21ST CENTURY CHALLENGES FOR THE DESIGN OF PASSENGER AIRCRAFT

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Abstract

The needs of the 21st Century are addressed for future passenger aircraft design to meet the important requirements of the customer airlines. In particular, the impact on two traditional major requirements are reviewed, the Design Mission and the Operating Costs. The effect of aircraft on the Environment and the huge increases in the cost of fuel will have a substantial effect on the way future aircraft are optimised. These demands are summarised before moving on to the basic equations affecting how the aircraft design must respond. Very similar targets driving research work have now been set in both Europe and the USA and some of the new technologies that we can expect to be incorporated are outlined. Finally a glimpse is given of the possible future aircraft configurations we may see in the skies in response to the new demands.

1 Introduction

A passenger aircraft will, or should, be designed to meet the requirements of the customer airlines. Safety goes without saying and airlines will have different needs for take - off and landing performance at the airports relevant to their route structure. However an almost universal requirement is to improve significantly on the direct operating costs of their current fleet and also to meet a mix of mission requirements in terms of number of passengers, seating layout and range. The manufacturer has to collate the requirements of potential launch customer airlines into a "Design Mission" and a Direct Operating Cost (DOC) target, usually in the range 15% to 20% less than existing competitive equipment. As an example, after discussions with both potential customer airlines and the major international airports, the Design Mission for the Airbus A380 was fixed as requiring to carry 550 passengers in a three class layout, plus a certain amount of freight, from Singapore to London against adverse winter winds. This would satisfy the majority of other route requirements around the world without unduly penalising the operating economics through defining an aircraft with too heavy or large a structure to carry enough fuel for ultra long range. For example Europe to Sydney Australia in one stage would not be satisfied.

The DOC target for the A380 was indeed set to be in the range 15% to 20% better per passenger kilometre than the Boeing 747- 400 in service in the late 1990's at the time of freezing the design of the A380. Whilst specifying a larger aircraft and newer engines helped significantly in reducing the DOC, the target could not be reached without the introduction of new technologies such as increased use of Carbon Fibre Reinforced Polymer and advanced metallic alloys to reduce weight, advanced integrated aerodynamics, improved systems etc.

A typical traditional build up of the contributions to the Direct Operating Cost of an aircraft is shown in figure 1, in this case for a typical medium range 150 seat aircraft. For the purposes of this paper, attention will only be drawn to the contributions due to fuel used and those affecting the purchase price of the aircraft.

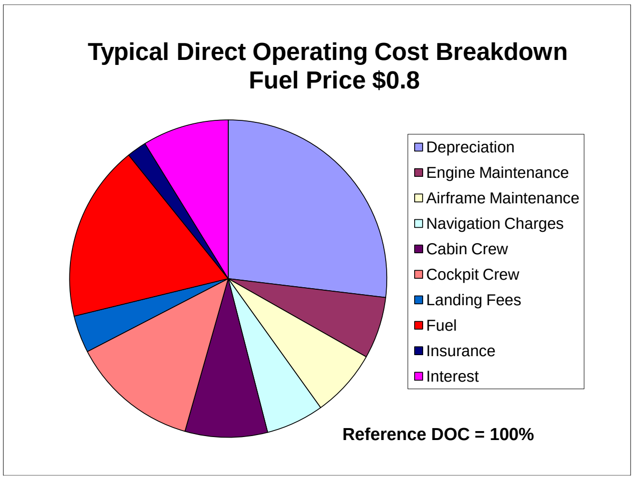

Fig. 1

The three sectors "Depreciation", "Interest" and "Insurance" are all a function of the first price and so it may be seen that for this traditional example the cost of fuel, although the second largest single sector, is actually significantly smaller than the total effect of purchasing the aircraft. Therefore there has been a very important drive for the manufacturer to reduce the manufacturing cost and hence the selling price of the aircraft at a level that still enables him to stay in business, even if this had some effect on the aircraft fuel burn. (In comparing this example with others, it may be noted that this build-up for costs per flight hour is very sensitive to utilisation, or flight hours per annum, which have been improving dramatically in recent years, emphasisiing the relative fuel cost.)

This paper goes on to explore the additional demands of the 21st Century on the design optimisation of a new passenger aircraft and in particular how that might affect the balance between performance and cost and what other aspects are becoming more and more important.

2. The Additional Demands of the 21st Century

The demand to meet required missions at minimum cost, whilst satisfying the requirements of the passengers for safety, reliability and comfort standards, will still of course continue to be important in the design of future passenger aircraft. However, over the last two decades the effect of aircraft operation on the environment has become an increasingly important aspect of airline requirements, driven by the concerns of the general public and governments and hence resulting or threatened legislation. Noise around airports has been an issue for many years, now being joined by air quality in affecting the population living close to airports. These local effects are already the subject of regulation under the auspices of International Civil Aviation Organisation (ICAO) agreements and are being taken into account in the current design of aircraft and engines. These and specific national regulations can be expected to be progressively tightened in the future. Of rapidly increasing significance has been the effect of emissions in the upper atmosphere and the potential effect on climate change and global warming affecting the whole population.

2.1 Summary of the impact on climate change

Whilst there has been much comment in the newspapers regarding the impact of aviation, particularly in the United Kingdom and to a lesser extent in Europe, USA and elsewhere, the current consensus is that Commercial Aviation currently contributes about 2-3% of the Carbon Dioxide produced by Man. However, the total effect on Global Warming is probably more like 3% to 4% when taking into account the effect of Nitrogen Oxides from combustion and contrail cirrus cloud formation. Future predictions range up to the order of 15% to 30% depending on the continuing growth in air traffic, perhaps to triple the passenger miles of today, and depending on other sectors meeting their targets for CO2 reduction. So the Aviation sector cannot be complacent about its relatively small current contribution and indeed is not!

Aviation chief contributors to Climate Change (after TRADEOFF, 2003)

- CO_2 100%
- NO_X (net effect of $O_3 - CH_4$) 45%
- Contrails plus Contrail Cirrus 79 – 355%

Total compared with CO_2 alone:- 224% to 500%

Fig. 2

The chief contributors to climate change from Aviation are summarised in figure 2, compared with the basic contribution from CO2. Oxides of Nitrogen NO and NO2 (collectively NOx) have a beneficially effect in countering the effects of Methane but a warming effect through a reaction at high altitude to produce ozone. The net effect is a warming influence which is still the subject of ongoing research. It may however be noted that reductions in fuel burnt, and hence reduction in CO2 emitted, will also assist a reduction in NOx emissions.

Persistent contrail induced cirrus cloud

Fig. 3

The effect of contrails and subsequent longer-lived cirrus cloud (figure 3) has been the subject of intensive research over the last few years and the conclusions are firming up into there being a significant contribution from this source, of the order of at least the same amount as CO2. There is little that can be done in aircraft design optimisation to reduce the effects of contrail cirrus, the way forward almost certainly being to concentrate on "tactical" air traffic control to reroute around the zones in the atmosphere where conditions favour their production, that is, supersaturated with water vapour at temperatures where ice crystals will precipitate out. The re-routing can be an increase or decrease in altitude as well as a lateral change. However, of course this will inevitably mean an increase in CO2 and NOx production, and we are still not yet sufficiently sure of the science to be able to give the right guidance in this respect. None the less, this is an issue to be considered in the future development in air traffic control systems.

2.2 Oil Prices

The second additional major issue for future aircraft design is the price of fuel. For the foreseeable future kerosene will be the only viable fuel for passenger aircraft, due to its excellent energy density by volume and by weight. It is probable, looking at least 10 to 20 years ahead, that the kerosene will be produced from both fossil oil and biomass, but in either case the effective cost is certain to increase substantially.

It is salutary to note that all aircraft in service, including the Airbus A380 and Boeing 787, were designed in a period of relatively low oil price (albeit recognising the almost inevitable increase in fuel costs and the need to reduce the environmental impact). The cost of aviation fuel since the year 2000 is shown in figure 4.

The design of the A380 was frozen just before 2000 and the Boeing 787 around 2003 when the fuel price was still of the order of $0.8 per US Gallon.

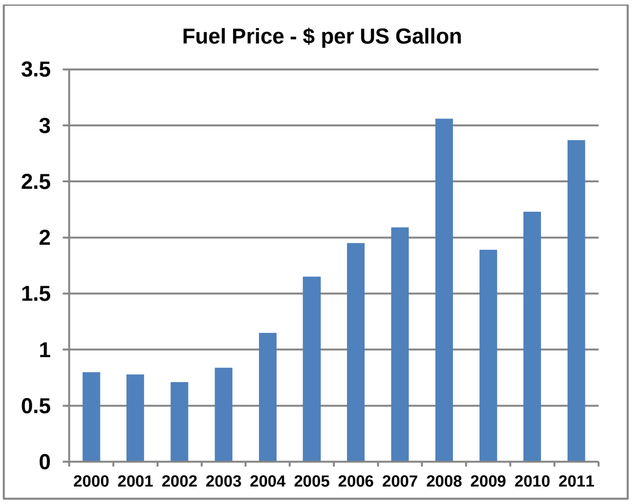

Fig. 4

Since then the fuel price rose to a peak of $4 in 2008 (with an average for the year of $3 - figure 4), then fell back but is currently in the region of 2.5 to $3 a US Gallon, or **over 3 times the cost of fuel at the freezing of the design of all large passenger aircraft currently in service.** The effective price of fuel can only be expected to increase either through the increasing pressure of demand over supply or by the addition of environmental levies by the world's governments. Much has been said in the last two to three years about the possibilities of using biomass to produce a "drop-in" replacement for fossil kerosene, producing a near neutral CO2 fuel. This is certainly an exciting possibility, but all the indications are that even if it becomes viable in the necessary quantities, the cost is going to be extremely high and will not affect the pressure to reduce fuel burn.

For once, therefore, there is a complete synergy between these two additional demands for the 21st Century. There will be both extreme economic and environmental pressure to reduce fuel consumption. The production of contrail cirrus will almost certainly also need to be addressed, most likely through route management on a tactical basis. Much is also already being done to reduce NOx as a product of combustion through improved combustor technologies, to improve airport local air quality that will also have benefits at high altitude. The remainder of this paper will concentrate on the overwhelming resulting demand to reduce fuel burn.

How will this affect aircraft optimisation? As an example, let's look at the effect of increasing the fuel price to, say, $4 per US Gallon on Direct Operating Costs. Taking the 150 seater example shown in figure 1, with everything kept the same except the increase in fuel cost, we get the result shown in figure 5.

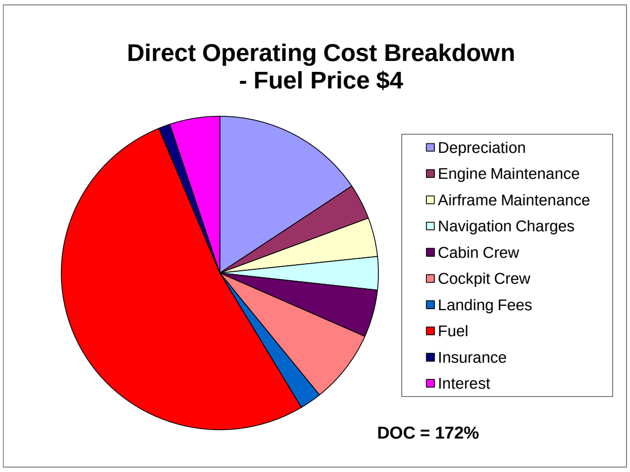

Fig. 5

The DOC has increased by 72% and inevitably the fuel cost has become the dominating sector, contributing just over half the DOC. Suppose there was another option available, to incorporate new low weight or aerodynamic technologies leading to halving the fuel burn which, however, led to an increase in the purchase price of the aircraft by 50%. Would the deal be of benefit to the airline? The new result is shown in figure 6, the answer being a resounding "yes"!

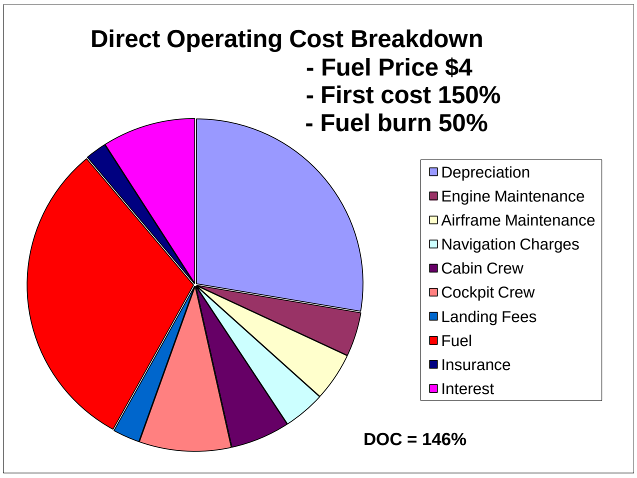

Fig. 6

The DOC is now reduced to a 46% increase and the fuel and first price dependent sectors are more in balance once again.

We have already seen something of this effect in the runaway success of the A320 "NEO" (New Engine Option). Mainly due to the new engines, this development of the Airbus A320 family offers a 15% reduction in fuel burn for a list price increase of order $8 million. Such an exchange at the traditional fuel price of $0.8 per US Gallon would not have been of any economic value to an airline, but certainly is at current and anticipated fuel prices.

3. Research Targets

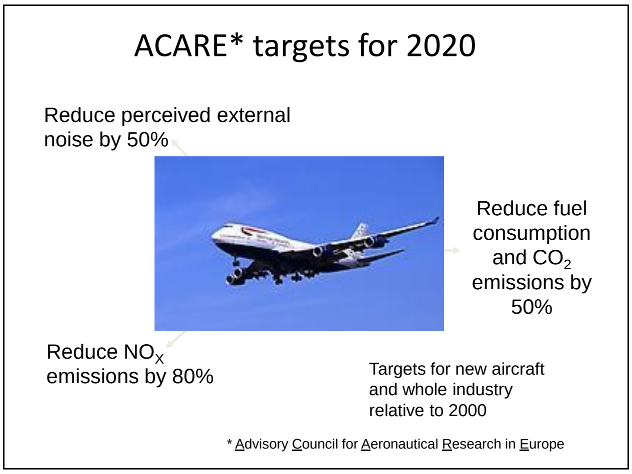

Fig. 7

Since the year 2000, the European Union has supported "stretch" targets for research to reduce the environmental impact of aviation, the ACARE targets, for aircraft entering service in 2020 relative to those that were being delivered in 2000, figure 7.

We are now more than halfway towards 2020, so how is progress? Major European research programmes are still ongoing and there is enough progress to demonstrate that with the technologies and aircraft configurations being explored, some of which are described later in this paper, the targets are achievable and probably can be beaten. However in all probability it will be well into the third decade before there is a significant number of such aircraft in service, and that will depend on the continuing drive from governments and airlines alike to ensure it happens. The review carried out by ACARE in 2011 resulted in more demanding goals but in a longer timescale, "Flightpath 2050", figure 8. The three previous goals have been strengthened and joined by others, the most important of which are the last two, referring to biofuels and leading in atmospheric research and developing environmental standards.

New ACARE Vision – "FLIGHTPATH 2050"

In 2050:-

- **Technologies and Procedures available to give 75% reduction in CO2 emissions , 90% reduction in NOx emissions and 65% reduction in perceived noise (relative to new aircraft delivered in 2000)**
- **Aircraft are emission free when taxiing**
- **Air vehicles designed and manufactured to be recyclable**
- **Europe established as a centre of excellence on sustainable alternative fuels including for Aviation**
- **Europe leading on atmospheric research and establishment of global environmental standards**

Fig. 8

Similarly in 2011 NASA in the USA issued environmental goals for aviation, figure 9. Their target date is "for a 2030 era aircraft" and the goals are relative to 2011 in-service standards rather than 2000. Also reducing costs is mentioned alongside reducing emissions. However, the main thrust of these targets is very similar in the direction aviation research will be driven on both sides of the Atlantic.

NASA's goals for a 2030-era aircraft

- **A 71-decibel reduction below current Federal Aviation Administration noise standards – aimed to contain objectionable noise within airport boundaries.**
- **A greater than 75 percent reduction on the ICAO CAEP/6 standard for nitrogen oxide emissions, to improve air quality around airports.**
- **A greater than 70 percent reduction in fuel burn to reduce greenhouse gas emissions and the cost of air travel.**

(Compared with an aircraft entering service today)

Fig. 9

4. The major parameters affecting fuel burn

As previously stated, the remainder of this paper will concentrate on the optimisation of aircraft to reduce fuel burn, concluding by giving some examples of the major relevant technologies and the direction that may be taken by aircraft configurations in the future. This can best be introduced by going back to basics and starting with an inspection of the fundamental Breguet Range Equation, figure 10, which holds true for any flying vehicle that has to support its own weight and carry its own fuel.

Options for reducing fuel burn per passenger-km

The Bréguet range equation

Fuel burn per tonne-kilometre

$$\frac{W_F}{W_P R} = \frac{1}{X}\left(1+\frac{W_E}{W_P}\right)\left(\frac{1.022\exp\left(\frac{R}{X}\right)-1}{\left(\frac{R}{X}\right)}\right)$$

W_F = Fuel Weight
W_P = Payload
W_E = Aircraft Weight-Empty
R = Range

X = $H\eta L/D$
H = calorific value of fuel
η = overall propulsive efficiency
L/D = lift/drag ratio

Fig. 10

The parameter on the left hand side of the equation is the fuel burn per unit payload per kilometre flown. The value of 1.022 has been introduced to allow for additional fuel used in climb and around the airport both for take-off and landing. A possible future optimum for this value might be 1.015 but the difference will not affect the conclusions significantly.

So it may be seen that the fuel efficiency will depend on the parameter "X", the aircraft empty weight per unit payload and the Design Range. It will also depend on the reserve fuel weight carried, but since in a normal flight it is constant through the complete mission it can simply be considered as an addition to the aircraft empty weight. (None-the-less on a long range mission the reserve fuel is a significant weight and looking at ways in which it can be safely reduced will be productive.) "X" is itself a product of three other variables: the fuel calorific value, the aircraft lift/drag ratio and the propulsive efficiency.

As mentioned in section 2.2, kerosene will be the fuel of choice for many years to come and hence the fuel calorific value, or energy content per unit weight, can be considered a constant. Liquid hydrogen might be an option in the distant future, depending of course on its production process not emitting any significant contributions to climate change. This is not considered any further in this paper.

4.1 Design Range

The aircraft Design Range has a fundamental effect on fuel efficiency. This was introduced by Greener By Design a decade ago as a possible way to reduce fuel burn [1]. The effect is two-fold. Firstly, for a long range mission the aircraft is carrying the weight of the fuel for the later part of the flight over the earlier part. This results in an increased fuel burn per kilometre due to the heavier average total weight of the aircraft. Secondly, due to the increased take-off weight for a given payload, the structure weight of the aircraft will be increased and to fulfill its mission the wing area and weight will increase. These two effects will combine to increase the fuel burn per unit payload per kilometre flown for a long range mission by up to 30 - 50% compared with the aircraft designed for the "optimum" range for fuel efficiency. Such an aircraft turns out to be one designed for about 5500 kilometres when carrying its maximum payload. Size has a relatively small influence on this value. At present this is an aircraft the airlines do not want as it lies between the short to medium range 150 seater requirement and the larger long range twin aisle aircraft able to operate over much longer ranges as well as those around 5000 to 6000 kilometres. A very thorough exercise has been done by DLR in Germany [2] showing the benefits that can be obtained by using such an aircraft. The problem of course is in airline and public acceptance of, for example, going from London to Australia in three stages instead of two! This could perhaps be a matter for future international regulation - no aircraft should be designed for a range longer than, say, 6000 kilometres! This also raises the issue of seating layout, since the aircraft fuel efficiency per passenger carried is much better for the passenger payload being close to the maximum payload rather than significantly less as it currently is in a three class layout. Whilst the A380 design mission was to carry 550 passengers in a three class layout, it is capable of carrying 845 in an all economy class with an equivalent improvement in fuel burn per passenger of order 30-40%, albeit over a somewhat shorter maximum range. However this is more an issue for the airlines and once again possible regulation, rather than for the manufacturer.

Another interesting option raised by the effect of design range is the possibility of air to air refueling of civil aircraft. There are obvious safety and operational issues to be considered here, including the operation and fuel used by the tanker aircraft, but the possibilities are explored by Nangia [3]. As long as an adequate level of safety can be guaranteed, this could be more acceptable to the public in so far as intermediate stops to refuel are no longer necessary.

4.2 Weight Reduction

Reducing the aircraft empty weight has a first order effect on improving fuel burn, as is obvious from inspection of the Breguet Range Equation (figure 10). Weight reduction through use of improved or new materials has been a continuing trend for many years, but has more recently accelerated through the much wider use of Carbon Fibre Reinforced Polymer (CFRP) in the aircraft primary as well as secondary structure. This has resulted in an increased percentage of composites (mainly but not only CFRP) in the aircraft weight build up, from of order 15% in the late 20th century through 25% in the A380 to about 50% of structure weight for both the Boeing 787 just entering service and the Airbus A350 due into service in two years time. This latter step forward has been due to the confidence to make the main load bearing wing box and the fuselage pressure shell from CFRP. Whilst replacing aluminium alloys with CFRP has the potential to reduce weight by as much as 30%, for various reasons the current benefits are nothing like that large and future development will be to force along the learning curve to develop much more of the basic potential of the material. Needless to say, metals are fighting back, for example aluminium lithium alloys particularly suitable for fuselage applications, and in general we can expect further significant weight improvements from advanced materials, particularly as the operating economics will encourage their use even when they will inevitably incur increased costs (see section 2.2). The current use in the latest projects will have reduced empty weight by about 7%, reducing fuel burn by about 5%.

The other avenue to reducing weight is through new more radical aircraft configurations. The major advance on the horizon in this regard is the blended wing body which is dealt with later on.

4.3 Propulsion Efficiency

This is a major subject in its own right and will only be covered here in so far as it affects the overall optimisation of aircraft design. Basically two development routes are opening up. One is the continued evolution of the current type of high bypass ratio turbofan (figure 11).

Fig. 11

This will include improvements to the power producing core, through increased pressure ratios and higher temperatures (through advanced aerodynamics in the compressor, combustor, passages and turbine blade design, advanced materials again, and turbine blade cooling systems). More efficient engine cycles are also being researched with intercooling of the main airflow for example, although the additional weight and size of heat exchangers remains a significant problem. Increasing the bypass ratio, that is, increasing the fan diameter to improve the Froud propulsive efficiency is still an option before the resulting fan cowl becomes so large and heavy that its weight and drag negate the basic improvement in the power plant specific fuel consumption. The bypass ratio for the B787 and A350 have now increased to 9 compared with around 6 for previous generation turbofans and certainly increasing to about 12 to 15 should be possible whilst showing an overall fuel burn benefit.

The second route is to remove the outer cowl of the turbofan and go back to propellers, or "Open Rotors" as they are now referred to (Figure 12).

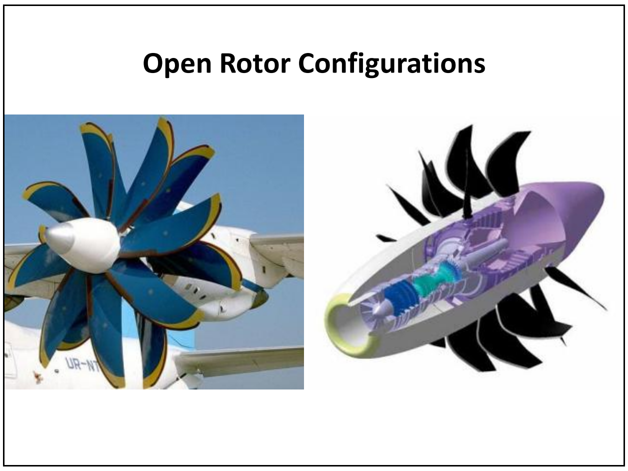

Fig. 12

These were first flight tested in the 1980's when fuel prices hit $2 a US Gallon for a while. However their external and internal cabin noise problems and increased maintenance costs meant that they were not worth pursuing when the fuel prices fell back to less than $1 once again. Effective by-pass ratios of order 50 are then possible, giving the better Froud efficiency of moving a greater proportion of the total airflow more slowly though the propulsion system to produce the thrust. The tip vortices from the propeller blades reduce the efficiency partially, but the energy going into swirl is minimised by having two counter-rotating sets of blades, either in a forward or aft mounted layout (figure 12).

A major issue with open rotor propulsion is noise, both externally and internally in the cabin. However, with the advance in computational fluid dynamics methods giving improved blade designs, the engine manufacturers are reporting good results in current research on this topic. Active noise suppression systems are also now available to reduce cabin noise, particularly with discrete tones as likely from the propeller blade passing frequencies.

The advantages of either the evolutionary turbofan or the open rotor routes are summarised in figure 13 (with thanks to Rolls Royce). It is expected that either route will be able to meet near future airport noise regulations, but the turbofan will always be the quieter whilst the open rotor has the advantage of at least a further 10% improvement in fuel efficiency.

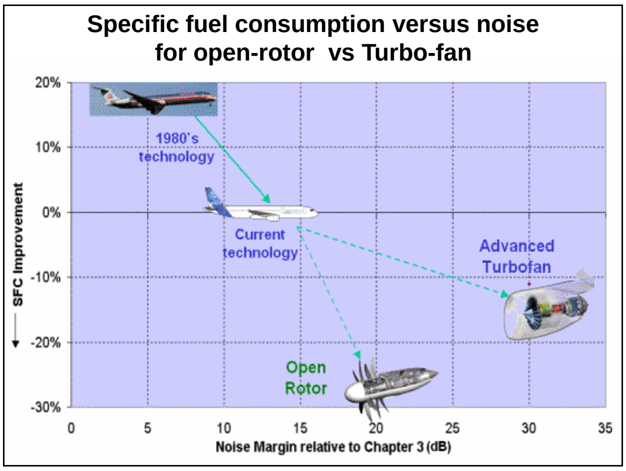

Fig. 13

Even with advanced computational capabilities, there are limits to the diameter and/or flight Mach Number for the Open Rotor, as the blade tips must not rotate at more than a limited supersonic speed otherwise shock waves and induced flow separations will give unacceptable drag, noise and vibration. This implies that they will be more appropriate for twin-engined aircraft up to around the 150 seat class, probably at somewhat reduced flight Mach Numbers compared with today, perhaps M=0.7 to 0.75 rather 0.78 to 0.80. Larger aircraft would have to consider multiple propulsion units and probably an absolute maximum cruise Mach Number of 0.80. There is a precedent here, the Russian Tupolev Tu-114 swept wing four engined aircraft with counter-rotating turboprop engines (figure 14) carried 120 passengers from Moscow to Cuba (for example) at a Mach No. of 0.70, although the noise was reputed to be horrendous! Maximum Mach No. was 0.78 and maximum passenger capacity 220.

Thus either future propulsion option will mean that the airframe must be optimised in the presence of larger diameter propulsion units than previously, particularly with the Open Rotor.

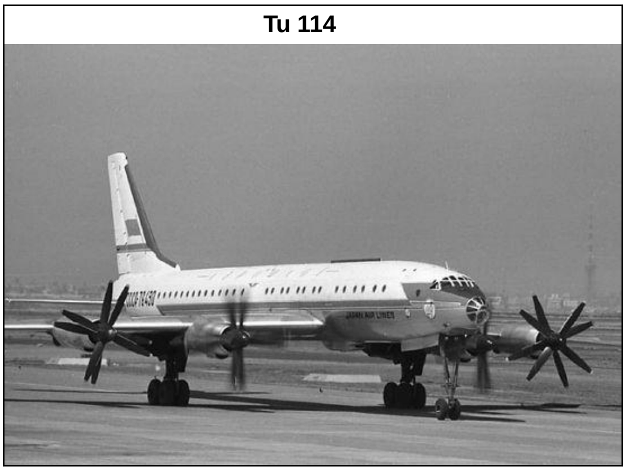

Fig. 14

4.4 Lift/Drag Ratio

The last major parameter to be operated on is the aerodynamic lift/drag ratio. To a first order, the optimum lift drag ratio can be broken down into more useable further parameters. Starting with the well known non-dimensional drag equation $Cd = Cdo + kCL^2/\pi A$, a dimensional form of the same equation is given in figure 15.

Maximising lift-to-drag ratio in cruise

Drag $= qS_{DO} + \frac{\kappa}{\pi q}\left(\frac{W}{b}\right)^2 \quad (C_D = C_{D0} + \kappa C_L^2/\pi A)$

L/D is a maximum when the two components of drag are equal, giving

$$\left(\frac{L}{D}\right)_{MAX} = b\sqrt{\frac{\pi}{4\kappa S_{DO}}}$$

when $q = W\sqrt{\frac{\kappa}{\pi b^2 S_{DO}}}$

$S_{D0} = \sum SC_{D0}$
W = Weight
b = Span
q = dynamic pressure
κ = Induced Drag Factor
L/D = Lift/Drag Ratio

Fig. 15

This is a simplification of course, ignoring other terms such as drag due to compressibility and shock-waves, which, however, at maximum lift drag ratio for a modern passenger jet are relatively small.

Remembering that the Lift L is equal to the weight W, re-arranging and differentiating with respect to W gives the equation for the maximum lift/drag ratio (L/D)max, given in the third line in figure 15. We can now inspect the crucial parameters:- Span, Induced Drag Factor and “Drag Area”. The latter is the sum of the surface wetted area of the various parts of the aircraft multiplied by the non-dimensional drag coefficient at zero lift (CDo) applicable to that part (eg the fuselage, wing, tailplane etc.). Again approximating, on a well designed aircraft there is some variation in the local values of CDo, but with turbulent boundary layers an average value of CDo is of order .0035, representing the skin friction drag plus some form drag due to the shape of the parts of the aircraft. Although Drag Area is an often used concept, we will look at this in the two parts, the total surface area of the aircraft and the average zero lift drag coefficient CDo based on that surface area.

4.5 Maximising the Lift/Drag Ratio

4.5.1 Span

Referring to figure 15, the span of the aircraft should be as high as possible. Unfortunately as the span goes up the weight of the wing also increases, particularly if this is without increasing the chord lengths to keep the surface area to a minimum (that is, by increasing the Aspect Ratio). To reduce wing weight one would like to reduce the flight Mach No. to reduce the wing sweep-back and to go to higher thickness to chord ratios. Also, using lighter stronger materials such as Carbon Fibre Reinforced Polymer will help the overall configuration optimising at a higher span.

4.5.2 Induced Drag Factor

Again for a well designed Civil Transport this is already close to the ideal value and close to the optimum of 1.0 (increased somewhat to allow for the inevitable increase in viscous form drag as a function of lift coefficient). There is nothing further to advise for this parameter other than to ensure that the total distribution of lifting loads and hence vortex drag of the complete aircraft are considered (that is for the wing plus the tailplane for example) when optimising drag and weight [4].

4.5.3 Surface Area and Zero Lift Drag Coefficient.

Both of these parameters need to be optimised to minimise the overall drag area. Clearly there are interactions between the two as well as with other drag components. However if a different configuration offers a significant reduction in total wetted surface area then there is the possibility of significant drag reduction. This is addressed later. As long as the aircraft is well designed with regard to interference drag between components and general excrescence drag (aerials, gaps and steps etc.) then the options for the drag coefficient are to reduce the fully turbulent skin friction drag coefficient or to generate areas of laminar flow. Where-as the value of turbulent drag coefficient is of order 0.0035, typical values for laminar flow are of the order 0.0005, that is just 14% of typical turbulent flow values (note, these are for Reynolds Numbers of order 10^7 typical of wing-like surfaces rather than traditional cylindrical fuselages, which will be an order of magnitude higher, but for which fully laminar flow would be impossible). Operating on the drag of turbulent boundary layers is the subject of ongoing research, but two current examples are the application of low friction paint or adding a layer with impressed longitudinal grooves (riblets). Either of these have a relatively minor effect on drag reduction but may find more favour as the reduction in fuel burn becomes ever more important compared with maintenance or structural inspection issues. However, these possibilities are unlikely to change the aircraft configuration significantly and are not pursued further in this paper.

4.5.4 Natural Laminar Flow

The reduction in drag if Laminar Boundary Layers can be maintained from the leading edges is so dramatic that even maintaining laminar flow over a relatively small proportion of the aircraft surfaces could be worthwhile. However for any wing-like surfaces, at the typical flight Reynolds numbers of a large passenger aircraft (ie 100 seats plus), the surface smoothness must be extremely good and the leading edge of aerofoil surfaces must be close to zero sweepback to avoid contamination by spanwise turbulent flow along the leading edge stagnation zone. This then implies significant problems of manufacturing with adequate smoothness and maintaining those standards through the life of the aircraft. It also once again implies aircraft with a lower Mach No. capability than today's jet transports but none-the-less perhaps adequate for relatively short range applications, perhaps 0.65 to 0.7 rather than the 0.75 to 0.80 currently. The most likely application would be over the forward part of the nacelles of ducted propulsion units and the first part of the wing chord, particularly on the outer wing. It is intended to flight test the latter concept in the major EU "Clean Skies" research programme using a heavily modified Airbus A340 aircraft (figure 16).

Fig. 16

4.5.5 Hybrid and Full Laminar Flow

There have been several examples over the last few decades of successful flight tests on both sides of the Atlantic to prove the aerodynamics of maintaining larger areas of laminar flow by suction through the surface to remove the low energy flow close to the surface. The typical application is suction through the upper surface of the leading edge area in front of the front spar of the load carrying/fuel tank wing box, that is, applied to the first 15-20% of the wing chord to maintain laminar flow over about the first 50% of chord. Maintaining laminar flow over more of the surface to the trailing edge will require suction over more of the chord with an increase in structural complexity and weight and is not at present seriously being considered to the author's knowledge.

Applying hybrid laminar flow over the wing upper surfaces, the tailplane and fin, and the nacelles (if ducted propulsors) would reduce cruise fuel burn by about 15%. The aerodynamics have been well proved but there are many other operational problems to be overcome as well as the structural and system complexities and additional significant costs. None-the-less Boeing are reported to be considering it for an initial application on the fin of their new 787 transport.

5. The possible impact on future civil transport configurations

Having reviewed the direction for the important parameters in reducing fuel burn, what will be the possible impact on the design and particularly the configuration of future civil passenger aircraft? Some of the general design repercussions are already implied in the preceding sections, weight reduction through the use of advanced materials or system concepts, reduction of turbulent skin friction drag or application of laminar flow concepts which may not significantly affect the overall configuration of today's aircraft.

Fig. 17

We can expect to see the classic tubular fuselage/low swept back wing/rear tailplane and fin/ underwing engines layout for many years. The latest large transports, the Airbus A380 and A350 (figure 17), and the Boeing 787 Dreamliner projects, perhaps with evolutionary improvements, will probably remain in service for several decades. What other options might we anticipate?
The first major move forward will probably be in the 150 seat short/medium range class, although a possible entry into service date has been delayed beyond 2020 (probably well beyond?) by both Airbus and Boeing having committed re-engined versions of their very successful A320 and 737 projects. Boeing were more limited than Airbus by the room under the wing for larger diameter ducted propulsors, but significant improvements in fuel burn of order 15% are claimed by both manufacturers with the new engines and a package of more minor modifications. A follow-up aircraft will have to demonstrate major fuel burn improvements relative to the latest versions of the A320 NEO and the 737 Max. That will not be easy. Boeing's problem of space under the wing for the 737 Max leads into the first significant configuration issue, allowing enough space for the efficient integration of large diameter propulsion units. This may force the change to high wing or rear engine configurations (figure 18).

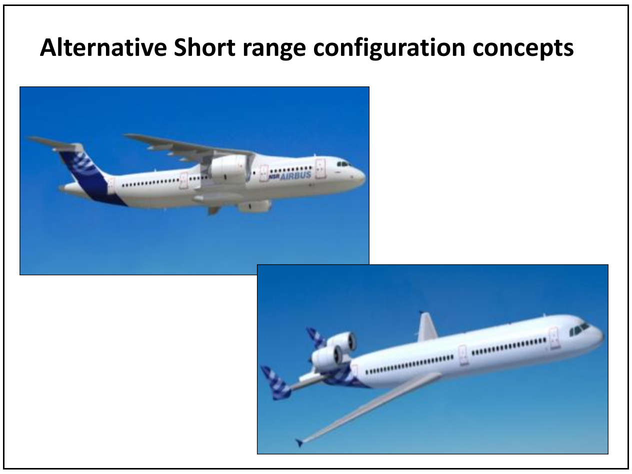

Fig. 18

Open Rotors mounted on the wing have the problem of increasing the air speed over the wing and hence the effective Mach No. Interference drag will then have to be minimised leading at least to some reduction in the potential fuel burn improvement with this type of propulsion. Rear engine installations will have their own problems, for example with an increase in the risk of a double engine failure from a blade loss or disk burst from one engine. Heavy propulsion units at the rear will also cause layout and loading problems.
For the 150 seater sized aircraft there is probably no radically new configuration that will reduce the wetted surface area significantly. Canards with a forward horizontal control surface have been looked at many times but never yet proved to show an advantage. There is certainly the possibility of generating natural laminar flow over some surfaces for this class of aircraft as reviewed in section 4.5.4.

Fig. 19

This could be combined with a very high aspect ratio wing with zero sweepback to give a substantial reduction in wing drag but subject to the issues already reviewed above. Such a layout was one subject of the NACRE EU Framework 6 research programme (figure 19). In response to a NASA call, Boeing have also proposed a very high span zero sweep configuration, probably in association with natural laminar flow, in their "SUGAR" proposal (Subsonic Ultra Green Aircraft

Research), but also applying the "Braced Wing" concept to reduce wing weight (figure 20).
So the next generation 150 seater aircraft may look very different to those in service today, with the passengers having to accept some modest increase in flight times.

NASA - Boeing "SUGAR" Braced Wing Concept

Fig. 20

Although probably even further into the future than a radically different 150 seater, the prime competitor to the classic configuration for longer range larger aircraft is of course the "Blended Wing Body" (figure 21). Some studies have suggested that for a given payload capacity and the same number of passengers the wetted surface area of such a configuration could be of the order of 70% that of a classic layout, with local drag coefficients which would be little different. Also, with the payload and fuel load distributed more across the span and with the integration of the control surfaces, there are significant opportunities for weight reduction, partially balanced by the need to maintain a smooth aerodynamic surface whilst designing an efficient structure to resist the cabin pressurisation loads. As suggested in the concept in figure 20, there is also the possibility of using the airframe for shielding the noise of the propulsion units for Take-off and Landing, although the ease and costs of engine maintenance will be compromised! The likely power plants would be large diameter ducted propulsors in this case due to the limits in diameter and hence power output of open rotors and a limit to the achievable Mach no.

Minimising Surface Area

Fig. 21

There is a possible middle ground between aircraft for the shorter range missions and the intercontinental very long range vehicles which would still be applicable to the Blended Wing Body concept. As reviewed in section 4.1, Design Range has a significant effect on fuel efficiency and a 250 - 300 seat blended wing-body aircraft designed for perhaps 5500 kilometres (3000NM approx) could cover much of the world's routes with excellent fuel burn. Such a design might look something like as shown in figure 22 (with thanks to NASA). (This also suggests the possibility of a further application of open rotor propulsion units but shows the problem of needing more units due to the probable thrust limitations reviewed in section 4.3).

Fig. 22

6. Concluding remark

This paper is intended as a general introduction into the requirements for future passenger aircraft design. Due to both the substantial increase in fuel prices and the threat of climate change, it is reasoned that the most significant driver for the optimisation of future passenger aircraft designs will be to substantially reduce fuel burn even with the almost inevitable increase in the cost and selling price. Weight reduction through advanced materials and application of advanced propulsion units are trends that are already well underway, although with little change in aircraft overall configuration. In the next two decades we may also expect to see more change in the look and performance of aircraft to incorporate more radical technologies, such as Laminar Flow, the Unducted Propulsor or the Blended Wing Body concept. One never gets something nothing however, and whilst very substantial reductions in fuel burn should be possible, the travelling public may have to accept some reduction in speed and increase in journey times to achieve the maximum improvement.

7. References

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