

Laminar Flow: A Viable Focus Point for a Sustainable Aviation Future?

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ABSTRACT: Aircraft designs have always tried to incorporate laminar airflow in order to reduce surface drag, but the recent shift towards sustainability has accentuated the need for reduced emissions, especially in the aviation sector. The European aviation sector alone is expected to deplete its carbon budget compatible with the UN 1.5°C warming goal as early as 2026. Whilst many efficiency gains have been made over the past years, namely the newer composite materials such as those used in the Boeing 787 or the next-generation engines used on Airbus's NEO variants, there is a renewed need for a revolutionary, sector-changing technology, and laminar flow control designs (LFCDs) may provide just this. Primary research in this field focuses on reviewing specific technologies or design elements, such as winglets, and analyzing their effect on aerodynamic efficiency. Very few, however, provide any reference to its maturity or ability to be implemented, where a metric such as the Technology Readiness Level (TRL) can be used. This paper provides an updated review and determination of the feasibility and overall effectiveness of laminar flow control designs to increase aerodynamic efficiency, focusing on commercial aircraft in the short-term future. Although LFCDs provide significant reductions in carbon emissions and, in turn, also decrease contrail production, an extremely harmful by-product of flight that traps heat and is a cause of global warming, they are extremely difficult to implement effectively on a more complex and commercial scale.

KEYWORDS: Engineering, Aerodynamics, Laminar Flow Control, Reynolds' Number, Boundary Layer.

■ Introduction

Minimizing aerodynamic drag remains one of the most important goals in aircraft design and development, especially with the growing environmental demands on the aviation sector.^{1,2}

With pressure being put on the aviation industry to decrease its carbon footprint, the European sector, by the end of 2026, is projected to deplete its allocated carbon budget compatible with the 2050 1.5°C global warming goal,³ much research has been done in this specific field to find new, innovative ways of decreasing aircraft emissions. For example, modern aircraft have seen incremental improvements in materials and propulsion, yielding moderate efficiency improvements such as those seen in the Boeing 787.⁴

However, a more favorable solution is to decrease the surface drag on the airframe. Recent research shows that every 1% decrease in drag can result in a reduction of 9 million tonnes of CO₂, indicating that small reductions in drag can achieve substantial emissions results.⁵ Consequently, laminar flow control has surfaced as a promising research field, presenting potential efficiency improvements that exceed those attainable through gradual advancements in traditional turbulent-flow designs.

A strategy that has been the focus of a large quantity of research for many years is the implementation of laminar flow control designs (LFCD), a technology that looks to reduce skin-friction drag by postponing the shift of fast-flowing air, predominantly over the wings, from laminar to turbulent flow.

Nonetheless, in spite of years of experimental research, the use of LFCDs in commercial aviation is still limited. A large portion of the current literature focuses on small aircraft, such

as business jets or specific parts like wings or nacelles. It is also important to note that LFCDs are not the only emerging technology based on drag reduction, and many other technologies have been or are currently being implemented. Namely, winglets or blended wingtips, as seen on newer aircraft like the A350, have been proven to provide around 15% less drag, a huge improvement with a fairly minor change to the actual airframe.⁶

Moreover, recent environmental and aviation research has widened its scope to include more than just fuel use, emphasizing how aircraft-generated contrails contribute to aviation's environmental footprint.⁷

These results point to LFCDs not only enhancing efficiency but also significantly decreasing non-CO₂-related climate impacts.

This paper's main objectives are to:

i) State and explain the principles of aerodynamics related to laminar flow that will be subsequently analyzed by focusing on the elements that govern the technology's airliner implementation and scalability potential.

ii) Examine the present state of laminar flow technology within both the engineering field and the commercial aviation sector, highlighting its real-world applications in existing airframes and potential implementations in conceptual aircraft.

iii) Assess the practicality of implementing laminar flow technology in large commercial aircraft in terms of the Technology Readiness Level (TRL) framework developed by NASA.

This evaluation examines both technological advancement and scalability, determining if laminar flow-based designs

can become an extensively used, operational technology. This analysis seeks to provide an assessment of the advantages and drawbacks of laminar flow as a means of enhancing aerodynamic efficiency in commercial aviation.

Most sources reviewed in this paper were found through Google Scholar or digital search engines. Priority was given to peer-reviewed papers and journal articles, whilst technical and experimental reports were used for empirical and quantitative data. These include a 1945 NACA airfoil data report and a 1965 X-21a flight test analysis. The only non-technical source used was an Airbus BLADE program press release, cited only to report test outcomes. Sources were selected only if they specifically applied to past or current subsonic aircraft, and the only literature focused on non-commercial aircraft was the X-21a report, which was included only due to its being a test flight for specific laminar flow control technology.

It is important to emphasize that current literature often labels laminar flow control as either hybrid (HLFC), active (ALFC), or full (FLFC). For clarity, this paper will refer to any non-passive laminar flow control methods, including HLFC, as ALFC, a system that actively stabilizes the boundary layer through suction applied through perforations in specific areas of the airframe.

■ Section 1 - Aerodynamic Principles

Section 1.1. - Skin Friction Coefficients:

As an aircraft moves through the air, skin friction arises due to viscous shear stress within the boundary layer. To quantify this friction, a laminar skin-friction coefficient is used. For this, an approximated Reynolds' number of 2×10^7 for an airliner in a cruise state is used.⁸ Using the formula, the average skin-friction coefficient for laminar flow over the whole wing can be calculated as a value of around 3×10^{-4} .

Under the same conditions, a typical turbulent-flow value is around 2.9×10^{-3} (See Appendix, Equation A1 and A2). These values are, however, derived from flat plate approximations and do not take into account crossflow instabilities or three-dimensional pressure distributions, yet still represent the quantitative incentive for laminar flow over aircraft surfaces.

Overall, the value for turbulent airflow is nearly one order of magnitude greater than that of the laminar flow, meaning that maintaining even small amounts of laminar airflow over a section of a wing is disproportionately beneficial in reducing total aircraft surface drag.

Section 1.2. - Reynolds' Number:

Reynolds' number is a fundamental tool used in the field of aeronautical engineering, and it represents the ratio between inertial and viscous forces in the flow of a fluid, helping to determine whether airflow, in this case, is turbulent or laminar.

Reynolds' number can be defined with the formula:

$$Re = \frac{\rho V x}{\mu} \quad (1)$$

Where ρ is the density of air, V is the velocity, x is the length at which transition occurs, and μ is the dynamic viscosity of air.

This formula can be used to determine the location of transition along the chord (the distance between the leading and trailing edges). Using a transitional Reynolds' number value of around 5×10^6 and substituting with typical aircraft cruise values:⁸ $\rho = 0.385 \text{ kg m}^{-3}$, $V = 230 \text{ m s}^{-1}$, $\mu = 1.45 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$.

Rearranging and solving for x gives a value of $x \approx 0.82 \text{ m}$.

Given that an Airbus A320's chord length is approximately 4 m ,⁹ the transition to turbulent flow would take place very early. This value results in around 20% laminar flow, highlighting the immediacy with which airflow loses its laminar properties on normal airliners.

Suction-based ALFC aims to achieve laminar flow over around 45% of the chord,¹⁰ which, applied to the context of the A320, is around 1.8 m along the chord. Substituting this value into Equation 3 gives a Re of approximately 1.1×10^7 , more than double the initial boundary layer stabilization.

Section 1.3. - Boundary Layer Thickness:

Using the previous calculations, the boundary layer thickness at the transition point can be approximated using the formula:

$$\delta_{lam} = \frac{4.91x}{\sqrt{Re}} \quad (2)$$

Substituting gives a value of around 0.002 m (2 mm), indicating just how prone the boundary layer is to any minimal contamination or surface roughness.

Section 1.4. - Pressure Gradients:

Another factor that affects the stability of the boundary layer is the pressure gradient along the wing.¹¹ Starting with the pressure coefficient formula:

$$Cp = \frac{p - p_{\infty}}{\frac{1}{2}\rho V^2} \quad (3)$$

Where p is pressure, p_{∞} is the pressure in the freestream, ρ is the air density, and V is the air velocity. Rearranging for ρ and differentiating to find the pressure gradient, seeing as p_{∞} is constant, then gives:

$$\frac{d\rho}{dx} = \frac{1}{2}\rho V^2 \times \frac{dCp}{dx} \quad (4)$$

To illustrate this, using an author's own estimated derivative of Cp of $-0.5/\text{m}$ from data about a 65-series airfoil, documented graphically in a NACA report analyzing various airfoil characteristics,¹² and using the constant values for air density and velocity, the pressure gradient is roughly -5000 Pa m^{-1} (See Appendix, Equation A3). This negative pressure gradient is favorable, which accelerates the airflow and stabilizes the boundary layer. This illustrative figure of -5000 Pa m^{-1} remains consistent with experimental tests such as the BLADE demonstrator, further analyzed in Section 2.2, and with the sustained laminar flow over 45% of the chord figure discussed in Section 1.2.¹⁰

Laminar flow airfoils are therefore designed with a favorable pressure gradient in mind, meant to sustain it over much of the forward chord. Shifting the hybrid suction systems towards the aft section of the wing, near the trailing edge, would, in theory, suppress instability growth by reducing the inflection

in the velocity profile.¹³ However, a design such as this one would inherently be extremely sensitive to different types of surface contamination and imperfections, having an unintended effect on the pressure gradient, potentially causing a transition to turbulent flow, and rendering its use impractical.

Section 1.5. - Summary:

The equations and calculations presented in this section highlight numerous implications and dependencies for ALFC implementation:

- i) There is a large difference between surface drag produced with laminar versus turbulent airflow, explaining how even minimal ALFC application can be extremely beneficial.
- ii) The underlying importance of operational service smoothness over surfaces that produce laminar flow, mostly wings, is due to the minute boundary layer thickness that is created.
- iii) Laminar flow is achieved and maintained not only through airflow manipulation but also through the creation of pressure gradients that stabilize the boundary layer and contribute to a delayed transition.

This quantitative information provides a basis for a feasibility assessment of the LFCD technologies, explored in a further section.

■ Section 2 - Design Strategies

Section 2.1. - Laminar Flow Control Technology:

The main goal of laminar flow control devices as aerodynamic design strategies is to reduce the skin-friction drag on certain areas of the airframe, mostly the airfoils such as the wings or horizontal stabilizers, by either delaying or, ideally, suppressing the transition from laminar to turbulent air, as shown in Figure 1 below. Seeing as the air flows in layers over the surface, the objective is to keep the boundary layer stable, the layer of air that is in contact with the aircraft, to stop the flow from becoming turbulent. This is done because the skin friction drag due to this turbulent air is the main cause of air resistance in an airliner's cruise state. Even very small improvements in delaying the transition can proportionally have much larger effects on drag reduction due to the airliner's greater size, as examined in terms of Reynolds' number in Section 1.2.

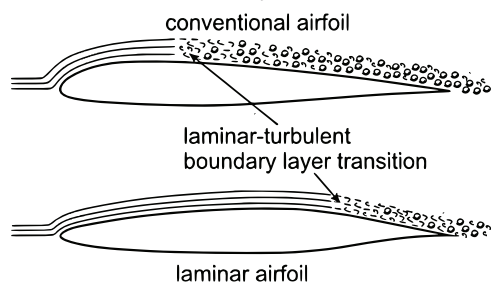


Figure 1: Laminar to turbulent transition on a laminar airfoil compared to a conventional airfoil - adapted from "Novel aeroelastic instabilities on laminar wings" by DLR.¹⁴

The term 'laminar flow control' encompasses a wide set of different strategies. These are most often categorized into 3 different approaches: Natural Laminar Flow (NLF), Active Laminar Flow Control (ALFC), and Full Laminar Flow Con-

trol (FLFC). They vary in both complexity and effectiveness. NLF is on the lower end of both of these scales, due to its nature as a passive approach, whilst active, hybrid, or fully controlled designs use different mechanical systems to stabilize the boundary layer.

Section 2.2. - Natural Laminar Flow:

Natural Laminar Flow (NLF) is the most widely implemented form of LFCD, relying on passive aerodynamic design instead of active boundary layer stabilization. The careful shaping of airfoils helps maintain a favorable pressure gradient, where pressure decreases in the direction of the flowing air, allowing the air to accelerate and the flow to remain attached to the surface. This delays the transition to turbulent air, prolonging laminar flow without the need for additional mechanical systems.

The most common way to increase NLF is to keep a seamless aerodynamic profile across the whole airframe, so as not to disrupt the flow of air. This can be done, for example, by integrating various structural components such as rivets or seams, requiring high-precision manufacturing. Another key element is the wing design, as NLF-based aircraft often make use of extended leading edges. This is because the extended section of the rounded surface divides the airflow softly, minimizing disruption to the boundary layer. The rounded leading edge also allows the stagnation point (where the airflow splits) to move as the angle of attack changes, helping it maintain attached flow in a variety of flight conditions, a necessity for commercial aircraft. It should be noted, however, that this is only applicable to subsonic aircraft since rounded leading edges are likely to cause shock waves at supersonic speeds.

Currently, NLF has been most effective when incorporated into airframes that function at relatively low Reynolds' numbers, where the boundary layer is naturally stable. Consequently, the focus on NLF is extensive in gliders, due to their heavy reliance on aerodynamics, and on several general aviation aircraft, in order to minimize fuel burn. In these situations, which have lower airspeeds, less turbulent atmospheric conditions, and smaller surfaces, NLF has been shown to deliver significant reductions in surface drag, translating to improved range.

However, NLF is much easier to achieve and maintain on these smaller scales. In the commercial aviation sector, whilst inspiration is taken from NLF when designing certain aerodynamic components (wings, stabilizers, tail, etc.), NLF has been limited to restricted surface areas, and these implementations usually only attain partial laminar flow. With larger aircraft and faster cruise speeds, Reynolds' numbers increase significantly, making the boundary layer much less stable and therefore more difficult to sustain constant laminar flow. NLF's huge susceptibility to atmospheric and weather conditions is another weakness. Even slight surface contamination, such as ice accumulation or manufacturing imperfections, can initiate the transition to turbulent air, hindering NLF's overall effectiveness. All of these factors restrict NLF's use to specific areas of the airframe.

The most influential and groundbreaking test was the Airbus BLADE demonstrator program, where NLF was tested using a modified wingtip section, integrated into an existing airliner, the A340-300. At the termination of the project, Airbus reported that the series of tests was highly successful, with a 50% reduction in wing-related skin-friction, leading to around 5% lower CO₂ emissions.¹⁵

Despite these constraints, NLF is still vital to the design and development of aircraft, offering a more simplistic approach to aerodynamic efficiency and serving as a base upon which sophisticated laminar flow control methods can be developed.

Section 2.3. - Active Laminar Flow Control:

The inherent limitations of NLF at higher Reynolds numbers motivate the development of active laminar flow control (ALFC) systems. This strategy serves as a middle ground between passive laminar flow systems and a theoretical full laminar flow control system. As previously mentioned in Section 2.2., ALFC builds upon NLF designs that enhance favorable pressure gradients, with active boundary-layer suction systems implemented through small perforations in the airframe. These suction holes extract low-energy air from the boundary layer, inhibiting the creation of disturbances that cause turbulence, allowing laminar flow to be sustained over greater areas. This area can be seen in Figure 2 by the section labeled X_{cr} .

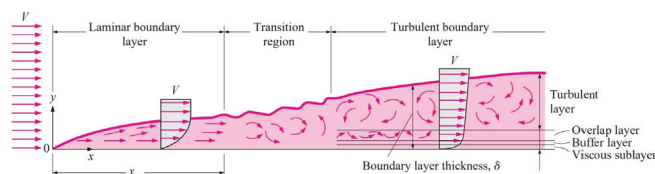


Figure 2: Illustration of the boundary layer during the laminar to turbulent transition, adapted from Fluid Mechanics: Fundamentals and Applications by Y. Cengel.¹¹

ALFC's main benefit is the capacity to maintain laminar flow under operating conditions where NLF fails, mostly seen at higher Reynolds numbers common in airliners. ALFC is appealing to airliners since NLF methods prove to be insufficient, and a full laminar flow control system would be too complex to integrate. Additionally, the ability for ALFC to be incorporated only in certain critical areas gives it an almost modular nature, meaning it can adapt to various airframe designs.

In practice, ALFC is still in its experimental phase. Numerous flight tests have been made, each mostly concentrating on one individual component, such as the wing leading edges or the engine nacelles. The latter has proven to be very effective due to its axial symmetry, leading to smoother pressure gradients that support laminar flow well.

ALFC, however, still presents considerable engineering difficulties due to its structural weight and complexity, which could nullify the drag reductions gained. In addition, just like with NLF, weather-related contamination, such as ice accumulation, can impair the ALFC's performance. These issues are the ceiling to what this technology can achieve in individual areas; a ceiling that can be removed by applying ALFC

across greater aircraft sections to increase aerodynamic effect, a technology known as FLFC.

Section 2.4. - Full Laminar Flow Control:

Full laminar flow control (FLFC) is the most ambitious and advanced method of boundary-layer management, by sustaining laminar flow over extensive areas of an aircraft, such as an entire wing section. By applying suction on the whole surface, FLFC could hugely decrease the chance of airflow disturbance and greatly delay the turbulent air transition, especially at high Reynolds numbers.

The closest example there has been to an FLFC-based aircraft was the X-21a, an experimental airplane developed by Northrop and used by NASA from 1963 to 1968. It was a modified Douglas B66 aircraft, with replacement engines, reduced wing sweep, and around 800,000 slots through which boundary-layer airflow was sucked, resulting in laminar flow over the wings.¹⁶ Whilst it brought in new data that could not otherwise be obtained, the project was eventually canceled due to its sensitivity to conditions and contamination.

Given this, FLFC is yet to take concrete form. Testing so far has consisted of wind tunnel experiments or digital simulations.¹⁷ These investigations have shown that continuous laminar flow can be attained under precisely regulated conditions, confirming what was speculated. Nonetheless, practical implementations have been limited to small-scale models or standalone test surfaces instead of full airframe configurations.

The main challenge that FLFC faces is its own technical demands, making it difficult to design and integrate into an aircraft. Ongoing suction requires elaborate networks of holes, internal piping, and pumping systems, all of which elevate structural weight and energy usage. This is why development so far has been confined to separate elements that have not been incorporated into real-world aircraft.

Additionally, just like for the other laminar flow strategies, the performance of FLFC is most responsive to surface conditions, and even slight surface imperfections can greatly interfere with the smooth airflow.

Due to these limitations, FLFC is currently seen as more of a theoretical benchmark used to evaluate other laminar flow approaches, rather than a short-term solution for commercial aviation. The actual future integration of FLFC will be later assessed in detail in terms of the TRL scale.

Section 2.5. - Application by Aircraft Component:

Laminar flow control technologies are concentrated on particular aircraft components, those where laminar flow is most advantageous and easiest to sustain.

Specifically, the upper-wing surface during cruise conditions presents considerable opportunities for reducing skin-friction drag if laminar flow can be maintained over a large enough chord distance. The leading edge tends to be the preferred wing section for NLF and ALFC concepts, where beneficial pressure gradients can be created. Nonetheless, wings are still one of the most difficult elements to engineer around laminar flow management due to the extreme aerodynamic forces and

their large area, making it a surface that undergoes major contact with precipitation and environmental contamination.

Another promising option for LFCD placement is on the engine nacelles, especially for hybrid methods. Their smooth and axisymmetric shape results in very stable flow conditions compared to other surfaces, such as wings, and the pressure gradients are often even more favorable.¹⁸ With this in mind, nacelle NLF and ALFC have been a focal point for many testing programs and experimental initiatives, such as those undertaken by Hurel-Dubois and Rolls-Royce.¹⁹ This makes nacelles an appealing solution for the initial implementation of laminar flow technologies in commercial aviation.

The empennage elements, such as horizontal and vertical stabilizers, provide several advantages when compared to other surfaces. These components function, due to their size, at much lower lift coefficients and have decreased pressure gradients, making them a more stable environment for the boundary layer. Additionally, their smaller dimensions and aft position on the airframe create a decreased risk of contamination from external sources. Whilst this makes them ideal, their effectiveness is the least significant of the three components that this paper presents, not only due to the reduced airflow that the surfaces receive, but also the complications of implementing flow control systems within a much smaller volume.

■ Section 3 - Discussion and Feasibility Study

Section 3.1. - The TRL Framework:

Whilst laminar flow control designs all promise drag reduction and fuel savings when compared to conventional wings and other aerodynamic strategies, their successful implementation on full-scale airliners relies on finding the correct balance between aerodynamic efficiency, operational reliability, and financial feasibility. This can be evaluated using the Technology Readiness Level (TRL) framework created by NASA during the 1970s. The TRL structure is a systematic method to assess and evaluate the maturity of various technologies, broadly utilized in the aerospace research and development sector. The TRL is based on a scale from 1 to 9, where TRL 1 is a mere observation of fundamental physics principles, and TRL 9 is a validated technology in its final form under full use in an operational environment.²⁰ This framework relates especially well to laminar flow control designs as it takes into account all aspects, not just aerodynamic effectiveness. This also means that each of the various strategies discussed in Section 1, whilst they are based on the same physics foundations, has a different feasibility level due to complexity and integration difficulties. It must be noted that, even if the TRL structure does give an overall view of technology readiness, it falls short in highlighting certain elements, notably the varying cost, a factor that affects the ability to implement the technology.

Section 3.2. - TRL Assessment of NLF:

Currently, Natural Laminar Flow (NLF) is the most advanced laminar flow design. In some cases, it could be given a TRL level of 9, due to its present incorporation into operating aircraft. As analyzed, NLF depends on passive aerodynamic

design techniques, making it straightforward to implement. This should make airworthiness certification and regular maintenance simple to achieve. NLF has been implemented on many general aviation aircraft, such as the HondaJet, and has been used on several components, such as engine nacelles, of mainstream airliners such as the Boeing 737 Max and 787, where Reynolds' numbers remain low enough to sustain pressure gradients suitable for laminar flow.²¹ However, whilst it has been fairly successful in low Reynolds' number environments and on small components, it is yet to be deployed on extensive surfaces of large aircraft since, as demonstrated in Section 1.2, airliner chord Reynolds' numbers exceed 2×10^7 leading to laminar-turbulent transition within the first 20% of the chord. Here, passive NLF shaping is insufficient to maintain boundary-layer stability that would constitute meaningful drag reduction. This element of NLF should remain at a TRL level 7, having been demonstrated in an operational environment, such as with Airbus BLADE. Despite the aerodynamic challenges faced and its lack of validation at a production scale for commercial airliners, NLF has proven to be resilient in real-world scenarios and has brought moderate improvements in skin-friction drag reduction.

Section 3.3. - TRL Assessment of ALFC:

Active Laminar Flow Control (ALFC) is situated, according to this analysis, at an intermediate stage of the TRL framework, at TRL 5-6, depending on the individual system. ALFC integrates passive aerodynamic shaping with active suction and has been the subject of many tests both in wind tunnels and in controlled flight conditions, confirming its aerodynamic advantages at relevant Reynolds numbers. This means it meets TRL standards concerning functional performance. Additionally, programs like the Airbus BLADE demonstrator have meant that ALFC has proven beneficial in an operational environment.²² However, it does not meet TRL 7 requirements due to the system not yet being scalable, with issues throughout the supply chain. Initially, at the manufacturing level, the high system complexity means the production of composite material components is intensive, considering surfaces must be built and maintained at a near-perfect smoothness. As established in Section 1.3, the boundary layer is approximately 2mm thick, meaning that even irregularities at a millimeter scale are enough to trigger turbulent transitions. This requisite precision makes long-term reliability and maintenance compatibility within the airline sector both complex and expensive, especially considering maintenance would need to be more thorough and frequent, causing possible scheduling problems across airline fleets. Due to such reasons, commercial manufacturers, along with airlines, are yet to commit to the implementation of such technology.²³ All of these problems have an underlying economic obstacle that hinders advancement past this TRL stage.

Section 3.4. - TRL Assessment of FLFC:

Full Laminar Flow Control (FLFC), designed to sustain laminar flow over most or all of a surface through continuous suction, is assigned by this paper a relatively low TRL, around

TRL 2–3. Although the fundamental principles behind FLFC are clearly understood and have been confirmed through both theoretical studies and experimental tests, this strategy has only been conducted in demonstrations in a laboratory setting. The key link that is missing in order for this technology to climb up the TRL scale is the lack of application on real-world aircraft. For now, the low TRL is due to outstanding issues concerning suction power needs and the structural integration of such technology. In contrast to ALFC, where active control is restricted to specific areas, FLFC requires complete functionality for the entire duration of operation to achieve notable gains in skin-friction. As a result, even with its immense potential for drag reduction, FLFC is still far from achieving the benchmarks needed for a higher TRL.

Section 3.5. – Future Pathways:

Looking to the future, advancements will certainly be made that permit the implementation of laminar flow control. For Active Laminar Flow Control, advancing into the higher end TRLs relies on the technological ability for flight testing that confirms operational durability in a working environment. Global policy and certification changes will also be necessary for ALFC technology to be utilized. However, likely, Full Laminar Flow Control will not progress as much in the short term. This is due to easier development routes that bring more immediate results in reducing drag and fuel consumption, such as winglets or surface coating, down to their lower system complexity. Consequently, it is expected that FLFC will remain in a research phase in restricted conditions until the difficulties associated with its integration can be solved. Significant certification issues also lie in the way of ALFC and FLFC implementation, with policy changes required in order to allow airworthiness. Most importantly, manufacturing and maintenance quality standards would need to be introduced, focused on maintaining minimal surface irregularities, as no current EASA or FAA standards exist for laminar flow surface quality. This would ensure operational reliability, something that would have to be taken into account when considering fuel planning and contingency regulations. Current reserve fuel percentages are around 3–5%, inadequate to cover a potential full loss of laminar flow over an extended cruise period.²⁴

Addressing TRL's economic limitation, according to a NASA computational study, a laminar flow wing design could achieve fuel savings of up to 10% on long-range commercial aircraft annually, equating to savings of millions of dollars per aircraft.²⁵ The optimistic introduction of such FLFC design would likely be similar to the increased costs of manufacturing and maintenance, meaning profitability would depend on how well controlled the operations of the industry are and how scalable the actual technology is. ALFC designs are unlikely to provide such large savings whilst they would still create similar increased costs, meaning, at least during the short term, it is improbable that their deployment would be financially advantageous.

■ Conclusion

This paper set out three main objectives: to explain the aerodynamic principles that govern laminar flow technology and its implementation; to examine the current state of LFCDs in commercial aviation; and to assess their readiness and scalability for the future using the NASA TRL framework. Overall, these objectives reveal that, whilst laminar flow control is well proven and understood, it is not yet industrially mature enough for commercial aviation.

Regarding the technology's present state, after examining the technological and aerodynamic principles behind different laminar flow control methods and the feasibility of their implementation in commercial aviation, this analysis confirms that there are several meaningful advantages in terms of drag reduction and associated fuel burn, a vital solution to reducing aviation's environmental footprint. Whilst these benefits have several practical limitations due to surface and condition sensitivity, when utilized effectively, they provide disproportionate gains in aerodynamic efficiency.

Using the Technology Readiness Level metric, different laminar flow control strategies have major distinctions. Natural laminar flow is operationally mature and in service on several aircraft, albeit at a component level on commercial aircraft. Active laminar flow control has shown promising performance in full-scale testing, representing the most realistic short-term pathway, yet its current characteristics sustain systematic, rather than aerodynamic, barriers involving maintenance and certification. Full laminar flow control, although it provides the most substantial theoretical benefits in airflow management, remains at a low TRL, with issues regarding structural implementation. There would also be the need for an introduction of new airworthiness standards that take into account new redundancies and failure behavior that such technology would create. Maintenance standards would also have to be updated, with strict operational procedures that prioritize safety. Only then will it be plausible for ALFC and FLFC systems to be used in commercial airliners.

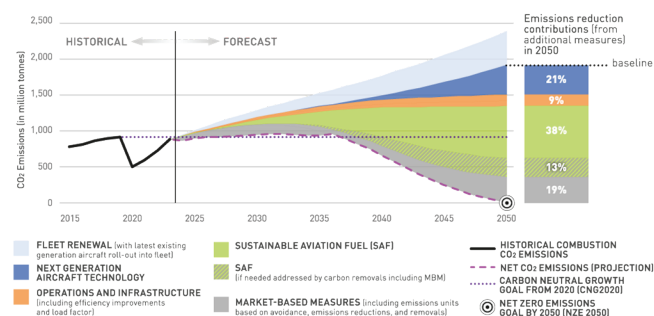


Figure 3: Future projection of aviation emission reductions by method. Adapted from Waypoint 2050 by ATAG.²⁶

Future progress within this field of technology is still likely to be gradual, as the many systems involved are made more effective, enabling progressive implementation into existing aircraft. According to the third edition of Waypoint 2050, as seen in Figure 3, without the introduction of any sustainability-focused technology, the commercial aviation sector would

generate approximately 2200 million tonnes of CO₂ emissions.²⁶ Also in Figure 3, next-generation aircraft technology, including laminar flow control, is expected to reduce emissions by 21% by 2050. Drawing from both of these values shows that laminar flow control devices could contribute, alongside the introduction of other technologies, to a total saving of 460 million tonnes of CO₂ emissions per year. In the context of modern passenger jets, laminar flow control therefore provides an appealing and credible pathway towards contributing to increased efficiency and a reduction of commercial aviation's global environmental impact.

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■ Appendix

Equation A1:

Using the formula for the laminar skin friction coefficient and using a value of 2×10^7 :

$$Cf_{lam.} = \frac{1.328}{\sqrt{Re}}$$

$$Cf_{lam.} \approx 3 \times 10^{-4}$$

Equation A2:

Similarly, using the turbulent skin friction coefficient formula and Re value of 2×10^7 gives:

$$Cf_{turb.} = \frac{0.074}{Re^{1/5}}$$

$$Cf_{turb.} \approx 2.9 \times 10^{-3}$$

Equation A3:

Substituting previous values into $d\rho/dx$ gives:

$$\frac{d\rho}{dx} = \frac{1}{2} (0.38) (230)^2 (-0.5) \approx -5000 \text{ Pa/m}$$