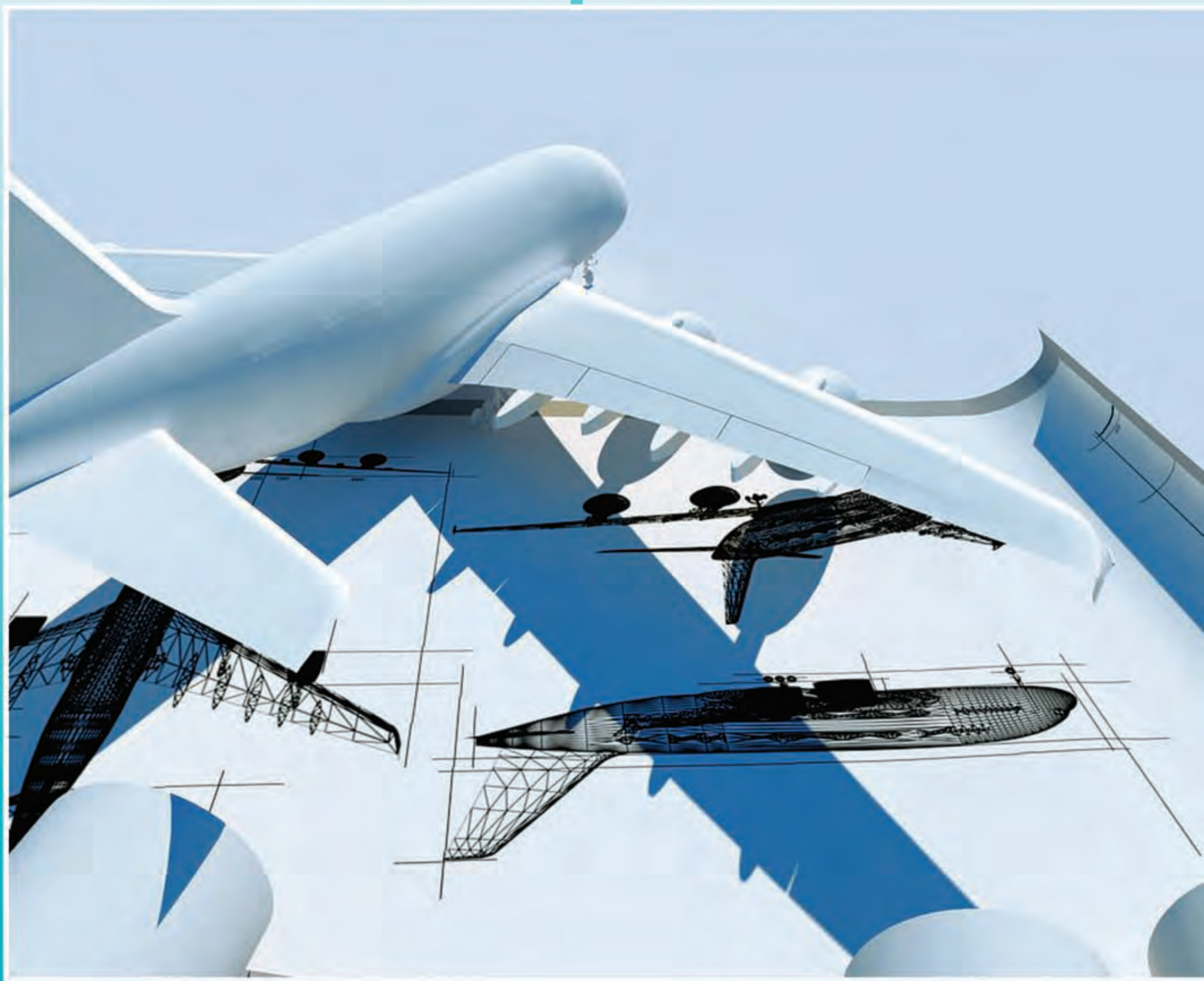
Chapter 2



AIRCRAFT TECHNOLOGY IMPROVEMENTS

ICAO ENVIRONMENTAL REPORT 2010

Technology Improvements

Overview

By ***ICAO Secretariat***

Aircraft provide a fast, reliable mode of transport with no comparable alternative for long distance travel. Throughout the years, technology improvements have been made to aircraft and engines to make them more fuel efficient. Today's aircraft are designed for more than 15% improvement in fuel burn than comparable aircraft of a decade ago, and will deliver 40% lower emissions than aircraft previously designed. Figure 1 provides an illustration of the tremendous improvements in fuel efficiency that have been achieved on a fleet wide basis since the 1980s. On a per-flight per-passenger basis, efficiency is expected to continue to improve through 2050.

ICAO projections (see Figure 2) show that the commercial aircraft fleet is expected to increase to about 47,500 by 2036, of which more than 44,000 (94%) aircraft will be new generation technology. Even under the most aggressive technology forecast scenarios, the expansion of the aircraft fleet, as a result of air traffic demand growth, is anticipated to offset any gains in efficiency from technological and operational measures. In other words, the expected growth in demand for air transport services, driven by the economic needs of all ICAO Member States, is outpacing the current trends in efficiency improvements. As a result, the pressure will increase to deliver even more ambitious fuel-efficient technologies – both technological and operational – to offset these demand-driven emissions, thus creating the need for new technologies to be pursued.

Overall fuel efficiency of civil aviation can be improved through a variety of means such as: increased aircraft efficiency, improved operations, and optimized air traffic management. Most of the gains in air transport fuel efficiency so far have resulted from aircraft technology improvements.

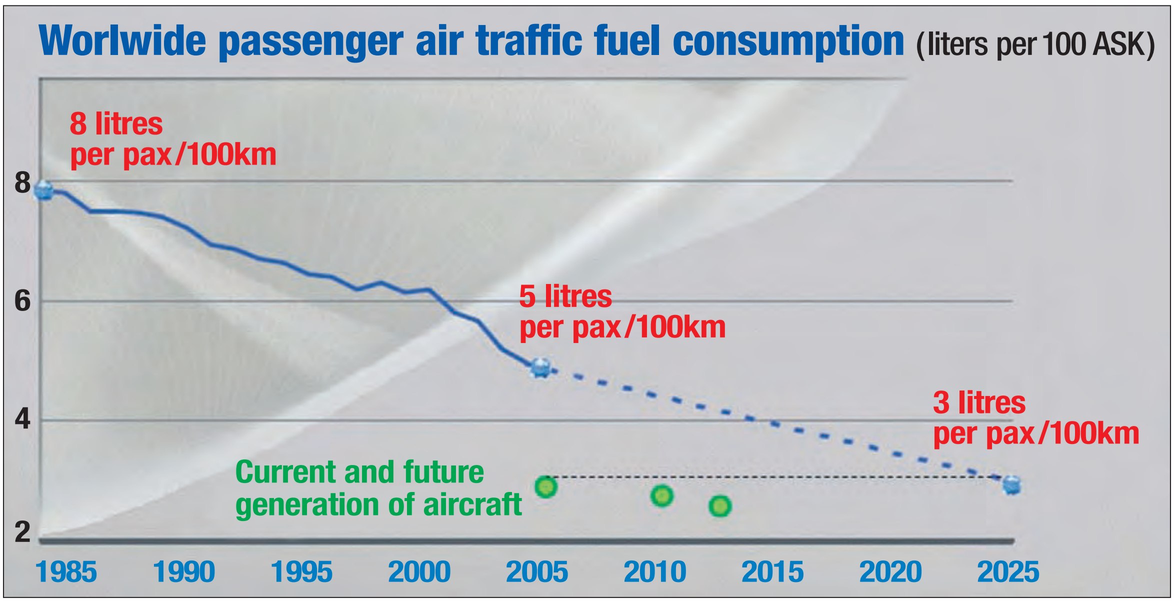


Figure 1: *Air traffic fuel efficiency trend and today's aircraft (source ICCAIA).*

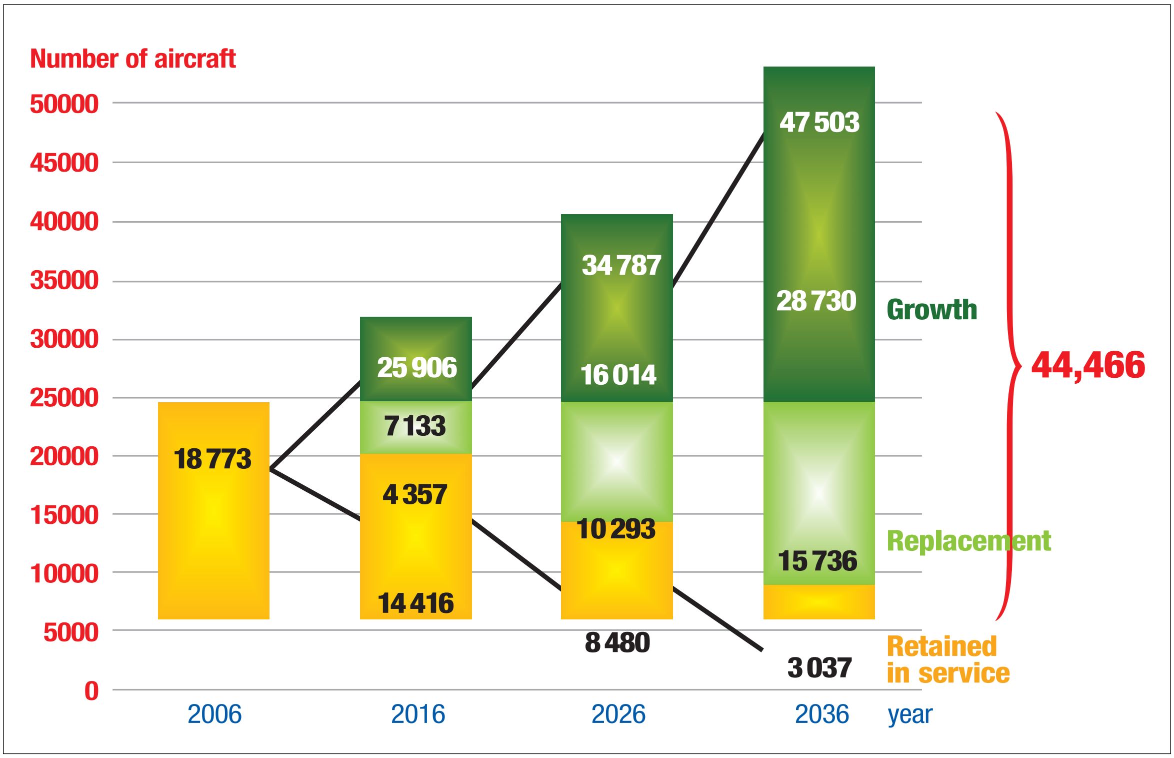


Figure 2: *More than 44,000 new aircraft are expected to be introduced by 2036.*

The articles in this Chapter of the report provide an overview of technology advances in aircraft and engine developments that have taken place and provide a high-level summary of goals that are expected to go beyond the current trends.

Background

Over the years, market pressure has ensured that aircraft continually become more fuel efficient. Since CO_2 production is directly related to fuel consumption, these economic pressures have also served to reduce CO_2 emissions. However, the concern over climate change over the last decade has meant additional pressure for solidifying the gains aviation has already made and to demonstrate the aviation sector's commitment to reducing its impact on global climate change. ICAO is cognizant of the global need for aviation to respond to these growing concerns.

A Programme of Action on International Aviation and Climate Change was adopted by the ICAO High-level Meeting on International Aviation and Climate Change in October 2009. A key component of this Programme of Action is the reliance on technological means including the development of a CO_2 emissions Standard for aircraft (see the article *Development of an Aircraft CO_2 Emissions Standard*, in Chapter 2 of this report). The programme includes a multi-faceted approach to reduce CO_2 emissions: technological advances, operational improvements, market-based measures, and alternative fuels. As mentioned before, the articles in this chapter provide an overview of technological advances.

Standards and Goals

Conscious of technology developments and the environmental needs, ICAO continuously reviews its environmental Standards, promoting more efficient and cleaner aircraft. Standards for emissions of NO_x, HC, CO and smoke from aircraft engines have been in place since the early 1980s. During this period, stringency in the NO_x Standard has increased by 50%. ICAO has also initiated work on certification Standards for non-volatile particulate matter (PM) emissions in light of the increasing scientific evidence linking PM emissions to local air quality and climate change issues.

Following the mandate from the 2009 ICAO High-Level Meeting, the eighth meeting of ICAO's Committee on Aviation Environmental Protection in February 2010 established a plan that aims to establish an aircraft CO_2 emissions Standard by 2013. More details on CAEP's work on a CO_2 Standard can be found in the article *Development of an Aircraft CO_2 Emissions Standard*, in Chapter 2 of this report.

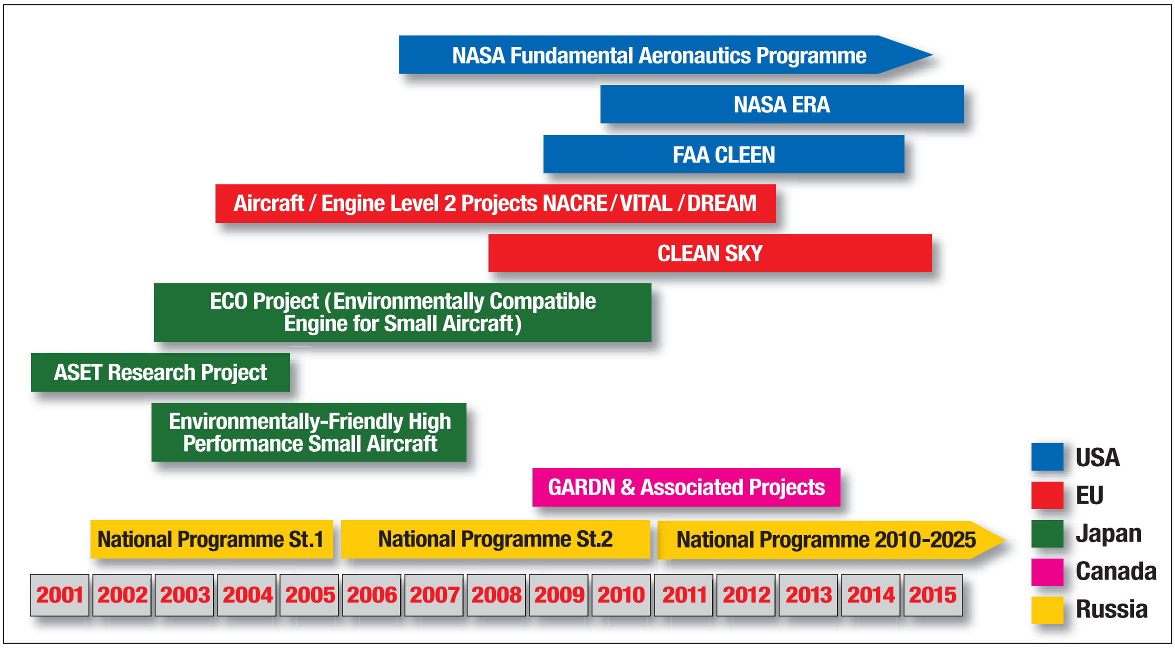


Figure 3: *National and regional research programs, worldwide (2001 to 2015). (adapted from an ICCAIA chart).*

Complementing the effort to establish a CO_2 Standard, CAEP had also requested advice from a panel of Independent Experts (IEs) on the prospects for reduced aviation fuel burn from technology advances, over ten and twenty years. This is to be based on the effects of "major technologies" on fuel burn/efficiency, as well as combinations of improvements from both aircraft and engines, including best possible integration. The IEs were requested to focus their analyses only on technologies, and not on operations, or new types of fuels, while quantifying interdependencies as much as possible. The objective of this effort is to complement the various research initiatives that are currently underway or planned in various regions of the world, as summarized in Figure 3.

It should be noted that some new initiatives have been launched whereby the research in the traditionally strong aerospace manufacturing regions has been sustained and generally expanded.

An overview of some of these research programs was presented at a workshop held in London in early 2009. In addition, the manufacturers provided detailed reviews of the work underway to improve the fuel efficiency of aircraft and engines. The article, *Pushing the Technology Envelope*, in Chapter 2 of this report gives a summary of the technology advances achieved by the manufacturing organizations and outlines the design process to optimize the overall performance of an aircraft.

The IEs augmented the expected technology improvements presented by research organizations and manufacturers with information collected from industry (e.g. IATA Teresa Project), and from some other sources in academia and research organizations. The IEs agreed on the necessity to do some modelling in parallel with that done by industry, in order to independently explore the effect of fuel burn using various technology configurations. Consequently, several academic and research institutions (e.g. Georgia Institute of Technology, DLR, Qinetiq, ICCT) are carrying out this task, thus complementing the industry modelling expertise. All organizations involved in detailed modelling efforts are ensuring that assumptions are consistent across all models.

A formal independent expert led review was held in May 2010. There, it was agreed that the independent experts group would need to consider "packages" of changes. For example, if one moves to an open rotor design, one cannot put an open rotor on an existing aircraft; it has to be a different design of aircraft. Similarly, a change to the aircraft design would be required if one moves to very high bypass ratio engines.

Of particular relevance to the 20-year goals, the IEs will consider three technology scenarios (TS) as follow:

TS1: Evolutionary technologies with low to moderate pressure for improvement.

TS2: Aggressive evolutionary technology development and insertion with high pressure for improvement.

TS3: Revolutionary technologies, doing things differently, with severe pressure for improvement.

Since the CO_2 Standard setting process has not yet been completed, a standard metric for fuel efficiency or fuel burn is not available. For this reason, IEs agreed that the fuel burn goals should be based on fuel quantity (kg) burned per available-tonne-kilometre (ATK) flown, namely kg/ATK. For this analysis, ATK is preferable to revenue-tonne-kilometre (RTK) because the IEs are looking at the technology and not at the operations. IEs adopted this metric as an interim measure; it is not intended to pre-empt the other work which is going on to formulate standards for aircraft CO_2 emissions.

The formal IE review in May 2010 was successful in gathering more information and outlining preliminary results which will help in ensuring that all modellers work from the same assumptions and uniform sets of technologies provided by IEs. The IEs plan to deliver a preliminary report for the first meeting of CAEP/9 Steering Group in late autumn 2010.

Future Directions

The current drawing boards of aircraft and engine developers contain blueprints for blended-wing-body airframes and ultra-high bypass ratio engines including open rotor and geared turbo-fans. These technologies are maturing and, depending on trade-offs with existing infrastructure and other environmental parameters, may soon be flying the skies. These technologies, together with improvements in operational procedures and deployment of alternative fuels, are helping to reduce aircraft emissions and their climate impacts.

At the same time, there have been exciting breakthroughs towards the development of radically new concepts that aim to drastically reduce or eliminate carbon footprints of aircraft. An example is the development of revolutionary conceptual designs for future subsonic commercial transports by an MIT team under a NASA contract (see article *Subsonic Civil Transport Aircraft for a 2035 Time Frame*, in Chapter 2 of this report). Another ambitious concept was demonstrated by a solar-powered airplane that took flight in July 2010. That experimental airplane with a huge wingspan completed its first test flight of more than 24 hours, powered overnight solely by batteries charged by its 12,000 solar panels that had collected energy from the sun during the day while aloft over Switzerland. The entire trip was flown without using any fuel or causing any pollution.

Technology advances in aircraft have been the major factor in improving the efficiency of air transport. Continued economic growth tied in with air traffic growth necessitates a multi-faceted approach to meeting the challenge of increasing emissions. ICAO is leading the way by establishing goals and developing standards based on the latest technologies that will pave the way towards zero-emissions aircraft of the future. ■

Pushing the Technology Envelope

By ***Philippe Fonta***

Philippe Fonta *was appointed Head of Environmental Policy of the Airbus Engineering's Center of Competence (CoC) Powerplant in March 2010. In this role, he leads the development and implementation of the environmental policy of the CoC Powerplant, which encompasses acoustics and engine emissions matters, from technological goal setting processes, associated research programs to certification and guarantees to customers. Mr. Fonta is also Chairman of the environmental committee of the International Coordinating Council of Aerospace Industries Associations (ICCAIA). Since 1999, Philippe Fonta is Airbus' representative in the ICAO FESG (Forecasting and Economic Analysis Support Group).*

The ***International Coordinating Council of Aerospace Industries Associations*** *(ICCAIA) was established in 1972 to provide the civil aircraft industry observer status as a means to be represented in the deliberations of the International Civil Aviation Organization (ICAO).*

Today ICCAIA provides an avenue for the world's aircraft manufacturers to offer their industry expertise to the development of the international standards and regulations necessary for the safety and security of air transport.

Airframe and engine manufacturers continuously strive to develop innovative technology and implement it into the eco-efficient design, development and manufacture of aircraft. This task involves compromises among many challenges, particularly on technical, economic and environmental issues; with safety remaining paramount. Continuous improvement is ensured through regular upgrades of the in-service fleet, and also to a wide extent, through the introduction of brand new aircraft types into the fleet. Over time, this results in remarkable continuous improvement evolution with respect to comparable previous generation aircraft.

Continuous Improvement - Ongoing Research For Better Technologies

Air transport's overall mission is to carry safely the highest commercial value, in passengers and/or freight, over an optimized route between two city pairs, with the minimum environmental impact. In that context, market forces have always ensured that fuel burn and associated CO_2 emissions are kept to a minimum. This is a fundamental impetus behind designing each new aircraft type. Historic trends in improving efficiency levels show that aircraft entering today's fleet are around 80% more fuel efficient than they were in the 1960's (see Figure 1), thus more than tripling fuel efficiency over that period. The two major oil crises, first in 1973, followed by the early 1980's, kept pressure on the industry to continue its ongoing pursuit of fuel efficient improvements. However, the impact of these crises on these ongoing efficiency improvements to the commercial fleet is hardly noticeable, demonstrating that market forces are the dominant driver of fuel efficiency improvements.

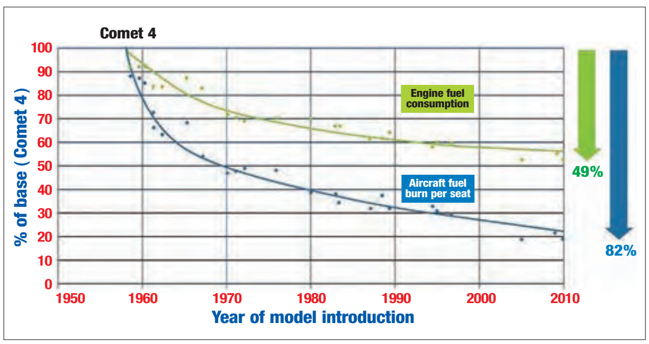


Figure 1: *Commercial aircraft fuel efficiency curve over time.*

Since the turn of the century, environmental awareness has increased and attention has increasingly been on CO_2 emissions, thus maintaining the incentive of manufacturers to achieve ever lower aircraft fuel burn.

In terms of practical measures, the Advisory Council for Aeronautics Research in Europe (ACARE) has established its Vision 2020, that targets an overall reduction of 50% in CO_2 emissions, coupled with a 50% reduction in the perceived noise level, and a reduction of 80% in NOx emissions. These ACARE objectives are technology goals that should be mature enough for introduction into an aircraft by 2020[1]. To achieve these goals, extensive, continuous, and consistent research programmes and joint initiatives are currently under way. Two significant examples are the Clean Sky Joint Technology Initiative (JTI) - one of the largest European research projects ever[2] - and the Single European Sky ATM Research project (SESAR)[3]. In North America, taking advantage of a single sky, continuous transformation of the Air Traffic Management (ATM) is, however, necessary to provide environmental protection that allows sustained aviation growth. This will be done mainly through the NextGen project, in cooperation with the aviation industry and comparable objectives to the European ones have been established in the US through extensive research programmes such as the US Federal Aviation Administration (FAA) CLEEN programme[4] and the NASA Environmentally Responsible Aviation Program[5].

In addition, some cooperation initiatives exist as a common goal to mitigate or reduce the impact of aviation on the environment. For instance, the Atlantic Interoperability Initiative to Reduce Emissions (AIRE) is a programme designed to improve energy efficiency and aircraft noise. It was launched in 2007, with cooperation between the FAA and the European Commission.

Understanding the Basics

Comparing different generations of aircraft is more difficult than it may seem because progress in design and technology is not made in isolation but rather, concurrently. For example, such elements as: structures, aircraft systems, aerodynamics, propulsion systems integration, and manufacturing techniques, all interact with one another, in a way that is specific to each product. Nevertheless, some significant key levers exist that will improve overall aircraft performance:

- Reducing basic aircraft weight in order to increase the commercial payload for the same amount of thrust and fuel burn.
- Improving the airplane aerodynamics, to reduce drag and its associated thrust.
- Improving the overall specific performance of the engine, to reduce the fuel burn per unit of delivered thrust.

The following paragraphs provide elaboration on how these factors affect the design and technology of an aircraft.

Weight Reduction

Generation after generation, aircraft manufacturers have demonstrated impressive weight reduction results due to the progressive introduction of new technologies such as: advanced alloys and composite materials, improved and new manufacturing processes and techniques (including integration and global evaluation simulation), and new systems (e.g. fly-by-wire). For instance, aircraft designed in the 1990's were based on metallic structures, having up to 12% of composite or advanced materials. In comparison, the A380, which has been flying since 2005, incorporates some 25% of advanced lightweight composite materials generating an 8% weight savings for similar metallic equipment. Aircraft that will enter the fleet in the next few years (e.g. Boeing 787, Airbus A350, Bombardier C-Series, etc.) will feature as much as 70% in advanced materials, including composite wings and parts of the fuselage, increasing the weight savings as much as 15% for this new level of technology. An illustration of this evolution is given in Figure 2 below.

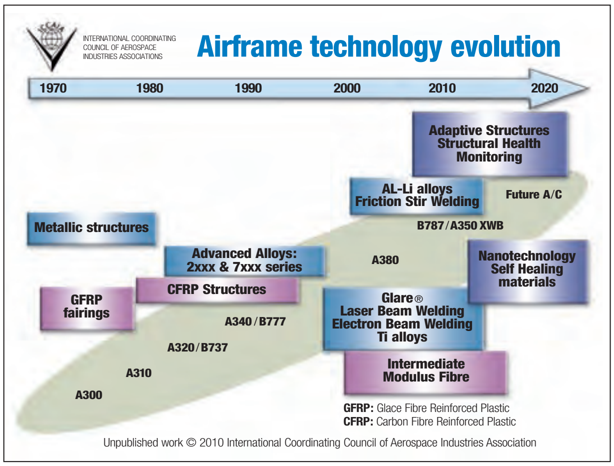


Figure 2: *Airframe technology evolution.*

Innovative manufacturing techniques have already been implemented, including advanced welding technologies such as: laser beam (see Figure 3), electron beam[6], and friction stir welding[7]. These innovations remove the need for traditional rivets, reducing aerodynamic drag, lowering manufacturing costs, and decreasing aircraft weight.

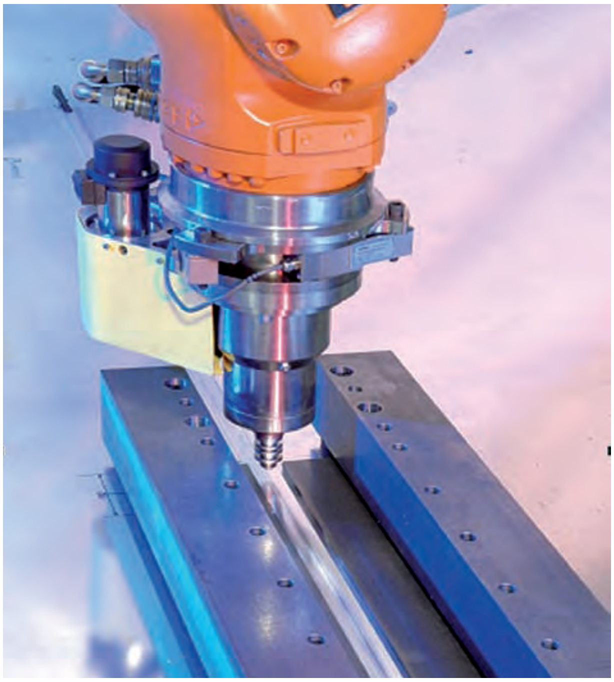


Figure 3: *Laser beam welder.*

Aerodynamic Improvements

The typical breakdown of total aircraft drag, in cruise mode, is shown in Figure 4.

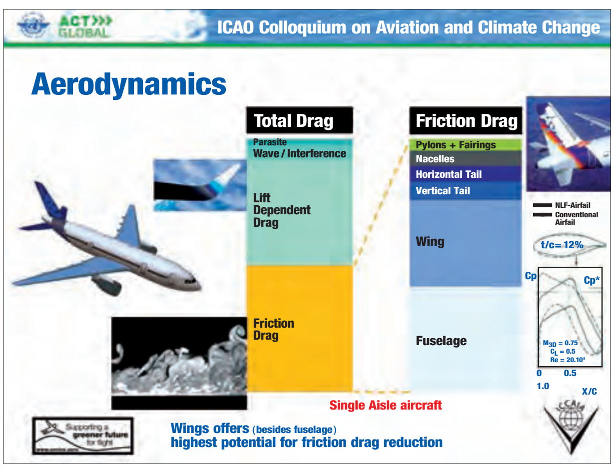


Figure 4: *Aerodynamic drag elements of a modern aircraft.*

Friction and lift-dependent drag are, by far, the largest contributors to aerodynamic drag. Advances in materials, structures and aerodynamics currently enable significant lift-dependent drag reduction by maximizing effective wing span extension. Wing-tip devices can provide an increase in the effective aerodynamic span of wings, particularly where wing lengths are constrained by airport (and/or hangar) gate sizes.

Friction drag is the area which currently promises to be one of the largest areas of potential improvement in aircraft aerodynamic efficiency over the next 10 to 20 years. Possible approaches to reduce it are to:

- Reduce local skin friction by maintaining laminar flow via Natural Laminar Flow (NLF) and Hybrid Laminar Flow Control (HLFC), thus reducing turbulent skin friction (e.g., via riblets).
- Minimize wetted[8] areas while minimizing/controlling flow separation and optimize surface intersections/junctures and fuselage aft-body shape.
- Minimize manufacturing excrescences (including antennas), and optimize air inlet/exhaust devices.

Potential NLF and HLFC application areas are wings, nacelles, empennages and winglets. The net fuel burn benefit depends on the amount of laminar flow achieved versus the extra weight required to maintain laminar flow.

NLF and HLFC have been demonstrated in aerodynamic flight demonstration tests on various components including: 757HLFC-wing, F100NLF-wing, Falcon900 HLFC wing, A320HLFC-empennage, and nacelles. Practical achievement of optimal laminar flow requires structures, materials and devices that allow manufacturing, maintenance and repair of laminar-flow surfaces.

Potential technologies have been presented by ICCAIA (see Figure 5) in the frame of the ICAO Fuel Burn Technology Review process, carried out under the leadership of independent experts, in May 2010. The level of technology maturity is expressed through the Technology Readiness Level (TRL) scale and the applicability to regional jets (RJ), single aisle (SA) and/or twin aisle (TA) aircraft is systematically looked at and indicated.

INTERNATIONAL COORDINATING COUNCIL OF AEROSPACE INDUSTRIES ASSOCIATIONS

Aerodynamic Technologies Considered by ICCAIA for 2010 Review

Technology	TRL	Improvement	Application	Caveats/notes
Riblets	Low/Med (4-6)	L/D: 1% to 2%	RJ, SA, TA	Material development: riblet material need to last longer than demonstrated in previous flight tests. Need to address installation and maintenance issues.
Natural Laminar Flow	Med (4-6)	L/D: 5% to 10%	RJ, SA, TA	Surface quality; design space, integration. Manufacturing, operational, and maintenance considerations.
Hybrid Laminar Flow Control	Low/Med (3-5)	L/D: 5% to 10+%	SA, TA	Need for simple suction-system design. Manufacturing, operational, power and maintenance considerations
Excescence Reduction	High (8)	L/D: 1%	RJ, SA, TA	Trade of benefit vs. manufacturing and maintenance cost
Variable Camber	Med/Hi (6-8)	L/D: 2%	RJ, SA, TA	Variable camber can also affect induced drag

- Only technologies that currently have TRL levels of a least 3 are considered here
- Benefits cannot be simply added (there can be aerodynamic interdependencies)

Figure 5: *Aerodynamic technologies for Fuel Burn Technology Review.*

Engine-Specific Performance

Engine manufacturers invest in technology to provide clean (i.e. for local air quality and global emissions), quiet, affordable (i.e. acceptable ownership costs), reliable (i.e. limited disruptions and maintenance costs), and efficient power. All trade-offs have to be properly handled and considered in evaluating an engine when it is being integrated into an airframe. This is a continuous process, and regular investments are made to maintain and improve the overall performance of in-service and in-production aircraft. For instance, multiple engine upgrade programs have been achieved in the last decade that delivered up to 2% fuel burn improvement (e.g. CFM56-5B Tech insertion, V2500 Select One, Trent 700 EP, GE90-115B Mat'y, etc.). Measurements, data gathering and analysis of in-service engines are regularly carried out, and scheduled maintenance (such as engine wash) is performed to keep engines operating at peak efficiency levels.

To support the development and testing of alternative fuels, some component, rig and engine ground tests have already been performed to determine engine performance and operability using blends of jet fuel and alternative fuels. In addition, engine and airframe manufacturers have been deeply involved with airlines in flight test demonstrations using alternative fuels over the past years. This major effort has led to the recent fuel type certification of up to 50/50 Fischer-Tropsch blend (ASTM7566 Annex 1 approval). Further certifications will be granted as other bio-jet fuels are tested and made ready for use.

As far as new products are concerned, engines and auxiliary power units (APUs) for new aircraft designs are expected to provide a minimum of 15% fuel savings with regards to the aircraft they replace. Some project and/or development aircraft (from business aeroplanes through regional and long-range aircraft, worldwide) are expected to bring significant benefits when they enter into revenue service in the near future. Engine technologies (e.g. materials, coatings, combustion, sensors, cooling, etc.) are modelled, tested and implemented as soon as they become mature. These technologies have a positive impact on:

Thermal Efficiency: higher operating pressure ratios (OPR) are targeted to improve combustion, and some engine cycle refinements are envisaged. All this must be balanced with the potential risks of increased maintenance costs, and weight and/or drag due to engine complexity in an overall context of maximum reliability.

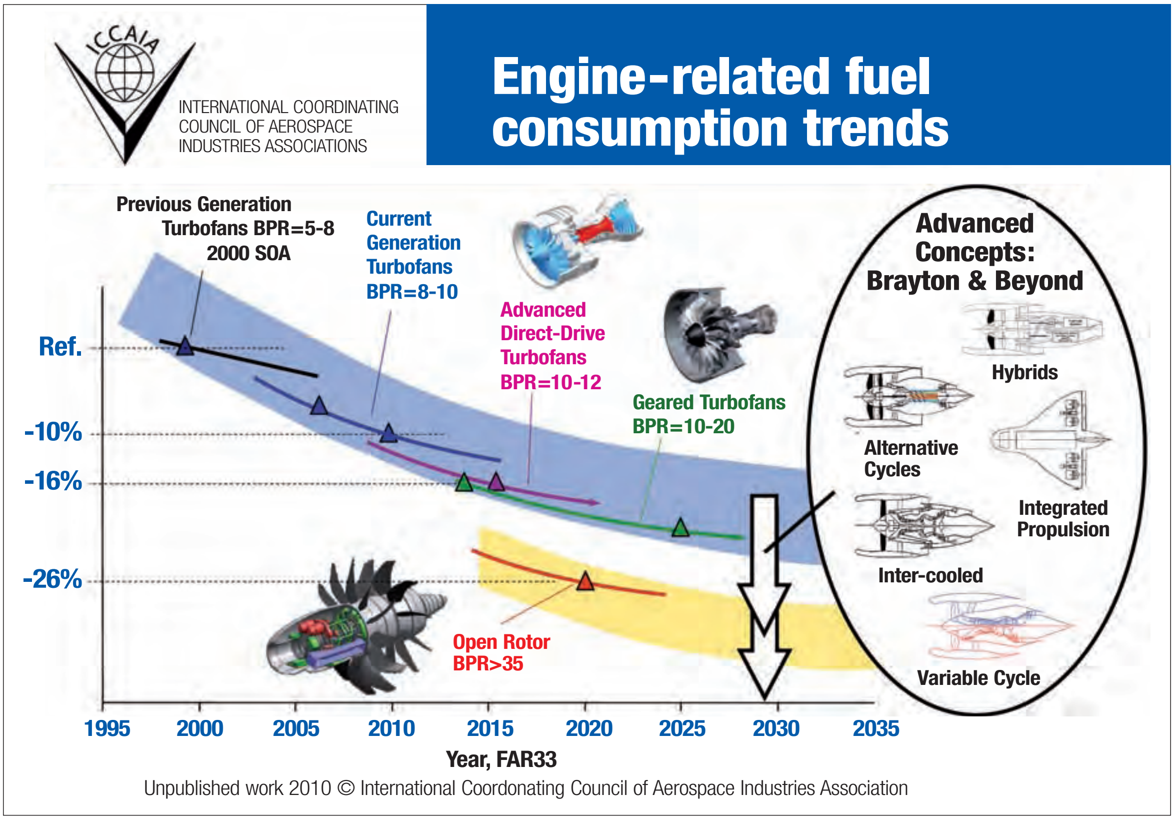


Figure 6: *History and future of engine fuel consumption trends.*

Transmissive Efficiency: through new components and advanced engine architecture.

Propulsive Efficiency: engine architectures are evolving (e.g. advanced turbofan), some different concepts are emerging (e.g. advanced geared turbo-fans, open-rotors, hybrids, etc.); each with their own multi-generation product development plans (see Figure 6).

In order to achieve the optimum improvements, massive investments have to be made in research programmes, and public/private partnerships are therefore essential.

New Design Methodologies

Due to non-linearity and strong interactions among components, the overall aircraft optimum is not obtained by simply summing the optimal solutions for each individual component.The design of a given component has to be directly driven by the benefits after integration.

Therefore, performance is gained by moving from a component-based design to a fully integrated design: wing, tail, belly fairing, pylon, engine, high lift devices, etc. Numerical simulation around complex geometries requires the development of new testing methodologies so that the behaviour and performance of the complete aircraft can be simulated. Within the next decade, simulation capabilities will be increased by up to a million times, to achieve that result.

Throughout the process of merging technology elements and design features to achieve the final product optimization, fuel efficiency and emission considerations, as well as noise, are major drivers. However, environmental solutions must remain compatible with all other major design requirements (i.e. performance, operability, reliability, maintainability, durability, costs, comfort, capacity, timing), keeping in mind that safety must and will remain the overarching requirement. Any new design needs to strike a balance between technological feasibility, economic reasonableness, and environmental benefit. The environmental requirements necessitate a balance in order to bring performance improvements across three dimensions: noise reduction, emissions reduction, and minimized overall environmental life-cycle impacts. For instance, increasing the fan diameter of an engine would normally result in a noise reduction. However, since this implies adding weight and drag, it may finally result in a fuel consumption increase.

Stable Regulatory Framework and Dependable Scientific Knowledge

Technological improvements are a key element of mitigating the impact of aviation on the environment. New products must be continuously developed and regularly introduced into the fleet to reduce aviation's environmental impact globally. However, significant global improvement is a long process. While the current and future generation of commercial transport aircraft will eventually burn less than 3 litres of fuel per passenger, per 100 kilometres, achieving this average fuel consumption for the worldwide fleet will take approximately 20 years.

Indeed, it can take up to 10 years to design an aircraft. Then, production can run over 20 to 30 years with each aircraft having a service life of 25 to 40 years. In an industry with such a long product life-cycle, today's choices and solutions must be sustained over several decades. Therefore, in order to make sound decisions for investments in future technologies, aircraft engine and airframe manufacturers need a stable international regulatory framework based on dependable scientific knowledge. Improved scientific understanding of the impact of aviation emissions on the Earth's atmosphere is key to optimizing priorities and assigning weight factors for prioritizing research, trade-offs, and mitigation measures.

The role of the manufacturers is stimulated and enhanced by their deep involvement in ICAO's Comittee on Aviation Environmental Protection (CAEP) activities and their participation in the achievements of that group in developing standards and recommended practices in a context that facilitates international harmonization and fruitful cooperation. ICAO has recently developed a basket of measures to reduce the impact of aviation on climate change and one element of this basket is the "development of a CO_2 standard for new aircraft types, consistent with CAEP recommendations", as highlighted in the recommendations of the ICAO High-level Meeting on International Aviation and Climate Change (HLM) in October 2009.

Aircraft and engine manufacturers are committed to working on the various steps that need to be achieved towards that new CO_2 standard. They also agree with the HLM recognition that a CO_2 standard for new aircraft is only one element of a series of measures that will need to be taken. Indeed, they welcome the additional HLM recommendations to "foster the development and implementation of more energy efficient aircraft technologies and sustainable alternative fuels for aviation" while recognizing the need to fully assess "the interdependencies between noise and emissions."

Climate change is a global issue that needs a global solution. Each stakeholder has a role to play in meeting the challenge, and no single player has the capability to solve the problem alone. It is understood that all parties involved: aircraft and engine manufacturers, their supply chain, airlines, airports, air traffic management services, research institutes, and civil aviation authorities; will have to work together towards their common objective – to reduce the overall impact of aviation on the environment. The industry (ICCAIA, IATA, ACI, CANSO) has presented a common position at various high level political meetings, advocating for a global solution to a global issue in which ICAO would play a leading role. This united position consists of three main elements:

- An average improvement of 1.5% per year in terms of fuel efficiency.
- Carbon neutral growth from 2020 onwards.
- An absolute reduction of net CO_2 emissions by 50% in 2050, compared to 2005 levels.

This united strategy will be based on aircraft and engine technology, together with operations and infrastructure measures. However, as can be seen in Figure 7 below, a 50% reduction of CO_2 emissions by 2050 cannot be achieved by advances in technology and operations alone. Alternative fuels and additional (yet to be developed) technology improvements will be required in order to achieve that aggressive goal.

Conclusion

Currently, policy makers are experiencing pressure from society to find rapid measures to mitigate the impact of aviation on the environment, and particularly on climate change. Meanwhile, industry is constrained by having to operate within the unchanged rules of physics.

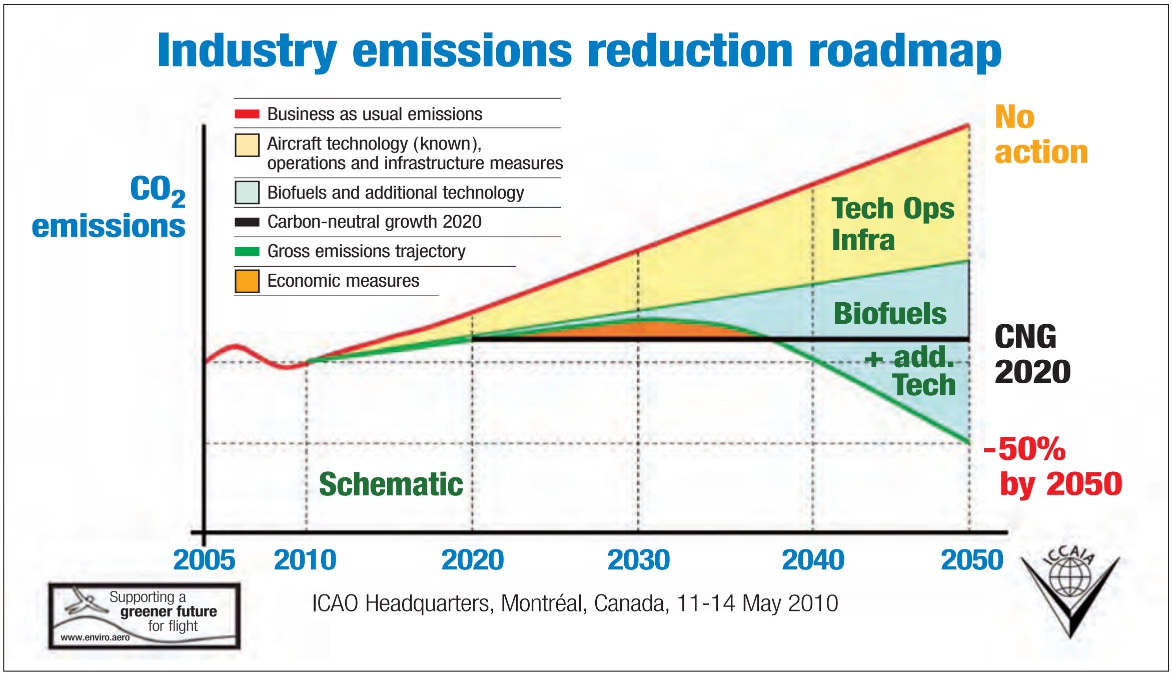


Figure 7: *CO_2 emission reduction measures over time.*

This environmental objective will not be achieved without cooperation between the industry and policy makers so that industry leaders can best anticipate the current and future expectations of society and devote significant resources to meet them. As indicated above, this will be achieved as a result of extensive research programs and their implementation in the design of aircraft and their engines. Governments must support the research programs so that the technology is ready as soon as it matures. Industry has a key role to play by putting forward the proposals and guiding the research, since these technologies will ultimately be incorporated into aircraft and engine designs.

This cooperation must balance short-term pressure-driven expectations with the need for technological breakthroughs in this long life-cycle industry. Resources must be enhanced and optimized, and new opportunities (such as alternative fuels) must continue to be explored. Some of the aircraft development projects that are currently envisaged will remain on the drawing board, while others will develop into real aeroplanes with substantial improvements that will ensure the environmental sustainability of aviation.

REFERENCES

1 With the conditions of operations of 2020, by comparison of a comparable aircraft technology, having been implemented in 2000 (with the operating conditions of 2000).

2 A budget of €1.6 billion, over the period 2008 – 2013, is equally shared between the European Commission and industry.

3 SESAR represents the technological dimension of the Single European Sky initiative, aimed at providing Europe with a high-performance air traffic control infrastructure which will enable the safe and environmentally friendly development of air transport.

4 FAA CLEEN (Continuous Lower Energy, Emissions and Noise) Programme Objectives are: 32 dB lower than Chapter 4, 60% lower NOx vs. CAEP/6, 33% lower fuel burn and use of alternative fuels.

5 Objectives are: 42 dB lower than Chapter 4, 70% lower NOx vs. CAEP/6, 50% lower fuel burn.

6 Directing a beam of fast-moving electrons at the metal surface – used on titanium components of the pylon for example.

7 A high-speed tool used to create heat through friction to join surfaces.

*8 In **aircraft**, the **wetted area** is the area which is in contact with the external airflow. This has a direct relationship on the overall drag of the aircraft.*

ICAO Technology Goals for NO_x Second Independent Expert Review

By ***Malcolm Ralph*** and ***Samantha Baker***

Malcolm Ralph *has longstanding connections with CAEP; most recently as an independent expert for Fuel Burn and NO_x Goals. Malcolm's working life has been mostly in aerospace, though he spent some years in the Air Pollution Division of WSL. He began his career working in transonic wind tunnels, and after studying mechanical engineering and post-graduate aerodynamics he rose to Technical Director Aerospace and Defence in the Department of Industry. There he was closely involved in launching many aircraft and aero-engine projects, and also worked on environmental matters. In 1999 he left that position to work as an independent consultant. Malcolm was elected Fellow of the Royal Aeronautical Society in 2000.*

Samantha Baker *is an Assistant Director at the UK Department for Business, Innovation and Skills, where she holds the Aviation Environment post in the Aerospace, Marine and Defence Unit.*

Samantha is actively engaged in CAEP, and currently leads a number of tasks including work on fuel burn technology goals. She has previously held posts in the UK Department of Energy and Climate Change and the UK Department for Environment, Food and Rural Affairs where she engaged with other UN organizations including UNFCCC and UNECE.

Background and Introduction

A certification Standard to control the amount of oxides of nitrogen (NO_x) permitted to be produced by civil turbo-jet and turbo-fan aircraft engines was first adopted by ICAO in 1981. The stringency of that Standard was successively increased at CAEP/2, 4, 6, and most recently at CAEP/8 in 2010. The introduction of a standard to control NO_x production was originally driven by concerns relating to surface air quality (SAQ) where NO_x is implicated in the production of ozone in the vicinity of airports. (see Local Air Quality Overview, Aviation Outlook of this report)

Consistent with these concerns, the Standards were set with reference to the amount of NO_x produced during a landing and take-off (LTO) cycle. Due to the accepted broad correlation between the amount of NO_x produced during the LTO cycle and that produced at cruise altitude, the standards also help to limit emissions at altitude. This is important, since scientists have linked NO_x emissions from aircraft engines to global climate change (GCC) and the production of particulate matter[1,2].

To complement the Standard-setting process, CAEP agreed in 2001 to pursue the establishment of technology goals over the medium and long term. These were to be challenging yet achievable targets for researchers and industry to aim at, in cooperation with States. Also they provide policy makers with a view of what technology could be expected to deliver for emission reductions in the future. The first of these reviews was to focus on NO_x, and to help achieve this, a panel of Independent Experts (IEs) was appointed and tasked with:

- Leading a review of technologies for the control of NO_x.
- Recommending technology goals for NO_x reduction from aircraft engine technologies over the 10 year and 20 year time horizons.

The first report of the IEs was presented to CAEP/7[3,4] in 2007 and the NO_x goals that were recommended - the first of their kind for ICAO – were adopted. The process has since been extended to include goals for noise, operations, and fuel burn. As part of the CAEP/8 cycle, progress towards the NO_x goals was reviewed once again by a panel of IEs to ensure transparency and involvement from all stakeholders[5]. As before, presentations were received from industry, research focal points, science focal points, NASA and EU researchers.

The Independent Expert Panel for NO_x

- Malcolm Ralph (Chair)
- John Tilston
- Paul Kuentzmann
- Lourdes Maurice

Recap of the NO_x Goals

The first NO_x IE review, conducted in 2006, proposed goals which were adopted at CAEP/7. The goals were defined as bands rather than single lines.

The goals can be seen in Figure 1, which is taken from the 2006 report of the IEs, together with goals proposed by the EU Advisery Council for Aeronautics Research in Europe (ACARE) and the US Ultra Efficient Engine Tecnology (UEET). It is important to note that these other goals were not used to influence the CAEP goals and were plotted simply for comparison. The graph also illustrates the historic ICAO NO_x Standards and highlights the large gap between the goals and the latest standard. It is important to note that the goals indicate that significant NO_x reductions are achievable over the 10 and 20 year timescales based on the leading edge of control technologies; while standards on the other hand are based on already certified technology.

Figure 1 uses the recognized NO_x certification metrics, and shows the amount of NO_x produced from an LTO cycle on the vertical axis (grams per kN of thrust), and the engine overall pressure ratio (OPR) at the take-off condition on the horizontal axis. It is evident that the larger, higher thrust engines operating at higher pressure ratios, and consequently at higher thermal efficiencies, produce greater amounts of NO_x. Note the slight change of slope of the Standard introduced at CAEP/4 at OPR 30. This explains why the IEs chose to define the goals as percentage reductions referenced against characteristic NO_x at OPR 30, as the goal bands did not mirror this change of slope. In relation to the degree of uncertainty, it should be noted that the band width was greater for the longer time period. The medium term (MT) goal for 2016 was agreed at 45% ± 2.5% below CAEP/6 at OPR 30, and the long term (LT) goal for 2026 at 60% ± 5% below CAEP/6 also at OPR 30.

Second NO_x IE Review

The second NO_x review was intended to be less extensive and was focused on what had changed in the intervening three years since the first review.

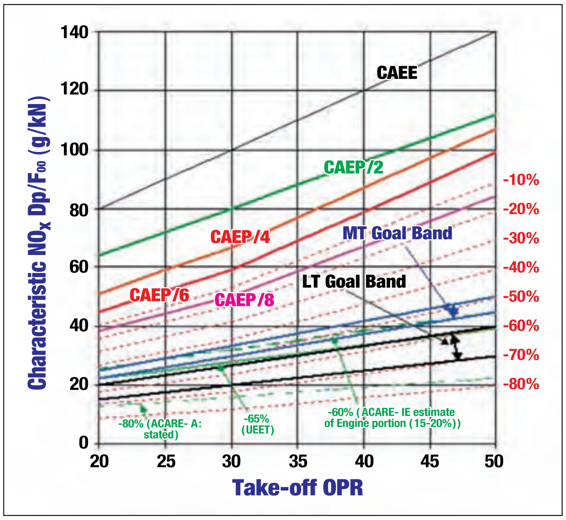


Figure 1: *Historical ICAO certification Standards together with the 2006 MT & LT goals.*

The IEs were asked to specifically include the following in their review:

- Science (global climate change and surface air quality).
- Technology progress towards the MT and LT goals.
- The validity of the goals.

However, in practice once the review got under way, in order to work through some difficult issues, the IEs extended the task list to also include:

- Small and mid OPR engines.
- Whether to change the definition of when a goal is met.
- Cruise NO_x.

Key discussion points and findings from the review are summarized below.

Science (Global Climate and Air Quality)

The IEs concluded that the scientific evidence supports continued efforts to reduce aircraft NO_x emissions and that the evidence of impact of aircraft NO_x on both surface air quality and global climate change was, if anything, more compelling than during the first review. Nevertheless, given the still considerable uncertainty about the quantification of these impacts, the IEs recommended continued research on NO_x emissions, and other emerging concerns such as particulate matter (PM), and the role of NO_x in PM formation. As in the 2006 report, it was again concluded that for SAQ, NO_x continues to be an important pollutant and in the context of Global Climate Change (GCC) its ranking versus CO_2 continues to depend crucially on the length of the time horizon. It appears that NO_x is more important in shorter time periods, with CO_2 dominating in the longer term, and then continuing to do so over many hundreds of years.

Progress Towards the Medium and Long Term Goals

Since 2006, further significant reductions in NO_x emissions have been evident, something for which manufacturers should be congratulated. Even further reductions are predicted using combustors still under development.

Advanced combustors can be categorized into two broad types: RQL systems (rich burn, quick quench, lean burn), and staged-DLI (direct lean injection), also called staged-lean burn systems. In very simple terms, RQL combustors control NO_x production through a series of changes to the air to fuel ratio as the combustion air progresses through the combustor. Staged-DLI combustors operate quite differently with NO_x control being achieved by switching (staging) between pilot and main burner zones arranged in concentric circles. Although reductions in NO_x production were shown to have been achieved by both types of combustor, neither was deemed to have met the goals set at the first review - defined as having reached Technology Readiness Level 8 (TRL8)[6] - although they were possibly close to that.

Figure 2 provides a summary presentation of the test data results received for this review with the two types of combustor identified separately; the data points coloured grey being for RQL combustors, and those in red being for the new staged-DLI combustors. As with the first review, the conclusion reached was that RQL combustors appear likely to meet the MT goal, though a significant challenge remains, but the LT goal may not be achievable particularly for high OPR engines. Dramatic reductions in NO_x production from the use of new generation staged DLI combustors were in line with the expectations recorded in the 2006 Report, although the migration towards the LT goal was not expected so soon. However, the wide spread of NO_x performance raised questions about how such families of engines might be handled in the future within a goals setting process.

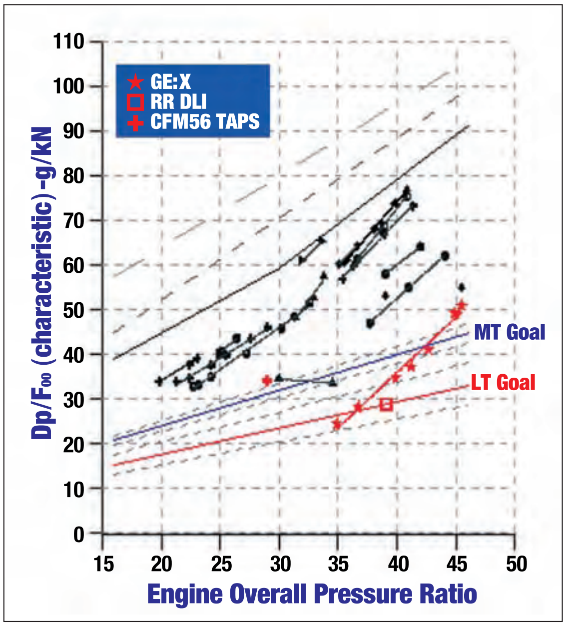


Figure 2: *2009 Review data with RQL combustors in grey and new generation staged DLI combustors in red. Note these data points are a mixture of certificated engines and high TRL developments.*

Mid and Low OPR Engines

Referring again to Figure 2 but this time focusing on engines below OPR 35, there are only three data points at or near the MT goal band, two coloured grey, using RQL combustors, and one red data point depicting staged-DLI. The two RQL (grey) points at around OPR 30 and OPR 34 are members of one engine family at TRL6 maturity and are shown as predicted to lie close to the top and bottom of the MT band. Uniquely, these are geared fan engines and it is thought likely that overall engine cycle effects may have contributed to these impressively low LTO-based results.

The staged-DLI, mid-OPR, single data point lies just above the MT band at just below OPR 30 and shows a prediction extrapolated from current TRL6 maturity. This was the only new generation staged-DLI demonstrator for which information was received for mid-OPR engines. No data was available to give confidence that staged-DLI combustors could sensibly be fitted to smaller (low OPR) engines, at least in the shorter term.

Validity of The Goals

Information presented for advanced RQL combustors was believed not to challenge the definition, or levels, of the goals established at the first review. The somewhat limited information relating to the new generation staged-DLI combustors however was thought to offer something of a challenge to both the definition and the goal levels. Nevertheless, since they are untested in commercial service, the IEs decided not to change the goals at this review but to wait until further experience had been gained. It was concluded that staged-DLI combustors were likely to be essential to meet the LT goal, particularly at high OPRs. A critical factor for future goal setting will be the extent to which advanced RQL and staged-DLI systems can be made to work effectively for (smaller) low and mid-OPR engines.

Cruise NO_x

Currently, there is an accepted broad correlation between the amount of NO_x produced during the heavily prescribed LTO cycle used for certification, as compared with the amount produced at cruise , but for which no standard exists or database is available. As in the first IE report, concern was expressed about future uncertainties with this relationship due to the significantly different behaviour of staged-DLI combustors, and the potential change in cruise characteristics of possible new engine architectures such as open rotor engines, and also possibly, geared turbo-fans.

Staged-DLI combustors have the potential to considerably reduce NO_x at cruise levels, but the IEs noted that, because the current NO_x Standard is LTO-based, manufacturers may trade off cruise NO_x if they need to address problems with meeting LTO NO_x for certification. IEs have therefore recommended that CAEP considers further scientific advice on the relative importance of cruise NO_x and then return to this issue for advanced combustors and engine architectures.

Conclusions

In light of the above, a number of conclusions can be made based on the second IE review of technology goals for NO_x:

- Evaluation of progress towards the goals is a key part of the goal-setting process, and the second NO_x review was able to take into account new developments in technologies as more information became available.
- The technology goal-setting process is of value. The goals provide challenging, yet reasonable targets for researchers and industry to aim at in cooperation with States, and they inform policy makers of what technology could be expected to deliver emissions reductions in the future.
- For RQL combustors, considerable progressive improvements were noted, although the IEs considered that these did not challenge the goals established at the first NO_x review.
- The first NO_x review anticipated that a significant change in technology through the use of staged combustors would occur in the future. At that time it was difficult to understand how these would impact the goals but data presented during the second review indicated that significant improvements are now more likely.
- IEs recognized that considerable progress had been made since the first review, but decided not to recommend a change, either to the goals or the definition of their achievement, in order to avoid hasty, and possibly ill-conceived changes to what were intended to be mid and long term targets.
- IEs were particularly concerned that sufficient time be allowed for the potential of staged-DLI combustors to be clarified, and also to await further evidence on the applicability of both advanced RQL and staged-DLI combustors to smaller low and mid-OPR engines. If precluded from these categories, there could be significant implications for future goals.
- IEs recommended that a further review be considered in about three years when, in all probability, it will be possible to resolve most of these outstanding issues. ■

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3 ***The 2006 IE Report is available on the FAA website:*** ***http://www.faa.gov/about/office_org/headquarters_offices/aep/research/science_integrated_modeling/media/Independent%20Experts%20Report.pdf***

4 ***Report of the Seventh Meeting of the Committee on Aviation Environmental Protection,*** *Montréal, 5 – 16 February 2007 (Doc 9886).* ***http://www.icao.int/icao/en/env/LongTermTechnologyGoals.pdf for the presentation at the CAEP/7***

Independent Experts NOx Review and the Establishment of Medium and Long Term Technology Goals *for NO_x (Doc 9887)*

5 ***Report of the Eight Meeting of the Committee on Aviation Environmental Protection,*** *Montréal, 1 – 12 February 2010 (Doc 9938)*

6 ***A now generally used NASA technology maturity scale,*** *Report of the Independent Experts on the 2006 NO_x Review, Appendix 2; and the 2009 Report, Appendix A*

Advision Council for Aeronautic Research in Europe (ACARE)
Ultra Efficient Engine Technology (UEET)
Global Climate Change (GCC)

Environmental and Economic Assessment of NO_x Stringency Scenarios

By ***Gregg Fleming*** and ***Urs Ziegler***

As Director of the Environmental and Energy Systems Center of Innovation at the Volpe Center, ***Gregg Fleming*** *has almost 25 years of experience in all aspects of transportation-related acoustics, air quality, and climate issues. He has guided the technical work of numerous, multi-faceted teams on projects supporting all levels of Government, Industry, and Academia, including the Federal Aviation Administration, the Federal Highway Administration, the National Park Service, the National Aeronautics and Space Administration, the Environmental Protection Agency, and the National Academy of Sciences. Mr. Fleming currently co-chairs ICAO's Modeling and Databases Group and represents the FAA at the UNFCCC. He is also Chairman Emeritus of the Transportation Research Board's Committee for Transportation Related Noise and Vibration.*

After receiving his doctoral degree in earth sciences ***Urs Ziegler*** *worked in the field of environmental protection for a Swiss civil engineering company. Later he joined the Swiss Office for Environmental Protection where he worked for more than 10 years. During this time Mr. Ziegler also acquired a masters degree in public administration. In 2005 he joined the Swiss Federal Office of Civil Aviation FOCA as Head of the Office's Environmental Affairs Section. He is the actual Swiss member in the International Civil Aviation Organization's Committee for Aviation Environmental Protection CAEP within which he currently co-chairs the Modelling and Databases Group. He also represents FOCA in various international bodies dealing with aviation and climate change.*

Introduction

This article presents an overview of the analysis conducted by CAEP of the cost impacts, emissions reductions, and environmental trade-offs of the NO_x stringency scenarios that were considered by the eighth meeting of the Committee on Aviation Environmental Protection (CAEP/8). In addition to examining the environmental benefits and associated environmental tradeoffs, the cost effectiveness for a range of scenarios was also considered. Cost-effectiveness results are presented as costs per tonne NO_x reductions during the ICAO Landing and Take-Off (LTO) cycle. The primary goal of conducting such an analysis is to indentify scenarios that result in substantial environmental benefits at reasonable costs.

In total, 10 scenarios were considered for modelling, as shown in Table 1. Small and large engine categories were assessed, and reported separately, to better understand if a

NOx Stringency Scenario	Small Engines [26.7 kN / 89 kN Foo][1,2]	Large Engines OPR[3] >30	Slope[4]
1	-5% / -5%	-5%	2
2	-10% / -10%	-10%	2.2
3	-10% / -10%	-10%	2
4	-5% / -15%	-15%	2.2
5	-15% / -15%	-15%	2.2
6	-5% / -15%	-15%	2
7	-15% / -15%	-15%	2
8	-10% / -20%	-20%	2.2
9	-15% / -20%	-20%	2.2
10	-20% / -20%	-20%	2.2

Methodology

[1] Foo – Thrust rating. For engine emissions purposes, the maximum power/thrust available for takeoff under normal operating conditions at ISA (International Standard Atmosphere) sea level static conditions without the use of water injection as approved by the certificating authority. Thrust is expressed in kilonewtons (kN).

[2] Incremental stringency options defined for small engines with thrust ratings (Foo) comprised between 26.7 kN and 89 kN.

[3] OPR – Overall Pressure Ratio. This engine pressure ratio is defined as the ratio of the mean total pressure at the last compressor discharge plane of the compressor to the mean total pressure at the compressor entry plane, at the engine takeoff thrust rating (in ISA sea-level static conditions).

[4] Slope of the line of the NO_x stringency options at engine pressure ratio (PR) greater than 30.

Table 1: *NO_x Stringency scenarios examined.*

given stringency scenario resulted in an inequity between the small and large engine categories. The 10 stringency scenarios were analyzed for the years 2016, 2026 and 2036, for two stringency introduction dates: 31 December 2012 and 31 December 2016.

Methodology

A Modification Status (MS) methodology was developed by CAEP to assess engine technology responses to the various NO_x stringency scenarios. The three MS technology response levels are: Minor Changes (MS1), Scaled Proven Technology (MS2), and New Technology (MS3). The MS methodology covers the situation where an engine family fails to meet a NO_x stringency scenario and a different category of response is proposed that may bring it into compliance with the stringency scenario. Only MS1 and MS2 technology responses were needed for the small engine group to meet the NO_x stringency scenarios, while all three MS technology responses were needed for the large engine group at the higher stringency scenarios, as shown in Figure 1.

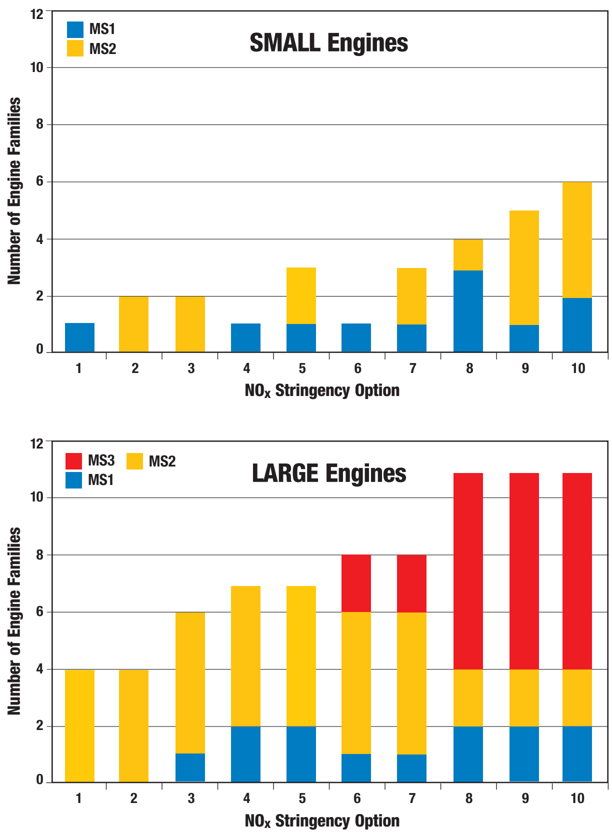

Figure 1: *Number of engine families requiring an MS technology response.*

Emissions Reduction Results

Figure 2 shows the total NO_x reductions for all engines for the below 3,000 ft case. Similar results were computed separately for large and small engines. The total savings for the large engines are about two orders of magnitude higher than for the small engines — large engines accounting for about 99% of the total NO_x savings across all scenarios. For the all-engines grouping, total NO_x reductions computed for the below 3,000 ft case range from about 6,300 metric tonnes to over 114,000 metric tonnes, or from 1.4% to 9.8% below the baseline "no stringency" case.

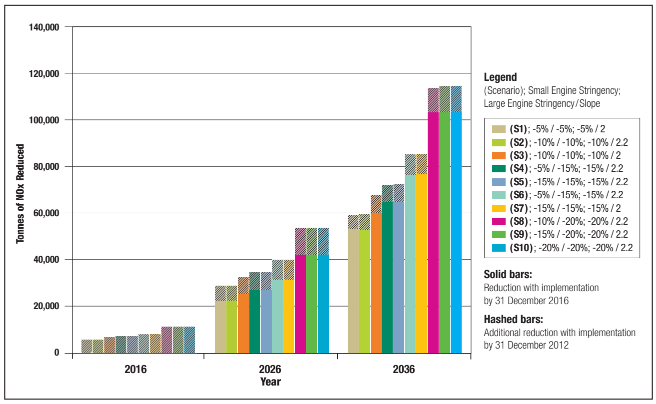

Figure 2: *Total below 3,000 ft. - NO_x reductions relative to baseline - all engines.*

The total NO_x reductions for the above 3,000 ft case range from about 54,000 metric tonnes to over 773,000 metric tonnes for all-engines, or from 1.5% to 10.1% below the baseline "no stringency" case – about the same percentage range as for the below 3,000 ft case.

Cost Results

Cost impacts were estimated for each stringency scenario listed in Table 1 for the two implementation dates, for both small and large engine categories separately. A range of values was used for a number of key assumptions, including: non-recurring costs, fuel burn penalty, fuel price, loss of resale value (LRV), and a variety of discount rates.

A 30-year time horizon through 2036 was used to calculate and assess the Net Present Value (NPV) of industry costs and to aggregate NO_x emissions reductions. The aggregate NO_x emissions reductions were computed using the modelled results from 2006, 2016, 2026 and 2036.

Table 2 summarizes total cost impacts for small and large engines combined. For stringency scenarios 1 through 5 they are broadly similar, but for scenarios 6 through 10 costs increase sharply, driven by non-recurring costs for engines under the MS3 technology response.

NOx Stringency Scenarios	Low Cost Estimate ($M) 3% discount, 2016, LRV	High Cost Estimate ($M) 3% discount, 2016, LRV
1-5	$ 1,922	$ 2,500
6-7	$ 6,412	$ 9,470
8-10	$ 10,878	$ 21,507

Table 2: *Cost results – large and small engines combined.*
LRV *– Loss in Resale Value.*

While efforts were made to comprehensively quantify all cost impacts, some costs were not included. For example, increased industry operational costs for scenarios involving higher fuel burn were partially itemized to include fuel costs and costs associated with loss in payload for payload limited flights. However, carbon costs for additional CO_2 emissions such as those resulting from the inclusion of airlines in the EU Emissions Trading Scheme were not itemized, and consequently were not included in the cost roll-up, although its effects could be assumed to be approximated by the sensitivity cases for the fuel prices.

Environmental Trade-Offs

An important part of the NO_x stringency assessment is the consideration of environmental trade-offs between the various NO_x stringency scenarios, fuel burn, and noise. The CAEP emissions technical group recommended a fuel burn penalty range of between 0% and 0.5% for engine families requiring a major modification (MS3). Figure 4 presents the maximum potential fuel burn penalty for the full-flight case.

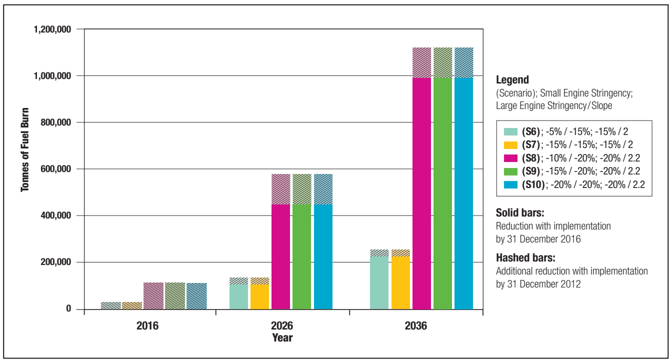

Figure 3: *Maximum potential full flight fuel burn penalty relative to baseline - all engines.*

In accordance with the CAEP emissions technical group recommendations, the MS3 fuel burn penalty only applies to large engines and only for scenarios 6 through 10. As can be seen in Figure 4, the maximum potential fuel burn penalty ranges from about 28,000 metric tonnes to 1.1 Mt (1.1×10^6 metric tonnes), which equates to between 0.01% and 0.19%, relative to the baseline "no stringency" case. This translated into additional CO_2 emissions of between 88,000 metric tonnes and 3.5 Mt. In accordance with the technical group's recommendations, the minimum fuel burn penalty is zero.

The noise technical group recommended a noise penalty range of between 0 decibels (dB) and 0.5 dB per certification point for 10% of engines requiring a major (MS3) modification, i.e. 10% of all engines. As with fuel burn, the MS3 noise penalty only applies to large engines and only for scenarios 6 through 10. The effect of the MS3 noise penalty on the 55, 60 and 65 Day-Night Noise Level (DNL) contour areas expressed as a percentage change was less than 0.12%. Based on these findings, it was concluded that the analysis indicated that there is **no** noise trade-off associated with **any** of the NO_x stringency scenarios. This conclusion has been verified at the global, regional, and airport levels.

Cost-Effectiveness Results

The cost-effectiveness results are dominated by large engines which, as stated earlier, account for approximately 99% of the benefits. Scenarios 1 through 5 are the most cost effective, all providing relatively low cost per tonne of NO_x reduction levels. For scenarios 6 and 7, cost per tonne of NO_x reductions increased by a factor of 3 to 4, using a 3% discount rate. Scenarios 8, 9 and 10 result in a further doubling of cost per tonne of NO_x reductions. Cost-effectiveness rankings for large and small engines are shown in Tables 3 and 4, respectively.

Although the analysis concentrates on NO_x reductions up to 3,000 ft, stringencies also have an effect on climb/cruise NO_x emissions. If these were taken into account, the total reductions achieved would increase by an approximate factor of 7 to 8, and the costs per tonne would diminish accordingly.

The early implementation date of 2012 gives overall lower values for the costs per tonne of NO_x reductions. This is due to the additional four years of NO_x reductions that would be gained, compared with 2016 implementation, coupled with roughly the same costs for both implementation dates. This

Ranking	Stringency Reference	NOx Reduction % Slope of Dp/Foo
1	NS01, NS02, NS03, NS04, NS05	-5% / 2.0, -10% / 2.2, -10% / 2.0, -15% / 2.2
2	NS06, NS07	-15% / 2.0
3	NS08, NS09, NS10	-20% / 2.2

Table 3: *Cost-effectiveness ranking - large engines.*

Ranking	Stringency Reference	NOx Reduction %
1	NS01, NS04, NS06	-5% / -5%, -5% / -15%
2	NS08	-10% / -20%
3	NS02, NS03	-10% / -10%
4	NS010	-20% / -20%
5	NS09	-15% / -20%
6	NS05, NS07	-15% / -15%

Table 4: *Cost-effectiveness ranking - small engines.*

implies that an early implementation year would be more cost effective. However, in the approach used, it is assumed that the non-recurring costs for the technology responses needed to start four years in advance of implementation (from 2009). This may mean that, in practice, a date somewhat later than 2012 is more reasonable, particularly for those scenarios involving MS3 modifications.

Figures 4 and 5 present NO_x cost-effectiveness results for large engines and small engines, respectively. Figure 4 includes large engine results for both 2012 and 2016 implementation dates. The gold columns represent cost uncertainty bands for the 10 stringency scenarios based on a 2016 implementation date; whereas, the red columns represent the uncertainty bands for a 2012 implementation date. The sloped "fan lines" indicate lines of constant cost per tonne of NO_x reductions.

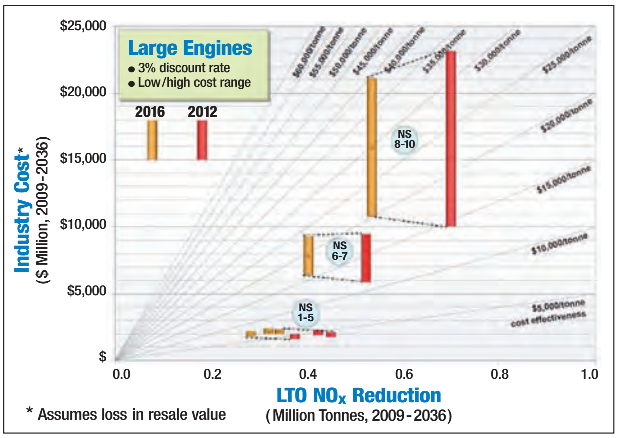

Figure 4: *NO_x cost-effectiveness results – large engines.*

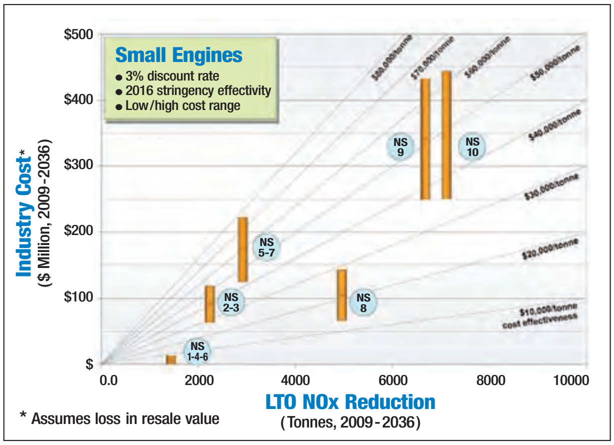

Figure 5: *NO_x cost-effectiveness results – small engines.*

Conclusions

The environmental and economic analysis that was conducted informed CAEP/8 of the emissions reduction potential, environmental tradeoffs, and cost effectiveness of the NO_x stringency scenarios under consideration.

The analysis revealed that small engine aircraft contribute approximately 1% of the aggregate NO_x reduction benefit. Additionally, while the total costs to make small engines compliant are low, their cost-effectiveness is weak, by a factor ranging from 30% to as high as 200%. It was also found that the discount rate does not affect the ranking of NO_x stringency scenarios, but higher discount rates give lower present value to the NO_x reduction in the future years. Similarly, none of the other sensitivity tests performed influence the ranking of scenarios. ■

Development of An Aircraft CO_2 Emissions Standard

By ***Curtis A. Holsclaw***

CURTIS A. HOLSCLAW *is the Manager of the Emissions Division in the FAA's Office of Environment and Energy. In that capacity he manages a staff that is responsible for the policy, regulatory, and technical aspects of aviation emissions as it relates to engine emissions, air quality, and global atmospheric effects. This includes research, engineering and development activities to advance the characterization of aircraft emissions, computer-modeling techniques and methodologies to better estimate the environmental and health impacts of aviation related emissions and to assess measures to reduce those impacts. He has about thirty years of experience in aircraft noise and engine emissions certification. In addition, he has been actively involved in CAEP activities for about twenty five years in order to develop noise and emissions certification standards for commercial transport aircraft and engines.*

Background

The eighth meeting of ICAO's Committee on Aviation Environmental Protection (CAEP/8) held in February 2010, made important decisions regarding technological means to reduce the impact of aviation on climate change. The meeting established a timeline for the development of a CO_2 certification Standard (see Figure 1). In addition, agreement was reached on increased stringency for aircraft NO_x emissions Standards, which also has an effect on global climate.

Considerable work has been carried out in the past by CAEP technical experts, especially over the last three years, which has enabled ICAO to adopt this promising timeline.

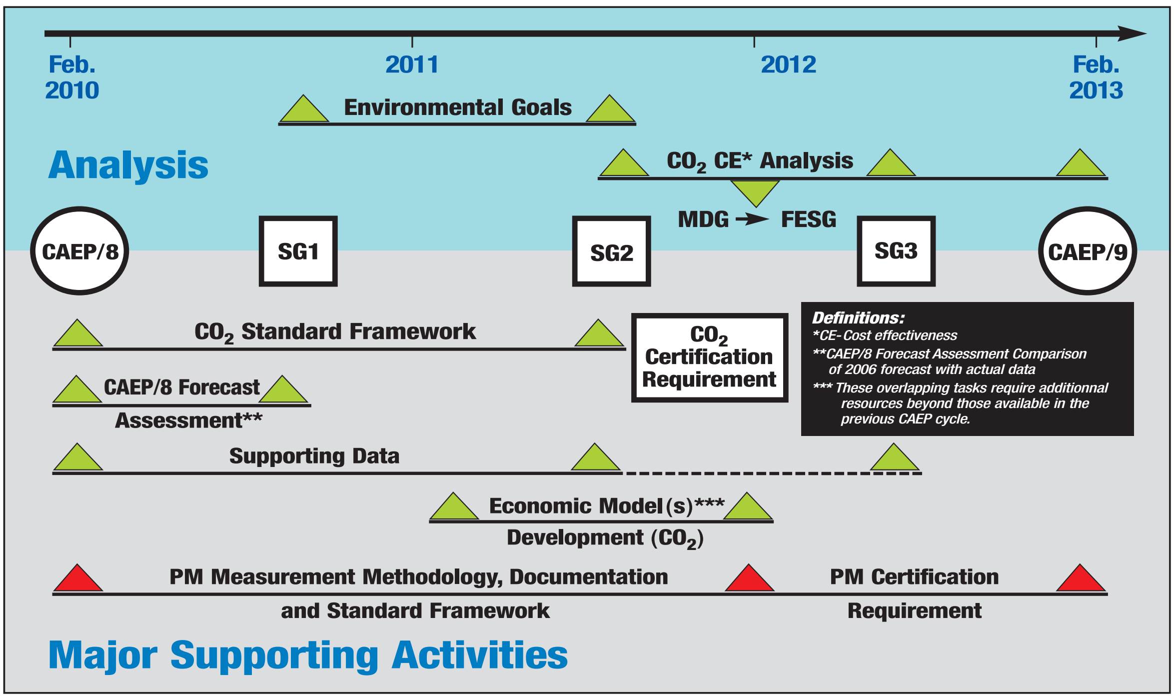

Figure 1: *CAEP/8 established timeline for an aircraft CO_2 emissions Standard.*

Introduction

Initial discussions within the CAEP technical expert group on emissions were held in order to clarify the high-level objective of the task. It was agreed that the effort would be referred to as a "CO_2 Standard" based on "fuel efficiency concepts" within the certification requirement metric. This was decided in order to ensure the necessary transparency and public understanding that is essential to demonstrate that this work is contributing to efforts to reduce aviation's impact on climate change.

It was also agreed that any mitigation of aircraft CO_2 emissions through the production and use of alternative fuels would be considered via a full life-cycle analysis, which was deemed to be outside the scope of the immediate work item. It is believed that, if alternative fuels are developed in the future with specifications significantly different from current aviation kerosene, then this would need to be addressed separately.

Specific issues addressed by technical experts during the scoping analysis were as follows:

- Historic CAEP work in this area.
- Terminology and high-level objectives.
- Scope of requirements/priority.
- Metric requirements and characteristics.
- Certification procedure options.
- Applicability.
- Certification instrumentation and measurement methodology.
- Regulatory level.
- Manufacturer compliance.

Historic CAEP Work In This Area

Work done previously by CAEP related to this issue needed to be considered first in order to benefit from critical lessons already learned and to avoid duplicating previous discussions and work efforts. Accordingly, a thorough review of the previous work resulted in the following points being agreed upon:

- A certification requirement allows differentiation of products with different technology.
- Any fuel efficiency certification requirement should be aircraft based.
- A certification scheme needs to be based on certified aircraft/engine parameters.
- There is a need to explore a range of possible aircraft fuel efficiency metrics, identifying their positive and negative aspects, before making a final choice.
- The choice of a representative mission or reference point (certification procedure) is a complex issue due to the wide range of aircraft types and operational missions.

Terminology

The following terminology was agreed to as a working basis for future discussions on this subject:

Standard – combination of a certification requirement and a regulatory level.

Certification requirement – the combination of metrics, procedures, instrumentation, measurement methodology(ies), and compliance requirements.

Parameter - a measured or calculated quantity that describes a characteristic of an aircraft (e.g. MTOW, Optimum Cruise Speed).

Metric – a certification unit consisting of one or more measurement parameters (e.g. Dp/Foo).

Procedures – specific certification procedures, including applicability requirements (e.g. Annex 16 Volume II, Chapter 2).

Instrumentation and measurement methodology – technical measurement procedures (e.g. Annex 16 Volume II, Appendix 3).

Certified level – approved for a specific product by a certification authority to demonstrate compliance with a regulatory level, as determined by the certification requirement.

Regulatory level – a limit which a certified level must meet (e.g. CAEP/6 NO_x).

High-Level Objectives

The following high-level objectives for an aircraft CO_2 emissions Standard were identified in order to assess future proposals and, as far as practicable, identify an optimum way forward:

- Provide an additional incentive to improve aircraft fuel efficiency, and thus, global fleet fuel burn performance.
- Measure fuel burn performance and relevant capabilities (e.g. range, size, speed) across different aircraft types.

- Ensure it is technically robust (now and future) with an acceptable level of accuracy.
- Maintain equity across products and manufacturers.
- Represent key aircraft design characteristics and environmental performance with respect to individual design philosophies (e.g. 2/3 spool engines or regional jet, narrow body, wide body aircraft types).
- Permit flexibility in aircraft design to comply with requirement.
- Minimize counterproductive incentives.
- Minimize adverse interdependencies.
- Base it on existing certified data.
- Account for proprietary data protection concerns.
- Not require an inappropriate level of resources on the part of national airworthiness authorities and the ICCAIA to implement.
- Be simple, transparent, and easily understood by the general public.
- Develop a Standard as soon as reasonably practicable to ensure that ICAO maintains its leadership in addressing aviation emission issues.

Scope of Requirement/Priority

The scoping study group agreed that there was need to prioritize the category of aircraft to be considered in the initial CO_2 Standard development task in order to improve the probability of agreement by CAEP/9 in 2013, while maintaining the expected level of quality. It was agreed that this could be achieved by focusing on the aircraft categories that burn the largest proportion of aviation fuel globally, and therefore reduce the number of affected industry stakeholders (engine and airframe manufacturers in particular), thereby simplifying and expediting the process for completion of the CO_2 Standard.

In considering the initial step above, major aircraft categories were identified as: subsonic jets, heavy propeller driven aeroplanes, light propeller driven aeroplanes, helicopters, tilt rotors, and supersonic aircraft. Of these major types, subsonic jet aircraft indisputably account for the vast majority of global aviation fuel use (approximately 95% according to MODTF 2006 data used in the CAEP/8 Environmental Goals Assessment). For that reason, the ad-hoc group agreed to limit the scope of the work to that category only.

Metric Requirements/Characteristics

The metric(s), should be objective and reflect fuel efficiency at the aircraft level. Improvements in fuel efficiency observed in the certification procedure and metric(s) should correlate, as far as practicable, with actual improvements in aircraft fuel efficiency (i.e. reductions in CO_2 emissions) during operational conditions. This analysis does not exclude the potential need to define and select multiple metrics for various type of aircraft or operations (e.g. passenger v. cargo, commercial passenger versus business).

The metric(s) should be based upon certified parameters to ensure commonality among different manufacturers. If this requires the certification of additional parameter(s) compared with existing practices, then an assessment of the implications (e.g. technical feasibility, workload, process) should be conducted.

The parameters that compose the metric should be easily measurable at the certification stage, or derived from engineering data, and should consider the industry standard practices of measurement and adjustment. In order to ensure the successful implementation of a CO_2 Standard, there is a need to limit the regulatory burden associated with obtaining and tracking information to a reasonable level.

The metric should be robust in order to minimize the potential for unintended consequences. The use of poorly defined metrics to establish policies can create equity issues and can result in the emergence of opportunities to influence the system in a way that may reduce the effectiveness of the policies and have the potential to drive the system to a different operating point than the one originally intended.

To the extent practicable, the metric should be fair across the set of stakeholders covered by the CO_2 Standard, including the distribution of cost and benefits, both when initially applied and with respect to the future.

The metric should limit interdependencies and any influence on other Standards (e.g. emission, noise Standards) in order to minimize unintended consequences. The construction and selection of a metric should minimize the effects on other performance indicators covered by other Standards.

Certification Procedure Options

The procedure ultimately recommended for demonstrating compliance with a CO_2 Standard will require key decisions and agreements in several respects. For example, a reference mission or operating mode could be defined in order to reduce the variation in aircraft operation during the certification process. At this time the exact approach and best definition is not known and must be further studied by the technical expert group on emissions.

The certification procedure will also need to incorporate certain aspects of relevant aircraft design characteristics. These parameters will be required, as appropriate, to provide information to the certification metric as discussed previously. Several aircraft design characteristic parameters may be considered during certification metric and methodology development, such as cruise conditions, operating range, and weight, etc.

Applicability

The Group on International Aviation and Climate Change (GIACC) Programme of Action recommended that CAEP seek to develop a CO_2 Standard for new aircraft types. While there has been general agreement within CAEP that the initial focus should be on new aircraft types, it was agreed to defer further debate and discussion to a wider group of experts during the next CAEP cycle.

In defining applicability requirements, there is also a need to examine and agree on when modified existing products are considered to have no change to their certified levels, when they need to demonstrate continued compliance with their existing certification basis, and when compliance with a new CO_2 Standard is required. This should take into account existing certification practices and procedures within this area.

Certification Instrumentation and Measurement Methodology

The scoping study group agreed that the measurement methodology and required instrumentation for a CO_2 Standard (e.g. Annex 16 Volume II, Appendices 2 and 3 for Smoke Number and Gaseous Emissions, respectively) would be highly dependent on the discussions concerning the certification metric and procedure.

While it was perceived as a subsequent issue which would be driven by the discussions in other areas, certification instrumentation and measurement methodology should be borne in mind at all times to ensure that proposals are technically feasible, appropriately quantify CO_2 emissions, and do not create an unreasonable regulatory burden.

As with the other emissions requirements, it was recognized that there may also be a need to consult with expert technical groups outside the CAEP domain (e.g. SAE International's E-31 Committee).

Regulatory Level

The terms of reference and underlying principles that have guided the CAEP work program, as they relate to the gaseous emissions engine certification requirements contained in Annex 16, Volume II (i.e. technological feasibility, economic reasonableness and environmental benefit in setting new Standards, noting also the environmental interrelationships and tradeoffs), have been a cornerstone of CAEP and ICAO decision-making as it relates to the setting of Standards.

It was recognized that the immediate priority was the development of a robust certification requirement against which a regulatory level may be applied. To the degree possible, work on assessing regulatory level options should be done in parallel to enable the earliest possible implementation once key elements of a certification requirement have been agreed. Ideally, the regulatory level should provide positive incentives for industry stakeholders to improve fuel efficiency while also improving the overall commercial performance of aircraft through the implementation of new technology.

Manufacturer Compliance

Historically, an aircraft type certification approach with a simple pass/fail criteria has been the primary means of implementing Standards to control engine emissions from all transport modes, including aviation. Compliance with LTO NO_x, CO, HC and smoke regulatory levels has been demonstrated through measurement of the emissions at the engine exhaust, along with analysis and correction of these emissions to reference standard day conditions. The results also take into account statistical compliance factors, depending on the number of engine tested. For aircraft, this approach has served primarily as a cap on emissions rather than as a technology forcing method. This application of type certification is well understood by the aviation community, and a CO_2 Standard which follows this approach may be more easily implemented within the industry's current institutional structure.

Next Steps

During the CAEP/8 meeting in February 2010 there was discussion and agreement on the way forward pertaining to the development of an aircraft CO_2 emissions Standard, taking into account the scoping analysis described above.

It was agreed that this effort would constitute the highest priority in the work program for the CAEP/9 cycle and that a CO_2 Standards task group would be formed to carry out the work program.

The CAEP/9 work program calls for the certification requirement to be presented to the CAEP Steering Group in 2011. In addition, there is the intention to produce a recommendation on the Standard, including applicability, during 2013, adjusting programme plans as necessary, while ensuring quality and effectiveness. ■

Subsonic Civil Transport Aircraft for a 2035 Time Frame[1]

By ***Elena de la Rosa Blanco*** *and* ***Edward M. Greitzer,*** *© 2010 Massachusetts Institute of Technology*

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Edward Greitzer*, the project Principal Investigator, is the H. N. Slater Professor of Aeronautics and Astronautics and the former Director of the Gas Turbine Laboratory. He is a Fellow of the ASME, the AIAA, a member of the National Academy of Engineering and an International Fellow of the Royal Academy of Engineering.*

[1] *The following article appears in the 2009-2010 issue of* ***AeroAstro****, the Massachusetts Institute of Technology Department of Aeronautics and Astronautics annual publication. ©2010 Massachusetts Institute of Technology*

In October 2008, NASA awarded four research contracts aimed at defining the advanced concepts, and identifying the enabling technologies that need to be put in place, for subsonic civil aviation in the 2035 timeframe. The work was part of the NASA N+3 program, where N+3 refers to aircraft three generations beyond those currently flying. The contracts were awarded to teams led by Boeing, Northrop Grumman, GE, and MIT, all of whom have since developed their different views of what the future aircraft might be. Aurora Flight Sciences and Pratt & Whitney were partners on the MIT team, the only team led by a university. As described in this article, collaboration between these three organizations (MIT/Aurora/P&W) has resulted in the development of revolutionary conceptual designs for future subsonic commercial transports.

Four metrics had been set by NASA for the design concepts: aircraft noise, engine emissions (as expressed in terms of the oxides of nitrogen (NO_x) produced during landing and take-off), fuel burn, and runway length for take-off. The targets were aggressive, for example the fuel burn goal was a reduction of 70% for a reference aircraft and the noise goal was comparable with that of the Silent Aircraft Initiative, namely aircraft noise imperceptible outside of the airport perimeter. A fifth metric, the global average surface temperature change due to the aircraft emissions, which reflected the aviation impact on climate change metric, was also included by the team as part of the concept aircraft evaluation.

Project Scope and Approach

The MIT-Aurora-Pratt collaboration applied its multi-disciplinary expertise to determine, in a rigorous and objective manner, the potential for improvements in noise, emissions, fuel burn, and airport use for subsonic transport aircraft. The project incorporated assessments of technologies in aerodynamics, propulsion, operations, and structures to ensure that a full spectrum of improvements was identified, plus a system-level approach to find integrated solutions that offer the best balance in performance enhancements. This assessment was enabled by a first-principles methodology, which allowed simultaneous optimization of the airframe, engines, and operations. The overall exercise also contained an assessment of the risks and contributions associated with each enabling technology, as well as roadmaps for the steps needed to develop the levels of technology required.

As the initial task — to frame the type of aircraft that would be most appropriate — the team defined a scenario for aviation in 2035: estimates of passenger demand, fuel constraints, airport availability, environmental impact, and

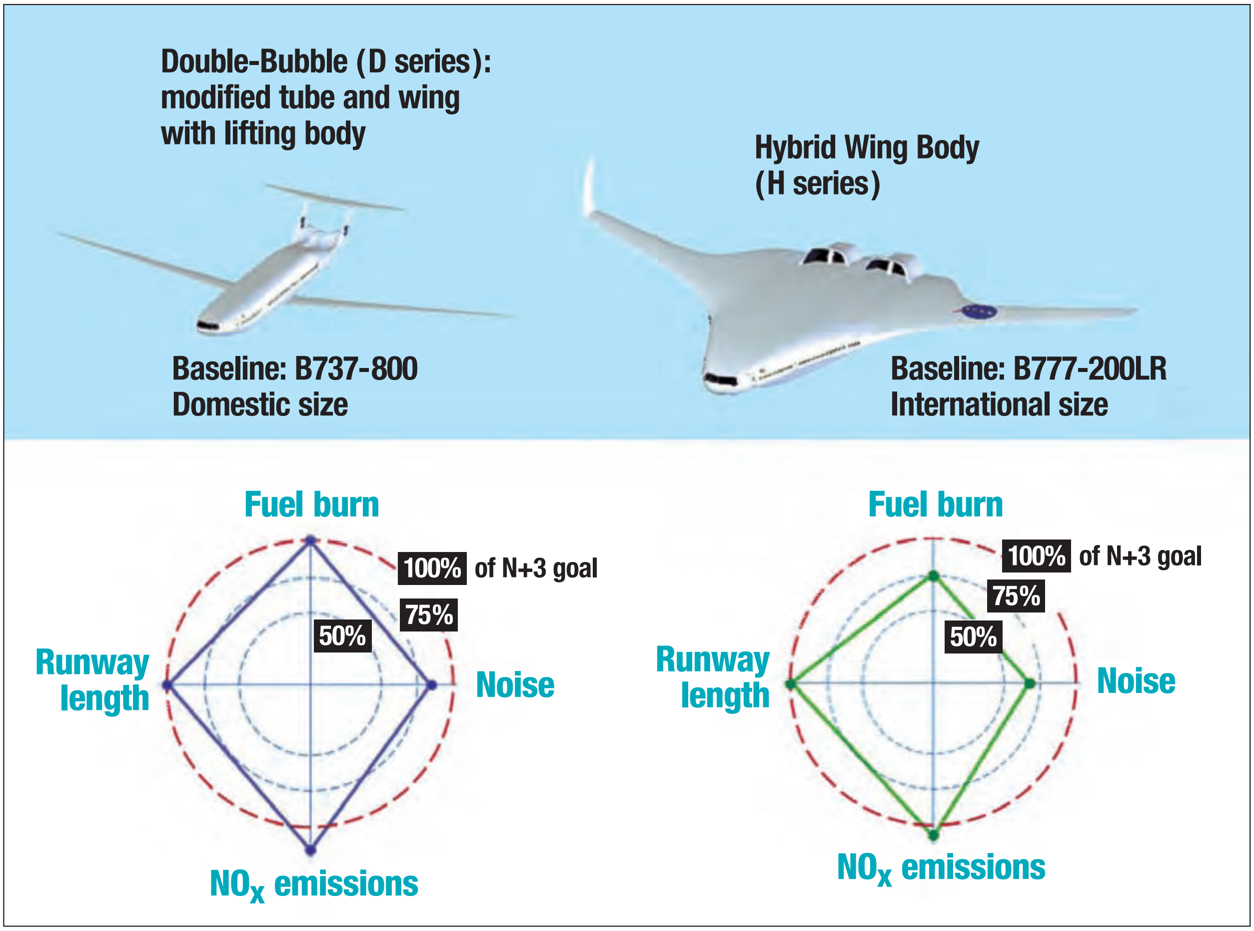

Figure 1: *(Upper) Double-bubble (D Series) and hybrid wing body (H Series) conceptual aircraft; (Lower) Comparison of aircraft attributes with NASA targets.*

other relevant parameters. This scenario, plus the NASA requirements, led to two conceptual aircraft designs. Their missions were selected from different market segments, but chosen so that, together, the two aircraft would represent a substantial fraction of the commercial fleet; implying that adoption of such designs could have a major impact on fleet-wide fuel burn, noise, emissions, climate, and airport use.

Features of the Concept Aircraft

One of the two designs is aimed at the domestic market, flights from 500 nautical miles up to coast to coast across the US. It represents a 180-passenger aircraft in the Boeing 737 or Airbus A320 class, which make up roughly a third of the current fleet. This concept is denoted as the "D Series," because of its "double-bubble" fuselage cross-section. The other conceptual aircraft, denoted as the "H series," for "Hybrid Wing-Body," is defined for international routes. This latter design, envisioned as a Boeing 777 aircraft replacement, features a triangular-shaped hybrid wing body that blends into the wings. It would accommodate 350 passengers in a multiclass configuration with cargo, and having a range of at least 7000 nautical miles.

The two aircraft concepts are illustrated in Figure 1, with the D Series on the left and the H Series on the right. The bottom of the figure gives information about the estimated aircraft attributes compared against NASA N+3 targets. The red dashed line shows 100 percent for each of the four NASA metrics, meaning that the goal has been met. The other lines are 50 percent and 75 percent of the goals respectively. The points on the solid line show, at the four points of the compass, the calculated aircraft performance for each of the four metrics. The D Series can be seen to have achieved three of the NASA metrics and nearly achieved the fourth (noise). The H Series meets only two of the target goals, but there are substantive gains towards the others. The performance levels achieved by the two configurations are the first major finding from the project.

A more in-depth view, which also provides some context for the changes compared to current aircraft is shown in Figure 2, which presents a schematic of a Boeing 737-800 aircraft (entry into service in 1998) on the left and a D Series aircraft on the right. Each aircraft has three views, a side view, a cross-section of the fuselage, and a top view showing the cabin layout. Both the 737-800 and the D Series are designed for 180 passengers.

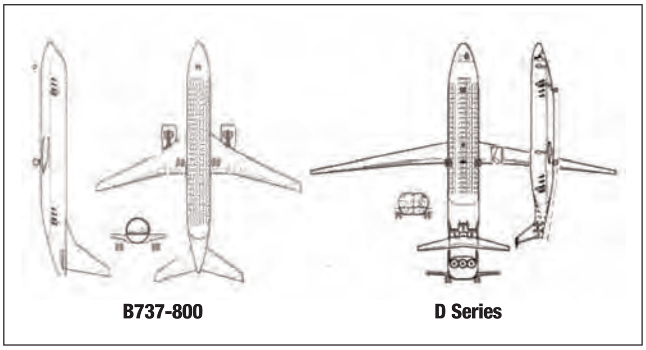

Figure 2: *Schematic of the 737-800 (on left) and D Series aircraft (on right)*

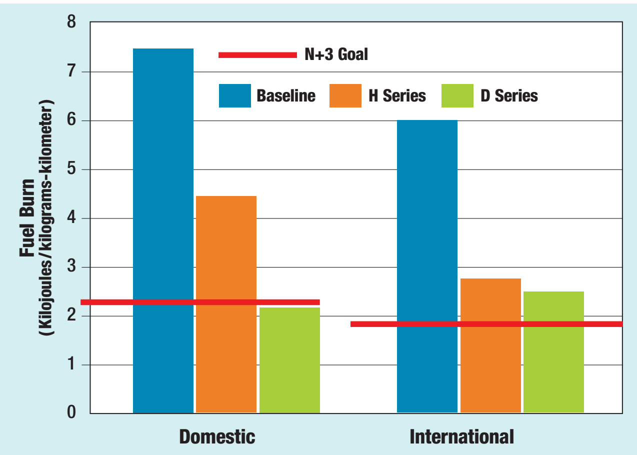

Figure 3: *Fuel burn performance of double-bubble (D Series) and hybrid wing body (H Series) aircraft.*

The D Series aircraft fuselage is shorter and wider than a 737's. It provides roughly 18 percent of the overall lift, whereas the 737 fuselage provides only 6 percent. While both aircraft can be classed as "tube and wing," the D series features a double-bubble (two parallel tubes) fuselage cross-section. The wider fuselage also allows two aisles, a possible time saver for passenger loading and unloading. A D series aircraft has three engines, placed above the aircraft, between the vertical tails. These engines ingest the slower moving (because of viscous effects) fluid from the fuselage boundary layer, providing an advantage from a fuel burn perspective. However the ingestion creates a non-uniform flow into the engines, and the integration of the aircraft and this unconventional propulsion system is one of the technical challenges that needs to be addressed. The D Series flies at a slightly slower (approximately 10 percent) speed than the 737 so that the wings on the former, which have a much higher (29 vs.10) aspect ratio require less sweep back than the latter's. The lower speed also allows numerous other changes that result in a lighter, more efficient aircraft, leading to the 70 percent fuel burn reduction mentioned earlier.

The studies conducted show that the two D and H aircraft configurations behave differently as the range and payload are varied. An example is given in Figure 3, which shows the fuel burn for the conceptual aircraft for the two missions described. The double-bubble exhibits a greater fuel reduction, compared to current aircraft, at the B737 (domestic) payload and range than at the higher payload mission. In contrast the hybrid wing-body achieves its best fuel burn at the B777 payload and range. Even at the larger payload (and aircraft size), however, the double-bubble configuration was found to give essentially the same performance (NASA metrics) as the hybrid-wing body. A second major finding, therefore is that although both configurations gave substantial benefits compared to the baselines, for the aircraft considered the double-bubble configuration exhibits better performance (or equal performance for large payload / range) compared to the hybrid wing-body.

Benefits of (i) Technology and (ii) Configuration

A third result stems from the investigation of specific contributions to the performance of the D8 Series aircraft. The benefits seen in the N+3 aircraft concepts are from two sources. The first is advances in specific technologies, such as stronger and lighter materials, higher efficiency engine components, turbine materials with increased temperature capability. The second is the inherent benefit of the *aircraft configuration*. In other words, even given today's technologies (aluminum wings and fuselage, current technology engines with current bypass ratios, etc.), there is a major performance benefit from the use of the configuration alone.

This finding relating to the benefit of the configuration change is shown in Figure 4, which compares benefits of configuration change with benefits due to advanced technologies for fuel burn, noise, and NO_x (all D Series aircraft meet the takeoff runway length goal). There is a 49 percent reduction in fuel burn compared to the baseline, and a 40 decibels decrease in noise and 52 percent reduction in landing and take-off NO_x relative to current noise and emission certification limits. The technology improvements then bring this number to the total level of improvements implied by Figure 1 (e.g., 70 percent decrease in fuel burn rather than 49 percent). The configuration includes the benefits of boundary layer ingestion on the top surface of the fuselage, a slightly increased engine pressure ratio from the baseline aircraft, and a present day but optimized engine cycle. The significant step change in capability provided by the D Series configuration is perhaps the most important finding of this project. It implies that an aircraft configuration change has the potential to alter the face of commercial aviation. Further, this change could occur on a much shorter time scale than required for maturation of many separate technologies

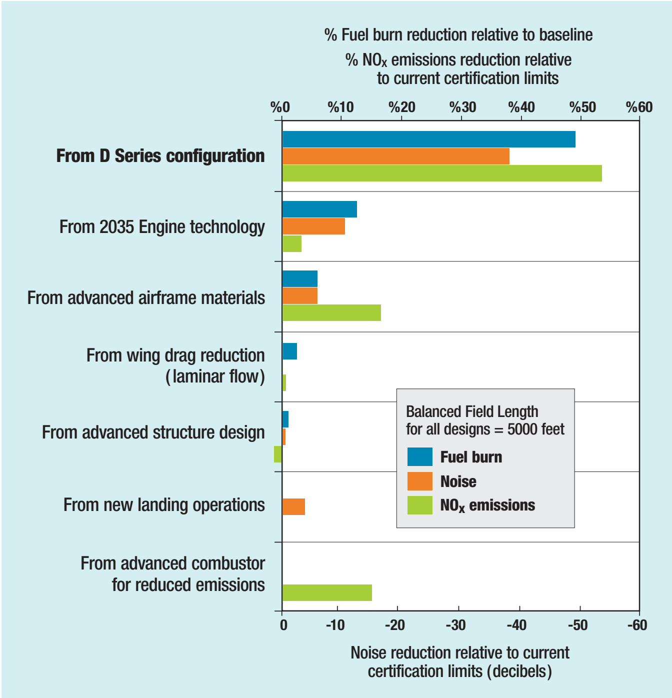

Figure 4: *Benefits to N+3 metrics – configuration change vs. technology advances.*

University-Industry Collaboration

Finally, two aspects of the university-industry collaboration are worth describing. The first was the virtually seamless interaction between the different organizations. The second, enabled by the first, was the strong emphasis on what is perhaps best described as the *primacy of ideas* rather than of organization or hierarchy. In other words, concepts and suggestions were considered directly on merit (e.g. content, strategic value, or impact) rather than the originator of the idea, or the legacy of the idea. From the start of the project, this was emphasized and fostered explicitly in team discussions. The consequence was that the team functioned with open-mindedness to new ideas and, as a direct corollary, a willingness to subject even cherished concepts to in-depth scrutiny. In sum, the goal was to create a team in which “the whole was greater than the sum of the parts” because of strong interactions between participants. The achievement of this goal in an enterprise involving students, staff, faculty, and engineers in industry from a number of fields, with benefits to all parties involved, is also a major finding of the project.

Team Members

Although this article was written by the two authors listed, it cannot be emphasized too strongly that the project was a team effort, with different faculty and staff, as well as engineers from Aurora and Pratt & Whitney, taking the major role on various aspects as called for. In this regard it is appropriate to list the MIT faculty and staff participants — Mark Drela, John Hansman, James Hileman, Robert Liebeck, Choon Tan — and to state that Jeremy Hollman and Wesley Lord were the team leads at Aurora Flight Sciences and Pratt & Whitney, respectively. The analyses and design information described came from all of these, from the students on the project (Chris Dorbian, David Hall, Jonathan Lovegren, Pritesh Mody, Julio Pertuze, and Sho Sato), and from many others at Aurora and Pratt & Whitney.