33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

IMPACT OF NASCENT TECHNOLOGIES ON THE SUSTAINABILITY ATTRIBUTES OF AN EVOLUTIONARY SINGLE-AISLE AIRCRAFT

N. J. Allen[1], M. R. Schofield[2]

[1]Aerospace Technology Institute, Cranfield, Bedfordshire MK43 0TR, United Kingdom

[2]Ellondee Ltd, Castle Donington, Derbyshire, DE74 2LN, United Kingdom

Abstract

An aircraft model has been developed which offers a view of the potential evolutionary development of conventional tube-and-wing aircraft, incorporating nascent technologies which are considered likely to be mature and ready to enter into service by 2035. The ATI's Single-Aisle Future Aircraft Model (SAFAM) has 160 seats in a 3-class layout and is capable of 3450 nm with a full passenger payload. SAFAM demonstrates that substantial improvements in fuel efficiency and operating costs can be realized with this approach, using 32% less fuel for a typical mission relative to an equivalent aircraft operating in 2000 (ACARE baseline). SAFAM also has 11% lower cash direct operating costs (Fuel price $2.50/USG) and therefore represents an interesting proposition for potential buyers, justifying the necessary investment in an aircraft development programme. Although zero emissions aircraft will be crucial to meet the environmental goals such as those set by ACARE, ultra-efficient aircraft like that presented here will also be essential to achieving global emissions reduction when combined with the use of Sustainable Aviation Fuel (SAF). SAFAM also offers a representative view of the standard that more radical architectures and technologies will need to exceed in order to justify any increased risks.

Keywords: Sustainability, emissions, operating cost

1. Introduction

A conceptual aircraft model (Single-Aisle Future Aircraft Model – SAFAM) has been developed in Pacelab APD in order to meet a set of Top-Level Aircraft Requirements (TLARs), representative of existing single-aisle aircraft, but including technologies and developments which are expected to be available in the timeframe for EIS 2035. This aircraft is intended to be a realistic evolutionary development for EIS 2035, which can be used as a baseline for evaluating other aircraft concepts in the same timeframe.

It should be noted that the philosophy for the design of SAFAM meant that all the benefits of technology innovation have been channeled into improving environmental performance and not improving aircraft capability. This is a departure from the historic development of new aircraft, which has seen generation-by-generation improvements in range, speed and other operational capabilities. Continuing this trend would be inappropriate in the current social and political climate, where a much greater emphasis has been placed on environmental considerations than ever before and aircraft are often not being operated to their maximum capability.

The Top-Level Aircraft Requirements (TLARs) for the aircraft are therefore very similar to those for existing single-aisle aircraft. It is notable that many studies evaluating radical aircraft configurations or technologies often compare their performance with existing aircraft, which can give a misleading impression of the potential benefit. The development of an evolutionary aircraft design such as SAFAM is critical in providing a contemporary 2035 baseline against which such aircraft can be compared.

2. Top-Level Aircraft Requirements

The SAFAM model is intended to be an evolutionary baseline, and as such many of the TLARs are carried over from the current single-aisle aircraft such as the Airbus A320neo and Boeing 737MAX. The starting assumption is made that the market will require the next generation single-aisle aircraft to have broadly the same capabilities as the current aircraft. Exploration of alternatives to this philosophy can be undertaken as derivations from the baseline model, which will also serve to improve the ease of understanding of the impact of high-level changes.

Table 1 Initial SAFAM TLARs

Maximum Range	3450 nm
Diversion and contingency	Typical international rules (200nm diversion, 30min hold and 5% trip fuel contingency)
Passengers	160 (assumed 100kg AUW) 2-class (ATI rules)
Cruise Mach number	0.78
TOFL	6000 ft (SL ISA)
Approach speed	131.5 kts @ MLW
Max structural payload	20500kg
Initial Climb Altitude Capability (ICAC)	FL350 (ISA +15) @ MTOW
Time to FL350	20 minutes (from 1500' ISA)
Distance to FL350	180 nm (from 1500' ISA)
ICAO aerodrome reference code	Code C (Wing span on ground <36 m; Outer main gear wheel span <9 m)

Environmental requirements are drawn from the ACARE FlightPath 2050 goals which are described relative to a baseline of aircraft in 2000. The requirements have therefore been scaled linearly between 2000 – 2050 to give a target for 2035. Given the likely make-up of the fleet in 2050 and the UK government's net zero target, it could be argued that this timeline should be accelerated, however these requirements are expected to be challenging at their current level and therefore seem reasonable. These targets will be treated as minimum requirements and could be stretched during the design process if this seems feasible.

The ACARE targets scaled to 2035, relative to 2000 are:

- CO_2 -> -52.5%
- NO_x -> -63%
- Perceived noise -> -45.5%

It should be noted that the ACARE 2050 targets on emissions reduction are stated to be through technologies and procedures and therefore it is reasonable to assume that a proportion of this reduction would be achieved through Air Traffic Control (ATC) measures rather than aircraft design.

3. Technology assumptions and model description

Although this aircraft design brings in some of the new technologies which are anticipated to be incorporated into the next generation aircraft, it is also important to account for the improvements that would arise from developments in technologies, materials, processes etc if the current aircraft were designed in the future without any architectural changes. Assumptions were therefore made around the likely drag reduction and structural and systems weight reductions which were included in the model.

The main technologies incorporated into the SAFAM model were a high aspect ratio wing and ultra-high bypass ratio engine. Based on ongoing technology development programmes, an aspect ratio of 14 was assumed for the aircraft, and three engines with bypass ratios (BPR) of 13, 15 and 18 were both modelled so that the preferred option could be selected.

On initial inspection, SAFAM does not look dissimilar to the single-aisle aircraft of today (see Fig. 1). The most easily observed differences are around the wing planform, engine diameter and horizontal tailplane, although there also other, less easily seen, changes.

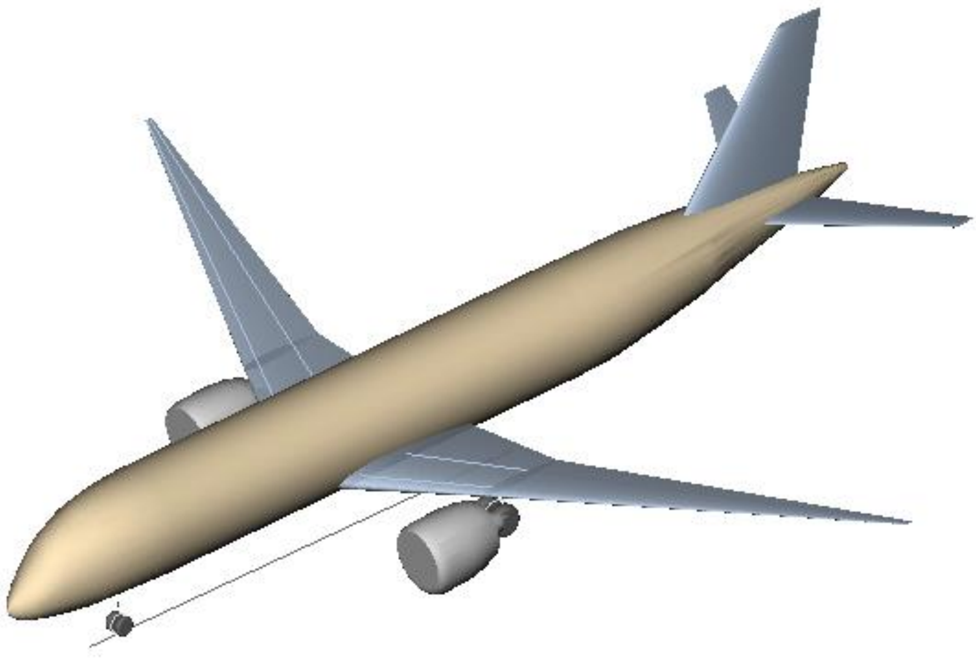

Fig. 1 SAFAM model in APD

3.1 Weights

The Maximum Take Off Weight (MTOW) for SAFAM is 9.4% lower and the Operating Empty Weight (OEW) is 9.3% lower than for the equivalent 2016 aircraft. This is driven both by the structural weight reductions and also the improved fuel efficiency requiring less fuel to be carried by the aircraft. Although the usable fuel capacity is reduced as a result of changes in the wing design, the improved fuel efficiency means that the aircraft range capability is maintained (and improved at reduced payload).

3.2 Wing planform

The increased aspect ratio of the wing gives rise to a noticeably different planform. Principal changes are:

- the increase in span due to the high aspect ratio,
- a significant reduction in tip chord and taper ratio,
- a small increase in the wing sweep angle.

3.3 Aspect ratio effects

The overall wing area is sized by the approach speed requirement for this aircraft, rather than for take-off performance or other potential constraints. The root chord and kink chord of the wing have been kept similar to existing aircraft, as these are defined by the space constraints depending on the detailed design of the landing gear, and to maximise the potential of managing the wing root bending moment given the increased wing span.

The aircraft span has therefore increased substantially as a result of the high aspect ratio, and is now just under 42 m. To meet the ICAO aerodrome Code C requirement of <36 m, the wing features folding wingtips which are deployed only on the ground and are locked out in flight. Further details around the folding wing tip are given in a later section.

Another visible change as a result of the high aspect ratio is the much-reduced wing tip chord and small taper ratio. This is both enabled by and required due to the folding wing tip. A small taper ratio results in a low volume outboard of the folding mechanism keeping the weights low and also reducing the loads. It was decided that none of the wing devices should extend outboard of the wing tip hinge, thereby making it feasible to have a small chord and thickness. This results in the ability to incorporate no systems (other than navigation lights) or structure outboard of the hinge other than that required to support the aerodynamic and inertial loads.

3.3.1 Sweep

An investigation of the aircraft performance with wing sweep gave the interesting result that both fuel burn and Direct Operating Cost (DOC) decreased with increasing wing sweep. The effect of wing sweep is related to a number of factors – for a fixed design, wing weight typically goes up with increased sweep due to the increased difficulty of reacting the wing root bending moment efficiently and high-lift performance requirements, while wave drag is reduced with increased sweep, increasing overall aerodynamic wing efficiency. As a result, there is typically an optimum sweep where these two effects balance to give the best aircraft performance, which on a current single-aisle aircraft occurs at a quarter chord sweep angle of around 25°.

For SAFAM, this optimum sweep for best performance was at a much higher angle. The reason for this is demonstrated in Figure 2. The assumption on the technology standard for structural weight (-20%) and aerodynamic efficiency (-2%) between 2015 and 2030 are substantially different, with the percentage reduction of the former being an order of magnitude larger than the latter. The result of this is to shift the balance of these two factors where the optimum sweep lies to a higher sweep angle.

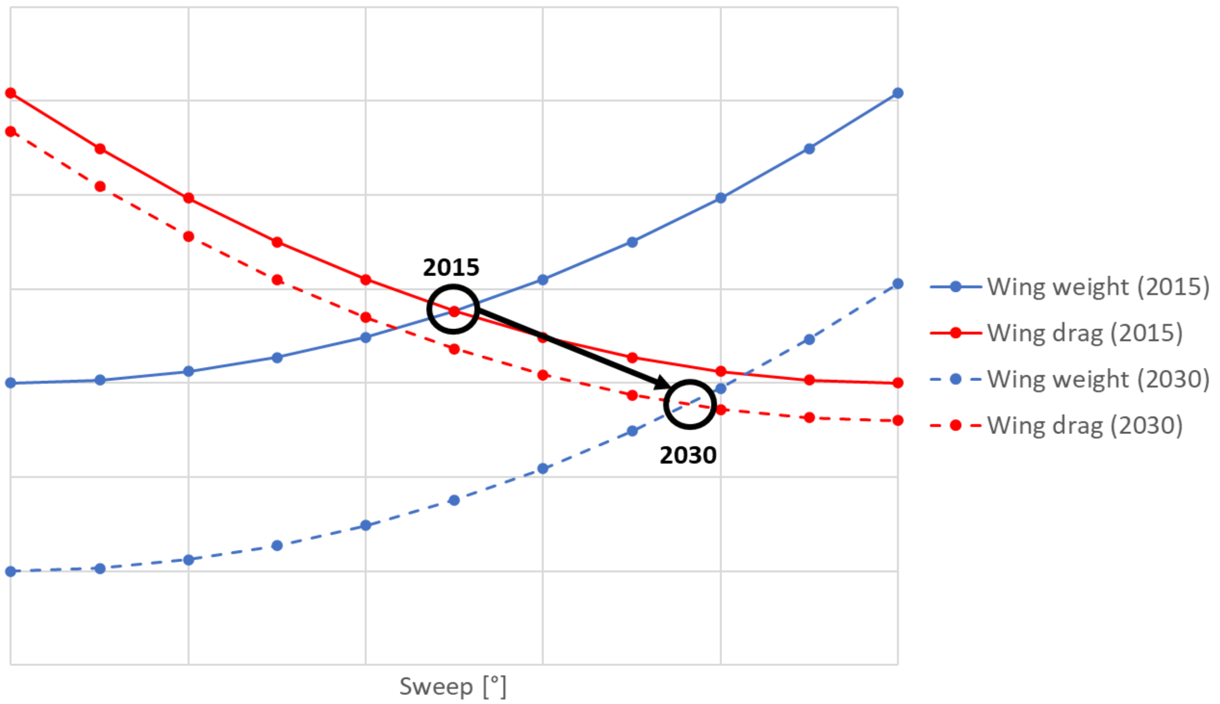

Figure 2 Effect of wing sweep on wing weight and drag for varying technology standards

It was found that due to other considerations it was not possible to increase the sweep to the minimum intersection of wing weight and drag which would represent the best wing performance. Increasing the wing sweep had detrimental effects on both the inboard wing geometry and the aircraft stability and centre of gravity (CG) limits.

Geometrically, the inboard trailing edge of the wing is fixed perpendicular to the longitudinal axis of the aircraft both to improve the aerodynamics and reduce structural complexity. This means that as the sweep increases the chord at the kink is reduced if the spanwise location of the kink is held constant. This therefore has the effect of limiting the maximum allowable sweep in order to ensure an acceptable kink chord length based on the requirement to mount and stow the landing gear and integrate the engine.

Another constraint on the maximum wing sweep was the aircraft longitudinal stability – increased wing sweep moves the aerodynamic centre in wing coordinates rearward relative to the CG location and therefore requires the wing to be moved further forward to maintain the static margin. However, the position of the wing is constrained by the need to maintain realistic CG limits, with the aft CG turnover limit being a particular issue.

The best compromise on quarter-chord wing sweep for this aircraft was therefore determined to be at 26°.

3.4 Folding wing tip design

It was not possible to model the folding wing tip in the conceptual design software, and given the intention to have the wing tip deployed throughout flight without in-flight modifications, it was not necessary to model it in detail for this level of design. However, some aspects or effects of the folding wing tip were modelled and are described below.

3.4.1 Geometry and structure of folding wingtip

The intent of the folding wingtip design was to allow the aircraft to use ICAO Code C aerodromes, which allow a maximum wingspan of 36 m. With an aspect ratio of 14, the resulting design has a wingspan of 41.24 m and therefore a span of 3 m is required for the folding wingtip to meet the requirement. This represents 14.5% of the aircraft semi-span. The resulting wing tip has a tip chord of 0.3 m and a root chord of ~0.4 m.

Since no moveable surfaces were incorporated into the wingtip, it is assumed that the structure could be optimised to be lightweight, without requirements to react high loading. However, no accommodation has been made in the model for changes in the specific wing weight in this part of the wing, relative to the main wing.

The mechanism for folding the wing tip on the ground and locking it out during flight has been assumed to weigh 25 kg per wing. In reality this mass would be positioned at the root of the folding wingtip, however, no mechanism for applying the mass at this location existed within the modelling tool, and therefore it was added to the wing weight as an increment which would occur at the total wing CG location. This will therefore be further forward than the real location. It should also be noted that no study of the flutter characteristics of the aircraft have been made, nor any consideration of the effect of a lump mass near the wingtip on the flutter margin.

3.4.2 Control surfaces and wing tanks

It has been assumed that the folding wing tip will not incorporate any control surfaces or high-lift devices. The definition of these components therefore ensured that their full length was contained inboard of where the folding wing tip hinge would occur.

The folding wing tips represent 14.5% of the total span. The slat span fraction was therefore reduced from 1, for a conventional design, to 0.85 for this aircraft. In order to maintain the slat area, the slat chord fraction was increased from 0.1 to 0.115. Similarly, the flap span fraction was reduced from 0.8 to 0.68 and the flap chord fraction increased from 0.25 to 0.29. The wing tank span limit was reduced from 0.85 to 0.75 to allow space for a vent tank inboard of the fold mechanism.

3.5 Engine

Three engine models were created in GasTurb software, with cruise BPRs of 13, 15 and 18. These models were used concurrently during the design process in order to give a balanced evaluation of which one gave a better overall aircraft performance.

Throughout the design work it was observed that the 15BPR engine gave slightly better fuel burn performance than either of the other two engines, with the benefit derived from a better balance of sfc, nacelle drag and propulsion system weight. In each case the undercarriage was sized to achieve a ground clearance with the bottom of the nacelle of approximately 0.4m.

The 13 BPR engine was sized to meet the take-off TLAR of 6,000 ft and the 15 and 18 BPRs by time to 35,000 ft.

Relative to the 15 BPR, the 13 BPR fuel burn on the 1,500 nm mission and at 16 tonnes payload is 3% higher and the 18 BPR is 2.2% higher. Cash DOCs are 1.7% and 2.0% higher respectively at a typical fuel price of $2.50/USG.

Due to these results, the 15 BPR engine has been used in the final aircraft design.

3.6 Maximum operating altitude

The improvement in L/D resulting from the changes described previously, causes the optimum cruise altitude for the aircraft to increase when compared with current aircraft. To maximise the fuel burn improvement potential, the maximum operating altitude has been increased from 39800 ft to 41100 ft (giving sufficient margin for the aircraft to fly at FL410). The impact on cabin pressure differential for this change in maximum operating altitude is incorporated into the model.

3.7 Longitudinal stability

Because the wing is swept, the increase in span causes the aerodynamic centre of the wing to move rearward relative to the wing apex. In order to maintain the static margin, the wing then moves forward relative to the fuselage. In order to return the wing to a better position, the CG position of the operational items and equipment was modified. A target of positioning the 25% Mean Aerodynamic Chord (MAC) location at between 45-46% of fuselage length from the nose, was set based on existing aircraft, with a margin between aerodynamic centre and CG of approximately 10% in cruise.

A CG location of 46.1% MAC for the operational items and equipment was found to give the best result in terms of wing position and cruise margin. However, this resulted in a higher than preferred stick-fixed static margin (more representative of an older single-aisle aircraft without fly-by-wire, which could result in reduced manoeuvrability).

3.8 Tail plane sizing and fin volume coefficient

Substantially increasing the wingspan while keeping the engine a similar distance from the side of the fuselage raises interesting questions over the applicability of the fin volume coefficient for vertical tail plane sizing. The fin volume coefficient, L_f is conventionally stated as

$$L_f = \frac{S_f l_f}{S_w b}$$

Where S_f is the fin reference area, S_w is the wing reference area, l_f is the distance between the wing aerodynamic centre and fin aerodynamic centre and b is the wingspan.

Recommended values of fin volume coefficient are based on historic aircraft and it can be seen that this has no dependence on the non-dimensional spanwise engine position. This engine position is substantially further inboard on SAFAM relative to the total wingspan due to the very high aspect ratio.

Since the critical sizing condition for the fin is typically the OEI condition for aircraft with wing-mounted twin-engines, the distance of the engine from to the aircraft centreline may be more critical than the overall wingspan. For similar aircraft one may be considered a surrogate for the other, as the engine position on the wing does not typically vary significantly, however the increase in aspect ratio raises doubt over the validity of this approach in this instance.

It is possible that the fin volume coefficient could therefore be reduced for SAFAM as a result of the engine position relative to the wingspan compared with previous aircraft. However, without data to suggest the degree to which this could be reduced, it was decided to leave the fin volume coefficient unchanged for SAFAM, as this would provide a worst-case fin size requirement.

3.9 Horizontal tail Aspect Ratio

The aspect ratio of the horizontal tail plane should typically vary with wing aspect ratio. In this case, the horizontal tail plane aspect ratio was increased from 5 to 7, thus maintaining a 1:2 ratio with the wing aspect ratio. No analysis of the effect of this change on the space available for actuators and systems or the aerodynamic performance implications traded against the structural weight changes was carried out during this work. There is the potential for further work in this area.

The horizontal tail volume coefficient was maintained at the same value as for current aircraft, since the high-lift design has not been modified and therefore the implicit assumption is that the pitching moment with high-lift devices deployed remained unchanged.

3.10 Undercarriage

As a result of the high bypass ratio, the fan diameter is larger than on the current generation of aircraft, leading to unacceptably reduced ground clearance without redesign of the landing gear. The length of the landing gear was increased to provide adequate ground clearance, necessitating a corresponding increase in the main gear track in order to allow space for the landing gear in the clean configuration. The ICAO code C track limit is however exceeded, and options will need to be considered (such as pre-retraction) to reduce the track dimension.

4. Results and aircraft performance

4.1 Performance relative to TLARs

The majority of the TLARs have been met, although there are some small deviations.

Table 2 SAFAM compliance with TLARs

		SAFAM compliance
Maximum Range	3450 nm	Design range 3450 nm; Ferry range >5000nm
Diversion and contingency	Typical international rules (200nm diversion, 30min hold and 5% trip fuel contingency)	Yes
Passengers	160 (assumed 100kg AUW) 2-class (ATI rules)	Yes
Cruise Mach number	0.78	Yes (Climb Mach number 0.76)
TOFL	6000 ft (SL ISA)	Yes
Approach speed	131.5 kts @ MLW	131.5 kts @ MLW
Max structural payload	20500kg	Yes
Initial Climb Altitude Capability (ICAC)	FL350 (ISA) @ MTOW	FL370 (ISA) @MTOW
Time to FL350	20 minutes (from 1500' ISA)	20.0 mins (from 1500' ISA)
Distance to FL350	180 nm (from 1500' ISA)	127.4 nm (from 1500' ISA)
ICAO aerodrome reference code	Code C (Wing span on ground <36 m; Outer main gear wheel span <9 m)	Code C Wing span (folded): 35.05 m Outer main gear wheel span: 9.49 m

It can be seen that most requirements are met by SAFAM with some exceptions. Due to the nacelle diameter, it has been necessary to lengthen the landing gear, which has resulted in the outer main gear wheel span for Code C aerodromes exceeding the limit. This would require further work in the more detailed landing gear design to evaluate whether it is possible to bring the wheel span within the limits.

4.2 Overall aircraft performance

The payload-range diagram for SAFAM is shown in Fig. 3, using typical international mission reserves on an ISA day. Unlike the A320neo which is marginally tank-limited on range for the design payload, SAFAM has a substantial margin of approximately 19% between the design payload and tank limiting payload. This is larger than would typically be targeted, indicating that if further improvements were achievable this could be taken advantage of by further reducing the wing area without causing difficulties on fuel capacity. SAFAM does have a wet centre section, but this represents too large a proportion of the fuel capacity for it to be removed and still meet the design payload and range requirements.

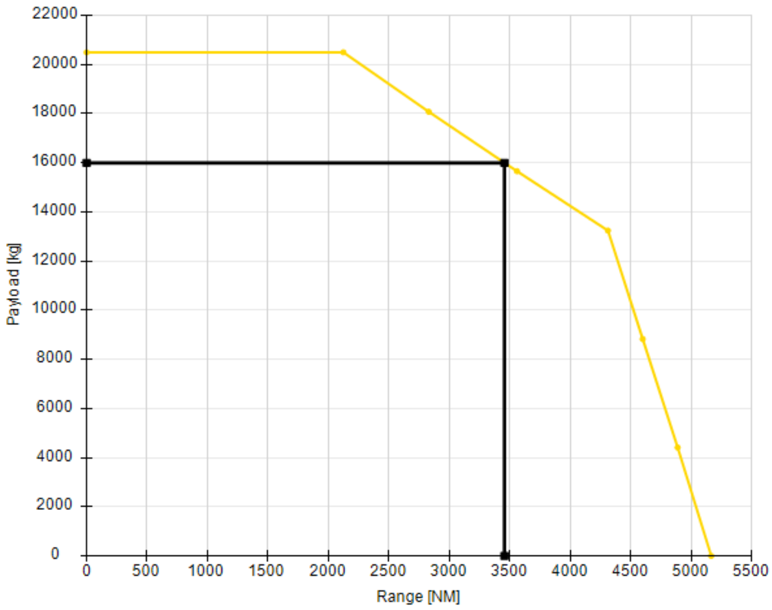

Fig. 3 SAFAM payload-range diagram

4.2.1 Fuel burn

The fuel burn reduction for SAFAM relative to previous technology standards is substantial and also dependent on range, since the propulsion efficiency improvements are not uniform through the mission, but more pronounced in cruise. This results in a larger improvement for longer range mission profiles. However, this result may be partially influenced by the use of the more full-featured propulsion model for SAFAM, which is being compared here with more simple propulsion models for the earlier technology standards. Comparison of the aircraft fuel burn for GasTurb engine models with simpler models suggests that the former typically shows a fuel burn increase; this means that the fuel burn figures for previous technology standards presented here are likely to be optimistic, and SAFAM actually represents a bigger improvement than this figure indicates.

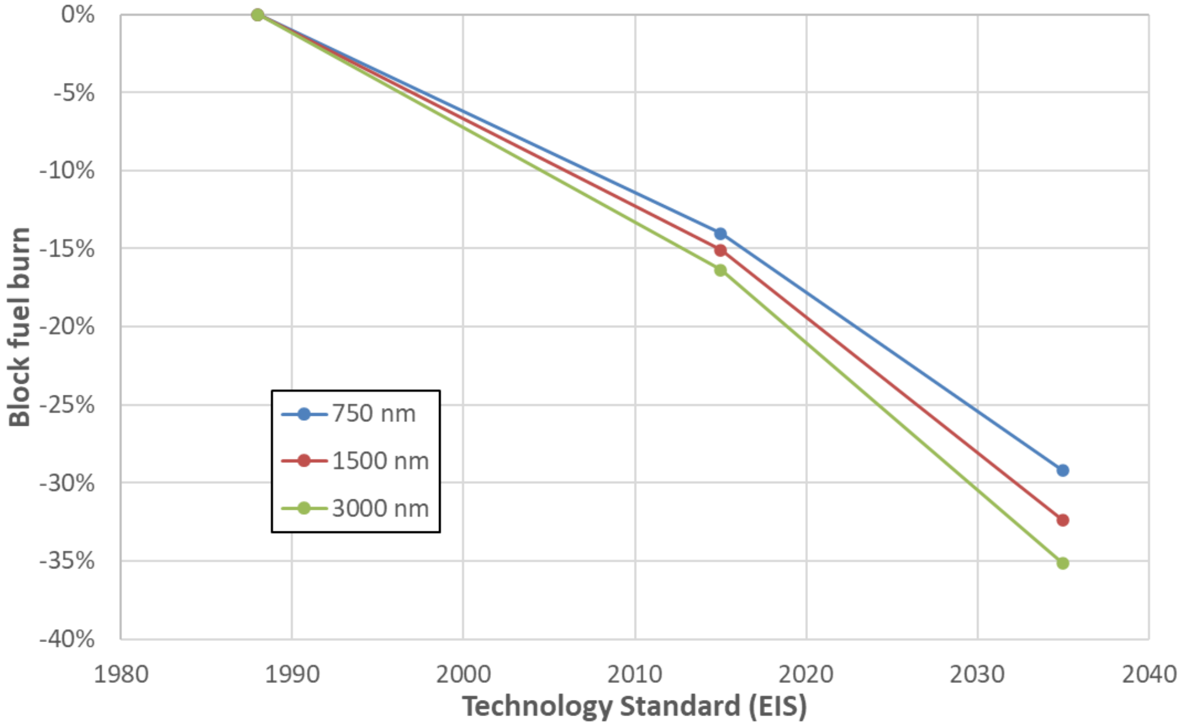

Figure 4 Fuel burn for progressive technology standards

The scaled ACARE target for SAFAM in 2035 was -52.5% CO_2 reduction relative to 2000 (including operational contributions). For a 1500 nm mission, the SAFAM CO_2 reduction between 2015 and 2035 was approximately 20%. However, the aircraft available in 2000 were those of the previous technology standard, which would give an improvement closer to 32%. Although this is a substantial fuel burn reduction, exceeding that achieved between the two previous aircraft generations, there is still further improvement to be found in order for global environmental targets to be achieved.

Although the environmental performance of SAFAM falls short of the targets, it represents a good step forward relative to the current state-of-the-art and provides the basis for future work to identify opportunities for further technology developments which could make the targets achievable in the desired timeframes.

4.2.2 Direct Operating Cost

The cash DOC has been calculated using the ATI OpCost model for a 1500 nm range mission profile and a payload of 16 tonnes for all aircraft. It can be seen that there is a substantial reduction in DOC for SAFAM relative to previous technology standards.

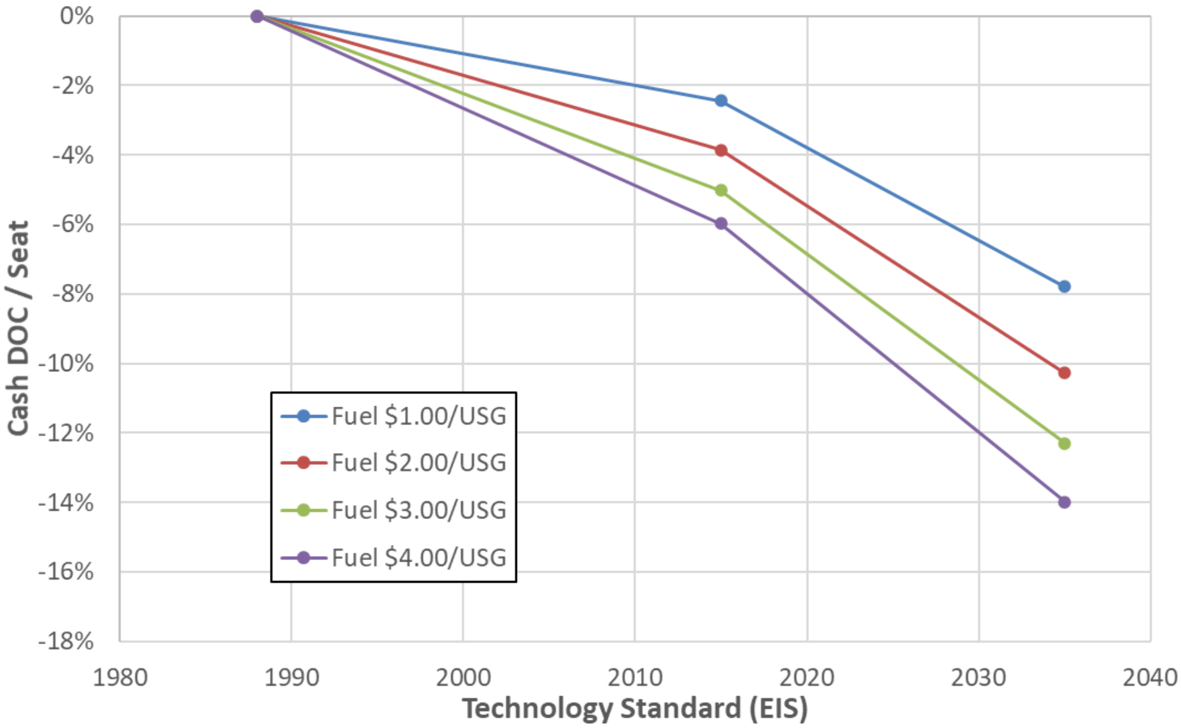

Fig. 5 Cash DOC for progressive technology standards

The breakdown of the cash DOC for SAFAM at a fuel price of $2.50/USG is shown in Fig. 6. The contribution from the fuel cost is very dependent on the fuel price and would be a substantially larger proportion for a higher fuel price. The reduction in the DOC is not uniform across all these contributions. The relative contributions of the components comprising the Cash DOC reduction between SAFAM and an equivalent aircraft with EIS 2016 are shown in Fig. 7. The fuel cost is a substantial contributor due to the increased fuel efficiency of the engine. The other largest component is the engine maintenance cost which is a function of the reference thrust as well as the technology standard.

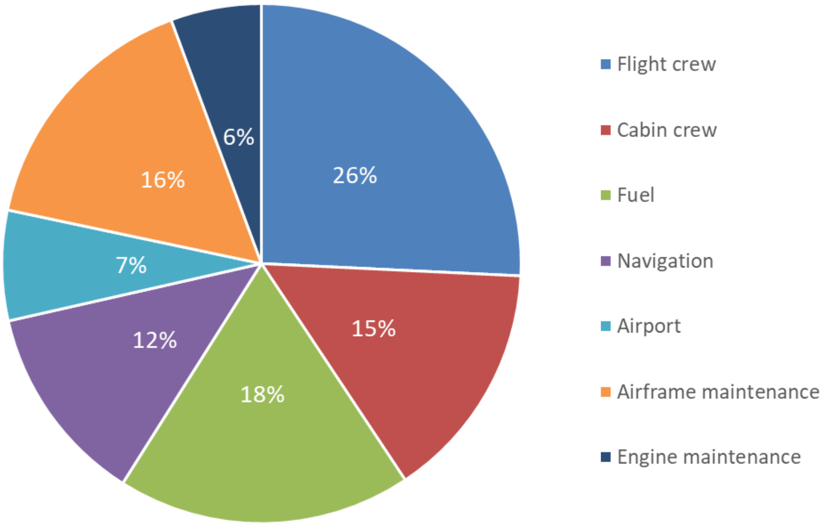

Fig. 6 Breakdown of Cash DOC contributions for SAFAM at a fuel price of $1.9/USG

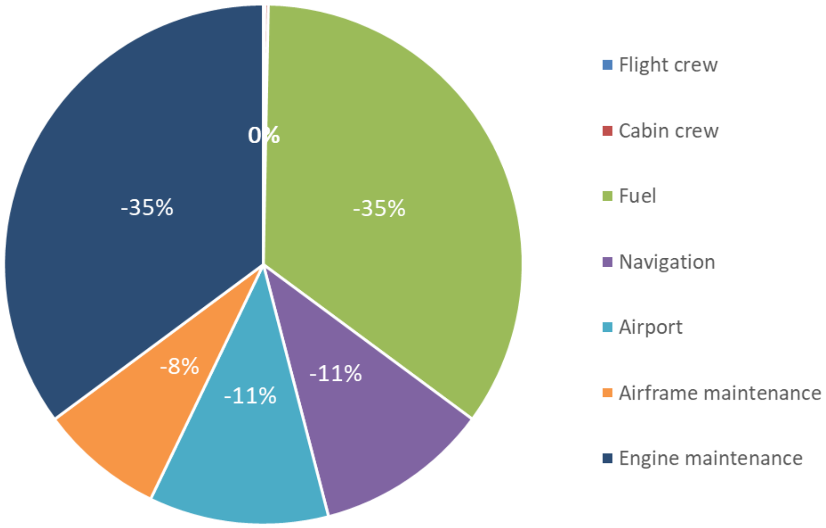

Fig. 7 Relative contributions of Cash DOC reduction per seat between 2015 and 2035 technology standard

5. Conclusion

The SAFAM model has been developed in line with the TLARs set at the outset of the project. The resulting aircraft meets or exceeds the TLARs in almost all cases and has equivalent or better performance than the single-aisle aircraft of today.

The performance of SAFAM in terms of fuel burn (-32% relative to 2000) and DOC (-11% relative to 2000) represent a big step forward relative to existing aircraft. However, there is still a gap between the performance which has been achieved with SAFAM and the ACARE environmental goals set by the global aerospace community and the net-zero target of the UK government. Although it is possible that further marginal improvements could be made to SAFAM by further detailed consideration of the design, it seems unlikely that the gap can be completely closed with the technologies and philosophy employed in the design of SAFAM. Achieving these goals is likely to require the development of Zero Carbon aircraft, but conventionally-fueled Ultra-Efficient aircraft such as SAFAM, in combination with SAF, will also have a key role to play.

This aircraft is a baseline from which further work can be undertaken to investigate technologies such as zero emissions or hybrid propulsion or to compare novel aircraft architectures. Additionally, the effect of operational measures on the aircraft can be evaluated.

6. Acknowledgments

Engine modelling was carried out using GasTurb by Glenn Knight of Specialised Aero Services Ltd.

7. Contact Author Email Address

mailto: naomi.allen@ati.org.uk

8. Copyright Statement