Aviation & Sustainability

ICAO Goals for Fuel Burn & Emissions

At the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP) 10th Meeting in Montreal, Canada, on February 2016, it was agreed that a process led by Independent Experts (IEs) would be used to conduct an integrated technology goals assessment and review.

The Independent Expert panel was tasked with providing goals for fuel burn, noise, and emissions in the mid-term (2027) and the long-term (2037). The panel was also asked to consider the interdependencies among changes to fuel burn, noise, and emissions. During the independent experts modelling process, it was only possible to consider interdependency between fuel burn and noise. In considering and optimizing for fuel burn, the independent experts used the fuel-burn metric (mass of fuel burned per payload-tonne-kilometre, kg/ATK), but for the final recommended goals, these were converted to be in terms of the CO2 metric value. The optimization for noise used the cumulative noise (in EPNdB) of the three certification points (side-line, fly-over and approach). The IEs considered four classes of aircraft: business jets (BJ), regional jets (RJ), single-aisle aircraft (SA) and twin-aisle (TA). To establish fuel burn, emissions, and noise baselines, reference aircraft were modelled which were chosen to represent the four major in-service categories. Originally, the plan was to use generic (i.e. hypothetical) Technology Reference Aircraft (TRA), which are representative of aircraft in service in 2017, so as to avoid competitive issues. However, to ensure the availability and consistency of input data, the most recently certified aircraft fitting as closely as possible into each class were used as notional references, and these aircraft are listed in Table 1.

TABLE 1: Technology Reference Aircraft Types and Related Operational Aircraft

Aircraft Class	Number of Seats	Notional Aircraft
Business Jet (BJ)	<20	Gulfstream G650ER
Regional Jet (RJ)	20-100	Embraer E190-E2
Single Aisle (SA)	101-210	Airbus A320neo
Twin Aisle (TA)	211-300	Airbus A350-900

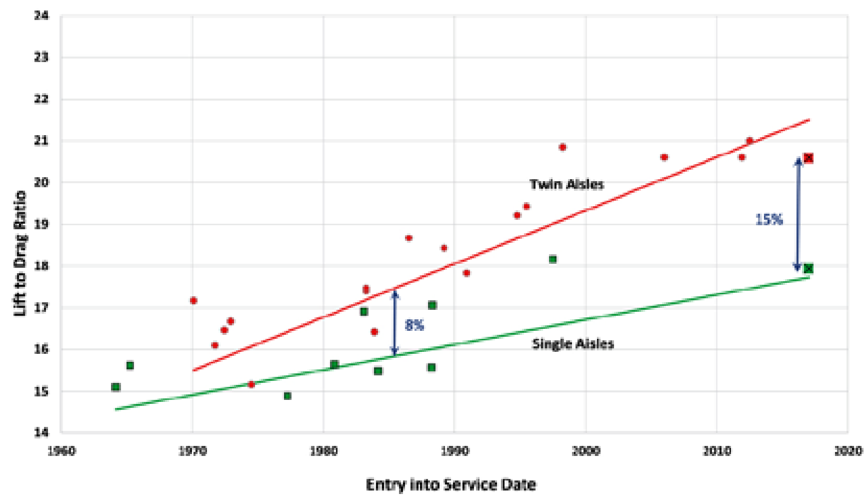
Attention was concentrated on the Single-aisle (SA) and the Twin-aisle (TA) aircraft, which overwhelmingly have the largest environmental impact. It became apparent during the review that the division between RJ and single-aisle aircraft was blurred. The Embraer E190- E2, used for this review, and the Airbus A220 (formerly Bombardier C-series) both carry more than 100 passengers although they are notionally classed as regional jets. Likewise, a large business jet (BJ), like the G650ER, is comparable in size to some smaller RJs, though it is very different in terms of mission.

The counter-rotating open-rotor (CROR) was discussed, but it was considered to have a low probability of being ready for service by 2037 and was not therefore modelled in this review.

Aviation Environmental Impact Overview

For climate change, the primary concerns are emissions of Carbon dioxide (CO_2), Nitrogen oxides (NO_x) and non-volatile particulate matter (nvPM). Also of concern are persistent contrails which lead to cirrus clouds when the atmosphere is icesupersaturated. A significant complication arises because the emissions (or their subsequent transformations) have quite different residence times in the atmosphere. They also have quite different values of radiative forcing, which is a measure of the associated heating or cooling effect. It is the combination of a number of factors which determine overall impact on global surface temperature over a given timescale. These factors are: quantities emitted, residence time, radiative forcing, and the temperature response profile of a particular pollutant. CO2 is of particular concern because of its exceptionally long residence time (thousands of years). The radiative forcing value for aircraft NOx per unit emission is now thought to be lower than the two previous Independent Expert NOx reviews, but it remains of concern. Although nvPM is implicated in cloud formation, the processes are less well understood. Contrails, leading to cirrus clouds and aircraft induced cloudiness, have large Radiative Forcing (RF) impacts but are short lived (hours). There is high confidence in the estimates of global warming due to CO2 whereas for all other emissions there is a significant level of uncertainty which needs to be reduced.

FIGURE 1: Historical Trend in Lift-to-Drag Ratio

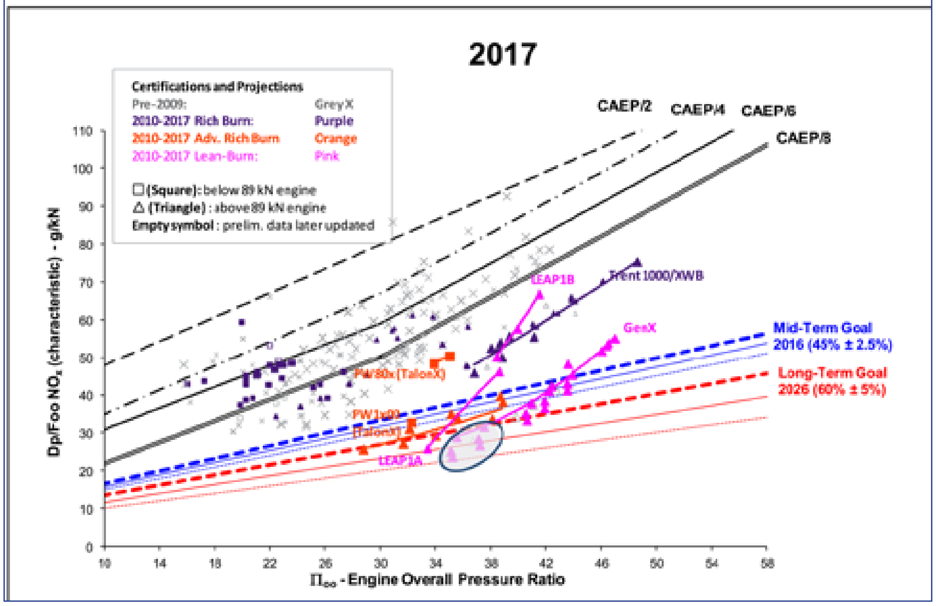


Technology Based Reduction Potential

Fuel burn is considered here for the two aircraft classes that burn the largest proportion of fuel, the single-aisle and twin-aisle. The discussion is separated into airframe and engines, with the airframe section itself being divided into aerodynamics and mass (often referred to as weight).

Airframe: A useful measure of aerodynamic performance of an aircraft is the lift-drag ratio, L/D. Historical data for L/D is shown in Figure 1 where trend lines have been drawn through the values for the single-aisle and TA. The L/D ratio is higher for longrange twin-aisle aircraft than for the shorter-range single-aisle aircraft. In both cases, the L/D has increased with time, but the average rate of improvement for the twin-aisle is about twice that for the SA. An important piece of information relating to the difference between the two aircraft sizes comes from the mid-1980s, when both Airbus and Boeing were building single-aisle and twin-aisle aircraft; because this was going on at the same time the technology level of the two aircraft classes was broadly the same. At that time, L/D was about 8% higher for the TA, and this difference is believed to be mainly because of different design and missions for the single-aisle and TA, each with the same level of technology. The IEs had the technology reference aircraft listed in Table 1 for 2017. The L/D for the twin-aisle in this case is about 15% higher than the SA, implying a relative slippage of about 7%. As Figure 1 shows, the aerodynamic performance of the airframe (characterized by lift/drag ratio) for a single-aisle aircraft, such as B737 and A320, has improved over the past four decades by approximately half as much as the larger twin-aisle aircraft. A significant part of this difference is believed to be because the B737 and A320 have their origins far in the past, with improvements in their airframe technology being incremental. Incremental change does not allow the gains possible for an all-new aircraft from a full basket of new technologies. The aerodynamic performance can be improved by the use of laminar

FIGURE 2: LTO NOx Levels as a Function of OPR. Points Refer to Engine Certification Levels

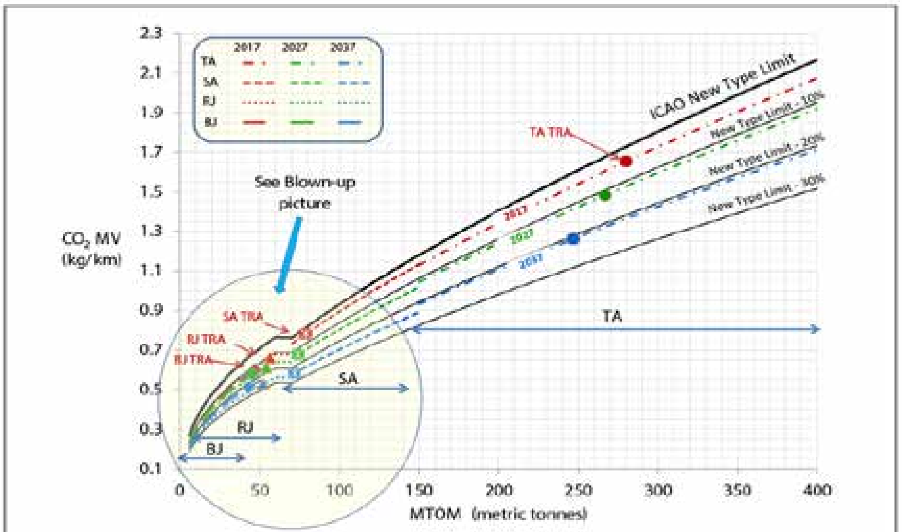


flow: natural laminar flow for smaller aircraft, which usually fly slower and have less sweep, and hybrid laminar flow (requiring suction) for the twin-aisle aircraft. The use of laminar flow technology on wings has primarily been held back due to manufacturing and operational considerations and challenges. Evidence provided by the International Coordinating Council of Aerospace Industries Associations (ICCAIA) suggests that reasonable goals for aircraft aerodynamics, adopting a basket of technologies, including laminar flow, are between 3% and 4% total draft reduction for single-aisle and twin-aisle aircraft by 2027 and between 8% and 10% by 2037. Based on the slower rate of historical improvement for the single aisle, the IE review panel have assumed that a wholly new airframe for the single-aisle size of aircraft will be able to improve the aircraft aerodynamic performance over and above the incremental improvements quoted by ICCAIA. In modelling the performance of the single-aisle aircraft, it was therefore assumed that there would be all-new airframes for this class by 2037. Based on this evidence, the total drag for the single-aisle aircraft was lowered by an additional 3% by 2027 and 7% by 2037, beyond the reduction from the new technologies presented by ICCAIA. There is now some evidence that the values of L/D for the twin-aisle aircraft may be approaching an asymptote (the value depending on materials properties and cost, as well as aerodynamic design). To get further significant improvements in L/D for the twin-aisle aircraft may require a switch to a non-conventional configuration (i.e. other than tube and wing) or to exploit the benefits of composites to increase wing span requiring increase to airport gate widths. Reducing aircraft empty mass is vital. Improved metals and metal construction is available, but the use of composites is generally favored for structural components for all new designs. From information provided by ICCAIA, potential overall mass savings with metal are in the range 5±2%. With advanced composites, possible savings of 8±2% for the single-aisle and 4±2% for the twin-aisle aircraft. There are other mass reduction technologies under consideration that could yield savings around 2.5% for small aircraft and 4% for large. Overall, for the purpose of setting fuel burn goals, the empty mass savings are in the range 2-4% for 2027 and 8-10% for 2037.

Engines

For engines, the overall efficiency is conveniently separated into propulsive efficiency, which depends only on the fan pressure ratio (FPR), and the thermal efficiency, which depends on the overall pressure ratio (OPR) and the turbine entry temperature. In addition, there is a strong dependence of overall engine efficiency on the component efficiencies of the fan, compression system, and turbines. OPR itself is limited by compressor delivery temperature at take-off and is unlikely to exceed 60. Turbine entry temperature is limited by available materials and airfoil cooling technology but is unlikely to increase significantly from the best current values since increased cooling air requirements reduce efficiency. Further improvements in thermal efficiency will require a combined approach, including incremental increases in OPR and turbine entry temperature, coupled with a continued increase in compressor and turbine efficiencies. Increasing, or even maintaining, compressor and turbine efficiencies becomes more important, but also more difficult, as OPR rises because of the reduction in core size. Fan pressure ratio has been reduced in recent years to yield significant reductions in fuel burn and noise. As FPR is reduced, the diameter of the fan must increase to produce the same thrust. With the increase in diameter comes an increase in power plant mass

FIGURE 8: CO_2MV versus MTOM and Percentage Reductions from the "New Types" Level



Points show Optimization for Nominal Confidence at the 50% fuel-burn/50% noise weighting, Performed at R_1 for 2017 TRA.

and drag, as well as growing issues with power plant-airframe integration. The larger diameter fan rotates more slowly and therefore makes the design of the low-pressure turbine (LPT) more difficult. Some amelioration of the integration issues comes with the insertion of a gearbox between the fan and the LP turbine. The selection of optimum FPR therefore requires the integration issues to be taken into account, particularly the increased drag and mass. For 2027, the potential fuel burn reductions attributable to the new propulsion technologies have been preliminarily estimated to be about 5% for single-aisle and about 6% for twin-aisle aircraft. For 2037, an extra 5% fuel burn reduction might be obtained. These numbers include gains in the propulsive efficiency, mass and drag, derived from all new propulsion technologies. These estimates exclude benefits from possible new nacelle technologies and improved propulsion system/airframe integration for which no information was available

Engine Emissions: Status and Reduction

Emissions from combustion of aviation fuel affect human health and welfare through degraded air quality as well as through climate change. Under all reasonable scenarios of technology change and aviation growth, total fleet fuel burn and the mass of NOx emissions are expected to continue to rise. Aircraft are unique in that they emit emissions that change air quality, both while on or near the ground and during cruise. At cruise altitudes, the emissions undergo chemical and physical transformations. The climate impact of NOx emissions is still thought to be significant relative to CO2, though less than in previous IE reviews. Some studies note that there is also the potential for aircraft emissions emitted at cruise altitudes to reduce surface air quality and affect human health. Historically, the focus has been on the landing and take-off (LTO) cycle, when aircraft are at their closest to populations around airports, with concentrations falling off rapidly with increasing distance from the airport. Nitrogen dioxide (NO2) from NOx emissions, and its photochemical derivative, ozone (O3), are identified as harmful to human health, though quantification of this is unreliable. More recently, attention has been directed at non-volatile particulate matter (nvPM), and of particular concern are ultrafine particles, less than 100 nano-metres, which is the particle size produced by aircraft combustors. Previously 'smoke' was a major concern, and standards are based on opacity measurements. In addition, NOx and oxides of sulfur (SOx) are precursors of secondary volatile PM formation, which takes place over considerable distances away from the source. The contributions to local concentrations of pollutants from LTO operations are higher than the contributions from cruise, but the numbers of people affected are relatively small. For emissions from higher altitudes, the increase in concentration at the surface is much smaller than for LTO but much larger numbers of people are potentially affected. The LTO levels of NOx plotted in the conventional way against engine OPR is depicted in Figure 2. Lines are shown for the certification levels and for the goals set by an earlier Independent Expert review. The current LTO based NOx goals set by Independent Experts for 2016 (mid-term) and 2026 (long-term) have both already been met. However, the engines which meet the goals are de-rated versions within an engine family. It should be noted that an engine operating at de-rated condition has poor fuel consumption and large weight in relation to thrust and would be uncompetitive. In most cases, higher power versions in the same family perform relatively poorly for emissions against the same LTO goals. A major cause is the increase in allowable turbine entry temperature used to promote higher engine efficiency and lower CO2 emission. The turbine entry temperatures are now reaching levels at which NOx formation becomes unavoidable and significant. At sufficiently high temperature, the NOx formation process is essentially independent of the technology to control the main combustion process itself, and is not dependent solely upon the OPR on which the current LTO goals and regulation for NOx are based. This results in a wide variation in performance of similar technology engines against the current LTO NOx metric. A new way to characterize NOx emissions needs to be found which accounts for the turbine entry temperature effect. This is of particular importance given the concern regarding NOx emitted at altitude. Looking at future NOx technology, the IEs believe that as a result of the turbine entry temperature increases, the NOx emissions from combustors with the best technology appear to be approaching an asymptotic value, with no step change envisaged during the goals timescale. In terms of goal setting, significant improvements in the best NOx levels set against the current LTO metric are not anticipated, although there are expected to be improvements in the general NOx levels across the range of engines. The IEs noted that full-flight NOx emissions per available seat kilometer across the fleet are not reducing significantly. The steps to reduce fuel burn, such as increasing OPR, have generally led to higher emissions of NOx which still meet the current LTO NOx standards and goals. The IEs propose the setting of a 2027 mid-term LTO-based NOx goal at the level of 54% below CAEP/8, which is 6% below the current 2026 goal-meeting level, with tightened criteria to be defined when the goal is met. The goal applies to all aircraft classes. The IEs recommend that CAEP consider carrying out urgent work to study two emission-related issues in particular. One is an assessment whether there is evidence of health impacts from aircraft-produced NOx both near the airport and at cruise. The other is the development of a method to allow a future review to set full-flight based NOx goals. On this basis, a goal for 2037 may be considered having in mind the interdependency with CO2 emissions and cost. The IEs were aware of the concerns regarding health impacts of nvPM, with increasing evidence of the harmfulness of ultrafine particles (smaller than 100 nm). It also appears that the particles emitted by aircraft engines are ultrafine, with the number of particles peaking at about 60 nm. Regulation is being considered for the much larger nvPM2.5 particles (2.5 mm which is 2500 nm). Fortunately, the new technologies directed at reducing NOx, which are currently entering service appear, initially, to offer an order of magnitude reduction in nvPM mass and number compared to most in-service engines. However, industry experts advise that early difficulties in service (making the combustors work stably and with adequate longevity) are likely to result in trade-offs between nvPM and NOx emissions at higher OPRs and turbine entry temperature. As a result, development issues with lean-burn and advanced rich-burn may not result in the full order of magnitude reduction in nvPM being achieved, though reductions are still expected to be substantial. Given the lack of data, the lack of technologies to reduce nvPM directly, and the prospective step reduction in nvPM emissions from recent combustors designed to reduce NOx, the IEs considered that the setting of nvPM goals at this time appears neither practical nor appropriate. Once technical data becomes available and climate and air quality impacts are better understood, there may be merit in setting goals for nvPM. FIP

TABLE 2: Fuel Burn Metric (FB/ATK) at Two Ranges for the Four TRAs in 2017.

	BJ	RJ	SA	TA
Design range	0.632	0.158	0.147	0.190
R_1 Range	0.343	0.146	0.125	0.126

TABLE 4: Current Fuel Burn Goals Compared to Prior Goals

Goals from 2010 IE Review

Year	SA	STA
2020	1.70%	1.43%
2030	1.38%	1.43%

Goals from Current Review

Year	BJ	RJ	SA	TA
2027	0.42%	0.77%	1.26%	1.04%
2037	0.71%	1.03%	1.22%	1.28%

This Article is based on the material from The ICAO Environmental Report 2019, Chapter One: Aviation and the Environment: Outlook By Prof. Nick Cumpsty (Imperial College, London), Prof. Dimitri Mavris (Georgia Tech University) and Dr. Michelle Kirby (Georgia Tech University)