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An Environmental and Economic Analysis of the Practicality of Incorporating Boundary Layer Ingestion

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ABSTRACT: Aerodynamic drag (e.g., wave drag, induced drag, and skin friction/boundary layer drag) has long remained and continues to be a caveat in aircraft fuel efficiency, despite decades of advancements in propulsion and design. However, boundary layer ingestion (BLI) propulsion systems have shown promising results in improving aircraft fuel efficiency through ingesting the lower velocity boundary layer air to reduce wake kinetic energy and overall power requirements. This study addresses the economic and environmental benefits of BLI integration in commercial aircraft through the use of power balance calculations, analysis of published computational data, and performing economic and environmental analyses through calculated performance results. We believe that BLI integration has the benefits that make it practical for commercial use, and using force coefficient data from fully coupled aerodynamic propulsion simulations, we calculated reductions of shaft power requirements up to ~1021 hp relative to conventional podded configurations. This corresponds to estimates around a 7-10% lower fuel burn and annual savings of ~\$400,000 to \$560,000 per BLI aircraft configuration. These savings also correspond to CO_2 emissions reductions of up to 3.4 million lb per aircraft, which result in more than ~100.0 million lbs of CO_2 over the course of its life cycle. However, challenges like fan efficiency, which require strict design requirements to mitigate, and challenges in structural integration of the system can lead to high developmental costs. Despite this, because of a rapidly increasing aircraft carbon footprint, the benefits that BLI provides ultimately prove the developmental costs to be superficial in light of achieving ambitious sustainability goals.

KEYWORDS: Boundary Layer Ingestion (BLI), Computational Fluid Dynamics (CFD), Pressure Ratio (FPR), Power-Balance, Thrust Specific Fuel Consumption (TSFC), Power Specific Fuel Consumption (PSFC).

Introduction

Despite decades of advancements in aircraft technology in terms of propulsion efficiency and design, there remain aerodynamic inefficiencies that limit improvements in fuel efficiency and environmental factors. Aerodynamic drag—especially induced drag during takeoff and landing, wave drag at transonic cruise, and skin-friction drag due to turbulent boundary layers—remains a dominant factor in fuel consumption. Confronting these issues is rather important, particularly considering ambitious targets such as ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), NASA's N+3 goal of a 70% reduction in fuel burn by 2035, and ACARE's 75% CO_2 emission reduction goal by 2050.[1,2]

A possible solution to reducing drag and improving overall aircraft efficiency would be Boundary Layer ingestion (BLI) systems, which, unlike traditional podded engine systems, BLI ingests the lower velocity boundary layer air either from the fuselage or over the airfoil, reducing the aircraft's power requirement.[2] This approach has been explored in configurations such as NASA's STARC-ABL and MIT/NASA's D8 Series, both incorporating aft-mounted BLI systems. Some models highlight up to 15% reductions in power for the D8 concept.[3] Furthermore, computational studies using the common research model (CRM) geometry also showed that BLI systems can reduce engine power requirements by as much as 15.6% while also reducing drag compared to podded engine systems.[4] These improvements are also linked to how the BLI system utilizes the fuselage wake, which reduces the required jet propulsive power.[4]

However, BLI is not without its limitations. Engine inlet distortion reduces fan efficiency by 0.5–5%.[5] Additionally, structural complexities arise from propulsion system and airframe integration, particularly for embedded or aft-mounted systems.[6] The D8 aircraft concept also shows that BLI systems cannot just be fitted onto any airframe, as in its design, the fuselage and propulsion system were designed specifically to utilize the thickened boundary layer.[6,7] Additionally, simulation modeling can be rather difficult for BLI systems. To accurately highlight the effects of BLI systems, Gray *et al.* suggest a coupled modeling of both the airframe and propulsion system rather than the traditional approach to design separately, in cases when the propulsion system is placed in free-stream air. The assumption that small changes to either system do not affect each other no longer applies to BLI systems, as fully integrated simulations (such as those used in NASA's STARC-ABL and MIT's D8 studies) show that these small changes to either system can significantly affect BLI engine performance.[3,8] Because of these challenges with research and development, the costs for developing BLI systems may be higher than the development costs of other aircraft.

Despite the extensive research into BLI systems and their benefits in fuel efficiency, there has not been significant discussion on the costs and practicality of actually incorporating BLI systems for commercial use. On top of the additional research

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and developmental costs that are a product of complexities with simulation and incorporation of BLI systems, there may also be additional maintenance and production costs due to the incorporation of an additional aft-mounted BLI propulsor.

That is why, when given the tradeoff between potential aerodynamic improvements and the challenges of incorporating BLI systems, it is necessary to assess the system's impact and practicality through performance-based analysis. This paper aimed to address the environmental and economic benefits of boundary layer ingestion (BLI) systems compared to standard podded configurations through the use of published data, power balance calculations, fuel consumption calculations, and emissions conversions. We hypothesize that the integration of BLI systems can produce reductions in propulsive power requirements, fuel burn & fuel cost, and CO_2 emissions that outweigh its integration and design challenges.

Background

2.1. Aerodynamic Drag in Aircraft:

In the case of aircraft, drag comes in the form of aerodynamic drag, which is the resistive force an aircraft experiences as it cruises through the atmosphere. For commercial transport aircraft, total drag is composed primarily of:

-Induced drag, which is mainly from lift generation (when the flaps extend out and down to produce lift via Newton's 3rd law and Bernoulli's principle), is mainly present during takeoff, aircraft climb, and landing.

-Wave drag, which is caused by compressibility effects of the air and shockwaves (where airflow locally exceeds the speed of sound) at transonic flight.

-Skin friction drag, which results from within the turbulent boundary layer along the fuselage and wings.

These forms of drag directly influence the thrust required for cruise flight, and as a result, they also bring about a plethora of other issues, such as effects on the fuel requirements/ efficiency and the environmental impact of the aircraft. Even with advances in aerodynamics and propulsion integration, these forms of drag are still major inhibitors to operational efficiency.[2]

2.2. Boundary Layer Ingestion:

BLI is a propulsion system where the engine inlets ingest the lower velocity boundary layer air from the fuselage or wing surface rather than the free stream air, as seen in traditional engine configurations. As a result, this reduces wake kinetic energy and recovers momentum that would be otherwise lost to drag, as seen in Figure 1.[2, 3]

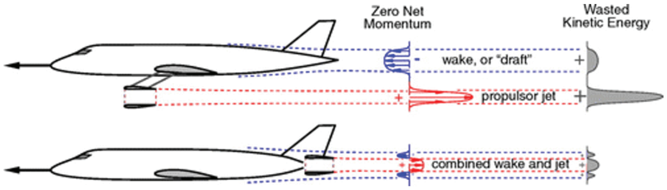


Figure 1: By absorbing the boundary layer air, the wake kinetic energy is reduced, thus reducing the energy required.

Computational fluid dynamics (CFD) studies have shown that BLI has reduced propulsive power requirements:

-The D8 concept estimates up to a ~15% cruise power reduction from twin rear-mounted fans ingesting a thickened boundary layer, and Common research model (CRM) based simulations done by NASA highlighted up to a 15.6% reduction in engine power at cruise.[3]

However, BLI also introduces challenges. Engine inlet distortion, which is caused by ingesting low-energy boundary layer air, resulting in deviations in pressure from the ideal condition, can reduce fan efficiency by up to 0.5-5%. Furthermore, there are difficulties in the integration of BLI systems, as oftentimes, they cannot just be retrofitted onto legacy frames.[5-7] Additionally, in the case of the D8 study, the airframe had to be specifically designed to produce a boundary layer profile to optimally match the propulsor inlet, as the fuselage shape was essential to the projected gains.[3]

Methodology

3.1. Research Approach:

This study uses CFD simulation data to calculate the power requirements of BLI systems and thus determine the propulsive benefits of Boundary Layer Ingestion systems relative to podded engine systems. Fully coupled aerodynamic propulsion data from Gray *et al.* for the STARC-ABL configuration (Figure 2) are analyzed to determine the changes in net axial force from BLI and podded systems. The data is then used to calculate the power requirements, which we then cross-compare with data for the Airbus A320 Neo (a narrow-body aircraft with roughly the same size as the STARC-ABL configuration). We will then use the calculated power requirements to compute CO_2 reductions, Fuel burn, and estimated life cycle cost analysis.

Figure 2: Simulation render of the STARC-ABL configuration. An aft-mounted electric BLI propulsor (powered by the podded engines) ingests the boundary layer air.

Figure 3: Rendering of Airbus A320-200 NEO. An incremental development aircraft part of the A320 aircraft family. This aircraft is fitted with next-generation engines, improving the aircraft's fuel efficiency.

3.2. Flight Conditions:

Both configurations in Gray *et al.* (2018) share the same cruise conditions as well as reference area (A = 1400 ft^2)

1. Baseline: Conventional twin podded turbofans
2. BLI: STARC-ABL configuration with an aft-mounted BLI system supported by podded turbofans for takeoff and climb

Cruise conditions:[8, 9]

- Mach: $M\infty=0.72$
- Altitude: 37,000 ft
- $\rho\infty=0.0008$ slug/ft3
- $V\infty=707.3$ ft/s

3.3.: Force to Power Conversion

Net axial force coefficient for the propulsor ($C_{fx\text{-}prop}$) is defined as

$$C_{F_{x-prop}} = \frac{2(Thrust - Drag)}{\rho V^2 A_{ref}} \#(3.1)$$

Net axial force coefficient for the fuselage ($C_{fx\text{-}fuse}$) is defined as:

$$C_{F_x-fuse} = \frac{2(F)}{\rho V^2 A_{ref}} \#(3.2)$$

Where F is composed of pressure and viscous forces that contribute to drag

This is a simplified version of the integration done in Gray *et al.*, as in the $C_{Fx\text{-}prop}$, drag is composed of outer nacelle pressure and viscous forces, as well as "ram drag" (the momentum deficit to suck in air flow). Thrust is composed of the jet momentum.

(Note the row and V values are still the freestream values from the cruise conditions listed above)

Step 1: Force

$$F_x = C_{F_x} \cdot \frac{1}{2}\rho_\infty V_\infty^2 A_{ref} \#(3.3)$$

The net force F_x is calculated using the net force coefficient (C_{Fx}), which is the combined force coefficient of the fuselage and propulsor. This coefficient is then multiplied by the free stream air density ρ_∞ at 37,000 ft, the free stream air velocity V_∞, and the reference wing area A_{ref}.

Step 2: Power

$$P_{net} = F_x \cdot V_\infty \#(3.4)$$

This is the standard formula for net power, which is calculated by multiplying the net force F_x by the free stream air velocity V_∞.

Step 3: Fuel Burn

$$\dot{m}_{fuel} = \frac{PSFC \times \Delta P_{net}}{6.71} \#(3.5)$$

This is the equation for calculating the fuel burn reductions $\dot{m}_{fuel}$, with PSFC being the power specific fuel consumption (which we calculate from thrust specific fuel consumption) multiplied by the difference in net power between the BLI systems and Podded configurations. It is then divided by 6.71, which is the lbs per gallon of Jet A-1 fuel.

3.4. Economic and Environmental Factors:

1. Fuel cost: Jet fuel price ~\$3.00/gal (Jet A-1 6.71 lb/gal).[10]
2. CO_2 Factor: ~21 lb CO_2 per gallon burned.[10]

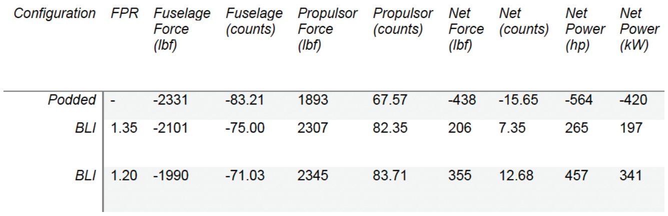
3.5. Integration Costs:

Despite the many benefits that BLI provides, there are also limitations when it comes to the integration of BLI systems. As mentioned previously, BLI systems cannot simply be fitted onto standard airframes, and there are structural modifications required to integrate them. Additionally, since BLI is designed to ingest and accelerate the slower-moving boundary layer air, the engine fans experience distortion, so to tolerate that distortion, specialized fan/inlet designs are also required.

Results

4.1. Force Coefficients:

Table 1: Given and calculated metric values for the comparison between BLI and Podded Configurations (The counts are the net axial force coefficients * 10^4).



Configuration	*FPR*	*Fuselage Force (lbf)*	*Fuselage (counts)*	*Propulsor Force (lbf)*	*Propulsor (counts)*	*Net Force (lbf)*	*Net (counts)*	*Net Power (hp)*	*Net Power (kW)*
Podded	-	-2331	-83.21	1893	67.57	-438	-15.65	-564	-420
BLI	1.35	-2101	-75.00	2307	82.35	206	7.35	265	197
BLI	1.20	-1990	-71.03	2345	83.71	355	12.68	457	341

The force coefficient and FPR (fan pressure ratio) values are taken directly from experimental results in Gray *et al.*, in which they conducted a fully coupled simulation on the STARC-ABL BLI system. This data shows that for both BLI configurations, power requirements were significantly reduced (with BLI at FPR 1.35 producing 197 kW of excess power, and BLI at FPR 1.20 producing 341 kW of excess power).

Using eq 3.3 and eq 3,.4 we were able to calculate the net axial force (lbf) and thus the net power requirement

4.2. Analysis:

For the Podded configuration (reference), the combined fuselage + podded propulsor has a net backward force (negative F_x). Converting that residual drag to power gives about 564 hp that the podded engines must additionally provide just to hold cruising speed on top of anything else they're doing. Comparatively, with the BLI configurations (paired 3500 hp aft-mounted boundary layer electric propulsor), the net force Fx (propulsor + fuselage) is positive. The BLI systems produce an excess of ~265 hp at 1.35 and an excess of ~457 hp at FPR = 1.20 (see Table 1).

With podded configurations, the podded under-wing engines must cover 564 hp just to cancel the system's residual drag. With BLI in the STARC-ABL configuration, the podded under-wing engines can throttle back by the BLI surplus, which is ~265-457 hp, because the system is already accelerating forward. Relative to the podded case, BLI improves the propulsive power balance by ~829 hp at FPR 1.35 and ~1021 hp at FPR 1.20.

In the BLI, the aft propulsor itself is being driven at a fixed 3,500 hp shaft, which is powered by the electric power gener-

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ated by the under-wing engines (which also provide the cruise thrust), so the generated power benefits are not a result of an additional power source.

4.3. Fuel and CO2 Savings Estimates:

We will be estimating PFSC (power specific fuel consumption) based on NASA's Glenn Research Center's reference of TFSC for turbofan values as 0.5 at sea level static environments.[11] It is important to note, however, that this value can vary with factors like altitude, velocity, and engine design, so we will be proceeding further with caution. Despite this, these values should be sufficient to serve as a basis for our estimates.

TFSC conversion to PSFC:

$$PSFC\ [lb/(hp \times hr)] = \frac{TSFC\ [lb/(lbf \times hr)] \times 550}{V\ [ft/s]} \#(4.1)$$

Through this, we find our PSFC to be

$$PSFC = 0.389\ [lb/(hp \times hr)]$$

We will be using the Airbus A320 NEO (Figure 3) cruising at 37,000 ft as our reference model since it is in the relatively same class size based on wingspan and passenger load as the STARC ABL model. We find that in a standard 7-hour flight, the Airbus A320 NEO model burns ~4732 gal.[12-14]

Now using eq 3.6 to calculate fuel savings per hour, we find:

- BLI at FPR 1.35 (Δ = 829 hp)
  - o Fuel savings (gal/hr) ~ 48.09 gal/hr
  - o CO_2 savings ~ 1009.26 lb/hr
- BLI at FPR 1.20 (Δ = 1021 hp)
  - o Fuel savings (gal/hr) ~ 59.19 gal/hr
  - o CO_2 savings ~ 1243.00 lb/hr

And adjusting for the 7-hour flight, we find that the BLI configurations can save an estimated ~7-10% in fuel burn per flight, and flying ~2700 flight hours per year, we find that the savings on fuel total up to around ~$400,000 - $560,000 per configuration each year.[15,16] Additionally, if we consider the reduction in carbon emissions, we find an estimated reduction in CO_2 by up to ~3,356,000 lb CO_2 per configuration each year.

The STARC-ABL configuration utilizes a 3rd aft mounted BLI propulsor, unlike the 2 narrowbody engines seen in the Airbus A320 NEO. Since there is no available data on the price for the tailcone propulsor, as it is still in the research and development phase, we will estimate the cost by aligning it with the cost of a Pratt & Whitney PW1100 (~$12,000,000 USD) as seen in an A320 NEO model. It is to be noted, however, that the price of the actual BLI propulsor may vary higher or lower than the estimated price.[17-19]

Discussion

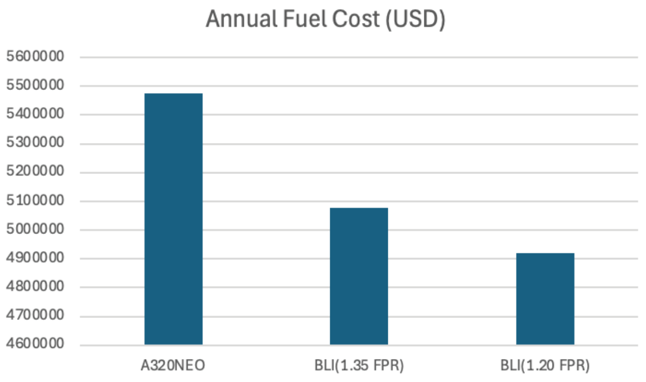

Figure 4: Fuel Cost comparison across A320NEO and 2 BLI Configurations. This data shows that both BLI configurations have significantly reduced fuel costs (upwards of 10%) when compared to their podded A320 counterpart.

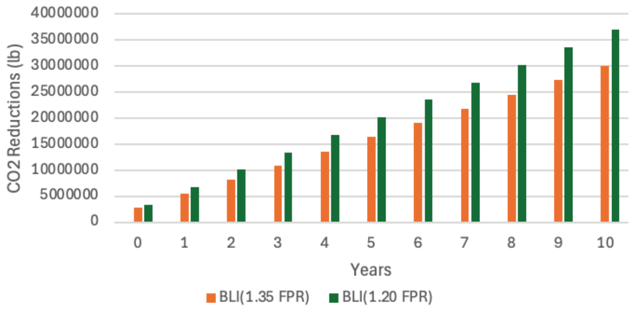

Figure 5: Reductions in CO_2 emissions for BLI at FPR 1.20 and at FPR 1.35 over the course of 10 years. This data shows that when compared to the A320 Neo configuration, both BLI configurations demonstrated significant CO_2 reduction (up to ~375 million lbs over the course of 10 years). It is also to be noted that BLI at an FPR of 1.20 is shown to be more efficient when compared to BLI at FPR 1.35.

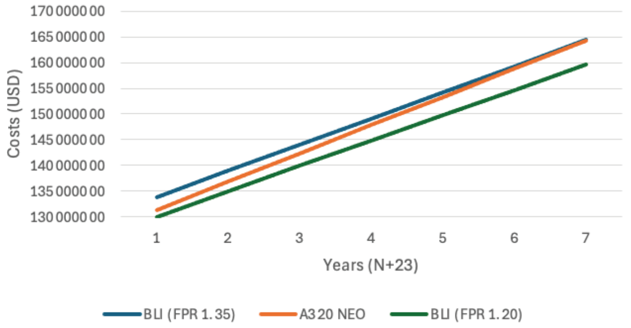

Figure 6: Lifespan cost assessment for the BLI systems and A320 NEO configuration, accounting only for the fuel burn savings and cost of an additional propulsor. This data predicts that over the course of a 30-year lifecycle for all three configurations, their life-cycle costs will remain roughly similar. BLI at FPR 1.20 is the cheapest to maintain, while the A320 Neo and BLI at FPR 1.35 have roughly similar life-cycle costs.

From the analysis of the STARC-ABL BLI configuration (see Figure 2) in Table 1, we find that under the realistic cruise conditions presented in section 3.2, BLI reduces shaft power by ~829-1021 hp compared to conventional podded systems. This translates to ~7-10% fuel savings. Figures 4-6 provide an overview of the results we found from our additional calculations. BLI in both FPR scenarios demonstrates significant benefits compared to standard podded configurations in several environmental and economic parameters. The BLI configuration's fuel efficiency improvements have led to significant reductions in estimated annual fuel costs and fuel burn. Furthermore, as a result of fuel burn reductions, BLI has been estimated to reduce CO_2 emissions by up to 35,000,000+ lbs of CO_2 per configuration over the course of 10 years and potentially triple that number over the course of its lifespan. However, in the STARC-ABL configuration, there is an additional propulsor configuration, but as demonstrated in Figure 6, BLI in both configurations is seen to nullify or even improve on that cost deficit over the course of its lifespan (30 years).[20] It is to be noted that in the case of BLI, which is a technology still in the research and development phase, there is no concrete value on the actual price of the propulsor, and as a result, the actual developmental value can vary significantly from our predicted value.

Additionally, this figure does not consider maintenance costs for these aircraft, as it is assumed that for all 3 configurations, it would be the same. This is because both the BLI configurations and podded configurations are roughly the same in aircraft size, and thus, maintenance costs should correlate.[21] However, this figure does not account for the maintenance cost of the additional aft-mounted propulsor in the BLI configurations, so our estimated costs for the BLI configurations are probably greater than the value we predicted for the total lifecycle cost.

Despite this, in the bigger picture, the difference in costs between the systems is ultimately going to be negligible. It is important to acknowledge, however, that despite the benefits, there are also significant challenges that come with the incorporation of BLI. Our use of a fixed TSFC value to calculate our PSFC introduces uncertainty, as fuel consumption changes varyingly on altitude and engine design. Additionally, with the incorporation of an additional aft-mounted electric propulsor, integration issues and complexities arise. For example, the developmental requirements needed to mitigate fan inlet distortion from ingesting the slow-moving boundary layer air can significantly increase research and developmental costs, as special inlets need to be designed to prevent performance deterioration or stalling. Adding on, additional maintenance systems such as a cooling system for the aft-mounted propulsor are also required, which will increase the cost and maintenance complexity even more.[22] Aircraft development programs can cost upwards of billions of USD to develop, making the financial commitment to realizing BLI quite extensive (notably seen in the Boeing-737 MAX with R&D costs estimated to be well over $2 billion USD).[23-25] However, with sustainability goals like NASA's N+3 target of fuel burn and NO_x reductions, and ACARE's 75% CO_2 emissions reductions by 2050, BLI serves as a promising tool to help meet those goals.

Conclusion

In this study, we utilized fully coupled CFD simulation data to support our power balance calculations, from which we were able to deduce that BLI improves on standard podded configurations in several important sustainability parameters, including fuel efficiency, fuel burn reductions, and CO_2 reductions. BLI has achieved ~7-10% reductions in fuel burn corresponding to up to ~$560,000 in annual savings per configuration, and they also reduce CO_2 emissions of up to +3,000,000 lbs. per configuration each year as well. From the rough estimate for a 30-year life cycle cost assessment, we found that the BLI systems cost less or roughly the same as a standard podded configuration despite having an extra BLI propulsor. It should be noted that this result is an estimate. It does not incorporate maintenance costs in the calculation, which may result in costs for BLI systems being higher because of the additional propulsor. Furthermore, since the technology is still in the research and development phase, it is hard to really put a concrete number on the exact cost of incorporating a BLI system, but with the integration and developmental complexities that come with BLI, the financial burden for research and development can be quite extensive.

However, in light of ambitious sustainability goals with NASA's N+3 target of 70% fuel burn improvement and 75% reduction in NO_x emissions by 2035, along with ACARE's 75% CO_2 emissions reductions by 2050, BLI demonstrates potential to help meet those sustainability goals. While significant research and development are still needed to address the challenges, BLI is ultimately something that should be pursued for research, development, and widespread incorporation.

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