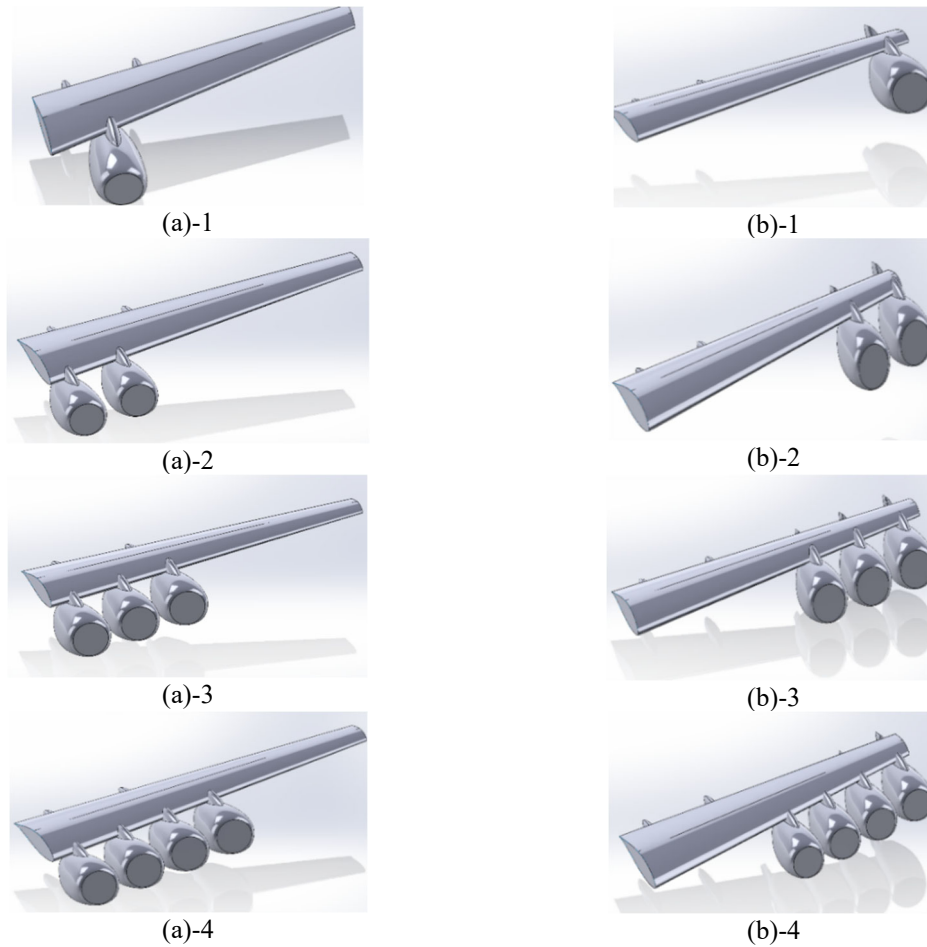
1. Designing 1:22 subscale models of the wing and engine of a commercial aircraft, Boeing 737 Max 800.
2. Wind tunnel tests are conducted on subscale models of the wing and single engine, with the engine location spanwise varied for different velocities and angles of attack.
3. Consider a proportionally distributed propulsion system; repeat the previous steps for two engines per wing, three engines per wing, and four engines per wing.
4. Compare the experimental results with numerical simulation results.

## Result

### A. Computational analysis

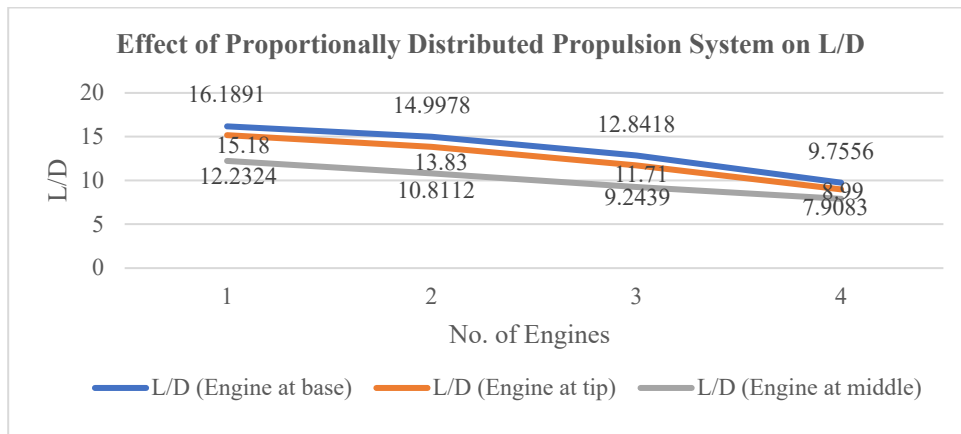
To understand the trend of a proportionally distributed propulsion system on the taper wing, a comprehensive aerodynamic simulation has been performed on a simple 15 m taper wingspan with an airfoil design of NACA 2412.





**Figure 3. Change of engine location as a group where (a) engines are at the wing base (left column), b) engines are at the wing tip (right column)**

The findings from computational studies are then plotted against each other to compare the change in aerodynamic efficiency (AE) for each configuration. Analyzing aerodynamic efficiency (AE) by adjusting the location of engine groups and considering multiple engines can help determine the optimal number of engines to use. The authors of this study used a proportionally distributed propulsion system to evaluate various engines. The effect of this change is illustrated in Fig. 4.



**Figure 4. An effect of engine position on proportionally distributed propulsion system**

It is observed from Fig. 4 that the best performance is expected when the engines are placed at the wing root. This is understandable because the remaining part of the wing can act as an uninterrupted L-generating surface. It can also be inferred from the figure that a single engine per wing is the optimal configuration when considering only the aerodynamic efficiency (AE). However, using a single engine per wing is not always the solution, mainly when more powerful engines are required for a different propulsion system. In this paper, the authors select two engines per wing and further analyze the engine by varying the engine distance.

2. Aerodynamic efficiency as a function of engines' inter-distance

The effect of changing the location of engines along the span of aerodynamic efficiency (AE) for two-engine-per-wing configurations warrants investigation. Initially, the first engine was placed 1.25 m away from the wing root, and simulations have been carried out by gradually altering the position of the second engine by 2.5 m towards the wing tip. This is demonstrated in Fig. 5.

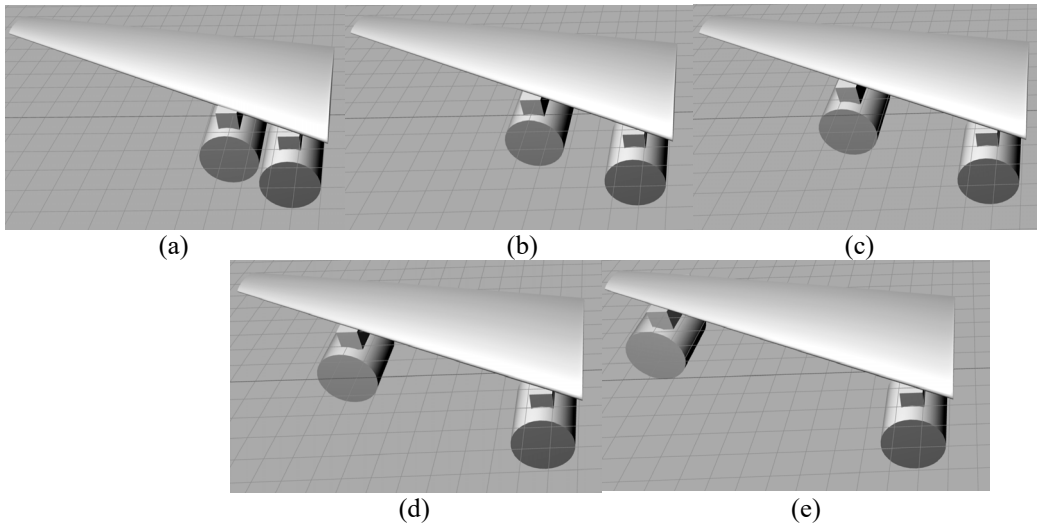


Figure 5. Demonstration of changing the engine locations for two engines per wing configuration

The same study has been repeated in the case of placing the first engine 3.75 m, 6.25 m, 8.75 m, and 11.25 m away from the wing root and putting the second engine, gradually altering the position of the second engine by 2.5 m towards the wing tip. This ensures that the complete array of possible engine locations has been studied.

3. Analyze the optimal location for the engines, considering the optimal number of engines.

The results from computational investigations are then plotted together to find the optimum location for the 2-engine configuration. Fig. 6 illustrates the effect on aerodynamic efficiency (AE) as the engine location is varied.

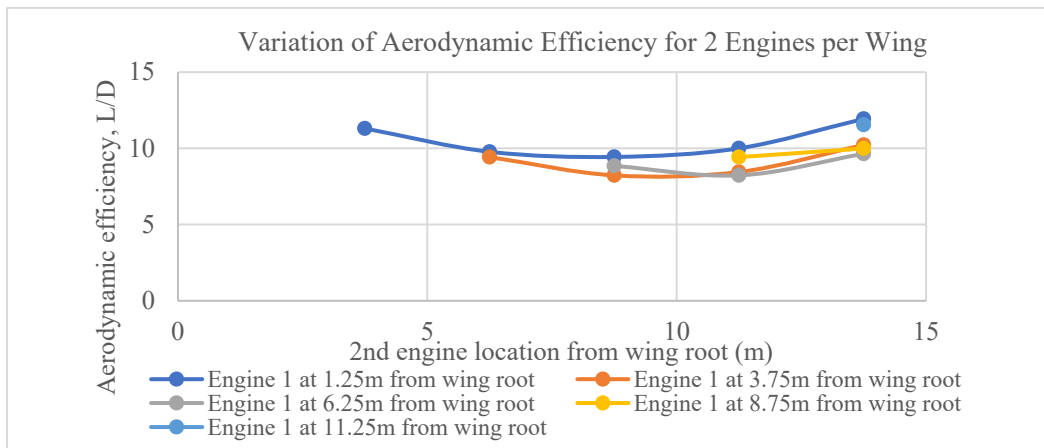


Figure 6. Effect of engine position on proportionally distributed propulsion system.

Fig. 6 shows the effect of changing the position along the span of two engines. It is observed that as the distance between the engines increases, the aerodynamic efficiency (AE) also increases. It can also be inferred that the best aerodynamic performance is achieved when one engine is positioned at the wing base and the other at the wing tip. The computational analysis revealed critical trends in the aerodynamics of nacelles, particularly concerning engine placement and propulsion distribution. For a baseline aircraft like the Boeing 737 Max, simulations have demonstrated that varying the engine positions along the wingspan has a significant impact on the aircraft's aerodynamic efficiency (AE). Placing engines closer to the fuselage achieves higher aerodynamic efficiency (AE) due to reduced wing-nacelle interference and minimized drag (D). Conversely, positioning engines near the wingtip can improve lift (L) distribution but at the cost of increased drag (D). When employing a proportionally distributed propulsion system with multiple smaller engines, simulations demonstrated a trade-off between aerodynamic performance and practical design constraints. For example, using two engines per wing helps mitigate ground clearance issues posed by larger nacelles while maintaining sufficient aerodynamic performance.

Wind tunnel validations corroborated these findings, highlighting that the optimal aerodynamic configuration balances engine size, spacing, and thrust output, paving the way for efficient designs compatible with future carbon-neutral propulsion systems.

## B. Wind tunnel test

Wind tunnel experiments have been conducted in conjunction with computational studies to provide a compelling argument regarding the impact of variations in engine numbers and changes in engine location. It is essential to consider multiple factors to assess aerodynamic properties accurately. As stated earlier, the subsonic, open-loop wind tunnel facility at Tennessee Technological University (TTU) is used in this study. A 1:22 sub-scaled wing section of NACA 2412 and proportionate engine-pylon configurations are used in this study considering the wind tunnel dimension constraints. Advanced 3D printing technology has been utilized to create the models, which is significant in accurately modeling the shape of the wings and other components without distortion.

The wind velocity is one of the most important parameters considered in wind tunnel testing. Wind velocity can be altered by adjusting the motor's frequency, as evidenced by the change in height in the manometer. The pressure difference is measured using the pitot tube of the wind tunnel for increased accuracy. This can be used to calculate the wind velocity using Eqn. 1 and 2. The temperature of the test day is also a crucial parameter for wind tunnel testing, as the air density decreases with increasing temperature. This influences the Reynolds number, which is necessary for aerodynamic studies. The corrected velocity on the test day can be calculated using Eqn. 3.

$$\Delta P = \rho_w g h \quad (1)$$

$$V_1 = \sqrt{\frac{2\Delta P}{\rho_a}} \quad (2)$$

$$V_2 = V_1 \sqrt{\frac{t_2 + 273}{t_1 + 273}} \quad (3)$$

Where,  $\Delta P$ : Pressure difference  
 $\rho_w$ : The density of water on the day of measuring velocity  
 $h$ : Deflection in manometer  
 $\rho_a$ : The density of air on the day of measuring velocity  
 $V_1$ : Wind velocity on the day of measuring velocity  
 $V_2$ : Wind velocity for the corresponding test day

The model is placed on the load cell to measure the lift and drag forces for varying test cases against different wind speeds. Fig. 7 shows a demonstration of the wing.

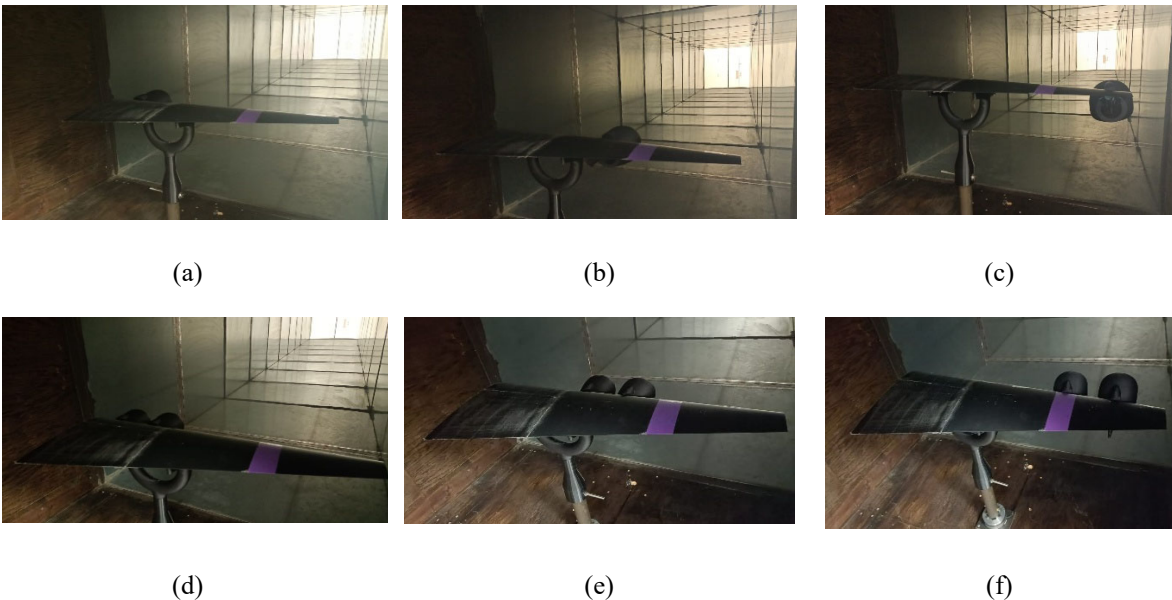


**Figure 7. The model test section of inside the wind tunnel.**

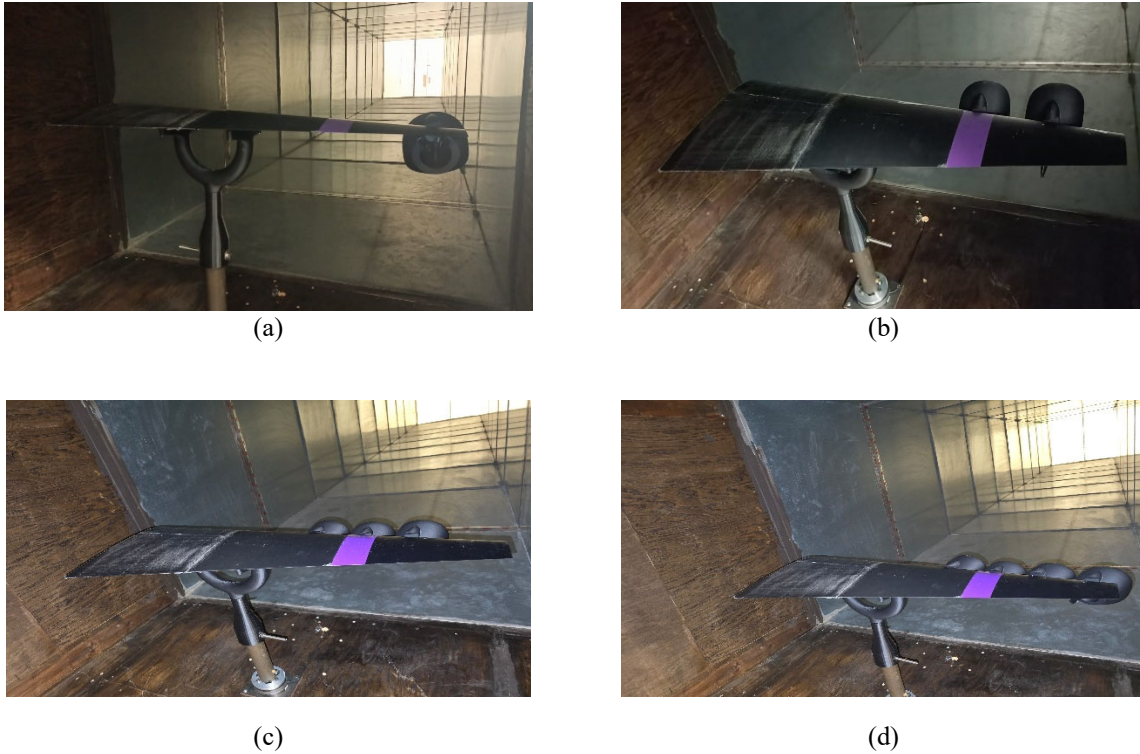
The wind tunnel has been used as a validation tool to strengthen the findings from computational studies. For greater clarity on the impact of changes in aerodynamic efficiency resulting from variations in engine number and engine location, wind tunnel tests have been conducted over a range of wind velocities and corresponding Reynolds numbers. The tests and subsequent results will be demonstrated in the following ways:

*1. Aerodynamic efficiency as a function of locations on single/multiple engines with varying wind speeds*

The authors have conducted wind tunnel tests to validate the findings from computational fluid dynamics (CFD) analysis. A 1:22 sub-scaled wing and proportionally distributed propulsion engines are used as the model wing and engines. The wing and engine models are 3D printed to ensure a smooth surface. Initially, one engine per configuration is tested in the wind tunnel, with the engine placed at the wing base, the midpoint of the wing, and the wing tip. Similarly, configurations with two, three, and four engines per wing are tested in the wind tunnel to assess the change in aerodynamic efficiency resulting from these variations. Fig. 8 shows the location of the engine for one-engine and two-engine per wing configuration, and Fig. 9 shows different numbers of engines inside the wind tunnel.

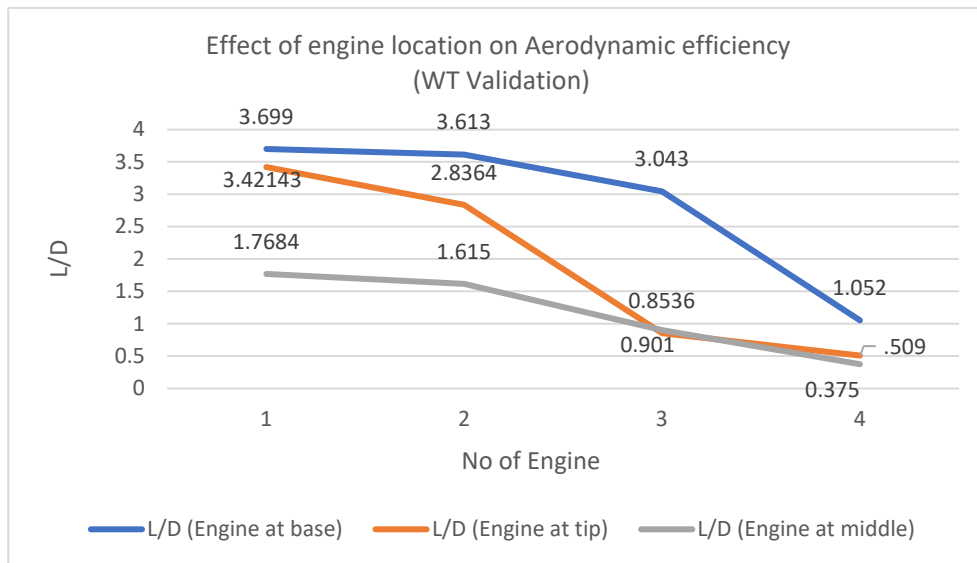


**Figure 8. Engines are placed at the base of the wing (a, d), at the middle of the wing (b, e), and at the tip of the wing (c, f) for one and two engines per wing configurations.**



**Figure 9. Wind tunnel test of (a) one engine per wing, (b) two engines per wing, (c) three engines per wing, and (d) four engines per wing configuration.**

The results obtained from wind tunnel studies are then plotted together to examine the effect of varying the number of engines and positioning them at different locations. The result of the wind tunnel study is shown in Fig. 10.

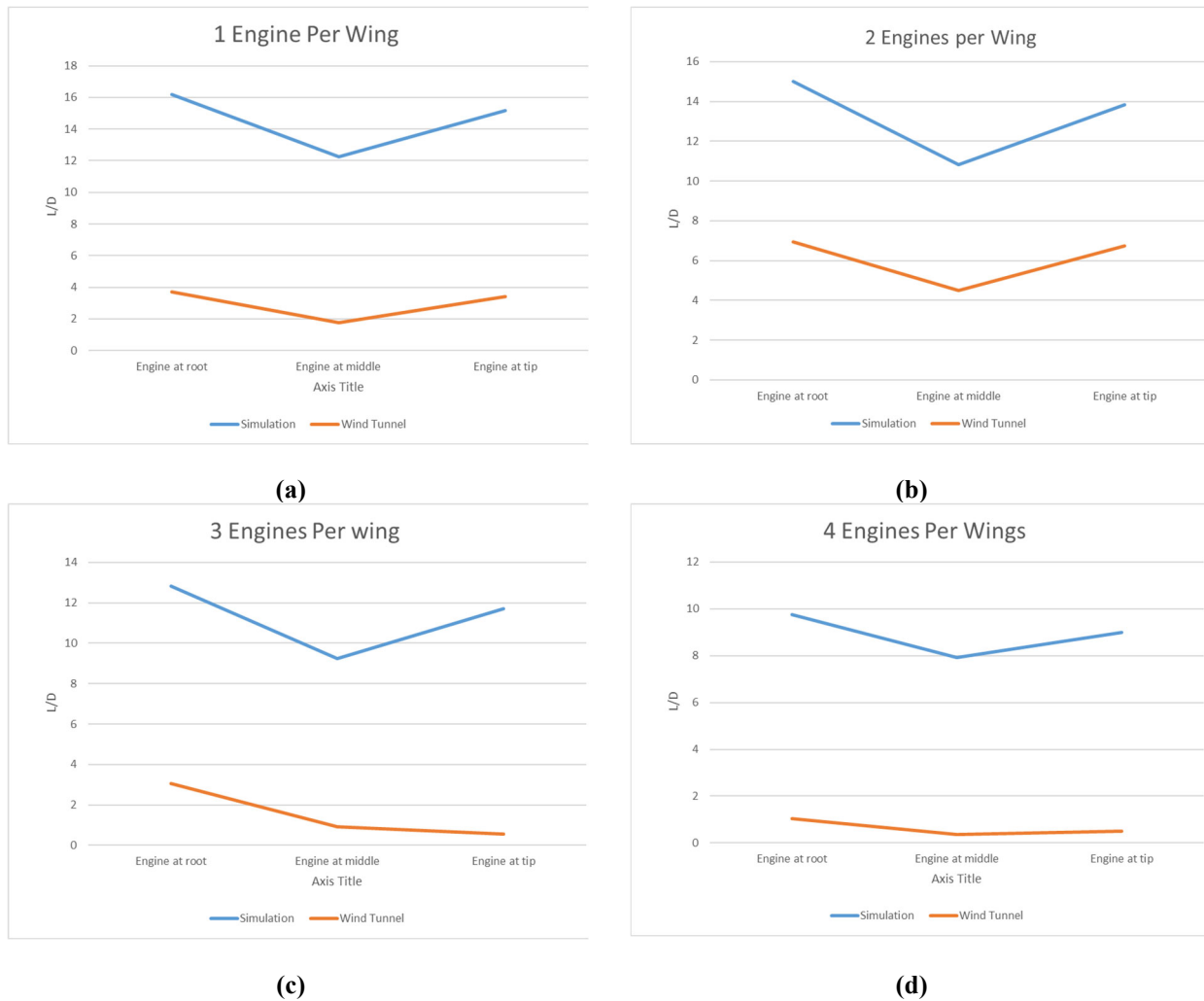


**Figure 10. Wind tunnel validation of the effect of variation of engine location on aerodynamic efficiency.**

Fig. 10 shows that aerodynamic efficiency decreases with the increase in engine number, as observed in the computational fluid dynamics (CFD) study. It can also be observed that the best aerodynamic efficiency is found when the engines are placed near the wing base.

2. Analyze the optimum location of the engines through wind tunnel testing

The results obtained through the wind tunnel tests can be used to suggest an optimum location for the engines. This result, along with the numerical simulation, will provide us with a more accurate insight. Another visual representation of the effect of engine location on aerodynamic efficiency, based on numerical simulation and wind tunnel validation, is shown in Fig. 11 for different engine configurations per wing.



**Figure 11. Effect of engine location on aerodynamic efficiency (numerical analysis and wind tunnel validation); (a) one engine per wing, (b) two engines per wing, (c) three engines per wing, and (d) four engines per wing**

It is worth noting that the difference in aerodynamic efficiency (AE) between the numerical simulation and the wind tunnel study is attributed to the flow conditions of the wind tunnel, specifically the Reynolds number and other factors. However, the graphs show the same trend.

Finding the optimum engine number and location is essential in the ongoing pursuit of designing sustainable aircraft. The author’s approach of combining numerical simulation and wind tunnel validation for a wide array of tests provides this study with a unique opportunity to propose design considerations for future carbon-neutral aircraft designs.

## Wind Tunnel Facility

After determining the optimum engine locations through aerodynamic simulation by varying the engine locations spanwise, the study proceeds to validate the results through wind tunnel testing. The Wind Tunnel Facility at Tennessee Technological University (TTU) comprises one subsonic, open-loop wind tunnel, utilizing a 125 horsepower (93 kW) motor with variable-pitch blades. This wind tunnel features a 3-meter-long test section with a cross-section measuring 1.25 meters in width and 1.25 meters in height. The 93 kW (125 horsepower) motor, equipped with variable-pitch blades, can accommodate a flow of up to 20 m/s at a rate of approximately 38 m<sup>3</sup>/s (80,000 CFM) through a variable frequency controller. Force measurements are taken by an ATI Mini85 Load Cell placed on the bottom surface of the tunnel's test section. They can accommodate any mount with a connection compatible with a 1.375-inch inner diameter tube with a 0.375-inch pinhole located 1.25 inches from the top of the tube, as shown in Fig. 12.

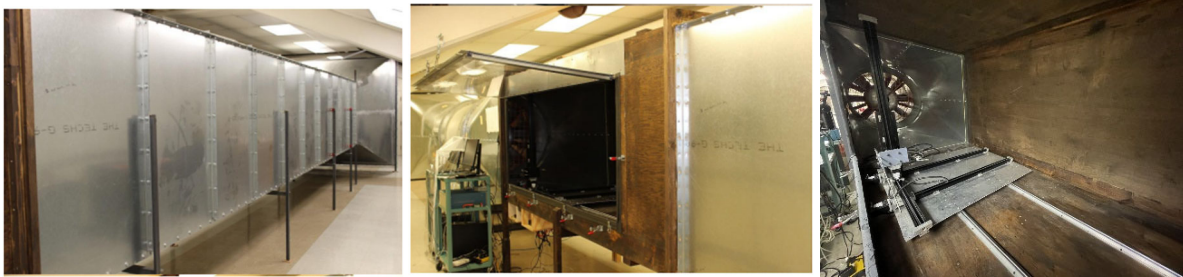


Figure 12. Tennessee Tech University (TTU)'s Wind Tunnel



Figure 13. (a) Traverse system, (b) load cell boom arm, and (c) DAQ

Fig. 13 illustrates the data acquisition (DAQ) and sensor suite used for the measurement. This load cell can measure forces and torques in all primary axes ( $F_x, F_y, F_z, T_x, T_y, T_z$ ). This is run using a DAQ (data acquisition) device in parallel with LabVIEW, supporting a sampling rate of up to 1000 Hz. The wind tunnel also features a three-directional traverse system, as shown above, for instrument integration, enabling the mapping of turbulence in the tunnel by measuring air velocity and direction at each measurement point. This data can be used to map the flow behind the article, highlighting the turbulent effects generated. The traverse system can travel 1 meter in the x, y, and z directions. The adequate test volume is 1 meter by 1 meter to accommodate the traverse system's full reach. The traverse system currently accommodates a hotwire anemometer probe, as well as various 1-D and 2-D probes. The adjustable alpha, beta, and roll stand used in the wind tunnel is a 3D-printed PLA device that utilizes servos for accurate angle adjustment, with gears rotating sections of the mount accordingly. These servos are rated for loads of up to 40 kg-cm and feature closed-loop position retention programming, along with a 5:1 gear ratio. The mount can adjust the model's roll, pitch, and yaw angles and simulate various flight conditions. Any directional adjustment can also be swapped to accommodate only one or two directions, ensuring greater accuracy for the desired angles. The mount itself can be controlled via a laptop, allowing users to set angles corresponding to the required data without significant work on the article. At the same time, it is positioned in the tunnel. This wind tunnel is used in this study to obtain lift (L) and drag (D), as well as other aerodynamic properties, for various angles of attack (AoA) and vary the location of engines spanwise. The results obtained from this wind tunnel testing are then plotted and compared with those from the computational simulation method.

## Summary

This study investigates the aerodynamic effects of engine placement and numbers on the performance of commercial aircraft, with a specific focus on the Boeing 737 MAX, a widely used commercial airliner. The research examines the aero-propulsion interaction by employing rapid but low-fidelity numerical simulation tools, which are validated through wind tunnel testing. Key variables include engine size, spanwise placement, and configurations for single and proportionally distributed propulsion systems. Findings reveal that engine placement has a significant impact on aerodynamic efficiency (AE), with configurations closer to the fuselage resulting in improved aerodynamic efficiency (AE). For a single engine per wing, an aerodynamic efficiency (AE) of 16.2 was found, which is best when placed near the wing root. The introduction of proportionally distributed propulsion systems featuring smaller engines distributed across the wingspan resolves ground clearance challenges posed by larger nacelles while maintaining acceptable aerodynamic performance. The same trend has been observed; in single-engine configurations, the engines closer to the wing roots provide a better aerodynamic efficiency (AE) of 15, 12.84, and 9.75 for 2, 3, and 4 proportionally distributed engines per wing, respectively. This trade-off between AE and practical design considerations is crucial for complying with Federal Aviation Administration (FAA) guidelines and ensuring the viability of carbon-neutral propulsion systems, such as those powered by solid oxide fuel cell (SOFC) engines. Additionally, the study emphasizes the significance of understanding aero-propulsion interaction for future aircraft designs. The combination of computational analysis and wind tunnel validation provides a robust framework for optimizing nacelle aerodynamics, paving the way for sustainable and efficient aviation solutions. This work contributes to the ongoing efforts to achieve carbon-neutral aviation while preserving high-performance standards.

## Conclusion

This research highlights the critical role of aero-propulsion interactions in optimizing aircraft design, with a specific focus on nacelle aerodynamics and engine placement. Through computational simulations validated by wind tunnel testing, the study demonstrates that an aircraft's aerodynamic performance can significantly influence engine configuration, size, and position along the wingspan. The findings reveal that placing engines closer to the fuselage enhances aerodynamic efficiency (AE) by reducing drag (D) and mitigating wing-nacelle interference. Proportionally distributed propulsion systems, with smaller engines strategically positioned across the wingspan, address challenges such as ground clearance while maintaining performance within acceptable limits. These insights are particularly relevant for integrating carbon-neutral propulsion technologies, such as solid-oxide fuel cell (SOFC)-based engines, into existing aircraft designs. For example, when we adopt a new carbonless propulsion system, two engines per wing will be the most optimal, with the engines positioned closer to the fuselage to achieve optimum aerodynamic efficiency (AE). The optimum aerodynamic efficiency (AE) will encounter range reduction due to the lower energy density of the carbonless propulsion system. By balancing aerodynamic performance with practical considerations such as regulatory compliance and manufacturability, this study provides a pathway for developing sustainable, high-performance aircraft. The methodologies and results presented here provide valuable guidance for future design efforts aimed at reducing environmental impact while meeting the growing demand for efficient, eco-friendly aviation solutions.

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