ISABE-2015-20201

Optimizing Propulsive Efficiency in Aircraft with Boundary Layer Ingesting Distributed Propulsion

Andrew Rolt
Propulsion Engineering Centre, School of Aerospace, Transport & Manufacturing,
Cranfield University Cranfield, Bedfordshire, MK43 0AL, United Kingdom

John Whurr
Rolls-Royce plc
Derby, Derbyshire DE24 8BJ UK

Abstract

Improved propulsive efficiency and reduced drag are major drivers for the application of distributed propulsion in civil aviation.

This paper explains the physics behind propulsive efficiency and the challenges of engineering practical Boundary Layer Ingestion (BLI) and Distributed Propulsion (DP) systems. Alternative concepts and design strategies are compared and optimization of propulsive and transfer efficiencies are shown to be crucial factors in determining the overall performance of new aircraft designs.

It is shown that the figures quoted for propulsive efficiency depend on how thrust and drag are accounted, and that traditional turbofan engine figures of merit such as net thrust and Specific Fuel Consumption (SFC) are potentially misleading in more highly integrated BLI and DP installations. At the whole aircraft level, takeoff and climb performance, payload/range and fuel-burn for a typical mission are more useful figures of merit.

Nomenclature

η	Efficiency
BLI	Boundary Layer Ingestion
DP	Distributed Propulsion
FG	Gross Thrust
FN	Net Thrust
MTOW	Maximum Takeoff Weight
OPR	Overall Pressure Ratio
OWE	Operating Weight Empty
SFC	Specific Fuel Consumption
TeDP	Turbo-electric Distributed Propulsion
TET	Turbine Entry Temperature
V0	True Airspeed (flight velocity)
V1	Corrected Intake Velocity
Vj	Jet Velocity (fully expanded)
W0	Inlet Massflow
Wf	Fuel Massflow
X	Specific Thrust
X’	Specific Thrust (alternative definition)
X/V0	Normalized Specific Thrust

Introduction

Propulsive efficiency is the ratio of the propulsive power generated by the fully expanded exhaust jets to the kinetic energy added to the air mass flow through the engine. It is a function of the true airspeed of the aircraft, and the specific thrust or jet velocity of the propulsive jets.

The long-term trend towards lower specific thrust turbofans is gradually raising propulsive efficiency, but larger fans and nacelles increase powerplant weight and increase nacelle drag and interference drag. Thus the fan diameters of modern engines give near optimum fuel-burn for state of the art materials and construction. Larger fans could give reduced noise, but would increase operating costs.

Open rotor powerplants offer much lower specific thrust and reduced nacelle drag, but noise remains a concern and the performance benefits reduce at higher cruise speeds. Propulsive efficiency is here discussed mostly in the context of ducted fans, but the same principles apply to open rotors.

On low-wing aircraft, where the ground clearance for under-wing engines is limited, interference drag between the nacelle, wing and pylon is likely to constrain significant increases in fan diameter. Increasing the undercarriage length or raising the wing comes with structural costs. Alternatively, increasing the number of engines and making them smaller tends to reduce the overall aircraft weight because of the square-cube law and wing-bending moment relief, and because more of the all-engines takeoff thrust is available if one engine fails.

Previous research [1] and [2] has considered the benefits of significantly increasing the number of engines, but this does not necessarily improve fuel-burn because gas turbines tend to become less efficient as their core mass flows are reduced. It is also generally considered that twin-engine aircraft should have lower operating costs.

An alternative solution is for each core engine to drive two or more fans. This may be achieved through a mechanical transmission and gearing, or by having multiple power turbines. An aircraft may have two relatively large and efficient cores or gas generators, but four relatively lightweight and more easily installed fans. Avoiding large diameter fans can also make engine transportation easier.

A further option would be to drive the additional fans electrically in a hybrid propulsion system. If battery technology continues to improve then stored energy could be used to boost main engine power at takeoff and top of climb. CO_2 emissions could be significantly reduced on shorter flights if the batteries were charged on the ground from non-fossil-fuel energy sources. With very good energy storage technology it may be possible just to have a single gas turbine as the sustainer for longer flights.

Fuel-burn benefits may also come from burying engines in the airframe to reduce nacelle drag and having propulsion systems that improve propulsive efficiency by ingesting and re-energizing airframe boundary layer air flows. Such BLI systems need greater engine/airframe integration and this may favour more radical novel aircraft and powerplant configurations.

For example, the MIT/Cambridge Silent Aircraft study's SAX-40 aircraft design proposed installing three engines on top of a blended wing body (BWB) airframe to ingest much of the upper surface boundary layer [3]. Each engine had three fans side by side, with one central fan driven directly from the LP turbine and two outer fans driven via bevel gears and cross-shafts.

A further BWB design from the NASA N+3 studies proposes powering a bank of sixteen BLI fans along the trailing edge using electric power transmitted from two wing-tip mounted turboelectric generators [4]. These aircraft concepts are shown in figure 1.

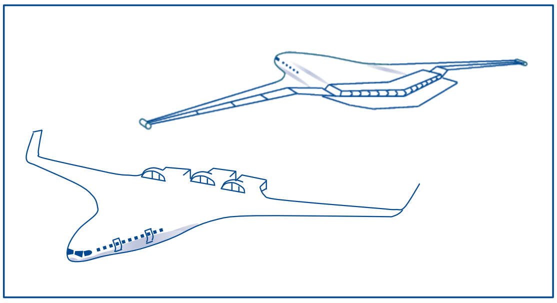


Figure 1: BWB Aircraft: SAX-40 and N3-X

In the medium term the authors consider BLI more likely to be applied to more conventional "tube and wing" aircraft and to target aft fuselage boundary layers, as indicated in figure 2.

These aircraft can have open rotor or ducted fan propulsion systems and ingest a large proportion of the aircraft's fuselage boundary layer air into a BLI propulsor integrated into the tail end of the aircraft.

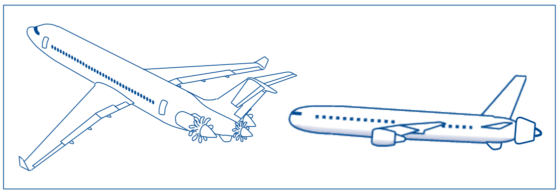


Figure 2: Possible Tube and Wing Aircraft with Aft Fuselage BLI Propulsion Systems

Potential Difficulties with BLI

Boundary layer ingestion can reduce fuel-burn, but engine and aircraft manufacturers have often gone to considerable lengths to avoid it. This is most noticeable in combat aircraft engine installations, where boundary layer diverters and boundary layer bleeds are commonly used to minimize inlet air flow distortions that might excite vibrations in fan and core compressors and lead to blade failures, or reduce component efficiencies, or even trigger an engine surge. Civil engine installations are usually designed to deliver very low inlet flow distortion for the same reasons.

In any BLI designs the adverse effects of the inlet flow distortion must be taken into consideration. In military aircraft, priority over small improvements in fuel economy is given to improving operability and saving weight. The severity of the inlet flow distortion depends on details of the proposed installation. One advantage of some more recent DP aircraft proposals, like the N3-X for example, relative to prior art, is that the core engine intake is separate from the intakes for the BLI fans. The fans can be designed to accommodate the distorted flow, while the core engines are protected from the detrimental effects of BLI. This is very helpful.

The physical phenomena associated with boundary layers and BLI are complex and this paper does not attempt a fully rigorous analysis. The objective of the following sections is to help to identify areas where DP and BLI are more or less likely to give performance benefits. Back to back comparisons of BLI and non-BLI propulsion systems should include more detailed airframe drag assessments.

Accounting Thrust and Drag

For turbofan engine installations in commercial and business aircraft, net thrust is normally calculated for the stream-tube of air that passes through the engine intake and goes on to provide a propulsive jet or jets. The bleed air taken from an engine for the aircraft's environmental control system, or for engine or airframe anti-icing, is not credited with producing any thrust, but fuel burned in the engine adds to the exhaust jet's mass-flow and to thrust (though this effect is almost negligible on subsonic aircraft). Net thrust is calculated as gross thrust minus the free-stream inlet momentum (W0.V0).

Thus for an engine with a single propulsive jet and no bleed air offtakes or air leakages:

$$FG = Vj.(W0+Wf) \quad (1)$$

$$FN = FG\text{-}W0.V0 \quad (2)$$

Net thrust approximates to the rate of change of momentum of the air passing through the engine, and specific thrust (FN/W0) approximates to the change in air velocity:

$$FN \approx Vj.W0 \quad (3)$$

$$X \approx Vj\text{-}V0 \quad (4)$$

For simplicity, the effects of fuel mass flow and bleed air offtakes will be neglected from now on and the equations 3 and 4 will be treated as if they were exact.

In steady straight and level flight, the thrust of the engines equals the aircraft's drag, and traditionally the airframer accounts for the drag on all of the aircraft's external surfaces, including the engine nacelles. Internal losses in the engine intake and exhaust systems, and any drag due to tailcones or afterbodies that can be present on separate jet powerplants, will affect engine performance, but are not accounted as contributing to airframe drag.

Thus an engine's installed net thrust is accounted after air and power offtakes are extracted for the aircraft, but without subtracting the external nacelle drag. The engine's installed SFC is calculated as the fuel flow divided by the installed net thrust:

$$SFC = Wf/FN \quad (5)$$

This thrust accounting convention can work to the advantage of the engine manufacturer when SFC figures are compared. A new engine with a larger fan, lower specific thrust and better propulsive efficiency would claim a significantly lower SFC, even though the nacelle drag is likely to have increased. Note that increased nacelle drag reduces the aircraft's lift/drag ratio and so also increases its thrust requirements.

To make a fairer comparison "fully installed" SFC figures are sometimes quoted, calculated using the engine's net thrust minus the nacelle drag. In this case nacelle drag may include estimates not only for the drag on an isolated nacelle, but also for the additional drag generated by a pylon that mounts the powerplant to the aircraft's wing, and for any interference drag due to the proximity of the wing.

Thermal, Transfer and Propulsive Efficiency

For a turbofan engine, the overall efficiency may be considered to be the product of its thermal, transfer and propulsive efficiencies:

$$\eta_{(overall)} = \eta_{(thermal)}.\eta_{(transfer)}.\eta_{(propulsive)} \quad (6)$$

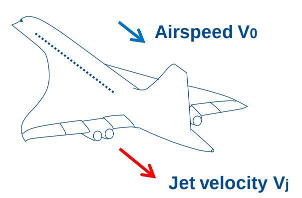
The thermal (or core thermal) efficiency is how efficiently the heat released from combustion of the fuel is converted into energy available to do work. Thermal efficiencies for simple cycle gas turbines increase with higher component efficiencies and increasing overall pressure ratio (OPR) and turbine entry temperature (TET). The cores of large aero engines now achieve over 50% thermal efficiency.

Transfer efficiency is how efficiently the energy released by the core is converted into kinetic energy in a propulsive jet or jets. In turbojet engines the core exhaust is simply expanded through a nozzle, so transfer efficiency can be very high, but as the industry progresses to engines with higher bypass ratios and lower specific thrusts, the losses that reduce transfer efficiency become more significant.

As already noted, propulsive efficiency is the ratio of the useful work done by the propulsive jets relative to their kinetic energy. For equal inlet and exhaust mass flows, this is just a function of the ratio of the propulsive jet's velocity to the aircraft's flight velocity or airspeed:

$$\eta_{(propulsive)} = 2/(1+Vj/V0) \quad (7)$$

The derivation is given in figure 3.



$$\text{Propulsive efficiency} = \frac{(V_j-V_0).V_0}{½.(V_j^2-V_0^2)} = \frac{2}{1+V_j/V_0}$$

Figure 3: Derivation of Propulsive Efficiency

Note relatively high jet velocities always give poor propulsive efficiency, but propulsive efficiency is improved by flying faster. Concorde's turbojet engines had very good propulsive efficiency when cruising at around Mach 2, but they were much less efficient when cruising subsonically.

The development of turbofan engines for subsonic aircraft has increased the propulsive efficiency by increasing the inlet air mass flow for a given thrust, reducing the required jet velocity. The larger fan diameters and bypass ratios have also led to the engines with separate bypass and core exhaust nozzles being preferred to engines with mixed exhaust jets. In separate jets engines the propulsive efficiencies of the two streams may be calculated separately, but overall propulsive efficiency is still the total net thrust divided by the total kinetic energy in the two exhaust streams.

Figure 4 compares typical thermal, transfer and propulsive efficiencies for a modern large turbofan engine and shows how these are tending to evolve. Increasing bypass ratio reduces transfer efficiency because more power has to be transferred via the LP turbine and the fan to the bypass jet. In engines with mixed exhausts some power is also transferred via the mixer, as sometimes this is more efficient than transferring all of the power through the turbo-machinery.

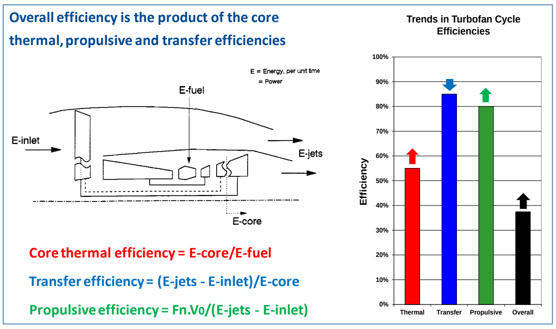


Figure 4: Comparison of Thermal, Transfer and Propulsive Efficiencies

In a separate jets engine the optimum amount of power to be transferred from the core to the bypass stream depends on how efficiently the power can be transmitted and the resulting trade-off with the propulsive efficiencies of the two jets. With 100% efficient power transmission the net thrust will be maximised by having equal hot and cold jet velocities with equal propulsive efficiencies. But with less efficient power transmission it is not worth transferring so much power to the bypass flow. For a fixed total mass flow, it is better to accept slightly lower propulsive efficiency from the hot jet in order to reduce the transmission losses.

Transfer efficiency is further reduced as specific thrust is reduced, because the intake, bypass duct and exhaust losses are all acting on an increased air mass flow. This reduction in transfer efficiency typically cancels-out about half of the increase in propulsive efficiency when the latter is improved by increasing the bypass ratio and reducing the mass weighted mean jet velocity.

Open Rotor Propulsion Systems

In an open rotor propulsion system, the main propulsive jet passes through the plane of rotation of the open rotor. Unlike a ducted fan's propulsive jet, it has no clearly defined outer limit and mass flow, but an axi-symmetric stream-tube boundary may be modelled with a diameter equal to the rotor tip diameter in the plane of the rotor. This makes it possible to define a mass flow and propulsive and transfer efficiencies for the open rotor, though in practice it is more usual to refer to a propeller efficiency that is equivalent to the product of fan and propulsive efficiencies in a ducted fan engine.

Open rotor powerplants are typically more efficient than fully installed ducted fan engines, but they are generally noisier, in part because they do not have the sound absorbent acoustic linings applied to turbofan engine intakes and bypass ducts.

Distributed Propulsion Systems

DP systems have multiple propulsors, which may be conventional turbofans or open rotor engines, and some at least of these thrust generating units (ducted fans, open rotors, mixer-ejectors or other exhaust jets) may be positioned remotely from the core engines or other energy sources that power them. Separating out the two functions can reduce fuel-burn provided the overall drag is reduced or the propulsive efficiency is increased, but only if these benefits are not outweighed by any increase in weight or in transmission losses that reduce the overall transfer efficiency.

Thrust Accounting with BLI Systems

An analysis of the performance benefits obtained with BLI will be given in the next section, but first it is necessary to consider how thrust and drag are accounted in a BLI installation.

The overall aircraft performance is not affected by accounting conventions, but improvement targets are often broken down separately for the airframe and engine manufacturers. Interpretation of these targets does depend on performance accounting conventions and BLI installations are particularly sensitive to this because the engine and airframe are more highly integrated.

In a propulsion system that exploits BLI, at least some of the air entering the propulsors has already washed over parts of the airframe, losing some total pressure. This is referred to as the approach loss and it is added to intake duct loss when calculating installed engine performance. It can be argued that this is equivalent to an engine having an extended intake that replaces part of the airframe, therefore reducing the total drag that is accounted by the airframer and also reducing the aircraft's thrust requirements. With this convention, the engine or propulsion system suppliers are seen as providing lower thrust levels, while aircraft manufacturers are credited with a drag reduction from BLI.

Because the intake loss has effectively increased, the transfer efficiency is reduced and the SFC is seen to get worse, even though there will be lower fuel-burn, provided the thrust saving is more significant than the reduction in transfer efficiency.

This approach to accounting for thrust and drag is that normally adopted for turbofan engines, but there are other options, depending on how airframe and propulsion system interfaces are defined.

An alternative is to include in the airframe drag the drag on all parts of the aircraft washed by air that will subsequently be ingested into the propulsion systems. In this case the net thrust requirement is not reduced and drag figure is quoted remains higher, but provided the fuel-burn is reduced, the propulsion system will be credited with improved SFC and increased propulsive efficiency.

How BLI Reduces Fuel-Burn

The main performance benefit from ingesting an airframe boundary layer into a propulsion system comes either from reduced drag or from improved propulsive efficiency, but the relative proportions attributable to each depend on how thrust and drag are accounted. A simple explanation comes from consideration of propulsive efficiency, using the alternative thrust and drag accounting convention proposed above.

Equations 4 and 5 for specific thrust and propulsive efficiency apply for propulsion systems that are not integrated with an airframe and ingest only free-stream air, but for the BLI engine installations new definitions of specific thrust and propulsive efficiency are proposed, based on the alternative thrust and drag accounting convention above. This recognises that the total pressure, inlet velocity and momentum of the air entering the propulsor have been reduced, but as the actual inlet velocity will depend on the static pressure in the plane of the intake, a "corrected" inlet velocity V1 is defined assuming that the static pressures are constant.

Specific thrust and propulsive efficiency can then be redefined as follows:

$$X' = Vj - V1 \quad (8)$$

$$\eta'_{(propulsive)} = 2/(V1/V0+Vj/V0) \quad (9)$$

Figure 5 compares BLI and non-BLI designs and provides simple numerical examples. Using the alternative definition of propulsive efficiency and converting an aircraft from a non-BLI design to a BLI design, it is clear that propulsive efficiency can be improved even when specific thrust is increased.

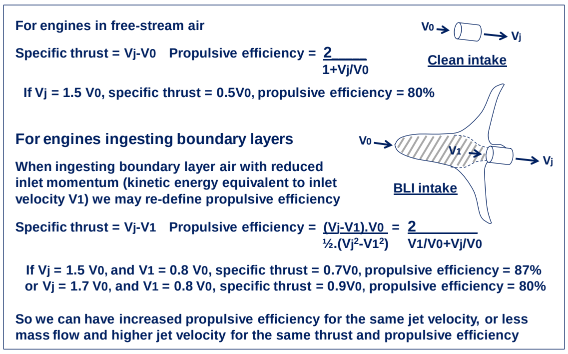


Figure 5: Illustration of Propulsive Efficiency Improvement with BLI

For the examples in figure 5, V1 has been taken as 80% of V0. This may, or may not, be a realistic figure, as it depends on the proportion of the depth of the boundary layer that is being ingested. V1 increases as more of the boundary layer is ingested and it will continue to increase if more free-stream air is ingested with it.

Optimizing Propulsive Efficiency with BLI

In a conventional aircraft with ducted fan engines it is easy to see how propulsive efficiency varies with specific thrust, but fuel-burn is not just inversely proportional to cruise propulsive efficiency. It has already been noted that transfer efficiency tends to reduce as propulsive efficiency increases, and gas turbine core thermal efficiency also tends to reduce as the required power levels reduce. Furthermore the propulsion systems must be designed to meet aircraft performance requirements at all flight conditions and cannot be optimised just for cruise.

An aircraft with ducted fans that are 100% electrically powered will not be subject to any of the changes in core thermal and transfer efficiency that would affect turbine powered aircraft, but there will still be some variation in transfer efficiency as the fan diameter and pressure ratio are varied. The nacelle drag may also vary with fan diameter, but to start with, these effects can be ignored when considering the cruise operation of an idealized ducted fan aircraft. Such an aircraft could have just one type of propulsor with a single exhaust jet that could be assumed to have uniform jet velocity.

For an engine operating in free-stream air, figure 6 shows how its propulsive efficiency varies with the ratio of (Vj-V0)/V0, which is the normalized specific thrust according to the standard definition.

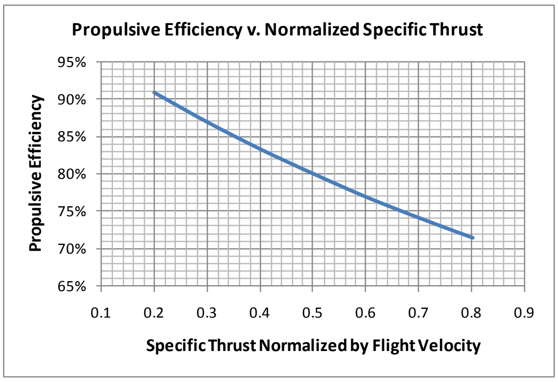


Figure 6: Non-BLI Fan Propulsive Efficiency

Figure 7 shows how propulsive efficiency (to the alternative definition) varies with the ratio of (Vj-V0)/V0 for boundary layer ingesting ducted fans, when the normalized corrected intake velocity (V1/V0) varies. Note that when V1=V0 (no loss of inlet momentum) there is an equivalence between the two definitions of propulsive efficiency.

Having a lower specific thrust gives a higher propulsive efficiency, but the optimum propulsive efficiency still depends on other factors, most significantly, how large the propulsor needs to be and what the required fan pressure ratio is. The fan pressure ratio is important because this can be correlated with fan efficiency and overall transfer efficiency. The required fan pressure ratio depends primarily on the cruise Mach number and specific thrust, and also to a lesser extent on the fan stage efficiency and the intake and exhaust duct losses.

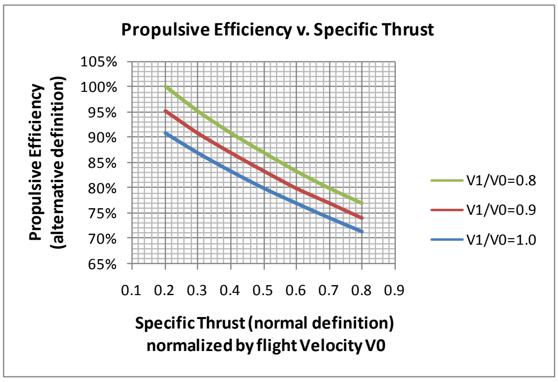


Figure 7: BLI Fan Propulsive Efficiency

In aircraft with multiple propulsors, at least some of which ingest boundary layers, the optimum sizing and relative mass flows for the each unit should depend on its cruise specific thrust and the proportion of the airframe drag associated with any ingested boundary layer air flows. For example, a BLI propulsion system may have V1=0.8(V0) and Vj=1.6(V0) at cruise, so its propulsive efficiency η' is 83.3% (from equation 9, using the alternative definition above) and its net thrust is four times the associated drag. If that drag were 25% of the overall cruise drag, then the BLI propulsion system would provide 100% of the required cruise thrust. But such a system might not be capable of meeting all of the aircraft's takeoff and climb performance requirements and meet its noise targets. For these reasons, and others that will become apparent, the authors consider it more likely near-term BLI propulsion systems will be used in combination with more conventional propulsors.

Figure 8 shows ratios of net thrust to ingested drag for a range of intake velocities and specific thrusts. Lower V1/V0 values, that will give a significant improvement in propulsive efficiency at a specific thrust, are achieved when only the inner part of the boundary layer is ingested. If the objective is to provide say 50% or 100% of the cruise thrust from the BLI propulsion system, then figure 8 shows how much drag needs to be ingested. As 45-50% of cruise drag is induced drag and not amenable to ingestion, capturing 25% of overall drag is quite challenging, but given this is possible, the question is how to maximize the performance benefit.

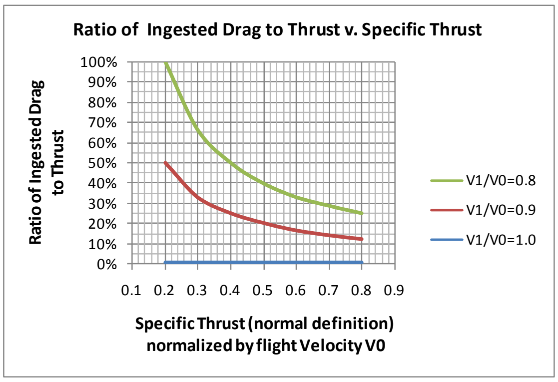


Figure 8: Ratios of Ingested Drag to Thrust for Different Inlet and Exhaust Velocity Ratios

Boundary layer thickness is generally defined as the height of the contour having 99% of free-stream velocity and for turbulent boundary layers the time averaged velocity profile is often approximated by a one-seventh power law as shown in figure 9. It should be understood that for turbulent boundary layers this is only a time averaged approximation to the instantaneous velocity distributions.

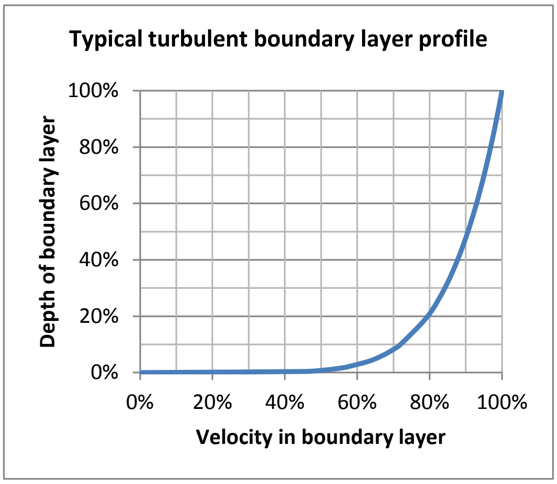


Figure 9: Velocity Profile in a Boundary Layer

The maximum propulsive efficiency benefit comes from re-energizing the lowest momentum part of the boundary layer, i.e. the inner 40-50%. If fan inlet distortion or increased inlet and exhaust losses reduce transfer efficiency, or if transfer efficiency is reduced because of increased transmissions loss in a DP system, then it may not pay to target the outer regions of the boundary layer. The benefit could also be negated by reductions in thermal efficiency if multiple smaller engines are used.

If the boundary layer is thought of as being sub-divided into different sub-layers, then an ideal BLI propulsor would re-energize each sub-layer by an optimum amount, without mixing the sub-layers together (as if in parallel compressors). This is because mixing the flows upstream of a propulsor creates additional losses. But real turbulent air flows are continually mixing themselves, so the objective is to minimise unnecessary mixing, such as mixing extra free-stream air with the boundary layer air upstream of the propulsor.

The overall improvement in efficiency will only match the propulsive efficiency improvement if the transfer and thermal efficiencies do not change, but in practice a propulsor that sees a wider range of inlet velocities (or higher inlet flow distortions) is also likely to have worse component efficiencies, so transfer efficiency will be reduced. Research at the Whittle Laboratory in Cambridge confirms that loss of fan efficiency increases disproportionately with increasing intake distortion, but also shows that the level of loss need not be so high as to outweigh the propulsive efficiency benefit [5].

BLI Propulsion System Optimization

Pros and cons of alternative aircraft configurations are discussed in more detail in another paper [6], but in this paper a tube and wing aircraft with two under-wing mounted turbofans is taken as the baseline. The alternative propulsion arrangements considered are a conventional tri-jet, a tri-jet with BLI on the centre engine and a Turbo-electric Distributed Propulsion (TeDP) aircraft with an aft fuselage ducted fan BLI propulsor driven by power from the two under-wing turbofan engines.

The upper half of figure 10 shows the potential TeDP configuration for BLI, while the lower half represents the conventional twin turbofan aircraft that is taken as the reference for comparison. The propulsive efficiency benefits equally well apply to a tri-jet with BLI on the centre engine.

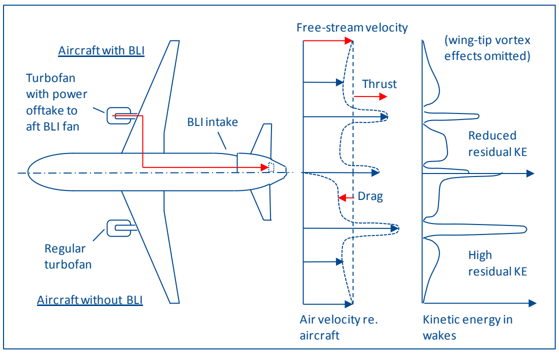


Figure 10: Benefits of an Aft Fuselage BLI Fan

The right hand side of figure 10 shows how the atmosphere is disturbed by passage of the aircraft. Drag on the airframe results in a forwards moving wake, while the propulsive jets move rearwards. In steady flight the forwards momentum of the wakes is cancelled out be the rearwards momentum of the jet plumes. The residual kinetic power in each of these airflows is proportional to the mass-flow rate and the square of the absolute velocity. It will be noted that the aircraft with BLI has lower residual kinetic power, showing that it has higher overall propulsive efficiency. (There will also be kinetic power in the wing-tip vortices that are not shown in figure 10, but it is assumed that these losses will be very similar for the different aircraft compared.)

Seitz et al. have compared a tri-jet with BLI on the centre engine, to a reference twin turbofan aircraft [7], [8]. The 360° BLI fan intake was located 85% of the way along the fuselage and ingested almost all of the available boundary layer, with drag equivalent to 21% of the overall cruise drag on the baseline aircraft. The proposed design has three similar core engines with roughly the same bypass ratio and air mass flow through each fan. All the engines have geared fans, but the unique BLI fan on the centre engine had larger diameter and higher hub/tip radius ratio, making this engine heavier than the under-wing engines. The two under-wing turbofans were scaled down to about 2/3 of the mass flow, so the total fan air flow was very similar to the twin-turbofan design, though the exhaust jet velocity and specific thrust X of the centre engine were reduced (the latter by about 25%) because of the loss of inlet total pressure resulting from BLI.

Consideration was given to varying the BLI fan's mass flow and it was shown that ingesting slightly less of the fuselage boundary layer would result in a lighter and slightly more fuel efficient aircraft (though it would probably have more noise at takeoff). The design point specific thrust of the under-wing turbofans was kept constant, though this is another potential variable for optimization.

Scaling down the under-wing engines gave them a 2.2% improvement in takeoff thrust/weight ratio, but the effects of scaling on engine efficiency were not apparent. Reducing the size and weight of the wing mounted engines had little effect on the mass of the wing, but adding a third engine at the tail increased the fuselage length and its weight and the overall structural weight. Changing to a T-tail configuration also increased the empennage weight though it might have been expected that reduced thrust asymmetry in the one engine inoperative case could have reduced the size of the vertical fin.

The BLI tri-jet configuration was estimated to save almost 9% fuel-burn on a 4800 nm design mission, but it seems likely this figure will be reduced when scale effects on advanced gas turbine performance are fully taken into account.

In comparison the TeDP arrangement for the BLI propulsor has some advantages and disadvantages relative to adding a third engine. A significant advantage is that the gas turbine cores are larger and therefore more efficient and probably less expensive to own and maintain. Further benefits should accrue from integrating energy storage into the electrical transmission system. The biggest disadvantage is that it the TeDP system is likely to be substantially heavier, to an extent that will depend on how much power is exported to the aft-fuselage propulsion system, the length scale of the aircraft and levels of transmission and storage technologies available.

Each turbofan might export up to 40% of its cruise power to the BLI propulsor, which could be a single ducted fan or open rotor driven by a super-conducting motor or motors, or a cluster of smaller fans, each driven by one motor. In the following example one BLI fan is assumed, driven by power from two turbofan engines. Alternatively having two or more BLI fans could enable simple synchronous transmissions without need for power electronics or complex variable geometry, though some power electronics would be essential if battery power were to be integrated into the system.

The reduction in power to the under-wing fans means they can have reduced diameter and bypass ratio, giving lower nacelle and interference drags. Alternatively lower pressure ratio fans, could give lower jet velocity and higher propulsive efficiency.

The jet velocities for the BLI fans and the under-wing engine fans can be optimized independently. Suppose that the conventional aircraft with twin turbofans has already been optimized for fuel-burn at cruise, and meets all its targets for takeoff and climb performance, noise and emissions. A small increase in the fan diameter of its engines would enable a further reduction in fan pressure ratio, cruise specific thrust and hot and cold jet velocities, increasing propulsive efficiency, but this benefit would be cancelled out by the reduced transfer efficiency resulting from the increased bypass ratio and increased weight and nacelle drag. (The real trade-off would be more complex, with additional factors like cost coming into play, but to keep the example simple such factors are neglected.)

Four propulsion system options are compared in figure 11 and are analysed in table 1.

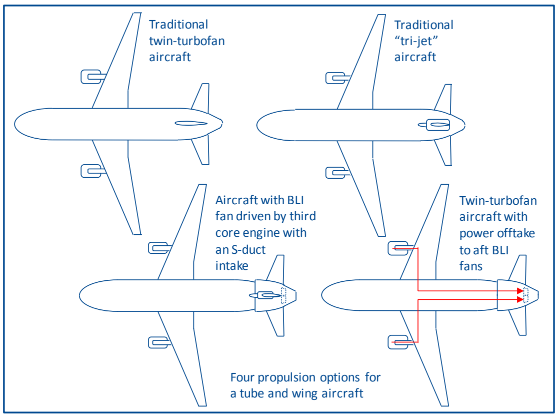


Figure 11: Alternative Propulsion Systems

Relative to a baseline twin-turbofan aircraft the first variant is a traditional tri-jet, the second has BLI on the centre engine and the third is a TeDP design where the two under-wing engines power the BLI propulsor or propulsors. The figures in table 1 refer to a generic long-range aircraft, with a weight break-down for the baseline aircraft similar to that given in [8]. Cruise thrusts are quoted relative to the baseline engines and all weights are quoted relative to MTOW for the baseline aircraft.

Table 1: Comparison of Alternative Propulsors

	Twin-jet	Tri-jet	Tri-jet +BLI	TeDP +BLI
Relative weights				
MTOW	100.0%	100.9%	101.5%	102.1%
Payload	16.8%	16.8%	16.8%	16.8%
Fuel	23.3%	23.9%	22.5%	22.5%
Equipment	14.5%	14.5%	14.5%	14.5%
OWE	59.9%	60.1%	62.1%	62.8%
Fuselage	14.4%	14.9%	15.4%	14.9%
Wings	18.7%	18.8%	19.1%	19.2%
Empennage	0.9%	0.8%	0.8%	0.8%
Undercarriage	3.0%	3.1%	3.4%	3.4%
Under-wing pylons	1.0%	0.8%	0.8%	0.8%
Nacelles	1.7%	1.7%	2.4%	1.9%
Wing engines	5.7%	3.7%	3.6%	4.6%
Tail engine/fan	-	1.8%	2.2%	1.1%
DP transmission	-	-	-	1.5%
Mid-cruise weight	89.9%	90.5%	91.7%	92.4%
Performance				
Lift/drag ratio	22.5	22.5	27.3	27.3
Total cruise thrust	100.0%	100.7%	84.1%	84.7%
Fuel-burn	100.0%	102.6%	96.6%	96.5%
Overall Propulsion				
System weight	8.3%	8.0%	8.9%	9.9%
Propulsive efficiency	84.2%	84.2%	86.4%	86.4%
Transfer efficiency	85.1%	84.8%	73.5%	72.9%
Thermal efficiency	50.0%	49.3%	49.1%	49.9%
Relative SFC	100.0%	101.9%	114.8%	113.9%
Under-wing engine				
Net cruise thrust	100.0%	67.1%	58.3%	60.8%
X/V0	0.367	0.367	0.319	0.326
Bypass ratio	19.0	18.6	19.8	13.2
Tail propulsor				
Net cruise thrust	-	67.2%	51.6%	47.7%
X/V0	-	0.367	0.270	0.256

Table 1 shows that while the conventional tri-jet benefits from lighter engines, these engines suffer from lower core thermal and transfer efficiencies at cruise because they are smaller. This effect offsets part of the benefit from BLI, but the aircraft with BLI on the centre engine still shows a fuel-burn reduction of about 6% relative to the more conventional tri-jet. The two turbofan engines for the TeDP aircraft are much less affected by scaling, but have an extra transmission loss for power sent to the BLI propulsor. For the levels of technology currently assumed, these effects largely cancel out. For the TeDP arrangement to show a fuel-burn benefit relative to the tri-jet with BLI, a more efficient or lighter weight transmission system would be needed.

The propulsion systems in table 1 are still not fully optimized as they all have the same total mass flow relative to aircraft weight and in each case the fans have equal mass flow and power. The one-seventh power law boundary layer velocity distribution and the BLI fan mass flows assumed mean that only about 82.5% of fuselage drag ahead of the BLI fan intake is ingested. Further trade-offs are possible between normalized specific thrusts (the X/V0 figures) for the under-wing engines and the BLI propulsors. The TeDP BLI propulsor has lower specific thrust than the under-wing engines, but a better solution could be to give it more of the total power at cruise and higher specific thrust relative to the under-wing engines. The optimum thrust and specific thrust for the BLI propulsor is not obvious because the extra transmission losses offset some of the benefit from ingesting the boundary layer.

Some further key assumptions made to derive the figures in table 1 are as follows:

- All the aircraft are sized for the same design payload and range.
- Aircraft lift/drag ratios and the proportion of total aircraft drag potentially available for ingestion (90% of 25% on the baseline aircraft) are taken from [8].
- The wing, horizontal tail, undercarriage and nacelle weights are proportional to mid-cruise weight (equal to maximum landing weight).
- Undercarriage weight is independent of fan diameter, but is increased by 10% to improve ground clearance for aircraft with BLI fans.
- Wing weight is independent of fuel tank volume and under-wing weight, (i.e. the wing reinforcement to support heavier engines is just cancelled out by wing bending moment relief).
- Fuselage weight increases to support a TeDP ducted fan or third engine and a core intake.
- Tail fin and pylon weights are reduced for aircraft with lower thrust under-wing engines.
- The under-wing engine takeoff thrust is proportional to 100% of MTOW for the twin-turbofan aircraft and 60% of MTOW for the tri-jet and TeDP designs.
- The engines are sized by cruise or top of climb thrust requirements, not by takeoff thrust, and overall propulsor mass flow at cruise is proportional to mid-cruise aircraft weight.
- BLI fans have reduced transfer efficiency and the electrical transmission system for the TeDP BLI propulsor is 97% efficient after allowing for power offtake to drive a cryo-cooler.
- Cruise core thermal efficiency is taken to vary with the twenty-fifth root of core power and transfer efficiency is varied with the eightieth root of core power. (These scaling rules allow for changes in component efficiency resulting from changes in component size.)
- Total fuel-burn is assumed proportional to mid-cruise fuel-burn for a long-range aircraft.

These assumptions will not always be applicable, so the figures in table 1 should only be considered as indicative, highlighting factors that should be taken into account in a more definitive assessment. The comparisons could be extended to consider the benefits of integrating stored energy into the TeDP aircraft. Stored energy could be used to boost performance at takeoff and top of climb, but its chief benefit is likely to be a reduction in NOx emissions around airports, particularly for short-range aircraft that spend more time flying in and out of airports and would be able to recharge their batteries on the ground at more frequent intervals.

A further option may be to use an open rotor for the aft fuselage BLI propulsor, as this would provide a substantial reduction in nacelle drag.

Conclusions

The ingestion of airframe boundary layer air into propulsion systems can improve an aircraft's performance by reducing drag and by increasing propulsive efficiency. However, the benefit attributable to each effect depends on conventions adopted for thrust and drag accounting.

DP systems may use extra engines to power BLI fans or open rotors, or transmit power from just two engines to the remote BLI propulsors. There are pros and cons for each of these arrangements.

Ingestion of boundary layers results in significant aerodynamic flow distortion at propulsor inlet and reduces propulsor and overall propulsion system transfer efficiency, offsetting some of the propulsive efficiency benefit. Transfer, thermal and propulsive efficiency must all be taken into account when optimising the overall propulsion system configuration and the relative mass-flows and jet velocities of its different components.

The fuel-burn benefits of different propulsion systems potentially incorporating BLI cannot be assessed on SFC figures alone. Holistic assessment is required, taking account of the costs and benefits of BLI at the whole aircraft level.

Acknowledgements

The authors are grateful to Cranfield University and Rolls-Royce plc for permission to publish this paper.

References

[1] Lundbladh, A. and Grönstedt, T., Distributed Propulsion and Turbofan Scale Effects, ISABE 2005-1122, 2005.

[2] Ameyugo G, Taylor M and Singh R., “Distributed Propulsion Feasibility Studies”, ICAS-2006-250, 2006.

[3] Hall, C., Schwartz, E., and Hileman, J. (2009). Assessment of technologies for the silent aircraft initiative. Journal of Propulsion and Power 2009, 0748-4658, Vol.25, No.6, pp. 1153-1162, DOI: 10.2514/1.43079.

[4] Felder, J., Brown, G. and Kim, H. D., (2011), “Turboelectric distributed propulsion in a hybrid wing body aircraft”, ISABE-2011-1340, Gothenburg, Sweden, September 2011.

[5] Gunn, E. and Hall, C., (2014) “Aerodynamics of Boundary Layer Ingesting Fans”. Paper GT2014-26142 ASME Turbo Expo 2014, Düsseldorf, June 2014.

[6] Rolt, A. and Whurr, J. (2015), “Distributed Propulsion Systems to Maximize the Benefits of Boundary Layer Ingestion”, ISABE-2015-20288, Phoenix, October 2015.

[7] Seitz, A. and Gologan, C. (2013), “Parametric design studies for propulsive fuselage aircraft concepts, paper No. 257”, 4th CEAS Air & Space Conference, Linköping, September 2013.

[8] Seitz, A., Bijewitz, J., Kaiser, S., Wortmann, G., (2014) "Conceptual investigation of a propulsive fuselage aircraft layout", Aircraft Engineering and Aerospace Technology: Vol. 86 Iss: 6, pp.464 – 472. AEAT-2014-079.