Aviation and the Environment: Outlook

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BACKGROUND

Growth in air travel is having an increasing environmental impact. Concerns about climate change are also increasing, and aviation is expected to contain the growth of its carbon footprint in the context of the global efforts to reduce CO_2 emissions. Reactions to aircraft noise still exist around many world airports, and there is growing concern about local air quality with an increased emphasis on small particles from engine combustion, referred to here as non-volatile Particulate Matter (nvPM).

At the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP) 10th Meeting in Montreal, Canada, in 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. That review process is described below. It was agreed that this review would be conducted for subsonic aircraft at an engine level, providing assessment of engine technology, including both non-volatile Particulate Matter (nvPM) and oxides of nitrogen (NO_x), and at an aircraft level, providing an assessment of aircraft fuel efficiency and noise technologies. It was also agreed that this review would consider progress relative to current ICAO Standards and goals. This article describes the process of the Integrated Review, summarizes the evidence, and presents the goals and recommendations. Extensive evidence was taken from industry, relevant scientists and engineers, and published reports and papers.

The panel consisted of 15 Independent Experts nominated by seven CAEP Member States (i.e., Brazil, Canada, France, Russia, Sweden, United Kingdom and United States), and two CAEP Observers from International Organizations, specifically the European Commission and the International Coalition for Sustainable Aviation (ICSA)[1]. The full report is available through ICAO[2].

PRECEDING IE REVIEWS, STANDARDS AND GOALS

ICAO Standards have been set to follow the latest available technology in order to prevent backsliding. This has given rise to the need to have a separate set of technology goals, to guide subsequent regulations, and to which industry and ICAO may aspire. The goals defined by present Independent Experts need to be "challenging but achievable", which is the same definition as that adopted by previous groups of Independent Experts established by ICAO CAEP. This section provides an overview of the current standards for noise, emissions, and fuel burn.

1 The IE Panel consisted of the following, with their nominator in parenthesis: Juan Alonso (ICSA), Fernando Catalano (Brazil), Nick Cumpsty (UK) Co-chair, Chris Eyers (EC), Marius Goutines (France), Tomas Grönstedt (Sweden), Jim Hileman (USA), Alain Joselzon (France), Iurii Khaletskii (Russia), Dimitri Mavris (USA) Co-chair, Frank Ogilvie (UK), Malcolm Ralph (UK), Jayant Sabnis (USA), Richard Wahls (USA), David Zingg (Canada).

2 ICAO Doc 10127, Independent Expert Integrated Technology Goals Assessment and Review for Engines and Aircraft, ICAO, 2019.

Noise from large aircraft was the first environmental impact to be regulated at an international level by ICAO, with the adoption in 1971 of Annex 16 to the Convention on International Aviation (Chicago Convention). Since then, the regulation has been made more stringent in subsequent cycles, most recently as Chapter 14 in 2014. The two previous Independent Expert noise reviews, reporting in 2010 and 2014, set goals for 10 and 20 years forward from their respective dates.

The first ICAO certification standard for engine emissions was adopted in 1981, with requirements for fuel venting, smoke, unburned hydrocarbons (UHC), carbon monoxide (CO), and NO_x (oxides of nitrogen). The regulated level of NO_x emission emitted over the landing and take-off cycle is allowed to increase in proportion to the engine overall pressure ratio. The original ICAO standard has been followed by a gradual increase in stringency, principally for NO_x, and new levels were defined most recently in 2010 at CAEP/8. The two previous Independent Expert reviews of NO_x emissions, reporting in 2008 and 2010, set goals 10 and 20 years forward from their respective dates. The goals for NO_x produced in the landing and take-off cycle were expressed on the same principle as the regulations and retained the proportionality to overall pressure ratio. More recently in March 2017, the ICAO Council adopted its first ever nvPM engine emissions standard, which will apply to turbofan and turbojet engines.

The Independent Expert review of fuel burn reduction technology reported in 2011. At the time, there was no standard for fuel burn, but goals were established for the single aisle (SA) and twin aisle (TA) aircraft with three different technology scenarios: TS1 ‘continuation of current trend’, TS2 ‘increased pressure’, and TS3 ‘further increased pressure’. These goals were in terms of the fuel-burn metric (mass of fuel burned per payload-tonne-kilometre, kg/ATK). In March 2017, the ICAO Council adopted the ICAO Aeroplane CO_2 Standard that will apply primarily to new aircraft type designs from 2020, and to aircraft type designs already in-production as of 2023. There is no direct read-across from 2011 fuel-burn metric to the current CO_2 standard.

The second review of noise technology carried out by Independent Experts drew attention to the interdependency between noise and fuel burn. Since the advent of the jet engine, the steps to increase efficiency have generally led to a reduction in noise, mainly by reducing the jet velocity. The jet noise now is no longer dominant, so this linkage is no longer obviously present. This raises the question as to whether noise and fuel burn will both decrease in the future or could attempts to reduce one, for example fuel-burn, lead to an increase in noise? Additionally, it has been known for many years that increasing the overall pressure ratio (OPR) of the engine leads to an increase in the emissions of NO_x, such that the regulations have been formulated so that more NO_x may be emitted as OPR is increased. Increasing OPR has been associated with more efficient engines and a reduction in fuel burn. Could the increase in pressure to reduce fuel burn lead to increased NO_x? Or could the technology to limit NO_x lead to higher fuel burn than the minimum possible? The above important questions are the underlying basis for the current review.

INTRODUCTION

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 IE modelling process, it was only possible to consider interdependency between fuel burn and noise. In considering and optimizing for fuel burn, the IEs 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 CO_2 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. 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 SA 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.

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

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 CO_2, NO_x and nvPM. Also of concern are persistent contrails which lead to cirrus clouds when the atmosphere is ice-supersaturated. 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. CO_2 is of particular concern because of its exceptionally long residence time (thousands of years). The radiative forcing value for aircraft NO_x per unit emission is now thought to be lower than the two previous Independent Expert NO_x 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 RF impacts but are short lived (hours). There is high confidence in the estimates of global warming due to CO_2 whereas for all other emissions there is a significant level of uncertainty which needs to be reduced.

TECHNOLOGY REDUCTION POTENTIAL

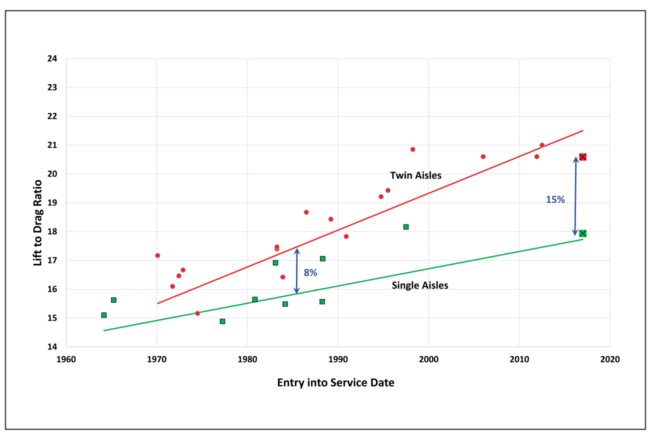
Fuel Burn Reductions

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 SA and TA. The L/D ratio is higher for long-range TA aircraft than for the shorter-range SA aircraft. In both cases, the L/D has increased with time, but the average rate of improvement for the TA 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 each

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



building SA and TA 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 SA 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 TA 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 SA aircraft, such as B737 and A320, has improved over the past four decades by approximately half as much as the larger TA 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 flow: natural laminar flow for smaller aircraft, which usually fly slower and have less sweep, and hybrid laminar flow (requiring suction) for the TA 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 SA and TA aircraft by 2027 and between 8% and 10% by 2037. Based on the slower rate of historical improvement for the SA, the IE review panel have assumed that a wholly new airframe for the SA 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 SA 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 SA 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 TA 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 TA 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 SA and 4±2% for the TA 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 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 SA and about 6% for TA aircraft. For 2037, an extra 5% fuel burn reduction might be obtained. These numbers include gains in thermo-propulsive efficiency, and 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.

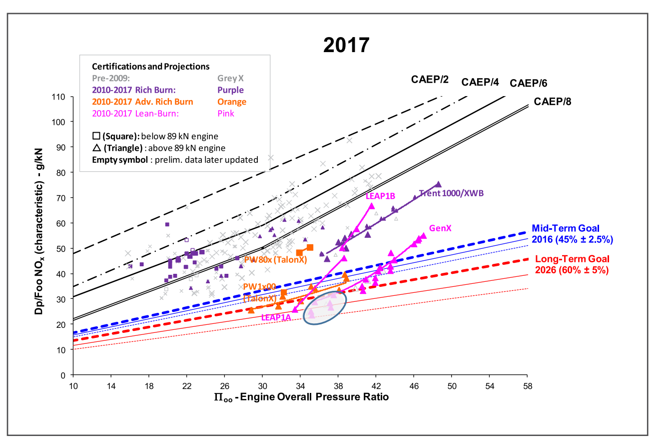
Engine Emissions: Status and Reduction

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 NO_x 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 NO_x emissions is still thought to be significant relative to CO_2, 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 (NO_2) from NO_x emissions, and its photochemical derivative, ozone (O_3), 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, NO_x and oxides of sulfur (SO_x) 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 NO_x 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 NO_x 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 CO_2 emission. The turbine entry temperatures are now reaching levels at which NO_x formation becomes unavoidable and significant. At sufficiently high temperature, the NO_x formation process is essentially independent of the

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



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 NO_x are based. This results in a wide variation in performance of similar technology engines against the current LTO NO_x metric. A new way to characterize NO_x emissions needs to be found which accounts for the turbine entry temperature effect. This is of particular importance given the concern regarding NO_x emitted at altitude.

Looking at future NO_x technology, the IEs believe that as a result of the turbine entry temperature increases, the NO_x 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 NO_x levels set against the current LTO metric are not anticipated, although there are expected to be improvements in the general NO_x levels across the range of engines.

The IEs noted that full-flight NO_x 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 NO_x which still meet the current LTO NO_x standards and goals. The IEs propose the setting of a 2027 mid-term LTO-based NO_x 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 NO_x 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 NO_x goals. On this basis, a goal for 2037 may be considered having in mind the interdependency with CO_2 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 $nvPM_{2.5}$ particles (2.5 mm which is 2500 nm). Fortunately, the new technologies directed at reducing NO_x, 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 NO_x 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 NO_x, 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.

Aircraft Noise: Status and Reduction

Aircraft noise has a unique impact, as no other noise sources fly over where people live. The findings of the CAEP/10 ISG study[3] on the effects of aircraft noise were reviewed. The CAEP/10 trends assessment showed tens of millions of people affected by aircraft noise at the 55 dB day-night level (DNL), with these figures expected to rise significantly, even under the most optimistic technology scenarios. The studies covered community annoyance, children's learning, sleep disturbance, and health effects. The number of people affected may also rise because, historically, noise reductions have come as a result of technology principally aimed at reducing fuel burn by reducing jet velocity. Because jet noise is no longer the major source for larger aircraft, the historical trend is thought to no longer apply. The reverse situation where significant fuel burn potential might possibly be sacrificed in the pursuit of lower noise is unlikely, given the concerns over CO_2 and to a lesser extent NO_x.

Compared with the past, noise from recent new aircraft is characterized today by a significant change in the relative

3 https://www.icao.int/environmental-protection/Documents/ICAO%20Environmental%20Report%202016.pdf, pages 30 to 37

FIGURE 3: Noise Source Breakdown for a Modern Twin-Aisle Aircraft

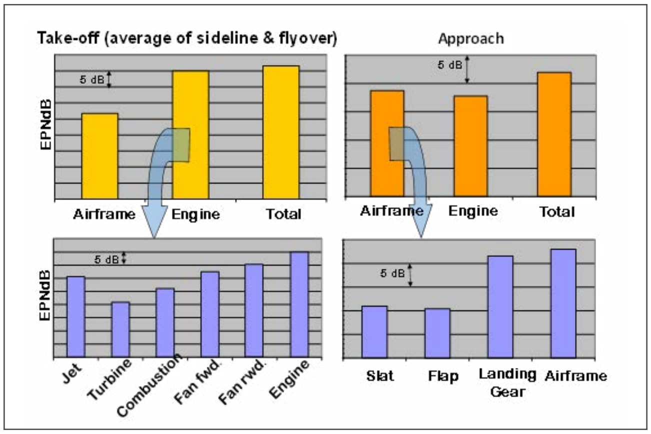
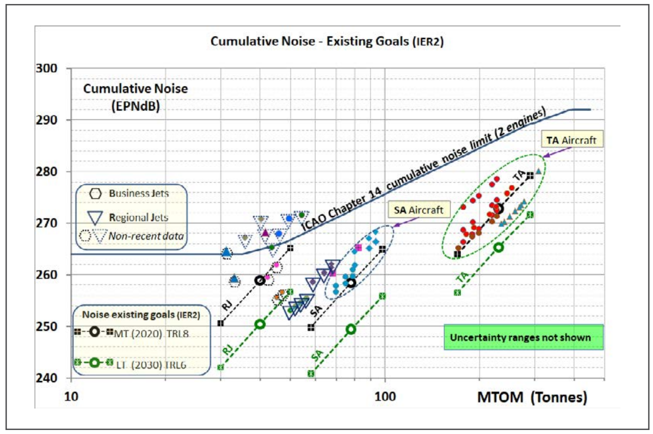


FIGURE 4: Prior IER2 Technology Goals and Recently Certified Noise Levels



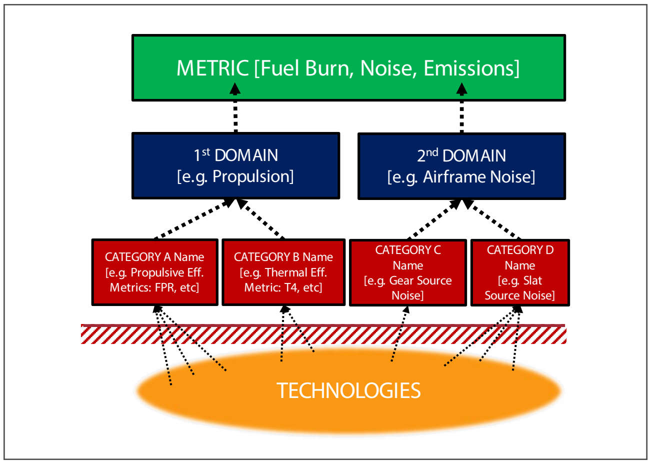
importance of engine and airframe noise sources. Figure 3 shows the current noise breakdown for a modern TA aircraft. For take-off, the engine is the largest contributor to noise, with the fan being the major component and jet noise some 5dB lower. For approach, the airframe noise dominates with the landing gear making the largest contribution. The jet noise is low because the fan pressure ratio has been reduced, thereby reducing jet velocity and increasing propulsive efficiency. The lower fan pressure ratio means that the engines have a larger diameter and specific features of design, including engine integration, aerodynamics, mass, and interaction effects become more important, leading to an increase in the level of interdependence. Furthermore, because jet noise is no longer dominant, basing noise levels on parameters such as bypass ratio, as in previous IE reviews, is no longer appropriate.

Today's new aircraft are meeting the existing mid-term noise goals with some margins. Figure 4 compares recently certificated cumulative aircraft noise with current 2020 and 2030 noise goals established by CAEP/9 (early 2013), following recommendations of the second Independent Expert Noise Review (IER2). The certification cumulative noise in EPNdB is shown versus maximum take-off mass for the four categories of aircraft considered (i.e., business jets-BJ, regional jets-RJ, single-aisle-SA, and twin-aisle-TA). In all cases, the recent noise levels are well below the ICAO Chapter 14 noise regulatory level. Because there is significant scatter within these classes, and there is no recent BJ data, older data is also shown for these types. Some of these do not meet ICAO Chapter 14 noise limits, and by some margin they do not meet the RJ goals set by IER2. The scope and potential remaining for further technology-based reductions in noise within conventional aircraft configurations are limited; although reduced speeds, particularly fan speed, will lead to some reductions. To achieve these, attention should focus particularly on acoustic wall liners in the power plant, noise from the fan, and airframe noise. In addition, consideration should be given to potential noise reduction from novel configurations of aircraft, as opposed to the existing "tube and wing" design.

MODELLING APPROACH AND RESULTS

The plan for the IE review was to perform modelling and from this, determine goals and interdependencies for fuel burn, noise, and emissions. The modelling used for the study is the Environmental Design Space (EDS), a modelling and simulation environment developed in Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology. EDS has been widely used on conventional aircraft-engine vehicles and also used to assess unconventional aircraft and propulsion systems in support of the NASA and FAA advanced aeronautics programs. The majority of the EDS analysis components are NASA developed programs. The foundations for the EDS systems analysis capability are advanced methods developed at ASDL, coupled with integrated aircraft modelling and simulation. While EDS is capable of predicting the fuel burn, NO_x emissions and noise metrics, it became apparent that the model for emissions of NO_x in EDS is

FIGURE 5: IE Integrated Review Taxonomy.



heavily dependent on available NOx correlation equations. In order to predict NO_x for advanced combustors under consideration, specific NOx correlation is needed, which is not available for the study. The model in EDS was therefore unable to allow goals or interdependencies in NO_x to be determined, and only the goals and the interdependencies for fuel burn and noise were obtained from the EDS model.

Because of time constraints and because detailed technology information is proprietary, the interdependencies, which would be explored, were limited to those associated with design parameters with a fixed set of projected technology basket impacts defined at the base of a technology taxonomy. The taxonomy that was adopted for describing the process and the findings of the modelling are illustrated in Figure 5. The technology baskets were defined as three point estimates based on the technology categories: high (80%) confidence, nominal (50%) confidence and low (20%) confidence. The confidence levels applied to the categories, such as an improvement in thermal efficiency. This was done for the mid- and long-term, based on the category levels. Examples of categories are: reductions in component mass, drag, and component noise sources. For baskets with technologies of a given confidence level, the design parameter interdependencies were explored; examples of this are wing loading, aspect ratio, and fan pressure ratio.

Information on the potential new technologies was provided by International Coordinating Council of Aerospace Industries (ICCAIA), research organizations, the IEs, and others. Technologies were provided with Technology Readiness Level (TRL) values with TRL8 achieved when an aircraft is flight qualified ready to enter service. The aircraft and its technologies for the goals covered in this review were required to be at TRL8 in 2027 for mid-term (MT) and at 2037 for the long-term (LT). On the basis of past experience, it is assumed in this review that there will normally be a seven-years gap between TRL 6 and 8. Therefore, to achieve TRL8 on the goal dates, the technology should be at least TRL6 by 2020 and 2030, respectively. Likewise, the technologies on the current Technology Reference Aircraft (TRA), listed previously in Table 1, were assumed to have been at, or close to, TRL 5 or 6 around 2010. For each technology, a benefit was assigned; for example, the wing mass might be reduced by 2% using a new technology at TRL6 in 2020. Although this suggests that it *could* be brought into service by 2027, it does not mean that it *will* be. Consequently, likelihood bands were established by industry to indicate their assessment of the chances of it being used, and the fraction of the potential benefit being achieved and these estimates were adopted by the IEs.

The EDS model was run for the four classes of aircraft, though only the SA and TA aircraft are discussed here. The mission was computed at the R1 range (maximum range at maximum payload) to optimize performance. The input data consisted of various input parameters such as wing loading and fan pressure ratio; and technology parameters, like drag, empty weight, and compressor efficiency. The technologies were quoted for 2027 and 2037 at the three confidence levels of: high (80%), nominal (50%), and low (20%). The starting point for the modelling of new design parameters and new technologies was the technology reference aircraft (TRA) in 2017 for each class. Optimization was performed for a weighting factor of noise (cumulative EPNdB) and fuel-burn metric in steps of 10%, from all-noise to all-fuel burn.

Figure 6 shows the Pareto plots[4] for the SA aircraft and Figure 7 presents the Pareto plots for the TA aircraft, with the ordinate being the cumulative EPNdB, and the abscissa is the fuel-burn metric (kg-fuel per available tonne-kilometer). The fronts are for the high, nominal and low confidence in 2027 and 2037. For each front, the

4 https://en.wikipedia.org/wiki/Pareto_efficiency

FIGURE 6: Single Aisle Pareto Fronts

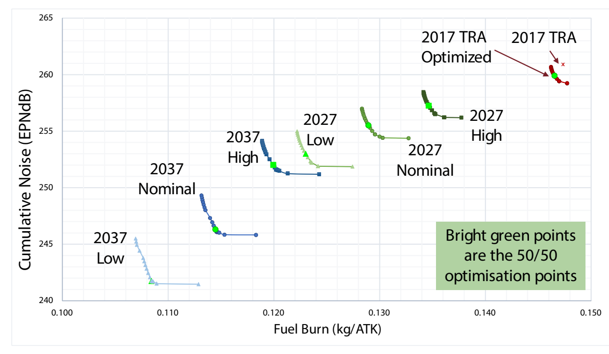
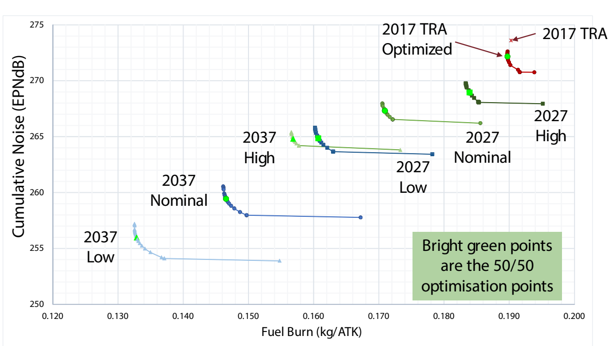


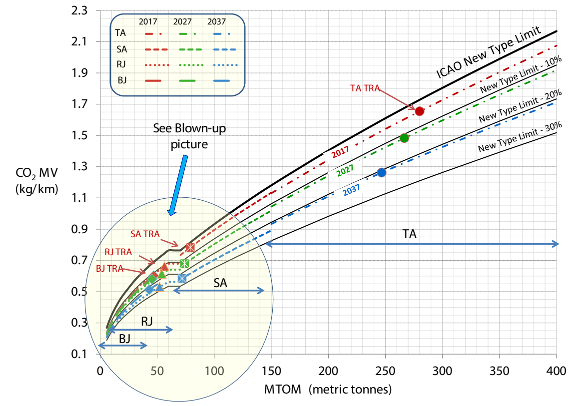
FIGURE 7: Twin Aisle Pareto Fronts



points correspond to different weightings for noise and for fuel-burn in the optimization; so the point on each front furthest to the right corresponds to an optimization for lowest noise whilst the highest point on each front corresponds to an optimization for lowest fuel-burn. The points along the front correspond to changes in the balance of optimization and the green dots correspond to equal weight in the optimization for noise and fuel-burn. It is apparent that this 50% noise/50% fuel-burn optimization gives a reasonable balance of benefits for noise and for fuel-burn and this optimization is used to form the goals.

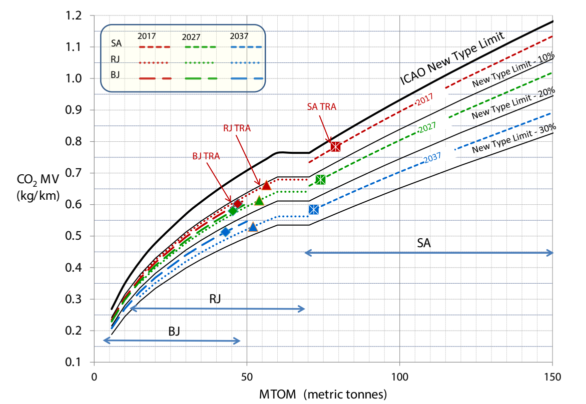
To allow improvements attributable to the use of new design parameters and technologies in 2027 and 2037 to be expressed in a consistent manner, the same EDS optimization method was applied to the technology reference aircraft of 2017, varying design parameters but holding technology constant. These 2017 TRA optimized Pareto fronts are shown in the top right corner as red curve of each figure and is closest to result for the TRA (with the given parameters and technologies).

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.

FIGURE 9: CO_2MV versus MTOM and Percentage Reductions from the "New Types" Level

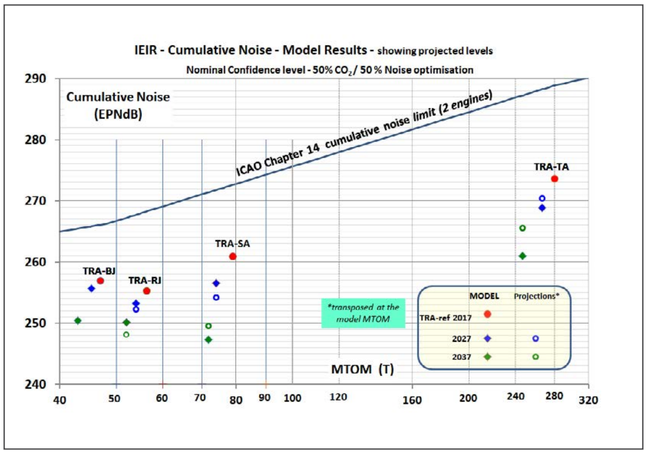


Points show Optimization for Nominal Confidence at the 50% fuel-burn/50% noise weighting, Performed at R_1 for 2017 TRA.

The goals have been created on the basis of nominal confidence, highlighted as the bright green points in each figure. Based on the selection of the 50% noise/50% fuel-burn weighting, the fuel burn metric was obtained. The fuel burn metric was then translated to the current ICAO CO_2 Standard for the goal setting and these are shown in Figure 8 as the CO_2 metric versus aircraft maximum take-off mass, MTOM. The heavy black line is the recently adopted ICAO CAEP/10 regulatory level for new types and the lighter black lines give notional reductions in the CO_2 metric of 10, 20 and 30%. The red points correspond to the 2017 TRA, whilst the green are the 2027 goals and the blue the 2037 goals. Figure 9 is a zoomed-in part of Figure 8 for lower MTOM and shows the BJ, RJ and SA aircraft classes. The dashed lines represent the final goal recommendations by the IEs.

The cumulative noise from the optimization process (50% noise/50% fuel-burn weighting) are shown as solid symbols in Figure 10: red shows the 2017 TRA, blue the 2027 goals and green the 2037 goals. Also shown, as open symbols, are projected goals derived from goals of the second IE noise review, IER2. In general, the agreement between the projections and the model are good. In all cases there is a large margin to the Chapter 14 regulatory line.

FIGURE 10: Noise Projections and Modelled Results versus Take-off Mass



RESULTS AND GOALS

Aviation Environmental Impact Overview

Air quality and health impacts

1. Better understanding of the effects, if any, of low-concentration NO_x engine emissions on human health is required; during both LTO and cruise phases of flight.
2. The nature of the particulates emitted by engines in terms of size, number, and composition, under different conditions while near the ground needs to be understood and quantified, as does their impact on human health.
3. Further evidence is needed about the effects of NO_x and sulfur oxides at altitude in creating particulates at ground level; this needs to include the process of formation, the regions of geographical concentration, and the health impacts.

Emissions and climate change

1. A new and robust consensus is needed on the climate change impacts, both present and future, of all aircraft emissions, both in absolute terms, and in relative terms, compared with other sources. For rational decisions to be made, the impacts are required over longer time spans than those presented to-date.
2. Contrails and the formation of related cloudiness make a large potential contribution to aviation radiative forcing but are still subject to large uncertainty with respect to their behavior and their radiative forcing. The potential to mitigate the effect of contrails by small alterations in aircraft flight paths or altitudes should be further investigated.

Aircraft Fuel Burn and CO_2 Reduction

1. Because fuel burn is a key industry competitive parameter, any review tends to be hampered by limited publicly available information. For this review, the IEs had to construct proxy Technology Reference Aircraft. With the future availability of certification values using the CO_2 metric system, a future review looking at actual fuel burn estimates can be conducted with a more solid foundation.
2. The evidence presented to the IE Panel convinced members that one reason that the single-aisle aircraft lift/drag ratio had improved more slowly than for the twin-aisle aircraft was that the airframes of the former were substantially older and had not had the benefit of the all-new configuration of the TA aircraft. The penalty for this was estimated to be 7% in 2027. The IEs believe that an all-new SA airframe is needed to obtain the full potential fuel-burn improvement by 2037.
3. The goals for fuel-burn reduction proposed by the IEs represent their view of challenging, but achievable, technology for new aircraft. The highest rate is about 1.3% per annum. Compared with the ICAO aspirational goal of 2% global annual average fuel efficiency improvement, these results confirm that technology alone will not be able to meet ICAO aspirational goals. In order for the technology goals for fuel burn to be achieved, a substantial increase in investment in aircraft technology is urgently required.

4. Although not part of the goal setting, the IE review showed the impact of operating range and aircraft type on the fuel-burn metric. The fuel-burn metric reflects environmental cost, in terms of fuel burned, in the numerator and the benefit (mass of payload times distance flown) as the denominator. Table 2 shows the modelling results computed for the TRA (i.e., at the 2017 standard) for two ranges: these are the R1 range (maximum range at maximum payload) and the design range which is larger. These two ranges are listed in the footnote.[5]

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

A number of important observations emerge from Table 2. First, the fuel-burn metric is very high for the business jet compared with the other classes of aircraft. This is a consequence of small payload and long range of the BJ. The other striking observation is steep rise in fuel-burn metric as range is increased from R1 to design range. For the TA aircraft this longer ranges increases fuel-burn metric by about 34%, which is to some extent attributable to the sacrifice of payload to allow extra fuel to be carried. For the business jet, the effect is even more striking, with the fuel-burn metric rising by over 45% when range is increased from R1 to design range. To put this in context, the goals for fuel-burn improvement from the model show that 20 years of intense application of new technology could reduce fuel burn of the TA aircraft by around 23%.

Lastly, it should be noted from Table 2 that the fuel-burn metric for the SA at R1 range is marginally lower than that for the TA, notwithstanding the markedly higher L/D for the TA. This reflects the potential for major fuel-burn improvements by designing for shorter range, a point noted in the IE Fuel Burn Reduction Technologies in 2010. None of these features are revealed with the CO_2 metric, which does not include the effect of range or payload.

Emissions from Engines: Status and Opportunities

NO_x

1. The current LTO-based NO_x goals set by Independent Experts for 2016 (mid-term) and 2026 (long-term) have both already been met, but only with de-rated versions within an engine family, not intended to have significant market share. It is therefore recommended that in a future requirement, including this one, the engine be in substantial serial production for the goal to be accepted as being met.
2. The evidence shows a dependence on combustor exit temperature as well as OPR and any further consideration of LTO NO_x goals must be based on a methodology which reflects this. A new, low-order model is needed to predict NO_x emissions including the effect of OPR, turbine entry temperature, and design style and geometry. Such a low-order model would allow adequate optimization against fuel burn.
3. To reflect the potentially increasing importance of altitude NO_x relative to LTO NO_x levels, consideration should be given to the development of a cruise-based NO_x goal.
4. Setting a cruise-based NO_x goal level should take full account of the interdependencies, in particular, the technical trade-offs with fuel burn, especially as a result of higher turbine entry temperatures. Any cruise-based goal should also embrace the emerging understanding of health and environmental impacts on humans due to nvPM and NO_x emissions.

5 Design and R1 Range in Nautical Miles for the Four TRAs in 2017

	BJ	RJ	SA	TA
Design range (nm)	7,500	2,850	3,500	8,100
R_1 Range (nm)	6,450	1,750	2,450	5,900

nvPM

1. The particles emitted by combustion in aircraft engines are mainly ultrafine particles (i.e., smaller than 100 nm) and these are believed to be most harmful to human health.
2. It is noted that combustors entering service which are designed for low NO_x also appear to offer a substantial reduction in nvPM mass and number compared with most in-service engines. There is great uncertainty about the details of processes that lead to the formation of nvPM.
3. Setting goals for nvPM at this time appears neither practicable 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.

Noise: Status and Opportunities

1. The IEs regard the opportunities to be limited for new technologies to reduce noise further, short of major aircraft configuration changes, but noise generation will be reduced because of reduced speed (most notably of the fan). Better propulsion system integration with the aircraft is needed to encompass aerodynamic performance, noise, engine efficiency, and aircraft fuel burn.
2. More work is needed to improve the sound absorbing performance of thin acoustic liners and to increase the area of coverage. Liners suitable for the hot jet pipe are also needed for turbine noise and potentially for attenuating combustor noise.
3. Steps to reduce airframe noise, including landing gear and high-lift systems for low noise are required. A goal must be to find suitable geometries with practical parametric characterization of noise, aerodynamic performance, and mass, which can be used in the aircraft optimization process.

SUMMARY OF GOALS RECOMMENDED BY THE INDEPENDENT EXPERTS

Fuel Burn and Noise Goals

The goals for fuel burn and noise should be taken together, both following from the combined optimization process with the optimization weighting equal for both.

The fuel burn goals, expressed in terms of the CO_2 certification metric system as percentage margins relative to the CAEP/10 New Type Regulatory Level are presented below in Table 3. The results for the SA include the 3% and 7% increase in L/D attributable to the all-new aircraft.

TABLE 3: Fuel Burn Goals Expressed as Margin to CO_2 Metric Level

EIS Date	BJ	RJ	SA	TA
*2017 TRA**	-13	-11	-4	-4
2027	-15	-16	-14	-12
2037	-23	-26	-24	-21

*The 2017 numbers are not goals, but are shown for comparison purposes only.

Earlier Independent Expert goals for fuel-burn reductions were expressed in terms of fuel-burn metric (kg-fuel/ATK) and these are compared with the current review in Table 4 on an annualized basis beginning from 2000 for the 2010 IE review and from 2017 for the current review. It should be noted that for the 2010 review, the STA corresponds to the TA of the current review. As explained earlier, the present expectation of achievable reductions are significantly lower than was in 2010.

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%

The complementary noise goals expressed as EPNdB cumulative below Chapter 14 Noise Limit are presented in Table 5.

TABLE 5: Noise Goals Expressed as EPNdB below Chapter 14 levels

EIS Date	BJ	RJ	SA	TA
*2017 TRA**	9	13	12	15
2027	10.0	14.5	15.5	19.5
2037	15.0	17.0	24.0	26.5

*The 2017 numbers are not goals, but are shown for comparison purposes only.

Interdependency of Fuel-Burn and Noise Goals

The interdependency of noise and fuel burn can be determined from the Pareto plots presented earlier. Interdependency of fuel burn and noise for the SA and TA were explored by varying the weighting of the optimization in the EDS method. Results are shown for the SA aircraft type (with the extra L/D to allow for all-new airframe) in Table 6 and for the TA aircraft in Table 7.

For the SA, the worsening of fuel burn between 100% and 50% fuel burn optimization is small, whereas the fuel burn is substantially greater for 100% noise optimization. The noise benefit of weighting the optimization to noise is barely more than 1 dB than the 50/50 optimization. For the TA aircraft type, Table 7, the optimization at 50% fuel burn again gives most of the benefits in fuel burn with less than 1dB noise penalty. Optimizing 100% for noise, however, causes large fuel-burn penalties for less than 2dB noise benefit.

TABLE 6: Variation with Optimization of FB/ATK and Cumulative EPNdB for SA

Year	Optimization weighting	% FB/ATK	Δ EPNdB
2017	100% FB	-0.23%	0.78
	50/50	0.00%	0.00
	100% Noise	0.81%	-0.67
2027	100% FB	-0.48%	1.49
	50/50	0.00%	0.00
	100% Noise	2.94%	-1.13
2037	100% FB	-1.15%	3.01
	50/50	0.00%	0.00
	100% Noise	3.36%	-0.50

Model Optimization for Nominal Confidence at the 50% fuel burn/50% noise Weighting, Performed at R_1 for 2017 TRA.

TABLE 7: Variation with Optimization of FB/ATK and Cumulative EPNdB for TA

Year	Optimization weighting	% FB/ATK	Δ EPNdB
2017	100% FB	0.00%	0.53
	50/50	0.00%	0.00
	100% Noise	2.16%	-1.33
2027	100% FB	-0.23%	0.66
	50/50	0.00%	0.00
	100% Noise	8.56%	-1.11
2037	100% FB	-0.30%	1.11
	50/50	0.00%	0.00
	100% Noise	14.08%	-1.66

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

Goals for Emissions

Based on the evidence available to them, the IEs recommend that a new 2027 goal for NO_x should be set at 54% below CAEP/8 at OPR=30, covering the entire OPR range, using the equation 5.75 + 0.577*OPR. There are no goal bands.

To avoid low-thrust versions of engines with small production possibilities being taken to achieve the goals, it is recommended that the goal be met only when the 50th goal-compliant engine model enters into service.

The IEs declined to set NO_x goals for 2037, pending the development of a methodology which will reflect the dependence on combustor exit temperature, and more evidence on the need in terms of harm to health and deleterious impact on climate.

The setting of nvPM goals at this time appears neither practicable nor appropriate.

APPENDIX

Remit of the Independent Expert review taken from CAEP Memo 102, Attachment A, (4th July 2017):

"Based on the material reviewed by the IE panel, the final report should provide a balanced view of the current state of noise and emissions reduction technologies, in a manner suitable for broad understanding and it should summarize the expected new technological advances that could be brought to market in approximately 10 years from the date of review ("mid-term"), as well as the approximately 20-year ("long-term") prospects suggested by research progress, without disclosing commercially sensitive information. The report will include:

- A scientific overview of aviation environmental effects related to the aircraft and engine at source;
- For each technology, assess the possibility of noise reduction and fuel efficiency improvement, with specific focus on the interdependencies and trade-offs between fuel efficiency and noise;
- An assessment of the technological possibilities for NO_x and non-volatile Particulate Matter (nvPM) emissions control with specific focus on the interdependencies and trade-offs between fuel efficiency and/or noise;
- An assessment of the likelihood of successful adoption or implementation of the identified technologies and trends for the future, based on experience from past research and development programmes;
- Details on progress, which should be stated with reference to the existing CAEP Standards and goals. It should be noted that:
  - CAEP/10 established a new technology-based standard for aeroplane CO_2 emissions and so the IEs will need to make recommendations to reconcile past fuel burn goals with the new CO_2 metric system as appropriate;
  - There are no existing baselines or goals for nvPM and ICAO-CAEP is currently in the process of developing Landing Take-Off (LTO) mass and number-based standards for nvPM, in which context related data is still being collected. At a minimum, the IEs are requested to give at least a qualitative assessment of the prospects of improvements in nvPM mitigation technologies in the foreseeable future."

ICAO

CHAPTER TWO

Aircraft Noise