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INDEPENDENT EXPERT INTEGRATED TECHNOLOGY GOALS ASSESSMENT AND REVIEW FOR ENGINES AND AIRCRAFT

REPORT

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INTERNATIONAL CIVIL AVIATION ORGANIZATION

INDEPENDENT EXPERT INTEGRATED TECHNOLOGY GOALS ASSESSMENT AND REVIEW FOR ENGINES AND AIRCRAFT

2017 INDEPENDENT EXPERT INTEGRATED REVIEW PANEL

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REPORT

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3D	Three Dimensional
A	Maximum Diameter
AATT	Advanced Air Transport Technology
ACARE	Advisory Council for Aeronautics Research in Europe
ADP	Aerodynamic Design Point
AFE	Above Field Elevation
ANOPP	Aircraft Noise Prediction Program
App	Approach Noise
AR	Aspect Ratio
ASDL	Aerospace Systems Design Laboratory
ATK	Available Tonne Kilometre
AQ	Air Quality
B	Maximum Length
BC	Black Carbon
BJ	Business Jet
BLI	Boundary Layer Ingestion
BPR	Bypass Ratio
BWB	Blended Wing Body
CAD	Computer-Aided Design
CAEP	Committee on Aviation Environmental Protection
C_D	Drag Coefficient
CFD	Computational Fluid Dynamics
CH_4	Methane
CLEEN	Continuous Lower Energy, Emissions, and Noise
CL	Lift Coefficient
CLmax	Maximum Lift Coefficient
CMC	Ceramic Matrix Composites
CMPGEN	Compressor Map Generation Tool
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2 MV	CO_2 Metric Value
CVC	Constant Volume Combustion
ΔL	Long-Term Change in Margin
ΔM	Mid-Term Change in Margin
DAC	Dual Annular Combustor
DF	Fuselage Height
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
DNL	Day-night-level
Dp/F_{oo}	Mass of emissions/sea-level static thrust
EAP	Electrified Aircraft Propulsion
EDB	Emissions Databank
EDS	Environmental Design Space
EI	Emissions Index
EIS	Entry into Service
EPNdB	Effective Perceived Noise in Decibels
EPNL	Effective Perceived Noise Level
$EPNL_A$	Effective Perceived Noise Level at Approach
$EPNL_F$	Effective Perceived Noise Level at Flyover

$EPNL_L$	Effective Perceived Noise Level at Lateral
EPA	Environmental Protection Agency
ERA	Environmentally Responsible Aviation
F_n	Maximum SLS Thrust (Installed)
F_{oo}	Sea Level Static Uninstalled Thrust
FAA	Federal Aviation Administration
FAR	Fuel/Air Ratio
FB/ATK	Fuel burn per Available Tonne Kilometre
FLOPS	Flight Optimization Program
Flt ENv	Flight Envelope
FO	Flyover Noise
FOA	First Order Approximation
FPR	Fan Pressure Ratio
FW	Fixed Wing
GCC	Global Climate Change
GE	General Electric
GT	Georgia Institute of Technology
GTF	Geared Turbo Fan
GTP	Global Temperature change Potential
GWP	Global Warming Potential
H_2O	Water Vapour
HAP	Hazardous Air Pollutants
HC	Hydrocarbons
HLFC	Hybrid Laminar Flow Control
HPT	High Pressure Turbine
HT	Horizontal Tail
hum	Humidity
HWB	Hybrid Wing-Body
ICAO	International Civil Aviation Organization
ICCAIA	International Coordinating Council of Aerospace Industries Associations
ICSA	International Coalition for Sustainable Aviation
IE	Independent Expert
IEIR	Independent Expert Integrated Review
IER2	Second Independent Expert Noise Review
IPCC	Intergovernmental Panel on Climate Change
ISG	Impact and Science Group
K	Degrees Kelvin
L/D	Lift-to-Drag Ratio
Lat	Lateral Noise
LAQ	Local Air Quality
LdgFL	Landing Field Length
LDI	Lean-Direct-Injection
$LIMIT_A$	Noise Limit at Approach
$LIMIT_F$	Noise Limit at Flyover
$LIMIT_L$	Noise Limit at Lateral
LPP	Lean, Premixed, Pre-vaporized
LPT	Low Pressure Turbine
LT	Long-term
LT_0	Long-term IER2 Margin
LTO	Landing and Take-off Cycle
M&S	Modelling and Simulation
M_{des}	Design Cruise Mach number

MDP	Multiple Design Point
MEW	Manufacturer's Empty Weight
MIT	Massachusetts Institute of Technology
ML/D	Aircraft Mach Lift-to-Drag Ratio
MLM	Maximum Landing Mass
MT	Mid-Term
MT_0	Mid-Term IER2 Margin
MTF	Mixed Flow Turbofan
MTOM	Maximum Take-off Mass
NASA	National Aeronautics and Space Administration
NLF	Natural Laminar Flow
NO_x	Oxides of Nitrogen
NO_2	Nitrogen Dioxide
NPD	Noise Power Distance
NPSS	Numerical Propulsion System Simulation
nvPM	non-volatile Particulate Matter
O_3	Ozone
OEM	Original Equipment Manufacturer
OEW	Operating Empty Weight
OGV	Outlet Guide Vanes
OML	Outer Mould Line
OPR	Overall Pressure Ratio
Φ	Stoichiometric Ratio
π_{oo}	Overall Pressure Ratio (OPR)
P3	Compressor Exit Pressure
PAI	Propulsion-Airframe Integration
pax	Number of Passengers
PM	Particulate Matter
PSO	Particle Swarm Optimization
P&W	Pratt & Whitney
R_1	Range at Maximum Take-off Mass and payload
R_2	Range at Maximum Take-off Mass and fuel
RF	Radiative Forcing
RFSL	Long-Term Slope Realization Factor
RFSM	Mid-Term Slope Realization Factor
RGF	Reference Geometric Factor
RJ	Regional Jet
RPK	Revenue Passenger Kilometre
RR	Rolls Royce
RQL	Rich-Quench-Lean
S	Slope
SA	Single Aisle Aircraft (101-210 seats)
SAC	Single Annular Combustor
SAR	Specific Air Range
ScL	Corrected Long-Term Slope
ScM	Corrected Mid-Term Slope
SFC	Specific Fuel Consumption
SLS	Sea Level Static
SN	Smoke Number
SO_x	Sulfur Oxides
STA	Small Twin Aisle
SW	Wing Area

SWR	Wing Loading
T_3	Compressor Rotor Exit Temperature
T_{40}	Combustor Exit Temperature
T_{41}	Turbine Rotor Inlet Temperature
TA	Twin Aisle (twin-engine) aircraft (>210 seats)
TOC	Top of Climb
TOFL	Take-off Field Length
TRA	Technology Reference Aircraft
TRL	Technology Readiness Level
TTBW	Transonic Trust Braced Wing
TWR	Thrust to Weight Ratio
UEET	Ultra-Efficient Engine Technology
VLCS	Very Long Chord Slat
VT	Vertical Tail
WATE++	Weight Analysis of Turbine Engines
WF	Fuselage Width
WG1	CAEP Working Group One (Noise)
WG3	CAEP Working Group Three (Emissions)
WHO	World Health Organization
XL	Fuselage Length

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The Independent Experts have been heavily dependent on the staff of the Aerospace Systems Design Laboratory. Gregory Busch (now with Boom) and Dr. Jimmy Tai were the primary generator of results, including the developing the logic for creating baskets of technologies for inclusion of the new technologies from ICCAIA.

As well as contributing significantly to the modelling work, Dr. Michelle R. Kirby has played an invaluable part in the compilation and preparation of the report. Dealing with 15 Independent Experts in seven countries required tact and patience; turning the information into a report required expertise, skill and much hard work.

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CHAPTER 1. **EXECUTIVE SUMMARY**

1.1 INTRODUCTION

At the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP) 10th Meeting in Montreal, Canada, 1-12 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 remit and process of the review is set out below in section 1.3. 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 agreed that this review would consider progress relative to current ICAO Standards and goals. The present report describes the process of the Integrated Review, summarizes the evidence and presents the goals and recommendations. Extensive evidence was taken from industry, from relevant scientists, and from published reports.

The Independent Expert Integrated Review (IEIR) process began with a series of telephone conferences from January 2017, but the first major event was a workshop held in Washington DC from 24 to 28 April 2017. There was a second workshop held in Berlin from 16 to 20 October 2017. The workshops were a chance for industry, research organizations and others to present material to the IEs; they were also an opportunity for the IEs to question manufacturers and representatives of other organizations and they were also an opportunity for the IEs to discuss amongst themselves. Whilst there was considerable transfer of information to the IEs in the workshops, the information transfer continued into 2018, particularly for the people involved in the modelling of aircraft behaviour.

The panel consisted of 15 Independent Experts nominated by seven CAEP Member States (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). Sub-groups were formed for Fuel burn, Noise, Emissions, and Modelling and Simulation; sufficient of the IEs were members of more than one group to ensure that an adequate level of integration could be achieved. The preparation of the report was an activity of all the IEs.

1.2 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 which may guide subsequent regulations and to which industry and ICAO may aspire. The goals defined by the present Independent Experts need to be "challenging but achievable" the same definition as that adopted by previous groups of Independent Experts established by ICAO CAEP.

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 tightened in several cycles, most recently as Chapter 14. The two Independent Expert noise reviews, reporting in 2010 and 2014, set goals for 10 and 20 years forward. Goals were set for the regional jet (RJ), the small medium-range single aisle aircraft (referred to elsewhere in this report as SA), the long-range twin-engine twin-aisle aircraft (referred to as TA) and the long range, four-engine aircraft.

The first ICAO certification Standard for engine emissions was adopted in 1981, with requirements for fuel venting, smoke, unburned hydrocarbons (HC), carbon monoxide (CO) and NO_x emissions. This has been followed by a gradual increase in stringency, principally for NO_x, which had new stringency levels defined most recently in 2010 at CAEP/8. The two Independent Expert reviews of NO_x emissions, reporting in 2008 and 2010, set goals 10 and 20 years forward. The goals were expressed as lines for NO_x produced in the landing and take-off cycle as a function of engine overall pressure ratio, adopting the same principle as the regulations. More recently, in March 2017, the ICAO Council adopted a first-of-its kind 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 SA and TA aircraft with 3 different technology scenarios: TS1, continuation of current trend, TS2 'increased pressure' and TS3 'further increased pressure'. The results were presented in terms of kg-fuel burned per available tonne-kilometer flown. In March 2017 the ICAO Council adopted the ICAO Aeroplane CO_2 Standard which will apply primarily to new aircraft type designs from 2020, and to aircraft type designs already in-production as of 2023. This new CO_2 Standard metric system is different from the prior fuel burn goal metric.

The second IE review of noise technology drew attention to the interdependency of 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. Will noise and fuel burn both decrease in future? 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.

Increasing air travel is having an increasing environmental impact. 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). Climate-change concerns are also increasing, and aviation is expected to contain its carbon growing footprint in the context of the global efforts to reduce CO_2 emissions.

1.3 REMIT AND PROCESS OF THE IE INTEGRATED 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."*

There is a chapter devoted to each of the main topics referred to in the remit. Chapter 3 addresses Aviation Environmental Impact; Chapter 4 Fuel Burn and CO_2 reduction, Chapter 4 Engine emissions and reduction; and Chapter 6 Aircraft noise and reduction. These chapters summarize the state of knowledge and, where appropriate, the progress towards achieving previous goals and possible considerations for future goals. The method of modelling the aircraft is discussed in Chapter 7 with the outcome from the results of the modelling described in Chapter 8. Chapter 9 looks at alternative configurations (alternative to the current tube-and-wing type) and Chapter 10 looks briefly at the opportunities to bring improvements with change in method of operation, sometimes requiring the appropriate exploitation of new technology.

1.4 MEMBERSHIP OF THE INDEPENDENT EXPERT PANEL

The Independent Expert Panels 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	(US)
• Alain Joselzon	(France)
• Iurii Khaletskii	(Russia)
• Dimitri Mavris	(US) Co-chair
• Frank Ogilvie	(UK)
• Malcolm Ralph	(UK)
• Jayant Sabnis	(US)
• Richard Wahls	(US)
• David Zingg	(Canada)

1.5 REFERENCE AIRCRAFT

The review considered four classes of aircraft. In order to establish fuel burn, emissions and noise baselines, reference aircraft were used which were chosen to represent the four major 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 references , and these aircraft are shown in Table 1-1. Also, by using current actual as opposed to generic aircraft, the different participating organizations were able to provide additional data points that were used to establish the reference aircraft. The four classes of aircraft provided the base for the modelling work described in Chapters 7 and 8; they also provided natural bases for the discussions of fuel burn, emissions and noise in Chapters 4, 5 and 6.

Table 1-1. Technology Reference Aircraft Types and Related Operational Aircraft Examples

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

It became apparent during the review that the division between RJs and single-aisle aircraft was blurred. The Embraer 190-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.

The counter-rotating open-rotor (CROR) was thoroughly discussed. The IEs assumed that the use of CROR would require not only the development of a new engine, but an all-new aircraft, and this is addressed in Chapter 9, "Advanced Alternative Aircraft". This raises huge risks to the airframe maker as well as the engine maker, since issues of customer acceptability and safety could threaten its viability. The independent experts considered there to be a low probability that the CROR would be ready for service by 2037 but may continue as a research interest. The CROR was not therefore modelled in this review.

1.6 MODELLING APPROACH

The modelling has used Environmental Design Space (EDS), developed in Aerospace Systems Design Laboratory (GT/ASDL) in the Georgia Institute of Technology. EDS has been widely used on conventional aircraft-engine vehicles and it has also been used to assess unconventional aircraft and propulsion systems in support of the NASA and FAA advanced 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. EDS is capable of predicting the fuel burn, NO_x emissions, and noise metrics for the current CAEP IEIR goals assessment. 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 the taxonomy. The taxonomy that was adopted for describing the process and the findings of the modelling are illustrated in Figure 1-1. The technology baskets were defined as three point estimates in the mid- and long-term, based on the category levels: examples of this are reductions in component mass, drag and component noise sources. For a given confidence level of the baskets, the design interdependencies were explored; examples of this are wing loading, aspect ratio and thrust to weight ratio.

Information on the potential new technologies was provided by ICCAIA, research organizations, the IEs, and others; some of this transfer of information was at the time of the Workshops in Washington DC and Berlin, but much more in later interactions between the IEs, GT/ASDL and industry. Technologies were provided with Technology Readiness Level (TRL) values: TRL8 is achieved when an aircraft is flight qualified ready to enter service. The aircraft and its technologies for the goals from this review will be 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 7 years will normally elapse between TRL 6 and 8. Therefore, to achieve TRL8 at the goal dates, the technology should be at least TRL6 by 2020 and 2030 respectively. Technologies on the current Technology Reference Aircraft (TRA), shown in Table 1.1, are 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.

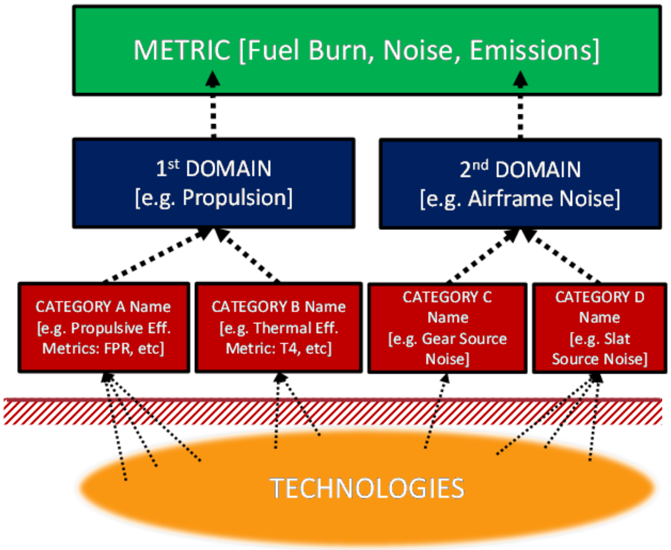

Figure 1-1. IE Integrated Review Taxonomy

1.7 PRINCIPAL FINDINGS AND CONCLUSIONS

1.7.1 Aviation Environmental Impact Overview

The effects of aircraft emissions and noise, based on information available to the IEs, are summarized in Chapter 3. Aircraft noise has a unique impact, as no other noise sources fly over where people live. Emissions from combustion impact human health and welfare through degraded air quality as well as through climate change. Aircraft are unique in that they emit emissions at both the surface and at cruise altitudes where the emissions undergo chemical and physical transformations leading to a change in air quality and greenhouse gas concentrations and affect the radiative budget of the atmosphere. Some studies note that there is also the potential for aircraft emissions emitted at cruise altitudes to reduce surface air quality. It was noted that 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. Nitrogen dioxide (NO_2) from NO_x emissions, and its photochemical derivative, ozone (O_3), are identified as harmful to human health. More recently attention has been directed at non-volatile particulate matter (nvPM), and of particular concern are ultrafine PM, which is the particle size produced by aircraft. Long ago 'smoke' was a major concern and standards exist based on opacity measurements. Concern for smoke and nvPM overlap and in some places in this report the expression smoke/nvPM is used. 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. 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. More recently, concern has extended to health effects from aircraft at higher altitudes including cruise. From LTO operations, the contributions to local concentrations are higher than the contributions from cruise but the numbers of people affected are relatively small. For emissions from higher altitudes, the modelled increase in concentration at the surface is much smaller than for LTO but much larger numbers of people are potentially affected.

For climate change, the primary concerns are emissions of CO_2, NO_x and nvPM, as well as persistent contrails, leading 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 (RF) which is a measure of the associated heating or cooling. It is the combination of quantities emitted, residence time, RF and the temperature response profile of a particular pollutant, which determines its overall impact on global surface temperature over a given timescale. CO_2 is of particular concern because of its exceptionally long residence time (thousands of years). The RF value for aircraft NO_x per unit emission is now thought to be lower than for the two previous Independent Expert NO_x reviews, but it remains of concern. nvPM is implicated in cloud formation though the processes are less well understood. Contrails, leading to cirrus clouds and aircraft induced cloudiness, have large RF impacts but are short lived (hours).

The findings of the CAEP/10 ISG study on the effects of aircraft noise were reviewed. The CAEP/10 trends assessment showed tens of millions of people affected by aircraft noise with these figures set to rise significantly even under the most optimistic technology scenarios. The studies covered community annoyance; children's learning (showing negative effects on cognitive skills); sleep disturbance (causing impaired performance); and health effects (including hypertension and cardiovascular problems). The number of people affected may also rise because historically, noise reductions have come about in tandem with technology to reduce fuel burn, principally reduction in jet velocity. Because jet noise is no longer the major source for larger aircraft the trend is thought no longer to 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.

1.7.2 **Aircraft Fuel Burn and CO_2 Reduction**

Fuel burn is considered in Chapter 4, principally for the two aircraft classes burning the largest proportion of fuel, the SA and TA. The treatment is separated into airframe and engines, with the airframe section itself being divided into aerodynamics and mass (often referred to as weight). A useful measure of aerodynamic performance of an aircraft is the lift-drag ratio, L/D. This 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. 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 TA may require the use of extensive laminar flow on the current tube and wing configuration or a switch to a non-conventional configuration.

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. The use of laminar flow technology on wings has primarily been held back due to manufacturing and operational considerations and challenges. Largely from evidence provided by ICCAIA, it is judged that reasonable goals for aircraft aerodynamics, adopting a basket of technologies including laminar flow, are between 3 to 4% fuel burn reduction for RJ, SA and TA in 2027 and between 8 to 10% in 2037; for the BJ the improvement goals for 2027 are probably a little smaller.

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, savings of 8±2% are possible for the SA and 4±2% for the TA. There are additional mass reduction technologies considered, worth around 2.5% for small aircraft and 4% for large. Overall the empty mass savings, as part of setting fuel burn goals, are in the range 2-4% for 2027 and 8-10% for 2037.

For engines, the efficiency is conveniently separated into propulsive efficiency, which depends only on the fan pressure ratio (FPR), and the thermal efficiency, which depends on the OPR and the turbine entry temperature (T_{40}). OPR itself is limited by compressor delivery temperature and is unlikely to much exceed 60. Turbine entry temperature is limited by available materials and airfoil cooling technology, but is unlikely to increase dramatically from the best present values, since increased cooling air requirements reduce efficiency. Further improvements in thermal efficiency will require a combined approach, including repeated small step increases in OPR and T_{40}, coupled with continued increase in compressor and turbine efficiencies. Increasing, or even maintaining, component efficiencies becomes more difficult as OPR rises because of the reduction in core size. Fan pressure ratio has been reduced in recent years giving significant reductions in fuel burn. 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 powerplant mass and drag, as well as growing issues with powerplant-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, in particular the increased drag and mass, to be taken into account.

The potential in 2027 of fuel burn reductions attributable to the new propulsion technologies have been preliminarily estimated by ICCAIA at about 5% for SA and about 6% for TA. In 2037, an extra 5% fuel burn reduction might be obtained. These numbers include gains from all new propulsion technologies (thermopropulsive efficiency, mass and drag) but exclude those from possible specific new nacelle technologies and improved propulsion system/airframe integration. For RJ, the benefit is expected to be less than the SA benefit and with possibly no benefit in 2027. Combining improvements which seem possible for the engine with those for the airframe, the reduction in fuel burn for the SA and TA out to 2037 is projected to be about 22% or around 1.25% per annum. Detailed numbers for all aircraft classes are provided in Table 8-6.

1.7.3 **Engine Emissions and Reduction**

The current state of emissions technology is considered in Chapter 6. The climate impact of NO_x emissions is still thought to be significant relative to CO_2, though less than in previous IE reviews. There is also concern that the health impact of NO_x emitted at altitude could be many times greater than the health impact of LTO emissions; consequently the IEs believe that the focus of NO_x control should shift from LTO to include all flight phases.

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. 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[1] temperature T_{40} used to promote better fuel burn and lower CO_2. These 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 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 the 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 have reached 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. There was not time in this review to develop a system of metrics and goals to reflect the revised emphasis on altitude NO_x. In the meantime, the

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[1] Turbine entry temperature is expressed in more than one way. At entry to the first set of stationary vanes, before the hot gas has had a chance to mix with vane cooling air, the temperature is T_{40}. After passing through the vanes, but before entering the rotor blades, the temperature is lower and is denoted by T_{41}. The difference is on the order of 100K.

IEs propose the setting of a 2027 medium-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 define when the goal is met. The goal applies to all aircraft classes. The IEs recommend that CAEP consider carrying out urgent work to study the issue and develop an appropriate method to allow a future review to set full-flight based NO_x goals.

The IEs were made aware of the concerns regarding health impacts of nvPM. There is 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 peak number at about 60 nm. Regulation is being considered for the much larger $nvPM_{2.5}$ particles (2.5 μm which is 2500 μm). 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 advises that early difficulties in service are likely to result in trade-off between nvPM and NO_x emissions at higher OPRs and T_{40}. 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 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.

1.7.4 **Aircraft Noise and Reduction**

Compared with the past, noise from recent new aircraft is characterized today by a significant change in the relative importance of engine and airframe noise sources. Jet noise, which previously used to dominate, is now significantly lower. This is because of the lower fan pressure ratio (accompanied by higher bypass ratio) producing lower jet velocity. In addition, the airframe noise tends to be higher than engine noise on approach. As the engines being installed on large aircraft continue to grow in size, the aircraft noise becomes more sensitive to specific features of design, including engine integration, aerodynamics, mass, and interaction effects - the level of interdependence therefore increases. Furthermore, because jet noise is no longer dominant, scaling noise on parameters such as bypass ratio is not appropriate.

Chapter 6 outlines the status of the different noise sources and their noise reduction potential, which depends on the aircraft class. Attention is focussed on the most important topics, in particular acoustic wall liners in the powerplant, fan noise and airframe noise. Today's new aircraft are meeting the existing mid-term noise goals with some margins. In general, however, the scope and potential remaining for further technology-based reductions in noise within conventional aircraft configurations are limited. Further noise reductions will require careful attention to design, ensuring that noise is not under-prioritized compared to fuel burn. Research is continuing and benefit should arise from analytical methods, simulation, noise prediction methods and testing, all of which are key to addressing noise issues. Along with the active pursuit of research, consideration should be given to different or novel configurations of aircraft, addressed in Chapter 9.

Noting that today's aircraft are meeting mid-term goals, an attempt is made in Chapter 6 to project existing goals to 2027 and 2037. It is noted that the largest of the RJs now is in the size category for the SA, whilst the largest of the BJs is in the RJ size category; in both cases the cumulative noise meets the existing goals for the higher size category. This prompts the suggestion that consideration be given for further work within ICAO/CAEP to address the issues of aircraft categories for goals, encompassing the wide range of current sizes and the evolution of size expected in the future.

1.8 MODELLING RESULTS AND GOALS

The recommendations below are partly directed at ICAO, but more widely they are directed at policy decision makers as well as funding and research communities.

1.8.1 Aviation Environmental Impact Overview

Air quality and health impacts

1. Better understanding of the effects of gases and particles emitted by engines on human health is required. Research on the specific impact of low concentrations of NO_x emitted and low-levels of particulates is needed. The effect on health of particle size, particularly ultrafines, and composition needs to be understood and quantified.
2. The nature of the particulates, in terms of size, number and composition, emitted by engines at different conditions whilst near to the ground needs to be understood and quantified.
3. The formation of secondary particulates needs to be understood and quantified. This needs to take into account different background levels of gases such as ammonia, as well as humidity.
4. Further evidence is needed of the effect of NO_x and sulfur oxides at altitude on 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. Although contrails and formation of cloudiness are large potential contributors to aviation radiative forcing, there is still large uncertainty surrounding their behaviour and their RF. Significant resources should be devoted to urgent studies of this topic. The potential to mitigate the effect of contrails by small alterations in flight path or altitude should be further investigated.
2. NO_x emitted outside the LTO cycle has some global warming potential, but the quantitative understanding of this effect needs to be improved. Though less important, the same is true for particulates and sulfur oxides.
3. 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.

Aircraft Noise and its impacts

1. Given the rapid increase in aircraft movements, leading to increasing exposure of populations to significant levels of noise, research needs to be maintained, both in relation to the generation of noise and understanding of the impacts.
2. The major sources of noise have changed so that the jet noise is subordinate to the fan noise at take-off and airframe noise dominates at approach. WG1 (with the support of other WGs as applicable) might wish to review the operational procedures used to mitigate noise and also review conditions of the aircraft certification scheme to take account of these changes.

1.8.2 Aircraft Fuel Burn and CO_2 Reduction

1. Fuel burn being a key competitive parameter, any review tends to be hampered by limited publicly available information. For this review the IEs had to construct Technical Reference Aircraft. With the future availability of certification values using the CO_2 metric system, a future review looking at fuel burn can be conducted with a more solid foundation.
2. The aerodynamic performance of the airframe (characterized by lift/drag ratio) for single aisle (SA) aircraft such as B737 and A320 has improved over the past four decades by approximately

half as much as larger twin aisle (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 which does not allow the gains possible to an all-new aircraft from a full basket of new technologies. Evidence available to the review is that a wholly new airframe for the SA size of aircraft will be able to improve the aircraft aerodynamic performance to reduce the difference from the TA. It is therefore recommended that goals be set for the SA on the expectation that all-new airframes will be produced for this class by 2037. Based on evidence of the benefits from this L/D for the SA has been raised by 3% in 2027 and 7% in 2037 over and above the increase from the new technologies presented by ICCAIA.

3. The annual reductions in fuel burn metric tabulated in Table 8-3 represent the IEs view of challenging but achievable technology goals 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 is urgently required. It is recommended that this evidence be included in discussions and planning of future steps.
4. It is foreseen that fan pressure ratio will be further decreased to reduce both fuel burn and noise. These larger, lower speed fans will present increased challenges for the integration of the engine with the airframe. Real optimization can only be achieved if there is effective close cooperation between the engine makers and the airframe makers, treating the whole aircraft (airframe, engine and systems) as an integrated whole.

1.8.3 Emissions

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 met.
2. The evidence shows a dependence on combustor exit temperature as well as OPR. Any further consideration of LTO NO_x goals must be based on a methodology which reflects combustors where emissions alter strongly with T_{40}. In other words NO_x emissions should be correlated against T40 as well as OPR, but some characteristics of the combustor geometry may be needed as well. New low-order models are needed to predict the behaviour and to allow adequate optimization against fuel burn – the very interdependency required in this review.
3. To reflect the potentially increasing importance of altitude NO_x relative to LTO NO_x, consideration should be given to the development of a cruise-based NO_x goal. This should use a climb/cruise (or full flight) metric system, ideally developed by CAEP, as part of cruise NO_x certification. Development of such a goal was too ambitious for this integrated review.
4. Methods exist to predict NO_x formation at cruise from information from LTO for current RQL combustors. Methods and corroborating tests are needed for the new generation of RQL combustors and the lean-burn combustors. Of particular concern is the staging of fuel injection.
5. Setting a cruise-based NO_x goal level should take full account of interdependencies, in particular the technical trade-offs with fuel burn, especially as a result of higher T_{40} values. Any cruise-based goal should also embrace the emerging understanding of health and environmental impacts due to nvPM and NO_x emissions. The IEs propose that CAEP ISG examine both types of impact for cruise.

nvPM

1. Measurement of particles emitted by engines, both mass and number, are becoming more common. Publicly-available measurements should be capable of quantifying ultrafine particles

(smaller than 100 μm) which are believed to be most harmful to health and are, in the main, the particles emitted by aircraft.

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 to most in-service engines. Whilst this is good news, it points to the need for better understanding and quantification of the processes leading to the generation of particulates.
3. The IEs considered that the setting of nvPM goals at this time appeared 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. This is a topic which CAEP should keep under review.

1.8.4 Noise

1. Fan noise, now the dominant source, will benefit from better aerodynamic integration to remove flow non-uniformities. Much of this will come from three-dimensional computation, but this must be supported by appropriate and representative experimental tests, including measurements in flight.
2. The IEs regard the opportunities to be limited for new technology to reduce noise further short of major configuration changes; not much improvement is to be expected by 2037, 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.
3. As fans become bigger, there is increased pressure to reduce the length and thickness of the nacelle. Therefore, more work is needed to improve the acoustic performance of thin 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.
4. Extended studies and development of landing gear and high-lift systems for low noise are required. These must include computation, experiments, and full-scale tests on aircraft, with the aim of achieving optimized design configurations in representative conditions. 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.

1.8.5 Advanced Alternative Configurations

1. It should be noted that in their considerations and recommendations, the IEs have assumed that conventional configuration ("tube and wing") is the only possibility for the medium-term, to 2027.
2. No clear consensus existed among the IEs of the likelihood of alternative configurations being available by 2037. New configurations are believed possible in 2037 with potential benefits, compared to conventional ("tube and wing") configurations at the same technology level, of:
    a. Fuel burn reductions on the order of 5-15%
    b. Noise reduction on the order of 10 EPNdB cumulative, if the configuration incorporates acoustic shielding.

   To achieve these potential benefits, substantial investment would have to begin very soon.
3. It is recommended that research and development of the most promising alternative configurations be intensified. To leave open the possibility of entering service in 2037, would necessitate a very significant investment over the next 5-7 years.
4. Large-scale transonic flight demonstrations of integrated alternative configuration concepts are necessary to lessen the unknowns and build the necessary confidence for the business leaders who make the ultimate decisions. This is essential to reduce the risks, both real and perceived, to address the "ilities," and demonstrate benefits.

1.9 SUMMARY OF GOALS

1.9.1 **Fuel Burn Goals**

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

EIS Date	BJ	RJ	SA	TA
2017 TRA[2]	*-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. The results for the SA use the 3% and 7% increase in L/D attributable to the all-new aircraft.

1.9.2 **Noise Goals**

The complementary noise goals expressed as EPNdB cumulative below Chapter 14 Noise Limit (Table 8-13) are:

EIS Date	BJ	RJ	SA	TA
2017 TRA[2]	*9*	*13*	*12*	*15*
2027	10.0	14.5	15.5	19.5
2037	15.0	17.0	24.0	26.5

1.9.3 **Goals for Emissions**

The IEs recommend, based on the evidence provided, that a new 2027 MT LTO NO_x Goal should be set at 54% below CAEP/8 at OPR=30, covering the entire OPR range, using the equation 5.75 + 0.577*OPR.

To ensure environmental benefit when meeting the goal, there are no goal bands and the goal is met only when the 50th engine of a single goal-compliant type enters service. The IEs declined to set NO_x goals for 2037, pending a methodology which reflects the dependence on combustor exit temperature.

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

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[2] 2017 TRA values are not goals but are included for reference.

CHAPTER 2. **INTRODUCTION**

2.1 REMIT

The remit for this Integrated Independent Expert Review was provided by the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP) [CAEP/Memo-102 (AN1/17), Attachment A, 4/7/2016] which is reproduced here in full in Appendix A. Reporting requirements were stated to be:

> *"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."*

2.2 BACKGROUND

Air transport continues to grow rapidly and according to ICAO[3], Revenue-Passenger-Kilometers (RPKs) increased by 7.4% in the year 2016 and an average increase of 5.2% per year is expected from 2007-2026. The growth is then expected to continue with air transport increasing at a rate of 4.5% per year up to 2042[4]. Over a similar period, ICAO has estimated that international aviation fuel consumption, which was calculated to be 142 million metric tonnes (Mt) of fuel in 2010, will increase between 2.8 (with full application of new technology and air traffic management improvements) and 3.9 times (without those improvements) by 2040[5]. NO_x emissions near airports were estimated to be about 0.15 Mt in 2010 and, with no improvement in emissions technology, this would increase about fourfold by 2040; with improved technology the increase could be between about 2.1 and 2.8. The emissions of particulate matter from international aviation below 3,000 feet were estimated to increase in a similar trend to those seen for NO_x. The number of people affected by aircraft noise above 55 dB day-night-level (DNL) near airports is already large and is expected to rise. It is estimated[6] that between 21 and 35 million people are currently affected at this level and, even with maximum inserted noise technology, between at least 31 and 52 million will be affected in 2040 without correcting for the effect of population encroaching inside geographical noise contours.

Whilst concern about the environmental impact of aviation in the vicinity of airports is increasing, as discussed later in Chapter 3, there is now concern that emissions of NO_x and particulates emitted at cruise

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[3] https://www.icao.int/annual-report-2016/Documents/ ARC_2016_Air Transport Statistics

[4] https://www.icao.int/Meetings/a39/Documents/WP/wp_064_en.pdf

[5] https://www.icao.int/Meetings/a39/Documents/WP/wp_055_en.pdf

[6] CAEP/10-WP/9. Note the values are global and the exact population exposure value varies by nearly a factor 2 depending on the population database used.

may affect health at ground level, whilst NO_x and nvPM during cruise also affect climate change in addition to the effects of CO_2 emitted. The climate change concerns are requiring aviation to take steps to reduce its carbon footprint in the context of the global efforts to reduce CO_2 emissions. In October 2016, significant milestones in the development of aviation emission commitments were affirmed by the 39th Session of the ICAO Assembly, including three Assembly Resolutions[7]. ICAO is undertaking several initiatives in response to the environmental challenges and this Integrated IE Review is one of these initiatives.

2.2.1 **Aircraft Noise**

Aircraft noise from large aeroplanes 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, Annex 16, Volume I has subsequently been modified to reduce allowable noise from large aeroplanes in Annex 16, Chapters 3, 4 and recently, Chapter 14 (2014). Additionally, other aircraft types were also included within the scope of the Standard, such as helicopters, small propeller-powered aeroplanes, and tiltrotors.

The reduction of aircraft noise at source, by the implementation of noise reduction technologies, is the first pillar of the ICAO "Balanced approach to aircraft noise management", which also includes land-use planning and management, noise-abatement operational procedures, and operational restrictions on aircraft. There have been two reviews[8,9] of noise technology carried out for ICAO by Independent Experts (IEs), one in 2008 (CAEP/8 cycle) and the other in 2012 (CAEP/9 cycle). Goals were established based on the review of the technology.

2.2.2 **Engine Emissions**

The first ICAO certification Standard for engine emissions was adopted in 1981, and covered requirements for fuel venting, smoke, unburned hydrocarbons (HC), carbon monoxide (CO) and NO_x emissions. This has been followed by a gradual increase in stringency, principally for NO_x, which had new stringency levels defined in 1993 (CAEP/2), 1999 (CAEP/4), 2005 (CAEP/6) and 2010 (CAEP/8). There have been two reviews[10,11] of NO_x technology goals carried out for ICAO by Independent Experts, one, referred to as the 2006 review (CAEP/7 cycle), reporting in 2008 and the other, referred to as the 2009 review (CAEP/8 cycle), reporting in 2010. Based on the review of the technology, goals were set. The 2006 review was the first goal setting review in any area by ICAO. To some extent, the emission of particulate matter is regulated by the regulation for smoke: this uses the smoke number, which is based on visibility criteria. With modern instrumentation, it is possible to measure both mass and number of particulates and it has therefore become possible to regulate non-volatile particulate matter, nvPM, more precisely. In March 2017, the ICAO Council adopted an nvPM engine emissions Standard, which will apply to turbofan and turbojet engines with rated thrust greater than 26.7kN, manufactured from 1st January 2020. The expectation is that sometime after CAEP/11, a regulation based on measured nvPM will supersede the smoke number.

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[7] A39-1, Consolidated statement of continuing ICAO policies and practices related to environmental protection – General provisions, noise and local air quality; A39-2, Consolidated statement of continuing ICAO policies and practices related to environmental protection – Climate change, and A39-3, Consolidated statement of continuing ICAO policies and practices related to environmental protection – Global Market-based Measure (MBM) scheme

[8] Report to CAEP by the Noise Technology Independent Expert Panel, Doc 9943, 2010

[9] Report by the Second Noise Technology Independent Expert Panel, Doc 10017, 2014

[10] Report of the Independent Experts on the LTTG NO_x Review and Medium and Long-term Technology Goals for NO_x, Doc 9887, 2008

[11] Report of the Independent Experts to CAEP/8 on the Second NO_x Review and the Establishment of Medium and Long-term Technology Goals for NO_x, Doc 9953, 2010

2.2.3 **Fuel Burn**

To address climate change, global aspirational goals were adopted by ICAO in 2010 and confirmed by the ICAO 39th Session of the Assembly. These call for fleet fuel efficiency improvement of 2 per cent per annum from 2020 and the net carbon emissions from 2020 kept at the same level. A basket of emission reduction measures has been identified to help States achieve these long-term aspirational goals, which includes aircraft-related technology development and improved air traffic management and infrastructure use. The IEs are clear that the goals for fuel efficiency and net carbon emissions cannot be met by technology alone and this will only be possible if alternative fuels and economic/market-based measures are included.

Key to the improvement in aircraft fuel efficiency is technology and a review[12] was carried out for ICAO by Independent Experts on fuel burn technology reduction goals which reported in 2010. The IEs expressed some reservations about expressing reduction goals in fuel burn in terms of annual compound reductions, because changes in technology often result in large but infrequent step changes. However, it is useful in comparison with the ICAO call for 2% fleet fuel-efficiency improvement to note that the goals recommended by the IEs out to 2030, based on all the technology they assessed, were 1.38% per annum for the SA and 1.43% per annum for the TA.

The development of an ICAO Standard for CO_2 emissions is recent. In March 2017, the ICAO Council adopted the ICAO Aeroplane CO_2 Standard which will primarily apply to new aircraft type designs from 2020, and to aircraft type designs already in-production as of 2023. Those in-production aircraft which by 2028 do not meet the Standard will no longer be able to be produced unless their designs are sufficiently modified to meet the Standard.

2.3 ICAO TECHNOLOGY GOALS AND THE INDEPENDENT EXPERT REVIEWS

ICAO noise and emissions Standards have been set by following the latest technologies actually available across all manufacturers and certified in each category of the aircrafts market, in order to prevent backsliding. The current Standards are provided in Appendix C. This approach to Standards has given rise to the need for separate technology goals which can guide subsequent regulations and provide levels for regulators and manufacturers to aspire to. These goals are defined by groups of "Independent Experts" (IEs) regularly established by ICAO CAEP. The first sets of goals were defined by the IEs to be "challenging but achievable" and that has been retained as the intention in the current review.

Significant gains have been made in reducing the environmental impact per passenger-kilometer but the rapid increase in operations means that the nuisance and potential damage is still increasing. For many years, air transport has become more efficient, whether measured in fuel used per passenger-kilometer or based on the newly agreed CO_2 metric. Much of the efficiency increase came from reducing the fuel burned in the engine and this reduction in fuel burn was achieved in large measure by reducing the jet velocity. Reducing jet velocity also reduced noise at take-off. In the last few years, however, engines are approaching, or in some cases have reached, the point where the jet velocity now cannot be reduced without *increasing* the fuel burn. Other steps which might be taken to reduce noise are also likely to lead to increased fuel burn and CO_2.

To use less fuel, the engine efficiency has also been increased by raising the overall pressure ratio and the temperature of the gas entering the turbine, both leading to higher gas temperature in the combustor. An increase in temperature in the combustor is known to lead to higher levels of NO_x and possibly to higher levels of nvPM. In other words, the requirements for low CO_2 and low emissions are in conflict. This, and the similar conflict between noise and CO_2, justifies the scope of this current Review, which will be the first one to define technology goals in an integrated manner for noise, CO_2 and emissions.

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[12] Report of the Independent Experts on Fuel burn Reduction Technology Goals, Doc 9963, 2010

In the 2014 Noise Review[5] the Independent Experts identified and commented on the interdependencies between fuel burn, noise and emissions. Specifically, they noted that features, benefits and penalties for any engine, nacelle and powerplant installation must not only be assessed in terms of noise but in terms of fuel consumption (equivalent to CO_2 emissions), NO_x emissions, mass and costs. They also noted that environmental and economic trade-offs are very challenging to understand and analyze. Although identifying the most appropriate balance between environmental requirements and other characteristics is difficult, it is crucial to make quantitative trade-offs for optimizing solutions. They also noted that in the context of ICAO noise technology goal setting, trade-offs between noise, fuel efficiency and emissions raise particular challenges in the little-explored territory of novel configurations where uncertainty bands are unavoidably large.

The importance of the interdependencies was recognized and picked up by CAEP and this formed the background to the decision by CAEP/10, at the meeting in Montreal in February 2016, to set up an Independent Expert led process which would conduct an integrated technology goals assessment and review. It was agreed that this review would be conducted at an engine level, providing assessment of engine technology, including both nvPM and NO_x, and at an aircraft level, providing as assessment of subsonic fuel efficiency and noise technologies. The review should consider progress relative to current ICAO Standards and Goals. This is the background to the remit provided in CAEP memorandum 102 and is provided here in Appendix A.

The IEs have endeavored to follow both the letter and spirit of the instructions in their remit. The interpretation of the meaning of 10 years (mid-term, to 2027) and 20 years (long-term, to 2037) was discussed amongst the IEs and with ICCAIA members of the Steering Committee. Based on this discussion it has been assumed that the Technology Readiness Level 8 (written as TRL8) would be achieved by 2027 and 2037. Applicable definitions for TRL are provided in Appendix B, where TRL8 represents "Actual system completed and flight qualified through test and demonstration". It implies that a new aircraft with new technology could be brought into service within a short time and would probably be well advanced in the certification process. To have a chance of reaching TRL8, the technology is presumed to need to be at TRL6 (System/subsystem model or prototype demonstrated/validated in a relevant environment) by 2020 and 2030 respectively. Using the TRL system could be considered crude, requiring subjective decisions and with different implications for a whole system, like an aircraft or engine, and a small subsystem. However, it does provide an easily understandable measure of technology readiness and is widely used and accepted. In practice in the review, TRL is augmented by assessments of the likelihood of implementation and a realization factor for improvements which are likely to be achieved from the individual technologies when integrated onto a single aircraft.

Chapter 3 of the report is an overview of aviation environmental impact. Chapters 4, 5 and 6 give brief overviews of the technology for fuel burn and CO_2 reduction, emissions reduction, and noise reduction, respectively, and discuss the possibilities and limits for improvement. Chapter 7 looks at the methodology for the review, in particular the use of the Environmental Design Space (EDS) modelling tool developed at the Georgia Institute of Technology, to model the performance of possible aircraft; the outputs include fuel burn, noise and emissions. As already noted, the previous IE reviews considered one aspect at a time (NO_x, noise or fuel burn) whereas the present review considers all three concurrently, together with the interdependencies. The coverage of each individual topic in the present report is therefore of necessity less detailed.

Chapter 8 describes the output of the modelling work and the proposed goals for fuel burn, emissions and noise. Chapter 8 also addresses, quantitatively, the interdependencies between fuel burn, emissions and noise. As the future potential with conventional tube-and-wing aircraft was found to be relatively modest, Chapter 9 looks at Advanced Alternative Aircraft Configurations. Alternative approaches to reduce environmental impact by changes other than new airframe or engine technology and design, are discussed briefly in Chapter 10. Finally, Chapter 11 gives the recommendations and some general conclusions of the Independent Experts.

2.4 COMPOSITION OF THE INDEPENDENT EXPERT PANEL

The panel consisted of 15 Experts nominated by seven CAEP Member States (Brazil, Canada, France, Russia, Sweden, United Kingdom and United States, and two CAEP Observers from international organizations (European Commission and the International Coalition for Sustainable Aviation (ICSA)). The names and nominators of the IEs are listed in Section 1.4.

The instructions to the IEs make clear that all the members of the panel should be involved with all the areas covered given that interdependencies is a common theme of the review. With 15 IEs the group was too large for detailed discussion of all topics and sub-groups were therefore formed for fuel burn, noise, emissions and model simulation. Sufficient of the IEs were members of several groups that an adequate level of integration could be achieved. The preparation of the report was an activity by all the IEs.

2.5 PROCESS OF THE REVIEW

The process began with telephone conferences with all the Independent Experts and a Steering Committee composed of the ICAO Secretariat, WG1 and WG3 rapporteurs and industry representatives. The first five-day workshop was held in Washington DC, April 24th to 28th 2017, with the second five-day workshop held in Berlin 16th to 20th October 2017. There has been, in addition, extensive further interaction between IEs and representatives of ICCAIA, and other technical/scientific experts.

CHAPTER 3. **AVIATION ENVIRONMENTAL IMPACT OVERVIEW**

3.1 INTRODUCTION

This chapter provides an overview of aviation environmental impacts to inform later discussions on interdependencies and potential trade-offs in setting goals for noise, NO_x and fuel burn. Aircraft emissions impact human health and welfare through degraded air quality as well as through climate change. Other sectors are expected to reduce their greenhouse gas and air quality related emissions, and against a background of continued growth in air traffic and total fleet fuel burn (outlined in Section 2.2 above), there will be further pressure on civil aviation to reduce its emissions. Aircraft are unique in that they emit emissions directly at high altitudes, and as such, aviation activity affects the climate in a variety of ways. There is also the potential for aircraft emissions emitted at cruise altitudes, as well as those emitted at low altitudes, to reduce surface air quality. Aircraft noise has a unique impact, as there are no other noise sources that pass over where people live, and there is continuing pressure on civil aviation from those exposed to aircraft noise. The remainder of this chapter considers in more detail both emissions and noise impacts and their implications for technology goals.

3.2 COMBUSTION EMISSIONS AND THEIR IMPACTS

Aircraft engine exhaust is composed, on a mass basis, of about 70% CO_2, and a little less than 30% water vapor. There are also oxides of nitrogen, NO_x, and other components, including hazardous air pollutants (HAPs) and particulate matter. The approximate exhaust composition of these emissions per kg of kerosene fuel burned for a fuel with a typical sulfur content is listed in Table 3-1. Particulate emissions, sometimes referred to as particulate matter (PM), originate from both volatile and non-volatile particles. The non-volatile particulate matter (nvPM) arise from incomplete combustion. The nvPM are sometimes also referred to as soot or smoke and historically smoke from aircraft engines has been regulated. The nvPM produced within the engine are mostly very small, referred to as ultrafine particles (effective diameters less than 0.1 μm) and are mainly composed of carbon but may include hazardous chemicals. The hazardous chemicals may be attached to the carbon particles. In this report, the terms smoke, PM, nvPM and ultrafine PM are used[13]. Some of the gases produced by aircraft engines react in the ambient atmosphere over hours or days and over distances of many kilometers to form ozone; the gases also contribute to ambient PM, including some ultrafine PM, though at this scale, aircraft are a minor source.

Table 3-1. Aircraft Engine Exhaust Composition per kg of Kerosene

Species	**CO_2**	**H_2O**	**NO_x**	**SO_x**	**CO**	**HC**	**PM**
Mass in grams	3160	1290	<15	1.2	<0.6	<0.01	<0.05

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[13] Particulate matter is often defined by its size. PM_{10} refers to particles with diameter 10 microns or less. $PM_{2.5}$ refers to particles less than 2.5 microns. $PM_{2.5}$ is often called fine particulate matter. $PM_{0.1}$ refers to particles with diameter of 0.1 microns (100 nm) or less and is often called ultrafine particulate matter. Since aviation PM is smaller than 0.1 microns, it qualifies as $PM_{0.1}$ $PM_{2.5}$ and PM_{10}. In mass terms, however, the larger particles, which are not combustion engine generated, overwhelm the smaller engine produced ones.

During the CAEP/10 cycle, an assessment was developed[14] of trends for the future growth of a number of key emissions with a base year of 2010 and forecast horizon of 2040. A summary of this assessment was presented to this Review at the Berlin workshop. Total fleet fuel burn (and hence CO_2 production) was predicted to grow by a factor of between 2.8 and 3.9. Landing-take-off cycle (LTO) NO_x burdens were forecast under three scenarios (The LTO cycle, as defined by CAEP, is described in Appendix C under the NO_x Standard description): Current Technology, Moderate Technical improvements coupled with some operational measures and finally Advanced Technologies plus significant operational improvements. In the CAEP assessment, moderate advances were defined as technology reaching 50% of the 2026 NO_x goal and Advanced Technologies defined as reaching 100% of the 2026 NO_x goal. The results of the assessment show the total LTO NO_x burden is set to rise fourfold in the case of current technology, tripling under the middle scenario and still doubling under the most optimistic scenario. The CAEP/10 trends assessment also shows a tripling by 2040 of total emitted LTO aircraft engine nvPM emissions.

The first international regulations for aircraft emissions were issued by ICAO in 1981 and included smoke, fuel venting and gaseous emissions, including NO_x. At that time, the only impacts considered were those on air quality in the neighbourhood of the airport. The regulations are based on a standard LTO, which includes approach and taxi phases. For NO_x, the regulation is based on the mass of emitted pollutants, written D_p, being normalized by the static engine thrust at sea-level, written F_{oo}, and the permitted level of NO_x, D_p/F_{oo}, is allowed to increase with the overall pressure ratio of the engine. Despite successive increases in the stringency of the NO_x Standards, the increase in the overall pressure ratio of engines means that the NO_x Emissions Index (g NO_x per kg fuel burned) has continued to rise. This is shown and discussed in Chapter 5. Concern has grown rapidly in recent years about the health effects of PM, and particularly $PM_{2.5}$ and ultrafine PM. In the current regulation, there is a limit on smoke based on a surrogate for plume opacity but CAEP is developing an nvPM Standard based on mass and number of particles less than 2.5 μm that is expected to eventually replace the smoke regulation.

The connections between aviation emissions and atmospheric processes, air quality, climate change and potential damages are shown in Figure 3-1. Aviation emissions undergo various chemical and physical transformations and accumulate in the atmosphere leading to a change in air quality and radiative forcing. Radiative forcing (RF in watts per square meter) is a measure of the imbalance in the Earth's radiation budget compared with the preindustrial era which, depending on its sign, has either a warming or cooling effect at the earth's surface. RF is used to compare the climate impacts of different gaseous and particulate emissions and their products, and expresses an instantaneous change in the energy balance due to these changes. A sustained positive RF imposes a warming effect, a sustained negative value imposes a cooling effect. A significant problem arises because the various pollutants emitted into the atmosphere, or their subsequent chemical transformations, have very different residence times, yet it is the combination of residence time and the value of RF associated with a particular pollutant which determines overall long-term impact on global surface temperature. In the case of aircraft emissions, there is great variability in both RF values and their residence times. This important factor is dealt with more fully in section 3.4 below, which covers the effect aircraft have on the global climate.

NO_x and SO_x are both precursors for secondary PM, also referred to as aerosols, and may interact with ambient ammonia, while NO_x, HC and CO can lead to ozone production. PM and ozone both then have an impact on air quality, in addition to affecting the radiative forcing. CO_2 and water vapour are both greenhouse gases directly emitted by the engine though, at the altitudes which subsonic aircraft fly, the water vapour effect is very small (although this would not be true of water vapour emitted into the mid-stratosphere by supersonic aircraft). NO_x emissions increase the concentration of ozone in the short-term but reduce the concentration of ambient methane (CH_4), both of which are greenhouse gases, and in turn the reduction in

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[14] Present and Future Aircraft Noise & Emissions Trends, Working Paper 55, ICAO 39th Assembly, 17 June 2016 https://www.icao.int/Meetings/a39/Documents/WP/wp_055_en.pdf

methane reduces the concentration of human induced stratospheric water vapour from CH_4 decomposition, which is also a greenhouse gas. In addition, the reduction in CH_4 causes a small long-term decrease in ambient ozone.

The PM species also affect radiative forcing both directly and indirectly through clouds. Contrails have an overall short-term effect on radiative forcing and result from water vapour emissions in combination with emitted or background aerosols. Persistent contrails, which form at high ambient relative humidity and low temperatures, can at times increase cloudiness by spreading into cirrus cloud-like structures which, like linear contrails, will have either a positive or negative effect on RF, depending on whether day or night, and whether summer or winter, but overall have a strong positive RF effect. Finally, aviation aerosols may modify natural clouds or trigger additional cirrus cloud formation, which also affects radiative forcing although the sign is currently uncertain. Lastly, the sulphate particles may affect lower-level clouds by decreasing the cloud droplet size, and increasing concentration – a brightening effect – which has a negative RF but the magnitude of this is uncertain.

In terms of air quality, previous IE NO_x reviews focussed mainly on the impact of aircraft emissions in and around airports from operations related to the LTO cycle. For this review, attention has also been given to the effects on air quality of aircraft emissions beyond the LTO cycle, including at cruise. These two elements, LTO and non-LTO aspects of emissions, are handled separately below.

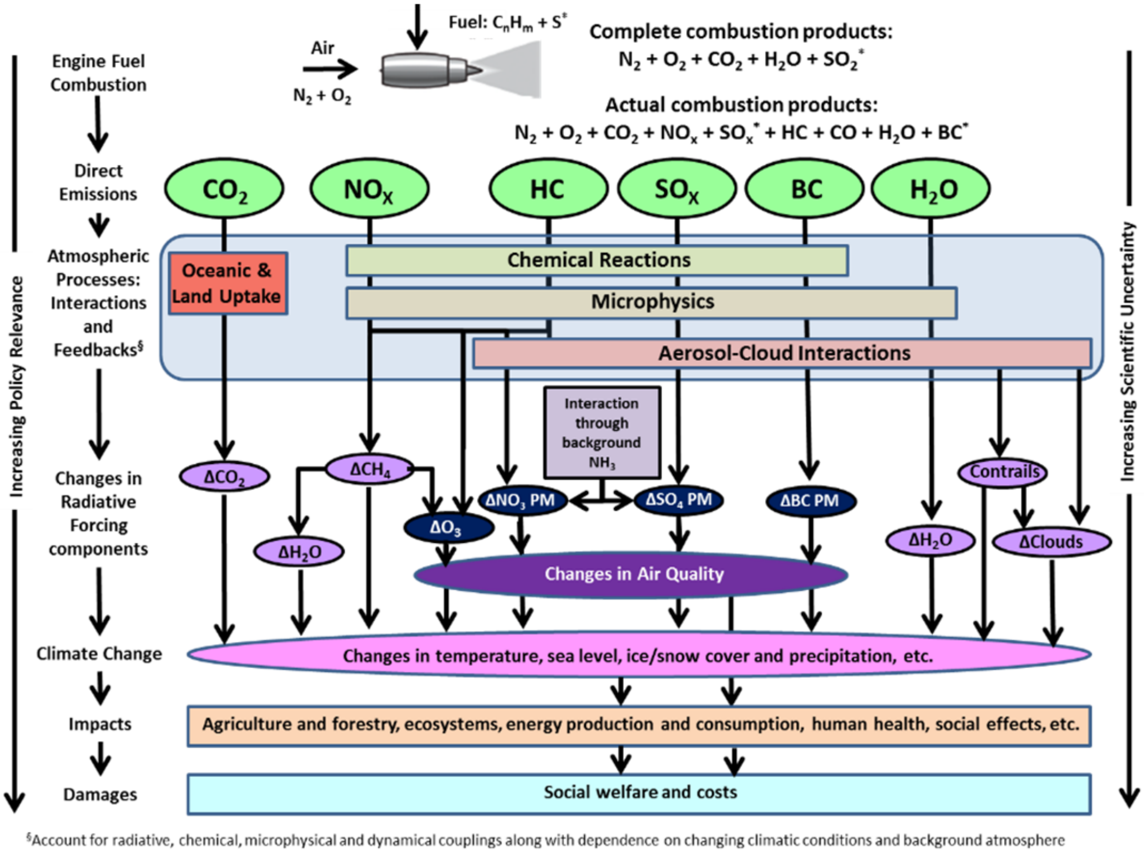

Figure modified from Brasseur et al (2016)

Figure 3-1. Relationship between Aircraft Emissions, Impacts, and Damages

3.3 AIR QUALITY IMPACTS

Knowledge about the health impacts of aircraft emissions have advanced since ICAO established its first emissions regulation in 1981. Prolonged exposure to elevated levels of ozone, and to some extent NO_2, has been shown to cause inflammation of the respiratory tract resulting in breathing impairment. Fine and ultrafine particulate matter has been shown to penetrate deep in to the lung tissue where they are absorbed in to the blood stream. There have been several large studies[15,16,17,18,19] and reports on the health impacts of aircraft related PM including ultrafine PM, O_3, NO_x /NO_2 and SO_2. In some areas, these studies have provided unclear or even conflicted findings, particularly when epidemiological methods are used to try and establish species-specific evidence of health effects. In some cases, associations with adverse health outcomes have even been shown from long-term exposure levels lower than those used as a basis for air quality guidelines and this is particularly true for PM, and to a lesser extent NO_2. With regard to ozone, there appears to be evidence emerging of adverse effects from long-term, in terms of months to years, exposure at levels below air quality guidelines. Further studies are continuing.

NO_x is a mixture of oxides of nitrogen of which NO_2 is considered to have the largest potential effect on health. For NO_2, epidemiological evidence appears confusing with some studies apparently reporting adverse effects from both short- and long-term exposures from which it seems reasonable to infer that NO_2 has direct effects. There is also evidence that some interpreted effects may have been due to other constituents present alongside NO_2. The U.S. EPA[20] reports that "breathing air with a high concentration of NO_2 can irritate airways in the human respiratory system. Such exposures over short periods can aggravate respiratory diseases, particularly asthma, leading to respiratory symptoms, hospital admissions and visits to emergency rooms. Longer exposures to elevated concentrations of NO_2 may contribute to the development of asthma and potentially increase susceptibility to respiratory infections". Some studies have concluded, for example REVIHAAP[21], that the effects on mortality of long-term exposure to typical concentration levels of NO_2 are similar to, if not larger than, for PM. Few people have long-term exposure to high concentrations of NO_2 due to aircraft.

Studies have linked long-term exposure of $PM_{2.5}$ to an increased risk of premature mortality and there does not appear to be a "no-effect" lower threshold. Furthermore, there is at present no *epidemiological* evidence that secondary $PM_{2.5}$ (e.g., from ammonium sulphate and ammonium nitrate) should be treated differently from other forms of $PM_{2.5}$ (e.g., non-volatile particulate matter) from a health impacts perspective. Toxicology, however, points to the toxic organic chemicals caused by incomplete combustion forming more harmful PM, with these organic compounds very likely coating or carried by small carbon particles, or soot. The epidemiological evidence leads to all of the $PM_{2.5}$ produced by aviation, whether it be produced within the exhaust plume of a jet engine or whether it be produced far from the aircraft operation, being treated as equally harmful. More recently, there has been growing concern about the health effects of ultrafine PM (smaller than 0.1 µm), which is the size of particle jet engines predominantly produce. Diesel engines also

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[15] Laden, F., Schwartz, J., Speizer, F.E., Dockery, D.W., 2006. Reduction in Fine Particulate Air Pollution and Mortality. Am J Respir Crit Care Med 173, 667–672. doi:10.1164/rccm.200503-443OC

[16] Jerrett, M., et.al.., 2009. Long-Term Ozone Exposure and Mortality. New England Journal of Medicine 360, 1085–1095. doi:10.1056/NEJMoa0803894

[17] WHO, 2008. Health risks of ozone from long-range transboundary air pollution. WHO, Copenhagen.

[18] Committee on the Medical Effects of Air Pollutants (2009) "Long-Term Exposure to Air Pollution: Effect on Mortality" Review of evidence on health aspects of air pollution REVIHAPP project, Technical Report 2013

[19] US EPA, 2011. The Benefits and Costs of the Clean Air Act from 1990 to 2020, http://www.epa.gov/cleanairactbenefits/feb11/fullreport_rev_a.pdf (accessed 5.5.15).

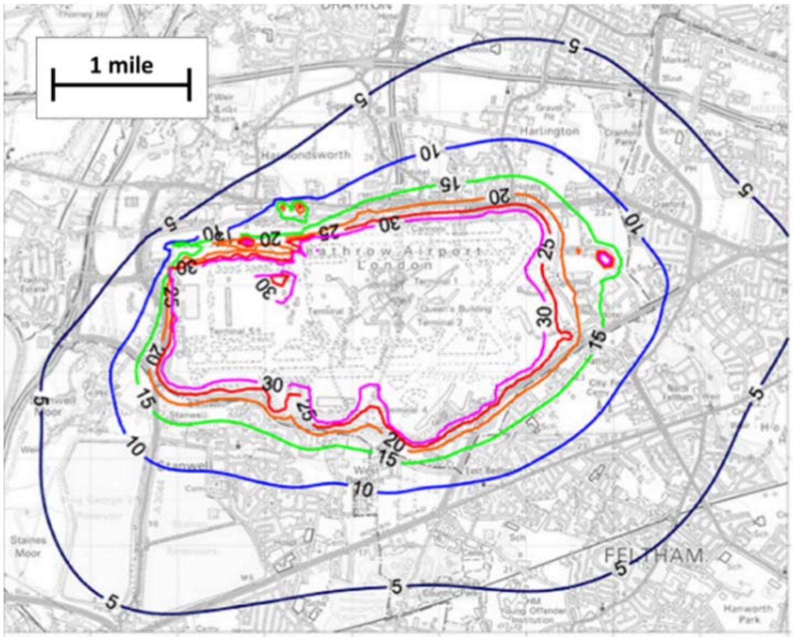
[20] U.S. EPA, "Basic Information on NO_2" see https://www.epa.gov/no2-pollution/basic-information-about-no2#Effects. Last updated Sept 8, 2016

[21] WHO/Europe, "Review of evidence on health aspects of air pollution – REVIHAAP project: final technical report," 2013. Available at http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report

produce particles in the ultrafine range and many diesel engines operate in or around airports. When particles are measured in terms of mass the large particles tend to dominate, although these do not appear to be produced directly by combustion in engines. It is therefore essential to consider the number and size distribution of particles, and not just the mass, to give appropriate emphasis to the smaller sizes which are thought to be more harmful. Further work is needed to confirm the extent of the effects from exposure to ultrafine PM as opposed to larger particles and on the relative toxicity of different chemical compositions. The membership of the IE panel did not include anyone sufficiently expert in toxicology or epidemiology to weigh properly the, sometimes conflicting, evidence on these matters.

3.3.1 **Air Quality Impacts from LTO Emissions**

It is well known that there are many sources of emissions in the vicinity of airports and that aircraft engines are not the major contributors to reduced air quality even a short distance beyond the airport boundary. Figure 3-2, taken from the Heathrow Airport Ltd.'s 2008/9 Emissions[22] inventory modelling evaluation, shows contours of the *airport contribution* to annual mean NO_x concentration around London Heathrow[23] Airport. A steep decline in concentration away from the airport is apparent to where air quality is determined by the contributions from other sources such as road transport, industry, agriculture and other local and regional sources. In considering the levels around the boundary of the airport it should be noted that the World Health Organization (WHO) 2005 guidelines for annual mean level of NO_2 (the more toxic part of NO_x) is 40 µg/m^3.



(Contours Shown for $5g/\mu m^3$ to $30g/\mu m^3$)

Figure 3-2. Airport Contribution to 2008/9 Period-mean NO_x Concentrations

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[22] Heathrow Air Quality Strategy 2011 2020, https://www.heathrow.com/file_source/Company/Static/PDF/Communityandenvironment/air-quality-strategy_LHR.pdf

[23] Several references are made to London Heathrow Airport. This reflects the easy accessibility of results, partly associated with the continuing controversy surrounding the proposed third runway. It is also an airport running near its maximum capacity.

Well within the airport boundary, and when considering only airport emission sources (including landside access traffic), the contribution from aircraft can be significant; for example, between 80% and 90% of NO_x[24] and around 40% of PM[25] being attributed to aircraft LTO operations. Even at the boundary of London Heathrow Airport only half of the NO_2 concentration levels are thought to be airport related, and of the airport related NO2 concentration at the airport boundary, about half is thought to be attributable to aircraft themselves[26,27].

Despite the evidence that NO_x from aircraft is, at worst, a localized problem, many airports are located in, or close to, areas of high ambient pollution levels. For example, in the US, 43 of the top 50 airports are in "non-attainment" ozone areas and 12 of the top 50 are in $PM_{2.5}$ "non-attainment areas", respectively[28,29]. The airports are therefore seen to be contributing to an already difficult situation. For example, Figure 3.3 shows a map of annual mean concentration of NO_2 for a wide area of London. Heathrow Airport is easily identified to the west of the city as a small island (small compared to the city itself) with NO_2 concentrations generally lower than business and residential areas of central London where the levels exceed the WHO guidelines for annual mean level of NO_2 of 40 μg/m^3.

Even though one can see London Heathrow on a wider area map of NO_2 concentrations, it is not observable on a similar map of $PM_{2.5}$ mass concentration. In fact, the $PM_{2.5}$ mass concentration levels within the airport perimeter of Heathrow are indistinguishable from those in the surrounding urban communities – aviation is a small contributor to the mass of $PM_{2.5}$. Models have found that non-volatile PM (i.e. soot or black carbon) due to aviation emissions contributes between 44 - 61% by mass of total aviation-attributable $PM_{2.5}$ at 2 km distances from airports, with the percentage decreasing as distance from the airport increases, although such attribution will be location-specific. At 20 km, the percentage has dropped to less than 6%[30]. However, PM from aviation is a small contributor and has been estimated to contribute about 0.5% by mass of all anthropogenic sources[31]. Similarly, the contribution from aviation-attributable $PM_{2.5}$ has been modelled to be less than 1% of the total levels of ambient $PM_{2.5}$ in the cities surrounding all of the major airports in the US[28]. Estimates of the aircraft contribution to the PM number burden are harder to find but have been estimated to range from 2% - 12%[31]. At the $PM_{2.5}$ mass level, the contribution of aviation seems minor but this finding, and even the number findings, may mask the contribution aircraft make in respect of ultrafine particles including those which may be much smaller than 0.1 μm and which are believed to be far more injurious to health. Therefore any intention to regulate PM should include this consideration. One significant issue being worked on is that the numbers of particles with sizes below 0.01 μm are difficult to establish due to sampling and instrument limitations[32].

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[24] Zurich Airport NO_x 2015, https://www.zurich-airport.com/~/media/flughafenzh/dokumente/das_unternehmen/laerm_politik_und_umwelt/luft/lokale_luftqualitaet.pdf

[25] Frankfurt Airport PM_{10} Umweltbericht 2005, https://www.fraport.de/content/fraport/de/misc/binaer/unternehmen/verantwortung/publikationen/umwelt/umwelterklaerungen/umwelterklaerung2005/jcr:content.file/umwelterklaerung_2005.pdf

[26] Heathrow Airport 2013 Air Quality Assessment, Ricardo –AEA/R/3438 2015

[27] D. Carslaw et al, Impact of Heathrow Airport Closure Due to the Eruption of Eyjafjallajokull DOI:10.1016/j.atmosenv.2012.02.020

[28] Aviation Emissions, Impacts and Mitigations: A Primer. FAA, Office of Environment and Energy, January 2015.

[29] US Clean Air Act Amendments of 1990, Title I-Provisions for Attainment and Maintenance of National Ambient Air Quality Standards, Section 101 (d)(1), November 15, 1990.

[30] Arunachalam, S. et al, 2011, Effect of Chemistry-transport model scale and resolution on population exposure to $PM_{2.5}$ from aircraft emissions during landing and takeoff, Atmospheric Environment 45, 3294-3300, doi: 10.1016/jatmosenv.2011.03.029

[31] Righi, M. et al, 2013, The global impact of the transport sectors on atmospheric aerosol: simulation for year 2000 emissions, Atmos. Chem. Phys 13, 9939-9970. doi: 10.5194/acp-13-9939-2013

[32] For particles of the same density and shape, one of 2.5 μm will have a mass 15610 times that of one of 0.1 μm

Figure 3-4[33] shows the measured size distribution close to the exit nozzle of an engine with an unstaged single annular combustor (CFM56-1) for four different power settings. The four peaks sit at between approximately 20μm to 50μm so well below a nominal $PM_{2.5}$. At further distances from the exit nozzle a second peak at even smaller sizes is formed from condensable gases with a nominal peak at 10μm but instrument limitations mask the true sizes which are even smaller and the numbers are consequently much larger. Further away still, coagulation and condensational growth occurs so the numbers fall off as the sizes increase.

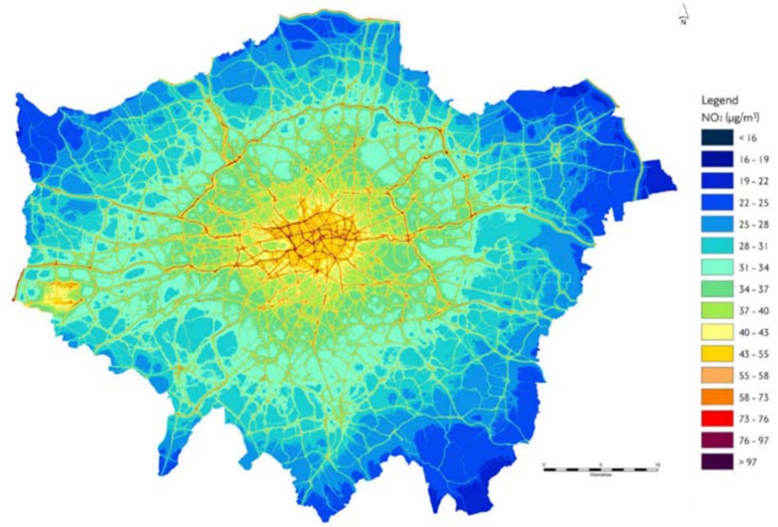

Figure 3-3. Greater London Annual Mean NO_2 Concentrations for 2013[34]

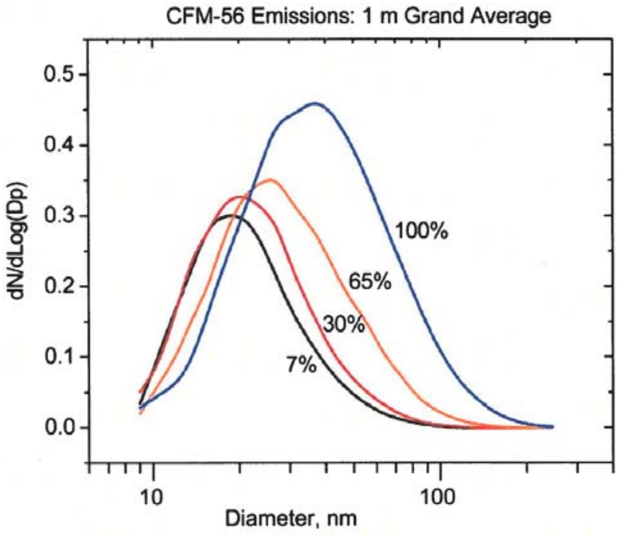

Figure 3-4. Measured Particle Size Distribution Close to the Exit Nozzle

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[33] C C Wey et al, Nasa Technical Memorandum, NASA/TM-2006-214382, APEX

[34] King's College London, "London Annual Pollution Maps," see https://www.londonair.org.uk/london/asp/annualmaps.asp. Updated 2016.

It should be remembered that there are many sources of $PM_{2.5}$ near airports and this $PM_{2.5}$ level includes ammonium nitrate and ammonium sulphate, in part, from reactions of aircraft-emitted species such as NO_x and SO_x with background ammonia. These reactions with other background chemicals often occur at downwind distances, up to hundreds of kilometres from the airport. As the impact of aviation emissions is dependent on the concentration of background chemicals, changes in background concentrations will alter the amount of aviation emissions that are converted to $PM_{2.5}$. As a result of potential changes in background concentrations[35,36], aircraft attributable $PM_{2.5}$ could rise faster than simply the growth in aviation emissions of precursor gases.

Recent modelling work was presented to this review which calculated an increase in human mortality due solely to the aircraft related LTO emissions of 2,400 to 6,200 premature deaths worldwide[37] with an average loss of 11 years. These are calculated on the assumption that particulates cause the same mortality regardless of chemical composition. The modelling work also calculated that health impacts of aviation LTO emissions are dominated by $PM_{2.5}$, with only 1% of the calculated premature mortalities from LTO attributable to NO_x and ozone pollution. It is difficult for this review to attribute confidence levels to such estimates, given the breadth of uncertainties and assumptions that are required to be made and the previously discussed difficulties with the identification of specific causes. Nonetheless, they are thought to provide some kind of comparison with the estimated worldwide total number of premature deaths due to particulate matter pollution, which was recently estimated as 4.2 million people[38].

3.3.2 Air Quality Impacts from Full Flight Emissions

Concerns about air quality effects resulting from NO_x and PM emitted from aircraft flying above LTO altitudes, mainly at cruise, did not feature in previous IE reviews. However, less than ten per cent of commercial aviation fuel is burned under the 3000ft LTO ceiling[39]. The FAA and several European organizations have been sponsoring studies to compare the impacts of non-LTO emissions from commercial aircraft activities worldwide on surface ozone, PM and ultrafine PM using climate-response and chemical-transport models. These studies have calculated that ozone produced from NO_x emitted at altitude by aircraft at cruise increases near-surface ozone between 0.4% and 1.9% globally[40]. However, mass of NO_x from natural sources exceed those from aviation by more than an order of magnitude. The perturbations due to aviation were shown to be highest in the northern-hemisphere winter when ambient ozone levels are lower, so are of less concern to human health; enhanced levels in the summer months, however, when ambient levels are also higher, are thought to be potentially of concern. Nevertheless, the increased ozone levels are small compared with other sources.

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[35] Ashok, A., Lee, I.H., Arunachalam, S., Waitz, I.A., Yim, S.H.L., Barrett, S.R.H., 2013. "Development of a response surface model of aviation's air quality impacts in the United States". Atmospheric Environment 77, 445–452. doi:10.1016/j.atmosenv.2013.05.023

[36] Woody, M., Haeng Baek, B., Adelman, Z., Omary, M., Fat Lam, Y., Jason West, J., Arunachalam, S., 2011. "An assessment of Aviation's contribution to current and future fine particulate matter in the United States". Atmospheric Environment 45, 3424–3433. doi:10.1016/j.atmosenv.2011.03.041

[37] Yim, S.H.L., Lee, G.L., Lee, I.H., Allroggen, F., Ashok, A., Caiazzo, F., Eastham, S.D., Malina, R., Barrett, S.R.H., 2015. "Global, regional and local health impacts of civil aviation emissions". Environ. Res. Lett. 10, 034001. doi:10.1088/1748-9326/10/3/034001

[38] The Lancet Commission on pollution and health (2017), The Lancet, Volume 391, No. 10119, doi:10.1016/S0140-6736(17)32345-0

[39] Grewe, V., et al., Attributing ozone to NO_x emissions: Implications for climate mitigation measures, Atmos. Environm., 59, DOI: 10.1016/j.atmosenv.2012.05.002, 102-107, 2012

[40] Cameron, M. A., et al. (2017), "An inter-comparative study of the effects of aircraft emissions on surface air quality", J. Geophys. Res. Atmos., 122, 8325–8344, doi:10.1002/2016JD025594

Modelled changes to surface-level $PM_{2.5}$ appear less consistent than for ozone. The models showed that full-flight aircraft emissions lead to a change in surface $PM_{2.5}$ that varied from -1.9 to +1.2%. The wide range in results depends on whether or not the models utilize feedbacks between aviation emissions and meteorology. Nevertheless, as for ozone, the levels of increase are relatively small compared with all other sources. However, a key concern put to the IEs is that even though the increases at ground level in ozone and PM pollutants attributed to aircraft emissions at cruise represent only a small increase on the overall level, the increase occurs on a global scale and therefore the number of people affected is much larger than for LTO related effects, with the presumption that there is no threshold level.

Data was presented which showed that aircraft are a significant producer of global PM by *number* as compared with other transport sectors; in the year 2000, aircraft produced similar numbers of particles as land-based transport sources and significantly more than shipping[31]. However, the data for aviation were for cruise altitudes and the authors did not comment on the proportion of this number of particles that would reach the surface of the earth as $PM_{2.5}$. Premature mortalities due to full-flight aircraft emissions impacts have been estimated to be 8,300 to 24,000 in 2006 at an average loss of 11 years[41]. This rests on the assumption that all particulate matter is equally harmful to health and that there is no threshold of concentration below which there is no effect. Of the total premature mortalities, 87% and 13% are said to be due to $PM_{2.5}$ and ozone, respectively. Of these, only about 25% is said to be attributable to the LTO portion. For the remaining 75%, cruise NO_x is said to be the dominant precursor to ozone formation and cruise NO_x and SO_x emissions were the dominant contributors to $PM_{2.5}$ formation through a coupling with non-aviation sources of ammonia. Once again, it is difficult for this review to attribute confidence levels to such estimates given the breadth of uncertainties and assumptions that are required to be made. Again, to provide some kind of comparison, the Lancet study[38] recently estimated worldwide total number of premature deaths due to particulate matter pollution as 4.2 million people. There is disagreement in the scientific community on this subject with noted researchers stating that due to, "the uncertainties and the small perturbations in $PM_{2.5}$ due to aviation, we think it is premature to make any conclusions about mortality of aviation impact with any certainty"[42]. A further paper[43] seeks to harmonize the different models and does find a surface effect of the emissions at cruise. Whilst none of the IEs have sufficient expertise to develop firm independent conclusions on the health effects of emissions, the emerging contribution of emissions during cruise is clearly of concern though as yet significant uncertainties remain.

3.4 GLOBAL CLIMATE CHANGE CONTRIBUTIONS

The Intergovernmental Panel on Climate Change laid out the basic attribution of aviation's role in climate change and quantified its contribution in a Special Report in 1999[44]. These findings were reported previously in technology goal reviews, notably the two CAEP Independent Expert NO_x reviews in 2006 and 2009, also for the CAEP Independent Expert Fuel burn Technology Review in 2010. More recently for the CAEP/10 cycle the CAEP Impact and Science Group (ISG) was tasked with convening a CAEP Aviation Environmental Impacts Seminar and a summary of the findings was reported in the form of a "White Paper" at the CAEP/10 meeting[45].

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[41] Yim, S.H.L., et al, 2015. Global, regional and local health impacts of civil aviation emissions. Environ. Res. Lett. 10.

[42] Lee, H. et al., 2013. Impacts of aircraft emissions on the air quality near the ground, Atmos.Chem.Phys., 13,5505-5522, doi.org:/10.5194/acp-13-5505-2013

[43] Cameron, M.A., et al, 2017. "An Inter-comparative Study of the Effects of Aircraft Emissions on Surface Air Quality". Accepted for Journal of Geophysical Research Atmospheres.

[44] Penner, J.E. et al, Aviation and the Global Atmosphere, A Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge

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

As already noted, the principal greenhouse gases emitted from aircraft engine exhausts are carbon dioxide and water vapour, though at the altitudes at which subsonic aircraft cruise, the effect of water vapour is very small. The much smaller quantities of NO_x emitted interact with other gases in the atmosphere, notably ozone and methane. Black carbon or soot is directly emitted as nvPM. Water vapour emissions, in combination with emitted or ambient aerosols already present in the atmosphere, may lead to contrail formation, depending on the background conditions of the atmosphere. If the atmosphere is ice-supersaturated, as it often is near the tropopause where turbo-fan powered aircraft in particular find it efficient to fly, the contrails can persist and lead to the formation of cirrus clouds. The RF associated with the aircraft induced cloudiness is much larger than that from linear contrails[46]. Separately, aviation aerosols may modify natural clouds or even trigger cloud formation.

Several metrics might be used to compare global climate impacts of aircraft emissions with those from other sectors as emission-equivalences to CO_2, including Global Warming Potential (GWP) and Global Temperature change Potential (GTP) as examples. However, these come with the complication of requiring a specified time period for the assessment. Radiative forcing, by contrast, is a measure of the effects of all releases up to the present day. As already noted RF is a commonly used metric to compare the change caused by each component and is a measure of the imbalance in the earth's radiation budget caused by changes in the concentrations of gases, aerosols and cloudiness. It is therefore a measure of 'impact', rather than emission equivalence, which is the case for GWP or GTP. However, RF only accounts for the change in the radiative balance so that it does not take account of future emissions and, therefore, does not fully describe the changes in global temperatures and other impacts.

The importance of longevity is well illustrated by considering the three most significant aviation RF components: CO_2, contrails/cirrus and NO_x. There have been some recent changes in the understanding of NO_x which have reduced its climate impact and these are discussed further below. CO_2 is considered to have the most significant long-term impact on global climate change because of the long residence times in the carbon cycle; 50% of a CO_2 pulse emission will be removed within about 30 years, another 30% will be removed within a few centuries but 20% will still be contributing to global climate change for many millennia. At the other extreme, contrails may survive for only minutes or hours and even induced cirrus clouds for less than a day, yet they are currently estimated to have a higher RF value than CO_2. The timing of contrail formation is significant as it could even have a cooling effect if created and dispersed only during the daytime. The NO_x impact timescale lies somewhere between CO_2 and contrails/cirrus with a pulse of NO_x converting to O_3 over a few days but then the O_3 warming effect gradually declines over months rather than centuries as in the case of CO_2, and the cooling effect from CH_4 reductions declines over decades.

The actual climate impact depends on the persistence of the forcing after the actual emission has occurred, sometimes long after, because the lifetimes of the various components are so very different. It is important to note that when assessing impacts on, for example global temperature, the assumed integration time, whether years, decades or centuries, is of paramount importance. In the very long-term (centuries and beyond), the accumulation of CO_2 is expected to be of the greatest importance. Previous goals reviews have received and considered charts showing the comparative contributions to Global Climate Change (GCC) only in terms of RF.

Figure 3-5, taken from Lee et al 2009[47], shows the RF contributions of the key aviation emissions together with a total for aviation at the bottom of the chart; the total is shown with and without the contribution from induced cirrus cloudiness. Despite the 2009 date, in fact the RF data mostly used base data from 2005 and was reviewed by the second CAEP IE NO_x review in 2009. The error bars exhibit a wide spread indicating considerable uncertainty, notably in ozone production, methane reduction (i.e. oxidation)

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[46] Burkhardt, U. and Kärcher, B. "Global radiative forcing from contrail cirrus". Nature Climate Change, Vol 1 (2011)

[47] Lee, D.S.,et al, Aviation and Global Climate Change in the 21st Century, Atmospheric Environment, 43 (2009): 3520-3537

associated with NO_x, and also induced cirrus or cloudiness. Consequently, the error bars for total RF from aviation are wide, particularly when induced cirrus is included. New information and further understanding has developed since Figure 3-5 was published, but no new consensus RF chart has been compiled and an international scientific assessment to revise the 2009 RF data has not taken place in the intervening years. Some explanation of the current understanding and the key changes since 2009 are captured below:

CO_2

- There has been no change in the basic scientific understanding as this is well understood (there is a high level of scientific understanding). The radiative forcing due to CO_2 will have increased because concentration has increased in line with the additional fuel burned between 2005 and the present day. Currently CO_2 is thought to contribute around 30-40% of the total aircraft-related RF.

NO_x

- There has been significant evolution in the science with the overall effect being that net RF per unit NO_x emission has roughly halved from that in Lee et al. 2009. The reduction is due to the inclusion of two additional negative terms that capture the long-term reduction in background ozone that results from NO_x production[48] and the decrease in background stratospheric water vapour[49]. An additional correction has been proposed[50] that addresses a detail in the calculation of the steady-state CH_4 response that would potentially offset some of these additional negative terms but the value of this is not well established. The increased RF due to increased overall concentration of aircraft produced NO_x since 2009 will not have been large enough to compensate for the possible halving due to improved scientific understanding.
- There remain difficulties in quantitatively evaluating the climate response to aviation NO_x because the atmospheric lifetimes associated with NO_x-induced O_3 and CH_4 responses are different and lead to non-uniform perturbations in these climate-forcing agents. The magnitudes of the O_3 and CH_4 responses also depend on the geographic location of the NO_x emissions and the amount of background NO_x emissions present. Recent studies[51] indicate that the background concentrations are likely to have a very significant effect on the overall NOx RF though further work is needed.

Water Vapour

- More recent assessments of water vapour indicate that this effect is smaller than the Lee et al. 2009 assessment.
- Water vapour emissions in the upper troposphere, where subsonic commercial aircraft fly, has a relatively small positive RF. However, water vapour emissions into the stratosphere, which is where any future supersonic aircraft are expected to operate, have a relatively large positive RF.

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[48] Wild O., Prather M. J., Akimoto H., 2001. Indirect long-term global radiative cooling from NO_x emissions. Geophysical Research Letters 28, 1719–1722.

[49] Myhre G., Nilsen J.S., Gulstad L., Shine K.P., Rognerud B., Isaksen I. S. A., 2007. Radiative forcing due to stratospheric water vapour from CH_4 oxidation. Geophysical Research Letters 34, L01807.

[50] Myhre G., Shine K. P., Rädel G., Gauss M., Isaksen I. S. A., Tang Q., Prather M. J., Williams J. E., van Velthoven P., Dessens O., Koffi B., Szopa S., Hoor P., Grewe V., Borken-Kleefeld J., Berntsen T. K., Fuglestvedt J. S., 2011. Radiative forcing due to changes in ozone and methane caused by the transport sector. Atmospheric Environment 45, 387–394.

[51] Freeman S., Lee D. S., Lim L. L., Skowron A. and De León R. R. (2018) Trading off aircraft fuel burn and NO_x emissions for optimal climate policy. *Environmental Science and Technology*. DOI: 10.1021/acs.est.7b05719

Soot and Sulfur

- There is no appreciable change in basic scientific understanding of direct effects of soot and sulphate aerosols. Considerable efforts are underway to better understand what contributes to aviation-induced cloudiness (see next section).
- Soot and sulphate aerosol themselves have relatively small direct RF impacts; soot has a small positive RF, and sulphate a small negative RF.

Aviation-induced Cloudiness

- Advances in science in recent years have resulted in relatively greater certainty in climate impacts of contrails and contrail cirrus. Recent publications consider there now is a "low" level of scientific understanding for climate impacts of aviation-induced cirrus clouds as opposed to the previously "very low"[52].
- Recent studies indicate RF contributions of between 13 to 50 mW/m^2 for both contrails and contrail induced cirrus combined; there are higher estimates, for example the IPCC estimates up to 150mW/m^2, but with low confidence.
- There is a large potential indirect RF contribution from soot-induced cloudiness (black carbon) and sulphur-induced indirect effects on lower-level clouds with large uncertainty; spot values from the soot effect ranging from -90 to +100 mW/m^2. What is new since the previous reviews is the focus on a potentially much larger aerosol-induced indirect effects giving changes in background cloudiness. Indirect effects are less studied, with few published RF estimates, reflecting the difficulty in understanding and modelling the necessary nucleation processes. For example, 2013 IPCC Fourth Assessment Report provides no estimates of indirect effects of aviation aerosol. The positive sign, if not the magnitude, of the effect of sulfur emissions on lower-level clouds is more certain.
- The IEs are aware that reducing the efficiency with which an engine converts energy in the fuel into propulsive power leads to a reduction in contrail formation. The reduction is small, however, so a large increase in CO_2 would not result in producing anything like a significant decrease in contrail/cirrus. Changes in fuel composition, to reduce nucleation, have been suggested, which might also be beneficial for reducing nvPM for health reasons, but would potentially involve increased costs at the refinery. Nevertheless, its evaluation could be useful. Re-routing some flights to avoid regions of ice supersaturated air is one non-technical potential solution which could be considered, but there are major implications, notably in the operational, infrastructure and environmental fields, along with trade-offs associated with any increased fuel usage, and therefore CO_2 emissions, resulting from re-routing.

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[52] Brasseur et al., 2016: Impact of Aviation on Climate: FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II. Bull. Amer. Meteor. Soc., 97, 561–583, https://doi.org/10.1175/BAMS-D-13-00089.1

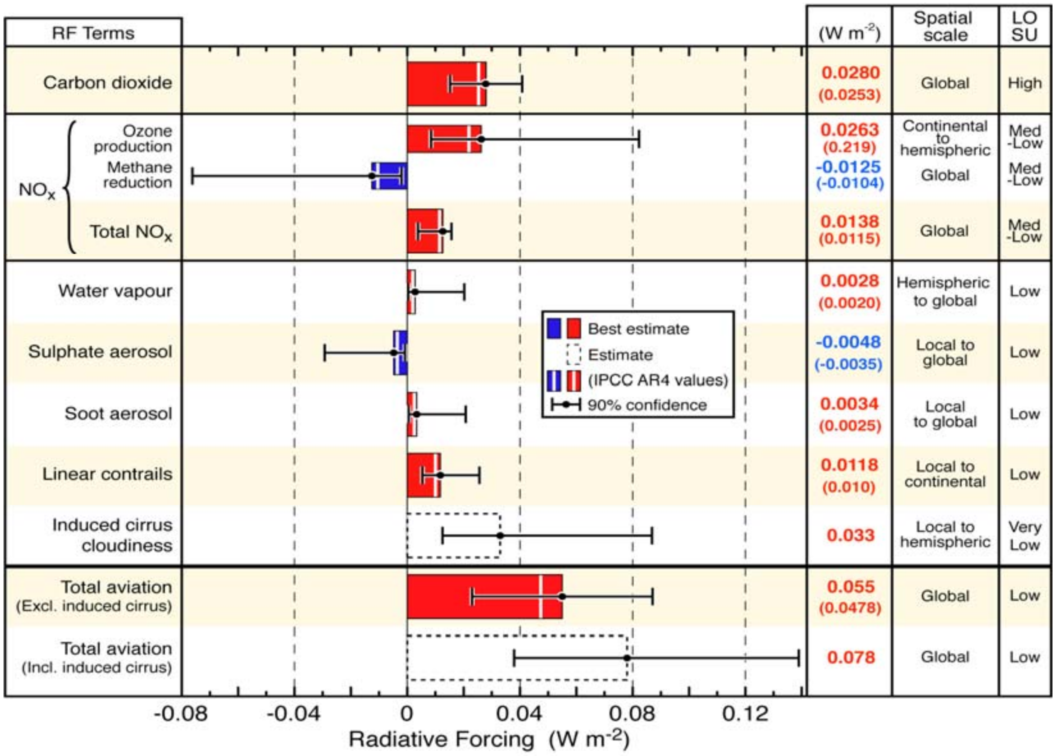

Figure 3-5. IPCC RF Components from Global Aviation from Pre-industrial Times to 2009

3.5 SUMMARY OF AVIATION EMISSIONS CONTRIBUTIONS

Against a backdrop of forecasts of significant increases in total fleet fuel burn and fleet emissions of NO_x and PM, the following key messages were noted from this review.

Air Quality associated with LTO Emissions:

- Well within the airport boundary, aircraft are a significant source of airport-related emissions, notably of NO_x and PM.
- At airport boundaries for many airports near cities, NO2 levels will be close to, or exceed, WHO annual limit values.
- Using London Heathrow as an example, in broad terms, at the boundary the airport contributes about half of the measured NO_2 concentration and the aircraft themselves contribute half of the airport contribution.
- Aircraft are a small contributor by mass of $PM_{2.5}$ and even at the airport boundary, concentration levels are indistinguishable from wider background levels in urban environments.
- There may, however, be an important health issue related to aircraft ultrafine PM as turbo-fan engines produce relatively large amounts by number of aerosols of less than 100μm .
- Beyond the airport boundary the aircraft influence decreases rapidly for NO_x/NO_2 and $PM_{2.5}$. Indeed aviation appears to be a low contributor to mass of $PM_{2.5}$ but aviation related ultrafine particles may be more important and deserve further study.
- There are many sources of $PM_{2.5}$ near, and downwind of, airports and this $PM_{2.5}$ level includes ammonium nitrate and ammonium sulphate formed, in part, from reactions with aircraft-emitted species such as NO_x and SO_x. These reactions with background ammonia occur at downwind distances up to several hundred kilometres from airports.

- Between 2400 to 6200 premature deaths in 2006 were attributed by some models to LTO operations with an average loss of 11 years, with $PM_{2.5}$ dominating over NO_x and ozone. These estimates assumed that all particulate matter is equally harmful and need to be compared with a total of 4.2 million premature deaths from all particulate matter.

Air Quality and Full-Flight Emissions:

- More than 90% of the fuel is burned above the LTO altitude and the corresponding emissions, notably NO_x and PM, are formally outside the LTO regulation and goals framework.
- It has been estimated that full-flight emissions of NO_x increase surface ozone by less than 2%, yet this is said to pose a health risk, particularly in summer months when background concentrations peak.
- Estimates for the impacts of full-flight emissions on surface PM are less consistent than for ozone and indicate a smaller increase.
- Data presented showed aircraft to be a significant contributor to global PM by number of particles, as compared with other transport modes, though the extent of its transport from flight altitudes to the surface was uncertain. Some of the particles at ground level are secondary in the sense that they are the result of NO_x or SO_x combining with ambient ammonia. Engines at cruise will also emit ultrafine particles and, as for LTO, these require more study.
- The exposure levels of the population to aircraft emissions from cruise are far lower than exposure for those who are close to LTO operations; however, the number of people exposed to small changes in surface emissions due to full-flight operations is much greater than for emissions from LTO operations.
- Mortality figures due to aircraft full-flight operations are even more difficult to estimate than for LTO. Nonetheless assuming that damage to health is linear with concentration, with no cut off below which there is no effect, an estimate was given to the IE Review of 8,300 to 24,000 premature deaths worldwide in 2006 with an average loss of 11 years. Again these numbers, which assume equal mortality to all chemical species, need to be compared with the total number of premature deaths due to particulate matter pollution, which was recently estimated at 4.2 million people.
- This increase in mortality due to full-flight emissions are greater than from those associated solely with LTO operations. As with LTO, losses due to $PM_{2.5}$ dominate though not quite as strongly. Cruise NO_x is the dominant precursor for ozone formation.

Global Climate Change contributions:

- It was noted that from the perspective of global climate change, the three most important aircraft concerns are CO_2, contrail/induced cloudiness and NO_x.
- CO_2 emissions are the prime concern due to their very long residence time in the atmosphere, lasting in part for thousands of years, and consequently their long-term contribution to climate change.
- It was noted during the reviews that anticipated aircraft fuel burn improvements arising from technological and operational advances will not keep pace with the expected rise in air travel and as a result total fleet fuel burn is expected, according to ICAO forecasts, to rise by a factor of between 2.8 to 3.9 by 2040 from a 2010 base year.
- Since the last NO_x review in 2009, the consensus view among scientists is that the net RF per unit emission of NO_x has reduced owing to additional negative terms. Nonetheless, it is still positive and it remains a concern.
- Recent studies have highlighted the considerable sensitivity of the aviation NO_x RF value to the concentration level of background NO_x and further work seems necessary in this area.
- It is regrettable that no recent comprehensive review commanding a consensus of opinion for all of the aviation RF components has been available to this review.

- It was noted that the mass of NO_x produced by the aircraft fleet is expected to rise by a factor of between 2 and 4 by 2040 from a 2010 base year.
- In the case of NO_x the only mitigation measures available are technological, and to a lesser extent, operational. This is in contrast to CO_2, where CAEP is proposing offsets and biofuels. There are no similar mitigation strategies planned to offset the climate effects of the expected significant rise in the mass of total fleet NO_x emitted, though it should be remembered that for a fixed value of EI NO_x, reduced fuel burn also results in reduced NO_x emissions.
- There is a large potential climate impact from contrails and aircraft induced cirrus/cloudiness. The level of understanding related to contrails is thought to be reasonably robust whereas there is only a low level of understanding of the impact of induced cloudiness with wide RF error bars.
- The contribution of aviation aerosols such as PM and sulfates to the formation of contrails and notably cirrus is not currently well understood.
- The formation of PM and soot is very dependent on the nature of the fuel used. Flight experiments with alternative fuels (with low aromatic content hydrocarbons or bio-fuels) reveal significant reductions in soot production.
- Aircraft CO_2 is thought to contribute about 30-35% of the total aircraft related RF.

3.6 AIRCRAFT NOISE AND ITS IMPACTS

Based on the CAEP/10 trends assessment, there are, and will continue to be, tens of millions of people affected by aircraft noise for the foreseeable future. According to the analysis, in 2010 there were between 21 and 35 million people across the globe exposed to a DNL[53] of 55 dB and between 2.3 and 4.7 million people globally exposed to DNL of 65 dB[54].

For CAEP/10, estimates were made for the year 2040 of the total world population forecast to be exposed to these two noise contour levels under four scenarios ranging from no technical change through to a maximum under scenario 4 of 0.3 EPNdB/year cumulative reduction over the whole period. For this analysis, aviation was assumed to grow according to the CAEP/10 forecasts. Table 3-2 lists that the number of people exposed to these two contour levels is expected to grow significantly even under the CAEP/10 Scenario 4 using the greatest rate of assumed technological improvement. It is important to note that the analysis assumed the population living near airports was unchanged between 2010 and 2040 and, therefore, probably under-predicts future population exposure to aircraft noise.

Table 3-2. Global Number of People Exposed to the DNL 55dB and 65dB in 2010 and in 2040

Noise Contour Level	Number Exposed in 2010 (millions)	Number Exposed in 2040 with no technology change from 2010 (millions)	Scenario 4: Number Exposed in 2040 with maximum technology change from 2010 (millions)
DNL 55 dB	21 - 35	53 - 85	31 - 52
DNL 65 dB	2.3 – 4.7	8.7 - 16	4.3 – 8.2

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[53] The measurement of noise is summarized in Appendix H. However, DNL or LDN is a cumulative noise exposure metric used in airport noise analyses, defined as the average noise level over a 24-hour period with noise at night (10pm to 7am) increased by 10 dB to reflect the added intrusiveness of night noise events, the community background noise typically decreasing by 10 dB at night.

[54] CAEP/10-WP/9. Note the values are global and the exact population exposure value varies by nearly a factor 2 depending on the population database used.

During the CAEP/10 cycle, the CAEP Impacts and Science Group (ISG) conducted a review on the subject of noise impacts. The result of its review was a report[55] which summarized the current state of scientific knowledge regarding the adverse effects of aircraft noise emissions on the public. Every effort was made by ISG to base findings upon peer-reviewed publications, carefully reviewed by specialists from around the world. The topics addressed were community annoyance, children's learning, sleep disturbance, and health impacts. Conclusions from their work are provided below on each of the aforementioned topics.

- **Community Annoyance:** Community annoyance refers to the average evaluation of the disturbing aspects or nuisance of a noise situation by a "community" or group of residents, combined in a single outcome, annoyance. There is substantial evidence that aircraft noise exposure is associated with annoyance indicators, and exposure-response relationships have been derived to estimate the expected percentage of highly annoyed persons at a community level. Several personal and situational factors still strongly affect the annoyance of individuals.
- **Children's Learning:** There is sufficient evidence for a negative effect of aircraft noise exposure on children's cognitive skills such as reading and memory, as well as on standardized academic test scores. To date, few studies have evaluated the effects of persistent aircraft noise exposure throughout the child's education and there remains a need for longitudinal studies (i.e., a study that involves repeated observations of the same people over long periods of time) of aircraft noise exposure at school and educational outcomes.
- **Sleep Disturbance:** Undisturbed sleep is a prerequisite for high daytime performance, well-being and health. Aircraft noise can disturb sleep and impair sleep recuperation. Remaining knowledge gaps are (a) the derivation of reliable exposure-response relationships between aircraft noise exposure and sleep disturbance, (b) exploration of the link between noise-induced sleep disturbance and long-term health consequences, (c) investigation of vulnerable populations, and (d) demonstration of the effectiveness of noise mitigation strategies.
- **Health Impacts:** There is good biological plausibility why noise may affect health through impacts on the autonomic system, annoyance and sleep disturbance. Studies suggest impacts on cardiovascular health, especially hypertension, but are limited and inconclusive with respect to quantification, with a relatively small number of studies conducted to date. More studies are needed to better define exposure-response relationships, the relative importance of night versus daytime noise and the best noise metrics for health studies, (e.g., number of aircraft noise events versus average noise level).

3.7 GEOGRAPHICAL AND TEMPORAL CONSIDERATIONS ON MITIGATION NEEDS

To an individual, the relative importance of the impacts of aviation noise and emissions depends strongly on their location relative to the aircraft and the timeframe of consideration. Those who live near airports are strongly affected by aircraft noise whilst those who live further away from airports, may rarely experience LTO noise. A similar trend holds for the air quality associated with LTO, though the transport of emissions over significant distances means that aviation emissions have some effect, though almost imperceptible, on surface air quality at larger geographical scales than is the case for aviation noise.

If aircraft were to suddenly stop flying, there would be an immediate cessation of aircraft noise and local air quality would be back to ambient levels in a short time; people living near the airport therefore have a very short time scale for their disturbance. Those living far from airports suffer from the effects of climate change and from some surface impacts attributable mainly to cruise emissions. The cruise-created concentrations at ground level are generally at lower levels than those from other sources and are unlikely to be something of

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[55] Basner et al., "Aviation Noise Impacts: State of the Science," ICAO Environment Report. 2016. Available at https://www.icao.int/environmental-protection/Documents/ICAO_Environmental_Report_2016.pdf

foremost concern. Everyone is subject to the consequences of climate change, but the changes are comparatively slow and the association of any climate event or experience is not directly associated with aviation. As already noted, CO_2 already emitted will decrease with time, but a significant proportion will be present in 1000 years.

Economists have attempted to overcome the issues discussed of time-scale and location by considering the damage of environmental impacts in terms of net-present-value with an assumed discount rate. Such an analysis is fraught with difficulties and opportunities for dispute, but one qualitative example is presented in Figure 3-6. If one considers the aggregate global damages, then the climate change does, as expected, have the overwhelming cost. However, if one considers only those living near airports, for which Figure 3-6 is based on, then noise is of higher and immediate concern. The different priorities need to be considered for trade-offs between fuel burn, noise and emissions.

Aircraft design involves many trades, including factors that impact the environment. More often than not, the development of new aircraft and engines results in improvements in fuel burn, noise and emissions. However, this may not always be the case and design choices need to be based on proper optimization. Fuel burn reduction always weighs prominently in aircraft technology development because it is a key component of aircraft payload/range capability and operating costs. From an environmental perspective fuel burn reduction is beneficial as it directly reduces CO_2 emissions, thus helping to address climate change. Assuming the emissions indices for NO_x and other pollutants remain unchanged, fuel burn reductions will also lead to fewer emissions that impact air quality and climate change. Further, fuel burn reductions can also result in less take-off noise because the lighter aircraft needs lower thrust.

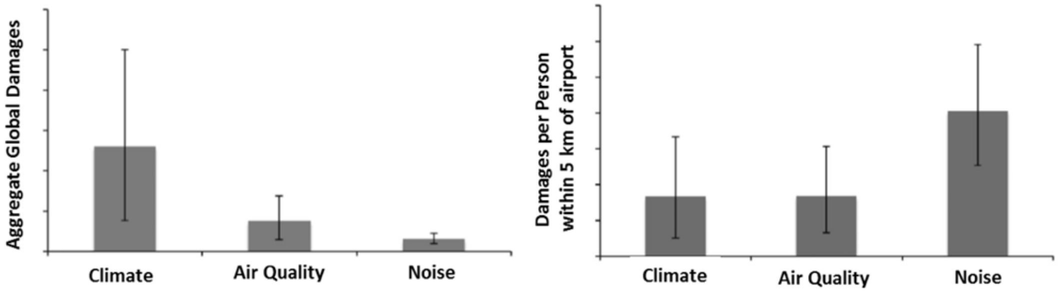

Figure 3-6: Comparison of Aviation Environmental Impacts at a Global Aggregate Level[56]

Historically, noise reductions have come about as a welcome side effect of design choice and technology development aimed to reduce fuel burn. This was principally by a reduction in jet velocity. With the exception of business jets and small regional jets, jet noise is no longer the major noise source, so, in the future, the reduction of noise and simultaneous reduction in fuel consumption by reducing jet velocity no longer applies. This increases the need for proper optimization of both at the design stage. More fundamentally, there may now need to be a decision process to decide what aspects of damage due to aviation are more important than others – that is to assign an ordering of importance. This is not a technical issue but one which is sometimes expressed by the term "world view". Should an individual, or a society, give relatively more weight to the long-term (so, for example, emphasizing climate change and CO_2) or to the present (for example, giving more attention to LTO noise)? The IEs are not equipped to wrestle with questions such as this but merely point out that to design with interdependencies will require decisions to be made.

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[56] Figure adapted from Wolfe et al., "Near-airport distribution of the environmental costs of aviation," Transport Policy Vol. 34, pp. 102–108, 2014. http://dx.doi.org/10.1016/j.tranpol.2014.02.023

CHAPTER 4. **AIRCRAFT FUEL BURN AND CO_2 REDUCTION**

4.1 INTRODUCTION

The treatment here separates the airframe from the engine, in line with convention and with the material presented to the IEs by ICCAIA in the two workshops. This approach has served well in the past for tube and wing aircraft but may not be appropriate for some unconventional aircraft configurations, such as those with boundary-layer ingesting engines (see Chapter 9). Furthermore, the trend to engines of larger fan diameter in relation to aircraft features like wing chord, means that the separate treatment will eventually have to be superseded. The agreed view within ICCAIA was that only "tube and wing" configurations were considered in this review, since it was felt that unconventional configurations would not be introduced within the 2037 time horizon of the IE study.

It is possible to get insight into some of the controlling features of commercial aircraft fuel burn by simple analytic methods based on some idealization. The approach goes back to Breguet[57] and was covered fairly completely in the IE Fuel Burn Technology Review in 2010. The aircraft is assumed to operate in an idealized manner during cruise (which is the majority of the flight for a long-haul mission), at constant lift-drag ratio, L/D. Likewise, the engines are assumed to operate at a constant overall efficiency, which corresponds to operating with constant specific fuel consumption, sfc. To achieve this there is a continual climb during cruise to maintain optimum L/D and sfc as the mass of the aircraft decreases with the consumption of fuel – an idealized procedure referred to as cruise-climb. Most aircraft on long flights change altitude in steps as their mass decreases.

If $(M_F)_{cruise}$ is the mass of fuel burned during cruise and M_1 is the aircraft mass at start of cruise, then the Breguet equation gives for optimum cruise-climb

$$(M_F)_{cruise}/M_1 = 1 - \exp\{-R/H\},$$

where R is the range and H is the range factor which is given, for flight speed V, by

$$H = (V\ L/D)/sfc$$

As H increases, due to better aircraft aerodynamics (higher VL/D) or better engine fuel consumption (lower sfc) the mass of fuel burned goes down. Very often Mach number rather than flight speed is used to characterize aircraft aerodynamic performance, the expression being ML/D.

M_1 is within a few percent of MTOM and for the present purposes, it may be assumed that they are equal. If plausible assumptions are made for lift/drag ratio and engine specific fuel consumption, numerical values may be created. As a concrete example, suppose L/D=20 and sfc = 0.535 kg h^{-1} daN^{-1}, which are values representative for recent twin-aisle aircraft. Also, cruise speed is taken to be 252 m/s, corresponding to a Mach number of 0.85 at 35000 ft in a standard atmosphere. It then follows that

$$H = 34.6\times10^3 \text{ if } R \text{ is in kilometre and } 18.65\times10^3 \text{ if } R \text{ is in nautical miles.}$$

Fuel is also burned during taxi, take-off, climb and landing. The significant additional fuel burn is during climb, but in principle this is recoverable during descent. It is also necessary to carry reserve fuel, with the amount dependent on rules and the region of operation.

The Breguet equation allows the mass of fuel consumed on a mission to be found subject to the stated assumptions. Three key masses determine the performance of the aircraft: maximum take-off mass (MTOM),

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[57] Breguet, L. Calcul du poids de combustible consumme par un avion en vol ascendant. 1923 *Comptes Rendus de l'acadmie des sciences*, 177, pp. 870-872.

operating empty mass (OEM) and maximum payload $(M_{PL})_{max}$. The ratio of empty mass to maximum take-off mass (OEM/MTOM) is a measure of the level of technology, the lower the ratio the better. Improving the material properties, joining technology and structural design all lead to a reduction in OEM/MTOM. A value of about 0.5 is typical of a recent twin-aisle aircraft. The ratio tends to be higher for single-aisle aircraft than twins, consistent with the higher number of cycles the aircraft is exposed to, and the ratio tends to fall as aircraft are stretched to make better use of the structure.

4.2 AIRFRAME AERODYNAMIC AND STRUCTURAL PERFORMANCE, DEPENDENCIES AND CONSTRAINTS

This section considers current aerodynamic performance and the dependencies and constraints which may limit further improvement relative to today's standards. A key reference point is a set of ICCAIA presentations given during the workshop held in Berlin in October 2017.

The principal measure of aerodynamic performance is the optimum product of Mach number and aircraft lift-drag ratio, ML/D, at the cruise design point. Lift-drag ratio is the optimum value for the trimmed aircraft at the optimum design cruise point. Estimated values of ML/D are shown in Figure 4-1 since about 1960, together with points for the TRA used for modelling in this study: the Single-Aisle (SA), which is the Airbus A320neo (notional), and Twin-Aisle (TA), which is the Airbus A350-900 (notional).

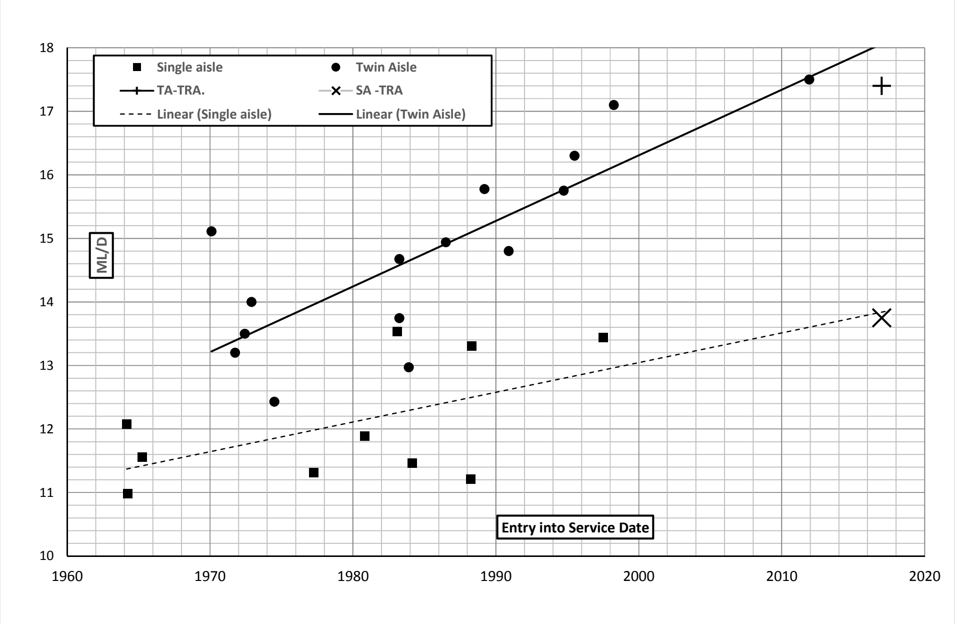

Figure 4-1. Single- and Twin-Aisle Aircraft Improvement in Terms of Estimated ML/D[58]

Two classes are shown in Figure 4-1, short-range aircraft and long-range aircraft, which in recent years coincide with the categories adopted here of single-aisle (SA) and twin-aisle (TA). The trend lines shown in Figure 4-1 are a linear least-square fit to the data. Generally, the improvement trend for twin-aisle aircraft (ML/D increasing about 0.10 per annum) has been significantly greater than that for the single-aisle aircraft

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[58] Data post 1998: for the A330-200 from RAW Aviation Consulting Ltd. (www.rawaviationconsulting.com); for the B787-8 from *Piano*, Lissys Ltd., (www.lissys.demon.co.uk)

(about 0.046 per annum). In the late 1990's, however, the Airbus A330 showed a step increase in ML/D, since when the improvement has been rather slower.

One reason the improvement in aerodynamic efficiency of single-aisle aircraft has been slower than that of the twin-aisle aircraft is that the majority of SA aircraft have their origins far in the past and have had a series of incremental changes in airframe technology. As a result, for the SA aircraft there has not been the opportunity to take advantage of a basket of new technologies as there has been with the TA. The improvements in aircraft performance in the SA sector have arisen primarily through changes in the propulsion systems, add-ons such as wing tip devices, and improved aerodynamic design aided by advances in computational fluid dynamics. Wing tip devices reduce induced drag relative to a planar wing of the same span. This benefit must be traded against possible increases in wing structural mass and viscous drag; hence the net benefit of wing tip devices will depend on aircraft and mission. The airframe designers have shown great skill in enabling the aerodynamic integration of engines with significantly increased nacelle diameters, corresponding to lower fan pressure ratio, without incurring large drag penalties; this has been aided by advances in computational fluid dynamics.

For the latest twin-aisle aircraft, ML/D≈17.5 and with a cruise Mach number of 0.85 gives an L/D of around 21. There might be up to about 10% improvement in L/D by 2037, taking the maximum value likely for a tube-and-wing configuration to about 23 by 2037. This is consistent with the slower increase in ML/D with time for recent TA shown in Figure 4-1. New configurations, not tube-and-wing, offer the potential for even higher ML/D, but are unlikely to enter service by 2037.

Natural laminar flow is achieved by the appropriate shaping of the aerodynamic surface, to maintain the laminar flow over a large proportion of the airframe surface. Hybrid laminar flow makes use of appropriate shaping of the surface but also incorporates a surface with micro pores through which air from the boundary layer is removed by suction through the surface, thus delaying the transitioning from laminar to turbulent flow. Whilst laminar flow technology has been demonstrated on transport aircraft in the past, the robustness and reliability of laminar flow technology for a transport category of aircraft have not yet met the criteria set by the Airworthiness Authorities, e.g. FAA and EASA. Application of natural laminar flow technology has been incorporated on the nacelles of the Boeing 737Max, 787 and is planned on the 777X, as well as on the winglet of the 737MAX. Variants of the Boeing 787 incorporate Hybrid Laminar Flow Control (HLFC) on the vertical empennage. Earlier versions included the hybrid system also on the 787-9 horizontal empennage, but this has since been deleted as part of a production cost saving programme.

If a decision is made to exploit HLFC, it can have a significant impact on the structural architecture of wings in the future. Natural and hybrid laminar flow control both require different structural arrangement to achieve sufficiently smooth joints and smooth surface finish. The standard finish of current carbon-fiber reinforced wings and fuselages is of a much higher standard than typical metallic structures, in terms of accuracy, surface roughness and waviness, all of which result in reductions in aerodynamic drag.

The Independent Expert Workshop in Berlin also covered the potential improvement in airframe structural mass. The ICCAIA data was presented for the same aircraft types as used for the aerodynamics review, but in this case the data was presented on the basis of percentage improvements in the mass in three particular structural groups namely: wing, fuselage, and empennage. It must be borne in mind that the structural mass of each group is only a proportion of the equipped mass of each of the groups. The equipped masses were not presented by ICCAIA for reasons of commercial confidentiality, but an allowance for this has been included in the flight physics numbers. Percentage reductions of mass were presented for the following technologies: advanced metallic technologies, potential improvements in composite technologies, potential improvements in optimized local design, potential improvement in multifunctional design, and potential improvements in advanced load alleviation.

The group percentage mass reductions given at the review cannot be used to calculate the mass reduction at aircraft level without the knowledge of the whole aircraft mass breakdown. As an example, historical data for the overall mass breakdown of a typical early business jet shows that moving from a metallic wing and empennage to composite yields about 3% reduction in structural mass at the aircraft level. This should be compared with the *group* percentage mass reductions for switching to composite in the case of wing and empennage as stated by ICCAIA as 8% and 4% respectively. This group data was used in the fuel burn modelling process for the four categories of aircraft. Since this has been validated using data provided by the aircraft manufacturers, it is likely that the group masses in the aircraft models will be sufficiently representative of the type of aircraft being modelled to provide accurate modelling of the effect of structural mass changes on fuel burn. The data presented showed that the change from metallic to composite wing and empennage structures had the highest potential benefit for the SA category of aircraft with a probability approaching 100% for entry into service by 2037.

In the workshop presentations, it was stated by the Structures and Materials Group that in order to gain an aerodynamic advantage, suitable aeroplane-level trades need to be made that include aerodynamic and structural (mass) considerations and some structural penalty is often accepted. A more accurate way to describe this is that aerodynamics and structures are closely linked together through the design process and the optimum aircraft will be neither that with best aerodynamics nor that with lowest mass. During refinement of the preliminary design, trade-offs will take place so that a combination of aerodynamic performance and structural mass is found that gives the best overall result at the aircraft level. Aircraft systems are also part of the optimization since there is the opportunity to employ load alleviation control and thereby lighten the structure. Current backlogs in the SA category (B737MAX and A320neo) occupy at least six years of production. Recent attention to this class has focussed on reduction of cost and increase in production. A replacement aircraft for the SA category with a wholly airframe is more likely in the 2027 to 2037 timeframe. In the ICCAIA presentation to the Independent Experts regarding structures and materials, it was clearly stated that for a replacement of this class of aircraft, composites would be used for wing and empennage structures.

4.3 PROPULSION DEPENDENCIES AND CONSTRAINTS

The conversion process from energy in the fuel to useful propulsive energy to the aircraft is traditionally broken down into two steps as illustrated in Figure 4-2. These steps are quantified through a thermal efficiency and a propulsive efficiency; their product is the overall efficiency. The overall efficiency is the power driving the aircraft (thrust times speed) divided by the rate of energy release by burning the fuel.

More elaborate ways to describe aero engine losses exist. However, for the purpose of this report, the division into thermal and propulsive efficiency suffices to describe the dependencies and constraints relevant for future propulsion. Rather than to refine engine related irreversibility, it is then more important to grasp how these thermodynamic measures interrelate with the engine installation effects through nacelle drag and engine mass. Relevant aspects of engine design and operation are described in Appendix D. Here the key results will simply be used to highlight important technology trends and constraints.

For a long time a major trend to increase thermal efficiency has been to increase the Overall Pressure Ratio (OPR) and turbine rotor inlet temperature (T_{41}). Improvements in the (adiabatic) efficiency of the turbomachinery (i.e., fan, compressor and turbine) have contributed to major increases in thermal efficiency. The improvements in propulsive efficiency have been achieved via reductions in Fan Pressure Ratio (FPR), resulting in lower specific thrust. Although a state of the art turbofan engine efficiency is around 40-45%, typically 50-53% thermal and 80-85% propulsive, it is becoming progressively more difficult to achieve further efficiency improvements.

Turbomachinery inefficiencies and challenges with high temperature turbine operation and cooling are holding back further increases in OPR and T_{41} and therefore restricting the associated increase in thermal efficiency. The high pressure compressor (HPC) exit is also becoming very hot relative to material capabilities, but suitable and promising new materials are not evident. Additionally, the increase in OPR reduces the size of the last stages of the high pressure compressor to a degree that the achievable compressor efficiency starts to drop. This reduction is driven by relative increases in tip-clearances, reduction of Reynolds number, small-size manufacturing imperfections and end-wall boundary layer interaction.

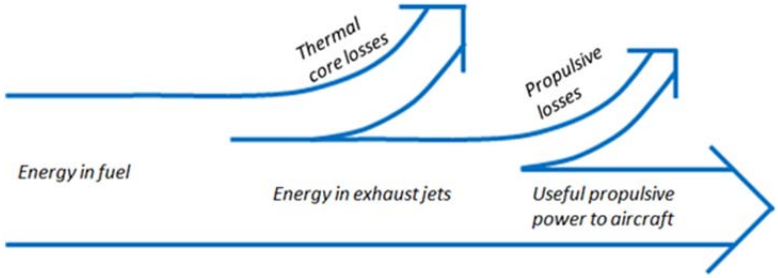

Figure 4-2. Two-step Conversion Process from Energy in the Fuel to Useful Propulsive Power

Increasing propulsive efficiency depends entirely on reducing the fan pressure ratio, leading to a reduction in jet velocity and specific thrust. For the same net thrust, the fan diameter must increase as FPR is reduced. Increasing the fan diameter increases the size of the low pressure turbine (LPT), unless a gearbox is introduced between fan and LPT. Increasing fan diameter increases the mass of the engine and the nacelle drag. The use of a gearbox does open up opportunities for better design and does lead to a lower optimum fan pressure ratio than direct drive. Nevertheless, further increase in propulsive efficiency is held back by increasing nacelle drag, increasing engine mass and more challenging airframe integration.

As discussed in Chapter 6, the FPR on new larger engines is now sufficiently low that jet noise is less than fan noise at take-off and less than airframe noise at approach. Further reductions in aircraft noise as a result of steps to reduce fuel burn are therefore not likely to occur. The penalty of mass and drag of the nacelle become more serious as FPR goes down and there will be pressure to reduce the length of the intake and bypass ducts in relation to diameter, meaning there is less room for acoustic liners. The shorter inlets will increase distortion entering the rotor and the pressure to make the engine shorter (by putting the stator blades nearer the rotor) could both lead to increased noise generation. It is therefore possible that further fuel burn reductions will challenge the noise characteristics of the aircraft.

In the past, NO_x was essentially fixed by the stoichiometric temperature in the combustor, which depended on the temperature of the air entering the combustor, that is, on OPR. The certification levels make allowance for this, as discussed in Chapter 5. Now, however, the temperature of the gas leaving the combustor is high enough to create NO_x, so a dependence on T_{40} has been observed. It therefore appears likely that pressure to reduce fuel burn will put a floor under the achievable level of NO_x.

4.4 FUEL BURN REDUCTION TECHNOLOGIES

4.4.1 Aircraft Aerodynamic Efficiency Improvement Opportunities

This section considers technologies for reducing fuel burn through reductions in aerodynamic drag. Net fuel burn reduction taking into account any mass increases or power requirements associated with the specific subsystems will be discussed. These discussions do not account for subsequent impact resulting from aircraft redesign to integrate the specific technologies. The values for aerodynamic improvement are to be found in Appendix L at all three confidence levels whilst the numbers quoted in this section are defined at low confidence, specifically a 20% expectation of being achieved.

Aerodynamic viscous drag reduction can be achieved either passively, through natural laminar flow or actively, through HLFC. Passive control is more appropriate for the smaller wings of regional or business jet aircraft because the Reynolds number is lower and, if the cruise Mach number is lower, the sweep is smaller. Hybrid laminar flow is more appropriate for twin-aisle aircraft. Larger single-aisle aircraft, similar in size to the current Airbus A320 and Boeing 737, could use either technology, and it remains to be seen which will be preferred for this class of aircraft. Natural laminar flow is achieved by an appropriate shaping of the wing surfaces to get large regions of favourable pressure gradients, in combination with very smooth surfaces and the avoidance of steps and gaps. Larger sweep angles are needed as the cruise Mach number rises and these larger angles can result in crossflow instabilities along the attachment line (leading edge) which is not conducive to natural laminar flow. The reduced sweep angles needed could affect cruise Mach number. HLFC generally requires smaller modification in shaping than natural laminar flow, but combines it with distributed suction on the airframe surfaces to keep the boundary layers from transitioning to turbulent flow. It therefore consumes some power, in contrast to natural laminar flow, and adds some mass. Hybrid laminar flow has been demonstrated on wings and other airframe surfaces such as vertical fins and horizontal stabilizers, with useful reductions in drag.

Natural laminar flow is likely to be restricted to operations at relatively low wing chord Reynolds number, which is the principal parameter determining the boundary layer transition from laminar to turbulent. This rules out large twin-aisle aircraft. Low density also reduces Reynolds number, so laminar flow is more possible at high altitude. In order to benefit from natural laminar flow, large single-aisle aircraft will have to have reduced sweep angles compared to current aircraft and possibly slightly reduced speeds. If the reduction needed in speed is excessive, then hybrid laminar-flow control will be preferred. Business jets may be able to retain sweep above 18 degrees and have natural laminar flow because of their small wing chord.

Both natural laminar flow and HLFC have been well understood for several decades. The difficulties in their practical implementation are primarily operational, including robustness and in-service factors affecting manufacturing, maintenance, and reliability. Substantial research and development addressing these issues is needed to bring the application of these two technologies to wings to maturity. To date, limited in-flight experience has been gained, and major demonstration projects have been undertaken or are in progress. Since leading edge sweep is a limiting feature, it is logical in the short-term to apply the techniques to airframe surfaces which have low or zero sweep, such as engine nacelles, for example. Natural laminar flow nacelles are currently in service on a limited number of aircraft types. The goals given below for net fuel burn reductions resulting from laminar flow wings are based on the expectation that only a portion of the flow on the upper surface of the wing will remain laminar, while the flow on the lower surface will be primarily turbulent. If significant regions of laminar flow can be achieved on both the upper and lower wing surfaces, then there would be a potential for larger net fuel burn benefits.

The manner in which laminar flow can be exploited depends on the aircraft class. Beginning with the large single-aisle class, a net 0.5% fuel burn reduction could be achieved by 2027 through natural laminar flow nacelles. A small fuel burn reduction of 0.3% is possible by 2027 through some natural laminar flow on the wing. By 2037, the potential benefit from natural laminar flow nacelles is 0.8%, and HLFC on the vertical tail could lead to an additional 0.4% net fuel burn benefit. As discussed above, it is not yet clear whether single-aisle aircraft will incorporate natural laminar flow or HLFC on their wings by 2037. Hence it is expected that some aircraft will be developed using the former and others with the latter. Overall 1% net fuel burn benefit can be expected from natural laminar flow and 1.4% from HLFC on the wings of SA aircraft by 2037.

For twin-aisle aircraft, due to their size and speed natural laminar flow is possible only on the nacelles, potentially producing a net fuel burn benefit of 0.5% by 2027 and 0.8% by 2037. On the wing, HLFC is necessary to achieve significant laminar flow. This is not expected to be sufficiently mature by 2027 but has the potential to produce a 3.1% net fuel burn benefit by 2037. HLFC on the horizontal tail could produce benefits of 0.2% and 0.3% by 2027 and 2037 respectively. For the vertical tail, the potential benefits are 0.4% and 0.7% by 2027 and 2037 respectively.

For regional jet aircraft a net fuel burn reduction of 0.5% can be expected by 2027 from natural laminar flow nacelles and 0.3% from natural laminar flow on the wings. By 2037, a 0.8% net fuel burn reduction from laminar flow nacelles and a 3.7% reduction from natural laminar flow wings are realistic goals.

For business jets, natural laminar flow nacelles can provide a net fuel burn benefit of 0.5% by 2027, with natural-laminar-flow wings providing 0.3%. By 2037, these target net fuel burn benefits increase to 0.7% from laminar flow nacelles and 4.1% from natural laminar flow wings.

The skin friction in turbulent boundary layers can be passively reduced with riblets and denticles (shark skin). A given surface on an aircraft can benefit from *either* laminar flow *or* riblets, but not both. On wings, laminar flow is preferable, as it provides a larger benefit, but riblets could be added on the wing in the region after the transition to turbulent flow occurs. Similar to HLFC, the physics of riblets are well understood and demonstrated; the remaining challenges are primarily related to installation and operational in-service considerations. The Airbus in-service tests in the late 80s and early 90s with an 80% coverage on an A340 showed expected fuel burn reduction, but in-service maintenance was unacceptable. The benefits of riblets are expected to be roughly equal for regional, single-aisle, and twin-aisle aircraft with a 1% fuel burn benefit possible by 2027. By 2037, the potential increment is lower at 0.6% because of substantial regions of laminar flow expected on the wings, where riblets would not be useful.

The wing span of most aircraft is less than optimal as a result of existing ICAO gate and runway/taxiway constraints. Folding wing tips can enable larger span in flight while meeting gate constraints; this will lead to significant reductions in induced drag along with a small mass penalty due to folding mechanism. Extra structural mass, due to the associated increase in the inboard wing bending moment, needs to be included in the standard aircraft wing design trade. This enables the optimal span to be achieved based on standard wing design trades without consideration of gate constraints. For single-aisle aircraft, this increase in wing span is unlikely to be implemented by 2027 but could contribute a net 2.4% reduction in fuel burn by 2037. For TA aircraft, a 0.9% reduction in fuel burn is possible through such span extension by 2027 and 3.2% by 2037. For regional and business aircraft, this is not expected by 2027 but has the potential to provide net fuel burn reductions of 2.2% and 1.4%, respectively, by 2037. Folding wing tips increase the bending moment on the wing, so there is an increase in structural mass, which is estimated as it would be without the folding mechanism. In addition, there is a contribution to mass associated with the folding mechanism, which is included when these are installed.

An aircraft flies under varying cruise conditions, depending on the payload and fuel mass, the altitude, and the speed. Current wings are designed to be optimal with respect to this range of flight conditions. By modifying, or morphing, the wing during flight, performance can be improved through improvement of the spanwise lift distribution to reduce induced drag or the section shape to reduce wave drag. The simplest way to do this is to make use of existing flaps and ailerons to enable variable camber near the wing trailing edge. The adaptive trailing edge in its slotless form, i.e. an adaptive continuous upper and lower surface trailing edge, is likely to give superior performance, and flight trials are currently underway of such a system in the USA. Modest net fuel burn benefits are possible with this technology, potentially on the order of 0.2% for business, regional, and single-aisle aircraft by 2027 and 0.7% by 2037. The potential benefits are larger for twin-aisle aircraft; 0.5% is possible by 2027 and 1% by 2037.

Further opportunities for drag reduction, short of adopting a novel aircraft configuration, as discussed in Chapter 9, are quite limited. For example, excrescence drag reduction on both single-aisle and twin-aisle aircraft could provide roughly 0.4% net fuel burn reduction by 2027 and 0.5% by 2037. For regional and business aircraft, a 0.5% net fuel burn reduction can be expected from reduced excrescence drag by 2027, with negligible further benefit by 2037. Active flow control also has the potential to enable small fuel burn benefits, likely no greater than 0.1%, on single-aisle aircraft and 0.2% on twin-aisle aircraft by 2037. Using actuators to delay separation on the vertical fin can enable enhanced effectiveness and thus reduced size and associated mass savings. In addition, a limited benefit is possible from advanced wing-tip treatments; 0.5% for the single-aisle class and 0.2% for the twin-aisle class by 2027. Devices of this type need to demonstrate in-service robustness. However, these benefits will not be seen in 2037 as a result of the span extensions described above. Summing these various net benefits and accounting for incompatible technologies, suitable fuel burn reduction goals from aerodynamic technologies for 2027 and 2037 are set out in Table 4-1.

Table 4-1. Potential Fuel Burn Savings Attributable to Aircraft Aerodynamics, Net of Mass and Power

Aircraft Class	Potential in 2027	Potential in 2037
Business Jet	2-3%	8%
Regional Jet	3%	9%
Single Aisle	3%	8%
Twin-Aisle	4%	10%

4.4.2 Airframe Structure Mass Reduction Opportunities

This section considers the opportunities that exist to reduce the structural mass of future aircraft. The structural mass of the aircraft is one of the key parameters that determine its fuel burn performance. The large single-aisle aircraft, such as A320neo and B737 MAX, and long range, twin-aisle B777 and A330 have metallic primary structures. The twin-aisle B787 and A350, however, have composite primary structures. The values for mass reduction are to be found in Appendix L at all confidence levels whilst the numbers quoted in this section are defined as low confidence, specifically a 20% expectation of being achieved.

For each class, the airframe structures were split into three major groupings: wing, fuselage, and empennage. The technologies included in the review are related to these groupings and do not include the mass of associated items such as systems and equipment installed within the structural groups. An allowance for these was provided within the Flight Physics improvement matrices. In the case of the propulsion system, engine, nacelle and pylon mass improvements are covered in the next section. Landing gear was treated as a "Systems" item, and was not dealt with in this review with regard to mass reduction technology. Within the airframe structures topic, mass-saving opportunities obtained by the use of advances in the following areas were considered: advanced metallic technologies, advanced composite technologies, optimized local design, multi-functional design and materials, and advanced load alleviation. Mass savings data were provided as a percentage increment for each of the three structural groups relative to a reference based on current aircraft technology.

The principal themes of the review were the better use of technologies and new materials, which was linked to a review of current structural design practices and rules which industry believes lead to over-conservatism. In addition, it is anticipated that the combination of new material and manufacturing technologies could lead to significant mass saving, particularly in enabling the use of novel structural architectures. In the context of this review, the use of carbon composite structures is being taken as a mass saving but this is not the only benefit arising from this technology, though it is assumed for the present study that these additional benefits have a small impact on performance. Mass reduction numbers are presented in the tables in Appendix E. They are percentages of the reference group masses for wing, fuselage, and empennage for each aircraft type. Without the knowledge of the reference mass of each group and its relationship to the aircraft manufacturer's empty mass, it is not possible to assess the mass savings at aircraft level for each aircraft type. For the purposes of the modelling activity associated with fuel burn reduction studies, it is understood that since the reference aircraft have been modelled and calibrated against appropriate data, the use of the mass saving percentage deltas given below are appropriate for use in the fuel burn modelling work. Changes in design methods and their capabilities were not covered explicitly in the review; all changes were referenced to technology levels employed on existing product types.

Advanced metallic technologies: For metallic technologies, new strategic opportunities are available, including the development of new alloys with targeted properties. These include lower density, e.g. aluminum lithium alloys, higher allowable stress alloys and properties targeted to particular design requirements. They also include the use of new design solutions to joining such as, for example, bonding of skin to stringers in both wing and fuselage structures, new rib/frame to skin attachment techniques, tailored integrated structures which allow load sharing, dual use. Also to be considered is ease of manufacturing, aided by new assembly processes such as laser, friction or hybrid welding. The use of fiber/metal laminates and metal laminate structures is also likely to produce some mass saving, as is the increasing use of metal matrix composites. The table in Appendix E gives the potential mass savings provided through advanced metallic technology. Overall there are possible savings in all classes of about 5±2% by 2037.

Advanced composite technologies: The composite technologies that were reviewed included new materials, such as high strength fibers, improved matrix material properties, the increased use of thermoplastics and manufacturing processes, such as out of autoclave curing. In addition, it is anticipated that improved textiles combined with techniques such as resin transfer molding, already in place in some parts of the industry, together with new jointing techniques are also coming into service, including more use of co-bonding of composite assemblies, and stitching of textile layups. Overall, for the TA, there are potential savings of about 4±2% and for the SA, about 8±2% by 2037. For business jets and regional aircraft, industry is of the view that the reference is metallic with composite empennage, components, and that the use of composites in the fuselage is not considered. It should be noted however that this is not a universal view, and during the review process, no rationale was given.

Potential improvements through optimized local design: As greater understanding is developed of the behaviour of current aircraft in service, it is becoming possible to relax some of the certification rules which have evolved. In this way, aircraft mass can be reduced without compromising safety. Manufacturing processes such as additive layer manufacturing will enable more appropriate geometries, as well as greater emphasis on the material properties of the component. It is also possible that these processes may enable the adoption of "bionic structure" which mimic those found in nature, for example the light weight structure of bird bones. Overall the potential savings are around 1±1% for small aircraft and up to 3±1% for large aircraft by the 2037 timeframe.

Potential mass saving through multi-functional design: The structures group of ICCAIA have put forward a philosophy which postulates that since current structures are developed in a "mono-skill" environment where structures are designed to serve a mechanical function only, broadening the scope of the design to meet multi-functional objectives would result in mass and cost savings. A similar approach is seen for the adoption of multi-functional smart materials with properties other than mechanical, examples of which are self-cleaning surfaces on airframe external surfaces and those with hydrophobic characteristics which are resistant to ice adherence, both of which would be enablers for the introduction of laminar flow technologies, with their attendant drag reductions. The potential mass saving for this topic takes into account the mass reduction of other functions in relation to component mass. Overall mass savings range from 1.5±1% for small aircraft to 3±1% for large TA by 2037.

Advanced load alleviation: This is a technology that has been a part of the aircraft design process for at least two decades and has two major manifestations. The first is maneuver load alleviation, which is accomplished by moving wing mounted control surfaces such as ailerons and spoilers and, more recently, inboard trailing-edge flaps. This is done when the lift of the wing is high to move the center of lift on the wings inboard, reducing the wing root bending moment. It can also be done passively by means of carefully designed wing tips with a high sweep planform which in a manoeuvre or vertical gust cause the outer wing to reduce in incidence, causing the main wing center of lift to move inboard, again resulting in a reduced wing root bending moment. This relies on the lift on the wing tip being aft of the wing flexural axis so that as the load on the wing increases, due to either a manoeuvre or vertical gust, the load on the swept wing tip will cause the outer section of the wing to twist in a manner that will alleviate the load. Advanced load alleviation makes use of improved actuation control laws, higher rate actuators, and innovative high response gust sensors as well as aeroelastic tailoring of internal structural elements. The mass fractions of the three groups are different for each class of aircraft as is the manufacturers empty weight. Unfortunately, no data are available for the latest composite structure aircraft but data do exist for metallic regional, single-aisle and twin-aisle aircraft.

4.4.3 Propulsion Fuel Burn Reduction Technologies

Section 4.3 briefly outlined the trades limiting the rate of improvement in core efficiency and propulsive efficiency. This section critically reviews technologies that relate to progress in these areas.

Technologies to improve thermal efficiency: The (adiabatic) efficiencies of the engine turbomachinery (i.e., fan, compressor and turbine) are already quite high. At constant turbomachinery size, there is certainly some further gain to be obtained, although the improvement rate is likely to be substantially lower than has been the case in the past. Over the long-term, it is viewed that the polytropic[59] efficiency of the compression system might be improved by ~2% beyond the current state-of-the-art (91-92%), thanks to advanced design methods, clearance management and even a change in design space, trading mass and cost for efficiency. However, with the overall trends to smaller and hotter cores, advanced technologies may well be implemented only to maintain the current efficiencies or to provide very modest gains. The compressor outlet and HP turbine blade heights are small in relation to diameter and this makes it particularly difficult to achieve high efficiencies and maintain high performance cooling systems. Here, tip clearance management and high temperature materials are key enablers. For turbine efficiencies, it is believed that large uncooled turbines running at moderate aerodynamic loading, such as LP turbines in geared engines, could reach somewhat beyond the efficiency limit claimed for compressors. However, LP turbine efficiency could be limited by trades, including steps to reduce tone noise, and as a result component length and mass may increase.

Allowing higher temperatures and/or reducing required cooling flows has a direct beneficial impact on thermal efficiency. However, current research on superalloys indicates that no further radical improvements are to be expected. The current development in temperature capability seems to be levelling out and designers now face having to trade one property for another. However, ceramic matrix composites (CMC) are expected to be progressively introduced into ever hotter parts of the combustor and turbine system. Long-term, it is feasible to have HPT parts including the nozzle and, ultimately, possibly turbine blades manufactured using CMCs. There are also new hot-section materials like eutectic ceramics and intermetallic alloys which are able to operate at higher temperature than superalloys currently in use.

It is expected that the design of HPT blades will continue to be refined, including the high thermal effectiveness cooling circuits inside blades and vanes, albeit with ever decreasing returns on temperature capability, reduction in cooling mass flow requirement, and efficiency penalties. Similar evolutionary progress is expected in the areas of thermal barrier coatings. A less conventional way to improve temperature capability is to use novel means for heat management. The introduction of variability in the cooling flow to adjust to the flight envelope requirements is expected. Other means to resolve compressor exit and turbine disc temperature limitations is to introduce water ingestion temporarily for hot take-off. Temperatures are, however, increasing in the entire flight cycle, due to the trends in lowering specific thrust, as discussed in Appendix D, and at some point of development, the top-of-climb operating condition could become critical for designing the cooling system. A requirement, if coolant water is to used, would of course be that it is used temporarily so as to avoid having to carry large amounts. However, weight and operations complexity have prevented water ingestion use since the Boeing 747-100. A final option to alleviate temperature constraints would be to introduce intercooling. Intercooling is already in use for ground-based gas turbines. Although it does seem possible to introduce intercooling with some fuel burn and NO_x emissions improvement, there are other challenges such as a reluctance to design a system that takes core air into a bypass coolant stream and then returns it to the core flow. There are concerns about engine cost, icing and other safety aspects, such as foreign object damage to the heat exchanger, as well as increase in engine mass.

Projection of possible OPR in 20 years, consistent with expected core technology progress, is around 52-62 for TA aircraft engines having conventional gas turbine cycles. This would result in thermal efficiencies around 55%. For smaller engines, it will be less. In a longer perspective, it is just possible that hybrid thermal/electrical propulsion systems may find their way onto the market. These systems would inject mechanical power on the fan shaft through electrical motors, fuel cells/batteries and manage the use within

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[59] Compressor and turbine efficiencies are expressed in two different ways: one is usually referred to as adiabatic or isentropic efficiency, the other is referred to as polytropic efficiency. For this report there is no need to distinguish.

the flight envelope. Studies are still on-going, but the current estimates of the gain specifically due to this system seem modest, partly because of the high mass of the electrical components but also because the aircraft engine is already comparatively well matched between take-off and cruise.

Technologies for improving propulsive efficiency: The gain in the propulsive efficiency of a turbofan comes from a reduced fan pressure ratio. It is foreseen that within the coming 20 years, the pressure rise in the fan could be reduced by 20 to 25%. As an example, for the SA, with medium confidence FPR could go from 1.475 in 2017 towards 1.35 in 2037, within a possible variation between 1.30 and 1.40. These low-speed fans will need to be accompanied by advanced nacelle technologies and design methods that allow thinning and shortening the nacelles. In turn, this will demand more complex optimization including combined aerodynamics and acoustics considerations. Shortening nacelles will limit noise shielding and use of acoustic liners; it will also make the fan more vulnerable to cross-wind distortion or the distortion at angle of attack, so that the fan and nacelle integration become more challenging. Design methods will be required that include the intake, the fan and the full by-pass duct taking multidisciplinary considerations into account.

Lighter nacelles, improved composite fan blades, and other advanced concepts for mass reduction will play a key role to enable future ultra-efficient and ultra-low FPR designs. Some nacelles already have natural laminar flow, so no further benefit is likely here, though better integration of the whole power plant with the wing may still bring benefits.

At the start of take-off, with low forward speed, low FPR fans are susceptible to flutter or are prone to stall and surge. Until now, this problem was managed by including this constraint in the aero-design, perhaps with a small penalty on performance at cruise conditions. As FPR is lowered, it is expected that a condition will be reached at which this no longer provides an acceptable installation and then a variable area bypass nozzle will be needed. The boundary where this change will occur is not known, or not publicly available, but the extra mass weight and cost of the variable nozzle will shift the optimum choice of FPR. Variable pitch fan technology is another option opening up the design space for even lower specific thrust, but requires advancements from current state-of-the-art to become attractive.

The reduction in FPR produces larger and heavier engines with greater interaction with the airframe. The fan is now the largest noise source for take-off, but the potential mass of the intake and nacelle tends to make these shorter with an adverse impact on noise. All this requires greater use of multidisciplinary engine design, but going beyond this requires strengthened co-engineering between aircraft integrators to include aircraft, engine and nacelle manufacturers. For very large fan diameter installations, even the overall structural concept to hold the engine under the wing may need revisiting, or a switch to a high wing may become necessary.

In the longer term, boundary layer ingestion (BLI) will be considered as a path forward. It must be noted however, that one of the major issues of the use of BLI is operating the fan with a permanent circumferential distortion that influences aerodynamic efficiency, blade dynamics and blade life. The fan is already the largest engine noise source, so a fan operating in a thick boundary layer would be even more of a nuisance. Another advanced concept that could become feasible is the use of distributed propulsion, allowing BLI to be integrated to a greater extent. Neither BLI nor distributed propulsion is judged by the IEs to be likely to be employed by 2037.

The potential in 2027 for fuel burn reduction (beyond the Technology Reference Aircraft in each category) attributable to the propulsion technologies discussed in this section have been preliminarily estimated by ICCAIA at ~ 5% for SA and ~ 6% for TA. In 2037, an additional 5% fuel burn reduction might be obtained. These values can vary depending upon the exact 2017 reference aircraft and engine combination. They include all impacts from new propulsion technologies (thermo-propulsive efficiency, mass, drag) except the impacts of possible new nacelle technologies and the impact of propulsion system/airframe integration. For the RJ, the benefit is expected to be less; and no benefit may be applicable in 2027.

CHAPTER 5. **ENGINE EMISSIONS REDUCTION**

5.1 INTRODUCTION

This chapter reviews technology for control of engine emissions. The focus is on NO_x and nvPM. Because of the nature of this integrated review, it has not been possible to be as comprehensive as in the previous two NO_x reviews. NO_x certification and goals have from their inception been based on the LTO cycle on the assumption that LTO emissions affect local air quality (LAQ) and that it is in the general environment of airports that the emissions will have an effect. Considerable reductions have been made in aircraft LTO NO_x relative to the initial NO_x Standard, such that the contribution from aircraft to concentrations around airports remains a small fraction of the total. Because more than 90% of the fuel is burned during climb and cruise, it is during these parts of the flight that most of the NO_x is emitted. Factors have emerged in this review concerning the most recent scientific understanding of the climate impacts of NO_x emissions showing less impact per kg NO_x emitted than was once believed, as well as some increased concern about the potential impact of NO_x emitted at altitude on ground level health. Combined with the forecast continuing increase in total mass of NO_x emitted due to increase in traffic, these factors require wider consideration of measures to monitor and control climb and cruise NO_x.

At one time smoke was highly visible at take-off and regulations were brought in to prevent this. The results have been highly successful and now smoke is not visible to the naked eye. Over the years, concern has grown about particulates and ICAO are introducing regulations based on $PM_{2.5}$, which is particles with a mean diameter less than 2.5 μm. In fact, most of the particulates emitted from the engine have sizes 50 times smaller than this, typically 50 nm.

5.2 COMBUSTION AND COMBUSTORS

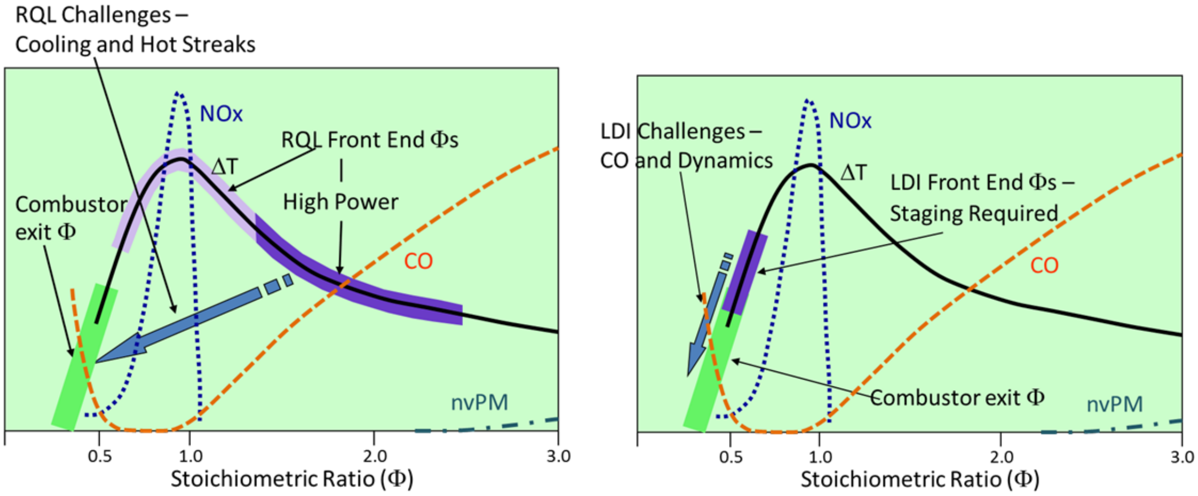
The emissions of CO_2 and water are determined by the amount of fuel burned and therefore depend on the design of the aircraft and engine but not on the design of the combustor. However, NO_x, PM, smoke, CO, and HC are mainly determined by the design of the combustor. There is some impact of the engine cycle design on the NO_x emissions. The sulfur content of the fuel and total fuel burned determine the SO_x emissions. Originally smoke was monitored visually but now the more specific nvPM is being measured. In this report the term smoke/nvPM will be used when needed to cover both.

Today's engines reflect over 50 years of evolution of the annular combustor design. There are options to vary these emissions within the combustor "design space", but the combustor faces several design requirements that limit these options. It is these limits, mostly for safety and operability, which separate the theoretical from the practical. Whereas NO_x and smoke/nvPM are the main emission of concern at high thrust conditions, the emission of CO and HC, tend to be greatest during the taxi and idle conditions. To remove CO, HC and smoke/nvPM is conceptually straightforward: the combustion process should be prolonged for as long as possible at high temperature in the presence of ample excess oxygen. The requirements for reducing NO_x are more complex, but are based on keeping low temperatures where possible and, when high temperature is unavoidable, having the shortest possible residence time. The design options for low NO_x are the opposite of those for low CO, HC and smoke/nvPM.

Combustion of jet fuel is a fast reaction, faster than the mixing times within a combustor. Formation of NO_x is slower, so normally the mixture never reaches chemical equilibrium. The NO_x formation process accelerates with increasing pressure and temperature. In total, rates of NO_x formation are dependent upon the fuel-air-ratio in the primary combustion zone, flame temperature, system pressure and the residence time spent at the flame temperature. Above about 1800K, NO_x formation speeds up dramatically. The combustor pressure is set by the engine cycle choice and the temperature entering the combustor rises with pressure. The push for greater fuel efficiency coupled with recent turbine developments, now allow combustor exit temperatures (T_{40}) to be above 1800K. Hence NO_x production after dilution, sometimes called "quenching", can no longer be ignored. Indeed, this may be the limiting mechanism for low NO$_x$ combustors operating at high power.

Within the overall annular combustor design, there are now two approaches, the rich-burn[60] combustor and the more recent lean-burn combustor. These combustor designs are differentiated by their different strategies for NO$_x$ control, specifically different approaches to fuel-air-mixture control through the combustor. In a fuel-air mixture at the exact stoichiometric ratio ($\Phi=1$), the fuel is able to burn just using all of the available oxygen from the air and this condition gives the highest possible temperature. This stoichiometric temperature depends only on the calorific value of the fuel and the temperature of the air entering. At higher values of fuel-air ratio (rich), there is excess fuel in the combustion products after all the oxygen has been consumed. At lower values (lean), there is excess of oxygen remaining in the combustion products after all the fuel has been consumed. Both rich and lean combustion regions have temperatures below the stoichiometric value. In a combustor, the local fuel-air ratio is not constant but varies throughout. Combustion temperatures for burning close to the stoichiometric ratio in a modern engine would be about 2600K. Because of turbine-related limitations, the maximum mixed-out temperature at combustor exit (T_{40}) is currently below 2000K; so not all the oxygen can be burned, requiring that the overall combustion process is lean.

Within this overall context, in rich-burn combustors, the fuel first burns rich so there is little oxygen free to form NO$_x$. Dilution air is introduced to take the mixture as quickly as possible through stoichiometric region (when it briefly gets very hot) to a cooler, lean state. This process is known as Rich-Quench-Lean (RQL) and is illustrated schematically along with some of the design challenges in Figure 5-1 on the left. It relies on the NO$_x$ formation process being relatively slow. In lean-burn combustors, enough air is introduced with the fuel from the injector so that it is never overall rich. In aviation combustors, the fuel is not premixed and pre-vaporized and in the microscopic region around each droplet, the mixture can be close to stoichiometric. However, the mixture remains lean throughout the combustor and temperature does not approach the stoichiometric value. This process is known as Lean-Direct-Injection (LDI) and is again illustrated along with some of the design challenges in Figure 5-1 on the right.



Source: Presentation at ICCAIA workshop by Kramer

Figure 5-1. Combustion Strategies: Rich-Burn (RQL) on Left and Lean-Burn (LDI) on Right

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[60] In this report rich-burn combustor is treated as synonymous with RQL (rich-quench-lean) combustor.

In a rich-burn combustor, most of the CO, HC and smoke/nvPM is produced in the rich combustion zone prior to the introduction of dilution air. With the introduction of dilution air NO_x is rapidly produced and it is important to drop the temperature quickly to limit this. Soot mass concentrations during rich-burn combustion can be two or three orders of magnitude higher than at combustor exit. Long residence times at high temperature after combustion would burn out these particulates in the downstream section of the combustor and beyond. However, this is in direct conflict with the requirements for low NO_x. There is therefore a trade-off between smoke/nvPM and NO_x in rich-burn combustors; the same is true for CO and HC but are generally now low enough not to be a major concern. Designers strive to minimize both smoke/nvPM and NO_x, most recently employing staging to separately optimize low and high-power conditions.

In a lean-burn combustor, the peak temperatures are not as high, so NO_x is low provided that the overall outlet temperature is not above about 1800K. At the same time the excess air means CO, HC and soot production are low too. However, a difficulty with hydrocarbon fuels is that they will not burn if the fuel–air-ratio is far below stoichiometric value and lean flames are inherently unstable. For the demanding operating conditions of aero combustors, a pilot zone is required for stability particularly during low power operation. Conditions in this pilot zone are akin to a small rich-burn combustor, producing NO_x, smoke/nvPM, CO and HC, but because of the small size of the pilot, and the small fuel-flow through it, the amounts of these pollutants are relatively small. Except during pilot-only operation, downstream lean-burn regions promote burn out of any particles formed by the pilot, so that levels of smoke/nvPM should be expected to be almost immeasurably low: test results have shown this to be the case.

For high power operation of a lean-burn combustor, the gas can be hot for a significantly long time. As mentioned earlier, when temperatures exceed about 1800K, NO_x formation speeds up dramatically. Combustor exit temperatures frequently now exceed this value during take-off and potentially during some altitude conditions. The consequence is that NO_x emissions from lean-burn combustors seem to rise more steeply with increase in T_{40} than rich-burn combustors, because in rich-burn combustors NO_x levels are determined mainly by the short time in the stoichiometric region where temperature does not alter much with T_{40}.

5.3 SCOPE AND OPPORTUNITIES FOR REDUCTION OF NO_X AND nvPM EMISSIONS

With the benefit of presentations from research organizations and industry[61], the IEs have formed a view on the scope and opportunities for technology-based reduction in NO_x and nvPM emissions over the mid- and long-term timescales (TRL6 by 2020 and 2030 respectively with a view to TRL8 by 2027 and 2037) based on the readiness level of the research program technology. The main NO_x reduction technologies also promise reductions in the less well-understood smoke/nvPM emissions. It is considered that for the period of the goals, emission reduction technology will continue, primarily, to be driven by reduction of NO_x while ensuring acceptably low levels of smoke/nvPM and with little or no compromise in overall engine fuel efficiency.

5.3.1 NO_x

The previous Independent Expert NO_x review in 2009 concluded that for combustion technology "history and judgment indicate that, on a rough scale, big steps (revolutionary) require on the order of 20 years from concept to product (TRL 2 to 8)". The current team concurs. The most recent "big step" in NO_x reduction technology was the introduction of lean-burn combustors (GE's TAPS in GenX and CFM LEAP engines). Although first entering service in late 2011 the technology remained the product of only one engine company on one large engine family until a second family was introduced in mid-2017, with combustion technology

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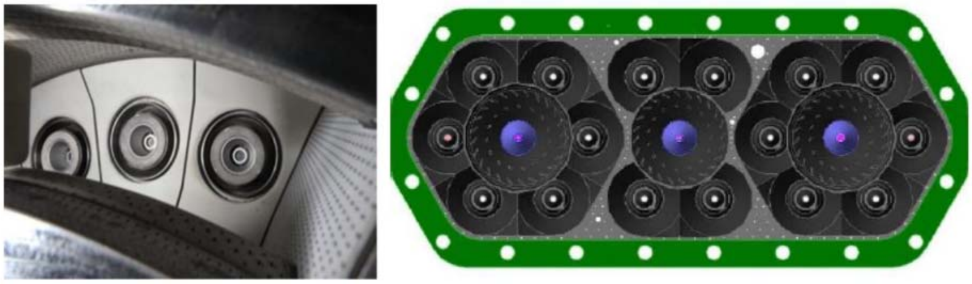
[61] NASA, FORUM-AE, GE. P&W, RR, Honeywell, Safran, PWC

essentially by the same company. As of late-2017, these two engine families are the only lean-burn engines in service. In parallel, a major reduction in NO_x emissions from an advanced, rich-burn combustor occurred with the introduction of Pratt &Whitney's TALON X combustor in the PW1100G and PW1500G series geared turbofan (GTF) engines and the PW 800 series business jet engines. Other engine manufacturers have continued to make incremental improvements in their NO_x technology. The question now is whether a further technology step will become available within the goal timescales.

The IE review of the research program covered multi-point lean direct injection (LDI), active combustor control, fuel composition optimization, improved diagnostics and design tools, and combustor materials[62]. All but the first of these technologies were judged to be at too low a TRL and firmly outside of the scope of the review, although improved diagnostics and design tools will provide opportunity for better design. The only potential technology step within the timescale of the goals was considered to be multipoint LDI, although even this is in many ways just an evolution of the existing lean-burn concept but with increased staging flexibility. NASA Research is focussed on significantly increasing the number of injectors (Figure 5-2) to allow better premixing and vaporization of the fuel and air. A key factor with this concept is the cost which would be incurred with this arrangement, as well as the complexity of the associated pipework.

Although lean, premixed, pre-vaporized (LPP) combustor designs are common in industrial gas turbine applications, the potential for catastrophic pre-ignition or flashback has prevented aviation application of LPP combustors and this remains a challenge for multipoint-LDI. With complex injectors, there are design constraints such as coking of hot passages inside the injectors. Fuel formulation improvements such as hydro-treating may assist this and indeed may become essential to allow more complex injector or combustor technology to enter service. Overall, multipoint-LDI offers a potential way forward for low- NO_x combustion at challenging engine cycle temperatures and pressures where the current lean-burn technology will struggle. However, solving all these issues to allow entry-into-service by 2037 appears unlikely.



Source: NASA Chang

Figure 5-2. Comparison of Current Lean-Burn (left) and Multi-point Injection LDI Combustor Sector (right)

Based on the full implementation of LDI and LPP, the European and US research program targets have been updated since the last NO_x review. The ACARE 2020 goal is in line with the existing CAEP NO_x Long-term Goal but at a steeper D_p/F_{oo} slope[63] above OPR=30. The NASA Ultra-Efficient Engine Technology (UEET) demonstration target equates to a level around 65% below CAEP/6. The ACARE 2050 goal and NASA's ERA target (both 75% below CAEP/6) and the NASA N+3 target are all beyond the timeframe of this review and require a step change in NO_x technology.

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[62] Constant volume combustion (CVC), pulse and rotating detonation engines and flameless combustion were also reviewed, but these are primarily low TRL fuel efficiency technologies requiring cycle changes and are not considered further in this section. Nor are they expected to reach TRL8 within the technology goal timescales

[63] The meaning of "slope" will be clearer in discussion below of Figure 5.3

Having looked at potential forward steps in technology, it is important to recognize a fundamental challenge for combustors. With rich-burn there is always a region of stoichiometric combustion, so the peak temperatures are independent of the fuel-air-ratio, but dependent only on combustor entry temperature, which itself depends only on overall pressure ratio. Ideally, for lean-burn combustors, because there is no region of stoichiometric combustion, the peak temperature tends towards the combustor exit temperature and the gases are held near their final temperature (T_{40}) for a relatively long time. This appears to become significant as turbine technology developments allow T_{40} to go up further beyond 1800K where NO_x production becomes rapid. It has been suggested that the comparatively high levels of NO_x at high thrust levels for LEAP1 and GEnx are because of high values of T_{40}. It is also likely that the injector, operating at higher fuel flow conditions, causes regions with locally higher equivalence ratio resulting in higher NO_x generation. It therefore appears that there is probably a lower bound on the level of NO_x that it is feasible to aim for, which could be expressed in terms of T_{40}. As a consequence, OPR is no longer a sufficient sole parameter to characterize combustor NO_x, but T_{40} or fuel-air-ratio must be included as well. It is worth noting that for the same turbine entry temperature the downstream end of rich-burn combustors (after dilution) and lean-burn combustors have similar T_{40}-dependent NO_x production conditions. The IEs are aware that there is a strong interdependency between NO_x production and T_{40}, but we do not have quantitative modelling tools for combustion, nor an adequate empirical base to allow them to quantify the effect. Crucially, however, residence times of the hot gas appear generally less for advanced, rich-burn combustors than for lean-burn ones.

5.3.2 Smoke/nvPM

Industry presented the IEs with qualitative information on the significant potential for nvPM reduction from recent engines, specifically from lean-burn combustion. There is little quantitative nvPM data available outside the confidential CAEP nvPM database so to assess the scope for reduction, the IEs carried out a study primarily using existing smoke data. The IEs were given limited access to the confidential nvPM database which enabled the study to be validated. Extracts from the study are contained in Appendix F.

The smoke/nvPM production process is much more complicated than the NO_x generation process. How the complex aerodynamics and mixing interact in the complicated process to form nvPM in a particular combustor design is still being determined, although nvPM mass formation is better quantified than nvPM number. The nvPM mass formed is influenced not only by combustor conditions defined by the engine cycle (T_{30}, P_{30}, and overall fuel-air-ratio), but additionally by the local fuel-air-ratio in the combustor. These define the formation of nvPM in the primary zone. Subsequent oxidation (burnout) of the formed particulates in the downstream part of the combustor is then dependent primarily on high temperature and long residence time. The nvPM number does not follow nvPM mass, so it is not currently possible to say what the main drivers for the nvPM number are.

It is known that nvPM size increases as temperatures, fuel-air-ratio, and pressure in the combustor go up. It was concluded in the study that for nvPM, the current in-service lean-burn (GE TAPS) combustors offer order of magnitude reductions in nvPM emissions compared to in-service rich-burn engines prior to the P&W TALON X combustor, which itself initially achieved levels similar to lean-burn combustors. The study concluded that achieving these levels will be much harder for smaller engines due to technical factors, such as lower cycle temperatures and shorter residence times, as well as market factors limiting economically-reasonable development spend.

It is known that smoke/nvPM formation is highly dependent on the composition of the fuel, particularly the aromatic content. Whilst altering the fuel composition offers a route to nvPM reduction, it also affects all measurements and fuel composition must be known or compensated for. Hydrocarbon fuels with low aromatic composition can be synthesized or refined, but will probably cost significantly more that current fuels. Despite these already demonstrated order-of-magnitude improvements, industry advises that early difficulties in service are likely to result in trade-off between nvPM and NO_x emissions at higher OPRs and T_{40}. 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. However, the technology is not yet mature enough and the design trades necessary not yet defined to provide any quantification for the likely nvPM reduction. Further significant improvements would require a step change in combustor technology driven by low nvPM design parameters but no such step change appears to be forthcoming.

5.3.3 Summary of Emissions Reduction Opportunities

To summarize the opportunities for reduction of NO_x and nvPM emissions from emerging combustor technology, the IEs have reviewed the research and technology information described above, taking into consideration the likely evolution of engine cycles, the current challenges with in-service lean-burn engines and the recent advances in the latest rich-burn engines. The IEs have concluded that only evolutionary developments of advanced rich-burn combustor and lean–burn combustor technologies are likely to be available within the timescale of mid- and long-term goals, with harder challenges for small engines. The IEs judge that further technology steps are unlikely within the Goals timeframe and have excluded them when setting the NO_x goals. A quantitative assessment of potential reductions in NO_x and nvPM emissions resulting from this conclusion is contained in Section 5.5.

5.4 IMPROVEMENTS SET AGAINST CURRENT GOALS

5.4.1 NO_x – Current Status Based on Certification

The information provided to this review in 2017 showed actual (as opposed to estimated) certification values of advanced rich-burn and the initial lean-burn engines which have become available in the eight years since the last IE NO_x review. In Figure 5-3, the NO_x certification data for the period from 2009 to 2017 is inserted, with the lean-burn and advance rich-burn combustors highlighted. The key new certification engine families from Figure 5-3 are described below. The GEnX engines within the shaded oval have been certified but are not in service.

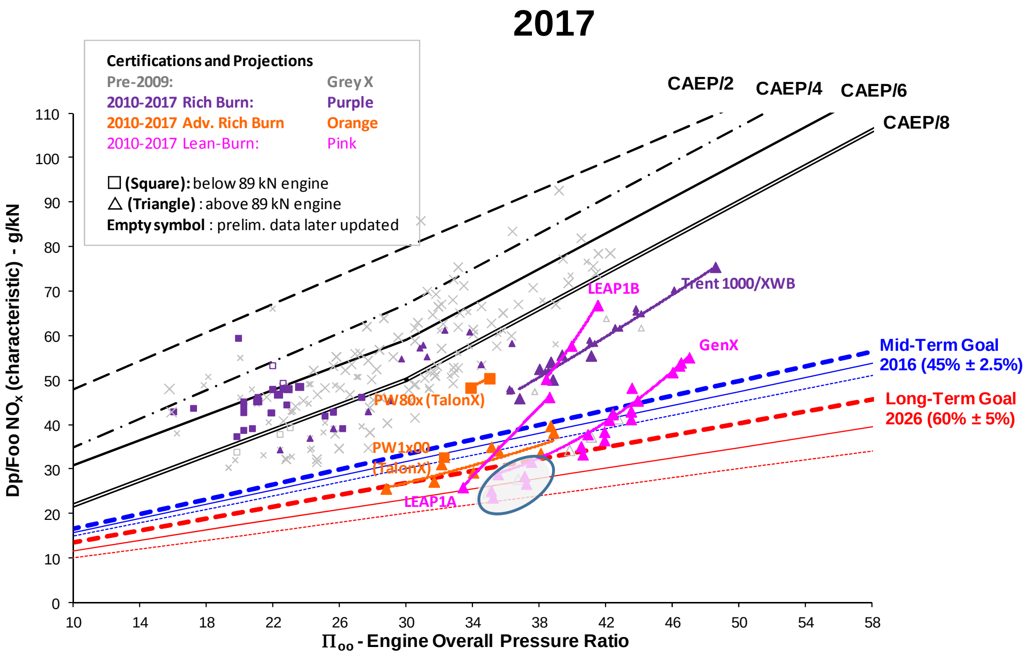

Figure 5-3. Certified and Projected Data from the 2009 NO_x Review Plus Recent Certifications from 2009-2017

RR Trent 1000 and –XWB: These large engines use the Phase 5 rich-burn combustor which has been in-service in various forms for some years. The Trent 1000 and –XWB use the new tiled version with margins to CAEP/6 of 22-35%, around 4% worse than their 2009 IE-review projected values in terms of their margin to CAEP/6. It is noted that a projected rich-burn combustor with a margin 40% below CAEP/6 from the 2009 review has not yet been certificated.

GE GEnX: This large engine is the first engine family certificated with a lean-burn combustor (TAPS). There have been three phases of certification – an initial version and two subsequent performance packages (P1 and P2) with a slight increase in NO_x for each successive phase. The latest phase is about 5-7% worse than the earliest for low OPR versions in terms of their margin to CAEP/6[64]. There is little change at the highest OPRs. A key feature of the GEnX lean-burn certification is the steeper slope of the engine family trend line versus OPR compared to rich-burn combustors, referred to above in Section 5.3.1. These lean-burn trend lines are slightly steeper than the stringency lines for higher OPR variants and are considerably steeper than the mid- and long- term Goal lines. For the latest GEnX family of engines (GEnX 1B-P2) in-service, margins to CAEP/6 range between 39% below CAEP/6 for the highest thrust versions and 53% below CAEP/6 for the lowest thrust versions[65].

CFM LEAP1A and 1B: This is the first mid-size engine certification for a lean-burn combustor, again the TAPS combustor. Certification data points are available at time of writing for the LEAP1A (A320neo) and LEAP1B (B737MAX) which has a different core engine and higher OPR cycle. The margin to CAEP/6 for the LEAP1A ranges between 40% and 61% below CAEP/6. However, margins for the LEAP1B are only 18% and 33% below CAEP/6, presumably reflecting the higher T_{40} in this version. LEAP1A and 1B data points in Figure 5-3 show an even steeper NO_x certification curve versus OPR than the GEnX lean-burn engine.

Pratt &Whitney PW1000G and PW800 with TALON X Combustor: This competitor engine to the lean-burn LEAP1 series does not have a lean-burn combustor but instead has an advanced rich-burn combustor. Certification results show the traditional rich-burn family slope but have NO_x certification values 55% below CAEP/6 for the GTF versions and 33% below CAEP/6 for direct-drive versions. The NO_x levels for the GTF versions are significantly below those seen for previous rich-burn combustor designs.

Other Recent (2009-1017) Engine Certifications: Other certifications since 2009 fall into the category of incremental NO_x improvements and thrust variants of existing designs. Most were reviewed in the 2011 and 2014 NO_x technology reviews carried out by CAEP.

Summary of New Certification NOx Data

The situation for all classes of engine is summarized in Table 5-1. For large and mid-size engines (>89kN) between OPR=30 and OPR=46, the recent advanced rich-burn (TALON X) and lean-burn (TAPS) certifications provide step reductions in NO_x emissions compared to traditional rich-burn combustor engines – improving from the previous 20%-30% below CAEP/6 to 40% to 60% below CAEP/6. For lean-burn, the lower levels of NO_x relative to CAEP/6 only seem to be achieved with current combustor technology if the T_{40} is sufficiently low, otherwise lean-burn can give NO_x levels higher than previous rich-burn technology in similar applications.

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[64] Percentages are approximate as there are other dependencies such as the number of engines tested

[65] Certificated P2 versions are available down to 59% below CAEP/6 but they are not in-service at time of writing

Table 5-1. Current Application of Advanced Rich-Burn and Lean-Burn Combustors to Certificated Products

OPR Range	Thrust Range <89kN	 89kN- 150kN	 >150kN
<OPR=30	-	Adv. Rich-Burn	-
30<OPR<46	Adv. Rich-Burn	Adv. Rich-Burn Lean-Burn	Adv. Rich-Burn Lean-Burn
OPR>46	-	Lean-Burn	Lean-Burn

For large and mid-size engines below OPR=30, these new combustor concepts have not yet been installed[66]. Although theoretically feasible, future installation is not likely as combustor retrofit is very difficult for existing engine types and the SFC would be too high for a new design. For smaller engines (<89kN), these new combustors have not yet been widely incorporated[67] and progress toward lower NO_x is not discernible since the last review. This matches the industry-stated opinion, particularly from the small-engine manufacturers, that scaling down these new combustors presents specific challenges (manufacturing, fuel thermal behaviour) as well as economic limitations related to the market for small engines.

5.4.2 Progress toward the Existing NO_x Technology Goals

At the 2006 NO_x review, the IEs defined that a goal is reached when one or more products cross the upper goal band line with mid-term in 10 years (2016) and long-term in 20 years (2026).

2016 Mid-term Goal: Using this definition of meeting a NO_x technology goal, the IEs consider that the 2016 mid-term goal (42.5% below CAEP/6 @OPR=30) has been met. Three engine families, GEnX, PW1x00G and LEAP1 have met the goal with one or more certificated products which are now in service. The IEs noted that:

- There are no engine families certificated below OPR=30 which meet the 2016 mid-term goal. Two advanced rich-burn engines do meet the goal (PW1522G and 1124G), but at OPR=29, these are the smallest members of a family designed for significantly higher thrust and OPR. Otherwise, the closest certificated engine in this OPR range is 11% (of the goal value) above the upper goal band line.
- There are no engine families below 89kN that meet the 2016 mid-term goal. One advanced rich-burn engine does meet the goal (PW1519G), but at 88kN, it is the smallest member of a family designed for significantly higher thrust. No engine family with the size of the core aimed below 89kN thrust is anywhere near the goal. The closest certificated engine exceeds the upper band of the goal by 31% of the goal value. The NO_x goals were not set with a thrust alleviation below 89kN, as seen in the NO_x emission regulations.

2026 Long-term Goal: Engines from the two lean-burn-combustor families, GEnX and LEAP-1 and the PW1100G advanced rich-burn combustor family have already been certificated at levels below the upper bound of the existing 2026 long-term goal. Under the existing definition of meeting a NO_x technology goal, the long-term goal has also been met. However, for both lean-burn engine families, the combustor results in a family characteristic steeper than traditional rich-burn combustors such that the higher OPR versions of the same engine families are 96% (of the LT goal value) above the upper bound line, whilst low OPR versions can fall below the upper (and median) long-term goal band line. It is also noted that for the GEnX engine family, only one of the versions certificated below the long-term goal upper bound have entered service at the time of the review, namely the GEnx-1B64 on the B787-8. The lower OPR and thrust versions were planned

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[66] The PW1122G and 1124G(1) with TALON X advanced rich-burn combustor is just below OPR=30 but is the lowest OPR member of a higher OPR family

[67] The PW800 with TALON X advanced rich-burn combustor is around 70kN and the PW1519G is just below 89kN

for the B787-3 and lighter versions of the B787-8 but, to date, these have not been delivered due to the cancellation of the B787-3 variant in 2010 and the increased mass and demanded performance of the initial B787-8.

The IEs have concluded that the existing 2026 long-term NO_x goal (upper bound) has been met by one or more low-OPR versions of three engine families, noting that:.

- There are no engines families certificated below OPR=30 which meet the 2026 long-term goal. Two engines do meet the goal (PW1522G and 1124G), but at OPR=29 these are the smallest members of a family designed for significantly higher thrust and OPR. Otherwise, no engine below OPR=30 is currently anywhere near the goal, the closest being 37% (of the goal value) above the upper goal band line.
- There are no engine families below 89kN which meet the 2026 long-term goal. One engine does meet the goal (PW1519G), but at 88kN, it is the smallest member of a family designed for significantly higher thrust. No engine family with the size of the core aimed below 89kN thrust is currently anywhere near the goal, the closest certificated engine being 64% (of the goal value) above the upper goal band. The original goals were not set with thrust alleviation below 89kN, as are seen in the NO_x emissions regulations. Therefore, it is to be expected that small engines do not approach the unalleviated goal levels. There is no evidence that the specific technical challenges at these small engine sizes will be solved to reach TRL8 before 2026.

Projected data: In addition to the certification data discussed above, industry has also provided information on the estimated certification values for engine programs currently in the demonstrator and development phases. These are shown as red open triangles and squares in Figure 5-4. The industry projected data represents a sample of engines planned to come into service in the next 10 years. None is projected to meet the existing 2026 long-term goal and only 3 of the 6 would meet the existing 2016 goal.

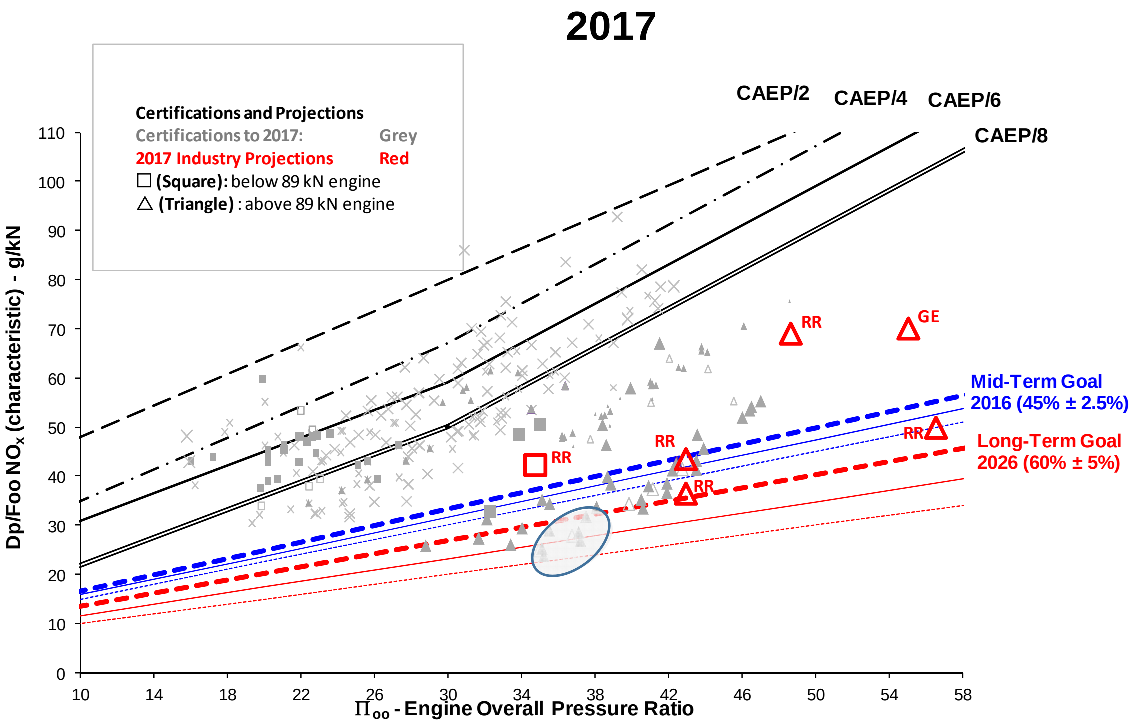

Figure 5-4. Recent Certifications Plus Estimated Demonstrator and Precertification Data

5.4.3 Smoke/nvPM

Smoke/nvPM has to date been controlled by a smoke-based visibility standard. Almost all modern engines now meet this Standard, often with considerable margins with the smoke below detectable levels[68]. At the time of writing, CAEP have an nvPM reporting Standard in place and are developing a prospective nvPM Standard with limits applicable to new and in-production engine types. However, there are currently no publicly available data or goals against which directly to assess progress toward reduction in nvPM emissions. Analysis of current technology carried out specifically for this review is described in Appendix G.

5.5 EMISSIONS TECHNOLOGIES – MID- AND LONG-TERM

In Section 5.3, the IEs concluded that only evolutionary developments of advanced rich-burn combustor and lean-burn combustor technologies are likely to be available within the timescales of the mid- and long-term goals. The consequences for future NO_x and nvPM emissions are discussed in this section, leading to consideration of updated NO_x goals.

5.5.1 NO_x Technology for LTO in the Mid- and Long-Term

The review of recent certifications in the previous section showed the results of initial application of lean-burn and advanced rich-burn combustors, meeting the 2016 mid-term and 2026 long-term goals. Although achieving a step improvement compared to traditional rich-burn combustors, recent certifications of lean-burn (Section 5.4) show a slight worsening of the NO_x characteristic compared to the 2009 predictions and since the initial certifications. The increase in NO_x levels are presumably a result of addressing combustion performance and combustor life issues which is typical of the initial application of new technologies and is not surprising. Having reached the judgment that no further technology steps will emerge during the mid- and long-term, the question posed is whether improvements can be made to existing combustor technologies beyond those in the initial certificated versions and whether these improvements merit the setting of new goals.

From a pure technology point of view, there do not seem to be routes to further stepwise improvement in NO_x relative to the most recently certificated advanced rich-burn system (TALON X) and the lean-burn TAPS systems. No doubt continuing efforts will be made to reduce NO_x. However, to quote the 2009 NO_x review for rich-burn combustors: *"Although manufacturers did not explicitly state that RQL has hit a limit, they [..] did acknowledge that the next 10% reduction below today's capability would be extremely hard to achieve"*. The quoted 10% reduction has now been achieved by TALON X combustors and there does not appear to be much more to come from rich-burn. For lean-burn, some improvement of premixing in lean-burn fuel nozzles is theoretically possible through improved fuel-air premixing and leaner combustion. However, the latter is critically dependent on increasing combustion air which must be at the expense of combustor and turbine cooling and may lead to loss in combustion stability – areas already under significant challenge particularly in the highest OPR engines. Improved staging and control strategies are also areas that require ongoing work. It is likely that all the innovations such as complex fuel injectors and manifolds and advanced wall cooling designs are increasing the mass associated with the combustion system and there will be a continuing focus on mass, cost, reliability and life-in-service. It has been thought that lean-burn offers greater NO_x reduction than RQL as it avoids stoichiometric mixing zones, but the TALON X results appear to challenge this for some engine cycles. As described in this chapter, to achieve further fuel burn reductions, T_{40} is being increased to above 1800K and there is some evidence that because of this, a lower limit on NO_x exists. Additionally, there is also a NO_x correlation method issue; it now appears that OPR alone is no longer a sufficient parameter to characterize combustor NO_x, but T_{40} or fuel-air-ratio must be included as well.

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[68] When using the smoke certification measurement methodology

From an overall, engineering point-of-view, the research and development is now most likely to be focussed on making the new advanced rich-burn and lean-burn systems more robust, to take out cost and to apply them to a wider range of engine OPRs and sizes. The engine cycle will determine the minimum NO_x achievable from a given combustor technology, in a trade-off with fuel burn. Because of the steep slope of the lean-burn D_p/F_{oo} vs OPR characteristic, the actual NO_x levels achievable expressed relative to CAEP/6 (or indeed relative to the Goals) will be highly dependent on the engine cycle. After balancing the relatively immature status of current advanced rich-burn and lean-burn combustors with the lack of room for further improvement, the IEs concluded that low-thrust versions of lean-burn engines with 60% margin to CAEP/6 should continue to become available but further significant improvement in margin to CAEP/6 appears unlikely within the timescale of the goals. Currently (2018), advanced rich-burn and lean-burn combustors are available only on two single-aisle and one twin-aisle aircraft types plus one business jet family. There are technical challenges in the wider application and these are summarized in Table 5-2.

Table 5-2: Challenges in Application of Advanced Rich-Burn and Lean-Burn Combustors

Application to:	Technical Challenge	Projected range of best NO_x Levels
Twin and Single Aisle	Both advanced rich-burn and lean-burn combustor technology should be applicable to new large and mid-size engine designs. Two aspects will dictate the NO_x levels achieved. Firstly advances in turbine design will allow higher T_{40} which will set a minimum level of NO_x somewhere close to the best achieved to date. Thereafter, this minimum level will worsen with time as turbine technology allows engine cycles with even higher T_{40}, offset potentially by incremental improvements in NO_x control. Secondly, for lean-burn, the lowest NO_x measured using D_p/F_{oo} will occur for low rated versions of an engine family, but not for higher rated versions.	**2027: 50% to 60% below CAEP/6** **2037: 55% to 60% below CAEP/6**
Regional and Business Jets	Scaling-down of complex fuel injector geometries is challenging since strength, tolerances durability and Reynolds number requirements will impose component dimension and manufacturing limitations. Larger RJ/BJ applications of these engines can be similar to engines for smaller single aisle aircraft and application of advanced rich-burn and lean-burn technology is technically feasible.	**2027: 40% to 50% below CAEP/6** **2037: 55% to 60% below CAEP/6**
Smaller Engines (below 50kN)	Scaling effects are even more challenging here. In addition, low combustor air temperatures and pressures reduce droplet evaporation rates and drag reducing the quality of the lean mixture and fuel placement precision. Combining this with the economics of the limited market for smaller engines, application of lean-burn and advanced rich-burn technologies by 2026 is very unlikely, so NO_x levels should be expected to remain at the current rich-burn levels. By 2037, application of lean-burn or advanced rich-burn to an engine below 50kN is conceivable, but economics may prevent it.	**2027: 35% to 40% below CAEP/6** **2037:40% to 50% below CAEP/6**

5.5.2 Climb and Cruise NO_x

NO_x certification and goals have from their inception been based on the LTO cycle. However, four confounding factors have come together in this review that require wider consideration of measures to monitor and control NO_x during climb and cruise, noting that it is during cruise that the majority of fuel is consumed, and hence, majority of NO_x is emitted:

- As described in Chapter 3, the most recent scientific understanding of the climate impacts of NO_x emissions shows that it is a significant greenhouse gas, though with less impact per kg NO_x emitted than was previously estimated.
- NO_x emitted at altitude may be important for ground level health impacts through a not yet fully understood mechanism of altitude to ground transport. Consequently, climb and cruise NO_x emissions may be more important than LTO NO_x emissions when considering total ground level health impacts at large scales.
- Staged combustors, including all lean-burn combustors, use substantial fuel placement and fuel-air-ratio changes as staging occurs. For rich-burn combustors a link was established allowing cruise NO_x to be predicted from sea-level static measurements based on the pressure and temperature of the air entering the combustor. When staging occurs, the simple link is broken, which introduces significant variability into the relationship between NO_x emitted during LTO and cruise. The dependence of NO_x emission on T_{40} for high-temperature engines introduces another complication. No quantitative data on the consequences of staging during cruise have been received. The IEs judge that lean-burn cruise NO_x is unlikely to be worse than an equivalent traditional rich-burn combustor unless staging (to operate with only the primary, as in a rich-burn combustor) takes place for a significant part of the cruise - which appears unlikely. However a methodology, if necessary validated by altitude measurement, and appropriate certification-level data, is required to monitor any technical goal for cruise and climb NO_x.
- Low engine fuel consumption requires high OPR and T_{40}. Control of NO_x at higher OPR is more difficult and this tradeoff has always been recognized in the slope of the LTO NO_x stringency lines (D_p/F_{oo} vs OPR). Consideration of the effect of T_{40} is new. Whilst huge reductions in NOx levels relative to these stringency lines have been achieved, the slide to the right with higher OPR engines means that actual NO_x per unit thrust has reduced less. In terms of LTO, climb and cruise NO_x emissions, this trend of increasing OPR has resulted in $EINO_x$ increasing over recent decades, including an increase of around 10% over the last 10 years. The result is that NO_x per seat kilometre offered has reduced only a few percent since 2005[69].

Looking forward, there is prospect of continuing increases in OPR and T_{40} contributing to the steep characteristics of lean-burn combustors. There is also no sign of a further stepwise improvement in NO_x technology. So, despite the apparent good performance of many advanced rich-burn and lean-burn combustors relative to the LTO NO_x certification levels, actual NO_x emissions at altitude per seat kilometre offered are not set to improve significantly. In light of these various factors, the IEs have concluded that:

- Confirmation of the method to calculate climb and cruise emissions from LTO certification data is required for all staged combustors, together with close-to-certification level data for any additional parameters required. Unless other means can be found, altitude test validation of the NO_x performance of recent staged combustors may need to be carried out.
- Consideration should be given to measures to assess and control altitude NO_x emissions, including consideration of possible goals for climb/cruise emissions.

5.5.3 nvPM Technology in the Mid- and Long-Term

For nvPM mass emissions, the IEs nvPM analysis in Appendix G concluded that:

- From previous generation rich-burn to lean-burn, an order of magnitude improvement in nvPM mass is likely for the LTO cycle. Potentially, a similar improvement would arise from previous generation rich-burn to recent advanced rich-burn combustor technology,

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[69] E.g. European Aviation Environmental Report 2016 (https://www.easa.europa.eu/eaer/topics/overview-aviation-sector/emissions) NO_x/ASK =0.44 (2005), =0.41 (2014).

- An interim conclusion, for the purposes of this review, is that lean-burn combustors will result in a reduction in cruise nvPM mass of one or two orders of magnitude compared to previous rich-burn combustors. For cruise with lean-burn combustors, there is a question regarding operating schedules for the rich-burn pilot during cruise.
- For latest advanced rich-burn combustors, improvements in cruise nvPM mass should be similar to LTO improvements (potentially an order of magnitude), subject to better understanding of the operation of these combustors under altitude conditions.

Similar key conclusions for nvPM number were:

- For LTO, in common with nvPM mass, lean-burn offers at least an order of magnitude reduction in nvPM number in LTO compared to previous rich-burn combustors. A further order of magnitude reduction is indicated from test measurements, but ICCAIA advise this may be a limit-of-detection issue and should therefore be discounted. Advanced rich-burn potentially offers an order of magnitude reduction in nvPM number in LTO.
- For cruise nvPM number, as for nvPM mass, the interim conclusion for this review is that lean-burn combustors will result in a reduction in cruise nvPM number of one or two orders of magnitude compared to previous rich-burn combustors.
- It is assumed for advanced rich-burn combustors that the improvements in cruise nvPM number should be similar to LTO improvements (potentially an order of magnitude), subject to better understanding of staging mechanisms.

However, caution must be exercised regarding future improvements. For advanced rich-burn combustors, only one example is in service. The low nvPM levels initially achieved were impressive but the mechanisms and design tradeoffs which resulted in such low nvPM levels are not well characterized, or understood by the IEs, and could be partly fortuitous. Indeed, during the drafting of this report, the higher thrust versions of the in-service advanced rich-burn combustors have been superseded with a modified version with considerably higher certificated smoke levels. For lean-burn, the levels achieved are better understood but, as the need to control NO_x in higher T_{40} and higher OPR applications increases, there will be a requirement to engineer trade-offs with nvPM. In both advanced rich- and lean-burn cases, nvPM levels are still expected to be better than earlier rich-burn combustors. However, industry has advised that the demonstrated order of magnitude reduction in nvPM may be reduced to as small as 50% once future cycle trade-offs are taken into account.

Looking further ahead with the lack of any stepwise development in combustor technology, and none related specifically to nvPM-technology, there are few prospects for significant further technology-driven reduction of nvPM from the current levels, which are almost-immeasurably low, within the timescale of the goals. The IEs are aware that if the levels are so very low, then substantial alteration of engines to reduce them further does not appear to be warranted.

With respect to nvPM emitted during climb and cruise, only limited data and understanding of nvPM mass and number formation processes in lean-burn systems are available. Robust correlations for ground and cruise nvPM emissions are therefore not well developed and validated. For cruise nvPM emissions, a combustor operating in pilot-only mode during cruise could produce as much as, or more than, the mass emissions of a good conventional rich-burn combustion system. Potentially, the correlations between LTO nvPM and altitude nvPM that exist for rich-burn combustors may be able to be applied to a lean-burn system operating in pilot-only mode. The LTO nvPM/Cruise nvPM correlations are different for staged operation, and these correlations would most likely contain additional terms, which have not been determined to date. Limited datasets, however, indicate significant change in nvPM mass and number during staged operation.

As to be discussed in Chapter 10, a route to lower nvPM is the alteration of the fuel to remove most of the aromatics. The nvPM mass reductions can potentially be of an order of magnitude. Industry has advised that except in cases where lean-burn combustors are already at very low nvPM emissions levels, reductions in nvPM emissions from aromatic removal can normally be added to those from combustor technology.

5.5.4 Emissions, Noise and Fuel Burn Trade-Offs

The technologies that are required to address emissions can have a mass and performance penalty – and hence some effect on fuel burn, and thereby an indirect effect on noise[70]. Similarly, noise reductions which increase fuel burn could result in an indirect NO_x and noise trade-off.

NO_x vs Fuel: Industry has been working on fuel efficiency and NO_x improvements concurrently, the one not holding the other back. Manufacturers indicated to the IEs that in terms of meeting the certification requirements, NOx technology would be developed to meet the needs of the most fuel efficient technically feasible cycle and, for the foreseeable future would not prevent fuel efficient technology being pursued. It is appropriate to point out, however, that the metric for NO_x makes allowance for the increase in OPR which has contributed to the reduction in fuel burn. However, in terms of the best achievable NO_x, the IEs believe that, combined with design pressure ratios and combustor geometry, T_{40} will become the limiting factor although its practical effect on limiting reductions in future NO_x emissions is not yet fully understood.

In the previous review, the IEs explored mass penalties as a result of advances in combustor technology to reduce NO_x. The additional mass of advanced combustors clearly results in a small but necessary trade-off in order to achieve the overall NO_x and fuel burn benefits. This trade-off was considered to be weak. In this review, the IEs were informed that for CAEP modelling purposes the fuel burn penalty resulting from minimizing NO_x at a given OPR and T_{40} has been assumed to lie in the range between 0.0% and 0.5%. Manufacturers indicated that generally the cost of the combustor technology is not a critical issue for larger engines.

Manufacturers who appeared to be less keen to move to lean-burn technology noted that the decision is largely influenced by the complexity of the combustor design as well as operability and potentially reduced in-service reliability. All manufactures noted that the mass penalty for lean-burn was probably not significant; those currently not using it believe that if they could achieve an overall performance improvement with lean-burn technology they could compensate for combustor mass increases. If the specific fuel consumption of an engine can be reduced without increasing $EINO_x$ of the engine, there will be a net reduction in NO_x emissions. This benefit needs to be set against possible increases in $EINO_x$ associated with the increase in OPR and T_{40} already described taken to reduce SFC. The improvements in SFC are normally small, a few percent at most, and smaller than the changes frequently noted in $EINO_x$. For constant $EINO_x$, improvements in aircraft fuel efficiency will provide NO_x reductions for a given payload/range requirement.

NO_x vs HC and CO: Compared to many other combustion sources, and to earlier gas turbines, HC and CO emissions are low. The environmental impact and likely health risks of aviation CO is small but manufacturers of small engines stated that for them the CO level was a limiting constraint. For larger engines, challenges with CO and UHC are only likely to originate as a result of the lean, low temperature combustion particularly at low thrust engine conditions. Manufacturers felt confident that these challenges would be addressed. For smaller engines, lower OPR leads to relatively higher CO (and UHC) when seeking to reduce NO_x, leading to dual constraints of NOx and CO in the combustor design. Although more CO is not desirable from an impact or fuel efficiency point of view, the merits of easing the CO Standard in order to enable better NO_x technology in small-engines was raised in the Review.

NO_x vs Smoke/nvPM: This topic was covered under the nvPM heading in Section 5.3.2.

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[70] Direct emission/noise and noise/emissions trade-offs are theoretically possible but are considered negligible for the technologies examined in this review.

5.6 CONSIDERATIONS IN SETTING NO_X AND nvPM GOALS AS PART OF AN INTEGRATED REVIEW

This chapter has set out the NO_x and nvPM emissions technology likely to become available within the timescale of the mid- and long-term technology goals. The implications for setting NO_x and nvPM goals are set out below.

5.6.1 NO_x Goals

Using the agreed criteria, the 2016 mid-term goal and the 2026 long-term goal from the previous NO_x review have been met. All engines which meet one or both of the goals contain either advanced rich-burn or lean-burn combustors. Only low thrust versions of engines with lean-burn combustors meet the long-term goal, but with their high thrust versions performing relatively poorly, being well above even the mid-term goal band and in one case approaching the CAEP/8 regulatory level. No small engines (below about 80kN) have met either goal and there is little evidence of progress here. In considering NO_x goals for this integrated review, the following points need to be taken into consideration:

- NO_x emissions technology appears to have reached an asymptote with no step change envisaged during the goals timescale. Future NO_x goals may have to be less stringent to maximize fuel burn improvement.
- The D_p/F_{oo} vs OPR slope of the lean-burn combustors has been confirmed as being very steep, particularly compared to the NO_x stringency lines and the technology goal lines from the previous review. Consequently, meeting a technology goal and the margin to the NO_x Standard is dependent as much on the engine cycle to which the technology is applied as on the NO_x technology itself. This is particularly significant where the goal-meeting criteria requires only one engine variant to meet it.
- Like the previous NO_x goals, the proposed 2027 NO_x goal is based on NO_x levels associated with engines with $F_{oo} > 89$kN. It does not incorporate the thrust alleviation seen in the current NO_x Standard. A single goal to apply to all thrust classes was agreed, recognizing that meeting the goal for some lower thrust classes and aircraft applications is particularly challenging.
- Climb and cruise NO_x may potentially be more important than LTO NO_x when considering aviation NO_x air quality impacts. It is certainly more important for climate-change impacts. Goal setting should reflect this change of emphasis as soon as clear evidence is available. If clear evidence emerges, steps should be taken to formulate goals for cruise emissions.
- Application of the current LTO NO_x Standards and goals has not been leading to significant reduction in $EINO_x$, the mass of NO_x normalized by the mass of fuel burned. Fleet-wide NO_x full-flight emissions per available seat kilometre are not reducing significantly.
- The current definition of achievement of a NO_x goal is not in line with the current definitions of fuel burn and noise goals. For this integrated review, a consistent set of goal-meeting criteria should be developed to cover the full set of technology goals.
- Recent staged combustion, including lean-burn, engines do not have a clear relationship between LTO and cruise NO_x.
- Some low thrust engines which are certified during the early part of an aircraft program never enter service, so there is no environmental benefit from many goal-achieving engines. It is recommended that goals contain a requirement that the engine which is taken to meet the goal is one that goes into serial production.

Taking these considerations into account, it is concluded that:

- A new 2027 MT LTO Goal should be set at 54% below CAEP/8 at OPR=30, using the equation $D_p/F_{oo} = 5.75 + 0.577*OPR$, to cover the entire OPR range. The complete definition is given in Chapter 8. This Goal is slightly more demanding than the best certified engine at time of writing and reflects the increasing difficulty in obtaining further improvements in NO_x during this period. To ensure environmental benefit when meeting the goal, there are no goal bands and the goal is met only when the 50th engine of a single goal-compliant type enters service.

- Any further consideration of LTO NO_x goals, including goals for 2037, must be based on a methodology which reflects combustors where emissions alter strongly with T_{40}.
- To reflect the potentially increasing importance of altitude NO_x relative to LTO NO_x, consideration should be given to the development of a cruise-based NO_x goal. This should use a climb/cruise (or full flight) metric system, ideally developed by CAEP, as part of cruise NO_x certification. Development of such a goal was too ambitious for this integrated review.
- Urgent action is required to obtain data for climb and cruise NO_x emission rates, focussed on staged combustion engines – including altitude testing to validate any theoretical methodology as necessary.
- Setting a cruise-based NO_x Goal level would take full account of interdependencies, in particular the technical trade-offs with fuel burn, especially as a result of higher T_{40} and the emerging understanding of relative nvPM and NO_x emission health and environmental impacts. The IEs would propose that CAEP ISG examine both types of impact for cruise.

5.6.2 nvPM Goals

There are no current nvPM Standards[71] or goals. 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 setting of nvPM goals at this time appears neither practicable nor necessary. Once data is becoming available and climate and air quality impacts are better understood, there may be merit in setting goals for nvPM. Again, examination of this issue by CAEP ISG would be appropriate.

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[71] A new nvPM Standard has been agreed to be set at the equivalent level of the current smoke number Standard, which will apply to turbofan and turbojet engines manufactured as from 1 January 2020, for aircraft engines >26.7 kN.

CHAPTER 6. AIRCRAFT NOISE REDUCTION

6.1 INTRODUCTION

The Integrated Review is performed with reference to the ICAO noise Standard, and to the existing goals established during previous Independent Expert Noise Reviews[8,9]. Because of the nature of this integrated review, it is not possible to be as comprehensive as in the previous two noise reviews. Some elements on the background are, however briefly, recalled below and in Appendix I. The noise from civil aircraft is regulated by ICAO Annex 16, Volume I. Certification for noise relies on measurements at three positions, two for take-off (referred to as lateral and flyover) and one for landing (referred to as approach). The levels are expressed in decibels (EPNdB) using effective perceived noise level (EPNL), described in Appendix H.

6.1.1 Local Noise Regulation

Complaints from residents living near busy airports, who were experiencing high noise levels despite the international regulations – have led to local regulations being adopted by some airports in Europe and elsewhere in the world. These have an effect on the design of aircraft, notably London Heathrow Airport for large aircraft, and London City Airport for regional jets. As a result, the Annex 16, Volume I limits (even at the most recent Chapter 14 of 2014) are not always the most demanding noise requirements that manufacturers have to meet. For example, the Airbus A380 operation into London Heathrow, in connection with the Quota Count system of aircraft noise classification, led to modifications by the aircraft and engine manufacturers to meet local requirements, thereby achieving a cumulative margin well below the ICAO Chapter 14 noise limit. Other recent aircraft, like the Boeing 787-8 and the Airbus A350, both achieve levels well below the ICAO Chapter 14 noise limit.

6.1.2 Noise Generation by Modern Aircraft

Understanding the generation of noise is very challenging as it involves propagating pressure fluctuations in a non-steady flow. Noise can be produced by moving objects, such as fan blades, by a jet or by flow past an open duct. The problem of understanding is greatly increased for aircraft engines because of blade speeds and flow velocities close to sonic. It is also challenging to determine precisely what the noise sources are, or what is their relative importance. This is a particular problem with broadband noise, such as that from the fan and from the LP turbine, which can be partially confused with jet noise.

The jet is a broadband source of noise attributable to turbulent flow mixing. Jet noise is approximately proportional to the eighth power of jet velocity; i.e. the acoustic power more than doubles (increases by 3 dB) for a 10% increase in jet velocity. The significance of jet noise to the overall noise depends on the engine characteristics, notably the fan pressure ratio. As fan pressure ratio is reduced, the fan diameter must be increased to compensate for lower thrust. For large engines, now including those for the large single-aisle aircraft (A320neo and B737max), the fan pressure ratio has been reduced with time, and jet noise is now comparatively small. For smaller aircraft, such as many regional jets and business jets, the FPRs are higher. The higher FPR is because for under-wing installations the engine diameter is constrained by ground-clearance requirements, whilst for rear fuselage mounted engines, the mass precludes large diameter fans. So a difference has emerged in the breakdown of engine noise sources for small and large aircraft, with jet noise still dominating take-off for the small ones and fan noise for the large ones.

The distribution of sources for large twin-engine, twin-aisle aircraft, such as the Airbus A350 or Boeing 787, is shown in Figure 6-1 for departure and approach, as provided by Airbus. The engine noise (mainly from the fan) is dominant at take-off, whilst the airframe may create 60% of the acoustic energy at approach with 80% of the airframe acoustic energy coming from the landing gear. The situation for a new large single-aisle aircraft (A320neo or B737MAX) is a little different from twin-aisle aircraft, as the undercarriage is far simpler and less progress has been made in reducing the noise from the high-lift system (slats and flaps); for the SA only about 25% of the approach airframe acoustic energy is from the undercarriage.

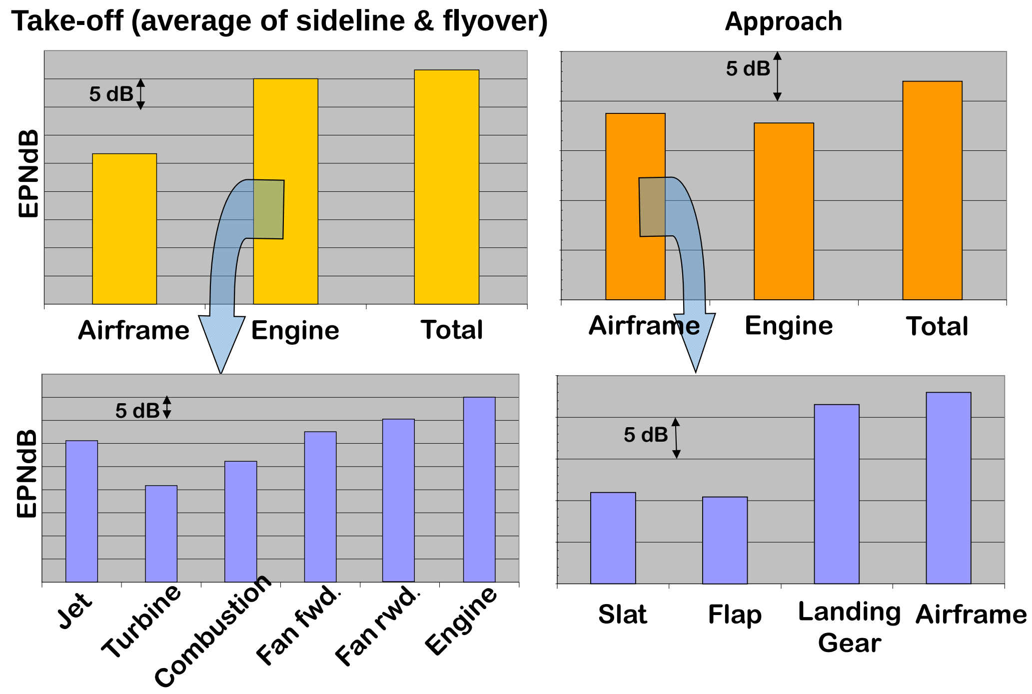

Figure 6-1. Noise Source Breakdown for a Representative Modern Large Twin-engine Aircraft

At approach, jet noise is negligible and the fan is the most important engine source. Because the fan is rotating much more slowly during approach than at take-off, the causes of fan noise are different, changing both the magnitude and frequency content of the noise. For the most recent RJ aircraft, the Airbus A220 (formerly Bombardier C-series), the fan pressure ratio is comparable to that for the large SA or the TA aircraft and jet noise is correspondingly lower than earlier RJ with higher fan pressure ratio. The relative importance of engine noise sources, and change associated with time, is shown schematically in Figure 6-2. When fan pressure ratios were high (low bypass-ratio engines), noise was dominated by jet noise. With modern engines, jet noise has become less significant. Figure 6-2 emphasizes that noise is highly directional and even in the rear arc, fan noise now dominates on new engines.

Although the separation of noise into engine noise and airframe noise is convenient, and brings out how the source breakdown has changed over the years, it is not entirely complete. There is an interaction between the engines and the airframe which can alter the noise. The upwash from the wings creates an angle of attack in the inlet and around the nacelle which can affect engine noise. The jet can interact with the wing, both aerodynamically, to create a powerful noise source, and acoustically, so that sound is reflected down to the ground. In summary, there has been a clear trend, more obvious on new large aircraft, for the airframe noise to become more important than engine noise in approach. Even for the engine, jet noise is no longer the dominant source. Scaling noise on engine parameters, notably bypass ratio, as was done in earlier Independent Expert reviews therefore needs to be reconsidered.

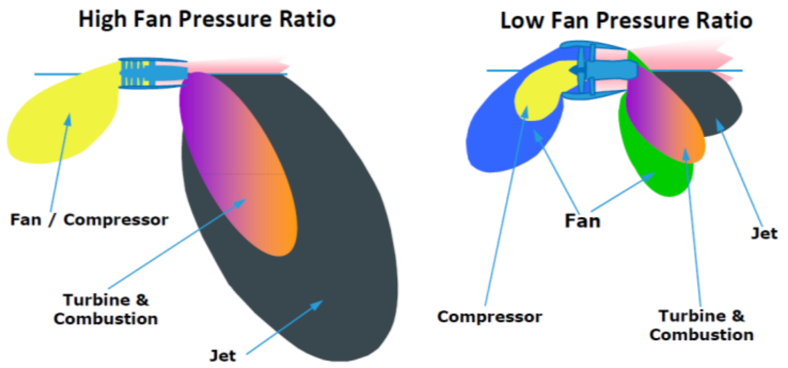

Figure 6-2. Noise Sources from Jet Engines with High and Low FPR

6.2 ENGINE NOISE

6.2.1 Jet Noise

As noted above, lower jet velocity has reduced jet noise below other sources on large turbofan engines. Jet noise is caused by high velocity turbulent mixing of fan and core jets in ambient air, resulting in broadband noise. Considerable progress has been made in reducing jet noise through engine design by reducing fan pressure ratio, which reduces the jet velocity and thus reduces the engine fuel consumption, whereas the scope for reducing jet noise at a given velocity is limited. This trend to lower fan pressure ratio will continue on large geared turbofans, and progress will hinge on installation effects and powerplant mass. On smaller engines for regional jets or business jets with higher fan pressure ratios, corresponding to bypass ratios in the range 3 to 6, jet noise is already mitigated through devices like long-duct[72] forced mixers. Advanced long-duct forced mixers are likely to continue to be installed in this class of aircraft in the future, possibly with fixed chevrons.

Engine chevrons at nozzle exit have been employed on some aircraft that have low fan pressure ratio engines to mitigate jet noise experienced in the cabin during cruise, but their effect on jet noise during take-off is small or negligible. It is therefore unlikely that chevrons will be widely used to reduce jet noise on large single-aisle, twin-aisle or regional jet aircraft with low fan pressure ratio engines, as the fuel burn penalty from the use of these devices will outweigh the marginal noise benefit. One technology, the variable area fan nozzle, could be available for use. This could drop the fan pressure ratio for take-off but allow it to revert to the optimum value for low fuel burn at cruise. This would assist the operation of the fan, mitigating the tendency of low pressure-ratio fans to approach instability during take-off. The benefit to fan operation might justify the complexity, mass and cost of a variable area nozzle; however, the engines which would benefit in operational terms are those which already produce levels of jet noise below that of the fan.

Jet noise prediction methods have been extensively developed, from empirical to semi-empirical to more sophisticated ones based on flow calculations. Understanding of the processes has been increased through the use of advanced optical diagnostics and noise source location techniques. These techniques allow to identify the jet noise source in the engine exhaust plume, and to characterize it by its signature in the spectrum

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[72] Note that on the original A330, the Rolls-Royce engines had a long duct with mixed jet at exit; the bypass ratio was about 5. For the A330-neo the balance has changed and the long duct has been removed. The fan pressure ratio for the new engine is significantly lower and the bypass ratio significantly higher. The long-duct is a well-established technology that is only appropriate for engines with fan pressure ratio higher than new large engines.

analysis. Methods based on improved modelling capabilities could lead to lower noise for future engines but are not expected to enable technologies reaching TRL8 by 2037.

6.2.2 Fan Noise

The fan on a modern large aircraft is the most powerful source of noise for take-off and the most important engine source for approach. Fan noise radiates forwards and rearwards as shown schematically in Figure 6-2. It involves broadband noise, tonal noise and buzz saw noise (multiple-pure-tone noise), with different spectra between take-off and approach. The buzz-saw noise is only in the forward arc and occurs when the relative velocity at the blade tips is supersonic. As the fan pressure ratio has been decreased, the blade tip speed has also been reduced and the buzz-saw noise is less important or non-existent. Reducing the fan pressure ratio has several benefits apart from the main historical driver, which is the increase in propulsive efficiency. One is that as the pressure ratio decreases, the blade relative Mach numbers are reduced and the fan efficiency increases. Another benefit is that decreasing the jet velocity reduces the jet noise. Lastly, the noise from the fan itself tends to fall as fan pressure ratio and fan speed go down. However, decreasing fan pressure ratio for a given engine thrust leads to larger diameter fans, which tend to be heavier and to have larger nacelle drag. Furthermore, the difficulty of installing the engine efficiently increases. Mass and installation problems are largely the reason why regional jets and business jets remained with relatively high values of fan pressure ratio.

Fan design is aimed primarily at achieving high efficiency and stability with pressure ratio and tip speed as constraints. Noise from the fan is strongly affected by tip speed, but also by fan efficiency, aero-mechanical and geometric features of the engine. Key amongst them is the location of the outlet guide vanes, which should be as far as possible downstream from the rotor to reduce the interaction tone noise. Increasing axial gap tends to increase mass and reduce engine rigidity, so another option is to sweep or lean the outlet guide vanes, but this too affects rigidity and mass. There is an inevitable tension between reducing noise and achieving low mass. The design of the engine air intake also affects propulsion system performance, mass and engine stability. The intake affects engine noise generation by its ability to make the flow entering into the engine relatively uniform, but it also affects the noise through the acoustic linings on the walls.

The interdependencies between engine performance, measured as fuel burn, and noise have reached a high level on current engines, and will further increase as fans of increased size are adopted. Fan noise is a function of several aerodynamic performance parameters already mentioned above. For high-speed fans, still used for regional jets and business jets, the forward noise at take-off is dominated by multiple pure tone noise (buzz-saw noise). The mitigation here is well understood and widely used: carefully managed blade shapes and efficient acoustic liners. Some mitigation for supersonic rotors is also achieved with rotor sweep. For lower speed fans, the interaction noise in the forward arc, either the rotor interacting with inlet non-uniformity or the rotor wakes with the outlet guide vanes (OGV), is predominantly tonal. Interactive tones associated with the OGVs are prone to occur when the gap between the fan blades and the struts is smaller. The interaction with the OGV is managed by choosing the rotor and vane numbers to cut-off the low harmonics of blade-passing frequency; also by keeping the OGV as far rearwards as possible and by leaning or sweeping the OGV. The interaction tones will also be important for the regional and business jets, at approach.

The fan noise rearwards component (interaction and broadband noise) is often more important than the forward arc component. Broadband noise generation mechanisms are imperfectly understood. Increased aerodynamic loss, either because of design flaws or because the fan is operating at a pressure ratio exceeding design value at fan speed, can increase broadband noise. The pressure ratio increase at take-off relative to cruise, due to the lower forward speed, could be mitigated with a variable area nozzle. ICCAIA provided a table (see Figure I-1 in Appendix I) showing fan noise technologies in two categories; those at high technology readiness level (TRL≥ 6) and those at lower TRL. The table also shows key integration issues, main impacts on fuel burn and emissions, active research activities and potential applications. All the high TRL technologies are evidently well established; indeed all but the variable area fan nozzle are already on engines in service. The decision to implement them has been taken on the basis of an overall optimization, including fuel burn. They are consequently likely to be implemented by 2037 but, given that most are already adopted, there is little further gain likely from them relative to what is used on aircraft like the A350, B787 or B747-8. The possible implementation of the variable area fan nozzle (flown on a demonstrator, but never installed or in service) in future engines with lower fan pressure ratio, will depend on overall performance optimization, including fan operability issues at low speed, rather than on acoustic benefits, although it could reduce broadband fan noise.

The low TRL technologies (soft vanes, over-the-rotor treatment, trailing edge blowing, trailing edge serrations, active stator, and active blade tone control) are unlikely to be implemented even for 2037. This is supported by the slow advance in the TRL since the first IE Review (2010). The slow progress is associated with significant integration or other issues (fan performance, drag, maintenance, integrity, complexity, mass or cost).

6.2.3 Liner Attenuation

Liner technology has been extensively developed and widely used over the last 30 years, benefiting from progress in structural and aerodynamic design, dedicated acoustic rig testing, analytical and numerical tools (e.g. for evaluating complex 3D ducts), measurement capability, manufacturing processes and acoustic materials. New technologies are implemented only after their mass, performance and cost effectiveness have been properly demonstrated, implying that potential benefits cannot be simply added-up. ICCAIA reported that the overall aircraft noise reduction achieved by fan forward and fan rearward noise attenuation through acoustic liners was in the range of 10 to 12 EPNdB (cumulative) on recent aircraft types.

Liners are installed at many locations in the engine and on the nacelle, in order to gain maximum acoustic area (see Figure 6-3). Fan noise is particularly targeted, as a major noise source with relatively large areas in the nacelle susceptible to acoustic treatment. In addition to the treatments in use, new ones have been developed which have reached TRL between 6 and 9, others look promising, but are still at low TRLs. These technologies have various noise reduction potentials and they need to overcome different integration issues. Some of the promising technologies have already been introduced on most recent aircraft types, in particular unspliced intake liners on twin aisle and single aisle aircraft, whilst more will follow on the next single-aisle and regional jet generations.

Acoustic treatment is a very efficient way to attenuate both fan tonal and fan broadband noise. Treatment attenuation increases with increasing duct length to height ratio. So, a long treated nacelle with small diameter is more efficient in reducing noise than a shorter treated nacelle with larger diameter. The tendency to increase fan diameter will increase the pressure to shorten the nacelle and thin the intake.

The challenge for the future will be to keep similar levels of noise attenuation from liners, on installations with less acoustic area potential, and less depth available for liners due to larger fans and shorter inlets and nacelles. This will require thinner, more efficient liners, relying on intensive research activity to develop and mature materials and technologies satisfying the demanding requirements.

Information on new liner technologies was supplied by ICCAIA and this has been reformulated into the table provided in Appendix I. Some of the technologies have reached relatively high maturity level ($TRL \geq 6$) and most of these have already been used in service. Little further attenuation can be expected beyond that already in recent twin-aisle aircraft. The practical application of the noise lip liner technology seems to be hampered by the conflict with the anti-icing system and it is unclear whether a solution has been identified to overcome this hurdle.

Other technologies at relatively low maturity level shown in Appendix I are therefore much less likely to be introduced in the mid-term and some technologies may not even be available for the long-term, depending on the level of difficulty involved to get from TRL 4, 5 or 6 to TRL8. However, the “optimized zone liner” technology seems able to reach TRL8 in 2037 without major difficulty.

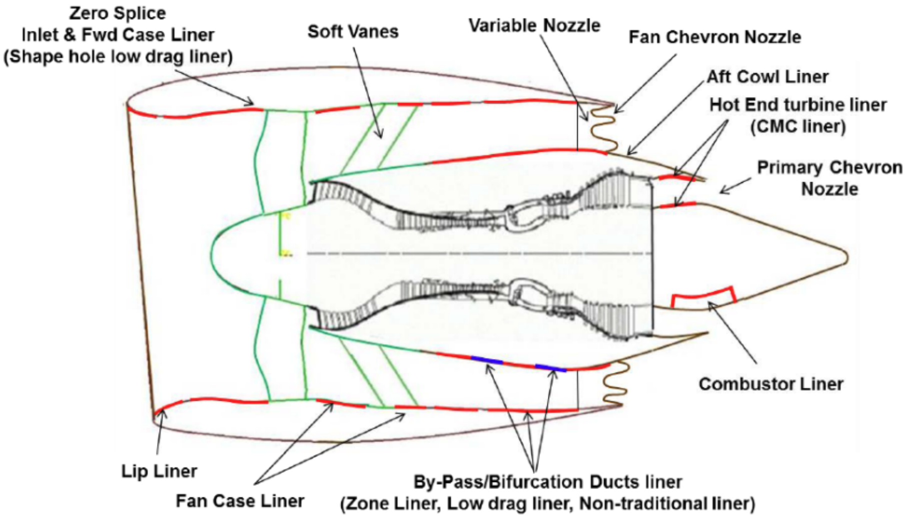

Figure 6-3. Liner Positioning on the Propulsion System

6.2.4 Core Noise

Core noise is not normally a dominant source on current large engines but does contribute significantly on smaller engines and may contribute to approach noise even on large engines. As fan and jet noise are reduced, core noise will tend to become significant and therefore needs to be addressed. Core noise sources (broadband and tones) are produced by the compressor/booster (detectable mostly at approach) and the combustor and turbine at both departure and approach. The largest core noise sources are usually the LPT and combustor noise sources propagating through the core nozzle. In addition, compressor bleed valves are sometimes needed at approach to maintain compressor stability and these can emit broadband or screech tones.

Core noise is still imperfectly understood and care is needed to ensure that it does not eventually emerge as an important noise source. In particular, the LP turbine could become a significant noise source with a geared fan if turbine tones are not cut-off. Also, as combustors are further refined to reduce pollutants, such as lean-burn combustors, there is a risk that the currently low combustion noise might become a significant nuisance. Liners could be very effective in the core nozzle region, particularly for attenuating the turbine tones, and there are opportunities to introduce them, subject to the development of lightweight, heat-resisting materials with adapted manufacturing processes.

6.3 AIRFRAME NOISE

Airframe noise, the aerodynamic noise generated by all the non-propulsive components of an aircraft is produced by landing gear, spoilers, high-lift systems (i.e. slotted flaps, flap and slat edges, and flap and slat tracks), parasitic noise sources, and component interaction sources, i.e. gear-wake/flap interaction. The parasitic sources, cavities and protuberances, are normally secondary noise sources, which however need to be watched. The interaction sources may be significant: jet with flap, landing gear wake with landing gear, landing gear wake with flap. Airbrakes are of less importance for noise depending on configuration.

Experimental measurements to investigate and reduce airframe noise are widely used, including wind tunnel aero-acoustics, far-field noise directivity, source localization, and flight tests. On most recent aircraft types, airframe noise has been reduced mainly because approach speed has been reduced, but there has also been some optimization of the configuration. In particular, the landing gear design and configuration has been improved, including wheel number, size combination and bogie tilt angle. Holes which can cause tones because of the flow past them have been covered or filled. The slats and flaps have been sealed and parasitic noise sources have been reduced or eliminated.

6.3.1 Landing Gear Noise

Landing gear noise is generally the largest airframe noise source, being both broadband and tonal. It is caused by various aerodynamic phenomena, notably flow separation from various struts, joints, and dressings. Although the landing gear is the predominant airframe noise source on twin-aisle aircraft, it is less significant on single-aisle aircraft, where it is comparable to high-lift system noise. This is because of reduced complexity of landing gear for the single-aisle, a smaller number of wheels and the size of the retracting bay and cavities. Also, on the single-aisle aircraft, there has been less work to reduce noise from high-lift devices.

Specific design recommendations to minimize landing gear noise have been followed for many years on every new project aircraft. A straightforward noise reduction approach would consist in covering the whole gear structure with streamlined fairings and wind-tunnel tests indicate a noise reduction potential of more than 10 dB at component level. However, such solution is not practical because of multiple constraints, including operational, safety, integration/kinematics, brake cooling, maintainability, mass, system complexity, and cost.

Many studies, including wind-tunnel tests of advanced designs have been carried out. These include add-on fairings, various improvements of nose and main landing gears, and passive and active flow control devices. The potential noise reductions at component level are from 2 to 7 dB, but always with limitations linked to various constraints referred to above.

Fairings to streamline flows, although extensively studied and tested, were never installed, as explained above. Fairing designs developed up to TRL6 could be implemented on twin-aisle aircraft, subject to a trade between acoustic benefit and cost. The noise benefit is approximately 3 to 5 dB at component level corresponding to only 1 to 1.5 EPNdB at aircraft level during approach. On single-aisle aircraft, however, where the landing gear noise is less important, the potential fairing benefit is reduced to ~0.5 EPNdB at aircraft level. Other technologies for low noise landing gear design and passive flow control, currently at TRL~4, would bring up to 5 dB benefit at component level, but are unlikely to be ready by 2037.

6.3.2 High-lift Systems Noise

High-lift devices represent the second most important source of aerodynamic noise from the airframe. High-lift systems are critical to low speed aerodynamic performance, with a significant influence on take-off L/D and maximum lift coefficient on landing. The high-lift devices have a major influence on equivalent aircraft payload and it is a requirement that reducing noise does not degrade the aerodynamic performance of the device or lead to deterioration in aircraft handling quality. The quiet high-lift devices, of course, must face the challenge of avoiding any adverse impact on the operational capability, on safety, on major structural elements and mass, on maintainability, economic viability, and costs.

Complete wing system simulation with accurate flow features cannot normally be performed at full scale because of the unavailability of large enough acoustic wind tunnels. Flight tests can be used but they are very expensive and only high TRL technologies can be tested. Scale model aircraft or wing configurations are used, but suffer from a non-representative Reynolds number. Noise originating from tracks has not yet been accurately quantified, due to inaccurate geometries in scale models. Further information on slat noise and flap noise are provided in Appendix I.

The main high-lift wing noise sources, in order of importance, are the slotted slats, the slat tracks, the slat horn (inboard slat side edge), the flap side edges, and the flap tracks. Because the flap edges are like point noise sources, whilst slat noise is an extended line source, the integrated power is higher for the slats than for the flap side edges.

As mentioned above, adding a requirement for low noise must not impact operation or safety and there is pressure to avoid significant increase in mass or cost. A major problem, in this regard, is a certification requirement that links the maximum lift coefficient to the minimum landing speed (linearly related to the stall speed). A noise mitigation measure which would reduce maximum lift coefficient would lead to a rise in landing speed at the same payload, which could increase noise, undoing the benefit of the original modification.

There are opportunities for reducing noise from slats. Leading edge droop or sealed slat is a silent high-lift device which has been deployed on most recently certified twin-aisle aircraft but only on a part of the wing span. Extending such devices to full span would further reduce noise from the wing leading edge but would involve a full wing re-design with a trade-off between high speed and low speed performance of the aircraft. Slat noise is no longer considered an issue on twin-aisle aircraft, whereas the opportunity for design optimization still exists on SA aircraft, which could bring 3-5 dB benefit at component level, but much less at aircraft level. Reducing the noise from flaps is possible, and a low noise design and treatment could bring 3-5 dB benefit at component level. More information is provided on slat noise reduction technologies and on flap noise reduction technologies in Appendix I.

6.3.3 Parasitic Noise Sources

Parasitic noise can have either tonal or broadband characteristics. It is very much design-dependent, and it may have a higher intensity than the traditional airframe sources, determining overall airframe noise signature. The main parasitic sources are cutouts on the airplane surface such as anti-ice vents, fuel vents, and pin-holes (mainly on landing gear, antenna, scoops, and more recently bulky internet receptors). Also important are components of the high-lift system such as cutouts in the wing leading edge to accommodate the slat tracks, and cavities in flap side edges. Reducing parasitic noise may go hand-in-hand with better aerodynamic design but attention must be paid to the potential loss of efficiency and functionality of systems. For example: slat tracks must allow proper operation and vents are needed to avoid the build-up of humidity resulting in corrosion.

6.3.4 Spoiler and Air Brake Noise

The potential application of airbrakes to enable or enhance the capability of the aircraft to perform low-noise steep continuous descent approaches requires a low-noise design of airbrakes. There is very little data available to date to quantify and characterize spoiler noise, primarily a low-frequency phenomenon, and very limited knowledge of the noise mechanisms underlying the complex potential effects of a spoiler on local wing aerodynamics and thus on slat noise.

6.4 AIRCRAFT AND ENGINE CONFIGURATION

Different configurations are being considered, within the conventional tube and wing arrangement, which depend on the category of aircraft and on the engine size. The underwing configuration is preferred, where possible, but large diameter fan engines are always a challenge because of wing height and necessary ground clearance. Fuselage mounted engines near the tail can cause particular problems due to mass /center of gravity, and such aircraft normally require high fan pressure ratio engines to keep size and mass down for a given level of thrust.

Engine airframe integration has become important in recent years, even in the new single-aisle aircraft because of the large diameter of a low pressure ratio fan. As noted above, the new engines produce much less noise than the former ones, but their underwing integration can lead to a number of issues. The extent of the leading edge high-lift device is reduced due to the proximity of the nacelle and the short pylon. The larger engines may lead to longer landing gear, which in turn increases noise. Lastly, there is more opportunity for the jet to interact with wings and flaps and produce a very strong noise source.

Figure 6-4, below, illustrates some features of a large diameter fan engine installation. The left hand plot shows the potential for the jet to interact with the wing and flaps and for the noise to be reflected by the wing. The upwash will also distort the jet with possible noise implications. All these effects will increase as fan pressure ratio falls and the engine becomes larger in relation to the wing chord. The right-hand plot shows a schematic regional jet for various fan diameters. Solutions for a better engine-wing integration range from gull wing[73] lay-out, optimized in-board slat geometry and a not-yet-applied technology of flap lower surface liner. The modifications may have implications for aerodynamic performance, notably cruise L/D. Another option is a longer landing gear, but this would increase mass and noise at approach.

In the last decades, the fleet benefited from a large overall noise reduction, thanks to a range of technologies added to the lower fan pressure ratio engines. The technologies included some rotor and stator sweep and lean, improved acoustic liners as well as airframe noise technologies. However, the progress in noise reduction at the aircraft system level is increasingly challenging. The production aircraft already meet the current certification requirements, in most cases by wide margins, and also meet additional limitations imposed by existing airports. The continuing demand for aircraft noise reduction leads to two questions: what are the prospects for new technologies and what new configurations would allow further noise reductions? This also leads to another question: what an aircraft would look like with a design philosophy prioritizing a step change in noise reduction? The ever-increasing economic challenges linked with fuel consumption, and with growing concerns about global climate change, mean that fuel efficiency is unlikely to be significantly sacrificed for noise.

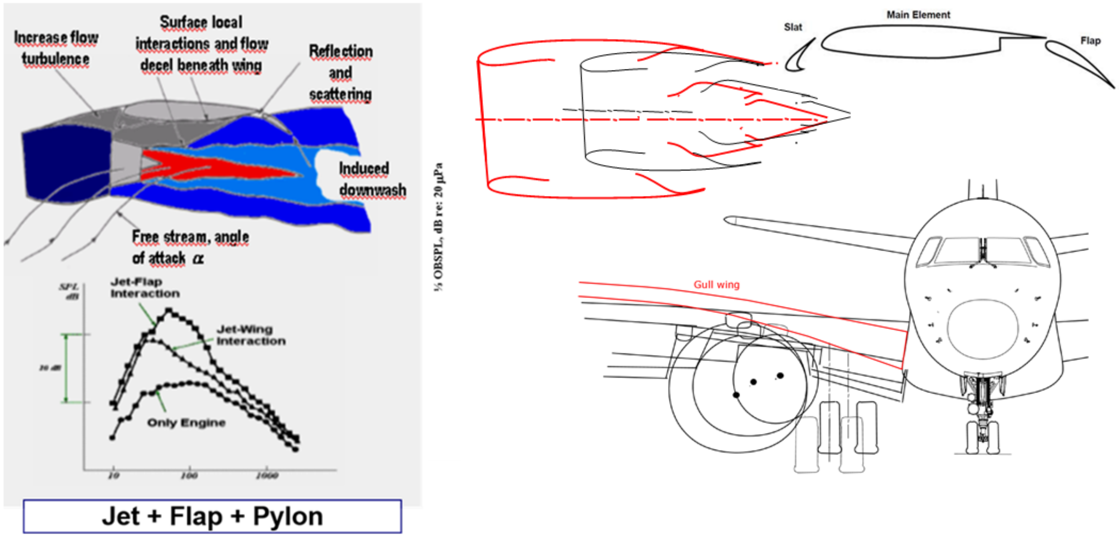

Figure 6-4. Installation of High Diameter Geared Fan Engine (Regional Jet Example)

As has been noted, noise from today's new large aircraft noise, both SA and TA, is no longer dominated during take-off by the turbulent mixing of the high-speed jet but by noise from the fan. Airframe noise dominates during approach and landing. To reduce the aircraft noise to below the background noise level of a well-populated area, and to reduce noise nuisance of increasing air traffic as a whole, probably requires a different overall configuration from the current tube and wing, with a refined integration of the airframe and of the propulsion system, a well-designed and faired undercarriage, and high-lift and drag generated quietly.

A number of new configurations lie beyond 2037, which are considered in Chapter 9. The new configurations may allow smaller engines for the same payload, which is one route to lower noise. Also, it may be possible to use the body or wing to shield some of the noise. If boundary layer ingestion is used, which is attractive from a propulsive efficiency point of view, the risk that the fan interacting with the

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[73] Wing configuration with a prominent bend in the wing inner section towards the wing root.

boundary layer creates a dominant noise source must be addressed. All the above considerations add uncertainty when assessing how much noise reduction can be achieved in future, how, and when.

6.5 IMPROVEMENT SET AGAINST CURRENT GOALS

This section uses progress against previous goals to project the likely noise levels for the medium-term and long-term. It does not attempt to sum the effects of individual technologies, but rather to use evidence of past achievements as a guide in assessing the output of the modelling described in Chapters 7 and 8. Figure 6-5 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 (business jets: BJ, regional jets: RJ, single-aisle: SA and twin-aisle: TA). In all cases, the recent noise levels are well below the Chapter 4 level. Because there is significant scatter within these classes and no recent BJ data, older data is also shown for these types: some of these do not meet ICAO Chapter 14 noise limit and by some margin do not meet the RJ goals set by IER2. The cumulative margins to Chapter 14 of the existing goals from IER2 are specified (converted from Chapter 4 margins) in Table 6-1 for nominal MTOM for each class. The aircraft noise recent certification data plotted were derived from EASA noise certification data sheets[74], where, for each major aircraft type, a representative sample of sub-types and MTOM variants was selected.

It is clear in Figure 6-5 that the recent certification levels of SA aircraft (A320 neo/A321neo and B737MAX), of the twin-aisle aircraft (A350 and B787-8/ B787-9) and of the regional jet aircraft (Airbus A220, formerly Bombardier C Series, and Embraer ERJ 190-E-2, at MTOM>50T) are well below Chapter 14 noise limits. They are also meeting, or are very close to meeting, the mid-term (MT) goals for 2020 set for their classes by IER2. Two business jet aircraft are shown in Figure 6-5 where the MTOM overlaps with RJ; the Bombardier Global Express meets the RJ MT goals with a small margin and the Gulfstream G650 almost meets the LT goals of the RJ.

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[74] The web link to the EASA noise certification data is: https://www.easa.europa.eu/document-library/type-certificates

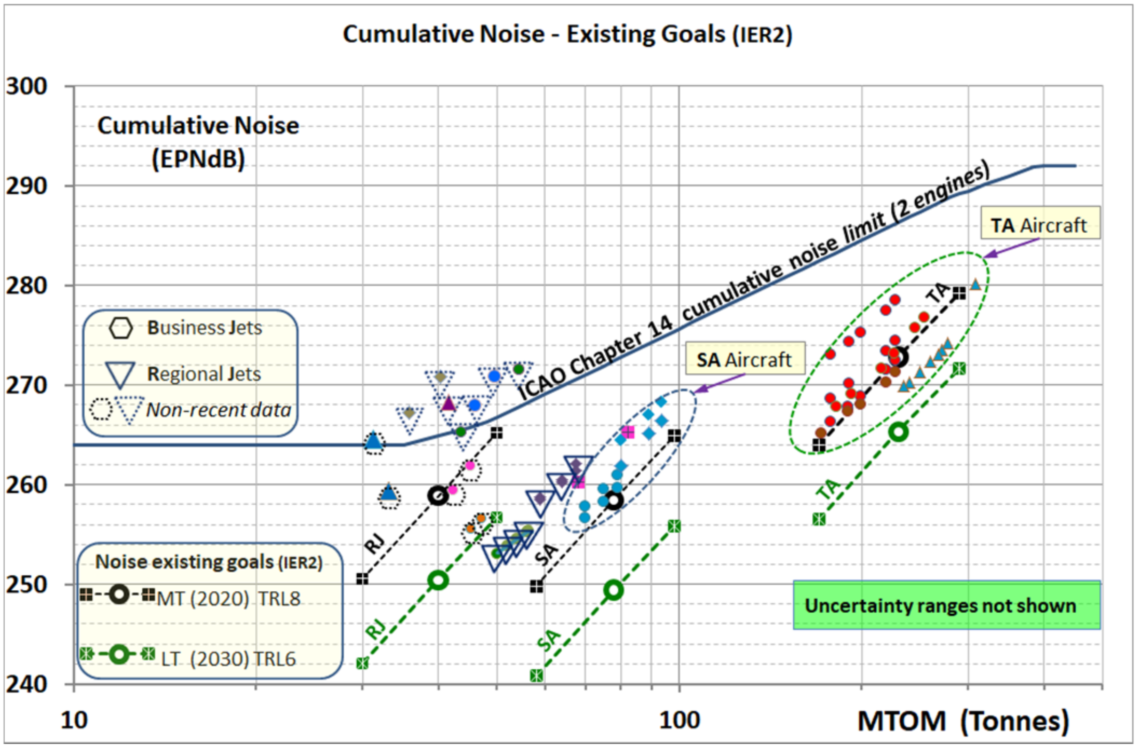

Figure 6-5. Current IER2 Technology Goals and Recently Certified Noise Levels

As Figure 6-5 shows, the MTOM of the BJ and RJ classes are overlapping, just as the larger RJ, such as the Airbus A220 (formerly Bombardier C-series), at more than 50 tonnes, overlaps with the SA class. The MTOM of the Embraer ERJ 190-E2, certificated at the end of February 2018, overlaps with the lower end of SA MTOM. This raises two questions: where should the limit (if any) be between RJ and SA, or between the BJ and RJ; and how should goals be defined if the categories are adjacent, overlapping or merged? The questions on goals relating to MTOM ranges, aircraft categories and uncertainties, will require work beyond the scope of the current IE review, and is likely to require involvement of CAEP/WG1, when other questions on the detailed formulation of noise Standard limits, such as kink points and slopes, could be considered. An attempt has been made to provide updated projections of goals for noise. These projections should give a test of reasonableness and a check on plausibility of the output of the modelling discussed in Chapter 8, which is based on the information provided by/agreed with ICCAIA. The projected goals for 2027 and 2037 are based on recent aircraft noise certification measurements, together with the 2020 and 2030 goals produced in the second IE noise review, IER2. The procedure for arriving at the projected goals is summarized in Table 6-1 and the results are listed in Table 6-2 and shown in Figure 6-6, the former table also outlines the underlying assumptions.

The projected goals were based on the following observations:

- Recent aircraft certified levels are considered as representative of 2017. For the SA, the levels are close to existing goals established in 2014 by IER2 for MT (meaning 2020) and for the TA, the levels are better than MT.
- The Airbus A220 (formerly C-series) has high MTOMs and a noise margin comparable to the B737 MAX in the SA class. The Embraer 190-E2 noise margin is comparable to the recent aircraft in the SA class, extrapolated to lower MTOM.

- One business jet (Gulfstream G650, a TRA in this review) is in the MTOM range of the regional jets and its noise is close to meeting the long-term goals set by IER2 for the RJ. This raises further questions concerning demarcation of BJ and RJ classes and corresponding noise goals.
- The current review has technology for MT achieving TRL8 in 2027, whilst IER2 had MT achieving TRL8 in 2020.
- The current review has technology for LT achieving TRL8 in 2037, whilst IER2 had LT achieving only TRL6 in 2030. About 7 years elapse time between TRL6 and TRL8 is assumed in the current review. The LT goals of IER2 and LT goals of the present review are thus close in terms of timing.
- Because of the limited changes in technology since the IER2, the prospects for MT and LT goals have not changed significantly.
- Assuming the validity of the goals for 2020 and 2030 established by IER2, a gradient in improvement with time can be found over that period. Since TRL6 was assumed by IER2 in 2030, a change to TRL8 pushes the date out to 2037 and the gradient is reduced accordingly. The gradient can be used to project goals for the present review for MT, 2017-2027 and for LT, 2027-2037.
- The above noise improvement gradients, expressed as margin in cumulative noise to Chapter 14, were corrected with "realization factors" to recognize that it is becoming harder to achieve noise reductions. These are shown as RFSM and RFSL in Table 6-1.

Table 6-1 summarizes the calculation process leading to the projected goals in each aircraft class expressed as cumulative noise margins to Chapter 14. The noise gradient calculations are for the same nominal MTOM as are in IER2, except for the RJ class which is 60 tonnes instead of 40 tonnes to better cover the range of recent aircraft. The gradients are then applied starting from the noise margins of the recent aircraft at their MTOM (which for the current SA and TA are slightly higher than the MTOM in IER). The noise level is assumed to vary with MTOM around the nominal values with the same typical slope used in IER1 and IER2 for turbofans[75], that is 67×$\log_{10}$(MTOM).

Table 6-1. Projected Goals Detailed Calculations at Nominal MTOM

Parameter	Cumulative Noise Margin (EPNdB)		
	RJ	**SA**	**TA**
Nominal MTOM (Tonnes)/(IER2nominal MTOM)	60/40	80/78	240/230
R = Recent aircraft margin (EPNdB)	10.3	12.7	16.6
MT_0 = MT IER2 margin (EPNdB)	6	14	13.5
LT_0 = LT IER2 margin (EPNdB)	14.5	23	21
$\Delta = LT_0 - MT_0$ (EPNdB)	8.5	9	7.5
S = Slope = $(LT_0\text{-}MT_0)/(2037\text{-}2020) = \Delta/17$	0.50	0.53	0.44
RFSM = Slope Realization Factor MT estimate	0.7	0.7	0.66
ScM = Corrected MT slope = S * RFSM	0.35	0.37	0.29
Δ M = Δ Margin MT (2027) = ScM * 10 (EPNdB)	3.5	3.7	2.9
Margin MT (2027) = R + ΔM (EPNdB)	13.8	16.4	19.5
RFSL = Slope Realization Factor LT estimate	0.6	0.7	0.6
ScL = Corrected LT slope = S * RFSL	0.30	0.37	0.26
Δ L = Δ Margin LT (2037) = ScL * 10 (EPNdB)	3.0	3.7	2.6
Margin LT (2037) = R + ΔM + Δ L (EPNdB)	16.8	20.1	22.2

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[75] The average sensitivity of noise to MTOM, namely 67×$\log_{10}$ (MTOM), was derived from a previous specific study carried out within CAEP WG1, using the Best Practices Database.

Uncertainty bands are not indicated in Table 6-1 for clarity, or in Figure 6-6 to avoid making the figure too busy. The uncertainty bands given in IER2 were ± 4 EPNdB. It is estimated that the uncertainty on gradients used here to derive projected goals is ± 0.3 EPNdB per annum, which gives ± 3 EPNdB over 10-year periods, and the mean squared errors for projected goals become ± 5 EPNdB for MT and ± 6 EPNdB for LT. These are shown in Table 6-2. The individual aircraft points are shown in faded color. The LT goals for the IER2 review are very close to some of the LT or MT goals discussed above and for clarity are omitted in the figure.

The regional jets raise an issue, as the latest measurements, for the Airbus A220 (formerly Bombardier C-series), are at considerably higher MTOM than the nominal value in the line corresponding to the MT or LT goals for RJ. Broadly it can be seen that this aircraft is achieving the MT goals for both the RJ and the SA. This reinforces the need for CAEP/WG1 to address the question of MTOM overlapping across different aircraft classes, finding a way to encompass the wide range of sizes, and the general evolution of MTOM in future.

For business jets, there is currently no set of goals and no recent certification data. As already noted, the large Gulfstream G650 has an MTOM, which would put it comfortably in the RJ category, and its measured noise is below the proposed MT level for the RJ. Many of the older and smaller BJs have much higher noise. These large differences, and the lack of recent noise certification data in the low MTOM range, make noise projections difficult for aircraft classes with nominal MTOM below 50-60 tonnes. No projection of MT and LT goals is offered here for the BJ, nor for the RJ with nominal MTOM below 60 tonnes. Nevertheless, it is desirable that CAEP/WG1 gives attention to how goals should be specified for BJ and RJ aircraft down to below 50 tonnes.

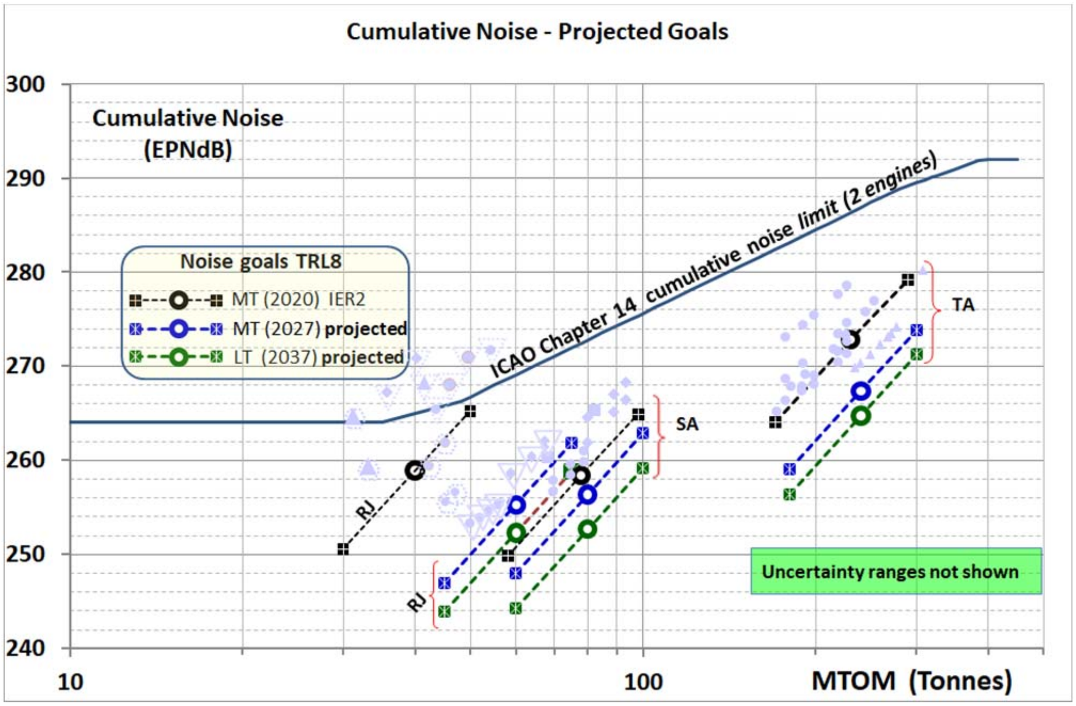

Figure 6-6. Existing Goals Extrapolation Study to get Projected Goals for 2027 and 2037

It should finally be pointed out that the projected goals given here implicitly integrate some considerations of trade-offs and overall aircraft optimization, through the use of actual aircraft noise, of existing goals from IER2 and of some assumptions, like the use of realization factors in noise reduction gradients. The existing IER2 goals have themselves been arrived at with similar considerations. In Chapter 8, the interdependencies will be explicitly addressed, notably between fuel burn and noise, and the projected goals in this chapter serve as a check on the results of the modelling.

6.6 SUMMARY

For modern large aircraft, SA and TA, jet noise is a secondary noise source even at departure, with fan noise dominating. For smaller aircraft, business jets and small regional jets, the noise from the jet may still dominate at departure, as it does for many older aircraft. Jet noise has been reduced by reducing jet velocity to improve fuel burn, but because jet noise is now a secondary source, further improvements in fuel burn will not bring automatic substantial reductions in noise.

Fan noise is the dominant departure noise for modern large aircraft whilst it is important at take-off for small aircraft; fan noise dominates engine noise at approach for all aircraft. Reduction in fan pressure ratio is likely to lead to a reduction in fan noise, both forwards and rearwards. Beyond reducing fan tip speed, further fan noise reductions are challenging. Extensive dedicated research (involving full engine ground and flight test demonstrators) combined with 3D unsteady, viscous analysis of the whole gas-path (air intake + fan + OGV + struts + bypass duct) can be expected to bring some additional gains. Better acoustic liner technology will help, but against this, the intake and bypass duct will get shorter in relation to diameter and this will reduce the area amenable to treatment.

A key technology for reducing fan noise is acoustic wall treatment, and liners in the inlet and bypass duct provide essential attenuation. Work continues to improve liner performance, but the task of maintaining current levels of liner attenuation will be challenging, given the incentives to make the intake and bypass duct shorter in relation to diameter, and to reduce nacelle length for fuel burn reasons.

Airframe noise is the largest noise source at approach for modern large aircraft, mostly from the landing gear. Potential airframe noise reductions are very dependent on aircraft category, design and operational characteristics, and the exploitation of this potential will be driven by multiple constraints.

As engines get larger in relation to aircraft size, corresponding to lower fan pressure ratio, it becomes more important for the engine and the aircraft to be designed together as an integral unit. The optimization of the aircraft needs to include acoustic design as well as design for minimization of fuel burn and emissions.

The scope for noise technology reductions of the conventional tube and wing configuration, particularly in large aircraft, now appears to be limited, and the potential additional benefits of acoustic design optimization will need to be properly assessed. Novel configurations, as discussed in Chapter 9, or even some very advanced tube and wing configurations, may bring new noise reduction opportunities, but at the same time these will introduce significant challenges of different nature, which will also need to be addressed.

Questions arose from the goal projection exercise concerning the overlap of maximum take-off masses between different aircraft classes (BJ, RJ, and SA) and the implications for noise goals. Some issues will require consideration in future by the ICAO/CAEP/WG1. Given the spreading of aircraft between previously established classes, consideration should be given to the possibility of setting goals on a line of noise margin to Chapter 14, where the margin is a function of MTOM. Such a continuum approach, if at all possible, would need to take into account the changing operating factors, the constraints, the evolution of MTOMs and the overall fleet noise impacts for different aircraft classes, sizes and types of use.

The projected goals with respect to ICAO Annex 16, Chapter 14 as derived from existing noise goals are summarized below in Table 6-2. These approximate cumulative noise margins have provided a plausibility check of the final noise goals developed in Chapter 8 of this report.

Table 6-2. Main Noise Goal Data Summary[76] of Projected Goals with Uncertainty Limits

Aircraft Class	MTOM Nominal (T)	MT (2027) TRL8 Projections*	LT (2037) TRL8 Projections*
RJ	60	14 ± 5	17 ± 6
SA	80	16,5 ± 5	20 ± 6
TA	240	19.5 ± 5	22 ± 6

** Cumulative margins to ICAO Chapter 14 noise limit, in EPNdB*

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[76] There are some small noise margin differences between Tables 6.1 and 6.2, resulting from the rounding of numbers.

CHAPTER 7. TECHNOLOGY REVIEW METHODOLOGY AND MODELLING APPROACH

7.1 INTRODUCTION

This chapter provides an overview of the modelling conducted for this IE led process. A summary of the top-level goal metrics is discussed along with the technology reference aircraft used as the basis for the goal setting. Next, the modelling and simulation environment utilized for the quantitative assessments is discussed along with the resulting Technology Reference Aircraft (TRA) baseline models. To enable the goal setting for noise, fuel burn, and emissions, a technology taxonomy was developed for modelling purposes and a process to assess the technology goals established.

7.2 GOALS AND METRIC DEFINITIONS

7.2.1 Applicable Goal Time Frame

The assessment of the status of technologies presented in the Washington DC and Berlin reviews was based on the TRL scale. The principle agreed within CAEP is that the technology goals will use new technologies that are expected to be TRL≥8 at a given time. For this review, the applicable goal time frames are 2027 for mid-term (MT) and 2037 for long-term (LT) goals. Each selected technology must be available to at least one manufacturer and the technology availability is specific to the seat-class being considered. In general, the large, long-range twin aisle aircraft use the advanced technologies first. It was agreed that those technologies that, in the opinion of the IEs, had reached a TRL of 5 to 6 or higher in 2020 were applicable to the MT goal with potential entry into service date of 2027. Those technologies at a TRL of 5 to 6 or higher in 2030 or at a TRL 3 or 4 in 2020 were applicable to the long-term goal assessment with potential entry into service date of 2037.

7.2.2 Noise Goal Metric

The IEs were presented with aircraft component noise reduction estimates for various technology concepts under development in various metric formats. The IEs had to interpret these estimates in terms of the possible reductions in the noise certification metric, Effective Perceived Noise Level (EPNdB), not only for the component for which the given technology applied, but also for how this reduction of component noise affects the total aircraft system noise. The review assessed the technology impacts at the three certification points of approach, flyover, and lateral. The noise metric for this goal setting process was selected to be the cumulative margin to the CAEP Chapter 14 noise limit in EPNdB. The current noise Standard is provided in Appendix C for completeness.

7.2.3 Fuel Efficiency Goal Metric

In the 2010 IE review of fuel burn technologies, no fuel-efficiency standard existed. As such, the goal metric utilized at that time was fuel quantity burned (kg) per available tonne-kilometer, written FB/ATK (units kg-fuel/ATK). This was evaluated at the R_1 range[77] for maximum payload. In February 2016, CAEP agreed on the new CO_2 fuel-efficiency Standard as documented in ICAO/CAEP document AN 1/17.14 – 17/50. The new CO_2 metric is described in Appendix C of this report and the goals are expressed in terms of

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[77] Note that the R_1 range is the maximum range at maximum structural payload, which corresponds to maximum take-off mass (MTOM). It was evaluated with normal fuel reserves.

the new CO_2 metric with the design payload and range of the new aircraft equal to those of the technology reference aircraft.

7.2.4 Engine Emissions Goal Metric

The engine emissions objective is to provide an assessment of combustion technology including both NO_x and non-volatile particulate matter, nvPM. The NO_x Standard is defined for a hypothetical LTO cycle with engine operation for fixed times at four thrust levels. The current NO_x Standard is CAEP/8 and the D_p/F_{oo} metric is reported as a percent margin to the standard. The current NO_x Standard is provided in Appendix C for completeness.

There are no existing baselines or goals for nvPM, but CAEP is currently in the process of developing standards for mass and number of particles during LTO, and for this, the necessary data is still being collected. Within the time horizon used in this report, the IEs provided only a qualitative assessment of the prospects for improvements in nvPM mitigation technology within the goals timescale.

7.3 AIRCRAFT CATEGORY SELECTION AND CONSIDERATIONS

MDG/FESG[78] uses generic aircraft categories in its forecast and fleet evolution analysis and has defined these different categories by seat capacities[79]:

• Business Jet (BJ)	≤20 seats
• Regional Jet (RJ)	20-100 seats
• Narrow Body	101-210 seats
• Wide Body	> 210 seats

The modelling assessment in this review aims to align with these categories as closely as possible while maintaining nomenclature consistent with previous Independent Expert reviews. Consequently, the term "single-aisle" (SA) will be used instead of "narrow body" and "twin-aisle" (TA) will be used for the two-engine wide body aircraft considered in this report (this review did not include long-range four-engine aircraft).

In order to establish fuel burn, emissions, and noise baselines, reference aircraft were used. The reference aircraft have been chosen to represent the four major categories of aircraft in service in 2017. Originally, the plan was to use generic (i.e. hypothetical) Technology Reference Aircraft (TRA) representative of aircraft in service in 2017 so as to avoid competitive issues. However, to ensure the availability and consistency of input data and to allow ICCAIA to provide an assessment of the baseline, notional representations of the most recently certified aircraft fitting as closely as possible into each class were used as references. Also, by using actual as opposed to generic aircraft, the different participating organizations were in a position to provide additional data points that could be used to establish the reference aircraft. The reference aircraft selected, with guidance from ICCAIA, were:

• BJ	Notional G650ER
• RJ	Notional E190E2
• SA	Notional A320neo
• TA	Notional A350-900

It became apparent during the review that the division between RJ and SA aircraft was blurred because RJs, such as the Embraer 190 and the Airbus A220 (formerly the Bombardier C-series), now have over 100 passengers and could be classed as a small SA. Likewise, a large BJ like the G650ER is comparable in size

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[78] MDG is the Modelling Design Group and FESG is the Forecasting and Economics Support Group

[79] CAEP/11-FESG-MDG/7-IP/09

(specifically with respect to MTOM) to some smaller RJs, although the speeds, range and payload capacity differ. All available public domain information on the notional aircraft, and industry provided additional performance information, were used to form the basis of the modelling.

7.4 MODELLING AND SIMULATION METHODOLOGY

The IE panel required a modelling and simulation capability to assess the impacts of the technologies for the two time frames. The Aerospace Systems Design Laboratory in the Georgia Institute of Technology (GT/ASDL) was engaged to assist the IEs in a modelling capacity[80]. The foundation for this systems analysis capability is the advanced methods developed at ASDL coupled with an integrated aircraft modelling and simulation environment known as the Environmental Design Space (EDS)[81]. EDS is capable of predicting the fuel burn, NO_x emissions, and noise metrics in a single environment with an automated link to provide necessary data for the current CAEP IEIR goals assessment (see Figure 7-1).

The majority of the EDS analysis components are NASA developed programs. EDS is capable of modelling the thermodynamic performance (NASA's NPSS) of any engine cycle coupled with a parametric component map generation tool (NASA's CMPGEN) and with a 1-D aeromechanical design/analysis for flowpath and weight estimation purposes (NASA's WATE++). This propulsion system simulation is well suited to assess the IEIR technology portfolio and in its ability to match the engine to a sized airframe using a simultaneous, multi-design-point sizing algorithm developed by ASDL. The propulsion simulation module is coupled with the mission analysis module (NASA's FLOPS) in an iterative fashion, to ensure that all coupling variables are internally consistent and have converged, and then passes information to the noise prediction module (NASA's ANOPP). These are used to assess acoustic impacts, including the generation of engine state tables from NPSS and the resulting aircraft noise flight trajectories for the sized vehicle. This data is used within ANOPP to generate the three certification noise values for sideline, cutback and approach as well as characteristic noise power distance (NPD) curves. Further details on the components of EDS are described in Appendix J.

The EDS environment executes four phases for each simulation run representing a single vehicle system.

- Phase 1: EDS Initialization Phase
    - Establishes the different options for running EDS (e.g. TA, SA, RJ, or BJ)
    - Determines the settings of the design variables
- Phase 2: Vehicle Design Phase
    - Depending on the desired design there can be a design iteration for the engine and a design iteration between the engine and airframe
    - The vehicle size and weights are fixed at the end of this phase
- Phase 3: Vehicle Performance Evaluation Phase
    - In this phase all desired performance evaluation is conducted including gaseous emissions, noise certification, take-off and landing performance, and fuel burn for off design points on the payload-range chart

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[80] The GT/ASDL has over 20 years of experience in the area of system-level analysis of current and advanced vehicle concepts and technology portfolios. GT/ASDL has used the EDS to assess unconventional aircraft and propulsion systems in support of the NASA Fixed Wing (FW), FAA Continuous Lower Energy, Emissions, and Noise (CLEEN), NASA Environmentally Responsible Aviation (ERA), and NASA Vehicle Systems programs. Within the context of the NASA FW project, GT/ASDL created integrated models of NASA's N3-X concept (distributed turboelectric, boundary layer ingestion), the Boeing Subsonic Ultra Green Aircraft Research (SUGAR) truss-braced wing (hybrid-electric), and the MIT double bubble (with boundary layer ingestion).

[81] Kirby, M. and Mavris, D., "The Environmental Design Space," 26th International Congress of the Aeronautical Sciences, Anchorage, Alaska, 14 - 19 September 2008

- Phase 4: Output Data Phase
    - All desired data is compiled into user-specified summary files.

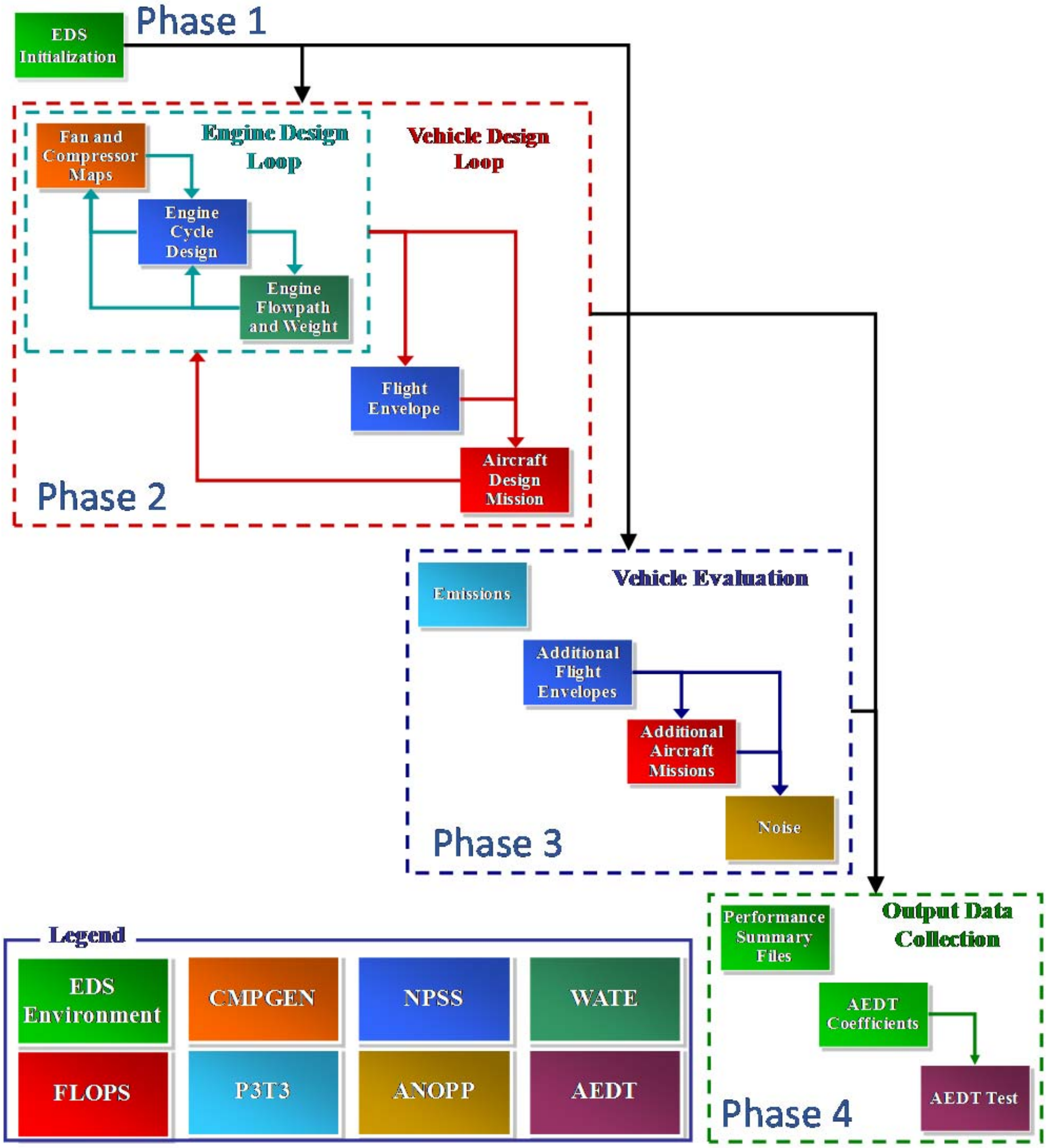

Figure 7-1. Environmental Design Space (EDS)

EDS uses a simultaneous, multi-design point method to generate the engine cycle, which means EDS converges on the following five design points simultaneously:

- Point 1, ADP (Aero Design Point)
    - Reference point used to define the performance of the turbomachinery components
    - Typically at cruise conditions for commercial aircraft systems
- Point 2, TOC (Top of Climb)

  - Thrust point established by airframe requirements. Sets maximum mass flow and corrected speed of the engine
- Point 3, TKO (Take-off)
  - Another thrust point established at aircraft rotation. Maximum T_{40} specified at this condition for high BPR engines
- Point 4, SLS Installed
  - Constraint point to ensure that flat rated thrust can be achieved. This point cannot exceed maximum T_{40} allowable
- Point 5, SLS Uninstalled Thrust
  - ICAO emissions point which sets the maximum SLS thrust (used for D_p/F_{oo}). Maximum SLS thrust is minimum of thrust generated at Nc = 100% or $T_{40} = T_{40max}$

EDS, like most conceptual sizing and synthesis design tools, uses physical performance constraints in both the engine and airframe analyses to ensure the resulting model is a feasible design. Two additional constraints were recommended by ICCAIA to the GT/ASDL team, specifically, engine ground clearance and wingspan (gate) constraints, where the values utilized for the study are contained in Appendix M. The following list enumerates the additional constraints used with EDS for all aircraft:

- Minimum rate of climb (300 ft/min) excess power at top of climb
- Turbine material limits (T_{4max}/cooling flow)
- Compressor material limits (T_3 limits)
- Thrust requirements for critical points in the mission
- Fuel capacity volume must be available
- Service ceiling constraint
- Take-off/Landing constraints (field-length, obstacle height, one engine out, etc.)
- Reserve mission fuel requirement

7.5 CAPTURING INTERDEPENDENCIES

It is important to note the interdependencies that will be captured with the modelling and simulation environment. To predict future aircraft performance and simultaneously capture interdependencies between fuel burn, noise and emissions (referred to here as top-level metrics), it was recognized that there are two types of interdependencies: top-level metric interdependencies due to design parameters and top-level metric interdependencies due to technologies.

The first interdependency refers to design parameter trades, which is the trade-off of one metric to another as a result of the aircraft being designed differently (i.e. fuel burn versus noise tradeoffs). Design parameters include design choices such as payload, range, thrust-to-weight ratio, wing-loading, etc., but not specific technologies like laminar flow or improved material properties. The strength and trend of interdependencies can be assessed by creating a large design of experiments and analyzing the data.

On the other hand, the interdependencies due to technologies refers to the trade-off of one top level metric to another as a result of the aircraft possessing different technologies or levels of technology. When the new technologies are incorporated into the aircraft, the relationship between different metrics is altered slightly. As an example, an aircraft with winglets will have a slightly different fuel burn versus noise relationship than that same aircraft without winglets. The strength and trend of such interdependencies can only be assessed by gathering detailed information about all technologies and then assessing the system level impacts.

Because of time constraints and the proprietary nature of detailed or specific technology information, it was only possible to model interdependencies associated with design parameter variations, subject to baskets of technologies, such as viscous drag reductions, mass reduction and engine component efficiency improvements.

7.6 TECHNOLOGY REFERENCE AIRCRAFT

The technology reference aircraft (TRA) were simulated within EDS based on public-domain available data and are representative of the four aircraft listed in Section 7.3. An iterative process was utilized to fine tune the generic aircraft modelling with guidance and feedback from ICCAIA to provide performance consistent with published information. The result was four TRAs upon which the technology area impacts could be inserted onto a given aircraft for 2027 and 2037.

The TRA models utilized aircraft geometry, mass, mission, and propulsion characteristics. Publicly available manufacturer data, where available, took precedence over other sources because of its greater accuracy. This data was taken from airport planning documents, CAD drawings, and brochures. Aircraft geometries were derived from manufacturer CAD drawings, where available, and aircraft masses were taken from airport planning documents. In the absence of publicly available manufacturer data, the Piano database (a professionally recognized tool for analyzing commercial aircraft) was used. The models were then calibrated to match this data.

The calibration process had two phases, one to calibrate the engine model and the second to calibrate the airframe model. The first phase required that a nominal engine be created to simulate a mission and this was calibrated using a combination of publicly available manufacturer data and ICAO emissions databank data. The manufacturers' data included information such as OPR, fan diameter, number of stages, etc. The notional model matched ICAO reported fuel flow and thrust levels.

The mission analysis model, FLOPS, was calibrated in two steps, one for each of its operating modes: mission analysis of a fixed aircraft (an aircraft of defined geometry and size) or sizing an aircraft for a specified mission. The first step was to calibrate the aerodynamic module of the aircraft using the fixed mode. This yielded aircraft maximum take-off mass (MTOM), fuel mass, operational empty mass, and design payload for the aircraft's design range. The design fuel and payload mass were derived from aircraft payload range charts from the manufacturer's airport planning documents, where available, based on a typical seating class. Within the payload-range diagram of a given TRA, the design point utilized for this assessment would typically be for a range a little below the R_2 range. Assuming a mass per passenger and an OEW, the design range could be inferred from the actual aircrafts payload-range envelope, typically provided in an Airport Planning Document.

Once the aerodynamic parameters were calibrated, the second mode of FLOPS was employed. Using the same design mission, scaling factors were used to match information from the Piano database. The calibration consisted of setting component mass scaling factors to match information from the Piano database. After the mass scaling factors were set, these results were verified by performing the analysis again using inputs for the thrust-to-weight ratio at take-off and wing loading. This calibration process verified that the results from EDS would match TRA data.

It should be noted that the calibration process utilized fuel burn as a matching parameter in lieu of the CO_2 metric value, since that data is yet to be made publicly available. The actual CO_2 Standard certification data is expected to emerge piecemeal over the next 5-10 years. When this data is available, it should allow some confirmation of the modelled 2017 TRA aircraft fuel burn performance. However, for optimizing the performance of the aircraft, the fuel burn metric has advantages because it correctly uses the physical parameters, specifically fuel burned normalized by payload times distance carried, and is proportional to a rational definition of efficiency.

The four Technology Reference Aircraft (TRA) are described briefly below. All were analyzed with EDS and the detailed results are presented in Appendix K.

7.6.1 Business Jet Technology Reference Aircraft

The BJ TRA is based on a notional Gulfstream G650ER. The assumed payload is 1,800 kg, carrying 8 passengers at 102 kg each at the design range[82] of 7500 nm, on the payload-range diagram, which corresponds to maximum fuel capacity and mass at take-off, which is at a slightly shorter range than the R_2 condition (this is the case for all other TRAs). The design cruise Mach number is 0.85 and the maximum cruise altitude is 51,000 ft.

7.6.2 Regional Jet Technology Reference Aircraft

The RJ TRA is based on a notional Embraer E190-E2. The assumed payload is 10,578 kg, carrying 106 passengers at 100 kg each at a design range of 2,850 nm. The design cruise condition is at Mach 0.77 and the maximum cruise altitude is 41,000 ft.

7.6.3 Single Aisle Technology Reference Aircraft

The SA TRA is based on a notional Airbus A320neo. The assumed payload is 16,840 kg, carrying 165 passengers at 102 kg each at a design range of 3,500 nm. The design cruise condition is at Mach 0.78 and the maximum cruise altitude is 41,000 ft.

7.6.4 Twin Aisle Technology Reference Aircraft

The TA TRA is based on a notional Airbus A350-900. The assumed payload is 32,149 kg, carrying 315 passengers at 102 kg each at a design range of 8,100 nm. The design cruise condition is at Mach 0.85 and the maximum cruise altitude is 43,000 ft.

7.7 TECHNOLOGY TAXONOMY

To understand the impacts of advanced aircraft technologies, a taxonomy to classify technologies and their impacts was developed. The technology taxonomy consisted of the four levels listed below and depicted in Figure 7-2 for two aspects, propulsion and noise.

- **Metric:** Highest level, what is the primary metric the technology is trying to improve?
  - Fuel burn, Noise, and Emissions
- **Domain:** Grouping of the technologies into high level groupings
  - Example: Propulsion, Structures/Materials, Engine Noise, etc.
- **Category:** Dividing the domains into fundamental technology impacts (e.g. L/D, %mass)
  - Example: Viscous drag, propulsive efficiency, jet source noise
- **Technology:** Lowest level, refers to specific technologies
  - Example: Fluidic Injection, riblets, etc.

The taxonomy was created because the initial information provided on the technologies by ICCAIA was not at a consistent level of abstraction for modelling purposes. A method was needed for translating information into workable modelling information. In an ideal modelling exercise, the technologies would be defined by the fundamental, physical parameters that they affect, both benefit and degradation due to integration. Given the sensitivity and proprietary nature of this type of information, technology categories were utilized and the analysis was conducted at the technology category level.

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[82] The typical payload or passengers carried quoted by the manufacturers was utilized at the design range, which falls on the constant volume line of the payload-range diagram between the R_1 and R_2 ranges. R_2 range is maximum range for take-off with maximum take-off mass at maximum fuel capacity, whereas R_1 range is maximum range for take-off with maximum payload and maximum take-off mass.

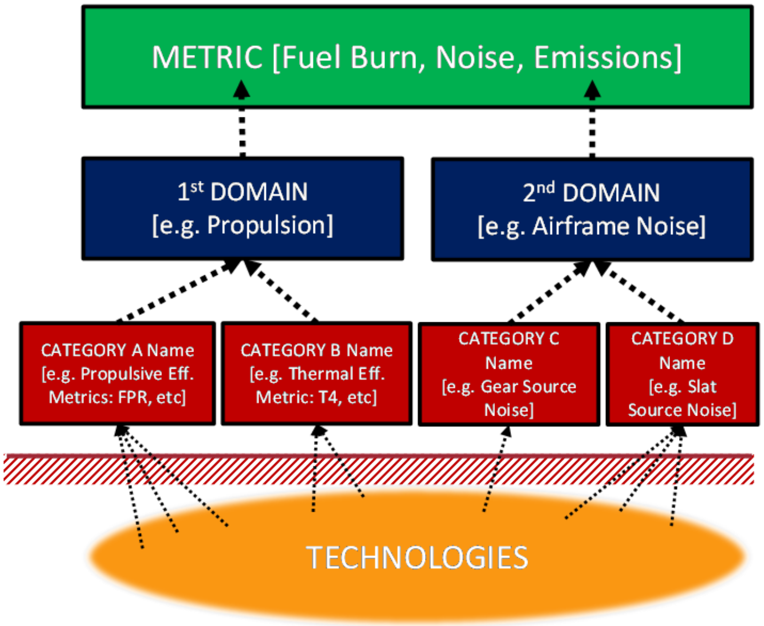

Figure 7-2. IEIR Technology Taxonomy

Domains are used to group together categories and technologies that are alike and affect aircraft performance in a similar way. Figure 7-3 shows this for technologies that have a direct influence on fuel burn. The individual technologies are grouped according to the category they aim to improve with benefits expressed in terms of a metric for that category. Technologies that improve one aspect, for example aerodynamics, may negatively impact parameters in another category, such as aircraft mass.

The technology taxonomies for noise and emissions are depicted in Figure 7-4 and Figure 7-5, respectively. Note the different character of the taxonomy for emissions which, as is discussed later, leads to the inability to carry out interdependency studies, including the emissions.

To conduct the modelling, information about the technologies at the category level was obtained, which:

- Combines technology impacts, effectively creating technology baskets to get the overall technology category impact;
- Allows for an assessment of the possible ranges for the three goal metrics (fuel burn, noise and emissions) due to future technologies; and
- Simulates putting any number of different technology packages or baskets or combinations to reach a desired goal for the category impacts.

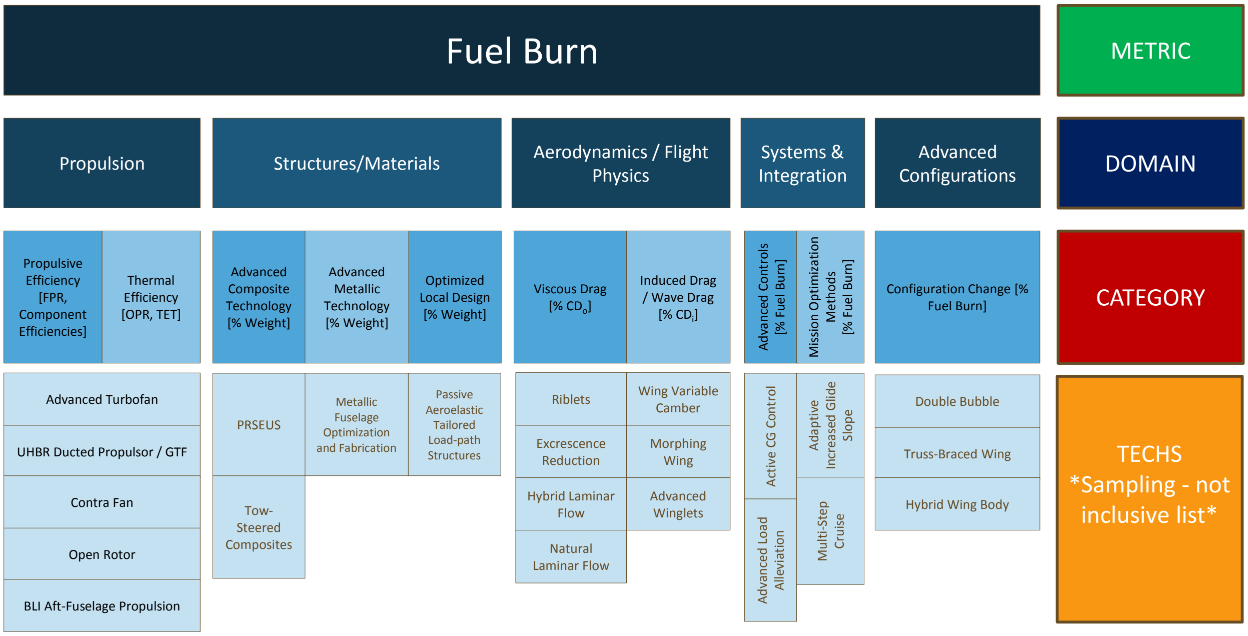

Figure 7-3. Fuel Burn Technology Taxonomy

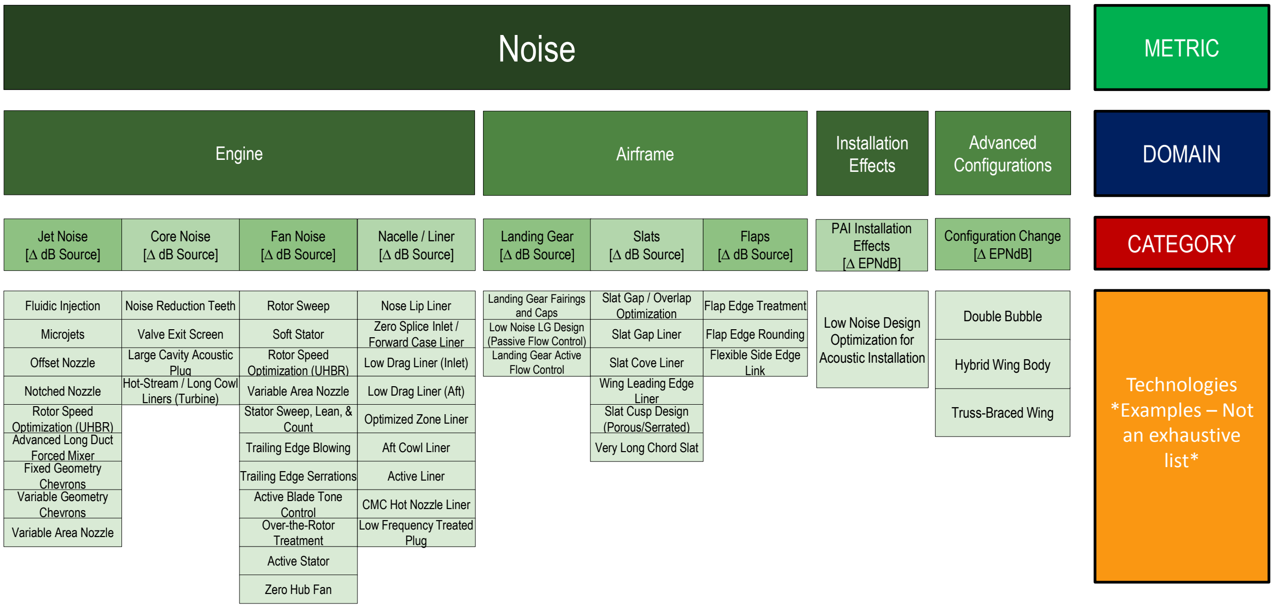

Figure 7-4. Noise Technology Taxonomy

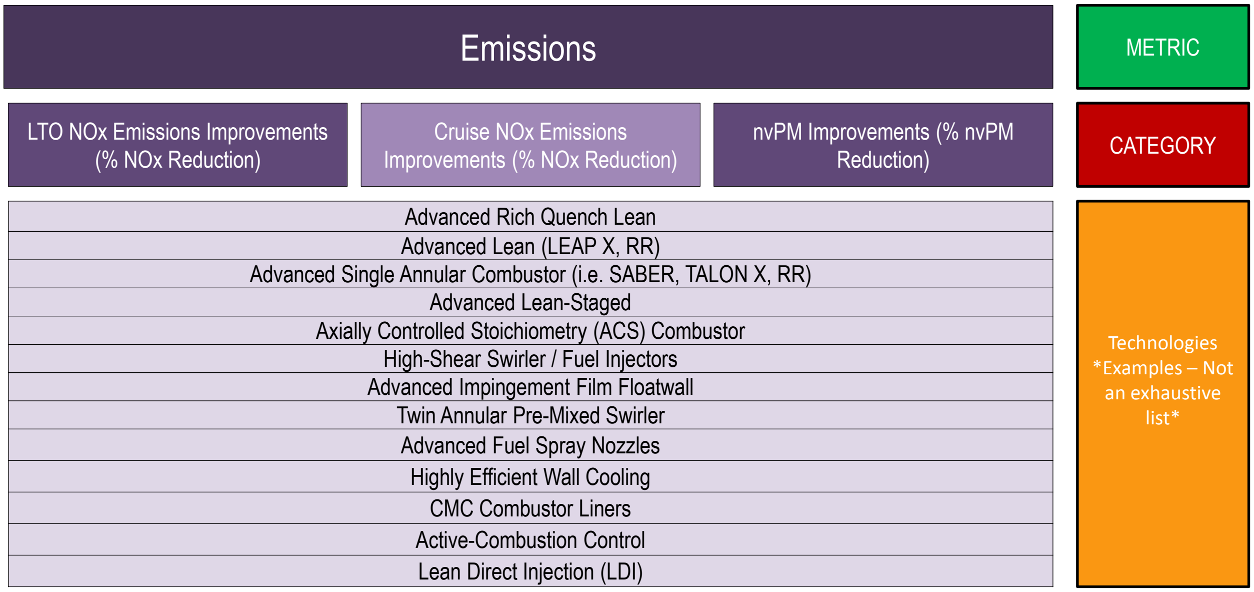

Figure 7-5. Emissions Technology Taxonomy

Based on the defined taxonomy, the impacts of the technologies potentially available in 2027 and 2037 were gathered from ICCAIA, NASA, prior studies conducted by GT/ASDL for NASA and the FAA, and from the IEs own sources. Unfortunately, no technology impacts were provided by ICCAIA for the propulsion system or emissions. As such, GT utilized prior research conducted for NASA's ERA and Advanced Air Transport Technology (AATT) projects to define a range of possibilities for improvements in the engine: including propulsion efficiencies, component mass, nacelle drag and mass, and the overall core efficiency. For the emissions improvements, NASA provided an emissions correlation equation representative of a notional advanced combustor system of the future, but this was incapable of reproducing the emissions behaviour shown in, for example, Figure 5-3.

As noted earlier, for 2027 it was assumed that the technologies should reach a TRL of at least 5 to 6 by 2020; whereas for 2037, a TRL of at least 5 to 6 should be reached by 2030. The basket of technologies therefore depended on time frame. The development of technology carries many uncertainties and three-point estimates of the technology-basket impacts were provided at the category level which encapsulated the uncertainty of technology progression with time. The three levels of technology-implementation confidence were defined as nominal (50% confidence), low (20% confidence) and high (80% confidence). The 20-80% technology-implementation confidence level was not intended to be a probability, but rather representative of the value of likelihood of achieving the benefit level and also the likelihood of being implemented on an aircraft system. The impacts were quoted as the change from the values for the respective technology reference aircraft. It was recognized that the potential ability to move a technology from low TRL to TRL6 by 2020 or 2030 did not mean that it would actually happen. There are many technologies which have reached low TRL but have languished for decades, usually because of cost or operational issues. Therefore the *likelihood* of the technologies being applied to the vehicles was qualitatively captured. A summary of the technology category impacts utilized for the modelling is provided in Appendix L.

ICCAIA provided quantitative estimates to the IE review of the net benefits of the various new technologies at the component level. The modelling and optimization then provide the overall system level improvements. The trade-off between noise and fuel burn is captured through Pareto fronts obtained by varying the relative importance of both metrics in the optimization. This approach is sufficient for the BJ, RJ, and TA aircraft. However, the TRA in the SA class is based on a relatively old airframe (first flight in 1987) that has been re-engined. Since the aerodynamic design of that notional aircraft, there have been significant improvements in aerodynamic efficiency in other aircraft classes, for example the TA aircraft. Figure 4.1 shows the different trajectories with time of single-aisle and twin-aisle classes in terms of ML/D. The average rate of improvement for the TA is about twice that of the SA, and the IEs were persuaded that an important contribution to this is the succession of all-new airframes that have been produced for the TA class. The all-new designs have allowed integrated designs incorporating the improvements in modern design tools. Consequently, the IEs believe that improvements in the aerodynamic efficiency of the SA relative to the 2017 TRA are possible, in addition to those resulting from the new technologies presented to the IEs by ICCAIA, if an all-new airframe is adopted. The IEs therefore concluded that allowance for these must be included in the modelling and optimization of the SA aircraft for 2027 and 2037.

The L/D of the 2017 twin-aisle TRA is 15% higher than that of the single-aisle TRA. There are several reasons why TA aircraft have higher L/D than the SA aircraft. Perhaps the most fundamental reason is that the larger TA aircraft have an inherent geometric advantage that leads to higher wetted aspect ratio and thus higher L/D. Moreover, as a result of their long-range mission, cruise drag is a much higher priority for the design of TA aircraft. Comparisons were performed for two pairs of SA and TA aircraft designed in the 1980s by two different aircraft manufacturers. Each pair was developed by the same company during overlapping programs incorporating equivalent aerodynamic and design technology standards. For each pair, L/D is about 8% greater for the TA than the SA. The IEs have taken this as solid evidence that the difference in L/D to be expected from these two aircraft classes, if they are developed based on equivalent technology, is about 8%.

The difference between L/D for the 2017 TRAs is 15%, whereas the expected value for the TA is estimated to be only about 8% greater than the SA aircraft designed with equivalent technology. The IEs therefore estimate that an SA aircraft in 2017 could have an L/D approximately 7% higher than that of the SA TRA actually adopted if all the design advantages available to the later TAs arising from all-new aircraft had been included. This would bring the L/D for the SA TRA to 8% below that of the TA TRA. The IEs concluded that in looking to total future possibilities, this 7% increment must be included in the modelling of the SA. Consequently, a drag reduction of 7% has been included in the SA modelling in 2037 in addition to the drag reductions associated with the new technologies presented by ICCAIA. As it may not be possible to achieve the full benefit of this improvement by 2027, only a 3% additional drag reduction is included in the 2027 modelling. Given that these drag reductions can be achieved with current technology levels, these increments are added for all confidence levels.

For each of the technology category impacts, the appropriate EDS input variables were identified. For example, the advanced metallic technologies, as inferred from the material presented by ICCAIA, could provide a percent reduction in wing, fuselage, and empennage mass in 2027 and 2037 relative to that of the TRAs in 2017 at the associated three confidence levels of low, nominal, and high. Repeating this example for all the technology categories defined a vector of technology impacts which formed the appropriate inputs to EDS.

As noted earlier, NO_x was considered separately because the improvements to the combustor technology relate to different geometries, chemical reactions and temperatures. Whilst NASA provided an emissions correlation capable of giving NO_x levels for conventional current combustors, it was not capable of picking up the geometry and temperature (T_{40}) trends for future combustors

7.8 METHODOLOGY TO ASSESS THE TECHNOLOGY GOALS

7.8.1 Optimization of the TRA

To provide understanding of the goal assessment modelling process of the technology categories and the design parameter interdependencies, a 3-step process was developed and used as depicted in Figure 7-6. The first step established the notional TRA baseline as described in Section 7.6. The TRA results were deemed fit for purpose by the IEs and ICCAIA as the point of departure for the technology taxonomy impacts.

However, each of the actual in-service aircraft on which the TRAs are based were optimized to a particular set of objectives defined by the manufacturers to produce a competitive product for the market, but the exact parameters optimized are not the same as those in the EDS modelling and the industry objectives are unknown to the IEs and also the modelling team. Therefore, each of the TRAs were optimized at the 2017 TRA technology levels (i.e. without inclusion of any new technology above that used to specify the TRA) within the ranges of the design parameters feasible in 2017, which were defined by the IEs, subject to a set of constraints.

The constraints included the items listed in Section 7.4, in addition to a wing span (gate constraint), fan diameter (ground clearance), and the maximum allowable compressor exit temperature, T_3. The specific design variable ranges and constraints utilized are provided in Appendix M for each applicable time frame. Comparing the optimized values for 2027 and 2037 with the optimization for 2017 would allow for an "apples to apples" comparison of the impact of parameter changes and inclusion of the technology category baskets. Thus for 2027 and 2037, the optimization yielded the fuel burn metric, CO_2 MV, and noise (cumulative EPNdB) at the different confidence levels. These optimized values were subtracted from the optimization for 2017, to get the reduction associated with parameter changes and technology input. The reduction could then be subtracted from value for the TRA, a value computed using the input data for the TRA without optimization to obtain the output value. (This value is referred to in some places as shifted.) It should be recalled that the MTOM is altered by the optimization process as well as fuel burn and noise.

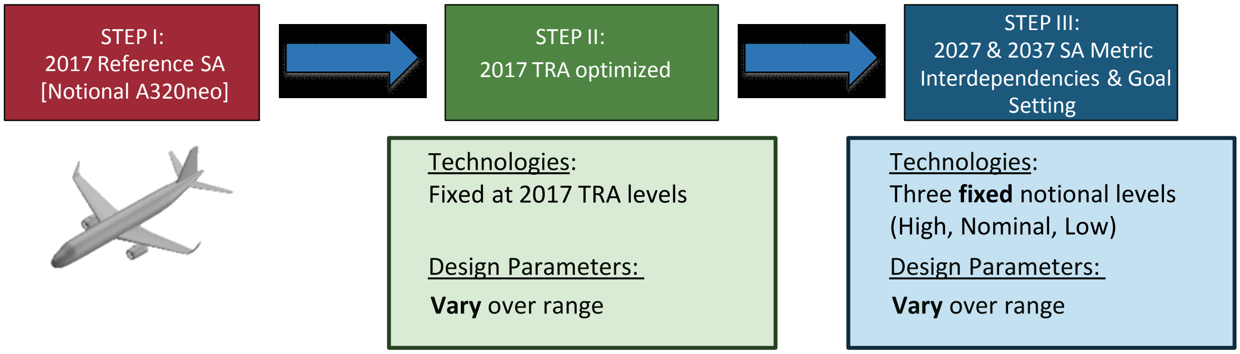

Figure 7-6. Process to Assess the Technology Goals

For the 2017 TRA optimization, the design space was explored with the approach depicted in Figure 7-7. The specific design variable ranges and constraints for each time frame are provided in Appendix M. With each combination of design variables in the evolutionary search, the design MTOM, OEW (specifically, OEW_{design}), operating items mass, trip fuel[83] mass, and cumulative noise at the certification conditions were calculated. The OEW_{design} was then held constant and an off-design analysis was executed at the 2017 TRA R_1 payload and range condition and the FB/ATK_{R1} computed. For the optimization at 2017, new technology, which might lead to lower empty mass, was not included. The optimization used an objective function of a weighted sum of the fuel burn metric at R_1 ($FB/ATK_{TRA\text{-}R1}$) and cumulative noise at the certification conditions, which includes the MLW as well as MTOM. The relative weighting in the optimization went from the weighting of 100% $FB/ATK_{TRA\text{-}R1}$ vs 0% cumulative noise in increments of 5 % to 0% $FB/ATK_{TRA\text{-}R1}$ versus 100% cumulative noise.

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[83] Trip fuel is defined as total fuel less taxi and reserves

The design space was explored via a particle swarming optimization (PSO)[84] technique with the vehicle sized at the 2017 design range and payload. The specific design variable ranges and constraints for each time frame are provided in Appendix M. With each confidence weighting, 10,000's of aircraft were created as part of the optimization search and a "cloud" of aircraft could be visualized as depicted in the left hand side of Figure 7-8, with cumulative noise at certification conditions versus FB/ATK quoted at the design range. Each point in the cloud represents a given setting of design parameters as defined by the optimization. The grey dots are designs that violate one of the constraints of wing span, fan diameter, or maximum allowable T_3. Only the black dots meet the constraints. The 2017 TRA is shown as the red star in the orange circle. The right hand side of Figure 7-8 shows the final Pareto front for the outputs consistent with the constraints with all other designs removed. The front terminates at 100% FB/ATK /0% noise and 0% FB/ATK /100% noise. The Pareto front is not coincident with the TRA, confirming the expectation that the different optimization used by the IEs would lead to a shift in fuel burn, noise and MTOM. The Pareto front comparison shows the potential trade-offs that can be made between fuel burn and noise, thus capturing the interdependencies of the design parameter variability.

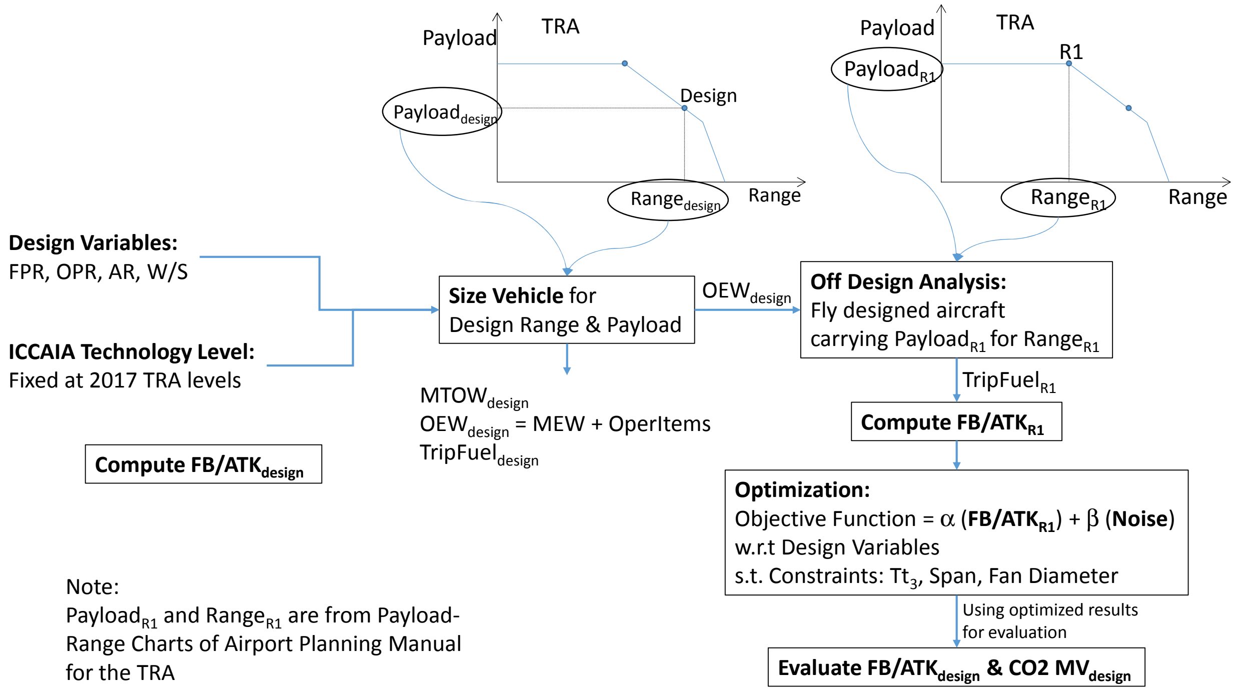

Figure 7-7. 2017 TRA Optimization Flowchart

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[84] Particle swarm optimization (PSO) is a population based stochastic optimization technique. It is similar with evolutionary computation techniques such as Genetic Algorithms by initializing a population of random solutions and searches for optima by updating generations. Unlike traditional evolutionary computational techniques, PSO has no evolution operators such as crossover and mutation. PSO is an efficient approach to exploring and optimizing the design space. Further information on the PSO technique is described in Kennedy, J.; Eberhart, R. (1995). "Particle Swarm Optimization". Proceedings of IEEE International Conference on Neural Networks. IV. pp. 1942–1948. doi:10.1109/ICNN.1995.488968.

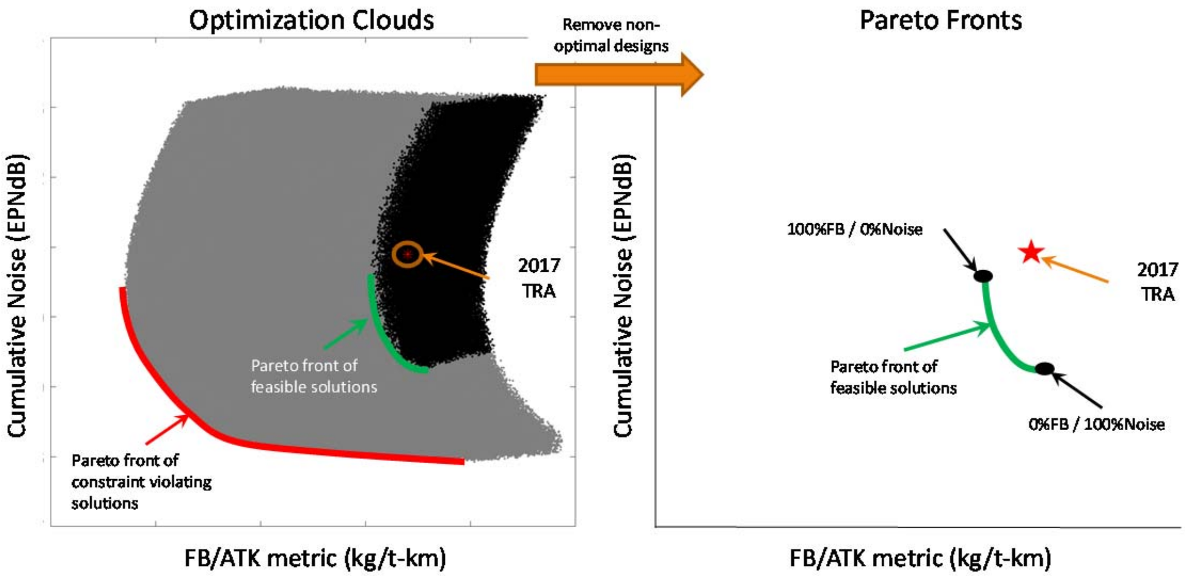


Figure 7-8. Visualizing the Optimization "Clouds" and Pareto Fronts (Notional Images)

7.8.2 Optimization for 2027 and 2037

For 2027 and 2037 the design parameters (aspect ratio, OPR, FPR, etc.) were given as ranges, going beyond those appropriate for 2017. The optimization was identical to that for 2017 shown in Figure 7-7, but this time baskets of technologies from ICCAIA were included at three levels of confidence. The technology category impacts were obtained for 2027 and 2037 at three levels of technology-implementation confidence: high (H), nominal (N), and low (L). For a given time frame, 2027 or 2037, and a technology-implementation confidence level (H, N, or L), the optimization process was repeated as depicted in Figure 7-9. The analysis was identical to the approach taken for the 2017 TRA optimization, but now, the technology level changed. Repeating this for each time frame and confidence resulted in six additional Pareto optimal fronts, as notionally depicted in Figure 7-10. Each point forming the Pareto front represents a different weighting of the composite objective function of cumulative noise and the FB/ATK, with the fuel burn metric evaluated at the design range. Although the Pareto fronts are depicted at the design range FB/ATK, the optimization leading to the specification of the optimized aircraft was carried out at R_1 for 2017. The bright green points in Figure 7-10 correspond to the 50% $\text{FB/ATK}_{\text{TRA-R1}}$versus 50% cumulative noise weighting (written elsewhere as 50/50 weighting), whilst the highest noise corresponds to the 100% FB weighting.

The results of the computations and the goals for the CO_2 metric value and cumulative noise are discussed in Chapter 8. In setting goals, the levels from the 2027 and 2037 optimizations are "shifted" to allow for the difference between the original TRA value and the corresponding optimization for 2017. To do so, the change in the FB/ATK, cumulative noise, MTOM, and CO_2 metric value between the 2017 TRA and the 2017 TRA optimized, at a given weighting of fuel burn and noise, were tabulated and then applied to the same objective function weighting values for a time frame and technology confidence level; effectively a "shift" of the Pareto fronts. For example, if the preferred weighting of the optimization by the IEs was 50% FB/50% noise for the 2027 nominal technology setting, then the Δ FB/ATK and Δ noise, shown in Figure 7-10, would be applied to the same weighting preference on the associate Pareto front point, highlighted as the bright green points. Figure 7-10 shows a set of notional Pareto fronts for one aircraft, which correspond to the 2017 TRA, 2017 optimization, the optimizations for the three confidence levels in 2027 and 2037.

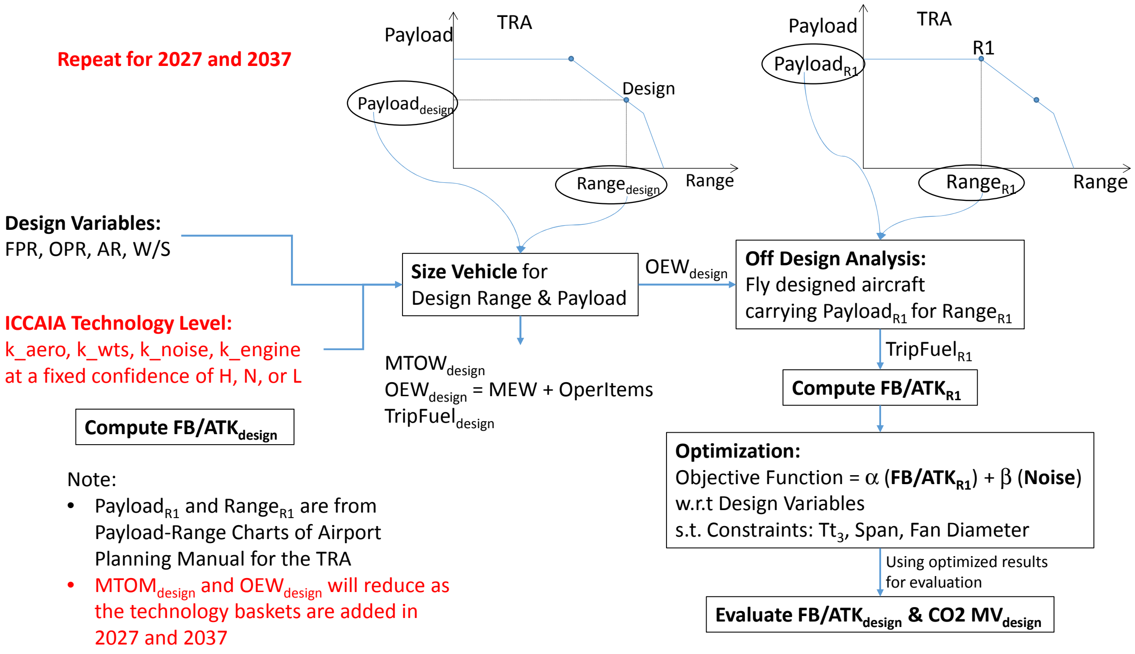


Figure 7-9. Optimization Process to Identify Technology Infused Pareto Optimal Solutions

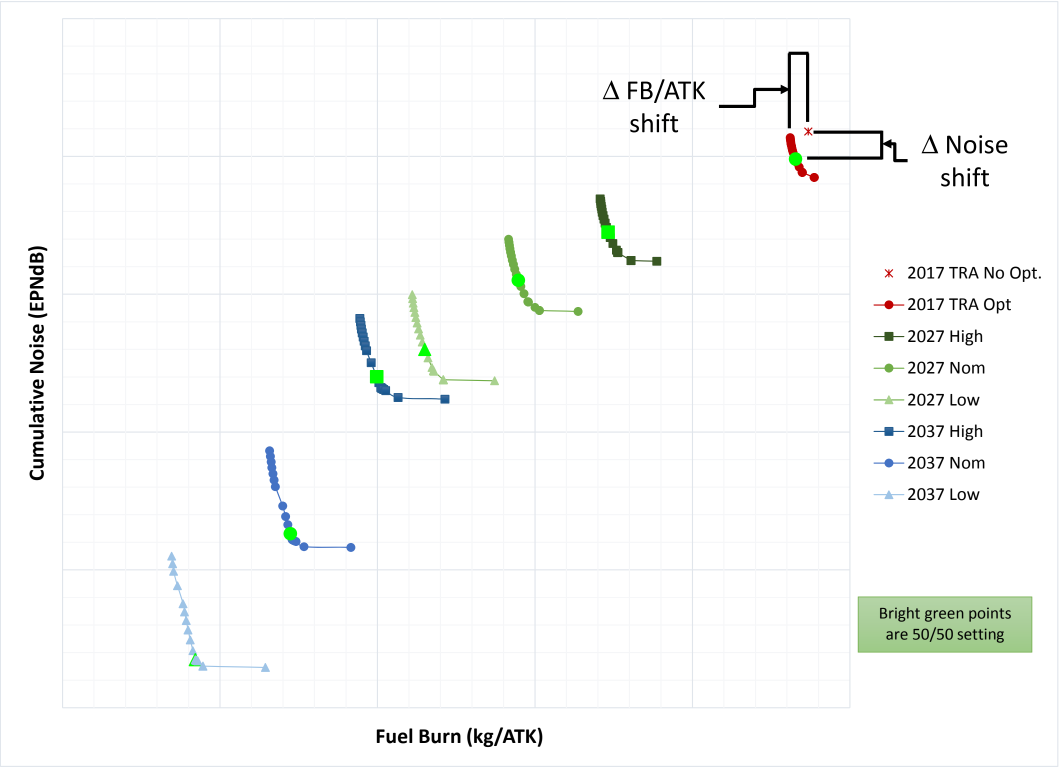


Figure 7-10. Notional Technology Pareto Optimal Fronts

CHAPTER 8. INTEGRATED TECHNOLOGY MODELLING RESULTS AND GOALS

8.1 INTRODUCTION

One task of the review was to consider the interdependencies between fuel burn, using the CO_2 certification metric system, the cumulative noise, and the emissions of NO_x and nvPM. To this end, the Independent Experts have looked at the available technologies, the previous goals set by IEs in earlier reviews, and the output of the EDS modelling environment for the four aircraft classes considered for this Review using Georgia Tech's EDS modelling environment. Chapter 7 outlined the modelling method and approach, whilst this chapter focuses on the results of the modelling and the derivation of goals.

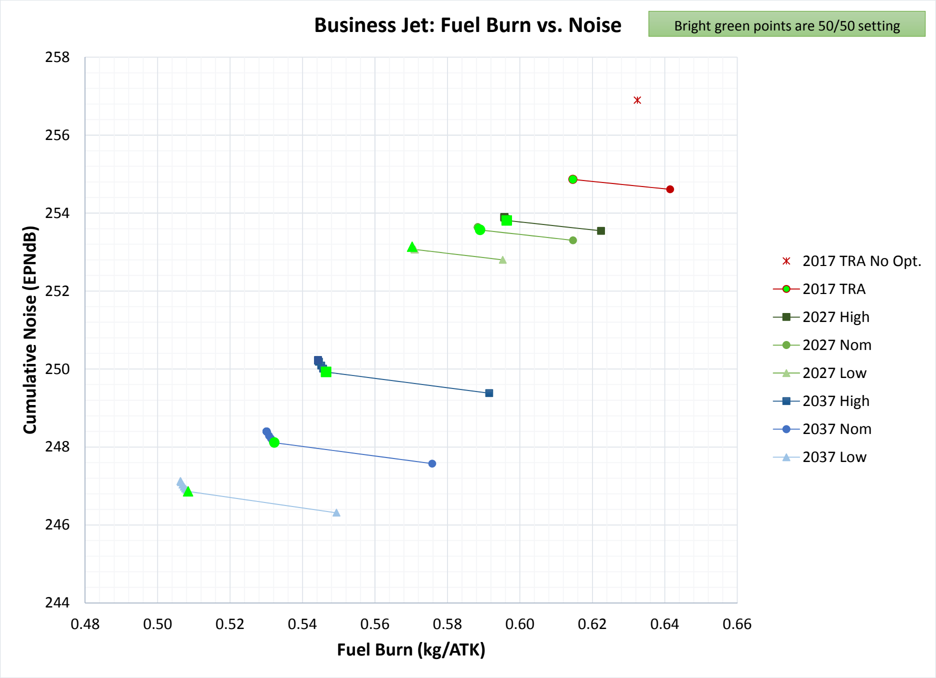
8.2 NO_X VS FUEL BURN AND NOISE INTERDEPENDENCY

The technologies that are required to address emissions can have a mass and performance penalty – and hence, some effect on fuel burn and noise. In Chapter 5, it was concluded that the mass penalty for lean-burn combustor technologies were probably not significant. On the other hand, increases in OPR and T_{40} can have a significant effect on NO_x. The output for NO_x of the EDS model shows an expected dependence on engine overall pressure ratio, but not on combustor geometry, nor T_{40}. This is because the EDS model does not have quantitative modelling tools for combustion nor an adequate empirical base to allow quantification of technology level and T_{40}. Therefore, the IEs have based their goals for NO_x on the considerations set out in Chapter 5 for this report and they are presented independent of the noise or fuel burn modelling efforts. With the interdependency between NO_x, noise, and fuel burn removed, the only interdependency considered from the EDS modelling is between noise and fuel burn for each vehicle.

8.3 FUEL BURN VERSUS NOISE OPTIMIZATION

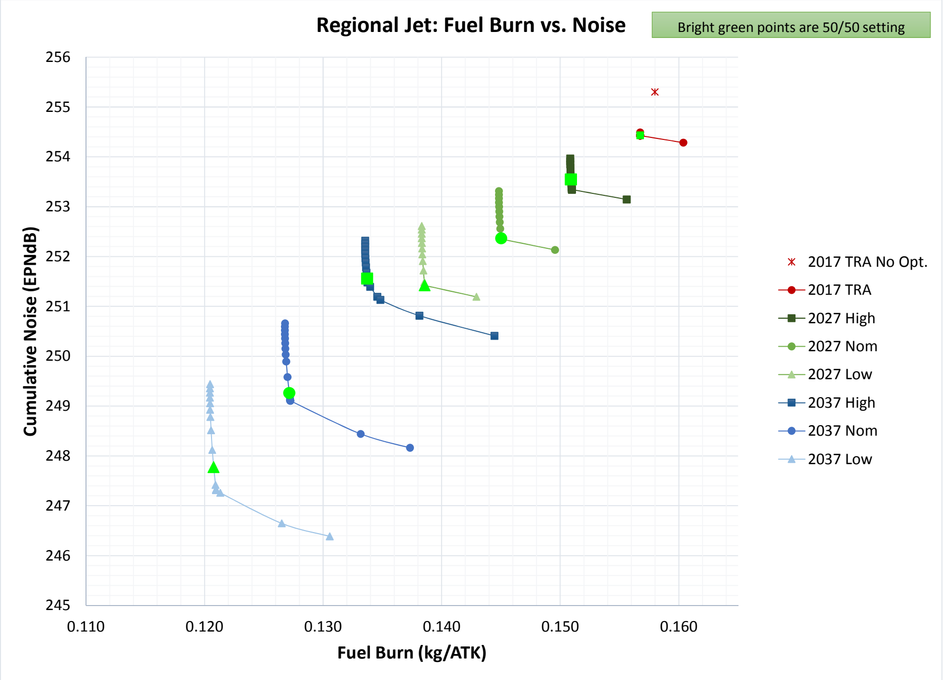
As described in Chapter 7, a key output of the EDS modelling efforts are the Pareto fronts found for the cumulative noise (EPNdB) and the fuel burn metric (FB/ATK with units kg-fuel/ATK). These are at the edge of the swarm clouds calculated for these quantities. Pareto fronts are shown in Figure 8-1 to Figure 8-4 for all four aircraft used as reference vehicles. Each figure shows the Pareto fronts for the optimized 2017 TRA, 2027, and 2037 aircraft. The future fronts (2027 and 2037) are shown at three levels of technology-implementation confidence: high (H)-notionally 80%, nominal (N)-notionally 50%, and low (L)-notionally 20%. The optimization was applied to the 2017 TRA so that the difference in values for the future cases can be made against an optimization for the TRA on the same basis as described in Chapter 7. FB/ATK is displayed at the design range, which was held constant, and the cumulative noise, which was based on the certification procedure.

The Pareto front consists of a number of points, each of which consists of different choices in the optimization process. The highest noise point corresponds to the weighting of the optimization being 100% biased to low fuel burn, whilst the lowest noise point corresponds to the bias being 100% to low noise. The green marker on each Pareto front corresponds to an optimization objective that is 50% fuel burn weighted and 50% noise weighted. Relative to the 100% noise weighted point, the 50%-50% point consistently leads to large improvements in fuel burn. Relative to the 100% fuel burn point, the 50%-50% point generally produces a significant reduction in noise without an unacceptable increase in fuel burn. Table 8-1 through Table 8-4 lists the reduction in fuel burn and noise in 2027 and 2037 for all four aircraft relative to the 2017 optimized value for 100% fuel burn optimization and 50% noise optimization and 100% noise optimization. The change in FB/ATK, CO_2 metric, and noise in 2027 and 2037 are relative to the associated optimization point in 2017. For example, if the weighting is 100% FB to 0% noise, then the difference is to the same weighting in 2017. This is done for each of the three technology-implementation confidence levels. It should be noted that the MTOM also reduces with the introduction of new technology.



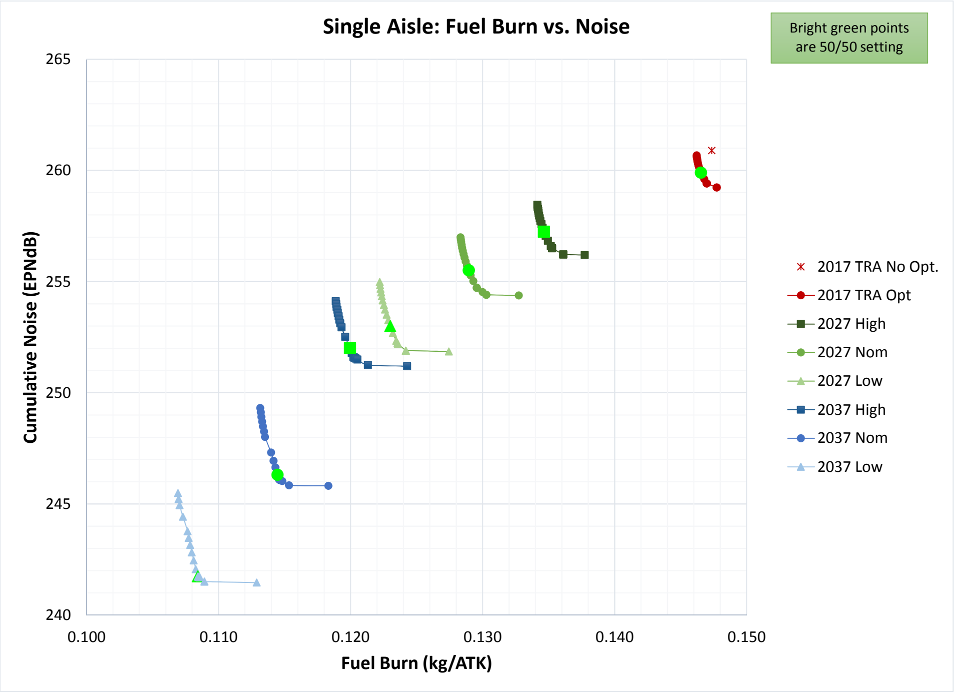
Aircraft sized at Design Range and Optimized at R1 of the 2017 TRA. FB/ATK shown at Design Range

Figure 8-1. BJ Pareto Fronts of Cumulative Noise versus FB/ATK



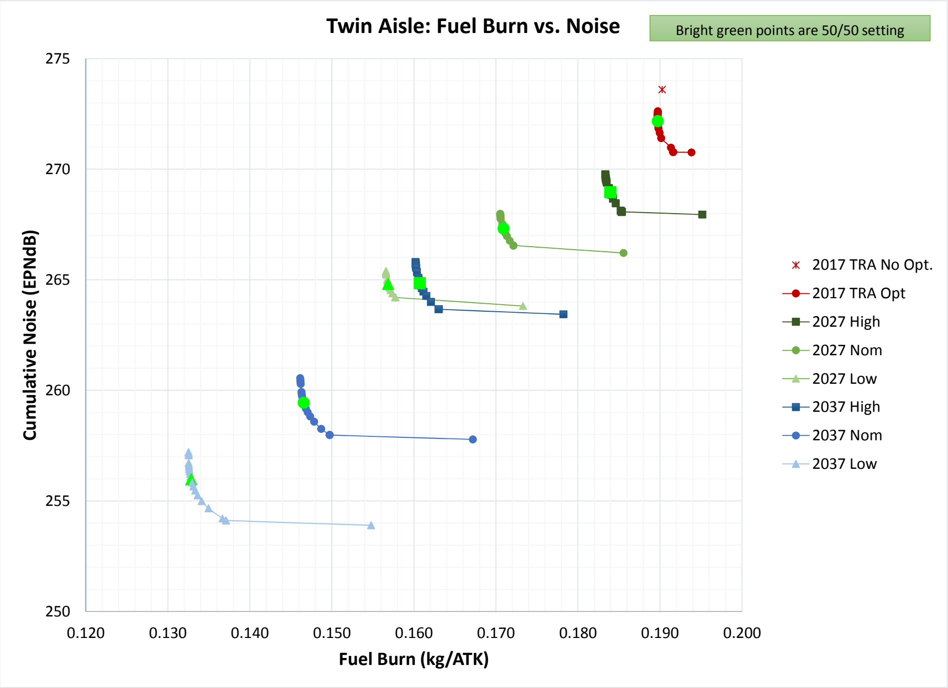
Aircraft sized at Design Range and Optimized at R1 of the 2017 TRA. FB/ATK shown at Design Range

Figure 8-2. RJ Pareto Fronts of Cumulative Noise versus FB/ATK



Aircraft sized at Design Range and Optimized at R1 of the 2017 TRA. FB/ATK shown at Design Range

Figure 8-3. SA Pareto Fronts of Cumulative Noise versus FB/ATK



Aircraft sized at Design Range and Optimized at R1 of the 2017 TRA. FB/ATK shown at Design Range

Figure 8-4. TA Pareto Fronts of Cumulative Noise versus FB/ATK

The slight overlap of the low confidence in 2027 and the high in 2037 for the TA is because the technology baskets provided by ICCAIA were similar in nature.

Table 8-1. BJ Model Output for 2017, 2027 and 2037 all at Design Range[85]

Year	Conf. Level	FB to Noise Preference	MTOM (kg)	FB/ATK (kg/ATK)	% FB/ATK relative to 2017	CO_2 Metric (kg/km)	% CO_2 Metric	Cumulative Noise (EPNdB)	Δ Noise (EPNdB)
2017	NA	0-100	47408	0.641		0.605		254.61	
2017	NA	50-50	46455	0.615		0.573		254.86	
2017	NA	100-0	46455	0.615		0.573		254.86	
2027	H	0-100	46285	0.622	1.26%	0.587	2.51%	253.55	-1.32
2027	N	0-100	45679	0.615	0.00%	0.579	1.10%	253.30	-1.56
2027	L	0-100	44736	0.595	-3.15%	0.559	-2.39%	252.80	-2.06
2027	H	50-50	45416	0.596	-3.08%	0.557	-2.81%	253.89	-0.97
2027	N	50-50	44859	0.588	-4.27%	0.551	-3.92%	253.64	-1.22
2027	L	50-50	43916	0.570	-7.22%	0.532	-7.17%	253.13	-1.73
2027	H	100-0	45416	0.596	-3.08%	0.557	-2.81%	253.89	-0.97
2027	N	100-0	44859	0.588	-4.27%	0.551	-3.92%	253.64	-1.22
2027	L	100-0	43916	0.570	-7.22%	0.532	-7.17%	253.13	-1.73
2037	H	0-100	45010	0.592	-3.76%	0.552	-3.60%	249.38	-5.48
2037	N	0-100	44026	0.576	-6.32%	0.536	-6.45%	247.57	-7.29
2037	L	0-100	42750	0.549	-10.61%	0.511	-10.91%	246.31	-8.55
2037	H	50-50	43349	0.544	-11.44%	0.498	-13.05%	250.23	-4.64
2037	N	50-50	42463	0.530	-13.74%	0.484	-15.54%	248.38	-6.48
2037	L	50-50	41185	0.508	-17.41%	0.460	-19.71%	246.94	-7.93
2037	H	100-0	43349	0.544	-11.44%	0.498	-13.05%	250.23	-4.64
2037	N	100-0	42459	0.530	-13.76%	0.484	-15.54%	248.40	-6.46
2037	L	100-0	41137	0.506	-17.62%	0.460	-19.70%	247.12	-7.74

Optimized Aircraft at High (H), Nominal (N) and Low (L) Confidence Levels. Each aircraft Optimized at R_1 *of the 2017 TRA.*

Table 8-2. RJ Model Output for 2017, 2027 and 2037 all at Design Range

Year	Conf. Level	FB to Noise Preference	MTOM (kg)	FB/ATK (kg/ATK)	% FB/ATK relative to 2017	CO_2 Metric (kg/km)	% CO_2 Metric	Cumulative Noise (EPNdB)	Δ Noise (EPNdB)
2017	NA	0-100	56661	0.157		0.655		254.43	
2017	NA	50-50	56661	0.157		0.655		254.43	
2017	NA	100-0	56638	0.157		0.655		254.49	
2027	H	0-100	55514	0.156	-0.72%	0.655	0.07%	253.14	-1.28
2027	N	0-100	54370	0.150	-4.58%	0.629	-3.98%	252.13	-2.29
2027	L	0-100	53183	0.143	-8.81%	0.600	-8.43%	251.19	-3.23
2027	H	50-50	55414	0.151	-3.70%	0.632	-3.58%	253.40	-1.02
2027	N	50-50	54301	0.145	-7.48%	0.606	-7.41%	252.35	-2.08
2027	L	50-50	53095	0.139	-11.60%	0.579	-11.56%	251.42	-3.01
2027	H	100-0	55177	0.151	-3.76%	0.631	-3.60%	253.97	-0.52
2027	N	100-0	53916	0.145	-7.60%	0.606	-7.47%	253.31	-1.18
2027	L	100-0	52688	0.138	-11.75%	0.578	-11.70%	252.61	-1.88
2037	H	0-100	53675	0.144	-7.84%	0.607	-7.29%	250.41	-4.02
2037	N	0-100	52277	0.137	-12.38%	0.575	-12.17%	248.16	-6.26
2037	L	0-100	50961	0.131	-16.69%	0.545	-16.82%	246.38	-8.04
2037	H	50-50	53637	0.134	-14.67%	0.552	-15.73%	251.48	-2.95
2037	N	50-50	52275	0.127	-18.88%	0.523	-20.16%	249.26	-5.16
2037	L	50-50	51015	0.121	-22.85%	0.495	-24.46%	247.42	-7.01
2037	H	100-0	53310	0.134	-14.80%	0.552	-15.76%	252.32	-2.17
2037	N	100-0	51772	0.127	-19.11%	0.523	-20.15%	250.66	-3.83
2037	L	100-0	50353	0.120	-23.14%	0.495	-24.45%	249.44	-5.05

Optimized Aircraft at High (H), Nominal (N) and Low (L) Confidence Levels. Each aircraft Optimized at R_1 *of the 2017 TRA.*

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[85] In this table and elsewhere in the report, differences were evaluated from the original EDS output and **<u>not</u>** from the rounded numbers appearing in the tables of the report. In consequence, small apparent inconsistencies may appear if differences are evaluated from the rounded numbers in the tables.

Table 8-3. SA Model Output for 2017, 2027 and 2037 all at Design Range

Year	Conf. Level	FB to Noise Preference	MTOM (kg)	FB/ATK (kg/ATK)	% FB/ATK relative to 2017	CO_2 Metric (kg/km)	% CO_2 Metric	Cumulative Noise (EPNdB)	Δ Noise (EPNdB)
2017	NA	0-100	79553	0.148		0.783		259.24	
2017	NA	50-50	79081	0.147		0.773		259.90	
2017	NA	100-0	78819	0.146		0.773		260.68	
2027	H	0-100	76568	0.138	-6.01%	0.728	-7.01%	256.20	-3.04
2027	N	0-100	74888	0.133	-9.42%	0.701	-10.54%	254.38	-4.86
2027	L	0-100	73063	0.127	-13.03%	0.670	-14.45%	251.86	-7.37
2027	H	50-50	75897	0.135	-8.12%	0.702	-9.23%	257.25	-2.65
2027	N	50-50	74190	0.129	-12.01%	0.669	-13.48%	255.51	-4.39
2027	L	50-50	72385	0.123	-16.06%	0.634	-17.98%	252.99	-6.91
2027	H	100-0	75551	0.134	-8.25%	0.701	-9.30%	258.45	-2.22
2027	N	100-0	73780	0.128	-12.23%	0.667	-13.62%	256.99	-3.69
2027	L	100-0	71857	0.122	-16.42%	0.632	-18.23%	254.98	-5.69
2037	H	0-100	73272	0.124	-15.19%	0.651	-16.81%	251.19	-8.04
2037	N	0-100	71271	0.118	-19.26%	0.615	-21.48%	245.82	-13.42
2037	L	0-100	69208	0.113	-22.97%	0.586	-25.12%	241.46	-17.77
2037	H	50-50	74022	0.120	-18.15%	0.600	-22.43%	252.01	-7.89
2037	N	50-50	71949	0.114	-21.89%	0.574	-25.75%	246.31	-13.59
2037	L	50-50	69841	0.108	-26.01%	0.547	-29.29%	241.74	-18.16
2037	H	100-0	72873	0.119	-18.69%	0.593	-23.29%	254.12	-6.56
2037	N	100-0	70613	0.113	-22.61%	0.566	-26.69%	249.32	-11.36
2037	L	100-0	68351	0.107	-26.86%	0.538	-30.33%	245.49	-15.19

Optimized Aircraft at High (H), Nominal (N) and Low (L) Confidence Levels. Each aircraft Optimized at R_1 of the 2017 TRA.

Table 8-4.TA Model Output for 2017, 2027 and 2037 all at Design Range

Year	Conf. Level	FB to Noise Preference	MTOM (kg)	FB/ATK (kg/ATK)	% FB/ATK relative to 2017	CO_2 Metric (kg/km)	% CO_2 Metric	Cumulative Noise (EPNdB)	Δ Noise (EPNdB)
2017	NA	0-100	286297	0.194		1.688		270.76	
2017	NA	50-50	281881	0.190		1.645		272.09	
2017	NA	100-0	280899	0.190		1.644		272.62	
2027	H	0-100	284397	0.195	2.85%	1.698	3.22%	267.95	-4.14
2027	N	0-100	273920	0.186	-2.21%	1.622	-1.41%	266.21	-5.88
2027	L	0-100	261074	0.173	-8.67%	1.519	-7.67%	263.81	-8.28
2027	H	50-50	280293	0.184	-3.06%	1.582	-3.87%	268.96	-3.13
2027	N	50-50	268504	0.171	-9.92%	1.474	-10.41%	267.32	-4.77
2027	L	50-50	255722	0.157	-17.32%	1.351	-17.90%	264.81	-7.28
2027	H	100-0	277964	0.183	-3.38%	1.579	-3.92%	269.78	-2.84
2027	N	100-0	266612	0.171	-10.13%	1.471	-10.50%	267.98	-4.64
2027	L	100-0	254108	0.157	-17.47%	1.347	-18.06%	265.40	-7.22
2037	H	0-100	269548	0.178	-6.08%	1.559	-5.27%	263.44	-8.65
2037	N	0-100	257039	0.167	-11.88%	1.460	-11.29%	257.78	-14.31
2037	L	0-100	245234	0.155	-18.42%	1.354	-17.73%	253.90	-18.19
2037	H	50-50	262810	0.161	-15.30%	1.381	-16.07%	264.84	-7.25
2037	N	50-50	248610	0.147	-22.75%	1.253	-23.83%	259.44	-12.65
2037	L	50-50	234636	0.133	-29.98%	1.127	-31.52%	255.97	-16.12
2037	H	100-0	260068	0.160	-15.57%	1.375	-16.32%	265.80	-6.82
2037	N	100-0	245973	0.146	-22.98%	1.244	-24.33%	260.55	-12.07
2037	L	100-0	232130	0.133	-30.15%	1.114	-32.20%	257.20	-15.42

Optimized Aircraft at High (H), Nominal (N) and Low (L) Confidence Levels. Each aircraft Optimized at R_1 of the 2017 TRA.

The IEs spent a significant amount of time in considering the appropriate confidence level for setting the goals; the nominal confidence level was selected based on a robust consensus of the group. This confidence level was driven by the intent that the goals would be realistic and achievable while remaining sufficiently ambitious. While the nominal level is used to define the goals, the other two levels provided an estimate of the uncertainties associated with the modelling, optimization, and prediction of future technology development and implementation. Future development and implementation will depend, in large part, on the degree of pressure applied to the aviation sector and the resulting level of R&D investment by government agencies, aircraft and engine manufacturers, in addition to market demands.

Table 8-5 lists the change in the fuel burn metric of technology-infused aircraft in 2027 and 2037 for the nominal confidence level relative to the 2017 TRA optimized aircraft, **<u>not</u>** to the baseline TRAs. The key assumption here is that all of the future cases are optimized at the 50% FB/50% noise weighting, with payload and range (at R_1 and the design range) equal to the 2107 baseline TRA. Also listed in Table 8-5 are the CO_2 metric and margin to the CO_2 New-Type limit (see Appendix C for further definition). The differences for FB/ATK are also converted into an annual[86] reduction, which can be compared with the annual rates of reduction from other sources, notably the Independent Expert Fuel Burn review of 2010.

Table 8-5. Differences between CO_2 Metric and FB/ATK at Design Range

Aircraft	Year	MTOM	FB/ATK	% FB/ATK	FB/ATK Per Annum from 2017	CO_2 Metric	CO_2 Margin to Limit
BJ	2017	46455	0.615			0.573	-16.5%
	2027	44859	0.588	-4.27%	-0.44%	0.551	-18.6%
	2037	42463	0.530	-13.74%	-0.74%	0.484	-26.8%
RJ	2017	56661	0.157			0.655	-12.2%
	2027	54301	0.145	-7.48%	-0.77%	0.606	-17.3%
	2037	52275	0.127	-18.88%	-1.04%	0.523	-27.5%
SA	2017	79081	0.147			0.773	-5.2%
	2027	74190	0.129	-12.01%	-1.27%	0.669	-15.0%
	2037	71949	0.114	-21.89%	-1.23%	0.574	-25.8%
TA	2017	281881	0.190			1.645	-5.2%
	2027	268504	0.171	-9.92%	-1.04%	1.474	-12.4%
	2037	248610	0.147	-22.75%	-1.28%	1.253	-21.9%

Differences between optimized aircraft in 2017, 2027 and 2037. All Optimization for Nominal Confidence at the 50% FB/50% Weighting, Performed at R_1 for 2017 TRA.

The above results for the nominal confidence, with the optimization at 50% fuel burn/ 50% noise weighting, are used as the basis to set the goals in later sections. Table 8-6 lists the basis of the fuel burn goals in terms of the FB/ATK, certification CO_2 metric, and the CO_2 margin to the New-type regulatory limit. The differences in the FB/ATK and the CO_2 metric in Tables 8.1 to 8.4 vs Table 8.5 was to adjust, or "shift", the technology infused and optimized aircraft back to the original 2017 non-optimized TRA, as described in Section 7.8. The shift values utilized are listed in Table 8-7. The approach for this "shift" was to simply calculate the changes in MTOM, noise, CO_2 metric value, and FB/ATK between the TRA and optimized 2017 TRA and then apply these differences to the technology infused optimized points in 2027 and 2037. The 2017 values provided in Table 8-6 are for <u>non-optimized</u> TRAs and the 2027 and 2037 values have been shifted from the Pareto front values provided in Table 8-5.

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[86] This is done as follows: suppose in 2037, the metric is 0.8 of the value in 2017. The ratio change per year is $0.8^{1/20} = 0.9889$. So annual reduction would be 1 – 0.9889 = 0.0111, or 1.11%

Table 8-6. Shifted FB/ATK, CO_2 MV, and CO_2 MV Margin to the Appropriate Limit Line[87]

Aircraft	Year	MTOM	FB/ATK	% FB/ATK	FB/ATK Per Annum from 2017	CO_2 Metric	CO_2 Margin to Limit
BJ	2017	46993	0.632			0.602	-12.7%
	2027	45396	0.606	-4.15%	-0.42%	0.580	-14.7%
	2037	43001	0.548	-13.35%	-0.71%	0.513	-22.8%
RJ	2017	56400	0.158			0.662	-11.1%
	2027	54040	0.146	-7.42%	-0.77%	0.613	-16.2%
	2037	52014	0.128	-18.73%	-1.03%	0.530	-26.4%
SA	2017	79000	0.147			0.783	-3.9%
	2027	74109	0.130	-11.94%	-1.26%	0.679	-13.7%
	2037	71868	0.115	-21.77%	-1.22%	0.584	-24.5%
TA	2017	280026	0.190			1.654	-4.3%
	2027	266650	0.171	-9.89%	-1.04%	1.483	-11.5%
	2037	246755	0.147	-22.69%	-1.28%	1.262	-21.0%

Results of Model Shifted to Allow for Difference between Optimized 2017 and TRA. All Optimization for Nominal Confidence at the 50% FB/50% weighting, performed at R_1 *for 2017 TRA. FB/ATK quoted at the Design Range.*

Table 8-7. Shift Values from 2017 Optimized to the Non-optimized TRA used to Determine Goals

Aircraft	MTOM (kg)	FB/ATK (kg/ATK)	CO_2 Metric (kg/km)	Cumulative Noise (Δ dB)
BJ	-537	-0.0178	-0.0289	-2.04
RJ	261	-0.0012	-0.0070	-0.87
SA	81	-0.0008	-0.0099	-1.00
TA	1855	-0.0005	-0.0085	-1.51

Figure 8-5 shows the reduction in fuel burn metric quoted at the design range against year, whilst Figure 8-6 shows the changes for the CO_2 Metric Value. In both cases, the results have been "shifted", so that the changes for 2027 and 2037 relative to the optimized value of the TRA in 2017 are the differences between the optimized value for 2017 and the actual TRA. Qualitatively and quantitatively, the changes in fuel burn and CO_2 metric are similar; though the values for the latter are in most cases slightly larger.

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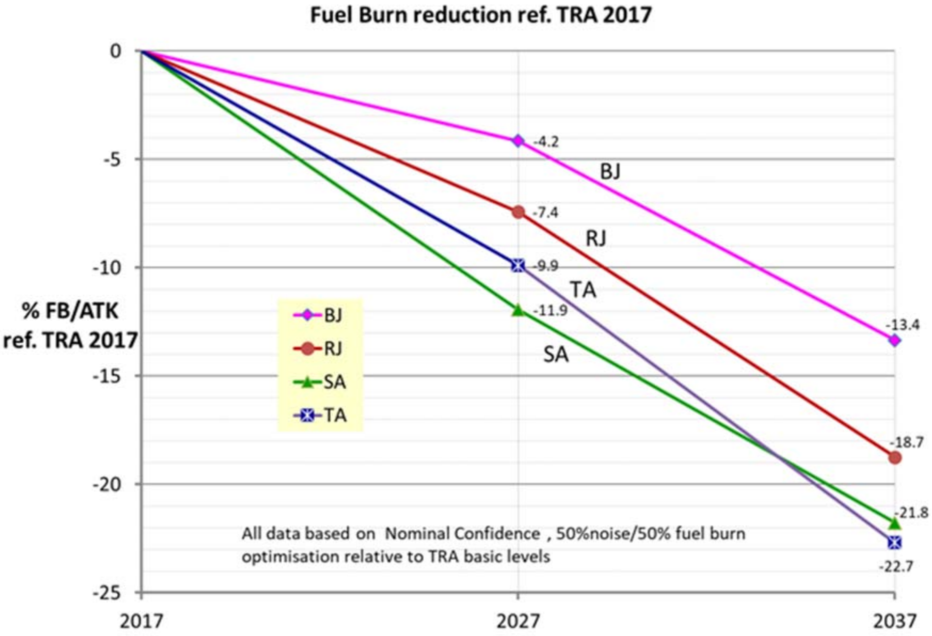
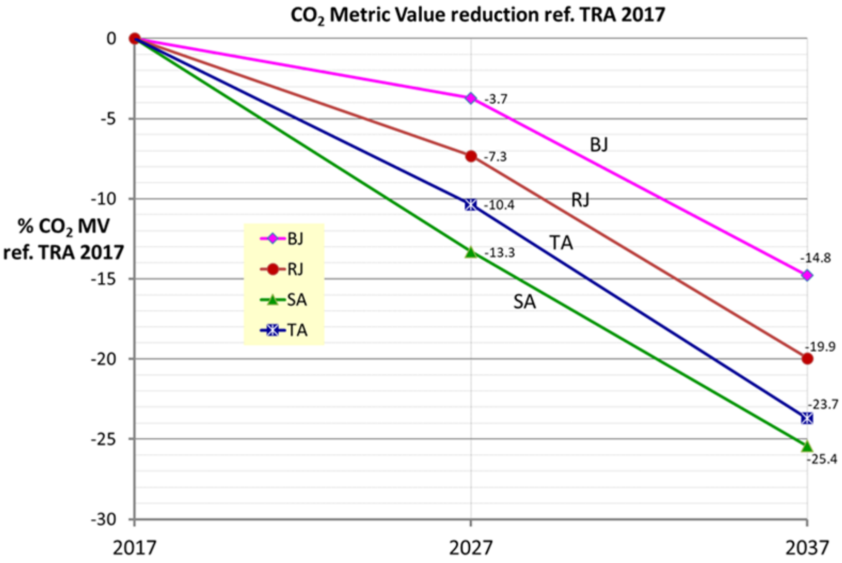
[87] The fuel burn per annum is calculated as: $((1\text{-}\%FB)^{(1/\#\text{ of years})})\text{-}1$, and %FB = (2017 FB-out year FB)/2017 FB



All Optimization for Nominal Confidence at the 50% CO2/50% Weighting, Performed at R₁ for 2017 TRA.

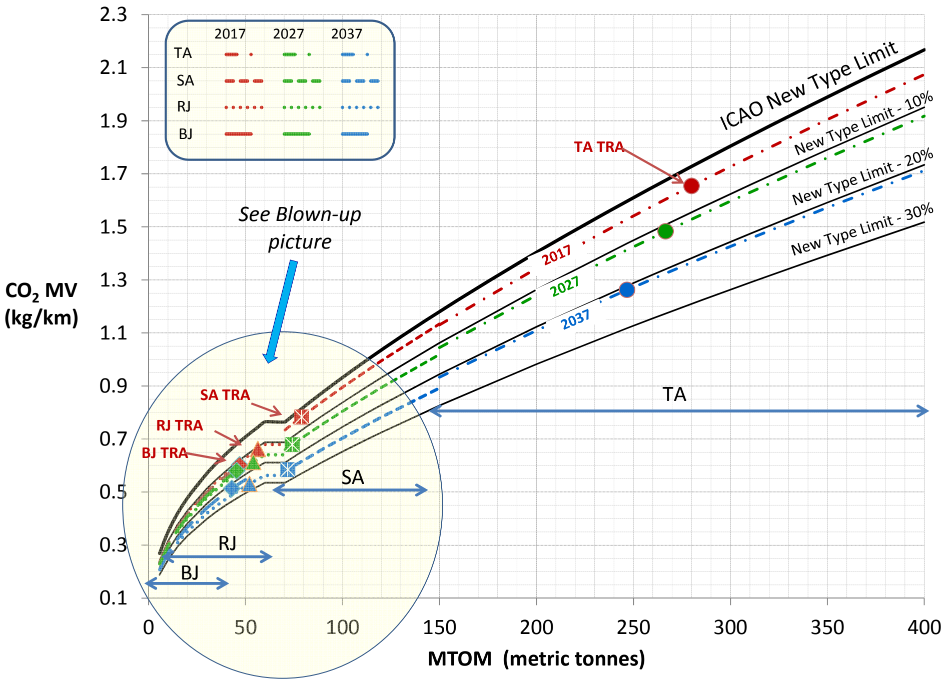
Figure 8-5. Reductions in Fuel Burn Metric at DR Relative to 2017 TRA



All Optimization for Nominal Confidence at the 50% CO2/50% Weighting, Performed at R₁ for 2017 TRA.

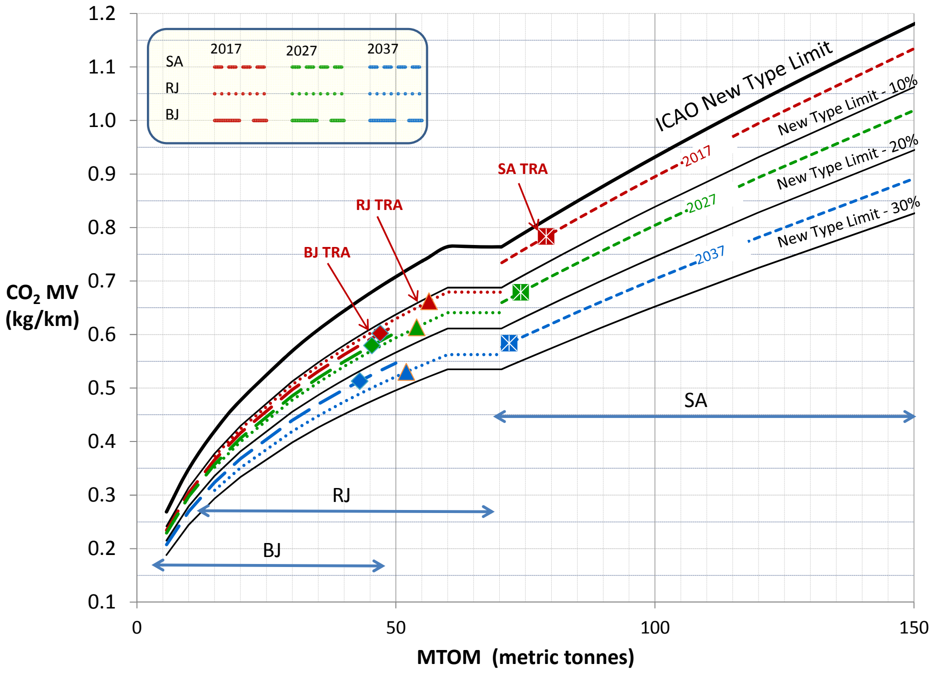
Figure 8-6. Reductions in CO_2 Metric Value at Design Range Relative to 2017 TRA

Figure 8-7 and Figure 8-8 (same figure just zoomed in on lower MTOM) shows the CO_2 Metric Value plotted against MTOM. The upper line is the CAEP/10 regulatory level for New Types, whilst the lower lines show margins to the New-Types line. As in Table 8-6, the values of CO_2 MV and MTOM used have been shifted relative to values given in Tables 8.1 to 8.4 (optimized) and Table 8-5 ("shifted") to allow for the difference between the optimized 2017 aircraft and the 2017 TRAs.



Points show Optimization for Nominal Confidence at the 50% FB/50% Weighting, Performed at R_1 for 2017 TRA.

Figure 8-7. CO_2MV versus MTOM and Percentage Reductions from the "New Types" Level



Points show Optimization for Nominal Confidence at the 50% FB/50% Weighting, Performed at R_1 for 2017 TRA.

Figure 8-8. CO_2MV versus MTOM and Percentage Reductions from the "New Types" Level

Fuel Burn Goal Recommendations

Based on the model results at nominal confidence level and the optimization at 50% Fuel Burn/50% noise weighting, the fuel burn goals for the new aircraft types are as follows:

Table 8-8. Fuel Burn Goals as % Margin of CO_2 Metric Value for the CAEP/10 New Type Level

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

In Table 8-8, the 2017 TRA margins are shown for comparison purposes only and are not goals. The fuel burn goals are based on modelling using the nominal confidence level estimates, specifically a 50% expectation that the technology benefits would be achieved.

Comparison with Earlier Fuel Burn Goals

In the Report of the Independent Experts on Fuel Burn Reduction Technology Goals, delivered in 2010, goals were provided for two aircraft, the Single Aisle and what was referred to as the Small Twin Aisle (STA): the former is close to the current SA and the latter is close to the current TA. The reference standard was taken to be in 2010 and goals were provided for 2020 and 2030. The IEs, for that review, adopted Technology Scenarios: TS1 was continuing along the current trajectory of improvement and TS2 was "increased pressure" to reduce fuel burn. The results of TS2 were accepted as the goals. The results of the 2010 study were expressed as the fuel burn metric (kg-fuel/ATK) at the R_1 range. However, the current goals are expressed in terms of the CO_2 certification metric system, specifically the margin of this metric to the certification line for new types.

The CO_2 metric is not exactly equivalent, but both this, and the fuel burn metric, have been evaluated in the present study. Table 8-9 lists the comparisons of the changes in the current CO_2 metric value with changes in the fuel burn metric evaluated at both flight distance ranges at the design range (DR) and R_1 range. Note, the value of R_1 used here is the value for the respective 2017 optimized TRA, not the value which would be achieved with the improvements of 2027 and 2037.

Table 8-9. Comparison of Percent Changes in CO_2 Metric Value and FB/ATK

	BJ			RJ			SA			TA		
Year	**CO_2MV**	**FB at DR**	**FB at R_1**	**CO_2MV**	**FB at DR**	**FB at R_1**	**CO_2MV**	**FB at DR**	**FB at R_1**	**CO_2MV**	**FB at DR**	**FB at R_1**
2027	-3.7	-4.3	-4.1	-7.4	-7.6	-6.8	-13.3	-12.2	-11.5	-10.3	-9.9	-9.0
2037	-14.8	-13.4	-13.1	-19.9	-19.1	-17.8	-25.4	-21.9	-21.6	-23.7	-22.7	-21.0

Calculated at Nominal Confidence, 50/50 Weighting. FB/ATK at Design Range (DR) and at R_1

Even though there is no account taken of the MTOM change, the striking feature of the comparison in Table 8-9 is the similarity in the numbers, the differences being generally lower than the probable uncertainty in the estimates. For the purpose of comparing improvements to aircraft, it is therefore apparent that using the CO_2 metric or the fuel burn metric (i.e., FB/ATK) is acceptable and the range at which the changes are evaluated (R_1 or design range) is not significant. Table 8-10 compares the current goals, expressed as annual changes for comparison with the goals proposed in 2010. Clearly, the current goals for fuel burn for the SA and TA are generally less challenging than those established in 2010.

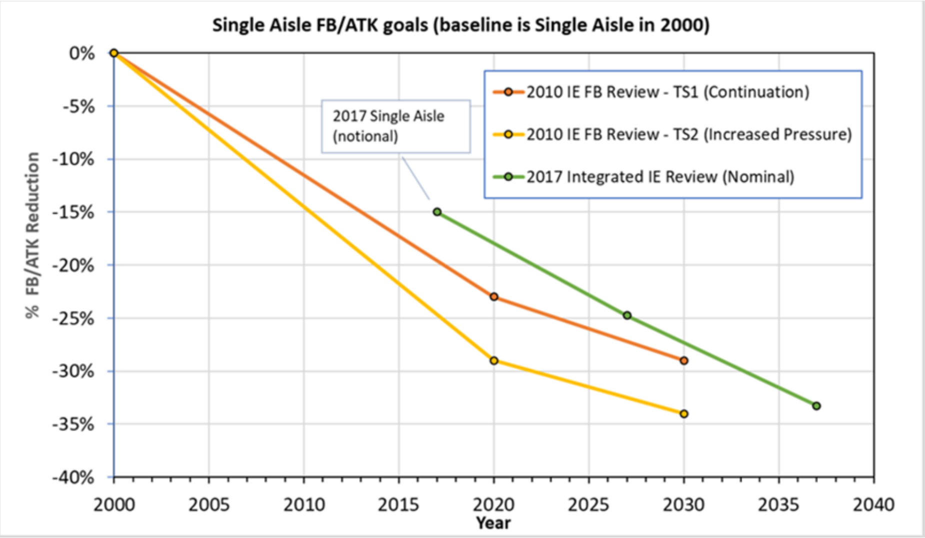
Table 8-10. Current Fuel Burn Goals Compared to Prior Goals

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%

Goals expressed as per annum improvements from 2017

Figure 8-9 compares the current goals for the SA with those made by the Independent Expert Fuel Burn Technology review in 2010. In the case of the SA, the A320-200 (or Boeing 737-800) was used in 2010 and the A320-neo in 2017; there is some agreement that the latter has a fuel burn metric approximately 15% better than the former. The data does not exist to repeat this for the TA. As Figure 8-9 shows, the TS1 of the 2010 IE review, which claimed to be "a continuation of the [then] current trend of improvement", considerably over-estimated the reduction by 2017; whilst TS2, which was used for the goals of the review, was far too optimistic when compared to recent achievements. The goals from the current review continue at about the same gradient as TS1 in its early years. From this, there is no reason to suspect that the present goals lack ambition.



Showing Goals from the 2010 Independent Expert Fuel Burn Review and the Goals from the Current Review

Figure 8-9. Comparison of Fuel Burn Metric with Year for the Single-Aisle

Effect of aircraft class and operational range on the fuel burn metric

By working with differences in the metric values, as in Table 8-9, important dependencies are obscured. The CO_2 MV does not depend on the range or the payload, but the fuel burn metric explicitly does. The values of fuel burn metric (kg-fuel/ATK) for the 2017 TRA (Table 8-6) are as listed in Table 8-11. Since the amount of CO_2 emitted is proportional to the amount of fuel burned, the fuel burn metric does provide one way to assess damage to the environment, whilst the denominator in the fuel burn metric is the benefit gained, specifically the mass payload times the distance carried.

Table 8-11. Fuel Burn Metrics (FB/ATK) at Two Ranges for the Four TRAs in 2017

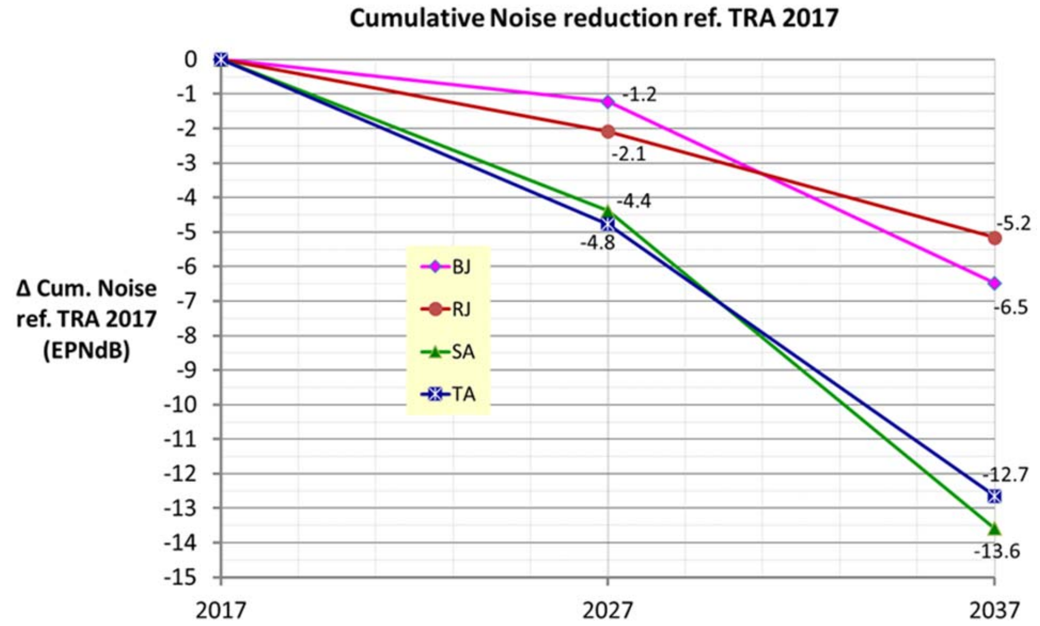
	BJ	RJ	SA	TA
Design Range	0.632	0.158	0.147	0.190
R_1 Range	0.343	0.146	0.125	0.126

Two features stand out from Table 8-11. One is the high values for the BJ, which is predominantly because of the long design range (7500 nm) demanded by the BJ market and low payload (8 passengers at 102 kg each). The other notable feature is the large impact of range on the fuel burn metric, shown when range is increased from R_1 to design range. This is consistent with the proposals of the Independent Expert Fuel Burn Technology review in 2010. The effect of range is particularly noticeable for the two long-range planes, the BJ and the TA. When the range flown for the TA aircraft is increased from R_1 (about 6000 nm) to design range (8100 nm) and the mass payload reduced, the fuel burn metric increase is 51%. This can be put in context by comparing the currently proposed 2037 fuel burn goal for the TA, which is 1.28% per annum, with the increase in fuel burn of 51%. This is equivalent to about 32 years of improvement and in considering the impact of aviation on climate change, the impact of long-range flights should be included. The importance of considering range is also apparent in Table 8-11 where the R_1 fuel burn metric for the SA is marginally lower than the TA metric, even though L/D used in the modelling in 2017 is significantly much for the SA.

8.4 NOISE GOALS FROM THE MODELLING AND THE HISTORICAL DATA BASE

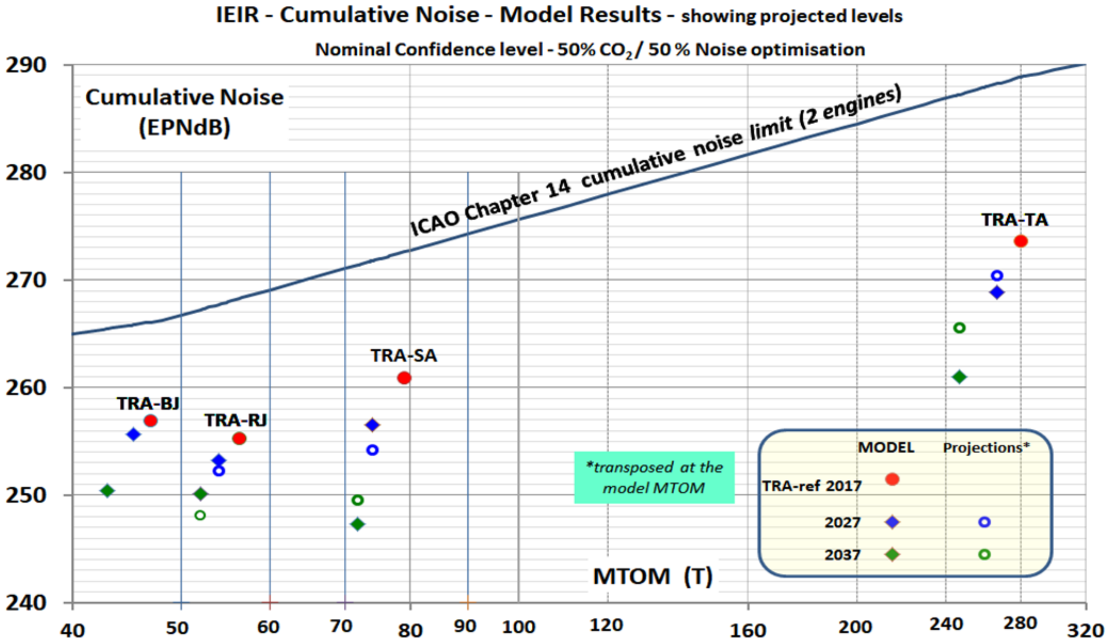
The modelling, described in Chapter 7 and discussed in the context of fuel burn earlier in the present chapter, has provided estimates for noise. The predicted noise reductions for the optimized aircraft are shown in Figure 8-10. These are all at nominal confidence with the 50% fuel burn/50% noise weighted optimization. The results for noise (cumulative EPNdB) and the MTOM are shown in Figure 8-11 together with the Chapter 14 noise limit. In Figure 8-11, the results of the modelling for the four 2017 TRAs are the red symbols whilst the diamonds are the EDS outputs for the 2027 aircraft and the 2037 aircraft. For each aircraft, the noise levels incorporated the shift equal to the difference between noise levels for TRA and the noise levels for the optimized 2017 aircraft to allow comparisons on a consistent basis. This follows the same rationale in the previous section for fuel burn. The smaller open symbols are the projected goals, as defined in Chapter 6, and shown here for comparison. They are only provided for TA, SA and RJ aircraft classes; being derived from the goals previously established by IER2, which did not include BJ aircraft. The projections are shown transposed to the MTOM values corresponding to the aircraft take-off masses predicted by the model for 2027 and 2037 using the 67 log MTOM relationship defined in Chapter 6.

In Table 8-12, the noise levels from the modelling and the projected noises are compared. The results are expressed as cumulative EPNdB - again corrected to allow for the difference between the actual TRA and the optimized 2017 aircraft. The projected values correspond to the values of MTOM derived from the modelling, as defined above. The margins for the projected noise are calculated with respect to the ICAO Chapter 14 noise limit, at the same values of MTOM. Similarly, the noise margins from the EDS modelling are referred to the Chapter 14 line at the same value of MTOM. The model used to calculate fuel burn and noise includes detailed technology inputs, notably those associated with the different noise components. The model also includes variation in design parameters which have allowed design space to be opened. The modelling methodology, therefore, captures the indirect compounding effects such that lower drag and engine SFC lead to a mass reduction and a performance improvement in general.



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

Figure 8-10. Reductions in Cumulative Noise for the Four Optimized Aircraft Relative to the TRA



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

Figure 8-11. Cumulative Noise versus MTOM. Model Results and Noise Projections

In comparing the noise estimates from the EDS model with the projected levels, it must be appreciated that the underlying approaches are quite different. The projected levels were derived from previous goals (i.e., IER2), overall cumulative noise improvement gradients, current trends, and estimated future improvement gradients; their role was primarily to provide a plausibility check on the modelling results. The EDS model is, as explained above, much more detailed and rigorous. The differences between the modelled and projected margins in Table 8-12 are generally small, for all aircraft classes, in both 2027 and 2037. The differences in the noise margins between model numbers and projected levels stay within a range of ±2.5 EPNdB, except in the case of the TA in 2037, for which the margin difference is +4.6 EPNdB. The uncertainty bands for the projected levels were estimated in Chapter 6, to ±5 EPNdB in 2027 and ±6 EPNdB in 2037, so the agreement is satisfactory and the use of the modelling to determine the goals is supported.

Table 8-12. Noise Summary: Comparison of Model Results with Projections

EIS Date	Cumulative Noise and Margins (EPNdB)	BJ	RJ	SA	TA
2027	Cum Noise (Model)	255.7	253.2	256.5	268.8
	Noise Margin (Model)	10.2	14.5	15.3	19.4
	Cum Noise (Projection)		252.3	254.2	270.5
	Noise Margin (Projection)		15.5	17.6	17.8
2037	Cum Noise (Model)	250.4	250.1	247.3	261.0
	Noise Margin (Model)	15.0	17.1	24.1	26.3
	Cum Noise (Projection)		248.1	249.6	265.6
	Noise Margin (Projection)		19.1	21.8	21.7

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

Noise Goal – Recommendations

Based on the above, it is recommended that the noise levels calculated by the EDS modelling effort at the nominal confidence level and the optimized weighting of 50% fuel burn/50% noise should be used as future noise goals for 2027 and 2037. The goals are listed in Table 8-13 for the four classes of aircraft, as cumulative noise margins versus ICAO Chapter 14 noise limit. The 2017 TRA margins depicted in italics are listed for comparison purposes only; they are not goals.

Table 8-13. Noise Goals Expressed as EPNdB below Chapter 14 Noise Limit

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

In Chapter 6, it was pointed out that specifying noise goals for specific types of aircraft may not be the best approach. Using specific aircraft types differs from the approach for other goals derived from Independent Expert reviews: fuel burn has been specified against MTOM and NO_x against OPR. A complication with the approach used for noise comes with the increase in RJ size - so that there is an overlap in MTOM with the SA. Also, another class of aircraft might be introduced between the SA and TA. It is therefore suggested that ICAO/CAEP/WG1 consider reviewing the manner in which noise goals will be specified in future, perhaps choosing a line defining cumulative noise as a continuous function of MTOM; in other words, setting the goal along a line underneath the line defining the Chapter 14 noise regulatory level.

8.5 INTERDEPENDENCIES: FUEL BURN AND NOISE

The process of optimization, where the balance is shifted between FB/ATK (effectively CO_2) and noise, allows an assessment of the interdependence of these metrics due to the design parameter variability outlined in Chapter 7. The trade-offs are not altogether consistent across the classes of aircraft and depend on the starting position of the TRAs and the sensitivity of the particular aircraft to the technologies and the design parameters. This is very clear from the Pareto plots in Figure 8-1 to Figure 8-4. Tables 8-14 through 8-17 show changes in fuel burn metric and noise as the weighting of the optimization is changed from 100% fuel burn to 100% noise. The changes are noted relative to the 50% fuel burn/50% noise optimized point.

Table 8-14. Variation with Optimization of FB/ATK and Cumulative EPNdB for BJ

Year	Optimization weighting	% FB/ATK	Δ EPNdB
2017	100% FB	0.00%	0.00
	50/50	0.00%	0.00
	100% Noise	4.37%	-0.25
2027	100% FB	0.00%	0.00
	50/50	0.00%	0.00
	100% Noise	4.47%	-0.34
2037	100% FB	-0.02%	0.02
	50/50	0.00%	0.00
	100% Noise	8.60%	-0.81

Model Optimization for Nominal Confidence at the 50% fuel burn/50% Weighting, Performed at R_1 for 2017 TRA. Change in FB/ATK reported at the design range.

Table 8-15. Variation with Optimization of FB/ATK and Cumulative EPNdB for RJ

Year	Optimization weighting	% FB/ATK	Δ EPNdB
2017	100% FB	0.00%	0.06
	50/50	0.00%	0.00
	100% Noise	2.32%	-0.14
2027	100% FB	-0.14%	0.96
	50/50	0.00%	0.00
	100% Noise	3.12%	-0.22
2037	100% FB	-0.29%	1.40
	50/50	0.00%	0.00
	100% Noise	8.01%	-1.10

Model Optimization for Nominal Confidence at the 50% fuel burn/50% Weighting, Performed at R_1 for 2017 TRA. Change in FB/ATK reported at the design range.

Table 8-16. 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% Weighting, Performed at R_1 for 2017 TRA. Change in FB/ATK reported at the design range.

Table 8-17. 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% Weighting, Performed at R_1 *for 2017 TRA. Change in FB/ATK reported at the design range.*

For each of the four aircraft under consideration for the goal setting, it is evident that the fuel burn and noise are affected very differently as the optimization weighting is altered, both for 2027 and 2037. When fuel burn is optimized, very little change in the cumulative noise is observed relative to the 50/50 weighting. However when noise is optimized, there is a large degradation in fuel burn, especially for the 2037 scenario, but with only a modest reduction in noise, in most cases less than 1 EPNdB, relative to the 50/50 weighting. This is a clear indication that weighting the optimization close to minimum fuel burn or CO_2 is fairly satisfactory for noise, but optimizing for minimum noise can be seriously detrimental for fuel burn.

8.6 GENERAL REMARKS ON GOALS AND IMPLICATIONS: FUEL BURN AND NOISE

It can be observed in Figures 8-5, 8-6 and 8-10 that the gradients in improvement are markedly lower for BJ and RJ aircraft than for the larger SA and TA, particularly significant for noise. This reflects the combined effects of specific constraints, such as engine diameter and limitations and non-scalable technologies associated with smaller vehicle size. The IEs did not challenge the more restricting constraints offered, particularly for the BJ. Nor was there serious discussion of the smaller gains which it was claimed were to be had from technology for smaller aircraft. It should be noted as well that there is a wide range of vehicle sizes in the BJ and RJ aircraft classes, so the smaller aircraft may diminish potential gains attributable to the whole class.

The IEs estimate that the fuel burn, CO_2 MV, and noise reductions for SA and TA aircraft, shown in Figures 8-5, 8-6 and 8-10, are ambitious, especially for 2037, and will require dedicated, intensive and coordinated research and development efforts in all domains. As noted earlier, the benefits for the SA are based on the assumption of an all new airframe for the SA class of vehicle, since this is judged on the evidence available as necessary to have airframe aerodynamic performance anywhere near that of the TA. If the BJ and small RJ aircraft are to achieve improvements comparable to the SA and TA, appropriate research and development addressing their specific challenges is needed to avoid further unwanted divergence in future aircraft environmental performance compared with larger aircraft.

8.7 GOALS FOR EMISSIONS

As stated in Section 8.2, the EDS modelling did not show a large NO_x interdependency because of limitations for combustion in the model. The NO_x goals are therefore based on the considerations set out in Chapter 5, i.e.:

- A new 2027 MT LTO Goal should be set at 54% below CAEP/8 at OPR=30.
- To cover the entire OPR range, the equation $D_p/F_{oo} = 5.75 + 0.577*OPR$ is to be applied.

- To ensure environmental benefit when meeting the goal, there are no goal bands and the goal is met only when the 50th engine of a single goal-compliant type enters service.
- Any further consideration of LTO NO_x goals, including goals for 2037, must be based on a methodology for combustors in which emissions alter strongly with T_{40}.

In addition, the EDS modelling did not attempt to model nvPM emissions, due in part to the lack of robust methodologies and to the lack of technologies to reduce nvPM directly. As set out in Chapter 5, the setting of nvPM goals at this time appears neither practicable nor necessary.

CHAPTER 9. **ADVANCED ALTERNATIVE AIRCRAFT**

9.1 INTRODUCTION

Previous chapters focussed on the projected improvement of today's conventional (tube and wing) configuration while noting the increasingly difficult challenges associated with improving highly optimized modern aircraft and engines. This chapter focuses on alternative aircraft configurations as a potential pathway to additional fuel burn and noise reduction. The status of several alternative aircraft configurations currently being researched was presented to the IE's in the April 2017 Washington DC review, and to a lesser extent in the October 2017 Berlin review. Opinions varied amongst the IEs as to the likelihood that any of these configurations could be in service by 2037, though no one disputed that there are significant technical and nontechnical challenges that would have to be overcome before a product launch.

This chapter summarizes the alternative aircraft concepts reviewed. Through 2027, there is no doubt that new business and commercial transport aircraft entering service will remain as a conventional configuration with balanced improvement across all metrics and meet market requirements. There is neither enough time nor planned investment to allow alternative concepts to reach TRL8 by 2027. By 2037, it is highly likely that conventionally configured business and commercial transport aircraft will incrementally improve and remain the dominant configuration. But given the suite of technologies that enable alternative configuration concepts, their current state of development, and the time remaining to reach TRL8 for entry into service by 2037, it is within the realm of the possible that an alternative configuration can be developed and compete with conventional configurations. This is not easy and is far from a certainty, but with the right drivers and sufficient, timely investment, it is possible we could see change not so much different from what we experienced 60 years ago with the emergence and convergence of swept wings and jet propulsion.

9.2 BARRIERS TO CHANGE – REALITIES OF AVIATION MARKETS

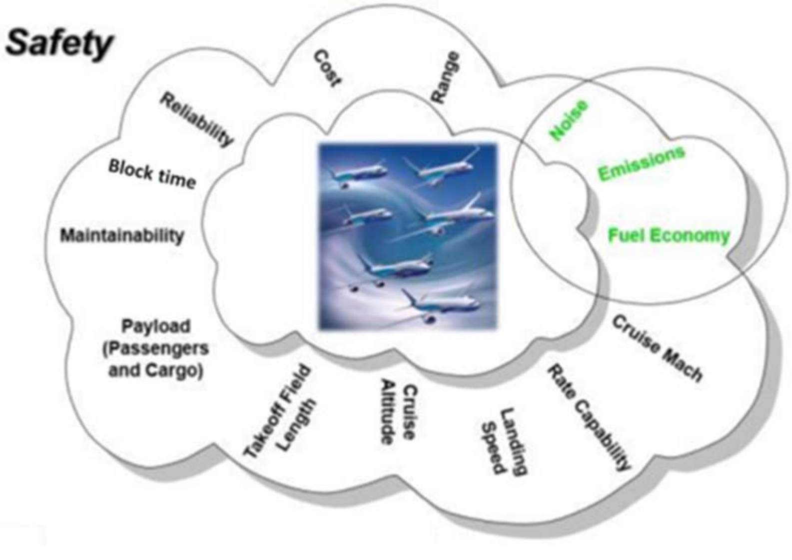
Change is never as easy as it sounds or looks on paper. Entry into and survival in civil aviation markets is hard, both for original equipment manufacturers (OEM) and air service operators. Aircraft are complex, integrated marvels of modern technology. They provide an unmatched capability to transport people and goods safely and economically at high speed over long ranges relative to other modes of transportation. And they are performance guaranteed and sold by OEM's to initial operators before detailed design, build, or certification. When do you launch a new product? Can you confidently meet operator and society requirements? How much risk are you willing to take? And for what potential reward? These are business decisions made by business leaders in a complex, high technology market place. A new or derivative aircraft product decision is based on the convergence of technology readiness, market and regulatory requirements, resource availability and financial viability. If one dimension is missed, then there is no product opportunity. If the benefits or associated risks are substantially under-estimated, the consequence is a potential loss that can threaten the company's future.

Aircraft design implies a subtle and complex balance of interdependencies and trade-offs. Figure 9-1 recalls general requirements and objectives for a product launch decision. First and foremost, there can be no compromise to safety (air transport safety is the gold standard). Accompanying safety, life-cycle economics is an inherent driving factor and includes non-recurring and recurring costs through design, build, certification, operations, maintenance, and end of use trade-in or disposal. And the aircraft must meet mission capability and performance requirements. When considering a new structural concept that offers the benefit of reduced weight and lower fuel consumption for example, one must also consider, among other factors, how it will be cost-effectively mass produced at a high rate.

Most of the advanced technologies discussed in previous chapters are broadly applicable to conventional and alternative aircraft configurations but some technologies uniquely enable specific alternative aircraft configurations. The challenge is that while new technologies bring benefits in one or more areas, the benefits must come without degrading other system-level aspects compared to previous generation aircraft. The same holds for conventional and alternative configurations; the alternative configuration itself must improve as many system-level aspects as possible without degrading others, as compared to an equivalent technology conventional configuration. The introduction of an alternative aircraft configuration only adds uncertainty and risk because of the unknowns.

Why is it so difficult to introduce new aircraft products to the market – whether advanced conventional or potentially alternative? The bottom line is economic risk - a multi-billion-dollar investment relative to potential benefits with some level of uncertainty. The decision process includes many dimensions to assess readiness and inform the necessary business decisions. Aircraft, and their major systems, subsystems and components, start at a conceptual level and mature to the point of confidence in applicability to given system requirements. Key aspects that must be fully addressed include technology readiness levels and many so-called "ilities," some of which are briefly characterized as follows:

- Manufacturability addresses the ability to cost-effectively produce the aircraft at high quality and rate.
- Integratability addresses interfaces and interactions between technologies and systems throughout the aircraft.
- Affordability addresses the development and production costs relative to a projected price dependent on guaranteed aircraft performance.
- Certifiability addresses the definition of a technical and cost-effective path to certification approval by relevant regulatory agencies.
- Reliability, sustainability (including the environmental aspects), and maintainability address relevant requirements and meeting customer expectations in service, which impact economics.
- Operability addresses the ability for in-use operations within the vehicle system, and within the broader system of systems (fit and compatibility with the air traffic system, airport/servicing, etc.).
- Stakeholder acceptability addresses the ability of financial investors, OEM's, regulators, operators, and the public to accept new technology in all ways (business and technical risk, disruption of development/production process, confidence in cost estimates, potential benefits, and schedule, willingness to buy a ticket).



Source: ICCAIA, Carnelly, DC IEIR Workshop, April 2017

Figure 9-1. Interdependencies and Trade-offs

All dimensions must be addressed for a new technology or system to buy its way on an advanced conventional or alternative configuration. Less risk is associated with established or known technologies and systems. For a truly disruptive technology or system concept, the uncertainty levels and lack of prior experience will very likely drive a necessary but not sufficient requirement for large-scale, integrated technology flight demonstration. The case where an alternative configuration itself is the disruptive "technology" will point to an X- or Y-plane type demonstration, as in military development programs. This is akin to Boeing's 367-80 in the 1950s which could have been a military transport or tanker, but in fact led to the Boeing 707. Such a demonstration would require significant investment and associated risks on its own but would very likely be necessary to demonstrate benefits and readiness in the broadest sense before any business decision to launch a new product could be made. Looking back to the dawn of the jet age, several drivers of change are evident. First, the driver for a disruptive technological change will be economic, although not necessarily driven by efficiency. After the end of World War II, all the civil transport aircraft were derivative developments of ex-military transports powered by either radial or inline piston reciprocating engines, typical of which was the Douglas DC 7C. Reciprocating engines were highly evolved, efficient, and affordable, but complex and costly to maintain due to high frequency need of overhaul.[88] Perhaps the most interesting and least broadly remembered driver of the change was that the new, relatively simple turbojet significantly reduced high maintenance costs while accepting a significantly higher fuel consumption at that time.

The second key enabler for disruptive change was substantial financial investment and acceptance of associated risk. After Boeing gained experience developing the government-funded B47 and B52 to meet military requirements, they bet two-thirds of their post-war net profits to produce the 367-80 prototype[89] for the KC-135 and the B707. The next significant change was driven by government-funded competition for a new military freighter in the USA. Lockheed ultimately won the competition for the C5A but in looking to salvage something from their efforts, Boeing invested, developed, and introduced the twin-aisle, four-engine, wide body B747-100 in 1970. Later, built on a pan-European-funded effort to consolidate and increase European presence in commercial aviation, Airbus introduced the A300 as the first twin-aisle, twin-engine aircraft in 1974. Although originally conceived as a short-range aircraft, this configuration has now become the norm for long-range aircraft configurations. It is economics which drives disruptive change in commercial aviation.

9.3 POTENTIAL ALTERNATIVE CONFIGURATIONS

Even with all the known and potentially unknown barriers and risks, research and development into alternative configurations has continued around the world with increasing emphasis and investment over the last decade. This was evident at the Washington DC. IE review in presentations by Bonet, Yutko, Martin and Page who discussed NASA, US Air Force, FAA, and industry investment in specific alternative configurations, including recent detailed vehicle system level requirements definition contracts for large-scale x-plane demonstrators completed in 2017. Previous chapters focus on advanced technologies as applied to advanced conventional configurations, with several having the potential to introduce a step change and shift curves off historical trends (e.g. natural laminar flow, hybrid laminar flow control, folding wing tips to extend span). Many of these technologies are already buying their way on aircraft in a practical, incremental manner with future incremental benefits discussed in previous chapters. These technologies are generally applicable to alternative configuration concepts as well. The question for this section is if there are alternative configuration concepts that enable step changes to new levels of noise, emissions, and fuel burn beyond that projected for conventional configurations. Are there key enabling technologies or integrated systems previously unavailable that enable the alternative configuration? Do the alternative configuration concepts lead to a balanced design

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[88] D.I.A. Poll: "21st Century civil aviation: Is it on course or is it over-confident and complacent? – thought the conundrum of aviation and the environment," The Aeronautical Journal, Volume 121, No. 1236, February 2017.

[89] http://www.boeing.com/history/products/model-367-80.page

when considering all dimensions? Could intermediate steps or mixed concepts exist between conventional and alternate designs? Even if an alternative concept is technically practical, will the operators and their customers accept the changes? And overall, are the projected benefits worth the associated risks, both technical and financial? The answer to many of these questions may be yes; with caveats. But on the question of acceptable risk the answer is presumably no, since an OEM has not yet committed to launch an alternative configuration product. More must be done to reduce associated risks.

There are alternative configuration concepts that offer step change benefits, each relying on key emerging technologies and/or integration concepts, and each with key barriers to overcome. The state of research and development varies for each concept, but primary barriers have been identified, and to varying degrees are being addressed beyond paper studies. Three classes of alternative aircraft configurations that have potential fuel burn benefits of 5-15% relative to the conventional configuration at an equivalent technology level were highlighted during the IE reviews: the hybrid wing-body, the truss-braced wing, and the double-bubble with aft-integrated BLI propulsion. The potential fuel burn benefit is obtained through the configuration change, which to varying degrees also enables simultaneous step changes in noise reduction on the order of 10 EPNdB cumulative from the best tube and wing configuration.

The estimated improvements stated below rely on various existing studies that each use self-consistent modelling and simulation toolsets to compare well-understood baseline conventional configuration aircraft models with advanced conventional and alternative configuration concepts at equivalent technology levels; this approach enables isolation of the configuration change benefits. Additionally, engine architecture (i.e. direct-drive or geared) is held at equivalent levels between conventional and alternative configurations. As such, the incremental quantities given below are representative of the potential benefits due to the alternative configurations. To varying degrees, the studies below are informed by hardware and experimental tests to reduce uncertainties. It is important to recognize that there remain significant challenges to be addressed, and benefits are likely to decrease as the configurations are refined and incorporate more practical requirements and necessary trade-offs, with higher fidelity.

9.3.1 Hybrid Wing Body

The hybrid wing-body (HWB) class is a fixed-wing aircraft with no clear external dividing line between the wings and the main body of the aircraft; external surfaces; internally, it is composed of distinct wing and body structures. The HWB has a lifting body and is distinctly different from the earlier, older Flying Wing class configuration that has no distinct fuselage. HWB configurations may or may not be tailless, and generally install the propulsion system on the upper surface, which also enables noise reduction through acoustic shielding. The HWB shape effectively blends volumetric and wetted area advantages for aerodynamic efficiency benefits and, though often sized to fit existing airport gate constraints, tends to fully optimize performance with a larger span that would benefit from folding wing tip technology. The cross-sectional area distribution can be nearly ideal for low transonic drag, and the more uniform distribution of loads provides structural weight benefits. Three primary HWB-variants are shown at the top of Figure 9-2. On the left is the Boeing Blended Wing Body (BWB) concept with over-the-body pylon-mounted nacelles, whilst on the right is the Lockheed Martin Hybrid Wing Body (HWB) concept with tail and over-wing pylon-mounted nacelles. Dzyne's tailless BWB concept with flush-mounted nacelles with boundary-layer diverter in front of the inlets is shown just below the Boeing and Lockheed Martin concepts. The four images at the bottom in Figure 9.2 illustrate a HWB concept corresponding to the "AHEAD" European research project launched in the context of the EU Framework Programme FP7 (2007-2013), led by TU Delft[90,91], targeting blended wing body aircraft carrying 300 passengers. This "AHEAD" program also has novel propulsion, a multi-fuel

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[90] Clean Sky presentation M.Goulain – IEIR Berlin workshop – October 2017

[91] "AHEAD" (Advanced Hybrid Engine Aircraft Development): collaborative project of TU Delft University in the Netherlands, with support from the European Commission and in collaboration with Airbus Group Innovations, engine manufacturers MTU Aero Engine, and WSK Reszov, EASA, and KLM - refer to http://www.ahead-euproject.eu/

engine using hydrogen and biofuels, and a dual hybrid combustion system with a low NO_x cryogenic combustor. The engine also has bleed cooling by cryogenic fuel and a contra rotating fan with boundary layer ingestion (BLI) capability.

The Boeing BWB configuration concept is the most studied and developed of all the alternative concepts. Conceived in the 1980s, research and development began in the 1990s and continues today. The origins, potential benefits, and key challenges are well described by Liebeck[92]. The key benefit comes from the configuration's high span/low wetted area, yielding high aerodynamic efficiency with L/D typically above 24, dependent on specific mission and design trades. Key technical challenges identified early on included transonic propulsion-airframe integration, weight of the damage-tolerant noncircular pressure vessel, low-speed flight dynamics and control, ride quality, passenger acceptance, airport compatibility, and emergency egress. Passenger acceptance discussion centers on ride quality and window availability. Liebeck notes piloted flight simulator studies that show the BWB "worst-seat" ride quality is no worse than on a B747-400. Liebeck also addresses benefits of the BWB for emergency egress while acknowledging the new class of interior will require coordination of a new criterion with regulatory authorities. The discussion about passenger acceptability and proximity to windows focuses on the acceptability of virtual windows via video display, an approach that appears to become more acceptable as time goes by. Transonic designs have been validated in a transonic wind tunnel at near full-scale flight Reynolds number for flush and pylon-mounted nacelles. Low speed flight dynamics and control were thoroughly explored and demonstrated to be practical using extensive flight tests of the Boeing/Cranfield/NASA remotely-piloted X-48B aircraft. A lightweight, damage tolerant, stitched/resin-infused composite technology was developed from coupon scale to an 80% full-scale[93] pressurized multi-bay structure, culminating in a test to failure well beyond design limits. The BWB's upper surface propulsion system integration offers the opportunity to reduce noise through shielding and extensive acoustic analysis has been validated with ground tests in subsonic wind-tunnel tests. The X-48B was modified to a twin-jet, lower noise configuration X-48C which has completed low speed flight dynamics and control flight tests without any surprises. Additional extensive low-speed operability tests for off-nominal flight conditions have been completed in a series of powered ground tests in subsonic wind tunnels.

Over the years, the BWB concept has been sized for a variety of civil and military missions with most focus in the 300-450 passenger classes. The benefits of the BWB are characterized below using aircraft modelling studies reported by NASA's Environmentally Responsible Aviation (ERA)[94] Project, wherein a suite of advanced technologies was applied to a range of aircraft missions. For the 301-passenger large twin-aisle mission, the study used a 2005 best-in-class baseline aircraft (representative of B777-200LR/GE90-110) to compare an advanced technology conventional configuration and equivalent technology BWB configuration. Results of the systems analysis indicate the BWB fuel burn benefits are 45 - 47% below the baseline and 10-11% lower than an advanced conventional aircraft with equivalent airframe and propulsion system technology assumptions. Similarly, BWB noise benefits are 18-20 EPN dB cumulative below an equivalent advanced technology conventional aircraft and 31-33 EPN dB cumulative below ICAO Chapter 14. Propulsion-airframe aeroacoustic effects were identified as the single largest differentiator yielding an over 10 EPN dB cumulative benefit for the BWB configuration compared to the equivalent advanced technology conventional configuration. The top of climb L/D for the BWB in this study was 23.7 compared to 22.0 for the advanced conventional configuration. Although the ERA studies were targeting challenging noise, emissions, and fuel burn goals simultaneously, BWB design experience has shown that a

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[92] Liebeck, R.H.: "Design of the Blended Wing Body Subsonic Transport," AIAA Journal of Aircraft, Vol. 41, No. 1, January-February 2004, p. 10-25

[93] The 80%-scale multi-bay section of the noncircular pressurized centerbody was 30 x 14 x 10 feet, pressurized and tested under combined loads. See reference by Jegley et al (NASA TM- 2016-218972)

[94] NASA ERA goals were to simultaneously achieve a 50% fuel burn reduction relative to 2005 best in class, a 42 EPN dB cum noise reduction relative to ICAO ChapterFAA Stage 4, and a 75% LTO NOx emissions reduction relative to CAEP6. Results were summarized in presentations at IEIR review in Washington DC, April 2017, with further detail referenced in papers by Nickol, et. al. (AIAA-2016-1030) and Thomas et al (AIAA-2016-0863).

trade of noise for additional fuel burn benefit on the order of a few per cent is possible through changes in nacelle location.

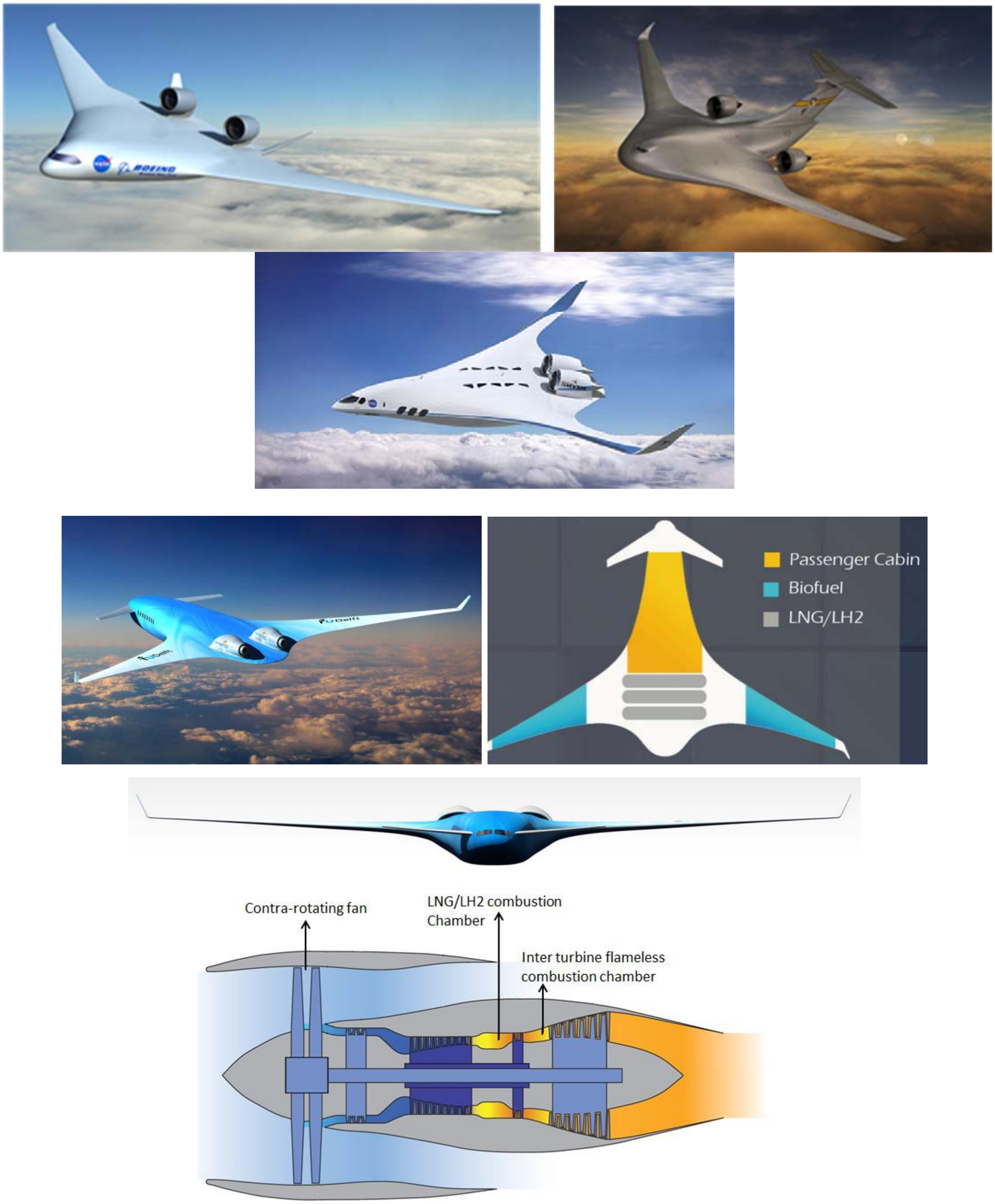

Figure 9-2. Hybrid Wing Body Concept Variants

The Lockheed Martin HWB concept in the top right of Figure 9-2 has been the subject of research and development since 2009 when it originated as part of an US Air Force Research Laboratory study[95] targeting future strategic and tactical military mobility missions. This HWB-variant has an over-wing nacelle installation and is further distinguished from the Boeing BWB by an empennage. Key technical challenges are generally similar to those described above (drag, weight, and low speed flight control) but with configuration-unique transonic propulsion-airframe integration challenges. Transonic, high Reynold's number wind-tunnel tests have validated cruise aerodynamic benefits of this configuration. Powered, low-speed flight dynamics and control tests to date have not shown issues, and an initial structural design and analysis shows promise, though is not as mature as for the Boeing BWB. Given the dual-use potential of this configuration, a commercial cargo derivative study was sponsored by NASA[96] and focussed on comparisons with advanced technology conventional configurations for B757F and B777F missions. Results show potential fuel burn benefits over 34% compared to the 2005 B777F-derived baseline and over 7% reduction compared to the equivalent advanced technology conventional configuration. For reference, the design L/D of this HWB is 22.4, compared to 20.9 for advanced conventional configuration in this study. Given the more recent interest in a commercial derivative, acoustic evaluations are just beginning; early analysis show benefits due to engine shielding but not to the extent of the Boeing BWB concept.

The Dzyne BWB concept[97] (second row from the top of Figure 9-2) was first unveiled in 2016 and is similar to the Boeing BWB concept in many ways, but targets smaller vehicles ranging from a large BJ through SA aircraft where previous BWB concepts have not been feasible. The key differentiating innovation is a novel landing gear design and placement that promises the first feasible single-deck BWB (previous feasible BWB designs have been limited to larger vehicles due to the necessity of a double-deck arrangement). Otherwise, the extensive technology and knowledge developed for the larger double-deck BWB's is directly applicable. Though the enabling landing gear concept remains to be demonstrated, it may be the key to unlock BWB concept fuel burn and noise benefits across all seat-classes.

9.3.2 Transonic Truss-Braced Wing

The truss-braced wing technology concept is not new; the idea has been around for decades and has been applied to low-speed aircraft. The technology has also been studied on many transonic transport aircraft concepts since 2008[98] and has led to focussed research with key tests to address the most significant uncertainties and refine design benefits. The truss-braced wing enables a substantial span increase without the typical weight penalty through coupled aero-structural design, thereby reducing induced drag to yield a net fuel burn benefit; wing aspect ratios in balanced designs approach 19-20. Given the large span, it will require folding wingtips in order to meet existing gate constraints. The relatively short chords and lower sweep are more compatible than current aircraft with natural laminar flow design. Figure 9-3 shows a SA concept aircraft incorporating the transonic truss-braced wing (TTBW) technology. The high-wing configuration provides ample room to integrate future large diameter turbofan engines as well. Initial concept designs had significant uncertainty in wing weight due to unknowns around aeroelasticity for the long thin wing. High fidelity finite element models of the structure were created and aeroelastic assumptions verified in tests in a transonic dynamics tunnel to verify weight estimation methods.

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[95] Hooker, J.R.; Wick, A.: "Design of the Hybrid Wing Body for Fuel Efficient Air Mobility Operations," AIAA 2014-1285, January 2014

[96] Hooker, J.R.; Wick, A.T.; and Hardin, C.J.: "Commercial Cargo Derivative Study of the Advanced Hybrid Wing Body Configuration with Over-Wing Engine Nacelles," NASA CR-2017-219653, November 2017

[97] Yang, S.L.; Page, M.A.; and Smetak, E.J.: "Achievement of NASA New Aviation Horizons N+2 Goals with a Blended-Wing Body X-Plane Designed for the Regional Jet and Single-Aisle Jet Markets," AIAA 2018-0521, January 2018

[98] Bradley, M.K.; Droney, C.K.; and Allen, T.J.: "Subsonic Ultra Green Aircraft Research: Phase II – Volume I – Truss Braced Wing Design Exploration," NASA CR-2015-218704, April 2015

A second key uncertainty is associated with the aerostructural design at the juncture of the TTBW, something absent on a cantilever wing. A high fidelity aerodynamic design was tested and validated in a transonic wind tunnel, confirming the ability of modern CFD to handle the novel shape. Initial designs focussed on cruise Mach numbers in the range of 0.70 to 0.75, but promising ongoing designs are focussed on Mach 0.80. Although the TTBW concept is presented as an unconventional configuration, it comes with a substantially lower risk than other configurations described here. In particular, this configuration is compatible with current fuselage designs. Research now is focussed on the higher cruise Mach number designs, high-lift system integration, buffet prediction (because of the unconventional structural configuration), and other unique challenges such as bird strike on the relatively thin truss structure. The truss-braced wing technology, independent of other advanced technologies, has the potential to provide fuel burn benefits in the range of 8-12% in the regional and single-aisle classes compared to advanced conventional cantilevered wings, depending on cruise speed. Acoustic benefits are similar to those projected for advanced conventional configurations.

Figure 9-3. TTBW technology aircraft from NASA/Boeing N+3 SUGAR

9.3.3 Double Bubble with Aft-integrated Boundary-Layer Ingestion Propulsion

The double bubble with aft-integrated boundary-layer ingestion (BLI) propulsion concept was conceived and initially studied by an MIT-led team including Aurora Flight Sciences and Pratt and Whitney under NASA sponsorship beginning in 2008. Figure 9-4 shows the baseline configuration on the left with a simplified version incorporating a conventional underwing propulsion installation on the right. Early studies focussed on a cruise Mach number of 0.72 for the fuel burn benefit associated with lower speed. Recent focus has been at a more common SA cruise Mach number of 0.78[99]. Although designed for a traditional SA mission, this configuration combines a twin-aisle lifting fuselage with an efficient non-cylindrical pressure vessel, a unique Pi-Tail arrangement, and an upper aft-mounted boundary-layer ingesting propulsion system. System studies of the integrated baseline configuration show potential fuel burn reduction of up to 13% compared to an equivalent technology level SA aircraft. As with the BWB, engines are mounted above the fuselage, however further acoustic analysis is required to assess the potential shielding benefits and unknown acoustic consequences associated with ingesting the boundary layer. The simplified configuration with underwing engines promises up to 5% fuel burn reduction, and as with the transonic truss-braced wing, acoustic benefits are similar to conventional aircraft configurations.

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[99] Yutko, B. et al.: "Conceptual Design of a D8 Commercial Aircraft,' AIAA 2017-3590, June 2017

There will be certification challenges with the upper aft, side-by-side twin engine placement, and in particular, with the so-called “1-in-20” rule that concerns engine design guidelines to prevent loss of aircraft in the unlikely event of an uncontained rotor failure in an engine. Lord, et.al [100] proposed an engine architecture solution to address this issue, but it would require a new engine to be developed, specifically for this aircraft. Beyond the engine architecture challenge, a key driver in the development of this concept is the need for distortion tolerant fan blades to accommodate the boundary-layer ingestion. Significant research and development has already been undertaken on this concept, including powered low-speed performance tests, low-speed stability and control tests, and detailed design of critical fuselage structural components. Initial transonic tests at cruise and off-design conditions are yet to come.

Figure 9-4. Aurora Alternative Configuration Concepts 2017

9.3.4 Boundary-Layer Ingesting Propulsion (BLI)

Concepts that incorporate BLI propulsion have been around for decades, and the principles are understood. Nevertheless, overall system benefits have not yet been proven to the point of incorporation into a commercial product. Aircraft designers worldwide continue to envision configurations with BLI, well beyond the D8 configuration. Figure 9-5 shows a range of alternative aircraft concepts with BLI having installations resulting in either 180- or 360-degree distortion on the fan. Note that a 360-degree distortion arises when the fan is at the rear of a tubular fuselage whereas 180-degree distortion is from the surface of a lifting surface. Designing a fan to operate efficiently in this severely distorted flow is a significant challenge. There is always some loss in efficiency compared to uniform inlet flow and, in addition, the aeroelastic excitation of the blades must be accommodated with stronger and heavier blades. The improved propulsive efficiency through BLI is also offset by the additional mass required for structural protection against fan inlet distortion, which can increase noise. The first transonic wind tunnel test [101] of an industry-designed boundary-layer ingesting inlet/distortion tolerant fan (BLI^{2}DTF) for civil applications was completed in 2016. NASA incorporated those test results into a system analysis of a variant of the MIT/Aurora configuration concept[102]. Even with a BLI penalty to fan efficiency of 3.5%, a net system-level fuel burn benefit of 5.6% is still realized in this study. While BLI is far from entering service, these high fidelity, experimentally-validated results encourage continued research and development.

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[100] Lord, W.K., et. al: “Engine Architecture for High Efficiency at Small Core Size,” AIAA-2015-0071, January 2015.

[101] Arend, D.J. et al: “Experimental Evaluation of an Embedded Boundary Layer Ingesting Propulsor for Highly Efficient Subsonic Cruise Aircraft,” AIAA 2017-5041, July 2017

[102] Marien, T.V.; Welstead, J.R.; and Jones, S.M.: “Vehicle-Level System Impact of Boundary Layer Ingestion for the NASA D8 Concept Aircraft,” AIAA-2018-0271, January 2018

(Celestina, Berlin IEIR workshop, October 2017)

Figure 9-5. Sample of Alternative Configuration Concepts incorporating BLI during the Last Decade

9.3.5 Electrified Aircraft Propulsion

Over the last decade, the possibility of electrified aircraft propulsion (EAP) has emerged supported by a perceived relative ease of electrical versus mechanical distribution of power around the aircraft. Many of the concepts in Figure 9.5 include at least one electrically driven propulsor, sometimes more. There is a range of EAP systems inclusive of all-electric, hybrid-electric, partially turboelectric, and turboelectric[103]. From a configuration standpoint, the possibility of decoupling energy source/power generation from a propulsor, or a having a single energy source/power generator driving multiple distributed propulsors, is attractive.

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[103] National Academies of Sciences, Engineering, and Medicine. 2016. Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions. Washington DC: The National Academies Press. DOI:10.17226/23490.

Although the benefits are easy to describe, they are not easily achieved[104]. Nevertheless, electrified aircraft propulsion research related activities are expanding, including distributed propulsion and demonstration of integration of hybrid electric propulsion components and architecture[105]. In the 2037 timeframe, the most likely initial application of electrical propulsion on larger aircraft (RJ to SA) could be turboelectric – gas turbines with power distributed electrically to the propulsor, or partially turboelectric where a gas turbine mechanically drives a fan and also has power extracted to drive distributed propulsors. The key feature of the turboelectric approach is that the energy source remains jet fuel and the configuration does not rely on an alternative energy source, like batteries. As the vehicle size and energy requirement drops, the possibility of a hybrid system increases because secondary energy storage via batteries begins to become more viable. But all-electric propulsion systems are not likely even for BJ by the 2037 timeframe. System studies indicate that the partially turboelectric system driving a tail-cone rotor could reduce fuel burn by 7-12%, but much research and development remains to prove this benefit.

9.3.6 Counter Rotating Open Rotor

The counter rotating open rotor (CROR) propulsor concept has been studied in Europe and the US over decades, with surges in research and development aligning with high fuel prices, and less interest when fuel prices are low. Presentations in the Washington DC and Berlin IE workshops touched briefly on the CROR concept. In the EU Clean Sky research project, the CROR propulsion system has been shown to be capable of providing fuel burn improvement over turbofans engines for short- to medium-range aircraft at a negligible speed penalty. The cruise speeds possible with this engine are in the Mach 0.75-0.80 range, typical of today's SA-class aircraft. The EU Clean Sky program led up to a ground test demonstrator campaign by Safran in 2017/2018.

Results presented in the Berlin workshop show potential fuel burn savings for CROR of about 5% (+/-2%) below advanced turbofans at same date of 2037, and to community noise compliant with Chapter 14 with some margin. Recent research in the US, culminating in acoustic wind tunnel tests, showed similar results; specifically cumulative noise levels for the CROR which were 8-10 EPNdB below Chapter 14 noise limits, with advanced ducted fans about a further 7 EPNdB quieter. However, in both European and US studies, the potential benefits are subject to significant uncertainty and critical challenges, such as:

- Blade-off containment, installation and cabin noise treatment will all lead to a weight penalty on the aircraft in comparison to an equivalent technology level under-wing ducted-fan configuration. Estimating these penalties is subject to significant uncertainty.
- The quoted potential improvements, both in terms of noise and fuel consumption, are likely to be significantly reduced due to installation adaptations and trade-offs that will be required throughout the design maturation process, and these effects are also subject to high uncertainty.
- Installation of the engine on the rear fuselage, as most commonly configured, requires an all-new aircraft for which TRL8 achievement in 2037 is unlikely, given today's research programs. It is not clear that the aircraft ML/D will be as high for engines installed on the rear fuselage as it is for the current under-wing installation.
- It is not certain that the acoustic margin versus the Chapter 14 noise regulation will be judged sufficient by the customers, as compared to the quieter ducted fan systems. The rear fuselage CROR installation is mandatory to achieve cumulative noise below Chapter 14, due to the wing upwash when installed under wing.

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[104] Epstein, A.H. and O'Flarity, S.M.: " Considerations for Reducing Aviation's CO_2 with Electric Propulsion," Submitted to the AIAA Journal of Propulsion and Power, 2017

[105] Clean Sky presentation. M.Goulain – IEIR Berlin workshop – October 2017

For these reasons, the IE's felt that the CROR technology was more appropriately acknowledged in this chapter as an alternative concept, and did not judge it appropriate to consider the potential benefits and associated uncertainties in early chapters, nor in the modelling and simulation.

9.4 SUMMARY

Exploring the wide range of alternative configurations, several observations can be made. First, the payload-carrying sections of fuselages remain roughly the same size for a given mission, but the promise of advanced composite materials, structures, and manufacturing enables improved aerodynamics with practical, noncircular pressurized shapes. Second, the trend of increasing aspect ratio with balanced drag/weight considerations continues for conventional configurations and applies to alternative configurations with the potential for a step increase through structural truss bracing. Novel integration, smoothly blending the wing and fuselage together for improved aerodynamics, is enabled by composite structures.

Novel propulsion-airframe integration (PAI) is another common thread which is manifested in many forms. Most alternative configuration concepts continue to use advanced gas turbine engines with larger, lower pressure ratio fans, but the larger size brings the increased challenge of integration under the wing in both conventional and alternative configurations. As a result, many alternative configurations locate and integrate the propulsion system above the fuselage or the wing resulting in noise benefits through acoustic shielding. Some alternative PAI concepts leverage electrified aircraft propulsion systems to distribute propulsors.

There is reason to be optimistic about the potential of alternative configurations to enable step change benefits on the order of 5-15% reduction in fuel burn and approximately 10 EPNdB cumulative reduction in noise beyond an equivalent technology of future conventional configurations projected in earlier chapters. But even with the amount of research and development completed to date, it is very clear that challenges and legitimate questions remain before business leaders will have the confidence to risk the future of a company on an alternative configuration. It is conceivable that the potential benefits of an alternative configuration and the magnitude of differences from today's conventional configuration will lead to a large-scale transonic flight demonstrator to fully gain stakeholder confidence for either military or commercial missions. Whilst it is just possible that an unconventional aircraft could be ready for commercial airline service in 2037, time is short and expensive risk mitigation research would need to begin very soon.

CHAPTER 10. ADDITIONAL CONTRIBUTIONS TO AVIATION IMPROVEMENT

10.1 INTRODUCTION

Previous chapters have looked at the application of new technology to the design of aircraft and powerplants to reduce fuel burn, emissions and noise. Opportunities have been identified and quantified, but technological progress appears to be getting slower. For example, the rate of improvement in temperature capability of metals is much lower now than in the early days of the high-bypass engines.

During discussions amongst the IEs, there was frequent reference to benefits from doing things differently, even with today's technology, in other words operating the aircraft or the air transport system slightly differently to increase or augment the benefits arising from technology alone. In order to avoid confusion, the IE's decided to keep the focus of earlier chapters entirely on technology, but to have this chapter near the end of the report.

This short chapter can be summarized along the following lines. To mitigate environmental damage the industry should not just look to advanced technology, for which the opportunities are not unlimited. The industry has to consider alternative design choices and operational approaches in addition to new technology. In some cases, operational changes can be made with existing aircraft; in other cases, they require aircraft to be redesigned but do not require new technology. The chapter is divided into four brief sections on climate change, emissions, air quality, and noise.

10.2 CLIMATE CHANGE

The 2010 IE Fuel burn technology review identified technologies which would lead to significant reductions in fuel burn if fully implemented. They also quantified the gains which could arise from designing the aircraft for a less challenging duty. Beginning with the 787-8, a redesign was carried out at Stanford University using the Program for Aircraft Synthesis Studies. The cruise Mach number was reduced from 0.85 to 0.76 and the maximum-payload range (R1) from 5750 nm to 4312 nm. In addition to benefits from introduction of new technology, these changes to aircraft mission specifications yielded another 7% reduction in fuel burn (measured as kg-fuel/ATK) in the medium-term and 5% in the long-term (which was to 2030). Flying slower is also helpful in enabling natural laminar flow through reduced wing sweep angles, but these benefits must be weighed against difficulties with passenger acceptance and reduced revenues. Moreover, there has been some discussion of reducing cruise altitudes in conjunction with decreased speeds in order to reduce NOx and contrail impacts, while retaining the fuel burn benefit. However, this could have important negative implications on passenger acceptance and air traffic management.

Another operational change that can reduce fuel burn that has been discussed for some time is multi-stage long-distance travel. This involves replacement of long nonstop flights with multi-stage flights enabling refuelling. With reduced range requirements, aircraft could be redesigned to be lighter and hence more fuel efficient. Furthermore, because less fuel is carried the induced drag is lower on average. An initial study suggested that quite substantial fuel savings could be achieved in this manner, up to 31% for relevant flights[106]. Subsequent studies by a major airframe manufacturer have concluded that an overall worldwide fleet benefit of 5% is possible. However, it is recognized that adopting this approach would be extremely disruptive, with huge implications that would affect all aspects of air transport, both for the passengers and the industry. The industry players affected include not only the manufacturers but the airlines, pilots, air

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[106] Green, J.E., Greener by Design – the Technology Challenge, Aeronautical Journal, Vol. 106, Issue 1056, 2002

traffic management, airports and infrastructure, and the aviation airworthiness authorities. It is against the realism of such a scenario that the fuel burn improvement due to multi-stage flights needs to be assessed.

A technological opportunity, which is known to have potential but is not considered because it involves doing things differently, is water ingestion in the engines during take-off and climb at low altitude. The efficient way to do this is to inject the water into the cooling air stream, for which the mass flow is an order of magnitude lower than the whole mass flow through the core. For example, using 7% water by mass in the cooling air drops the air temperature by 210 K, allowing reduced cooling air mass flow. After take-off and initial climb (when inlet air temperature has dropped) the water is switched off. The reduction in turbine cooling air during cruise gives[107] a 2% reduction of SFC. Such a strategy could be particularly relevant to the large heavy aircraft now using hot airports in the Middle East. Water ingestion was used on some B747-100 aircraft, so it is not without precedent.

The thrust reverser is a source of weight, cost and maintenance cost. The Boeing 767 fleet operated successfully for some years without thrust reversers, and the A380 has thrust reversers on only two of its engines. Emergency chutes could be provided for the exceptional circumstance when wheel braking is not adequate. If it becomes necessary to have a variable area nozzle in the bypass flow, the incentive to remove the thrust reverser will be much greater. For the present, a quantification of the fuel burn and cost implications of keeping thrust reversers would facilitate rational decision making, once it is established that the aircraft safety level is not affected by the fact of removing them.

Estimates from industry for the energy consumption to pressurize the cabin vary from about 2% of the energy to propel the aircraft to several times this number. This large variation may indicate peculiarities in design and use, but even the lower figure is considerable. Most aircraft take air from the engine, but at cruise this needs to be cooled. There is some reason to think that the whole Environmental Control System (ECS) could be made more efficient, though possibly heavier and more costly. The current air-change of about 0.5 kg/minute for each passenger, which is about twice the current FAR 25.831 requirement, could be reduced[108], with greater use of filtering and recycling. The dump of the exhaust air could potentially be accelerated in a nozzle to augment engine thrust. However, it is inherently costly to provide rapid turnover of outside air when this has to be pressurized and then cooled.

Any steps which reduce distance flown have the potential to reduce the fuel consumed and hence CO_2 and NO_x emitted. The current system of air traffic control does not always lead to routings close to that required for lowest fuel burn. The IEs are conscious of the opportunity which exists to route flights more directly, taking account of wind, to perform fuel efficient descents (such as continuous descent approaches), and to avoid stacking at the destination. Reducing fuel burn in this way will contribute to climate-change mitigation. The challenges here are, of course, largely technical in terms of air traffic management.

A special contribution from aircraft is in the formation of contrails leading to cirrus clouds. Very little to reduce the formation of contrails seems possible, but contrails on their own cause substantially lower radiative Forcing then comes from subsequent cirrus clouds which can form if the atmosphere through which the aircraft is flying is supersaturated with respect to ice. The regions of supersaturation are quite narrow, and near the tropopause, where commercial aircraft find it convenient to fly. Information on air saturation could be communicated between aircraft, rather as information currently is on turbulence, and route changes could be arranged to avoid cirrus. A NASA study showed that altitude changes of ± 2000ft would allow the

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[107] Cumpsty, N.A. Preparing for the Future: Reducing the Environmental Impact of the Gas Turbine. IGTI Scholar Lecture. Trans ASME Journal of Turbomachinery, Vol. 132, No. 4, 2010

[108] For a large TA such as the TRA, carrying 325 passengers, with 0.5 kg/min per passenger there are a bit over 5 changes with outside air per hour. For comparison, a minimum of 3 changes with outside air per hour are recommended in hospital procedure rooms (Guidelines for Design and Construction of Hospital and Health Care Facilities. The American Institute of Architects Press, Washington DC)

supersaturated zones to be avoided with a flight efficiency penalty (implying extra CO_2) of less than 1%[109]. However, other studies suggest substantially higher fuel burn penalties. In any case, the impact of contrails and the associated cirrus clouds must be better understood before the overall climate impact of such measures can be properly assessed. Implementing such a strategy would require meteorological data to be transmitted to individual aircraft. In order to supplement current data, aircraft could be equipped with hygrometers and communicate their data to following aircraft. All this, once the scientific background and the overall environmental potential benefits are robustly established, implies considerable coordinated efforts, including development work, validation, and in flight demonstration, involving aircraft manufacturers, systems and equipment suppliers, ATM, airlines, and meteorological organizations. The probability for such strategy to be implemented efficiently may depend also on the connectivity (communication systems) improvements and on the degree of automation available.

10.3 EMISSIONS

Two interventions are possible, both relating to the fuel. Sulfur can be easily removed during oil refining, subject to a moderate cost impact. Elimination of Sulfur not only would avoid Sulfur Dioxide (SO_2) but would also take away one of the contributors to PM formation. In recent literature particular concern is shown for the nvPM matter associated with unburned carbon, not only elemental carbon but organic products of incomplete combustion. There is good evidence that reducing the aromatic content of the fuel (sometimes expressed as reducing the carbon content of the fuel) reduces the soot formation. This reduction in aromatics and soot also occurs with the use of bio-fuels.

10.4 AIR QUALITY

Modern jet engines are surprisingly clean, particularly when operating at high power. Rather than impose further regulation on the engine, the operation of the airport could be considered:

- Ground vehicles should not be diesel (the dirtiest of the prime movers) but could well be battery electric.
- Aircraft should not normally be taxi powered by their engines, but should be moved by electric tugs.
- Aircraft at the stand should normally be connected to ground power and not use the APU.

10.5 NOISE

It has been seen in Chapter 7 that the scope for reducing the generation of noise appears relatively limited. This is particularly the case for approach noise, where most noise is produced by the airframe, mainly the landing gear, and the attempts to reduce this at source have only been modestly successful. This highlights an area where the potential of noise abatement operational procedures is needed. Such procedures have been used for a long time, but the scope should be extended. It has to be noted that a number of operational-related improvements are not captured by the noise certification scheme, and therefore not taken into account when defining noise reduction goals on the basis of margins versus certification Standards. There are design and operational opportunities, some of which are inter-related, that need to be maximized to fully utilize the design space for noise reduction.

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[109] Guynn, M.D., First-Order Altitude Effects on the Cruise Efficiency of Subsonic Transport Aircraft, NASA/TM-20110217173, August, 2011

There are opportunities to reduce take-off noise through modified operational procedures, but it is reducing approach noise where the scope is greatest. Consideration should be given to delayed undercarriage deployment[110], reduced approach speed by additional drag and opportunities to enable the aircraft to operate at steeper approach angles[111]. Continuous descent approaches have also been shown to reduce approach noise. There is some reluctance to delayed landing gear deployment and steeper descent on the grounds of pilot overload and safety aspects. Nevertheless, at busy airports where noise is a serious nuisance, automatic landing of modern large airliners may address the concern. The increased drag should be produced with minimal impact on noise, perhaps with airbrakes designed to generate noise in the upward direction, and steeper descent may require aircraft design modifications. Recent in-service experience at Luton Airport has shown approach noise reductions of about 3 dBA.

Other noise reductions can be obtained in the future by combining operational aspects and technology, such as in-flight system software allowing minimization and optimization of community noise exposure around given airports. Some aircraft, like the A380 and the A350, have such functions embodied in their FMS software, allowing the aircraft to follow optimum noise trajectories (at take-off for A380, both at take-off and approach for A350), taking into account ambient conditions, specific airport constraints, areas to be protected, and actual aircraft parameters. Such functions could be further refined in future aircraft.

For advanced alternative aircraft, such as those described in Chapter 9, where airframe and propulsion system noise reduction or attenuation technologies may be difficult to implement and may not provide the magnitude of targeted noise reduction, alternative operations should be explored by CAEP and other relevant organizations.

10.6 SUMMARY

This short chapter is a collection of ideas and suggestions which all have potential. By collecting them it has been possible to avoid complicating earlier chapters. It is not intended to imply that these would be easy to implement – anything which alters the operation of the air transport system is fraught with complications and requires close stakeholder coordination. However, the straightforwardly technical solutions are not easy either. They are getting harder to implement and the returns are generally getting smaller. Where possible, improvements in operational procedures should be combined with technology-based improvements.

The IEs encourage CAEP and other relevant organizations to perform studies required to support these alternate approaches which should help meet the goals defined in Chapter 8 and could bring further environmental benefits that are not covered by goal metrics. Revised operational procedures should be incorporated considering novel aircraft configurations, such as those described in Chapter 9.

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[110] Smith, K., Delayed Landing Gear Deployment Trial Report London Luton Airport, August 2017

[111] Millwitz, V., and Korn, B., Steep Segmented Approaches for Active Noise Abatement – A Flyability Study, ICNS 2104, Herndon, April 2014

CHAPTER 11. **RECOMMENDATIONS**

11.1 INTRODUCTION

The increasing aircraft fleet fuel consumption associated with growth in air traffic will cause consequent increases in mass emissions of key pollutants. The pressure to control aircraft emissions is therefore expected to continue and seems certain to increase especially given that other sectors are being expected to reduce their emissions. If a mitigation adopted for one concern leads to increases in other harmful areas, such as noise, the net benefit could be negative. For example, further reduction in LTO emissions might give small improvements in health, but could be found to lead to a rise in CO_2 and increased climate change. This underpins the requirement to have a review considering interdependencies. To do this rigorously and efficiently requires a clear understanding of the potential for damage; for example a clear quantitative understanding of the impact of NO_x on human health. The level of understanding and quantification of the behaviour of aircraft and their engines is relatively good, but the uncertainties and lack of quantification in health and climate change impacts are large and need to be reduced.

These recommendations have been deliberately written in a brief and concise manner, highlighting what the IEs considered as the most important points, with the background given in Chapters 2 through 10. In most cases below, a reference is given to the part of the report to which each recommendation applies. The recommendations below are partly directed at ICAO, but more widely they are directed at policy decision makers, funding, and research communities. The recommended goals are set out at the end of the section.

11.2 AVIATION ENVIRONMENTAL IMPACT OVERVIEW

Air quality and health impacts (Chapter 3, section 3.3)

1. Better understanding of the effects of gases and particles emitted by engines on human health is required. Research on the specific impact of low concentrations of NO_x emitted and low-levels of particulates is needed. The effect on health of particle size, particularly ultrafines, and composition needs to be understood and quantified.
2. The nature of the particulates, in terms of size, number and composition, emitted by engines at different conditions, whilst near to the ground, needs to be understood and quantified.
3. The formation of secondary particulates needs to be understood and quantified. This needs to take into account different background levels of gases such as ammonia, as well as humidity.
4. Further evidence is needed of the effect of NO_x and sulfur oxides at altitude on 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. Although contrails and formation of cloudiness are large potential contributors to aviation radiative forcing, there is still large uncertainty surrounding their behaviour and their RF. Significant resources should be devoted to urgent studies of this topic. (Chapter 3, section 3.4) The potential to mitigate the effect of contrails by small alterations in flight path or altitude should be further investigated. (Chapter 10, section 10.2).
2. NO_x emitted outside the LTO cycle has some global warming potential, but the quantitative understanding of this effect needs to be improved. Though less important, the same is true for particulates and sulfur oxides. (Chapter 3, section 3.4).
3. 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. (Chapter 3, section 3.4).

Aircraft Noise and its impacts

1. Given the rapid increase in aircraft movements, leading to increasing exposure of populations to significant levels of noise, research needs to be maintained, both in relation to the generation of noise and understanding of the impacts. (Chapter 3, section 3.6).
2. The major sources of noise have changed so that the jet noise is subordinate to the fan at take-off and airframe noise dominates at approach. WG1 (with the support of other WGs as applicable) might wish to review the operational procedures used to mitigate noise and also review conditions of the aircraft certification scheme to take account of these changes. (Chapter 3, section 3.7).

11.3 AIRCRAFT FUEL BURN AND CO_2 REDUCTION

1. Fuel burn being a key competitive parameter, any review tends to be hampered by limited publicly available information. For this review the IEs had to construct Technical Reference Aircraft. With the future availability of certification values using the CO_2 metric system, a future review looking at fuel burn can be conducted with a more solid foundation.
2. The aerodynamic performance of the airframe (characterized by ML/D) for single-aisle (SA) aircraft such as B737 and A320 has improved over the past four decades by approximately half as much as larger twin aisle (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 changes do not allow the gains possible for an all-new aircraft from a full basket of new technologies. Evidence available to the review is that a wholly new airframe for the SA size of aircraft will be able to improve the aircraft aerodynamic performance so as to approach that of the TA. It is therefore recommended that goals be set for the SA on the expectation that all-new airframes will be produced for this class by 2037. (Chapter 4, section 4.2)
3. The annual reductions in fuel burn metric tabulated in Table 8-3 represent the IEs view of challenging, but achievable, technology goals for new aircraft. The highest rate is about 1.3% per annum. These results confirm that technology alone will not be able to meet ICAO aspirational goals of 2% global annual average fuel efficiency improvement. Moreover, for the technology goals for fuel burn to be achieved, a substantial increase in investment is urgently required. It is recommended that this evidence be included in discussions and planning of future steps.
4. It is foreseen that the fan pressure ratio will be further decreased to reduce both fuel burn and noise. These larger, lower speed fans will present increased challenges for the integration of the engine with the airframe. Real optimization can only be achieved if there is effective close cooperation between the engine makers and the airframe makers, treating the whole aircraft (airframe, engine and systems) as an integrated whole.

11.4 EMISSIONS

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 met. (Chapter 5, section 5.4.1).
2. The evidence shows a dependence on combustor exit temperature as well as OPR. Any further consideration of LTO NO_x goals must be based on a methodology which reflects combustors

where emissions alter strongly with T_{40}. (Chapter 5, section 5.4.1). In other words NO_x emissions should be correlated against T_{40} as well as OPR, but some characteristics of the combustor geometry may be needed as well. New, low-order models are needed to predict the behaviour and to allow adequate optimization against fuel burn – the very interdependency required in this review.

3. To reflect the potentially increasing importance of altitude NO_x relative to LTO NO_x, consideration should be given to the development of a cruise-based NO_x goal. This should use a climb/cruise (or full flight) metric system, ideally developed by CAEP, as part of cruise NO_x certification. Development of such a goal was too ambitious for this integrated review. (Chapter 5, section 5.5.2).
4. Methods exist to predict NO_x formation at cruise from information from LTO for current RQL combustors. Methods and corroborating tests are needed for the new generation of RQL combustors and the lean-burn combustors. Of particular concern is the staging of fuel injection. (Chapter 5, section 5.5.2.)
5. Setting a cruise-based NO_x goal level should take full account of interdependencies, in particular the technical trade-offs with fuel burn, especially as a result of higher values of T_{40}. Any cruise-based goal should also embrace the emerging understanding of health and environmental impacts due to nvPM and NO_x emissions. The IEs propose that CAEP ISG examine both types of impact for cruise. (Chapter 5, section 5.6)

nvPM

1. Measurement of particles emitted by engines, both mass and number, are becoming more common. Publicly-available measurements should be capable quantifying ultrafine particles (smaller than 100 μm) which are believed to be most harmful to health and are, in the main, the particles emitted by aircraft (Chapter 3, section 3.3).
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 to most in-service engines. Whilst this is good news, it points to the need for better understanding and quantification of the processes leading to the generation of particulates. (Chapter 5, section 5.5.3)
3. The IEs considered that the setting of nvPM goals at this time appeared 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. This is a topic which CAEP should keep under review. (Chapter 5, section 5.6.2)

11.5 NOISE

1. Fan noise, now the dominant source, will benefit from better aerodynamic integration to remove flow non-uniformities. Much of this will come from three-dimensional computation, but this must be supported by appropriate and representative experimental tests, including measurements in flight. (Chapter 6, section 6.1).
2. The IEs regard the opportunities to be limited for new technology to reduce noise further short of major configuration changes (Chapter 9); not much improvement is to be expected by 2037, 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. (Chapter 6, section 6.4 and 6.6).
3. As fans become bigger there is increased pressure to reduce the length and thickness of the nacelle. Therefore more work is needed to improve the acoustic performance of thin 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. (Chapter 6, section 6.2.3).
4. Extended studies and development of landing gear and high-lift systems for low noise are required. These must include computation, experiments and full-scale tests on aircraft, with the aim of achieving optimized design configurations in representative conditions. 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. (Chapter 6, section 6.3.1 and 6.3.2).

11.6 ADVANCED ALTERNATIVE AIRCRAFT

1. It should be noted that in their considerations and recommendations, the IEs have assumed that that conventional configuration ("tube and wing") is the only possibility for 2027.
2. No clear consensus existed among the IEs of the likelihood of alternative configurations being available by 2037. New configurations are believed possible in 2037 with potential benefits, compared to conventional ("tube and wing") configurations at the same technology level, of:
    a. Fuel burn reductions on the order of 5-15%.
    b. Noise reduction on the order of 10 EPNdB cumulative, if the configuration incorporates acoustic shielding.

    To achieve these potential benefits, substantial investment would have to begin very soon. (Chapter 9, section 9.4).
3. It is recommended that research and development of the most promising alternative configurations be intensified. To leave open the possibility of entering service in 2037, would necessitate a very significant investment over the next 5-7 years.
4. Large-scale transonic flight demonstrations of integrated alternative configuration concepts are necessary to lessen the unknowns and build the necessary confidence for the business leaders who make the ultimate decisions. This is essential to reduce the risks, both real and perceived, to address the "ilities," and demonstrate benefits. (Chapter 9, section 9.2).

11.7 INTERDEPENDENCIES

The present goals are based on Nominal confidence levels and used a multi-objective optimization function that applies chosen weighting to fuel burn and to noise. This weighting for the goals was chosen based on the shape of the Pareto fronts obtained by varying the weighting from 100%FB to 100% noise. It was observed that, relative to the 100% fuel burn weighting, the point on the Pareto front with equal weighting (50% fuel burn/50% noise) leads to a significant reduction in noise with only a minimal increase in fuel burn. Using 100% noise weighting, however, leads to a large and unacceptable increase in fuel burn. This is an empirical observation based on the shape of the Pareto fronts for the current modelling; it does not imply any universal applicability and does not imply that the IEs give equal importance to fuel burn and noise. (Chapter 8, section 8.4). It should be noted that the IEs found that the 50% fuel burn/50% noise optimization weighting provided a good balance between the requirements of fuel burn and noise appropriate for consistent comparisons between different dates.

11.8 GENERAL CONCLUSIONS

The present review identified some of the challenges associated with the potential improvement of future aircraft in the mid-term (2027) and in the long-term (2037), in particular the growing integration challenges of larger propulsion systems. There is also a relative narrowing of technology improvement routes with possibly some asymptotic effects limiting the potential technology gains. The “tube and wing” configuration, which was judged as being the only configuration compatible with the mid-term timescale under consideration (and still the most likely in the long-term timescale), also implies constraints and limitations. The evidence available to the IEs showed an improvement in aerodynamic performance, ML/D, for the TA about twice that for the SA over the last 40 years. An important factor is the all-new airframes for the TA over the period examined. The IEs were convinced that the full potential for low fuel burn for aircraft of the SA size is only possible if an all-new airframe is adopted.

The modelling process followed by the Independent Experts, described in Chapter 7 and used in Chapter 8, included the consideration of interdependencies between environmental issues, especially between noise and fuel burn (equivalent to CO_2 emissions) using a multi-objective optimization factoring. In addition, the quantified potential improvement inputs provided by manufacturers' experts included confidence levels of the technology impacts, interdependencies and trade-offs based on their specific experience. This was directly reflected in the methodology followed by the Independent Experts, where three different confidence levels were introduced in the computation. After extensive discussion, the confidence level taken for the results was the Nominal level, implying that each new technology was given a 50% chance of being realized. In spite of this caution, the Independent Experts are aware that the modelling may not capture all of the difficulties and complications that go with detailed design, notably the interdependencies and constraints involved in the development of new aircraft to enter service. Nevertheless, it was agreed that the choice of the Nominal confidence level should lead to goals that are realistic and achievable while remaining sufficiently ambitious.

The IEs believe that meeting these goals requires that research and development activities be strengthened in every critical area. Where appropriate, basic research at low TRL can be carried out in academic centers and research organizations, but the IEs are very aware that many promising technologies are not further developed due to the increasing cost of development with increasing TRL. Obtaining funding and supporting the development of technology through the medium and high TRLs is crucial to moving effectively towards the goals set out in this report and represents the highest challenge for achieving large improvements in these time frames.

11.9 SUMMARY OF GOALS

11.9.1 Fuel Burn Goals

These goals should be seen together, both following from the optimization process described in preceding chapters. 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:

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

2017 TRA values are not goals but are included for reference. The SA results use the increased L/D of 3% in 2027 and 7% in 2037to account for an all-new airframe

The corresponding improvements in FB/ATK for the selected aircrafts are provided in Chapter 8, Table 8.3, together with changes expressed as annual improvements.

11.9.2 Noise Goals

The complementary noise goals, expressed as EPNdB cumulative below Chapter 14 Noise Limit are:

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

2017 TRA values are not goals but are included for reference.

11.9.3 Goals for Emissions

The IEs recommend, based on the evidence provided, that a new 2027 MT LTO NO_x Goal should be set at 54% below CAEP/8 at OPR=30, covering the entire OPR range, using the equation 5.75 + 0.577*OPR.

To ensure environmental benefit when meeting the goal, there are no goal bands and the goal is met only when the 50th engine of a single goal-compliant type enters service. The IEs declined to set NO_x goals for 2037, pending a methodology which reflects the dependence on combustor exit temperature.

APPENDIX A. INDEPENDENT EXPERT (IE) PANEL COMPOSITION

CAEP/Memo-102 (AN1/17), Attachment A, 4/7/2016, contains the composition and report requirement for the Integrated Technology Goals and Review Independent Experts Panel and is included here.

1.1 The Independent Expert (IE) Panel should be nominated and sponsored by CAEP Members or Observers, and agreed to by CAEP Members. Considering the technology review timeframe as detailed in Attachment C, the CAEP Members' agreement may have to be obtained either electronically or through a delegated authority to WG1 and WG3. Ideally, the IE panel should reflect the broad diversity of stakeholders in terms of industrial/business sectors as well as geographic regions. It is expected that the CAEP Members and Observers will seek broad consultation in nominating IE panel members to ensure that the IE Panel reflects the required technical expertise. A level of continuity may be considered relative to the panel in charge of the past technology IE reports for noise, $NO_{x,}$ and fuel burn.

1.2 The technical expertise and background sought for the IE Panel would include:

- Broad array of noise reduction technology development and transition;
- Broad array of fuel burn reduction technology development and transition;
- Broad array of combustion emissions reduction technology development and transition;
- Airframe and/or engine product development;
- Airworthiness;
- Customer Requirements;
- Broad technical expertise with experience from several industries, including aviation;
- Multidisciplinary integration and optimization; and
- Knowledge of policy implications (to provide context to the panel).

1.3 The following information should accompany each nominated IE candidate: the nominees' fields of expertise, the Curriculum Vitae for the nominee, the nominating CAEP Member or Observer, and an assurance that the nominee will receive funding from his/her sponsor in order to participate in the panel and for subsequent coordination/documentation of the results.

1.4 For the purposes of conducting an integrated technology goals assessment and review, it would be ideal if each IE has focus of multiple disciplines of combustion, fuel efficiency, and noise. At a minimum, it is expected that each IE will have focus of at least one discipline (combustion, fuel efficiency, or noise), but with some knowledge of other disciplines.

2.1 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 technology in the foreseeable future.

APPENDIX B. TECHNOLOGY READINESS LEVEL DEFINITIONS

The TRL scale is used worldwide as a means for analyzing and communicating the readiness of technologies and systems under development. TRL captures the type of experimentation that has been performed on a given entity, including details of the experimental environment, test article, and test purpose. There are nine total levels in the TRL scale, and they are:

- TRL 1 = Basic principles observed and reported
- TRL 2 = Technology concept and/or application formulated
- TRL 3 = Analytical and experimental critical function
- TRL 4 = Component and/or breadboard test in laboratory environment
- TRL 5 = Component and/or breadboard verification in relevant environment
- TRL 6 = System/subsystem model or prototype demonstration/validated in a relevant environment
- TRL 7 = System prototype demonstration in flight environment
- TRL 8 = Actual system completed and “flight qualified” through test and demonstration
- TRL 9 = Actual system "flight proven" on operational flight

APPENDIX C. CURRENT CAEP REGULATORY STANDARDS

C.1 NOISE REGULATION

This review has assessed the technology impacts to the three certification points of approach, flyover, and lateral, and as depicted in Figure C-1. The noise metric for this goal setting process was the cumulative margin to the CAEP Chapter 14 noise limit, which is defined in Table C-1.

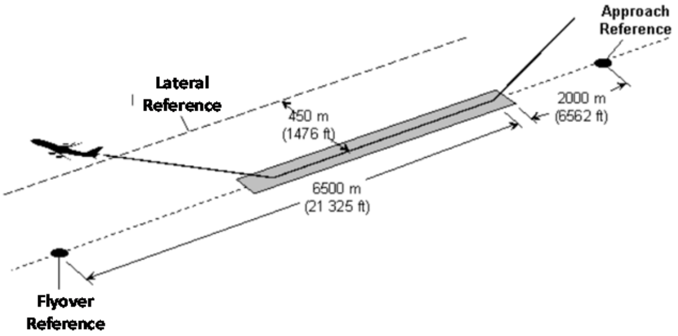


Figure C-1. CAEP Noise Certification Points

Table C-1. CAEP Chapter 14 Regulatory Limit

Maximum takeoff mass range of applicability

M = Maximum takeoff mass in 1,000 kg		0	2	8.618	20.234	28.615	33	48.125	280	385	400
Lateral full-power noise level (EPNdB) All aeroplanes		88.6	86.03754 + 8.512295 log M	94			80.86511 + 8.50668 log M				103
Approach noise level (EPNdB) All aeroplanes		93.1	90.77481 + 7.72412 log M	98			86.03167 + 7.75117 log M		105		
Flyover noise level (EPNdB)	2 engines or less	80.6	76.57059 + 13.28771 log M	89				66.64514 + 13.28771 log M		101	
	3 engines			89		69.64514 + 13.28771 log M				104	
	4 engines or more			89	71.64514 + 13.28771 log M					106	

Each of the following conditions shall apply:

$(\text{LIMIT}_L - \text{EPNL}_L) \geq 1$; $(\text{LIMIT}_A - \text{EPNL}_A) \geq 1$; $(\text{LIMIT}_F - \text{EPNL}_F) \geq 1$;

$[(\text{LIMIT}_L - \text{EPNL}_L) + (\text{LIMIT}_A - \text{EPNL}_A) + (\text{LIMIT}_F - \text{EPNL}_F)] \geq 17$

Where,

EPNL_L, EPNL_A and EPNL_F are respectively the noise levels at the lateral, approach and flyover reference noise measurement points when determined to one decimal place. LIMIT_L, LIMIT_A, and LIMIT_F

are respectively the maximum permitted noise levels at the lateral, approach and flyover reference noise measurement points determined to one decimal place.

C.2 FUEL EFFFICIENCY REGULATION

In February 2016, CAEP adopted the new CO_2 fuel efficiency Standard as documented in ICAO/CAEP document AN 1/17.14 – 17/50. The metric is defined in terms of the average of the 1/SAR values for the three reference masses based on the maximum take-off mass (MTOM) and the reference geometric factor (RGF). The 1/SAR value is established at each of the following three reference aeroplane masses expressed in kilograms:

a) high gross mass: 92% MTOM
b) mid gross mass: Simple arithmetic average of high gross mass and low gross mass
c) low gross mass: (0.45 × MTOM) + (0.63 × ($\mathrm{MTOM}^{0.924}$))

The reference geometric factor (RGF) is a non-dimensional parameter used to adjust $(1/\mathrm{SAR})_{\mathrm{AVG}}$. RGF is based on a measure of fuselage size normalised with respect to 1 m^2, and is derived as follows:

a) for aeroplanes with a single deck determine the area of a surface (expressed in m^2) bounded by the maximum width of the fuselage outer mould line (OML) projected to a flat plane parallel with the main deck floor; and
b) for aeroplanes with an upper deck determine the sum of the area of a surface (expressed in m^2) bounded by the maximum width of the fuselage outer mold line (OML) projected to a flat plane parallel with the main deck floor, and the area of a surface bounded by the maximum width of the fuselage OML at or above the upper deck floor projected to a flat plane parallel with the upper deck floor is determined; and
c) determine the non-dimensional RGF by dividing the areas defined in a) or b) by 1 m^2.

The RGF includes all pressurized space on the main or upper deck including aisles, assist spaces, passage ways, stairwells and areas that can accept cargo and auxiliary fuel containers. It does not include permanent integrated fuel tanks within the cabin or any unpressurized fairings, nor crew rest/work areas or cargo areas that are not on the main or upper deck (e.g. 'loft' or under floor areas). RGF does not include the cockpit crew zone. The aft boundary to be used for calculating RGF is the aft pressure bulkhead. The forward boundary is the forward pressure bulkhead except for the cockpit crew zone.

The CO_2 metric value is calculated according to the following formula:

$$\mathrm{CO_2\ emissions\ metric\ value} = \frac{\left(\frac{1}{\mathrm{SAR}}\right)_{\mathrm{AVG}}}{\mathrm{RGF}^{0.24}}$$

Based on ICAO Annex 16, Volume III, the CO_2 Standard shall be applicable to:

a) subsonic jet aeroplanes, including their derived versions, of greater than 5,700 kg maximum take-off mass for which the application for a type certificate was submitted on or after 1 January 2020, except for those aeroplanes of less than or equal to 60,000 kg maximum take-off mass with a maximum passenger seating capacity of 19 seats or less;
b) subsonic jet aeroplanes, including their derived versions, of greater than 5,700 kg and less than or equal to 60,000 kg maximum take-off mass with a maximum passenger seating capacity of 19 seats or less, for which the application for a type certificate was submitted on or after 1 January 2023;
c) all propeller-driven aeroplanes, including their derived versions, of greater than 8 618 kg maximum take-off mass, for which the application for a type certificate was submitted on or after 1 January 2020;

d) derived versions of non-CO_2-certified subsonic jet aeroplanes of greater than 5,700 kg maximum certificated take-off mass for which the application for certification of the change in type design was submitted on or after 1 January 2023;
e) derived versions of non-CO_2 certified propeller-driven aeroplanes of greater than 8,618 kg maximum certificated take-off mass for which the application for certification of the change in type design was submitted on or after 1 January 2023;
f) individual non-CO_2-certified subsonic jet aeroplanes of greater than 5,700 kg maximum certificated take-off mass for which a certificate of airworthiness was first issued on or after 1 January 2028; and
g) individual non-CO_2-certified propeller-driven aeroplanes of greater than 8,618 kg maximum certificated take-off mass for which a certificate of airworthiness was first issued on or after 1 January 2028.

The CO_2 emissions evaluation metric value shall not exceed the value defined in the following paragraphs:

a) For aeroplanes specified in a), b) and c) with a maximum take-off mass less than or equal to 60,000 kg:

$$\text{Maximum permitted value} = 10^{(-2.73780 + (0.681310 * \log_{10}(\text{MTOM})) + (-0.0277861 * (\log_{10}(\text{MTOM}))\hat{}2))}$$

b) For aeroplanes specified in a) and c) with a maximum take-off mass greater than 60,000 kg, and less than or equal to 70,395 kg:

Maximum permitted value = 0.764

c) For aeroplanes specified in a) and c) with a maximum take-off mass of greater than 70,395 kg:

$$\text{Maximum permitted value} = 10^{(-1.412742 + (-0.020517 * \log_{10}(\text{MTOM})) + (0.0593831 * (\log_{10}(\text{MTOM}))\hat{}2))}$$

d) For aeroplanes specified in d), e), f) and g) with a maximum certificated take-off mass less than or equal to 60,000 kg:

$$\text{Maximum permitted value} = 10^{(-2.57535 + (0.609766 * \log_{10}(\text{MTOM})) + (-0.0191302 * (\log_{10}(\text{MTOM}))\hat{}2))}$$

e) For aeroplanes specified in 2.1.1 d), e), f) and g) with a maximum certificated take-off mass greater than 60,000 kg, and less than or equal to 70,107 kg:

Maximum permitted value = 0.797

f) For aeroplanes specified in 2.1.1 d), e), f) and g) with a maximum take-off mass of greater than 70,107 kg:

$$\text{Maximum permitted value} = 10^{(-1.39353 + (-0.020517 * \log_{10}(\text{MTOM})) + (0.0593831 * (\log_{10}(\text{MTOM}))\hat{}2))}$$

C.3 NO_X REGULATION

The engine emissions reduction focus is to provide an assessment of combustion technology including both NO_x and nvPM. The NO_x Standard is defined for a LTO at four conditions and time in mode as depicted in Figure C-2. The current Standard is CAEP/8, which is defined for engines of a type or model of which the date of manufacture of the first individual production model was after 1st January 2014:

1) for engines with a pressure ratio of 30 or less:

   i) for engines with a maximum rated thrust of more than 89.0 kN:

   $D_p/F_{oo} = 7.88 + 1.4080\pi_{oo}$

   ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$$D_p/F_{oo} = 40.052 + 1.5681\pi_{oo} - 0.3615F_{oo} - 0.0018\ \pi_{oo} \times F_{oo}$$

2) for engines with a <u>pressure ratio of more than 30 but less than 104.7</u>:

   i) for engines with a maximum rated <u>thrust of more than 89.0 kN</u>:

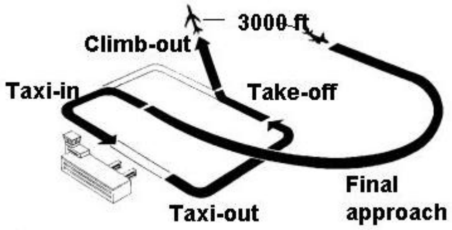
$$D_p/F_{oo} = -9.88 + 2.0\pi_{oo}$$

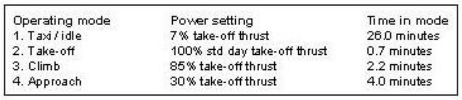
   ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$$D_p/F_{oo} = 41.9435 + 1.505\pi_{oo} - 0.5823F_{oo} + 0.005562\pi_{oo} \times F_{oo}$$

3) for engines with a <u>pressure ratio of 104.7 or more</u>:

$$D_p/F_{oo} = 32 + 1.6\pi_{oo}$$





Operating mode	Power setting	Time in mode
1. Taxi / idle	7% take-off thrust	26.0 minutes
2. Take-off	100% std day take-off thrust	0.7 minutes
3. Climb	85% take-off thrust	2.2 minutes
4. Approach	30% take-off thrust	4.0 minutes

$$\text{Average [Dp/F}_{00}\text{]*}_{\text{emittant}} = \frac{\sum \text{(Operating Mode Emission Rate)*(Time in Mode)}}{\text{Seal Level Static Take-Off Thrust (F}_{00}\text{)}}$$

Figure C-2. CAEP LTO NO_x Cycle

APPENDIX D. THE HIGH-BYPASS JET ENGINE

D.1 INTRODUCTION

This note attempts to provide a brief explanation and clarification of aspects of engine performance and behaviour, with a view to giving guidance on future opportunities and directions. It is assumed that the reader is familiar with the operation, layout and terminology for engines. However the issues that have to be addressed include the operation of the engine at different conditions, notably take-off and cruise, and these are affected by the performance of the aircraft. This is rarely taught in courses and relatively few people are familiar with it so it seemed to the authors that it would be constructive to put some ideas in writing. To provide rigorous justification for all the statements made would require a text book and so for brevity a number of statements are made here without justification, sometimes carrying caveats like “mainly” and “approximately”. The description is for engines for large civil aircraft, but would mainly carry across to the middle of the market and larger regional aircraft whereas smaller business jets tend to be a little different, bearing similarity in the parameters to large engines of a few decades ago.

For flights above about 500 NM most of the fuel is burned at cruise and during this phase of the flight most of the emissions are released. Cruise therefore forms the natural condition for the design of engines. As the weight of the aircraft is reduced, as a result of burning the fuel, the aircraft normally climbs to less dense air so that the lift/drag ratio of the aircraft remains close to its optimum: by doing this the engine also can remain at its optimum condition. Although cruise may be the design condition it is obvious that the aircraft must be able to take-off and climb out to cruise altitude. The key feature of operation during take-off and climb-out is the high temperatures in the engine, both at compressor delivery and turbine entry. As will be explained below, for more recent large engines the take-off condition has become less onerous than in the past and the condition which stretches the engine is top-of-climb, when the aircraft is climbing and is about to reach the cruising altitude; to a large extent the rate of climb is a design choice.

All recent commercial engines are of the high bypass ratio type, so there is a large fan driven by the core. The bypass ratio is the ratio of the mass flow which goes through the bypass duct to the mass flow through the core. This ratio depends on the fan pressure ratio and the power of the core. Over the years the specific power of the core, that is kilowatts per unit mass flow through the core, has increased and the fan pressure ratio has tended to fall so that for larger engines the bypass ratio is now about 10. The jet velocity of the bypass stream and the core stream are similar in magnitude, so roughly 90% of the thrust comes from the bypass stream and it is the pressure ratio of the fan and the mass flow through it which largely determines the engine thrust. The fan determines the general shape and overall diameter of the engine and, together with the containment system (to prevent a blade flying through the aircraft fuselage in case one of them detaches) is the largest contributor to the weight. The low-pressure turbine, which drives the fan, is also a large and heavy component in most engines. An important reason for adopting a gear box between the LP turbine and fan in the GTF architecture is to reduce the size and weight of this turbine.

Terms like full-power and low-power are used to describe the engine operating condition, often when discussing NOx emissions. This needs to be handled carefully, because full power, in the sense that the core of the engine is producing all the power it is capable of, depends on the density of air and is much lower at cruise than at sea-level. In terms of thrust the same engine operating at the same internal conditions produces more thrust as the forward speed is reduced and is highest when the engine is stationary. Here, rather than high or low power the rather wordy expression “non-dimensional operating point” will be used to indicate the condition of the engine. The engine exists to produce thrust and for a given engine this is predominantly determined by the density of the ambient air, the flight speed and the fuel flow.

- The density of the air is important because it influences the mass of air passing through the engine and, as noted above, the power from the core is reduced as the density falls.

- The flight speed is important for two reasons. One reason is that the thrust is proportional to the difference between the velocity of the air entering and the velocity of the jet. The other reason is that the engine is affected by the stagnation pressure and stagnation temperature coming in and by the static pressure downstream of the nozzles. The difference between inlet stagnation and exit static pressure depends on flight speed.
- The fuel flow is the quantity which is used as the main control variable for the engine. For a current large civil engine the temperature of the air is increased by about 800 K in the combustor at cruise.

The engine is controlled by varying the fuel flow to achieve the required thrust. As the fuel flow is varied the pressure ratios, notably the fan pressure ratio and the overall pressure ratio, vary; put another way, the non-dimensional operating point changes. Design point corresponds to one set of pressure ratios and temperature ratios and this combination is expected to give the highest efficiency. At conditions significantly different from design the engine efficiency is expected to be lower – at idle or during descent the engine is far removed from design but the consumption of fuel at these conditions is small enough for it not to be too important. It seems natural to consider the behaviour and design of the fan as separate from the remainder of the engine. What this shows is that the fan has a strong influence on the operation of the core and this comes about because the engine is forced to operate at very different conditions for cruise and take-off.

D.2 CRUISE AND TAKE-OFF: THE INFLUENCE OF THE FAN ON THE CORE

The direct significance of the fan pressure ratio to specific fuel consumption is discussed below in the context of propulsive efficiency. What is less familiar is the impact that the fan pressure ratio has on the core of the engine. Most of the fuel burned in a flight is consumed during the cruise so that operation during cruise is the condition at which the efficiency of the engine is most important. Cruise therefore forms the natural design point for the engine. It is clearly essential that the engine is able to produce sufficient thrust for take-off, and historically this was the condition most difficult for engines to meet. Because of this, and because this condition is so important, engines are still usually categorized by some measure of the take-off thrust.

For our purposes we want some estimates of thrust at cruise and take-off. At cruise, the thrust, F_{cr}, is the weight÷(L/D) and for recent large aircraft $L/D \approx 21$. A plausible[112] value of take-off thrust (at sea-level static conditions), based on values for a number of existing aircraft, is $F_{TO} = 0.275$ MTOW. We make the assumption that the weight at start of cruise is adequately approximated by that at take-off, in fact it is a few percent less, and then obtain:

$$F_{TO} = 21 \times 0.275\, F_{cr} = 5.78\, F_{cr}$$

Calculations have been undertaken using the program Gasturb[113] for an engine core representative of an engine on a Boeing 787 or Airbus A350. The engine is specified for cruise and then is required to give 5.78 times cruise thrust when sea-level static. Designs are carried out for a range of fan pressure ratios at cruise from 1.3 up to 1.9. The design (cruise) OPR is just under 40. Conditions at take-off are illustrated in Figure D-1 for the OPR and in Figure D-2 for the turbine inlet temperature. In Figure D-1, each point represents a different engine with identical core but changed design FPR and in Figure D-2, each point represents a different engine with identical core, including cruise turbine entry temperature, but changed design fan pressure ratio. The overall pressure ratio is equal to the cruise pressure ratio (just under 40) if the fan pressure ratio were 1.4; at the currently typical value for FPR=1.5 the pressure ratio is increased to just

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[112] N.A. Cumpsty, “Preparing for the future: reducing environmental impact of the gas turbine”. Trans. ASME, Journal of Turbomachinery, Vol. 132, No4 2010

[113] Gasturb, software from J. Kurzke available form http://www.gasturb.de/

above 41 whilst for FPR=1.7 it is up to about 46, a significant increase. If the pressure ratio at take-off is equal to that at cruise the non-dimensional condition of the engine is about the same so the engine will be efficient and not seriously compromised between cruise and take-off. (It is not so much the extra fuel which would be burned during take-off which matters but the increase in engine temperatures which follows from trying to get the required thrust with reduced component efficiency.)

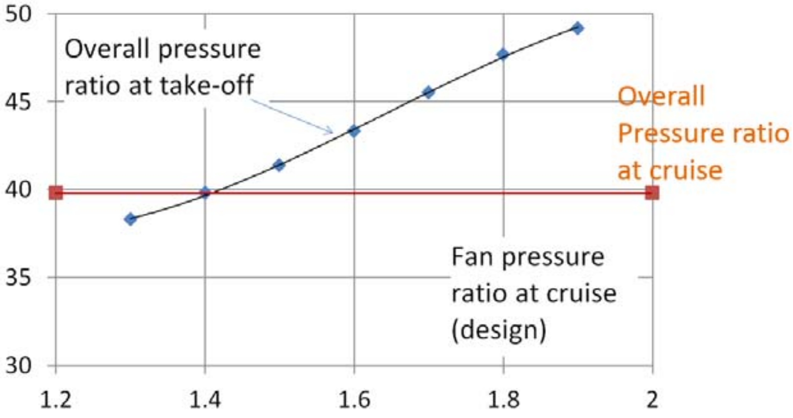

Figure D-1. Variation in Take-off OPR with Design FPR

For the earlier generation of aircraft engines, with fan pressure ratios nearer 1.8 than 1.4, achieving the take-off thrust was challenging and at this condition the pressure and temperature ratios could be at their highest. The compressor delivery and turbine entry temperatures were particularly onerous for take-off because of the higher inlet temperature. For modern large engines, with low pressure ratio fans, the differences between the pressure and temperature ratios between take-off and cruise temperature are smaller. Since the limits on temperature are set at take-off, this allows significantly higher values of turbine entry temperature and overall pressure ratio for cruise for given material properties. The rear of the compressors and the core turbine parts are made of high-temperature nickel alloys which are able to operate at temperatures up to about 950 K and this puts an effective limit on the pressure ratio[114] in the engine for hot take-offs. The metal in the turbine blades can operate close to 1300 K but because the turbines can be cooled, using the compressor delivery air, the gas temperature into the HP turbine can be significantly higher, up to about 1500 K at cruise and several hundred degrees higher at take-off. In the past it was turbine delivery temperature at take-off which was the crucial limiting quantity but now overall pressure ratios are so high that compressor delivery is at the metal limit.

Take-off is no longer the condition which “stretches” the engine, i.e. forces it to work at higher pressure ratios and temperature ratios, and this now occurs for top of climb. This is when the aircraft is climbing at its maximum rate as it approaches its cruise altitude. The maximum climb rate is a design choice and 500 ft/minute (2.5 m/s) might be typical. At this condition with a good modern aircraft (lift/drag ratio 21) the thrust required for top of climb is about 21% higher than that needed for cruise. Designing engines to make this extra thrust available necessarily incurs some loss in efficiency at cruise and this could be improved if a more modest climb rates were allowed.

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[114] In fact with a good compression system (polytropic efficiency 92%) and ISA sea-level conditions, 288.15K, the compressor delivery reaches about 871 K for an OPR of 40 and 927 K for OPR =50. Were the efficiency only 90% the temperatures would be 891 and 949 K. If the sea-level temperature is at a typical design value, ISA+20K, in other words 35° C with the efficiency of 92% the temperatures are 952 K and 1021 K. Nowadays, it is normal to design assuming full take-off thrust for days significantly hotter than ISA.

Because pressure ratios and temperature ratios rise less for take-off when FPR is low, the engine with a low FPR can be designed for higher OPR and turbine inlet temperature at cruise. For a given combustor, the formation of NO_x is strongly affected by the temperature of the air entering and products leaving the combustor. Because the cruise OPR and TET can therefore be higher for an engine with low FPR than one with high FPR, NO_x at cruise relative to that at take-off is likely to be higher for the low FPR engine.

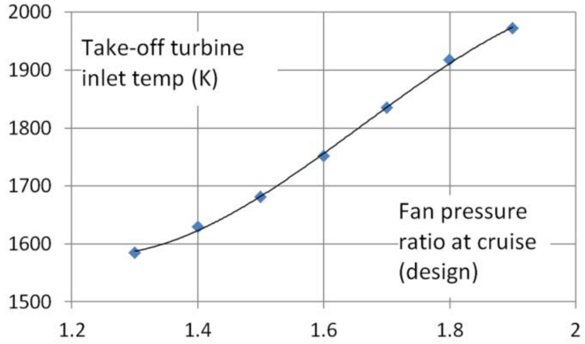

Figure D-2. Variation in Take-off Turbine Entry Temperature with Design FPR

D.3 SPECIFIC FUEL CONSUMPTION AND FUEL BURN

Performance of engines is often described in terms of specific fuel consumption, SFC, which is the fuel flow rate required to achieve a given unit thrust. It is often expressed as (kgm fuel/hour)/ kgf-thrust, which is numerically identical to (lbm fuel/hour)/lbf thrust. The rigorously correct units are g $s^{-1}kN^{-1}$ and numerically.

1 (kgm fuel/hour)/ kgf-thrust = 1 (lbm fuel/hour)/lbf thrust = 0.0283 g $s^{-1}kN^{-1}$.

The definition of SFC is open to criticism since it is dependent on speed and is not dimensionless. The performance of the engine can be described in terms of overall efficiency η_o, where

$$\eta_o = V F/(\dot{m}_f LCV)= V/(sfc\ LCV)$$

where V is flight speed, F is the thrust, $\dot{m}_f$ is the mass flow rate of fuel and LCV is the heating value of the fuel. The overall efficiency can be conveniently divided into propulsive efficiency η_p and core efficiency η_c so that

$$\eta_o = \eta_p \eta_c.$$

The core efficiency as specified here lumps together the conversion of energy in the fuel to the energy transferred to the jet; this could be subdivided, but for simplicity it is not done here. The overall efficiency depends on many variables, most obviously the overall stagnation pressure ratio $OPR=P_{03}/P_{02}$ and the overall stagnation temperature ratio T_{04}/T_{02}, where 2 here refers to entry to the engine, 3 is exit of the compressor (entry to the combustor) and 4 is exit from the combustor. Core efficiency also depends on the efficiency of the inner stream of the fan, the core compression system and the turbines. The core efficiency is also reduced by the cooling air which is taken from the compressors, bypassing the combustor, and used to cool discs and aerofoils. In total the cooling air may be in excess of 20% of the air entering the compressor. Perhaps half of this cooling air is used to cool the nozzle guide vanes at entry to the HP turbine and this air does not lead to a loss in efficiency in the normal accounting because the turbine entry temperature is the mixed-out value downstream of the nozzle guide vanes.

Although the SFC and the overall efficiency describe the effectiveness of the engine in converting chemical energy of the fuel into engine thrust, there is an aspect which is less satisfactory. Imagine a modification to the engines which reduces the SFC by 1%, an apparent improvement without reduction in

L/D for the aircraft. But suppose that this increase had come with an increase in engine weight of 10%. The powerplant (meaning the bare engine, plus the nacelle and pylon) each weigh about 5% of the aircraft maximum take-off weight for a large twin so the additional drag attributable to the engine modification is about 1%, therefore undoing the benefit of the reduced SFC. In considering the impact of changes it is therefore necessary to consider the alterations to the fuel burn. (A similar argument would apply to the airframe: if L/D were increased by 1% but the aircraft weight were increased by a similar amount there would be no reduction in fuel burn.)

D.4 THE FAN AND PROPULSIVE EFFICIENCY

About 90% of the engine thrust is produced by the flow through the bypass duct for a typical modern large engine with a bypass ratio of about 10. The jet velocity of the core is chosen to be similar to, but slightly greater than the bypass jet velocity. The pressure ratio of the bypass stream through the fan therefore determines jet velocity and propulsive efficiency for the engine.

The propulsive efficiency relates the energy which is given to the jet to the work done in propelling the aircraft. With only a slight approximation η_p depends only on the jet velocity V_j and flight speed V and is given by:

$$\eta_p = 2V/(V + V_j)$$

As a good approximation, the jet velocity depends only on FPR, see Figure D-3.

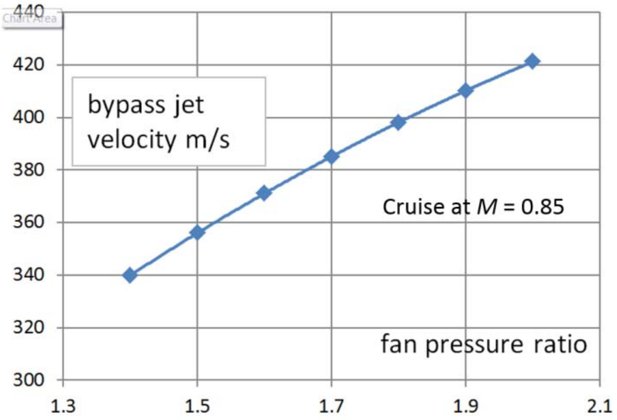

Figure D-3. Jet velocity as a function of FPR

In other words, choosing the fan pressure ratio fixes the propulsive efficiency for a given flight speed. The net thrust is given by $\dot{m}(V_j - V)$, where $\dot{m}$ is the mass flow through the engine. For M=0.85 at 35000 ft., the flight velocity is about 250 m/s so the difference in the velocities in Figure D-3 approximately doubles over the range of pressure ratios shown.

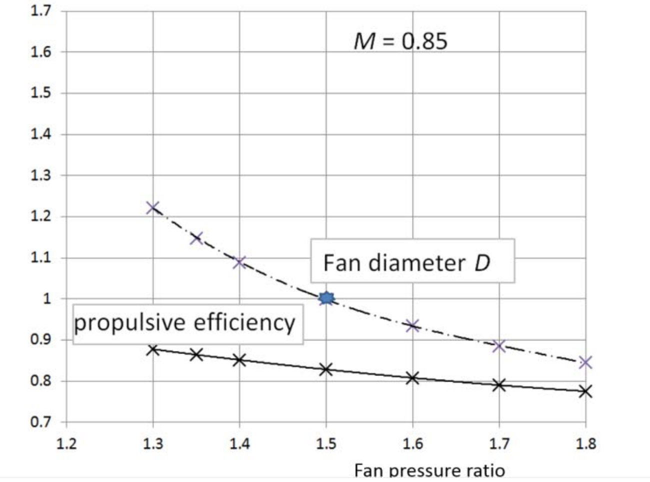

Figure D-4. Variation in Fan Diameter for a Constant Thrust at Cruise with FPR

To increase propulsive efficiency it is necessary to reduce jet velocity and fan pressure ratio, but to achieve a given thrust this requires the mass flow through the engine to be increased. It is a good approximation to assume that the area of the front of the fan is proportional to the mass flow, so as the jet velocity is reduced the flow area increases in inverse proportion to $V_j - V$. The implications of this are shown in Figure D-4, which shows the fan diameter as a function of fan pressure ratio, normalized by the value for a FPR=1.5. Also shown in Figure F-4 is the propulsive efficiency. A study[115] showed the weight to increase only as the 2.4 power. (Whereas the sums leading to Figure 4 are robust, the assumption for weight increase is approximate[116].

Figure D-5 reproduces Figure D-4 with the addition of this estimate of weight again normalized by the value for FPR=1.5. It can be seen that in reducing FPR from 1.5 to 1.4 the weight increases by about 23% whilst the propulsive efficiency increases from about 82.8% to 85.2%. If the total powerplant weight is about 10% of maximum take-off weight the increase in weight is equivalent to an increase in fuel burn of 2.3%, very similar to the reduction in SFC.

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[115] C.A. Hall, E. Schwarz and J.I. Hileman, AIAA Jnl of Propulsion and Power, Vol 25, No6, 2009 C.A.Hall and C.Crichton, ISABE-2005-1164

[116] Not only is it approximate but a change in architecture, like a power gearbox between fan and LP turbine, will give a step reduction in weight. Once that step has been taken, a similar relationship between weight and a power of diameter is plausible for subsequent changes in diameter.

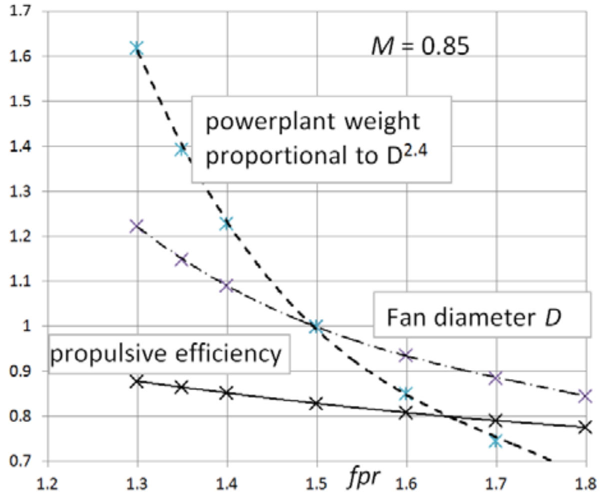

Figure D-5. Variation in Powerplant Weight (Bare Engine, Nacelle and Pylon) for a Constant Thrust with FPR

It is possible to include the effect of the powerplant weight to see how the optimization changes when it is included. Figure D-6 shows first the effect of varying fan pressure ratio on SFC using calculations based on a perfect gas. The curve including the drag for the wings indicates the variation in fuel burn with FPR. The SFC continues to fall quite steeply as FPR is reduced. If an estimate for the nacelle drag, which increases with the diameter of the engine, is included the SFC still falls with pressure ratio and no optimum FPR occurs. Only when the increased drag of the aircraft associated when the weight of the powerplant is included does the SFC show a minimum. The minimum here is flat and other factors, like reduced noise, might shift the design to lower FPR; on the other hand the need for adequate ground clearance might shift the design to higher FPR.

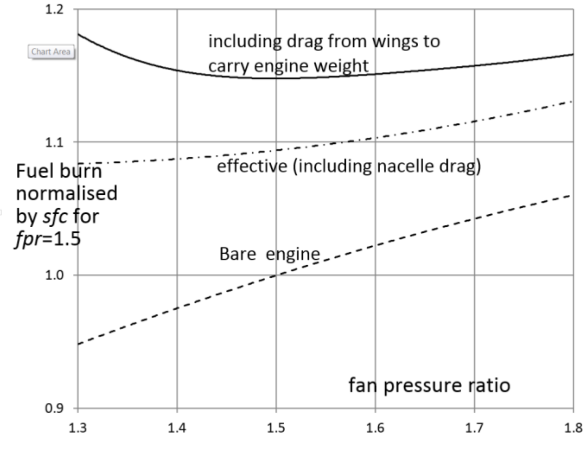

Figure D-6. Variation in SFC with FPR, Constant Core

The design of the fan is crucial to the success of an engine. There is an almost one-to-one relation between efficiency of the fan in the bypass stream (meaning the fan rotor and the fan stators, often called outlet guide vanes) and the efficiency of the engine. Although the cruise condition has the largest influence on fuel burn, the engine has to be able to generate the required thrust at top-of-climb, forcing the fan to operate at higher speed, pressure ratio and mass flow rate. The fan has to be able to operate stably on the ground when there are strong crosswinds and to be stable when the aircraft is at a high angle of attack. It must be able to cope with bird strike. The fan is also an important noise source and one of the important reasons for engines becoming quieter is that the fan pressure ratio has been decreasing, allowing a decrease in blade speed.

D.5 THE ENGINE CORE AND CORE EFFICIENCY

Here we will consider the compression system downstream of the fan, the combustor and the turbines. Calculations have been performed with Gasturb to explore the effect on specific fuel consumption at cruise of changes in engine specification, notably the overall pressure ratio and the key specified temperature ratio, the ratio of turbine inlet temperature to inlet temperature to the engine T_{04}/T_{02}. Here, turbine entry temperature T_{04} is the temperature at exit from the first row of turbine nozzles, assuming mixing of the cooling air. Elsewhere in the body of the report it is written T_{41}. Because the weight of the core is *comparatively* small and the changes in weight associated with small changes in pressure ratio or temperature ratio are small, the benefits in terms of SFC may be taken to be those for fuel burn.

The calculations have been performed for a hypothetical reference engine representative of those which have recently entered service for a large twin-aisle. Fan pressure ratio is held constant. Unless otherwise stated the polytropic[117] efficiencies of the compressor and turbine have been held constant as the OPR is changed. The cooling air has also been held as a constant fraction of air through the core, though in practice this would be impossible to justify in a more detailed analysis. The bypass ratio is allowed to vary and the SFC is computed for the value of bypass ratio at which SFC is a minimum.

Figure D-7 shows that the overall pressure ratio chosen for the reference engine, shown by the diamond for OPR = 40, does not give the lowest SFC but about 0.7% of reduction is possible a pressure ratio in excess of 50. The cost of this higher OPR $=P_{03}/P_{02}$ would high compressor delivery temperature at take-off, which would be a problem for the disk life and also for the cooling of the turbine. In other words, the decrease in fuel consumption is small compared to the added difficulty and this contrasts with the benefits in going from OPR of 30 to 40, which would have been the equivalent step taken a few years ago, where the benefit was about 2%.

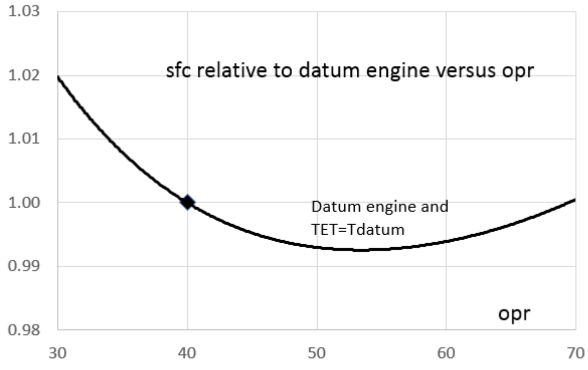

Figure D-7. Variation in SFC versus OPR

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[117] The polytropic efficiency of a compressor is defined by $T_{03}/T_{02} = (P_{03}/P_{02})^{(\gamma-1)/\eta\gamma}$. The polytropic efficiency has the property that it indicates the quality of the aerodynamics of a compressor or turbine and is independent of the overall pressure ratio.

Figure D-8 is similar to Figure D-7 but with the addition of increased turbine entry temperature of 50 K and 100 K; note that the component efficiencies and cooling flows are constant. Historically turbine entry temperature have increased by a typical average of 10 K per annum, so the changes represent five and ten years respectively. Two things are noticeable for the range of values being used here: the influence of turbine entry temperature is larger than the influence of OPR, but the value of OPR at which the minimum SFC occurs increases as the temperature rises. So an increase of 50 K and a rise in OPR to 60 would lead to a reduction in SFC of about 2.3%; an improvement of 1% could be achieved by the 50K temperature rise at OPR =40 and 2% at OPR =50. The extra 0.3% requiring the OPR to be raised to 60 would come at large cost in terms of temperature out of the compressor.

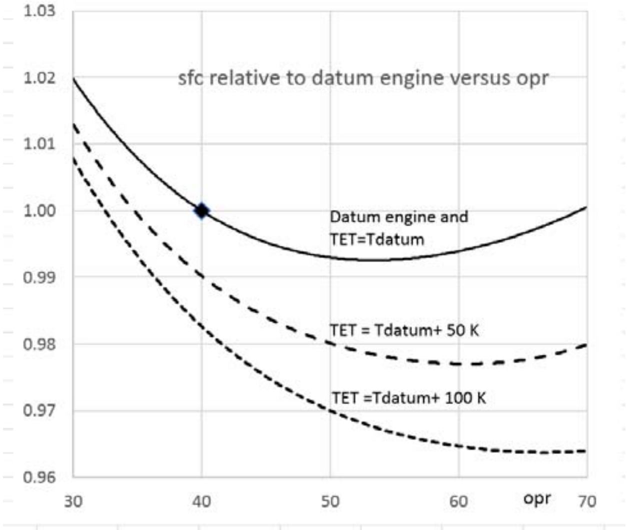
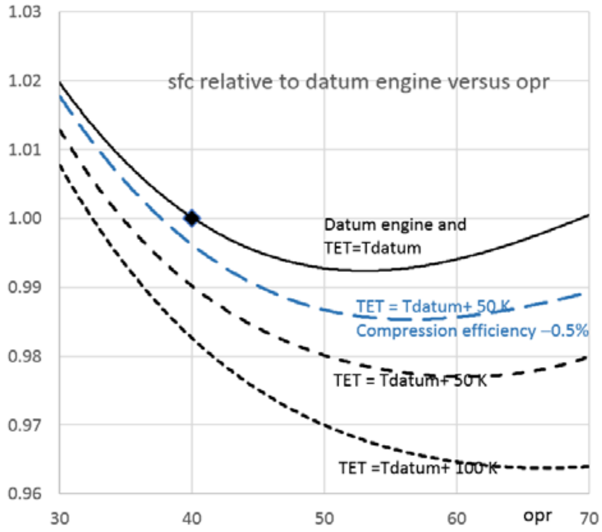


Figure D-8. Variation in SFC versus OPR for Three Turbine Entry Temperatures

In the calculations for Figure D-7 and Figure D-8, the polytropic efficiencies of all components have been held constant. In fact, it is unlikely that this would prevail. For compressors, the problems of matching make it progressively harder to get high efficiency as the pressure ratio increases. For turbines, the higher pressure ratios inevitably give larger volumetric expansion which tends to give a steeper (i.e. more inclined to radial) flow path with loss in efficiency. With higher pressure ratios it is harder to maintain good tip clearance, particularly during transients, for the thermal effects are bigger and the mechanical loads get applied to a smaller core. For all these reasons, the polytropic efficiencies are likely to decrease as OPR is increase.

Figure D-9 shows what would happen if the polytropic efficiency of the compression through the core, including the fan inner section, is reduced by 0.5%, a value which is entirely plausible. This has been done for the turbine entry temperature which is 50 K above the datum. The increase in SFC associated with the drop in compression efficiency increases with OPR but in the area of low SFC the increase is somewhat greater than 0.5%. Put another way, for the +50 K case about 2/3rds of the decrease of about 1% in SFC for an increase in OPR from 40 to 50 could be undone by this small drop in compression efficiency. In practice, the turbine efficiencies are also likely to be decreased and the cooling flow rates raised by the increase in OPR both leading to increase in SFC. Figure D-9 also shows that increase in turbine entry temperature with no increase in OPR (and therefore no expected loss in compressor and turbine efficiency) would give 1% reduction in SFC. Engines have already reached temperatures and pressures such that raising TET is a more promising route to low SFC than large increases in OPR.



Blue Curves Shows Compression Efficiency Reduced by 0.5%.

Figure D-9. Variation in SFC versus OPR for Three Turbine Entry Temperatures.

In the plots above, the OPR has been treated as an unconstrained variable. In fact the temperature rise in the compression system is one of the main constraints on the specification and operation of an engine. The compressor deliver temperature is shown in Figure D-10 as a function of overall pressure ratio. The curves are shown for three different inlet temperatures that might be adopted for sea-level: ISA, ISA+15 K and ISA+30 K. Nowadays it would be unusual to specify ISA and engines are “flat rated”, meaning they can give full thrust during take-off to a higher value and ISA+15 K is typical. The curves have been produced for two polytropic efficiencies, 92% and 94%. The former would be regarded as a very good compressor which is clean and in pristine condition; compressor efficiency can be 1% lower than this when they come back for overhaul without having suffered major damage. An efficiency of 94% has been sometimes estimated to be about the ultimate level achievable; 2% improvement does not sound much but it is more enlightening to think that this represents a 25% reduction in losses. Also shown in Figure D-10 is a grey band centered at 973 K (that is 700°C) which is about the upper limit of usability for nickel allowed in high-stress regions.

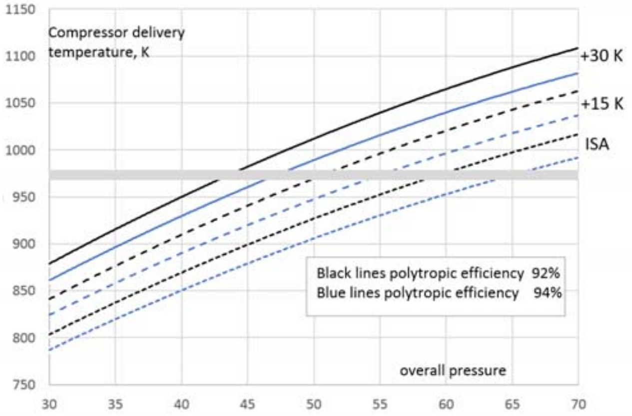


Figure D-10. Variation in Compressor Delivery Temperature versus OPR

Some messages are clear from Figure D-10. Increase in OPR depends on the efficiency of the compressor but, even more, on the temperature rating of the engine. With the current level of efficiency OPR of nearly 60 would be possible if full-thrust take-off were not to be allowed at sea-level temperatures about 15 °C. If the highest ambient temperature is to be used OPR in excess of about 47 is improbable even with the compressor of 94% efficiency, better than any yet available.

High compressor delivery temperature has another effect on the engine, it increases the amount of air needed to cool the turbine and in this way reduces the core efficiency. It is possible to cool the cooling air by an air-to-air heat exchanger in the bypass duct but there are several drawbacks to this. One is that it introduces complexity into the cooling system: weight, cost and reliability issues. Another is that it introduces drag or loss into the bypass duct and this is incurred throughout the flight, not just during take-off when it is needed. There is another way to mitigate the impact of high-temperatures on cooling air and that is to evaporate water in it. Evaporating 1% by weight of water in air drops the temperature of the air by about 30 K, so quite modest amounts of water during hot take-offs would be enough to allow higher OPR. Although a nuisance it is by no means impractical[118] as is shown by the studies carried out.

D.6 PRINCIPAL LESSONS FOR THE IE REVIEW

1. The key parameters defining the aerodynamic and thermodynamic performance of the engine are the fan pressure ratio, the overall pressure ratio and the ratio of turbine inlet temperature to engine inlet temperature. The bypass ratio follows from these and depends on the choice of ratio of bypass jet velocity to core jet velocity.
2. The FPR determines the propulsive efficiency, which rises monotonically as fan pressure ratio reduces. Fan diameter and powerplant weight rise rapidly as fan pressure ratio is reduced for the same thrust, so minimum fuel burn is achieved currently for large commercial engines (using direct-drive architecture) with fan pressure ratios in the region of 1.5. The key requirement for utilizing lower FPR is reduced weight of the LP system including the nacelle and pylon and one contribution to reducing the weight can be a gearbox between fan and LP turbine.
3. The FPR has a large influence on the variation in engine operating conditions of the engine core (pressure ratios and temperatures) between cruise and take-off. As the FPR is reduced the increase required for take-off relative to cruise become smaller, so for the same limiting values of pressure ratio and turbine entry temperature at take-off, one can design for higher values of OPR and TET for cruise. Engines are now usually designed for take-off at higher than ISA temperatures, typically ISA+15 K or ISA+20 K.
4. As FPR is reduced the engine is better matched (i.e. similar non-dimensional condition) for cruise and take-off. For FPR = 1.4 at cruise the values of OPR and FPR are virtually the same for cruise and take-off. When take-off gives the limiting temperatures, lower FPR means that higher pressure ratios and turbine entry temperature can be designed for cruise than was the case with higher FPR.
5. Core efficiency depends on OPR and turbine inlet temperature. For current engines with OPR $\approx$40, increasing OPR whilst holding turbine entry temperature constant offers at best about 0.75% improvement. Allowing the turbine inlet temperature to increase by 50K, representing

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[118] Daggett D L, Fucke L, Hendricks R C and Eames D J H. Water Injection on Commercial Aircraft to Reduce Airport NOx. Paper AIAA 2004-4198 presented at 40th AIAA.ASME.SAE.ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, Florida 2004.

Becker A. Engine Company Evaluation of Feasibility of Aircraft Retrofit Water-Injected Turbomachines. NASA CR-2006-213871, 2006

Daggett D L, Hendricks R C, Mahashabde A and Waitz I A. Water Injection – Could it Reduce Airplane. Maintenance Costs and Airport Emissions. Paper ISABE -2005-1249 Presented at 17th International Symposium on Airbreathing Engines, Munich, Germany, 2005 about 5 years development, would allow about 2.3% reduction in SFC at the optimum OPR of about 60, assuming component efficiencies and cooling air quantity were unchanged. Increasing the turbine inlet temperature by 50K but holding OPR at 40 would give about 1% reduction in SFC.

6. The efficiency of the compression system and the turbines are likely to be reduced as the OPR is increased for a number of reasons. A reduction in compression efficiency of 0.5%, a very plausible drop, leads to a change in SFC comparable to the benefits being sought by increasing OPR from about 40.
7. A key quantity for the operation of the engine is the temperature of the air leaving the compressor. This surrounds the discs, which are highly stressed and limited to temperature somewhat below 973K (700°C). Current engines are close to the limit for allowable compressor delivery temperature, 973 K, with OPR≈47 at ISA+15 K. Higher OPR will require some form of cooling for the compressor delivery air. This could take the form of a heat exchanger (with attendant costs, weight, drag and risk) or it could be more unusual, like water injection during the hottest take-off part of the flight. Without this, proposals for higher OPR need to be viewed skeptically.
8. Compressor delivery air is used to cool the turbines and as the cooling air temperature rises the quantity needed rises unless the air is cooled. More cooling air increases SFC.
9. Increased turbine inlet temperature is possible, as military engines have shown, but at the cost of increased cooling air and/or reduced service life. The increase in cooling air can soon erode the apparent benefits to efficiency of temperature increase. Advantage can be taken of improved cooling, better thermal barrier coating and better metal alloys, but these have been worked hard for a long time and breakthroughs are not probable.
10. It is clear that increasing fan, compressor, and turbine efficiencies is important as a way of reducing SFC. Most of the improvement in SFC since the advent of the high bypass engine to the present day has come from component efficiency improvement and not from higher OPR and higher TET. It is probable, therefore, that turbomachinery efficiency will creep up from current values. It is crucial for this that the mechanical aspects are adequately handled (for example, it is hard to have high efficiency is the casing around the turbomachine becomes oval or if thermal transients lead to tip-rubs or large clearances). The mechanical issues become more difficult as the overall pressure ratio and the temperatures get higher.
11. Reducing FPR increases the propulsive efficiency and therefore reduces SFC. Moreover, as the fan pressure ratio goes down the fan tip speed can be reduced which has tended to raise the fan polytropic efficiency and reduce noise. The fuel burn does not reduce as much because there is a tendency for the weight, and the nacelle drag, to rise. This will create pressure to make the inlet and bypass duct shorter. The shorter inlet will probably lead to higher distortion into the fan with possible operability problems and higher noise generation. The shorter inlet and bypass duct offers less area for acoustic treatment so the fan noise may not reduce as much as anticipated. The current key factor in limiting the reduction in FPR is weight.
12. One of the routes to reducing engine weight and facilitating lower FPR is the gearbox between the LP turbine and the fan.
13. While the “non-dimensional operating point” for the turbomachinery and the thermodynamics of the core is determined by the OPR and T_{04}/T_{02}, these non-dimensional parameters are not useful for understanding the emissions formation in the combustor. The scaling parameters for operation of the combustor are controlled by the reaction chemistry and we need to pay attention to them for emissions considerations.

14. For historic reasons the NO_x emissions are usually correlated against OPR for sea-level static conditions at 15°C (ISA). This gave some recognition of the pressure dependence in the formation of NO_2. The additional effect of the rise in combustor inlet temperature T_{03} with OPR was not separately addressed. There will be some dependence too on combustor exit temperature which appears to become particularly powerful for the lean-burn combustor. For the reasons outlined in this note associated with compressor delivery temperature there is unlikely to be much increase in OPR for some time to come.

APPENDIX E. POTENTIAL AIRFRAME MASS REDUCTION TECHNOLOGIES

The mass reduction technologies provided in this appendix were acquired through the two IE sessions (Washington DC and Berlin) and were refined for use in the modelling, as provided in Appendix L

Advanced Metallic Technologies

The table below gives the potential mass savings provided through advanced metallic technology.

Table E-1. Advanced Metallic Mass Technologies

Technology	Aircraft Category	Structural Group	% Reduction in Group Mass	Probability of service Entry in2027	Probability of Service Entry 2037	TRL -2017	Reference Structure
Advanced Metallic Technologies	**BJ**	Wing	5% +/-2%	50%	80%	Med (5-6)	Metallic Design
		Fuselage	3% +/-2%	50%	80%	Med (5-6)	Metallic Design
		Empennage	3% +/-2%	50%	80%	Med (5-6)	Metallic Design
	Regional	Wing	7% +/-2%	50%	80%	Med (5-6)	Metallic Design
		Fuselage	5% + /-2%	50%	80%	Med (5-6)	Metallic Design
		Empennage	5% +/-2%	50%	80%	Med (5-6)	Metallic Design
	Single Aisle	Wing	N/A			Med (5-6)	Future is Composite
		Fuselage	5% +/- 2%	60%	90%	Med (5-6)	B737Max,A320 neo, Metallic
		Empennage	N/A			Med (5-6)	Future is Composite
	Twin Aisle	Wing	N/A			Med (5-6)	Future is Composite
		Fuselage	4% +/- 2%	60%	90%	Med (5-6)	B777,A330 , metallic
		Empennage	N/A			Med (5-6)	Future is composite

Advanced Composite Technologies

The table below shows potential mass benefits from use of composite technologies

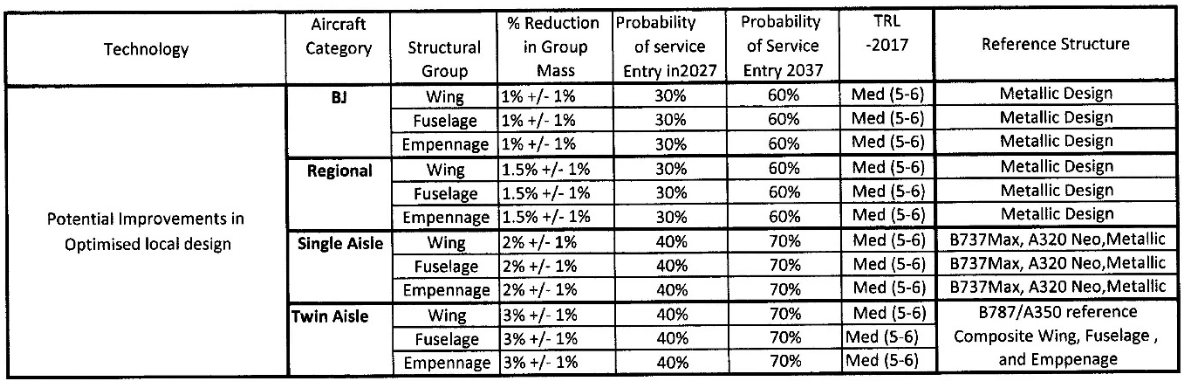
Table E-2. Advanced Composite Mass Technologies

Technology	Aircraft Category	Structural Group	% Reduction in Group Mass	Probability of service Entry in2027	Probability of Service Entry 2037	TRL -2017	Refrence Structure
Potential Improvements in Composite Technologies	**BJ**	Wing	8% +/- 2%	60%	80%	Med (5-6)	Metallic Design
		Fuselage	N/A			Low (1-4)	Metallic Design
		Empennage	4% +/- 2%	60%	80%	Med (5-6)	Metallic + Composite parts
	Regional	Wing	8% +/- 2%	60%	80%	Med (5-6)	Metallic Design
		Fuselage	N/A			Low (1-4)	Metallic Design
		Empennage	8% +/- 2%	60%	80%	Med (5-6)	Metallic Design
	Single Aisle	Wing	10% +/-2%	80%	100%	Med (5-6)	B737Max, A320 Neo,Metallic
		Fuselage	8% +/- 3%	80%	100%	Med (5-6)	B737Max, A320 Neo,Metallic
		Empennage	8% +/-2%	80%	100%	Med (5-6)	B737Max, A320 Neo,Metallic
	Twin Aisle	Wing	5% +/- 2%	80%	100%	Med (5-6)	B787/A350 reference Composite Wing, Fuselage , and Emppenage
		Fuselage	4% +/- 2%	80%	100%	Med (5-6)	
		Empennage	4% +/- 2%	80%	100%	Med (5-6)	

Potential Improvements through Optimized Local Design

The potential benefits from optimized design are shown in the table below.

Table E-3. Optimized Local Design Mass Technologies

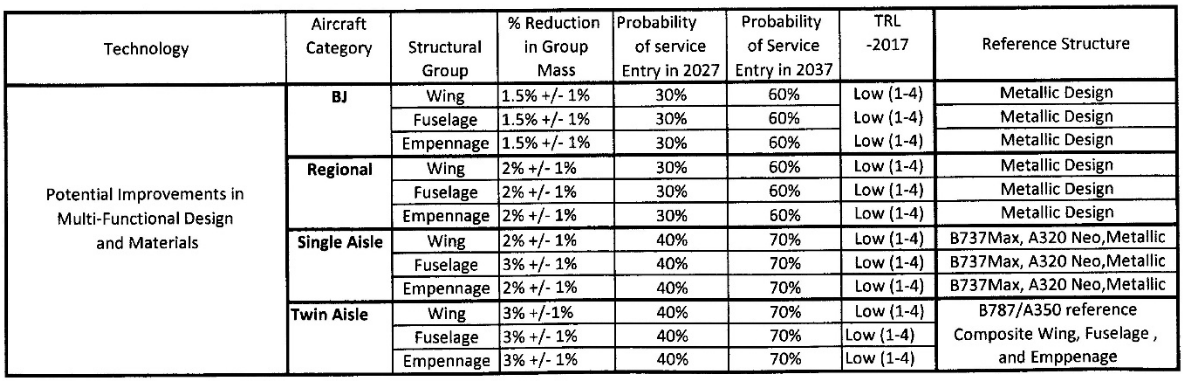


Technology	Aircraft Category	Structural Group	% Reduction in Group Mass	Probability of service Entry in2027	Probability of Service Entry 2037	TRL -2017	Reference Structure
Potential Improvements in Optimised local design	**BJ**	Wing	1% +/- 1%	30%	60%	Med (5-6)	Metallic Design
		Fuselage	1% +/- 1%	30%	60%	Med (5-6)	Metallic Design
		Empennage	1% +/- 1%	30%	60%	Med (5-6)	Metallic Design
	Regional	Wing	1.5% +/- 1%	30%	60%	Med (5-6)	Metallic Design
		Fuselage	1.5% +/- 1%	30%	60%	Med (5-6)	Metallic Design
		Empennage	1.5% +/- 1%	30%	60%	Med (5-6)	Metallic Design
	Single Aisle	Wing	2% +/- 1%	40%	70%	Med (5-6)	B737Max, A320 Neo,Metallic
		Fuselage	2% +/- 1%	40%	70%	Med (5-6)	B737Max, A320 Neo,Metallic
		Empennage	2% +/- 1%	40%	70%	Med (5-6)	B737Max, A320 Neo,Metallic
	Twin Aisle	Wing	3% +/- 1%	40%	70%	Med (5-6)	B787/A350 reference Composite Wing, Fuselage , and Emppenage
		Fuselage	3% +/- 1%	40%	70%	Med (5-6)	
		Empennage	3% +/- 1%	40%	70%	Med (5-6)	

Potential Mass saving through Multi-functional Design

The potential mass saving for this topic, take into account the mass reduction of other functions in relation to component weight.

Table E-4. Multi-Functional Design Mass Technologies



Technology	Aircraft Category	Structural Group	% Reduction in Group Mass	Probability of service Entry in 2027	Probability of Service Entry in 2037	TRL -2017	Reference Structure
Potential Improvements in Multi-Functional Design and Materials	**BJ**	Wing	1.5% +/- 1%	30%	60%	Low (1-4)	Metallic Design
		Fuselage	1.5% +/- 1%	30%	60%	Low (1-4)	Metallic Design
		Empennage	1.5% +/- 1%	30%	60%	Low (1-4)	Metallic Design
	Regional	Wing	2% +/- 1%	30%	60%	Low (1-4)	Metallic Design
		Fuselage	2% +/- 1%	30%	60%	Low (1-4)	Metallic Design
		Empennage	2% +/- 1%	30%	60%	Low (1-4)	Metallic Design
	Single Aisle	Wing	2% +/- 1%	40%	70%	Low (1-4)	B737Max, A320 Neo,Metallic
		Fuselage	3% +/- 1%	40%	70%	Low (1-4)	B737Max, A320 Neo,Metallic
		Empennage	2% +/- 1%	40%	70%	Low (1-4)	B737Max, A320 Neo,Metallic
	Twin Aisle	Wing	3% +/-1%	40%	70%	Low (1-4)	B787/A350 reference Composite Wing, Fuselage , and Emppenage
		Fuselage	3% +/- 1%	40%	70%	Low (1-4)	
		Empennage	3% +/- 1%	40%	70%	Low (1-4)	

APPENDIX F. LEAN BURN NO_X CHARACTERISTIC SLOPE

Figure 5-3 in the main body of the report showed the steeper D_p/F_{oo} vs OPR characteristics of engine families using lean-burn combustors. This appendix seeks to examine and explain this phenomenon.

From a combustion science point of view, in lean-burn combustors, enough air is introduced with the fuel from the injector so that it is never overall rich, though if the fuel is not premixed and pre-vaporized, the microscopic region around each droplet the mixture can be close to stoichiometric. The mixture remains lean throughout the combustor. However, a difficulty with hydrocarbon fuels is that they will not burn if the fuel–air-ratio is far below stoichiometric value and lean flames are inherently unstable. For the demanding operating conditions of aero combustors, the fuel cannot currently be fully premixed and pre-vaporized but requires a pilot zone for stability and low power operation. For high power operation, the lean-burn zone is hot, and as mentioned earlier, when above about 1800K, NO_x formation speeds up dramatically. Turbine entry temperatures (T_{40}) now exceed this value, resulting in a steep NO_x characteristic when the lean-burn combustor is operated at high T_{40} conditions i.e. at high power settings in high thrust versions within an engine family. This T_{40} effect provides a dependency on fuel-air-ratio which is almost absent in a rich-burn combustor.

From an engineering point of view, in the IE review in Washington DC, ICCAIA showed the LEAP certification data, and then described the terms in the following equation, normally used to correct measured NO_x emissions to standard conditions:

$$EI_{corrected} = EI_{measured}\left(\frac{P3_{ref}}{P3_{measured}}\right)^{a}\left(\frac{FAR_{ref}}{FAR_{measured}}\right)^{b} e^{(hum_{measured}-0.00634)d}$$

For lean-burn systems, exponent "b" is not zero (as is assumed for rich-burn systems)[119]. In the life of the engine family, the engine cycle typically migrates such that fuel-air-ratio increases as the product matures and therefore moves in the direction to worsen NO_x emissions. In addition, the lean-burn systems are moving along the lean side of a NO_x/fuel-air-ratio curve so any increase in fuel-air-ratio drives NO_x emissions higher. Staging can help to offset NO_x increases but may not be able to eliminate the NO_x increase in order to balance fuel burn, durability and operability of the engine.

Another aspect is that engine manufacturers will size an engine core for an average engine thrust range. As more thrust is needed for higher ratings, cycle migration, etc., the fuel-air-ratio is also driven upward, increasing NO_x. This is another reason for the steepness of the curve for engines with higher-thrust ratings. The practical outcome of this fuel-air-ratio dependency is shown in Figure F-1, where the four power settings from the engine certification data for all the engines from two engine families, one rich-burn, one lean-burn, are plotted on one chart:

The lean-burn fuel-air-ratio-dependency described above is seen for both lean-burn engine families, with the steeper characteristic at high power. For both rich-burn and lean-burn engine types, lower rated versions within the engine family do not use the steepening right hand potion of the characteristic. Because the lean-burn characteristic is steeper, lower rated versions of lean-burn engines benefit proportionally more when the characteristic is summed into the LTO D_p/F_{oo} format. The result in terms of D_p/F_{oo} vs OPR for the same four engine families is shown in Figure F-2, showing the steepening characteristics of the lean-burn GEnX and LEAP1 engine families.

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[119] Although for application of this SLS correction equation to altitude conditions, the pressure exponent "a" is changed from 0.5 to 0.4.

Left are Large Engines; Right are Mid-Size Engines

Figure F-1. Comparison of Rich- and Lean-Burn NO_x Characteristics

To a certain extent, the existence of lean-burn engine variants with poorer NO_x performance is a manufacturer choice or trade-off. These higher NO_x variants within a family are those where the core engine is being pushed harder to provide greater thrust, and probably greater fuel efficiency. However, in theory, the same job could be done with a resized core and combustor, thereby restoring the NO_x levels to the levels seem in the lower thrust variants. Economically such a course is often not reasonable.

One further aspect of the fuel-air-ratio dependence of lean-burn combustors are the NO_x emissions during climb and cruise. Fuel-air-ratio changes due to altitude will change the NO_x emissions to a greater extent than in rich-burn combustors. How the fuel is staged during operation is also a factor. Whilst improvements in LTO NO_x would still appear to promise improvements in altitude NO_x for lean-burn combustors, the extent of this improvement for the increasingly important climb-cruise NO_x is remains unclear. Data and calculation methodologies are needed.

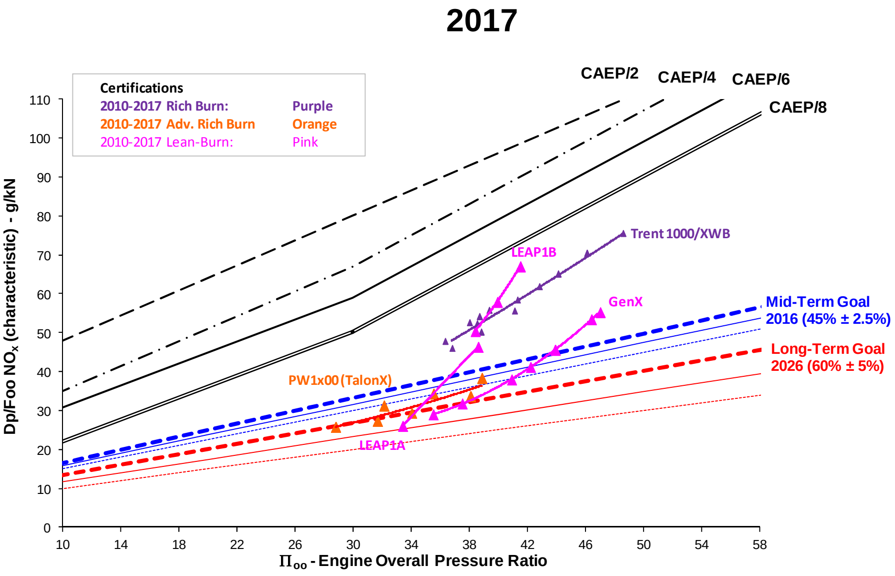

Figure F-2. D_p/F_{oo} vs OPR Characteristics for 2 Rich-Burn and 2 Lean-Burn Engine Families

APPENDIX G. NVPM – REVIEW OF EXISTING TECHNOLOGY AND DATA

ICCAIA presented information on nvPM at the Washington DC review but were unable to quote quantitative data from recent pre-certification testing due to commercial confidentiality. In this appendix, we indicate the relative nvPM performance of existing combustion technologies based on publicly available smoke number data from the CAEP Emissions Databank (EDB) and limited access to the CAEP nvPM database[120]. No commercially confidential data is disclosed in this report. To broaden the available analysis information for nvPM mass, a rough correlation of nvPM mass and Smoke Number (SN) data was made for the engines in the nvPM database. Showing that there was a rough correlation between SN and nvPM mass then allowed the much more extensive SN data in the ICAO EDB to be used to compare nvPM for different combustor technologies. Obviously, no such comparison is available for nvPM number where the confidential database was the only information source available. To elicit the technology issues, it was found necessary to work with emissions index (EI) data from the four individual LTO modes, rather than the LTO total (D_p/F_{oo}) used normally for goals etc. No cruise data is available, although inferences and extrapolations can be, and are, drawn from the LTO mode data. The combustor technologies compared here are roughly grouped into:

- Recent rich-burn technologies (e.g., RR Phase 5, GE SAC/DAC, P&W TALON I/II),
- Advanced rich-burn technologies (specifically P&W TALON X),
- Lean-burn technologies (specifically GE TAPS).

Smoke Number data for representative maximum and minimum thrust versions of in-service engine types were selected from the EDB for four thrust ranges, namely largest (>350kN), large ((250-350kN approximately), medium (100-150kN approximately) and small (<89kN approximately). Results of the data comparison were:

Largest engines (> 350kN): Recent rich-burn certifications suggest reducing smoke levels compared to previous rich-burn but there appears little prospect that these will reduce much further. Reductions would depend on detail design trades with NO_x for the particular combustor. Lean-burn, when introduced should give similar benefits as for "large engines" below.

Large engines (250-350kN approximately): Recent rich-burn certifications suggest reducing smoke levels relative to previous rich-burn technology but no reason to think that these will reduce much further. Lean-burn (here, TAPS) shows little change in smoke/nvPM for idle and approach settings compared to rich-burn for the initial versions, probably due to the rich-burn pilot being the dominant combustion here. However, at least from the published smoke number data, this seems to have been vastly improved for the latest (P2) version. For all versions, lean-burn shows at least an order of magnitude reduction in smoke for climb-out and take-off settings (where the lean-burn is operating). Any smoke/nvPM from the (rich-burn) pilot appears to be burned out at these settings. This is an important issue for climb and cruise.

Medium size engines (100-150kN approximately): More so than for the larger engines, advanced rich-burn certifications (TALON X) suggest substantial reduction in smoke levels compared to recent rich-burn, particularly at lower thrust rating, but there is no reason to think that these will reduce much further with this technology. Indeed the most recent certifications of a modified TALON X combustor shown smoke levels only 20% below the certification limit, significantly worse than the initial version and worse than older, similar-size engines. Lean-burn (again, TAPS) shows higher smoke for idle and approach settings compared to advanced rich-burn, performing better only at higher thrust ratings. We are comparing smoke number readings of around 1 (one) here – which is a highly subjective measurement. However, nvPM mass

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[120] One IE had access to the CAEP confidential nvPM database.

measurements confirm similar EIs for the two technologies for the engines, at least for the initial versions which entered service.

Smaller Engines (<89kN approximate): There is currently no lean-burn in this category and advanced rich-burn only in the very top of the thrust range. Currently, there is a large variation in smoke number, also reflected in the nvPM mass data between engine types. Even without the advanced rich-burn or lean-burn technologies, smoke/nvPM can vary by over an order of magnitude between similar thrust range small engines. Around half of this order of magnitude variation could be due to the mixed turbofan (MTF) measurement issue[121]. The remaining half appears to be related to the smoke/ NO_x design trade-off and perhaps to measurement issues, accompanied by the significant available margin to the regulatory smoke number limit.

To bring together the qualitative conclusions from the above analysis in quantitative form, available data has been summarized in the form of the nvPM mass emitted per LTO cycle per kN rated thrust (i.e. D_p/F_{oo}) for the four engine sizes and the three technology generations considered above.

Table G-1 shows this data collated and summarized from smoke number data in the EDB, converted to nvPM mass by the CAEP FOA3 method. A range of values is shown for previous rich-burn combustor technology in medium and smaller engines, reflecting manufacturer-to-manufacturer variation, rather than any other factor. The color coding is defined as: red shading is >1000 mg/kN/LTO, yellow is 100-1000 mg/kN/LTO, and less than 100 is green.

<table>
<tr><th>Engine Size</th><th colspan="2">Previous Rich-Burn</th><th colspan="2">Recent Rich-Burn</th><th>Initial Lean-Burn</th><th>Latest Lean-Burn</th></tr>
<tr><td>Largest</td><td colspan="2">60</td><td colspan="2">20</td><td>?</td><td>?</td></tr>
<tr><td>Large</td><td colspan="2">30</td><td colspan="2">40</td><td>30</td><td>8</td></tr>
<tr><td>Medium</td><td>100</td><td>500</td><td>15</td><td>70</td><td>15</td><td>?</td></tr>
<tr><td>Smaller</td><td>70</td><td>500</td><td colspan="2">500</td><td>?</td><td>?</td></tr>
</table>

Table G-1. LTO nvPM Mass per Rated Thrust (mg/kN/LTO) Based on SN data

Table G-2 shows the same type of data but this time rounded from confidential nvPM mass data. Compared to the hundreds of engines with smoke number data, there is only a limited sample (around 25 engines) of nvPM mass data available here. Note that some engines in the nvPM database are not yet available in the EDB. However, overall trends are confirmed. The color coding is defined as: red shading is >1000 mg/kN/LTO, yellow is 100-1000 mg/kN/LTO, and less than 100 is green.

<table>
<tr><th>Engine Size</th><th colspan="2">Previous Rich-Burn</th><th>Recent Rich-Burn</th><th>Initial Lean-Burn</th><th>Latest Lean-Burn</th></tr>
<tr><td>Largest</td><td colspan="2">200</td><td>10</td><td>?</td><td>?</td></tr>
<tr><td>Large</td><td colspan="2">200</td><td>125</td><td>?</td><td>?</td></tr>
<tr><td>Medium</td><td>?</td><td>500</td><td>10</td><td>15</td><td>5</td></tr>
<tr><td>Smaller</td><td>100</td><td>2500</td><td>50</td><td>?</td><td>?</td></tr>
</table>

Table G-2. Indicative nvPM Mass per Rated Thrust (mg/kN/LTO) Based on nvPM Mass Measured Data

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[121] Smoke measurement in MTF engines can be made after mixing in of the bypass stream. The nvPM measurements are core only.

These tables confirm the earlier conclusion that an order of magnitude improvement in nvPM mass from previous rich-burn to lean-burn and, often to advanced rich-burn combustor technology, is likely for the LTO cycle.

For cruise, no data is available in the nvPM database or the EDB on the translation of LTO nvPM mass or smoke number data to cruise nvPM. However, LTO data provides some insight:

- For most rich-burn systems, maximum sea level smoke number can lie between the 4 measured LTO points. This maximum may correspond to common cruise conditions, giving higher nvPM mass than implied by the 4 LTO values.
- Rich-burn systems usually have higher smoke (and EI nvPM mass) at higher powers. By contrast, lean-burn combustors have a flatter profile. The LTO cycle emphasizes the idle phase (26 minutes) compared to approach (4mins), climb-out (2.2mins) and take-off (0.7mins). Even accounting for the fuel-flow, for a flat profile, improvements in cruise nvPM should be greater than the calculated LTO improvements.
- For "staged" rich-burn systems, there is an additional uncertainty relating to the staging points[122] and how they relate to cruise conditions.
- For lean-burn systems, a similar uncertainty relating to the scheduling of the (partially rich-burn) pilot also exists. However, in this case, there is a likelihood that at higher powers, the lean-burn system will burn out any pilot-generated nvPM, resulting in very low cruise nvPM mass. However, under which cruise conditions the pilot is operating alone and at which cruise conditions there is substantial lean-burn combustion is not known.

It is concluded that lean-burn combustors will result in a reduction in cruise nvPM mass of one or two orders of magnitude compared to previous rich-burn combustors, subject to better understanding of staging mechanisms (which may reduce this improvement). For advanced rich-burn combustors, improvements in cruise nvPM mass should be similar to LTO improvements (one order of magnitude), subject to better understanding of staging mechanisms.

There are no nvPM number results other than the confidential nvPM engine tests within the CAEP dataset. CAEP Working Group 3 have, in developing a so-called SCOPE11 modelling methodology, assumed particle size by LTO mode as 15μm for idle/taxi, 20μm for approach, 40μm for climb-out and 50μm for take-off mode, presumably based mainly if not exclusively on rich-burn combustion based results. There could be substantial difference with lean-burn due to the burn-out process.

In terms of nvPM number changes for different generations of technology and different sizes of engine, the same analysis of the confidential nvPM data has been carried out as was done for Table G-2 – except this time for nvPM number rather than mass (Table G-3). As before, values shown are rounded typical values for combustor technologies in the various engine sizes. The color coding is defined as: red shading is >1000 x 10^{12}/kN/LTO, yellow is 100-1000 x 10^{12} /kN/LTO, and less than 100 is green.

Engine Size	Previous Rich-Burn		Adv Rich-Burn	Initial Lean-Burn	Latest Lean-Burn
Largest	1500		250	?	?
Large	1500		1500	?	?
Medium	750	5000	100	50	50
Smaller	1500	10000	500	?	?

Based on nvPM Number Measured Data

Table G-3. Indicative nvPM Number per LTO per Unit Rated Thrust (million/kN/LTO)

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[122] "staged" refers here to significant steps of any form in the fuel input scheduling.

It should be stressed that for both mass and number data – more so for number data – there are apparent inconsistencies and unexpected results which are not fully explained. It is recognized that as for low smoke numbers, the mass and number measurements for low emission engines are at the lower limit of detection for the measuring systems and data will be subject to procedural and operator variation –as well as the usual engine-to-engine variation. This uncertainty is reflected in the conclusions which speak only in terms of orders of magnitude differences.

LTO Cycle – nvPM number: Data is sketchy, but in common with nvPM mass, advanced rich-burn offers an order of magnitude reduction in nvPM number in LTO for the best performing engines. Lean-burn appears to offer more than this. For lean-burn, initial data suggests a much greater mass per particle in climb-out and take-off modes compared to rich-burn. If this apparent change is real, this gives even greater proportional reduction in particle numbers than simply the reduction in mass, up to a further order of magnitude. However, ICCAIA advise that the measurements are too close to the limit of detection and should be discounted.

Cruise – nvPM number: As for nvPM mass, the interim conclusion is that lean-burn combustors will result in a reduction in cruise nvPM number of one or two orders of magnitude compared to previous rich-burn combustors. For advanced rich-burn combustors, improvements in cruise nvPM number should be similar to LTO improvements (an order of magnitude) for the best performing engines, subject to better understanding of staging mechanisms.

APPENDIX H. HISTORICAL BACKGROUND ON NOISE CERTIFICATION AND IMPROVEMENT TRENDS

Aircraft noise has been a subject of concern for over a century. The introduction of jet aircraft exacerbated the challenge of aircraft noise reduction. However, continuous design improvements have been introduced since the advent of the jet age and noise levels from individual aircraft operations have decreased considerably. These noise reductions have resulted primarily from the reduction of jet velocity to increase engine efficiency, but technological advances and design choices have also led to a considerable reduction in noise. Recent new aircraft and engines are carefully designed using state of the art methods that allow the manufacturer to simultaneously improve efficiency while maintaining or reducing noise. Today, noise is a top-level design and operational requirement for manufacturers and airlines as it presents a constraint on air traffic growth.

This progress has been a result of a long history of innovation and technical progress – some of which had noise reduction as a useful co-benefit. Improvements in the scientific knowledge has led to significant progress in the analytical tools and testing methods to enable reduced noise designs. Government and industry-sponsored research programs have supported the development of quieter, more fuel efficient turbofan engines as well as quieter airframe high-lift systems that ensure safe aircraft operations. This has all been accompanied by aircraft noise Standards of progressively increased severity. National aviation authorities, airports, and airlines are also implementing operational procedures to reduce the noise experienced by those living under flight paths. In addition, airports have implemented rules to control noise impact on the neighboring populations under the ICAO balanced approach.

During the design process, it is not uncommon for a manufacturer to consider compliance with the latest noise certification limit, or an anticipated certification limit, with a given margin, and a number of relevant local airport noise rules, as well as the anticipated noise impact of a fleet over a given period of time. Aircraft design and operation are driven by multiple requirements, including safety and certification requirements that cannot be compromised, as well as fuel burn and emissions. These varied requirements will lead to more environmentally-friendly products, but to an extent that depends on multiple constraints, which include operational capability, reliability, safety, certification, performance, systems, maintainability and operating costs. The designer has to simultaneously address these aspects, including fuel burn in particular, while optimizing design and refining configuration, hence the growing importance of interdependencies, trade-offs and optimization aspects. In doing so, new features are introduced from one aircraft (and engine) generation to the next one, and new configurations are utilized.

The noise from civil aircraft is regulated by ICAO Annex 16, Volume I. Certification for noise relies on measurements at three positions, two for take-off (referred to as lateral and flyover) and one for landing (referred to as approach). The levels are expressed in decibels (EPNdB[123]) using effective perceived noise level (EPNL). The layout for testing is shown in Figure H-1 below.

The noise at the lateral position is the highest noise measured along a line parallel to the runway whilst the aircraft is departing at full power and the maximum usually occurs when the aircraft has climbed to about

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[123] Noise is always measured in terms of decibels, dB. Perceived Noise Level (PNL) forms the basis of the aircraft noise certification measurements by making allowance for the sensitivity of the human ear. Humans are more annoyed by noise at mid frequencies. Further, they are also more annoyed by tonal content than noise of a broadband nature. The measured noise is corrected for both of these to give PNLT. Finally the annoyance is affected by the duration over which the noise is present and allowance is made for this. The result is that a set of defined procedures are made to convert the instantaneous measurements of sound pressure level into a single number, the Effective Perceived Noise Level, EPNL, which is measured in units of EPNdB. The regulations adopted by the ICAO are expressed in terms of EPNdB.

1000 feet. Flyover noise is measured directly under the flight path after take-off and at an altitude where it is normal to cut-back the power to reduce the noise whilst still maintaining a safe rate of climb. The approach noise is also measured directly under the flight path as the aircraft prepares to land, with the glide slope carefully controlled. The flights are for the maximum allowed weight of the aircraft and measurements are corrected to standard atmospheric conditions. Tests differ from actual operating conditions, but provide a standard way of comparing aircraft and thereby regulating aircraft noise. Past studies made within ICAO/CAEP have shown that the ranking of actual aircraft noise measured in real operation was consistent with the one based on certification levels. Approximate absolute levels of the certification levels shown for a range or aircraft are shown in Figure H-2, compared with the Chapter 3 levels (introduced in 1977). The cumulative noise is the sum of the noise at all three of the measurement conditions.

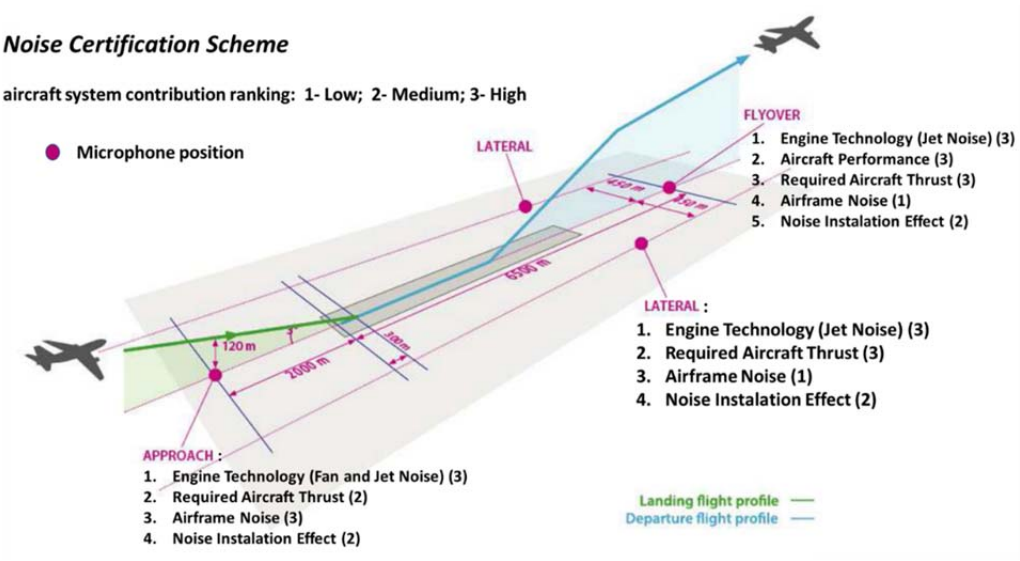


Figure H-1. Noise Certification Reference Positions with Principal Noise Sources

In 2001, Chapter 4 of Annex 16, Volume I required for new-type certification a reduction in cumulative margin of 10 EPNdB from the levels in Chapter 3. In addition, at no condition must the level exceed that for Chapter 3 and there must be a cumulative margin of at least 2 EPNdB from Chapter 3 for any two conditions. Chapter 14, agreed in 2014, applies to new-type certification from 2017 (small aircraft from 2020); it requires a cumulative reduction of 7 EPNdB relative to Chapter 4 (17 EPNdB relative to Chapter 3).

Very large reductions have been achieved in aircraft noise since the introduction of Annex 16 in 1971 (about 20 EPNdB at sideline condition), irrespective of large increases in aircraft size and weight. A large part of this has been achieved thanks to the introduction of turbofan engines with reduced jet noise.

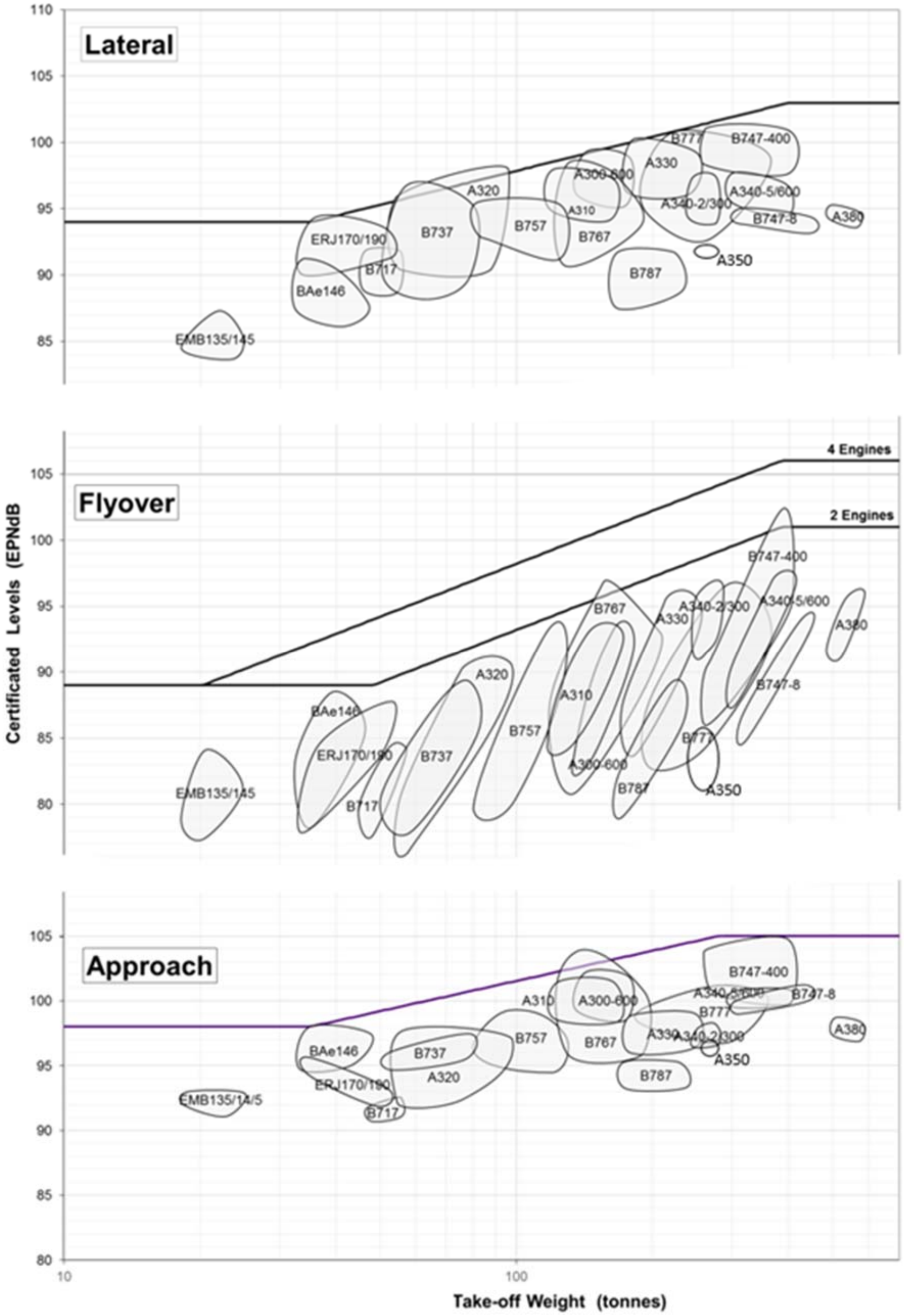
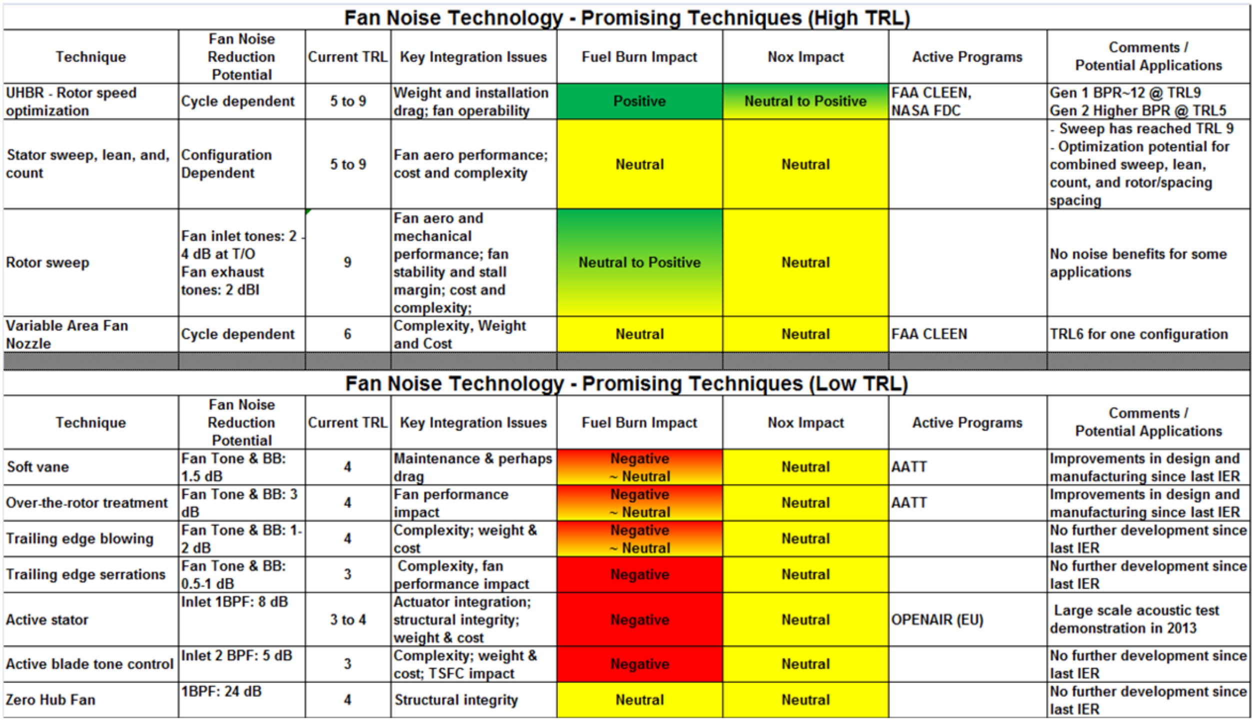


Figure H-2. Approximate Aircraft Certification Noise Levels Relative to ICAO Annex 16, Volume I, Chapter 3

APPENDIX I. POTENTIAL NOISE TECHNOLOGIES

I.1 FAN NOISE



Fan Noise Technology - Promising Techniques (High TRL)

Technique	Fan Noise Reduction Potential	Current TRL	Key Integration Issues	Fuel Burn Impact	Nox Impact	Active Programs	Comments / Potential Applications
UHBR - Rotor speed optimization	Cycle dependent	5 to 9	Weight and installation drag; fan operability	Positive	Neutral to Positive	FAA CLEEN, NASA FDC	Gen 1 BPR~12 @ TRL9 Gen 2 Higher BPR @ TRL5
Stator sweep, lean, and, count	Configuration Dependent	5 to 9	Fan aero performance; cost and complexity	Neutral	Neutral		- Sweep has reached TRL 9 - Optimization potential for combined sweep, lean, count, and rotor/spacing spacing
Rotor sweep	Fan inlet tones: 2 - 4 dB at T/O Fan exhaust tones: 2 dBI	9	Fan aero and mechanical performance; fan stability and stall margin; cost and complexity;	Neutral to Positive	Neutral		No noise benefits for some applications
Variable Area Fan Nozzle	Cycle dependent	6	Complexity, Weight and Cost	Neutral	Neutral	FAA CLEEN	TRL6 for one configuration

Fan Noise Technology - Promising Techniques (Low TRL)

Technique	Fan Noise Reduction Potential	Current TRL	Key Integration Issues	Fuel Burn Impact	Nox Impact	Active Programs	Comments / Potential Applications
Soft vane	Fan Tone & BB: 1.5 dB	4	Maintenance & perhaps drag	Negative ~ Neutral	Neutral	AATT	Improvements in design and manufacturing since last IER
Over-the-rotor treatment	Fan Tone & BB: 3 dB	4	Fan performance impact	Negative ~ Neutral	Neutral	AATT	Improvements in design and manufacturing since last IER
Trailing edge blowing	Fan Tone & BB: 1-2 dB	4	Complexity; weight & cost	Negative ~ Neutral	Neutral		No further development since last IER
Trailing edge serrations	Fan Tone & BB: 0.5-1 dB	3	Complexity, fan performance impact	Negative	Neutral		No further development since last IER
Active stator	Inlet 1BPF: 8 dB	3 to 4	Actuator integration; structural integrity; weight & cost	Negative	Neutral	OPENAIR (EU)	Large scale acoustic test demonstration in 2013
Active blade tone control	Inlet 2 BPF: 5 dB	3	Complexity; weight & cost; TSFC impact	Negative	Neutral		No further development since last IER
Zero Hub Fan	1BPF: 24 dB	4	Structural integrity	Neutral	Neutral		No further development since last IER

Figure I-1. Fan Noise Technologies

I.2 NACELLE LINER NOISE TECHNOLOGIES

Propulsion System area	**Technology Area**	**Source Noise Affected**	**Noise Reduction**[1]	**Potential Aircraft Application**	**High TRL**[3]	**Low TRL**[3]
Nacelle-Air Inlet	Zero-splice	Forward fan	1-3 dB low power, (0.5-1.5 EPNdB), 3-4 dB high power, +LPC noise /MPT/BSN	TA-SA-RJ	7-9	
	Inlet low drag liner	Forward fan	b.c.t.(2)	TA-SA	7-9	
	Nose lip liner	Forward fan	1-3 dB high power, (0.5-1.5 EPNdB), +LPC noise	TA-SA	6-7	
Nacelle cowls	Aft cowl liner	Fan rearward	1-3 dB broadband	TA-SA	6-9	
Nacelle Plug	High Temp CMC liner	Core	Similar to metallic liners, but allows higher temperature	TA-SA	6-7	
Nacelle	Optimized zone liner	Fan rearward	5 dB peak noise, (1-1.5 EPNdB)	TA-SA-BWB		4-6
Nacelle	Aft-fan duct low drag liner	Fan rearward	b.c.t.(2)	TA-SA		5
Nacelle cowls	Aft cowl liner	Fan rearward	1-3 dB broadband	TA-SA		5
Nacelle	Combustor liner	Core	5-10 dB low frequency (peak at low power) but no significant EPNdB impact on current turbofans	TA-SA-RJ		4-5
Concept	Active/adaptive liner	Fan	2-7 dB fan tones	TA-SA		3

(1) ICCAIA estimations
(2) b.c.t. bookkept as current treatment
(3) ICCAIA categorization

I.3 SLAT NOISE TECHNOLOGIES

A vortex flow develops in the slat cove driven by the flow through the slat slot. Between this vortex and the undisturbed slot flow, a free, unstable shear layer develops. The impingement of the vortical shear flow on the downstream cove surface represents one of the slat noise sources followed by a noise that is generated when this unsteady flow is shed on the slat trailing edge. Because the wing leading edge is located in the acoustic near field of this trailing-edge noise source, it can also be assumed that the wing leading edge reacts as a sound source. The vortex position in the slat cove is not stationary but slightly oscillating and contributes to the low-frequency part of the slat noise spectrum. Coherent vortex shedding of slat trailing edge is observed in two-dimensional scale model experiments as tonal noise phenomena, however, it was never observed at full-scale because of its smaller relative trailing-edge thickness and Reynolds number. High-frequency tone noise can be observed due to boundary layer instabilities on the slat suction side, in particular at the aileron section of the wing. At the leading edge of this section, the high-lift device must be designed taking into account the fact that circulation is much less intense due the inexistence of a flap. With the exception of these tone noise artifacts, slat noise is broadband. The slat noise directivity shows maximum levels in rear arc direction and levels decrease slightly with increasing aircraft angle of attack. However, this is only valid for low and moderate values of angle of attack (typical for landing conditions), whereas for higher angles there is a rapid and massive level increase.

I.3.1 Slat Noise Reduction

The first ideas focussed on add-on devices based on the current knowledge of unsteady flow characteristics in the slat cove/slot area. A slat cove cover, or slat cove filler, was designed to attenuate the strength of the vorticity in the free shear layer between the cove vortex and the slot flow. It was noted that the filler shape was an extremely sensitive parameter and that the filler could cause a noise increase for only slight deviations of the angle of attack from the design point. This characteristic makes difficult the practical application of the cove filler devices unless a morphing or other smart control system is available to adjust the cove filler shape.

Perforated/foam material or brushes can be applied to the slat trailing edge in order to alleviate the transformation of boundary-layer flow turbulence into propagating sound waves. However, the appropriate brush design and installation must be carefully chosen to not degrade the high-lift performance, and the airworthiness of such materials must be proven through dedicated studies. In contrast to cove fillers and trailing-edge modifications, liners do not affect the source mechanisms in the first place but aim at the attenuation of sound waves along their propagation path between the slat cove and the wing leading edge. Recent experimental studies on wing leading-edge liners indeed provided some appreciable reduction. However, all these technologies, which were not bringing a breakthrough improvement, were accompanied by some high-lift performance degradation, or turned out to be impractical for aircraft application. A balanced aerodynamic and acoustic design of both slat shape and setting was envisaged which actually showed a marked noise reduction potential.

Very long chord slat (VLCS) can be designed, balancing the aerodynamic and the acoustic performance. A VLCS device can provide higher maximum lift coefficient and at the same time reduce slat noise by about 4dB. Although VLCS produces high CL_{max}, it decreases the wing performance at operational incidence angles, mainly because the main CL contributing element is smaller, therefore it cannot be designed for the full wingspan. Another interesting leading edge high-lift device is the droop leading edge or leading-edge flap already in use. This device avoids the slat noise and if is used at wing inboard, it can reduce weight and take-off drag, which is beneficial to 2nd segment climb performance (about 3% improvement versus the slat) while the adverse effect on the maximum lift was still acceptable (about 5% loss versus the slat). The main recommendation concerning silent leading-edge high-lift design is to combine a regular slat, VLCS and droop leading edge. Krueger-flaps are also a possible alternate leading edge device, due to its high aerodynamic performance despite its complexity and weight. Krueger-flaps aeroacoustics is not well tested but should be developed in the next years since it could be an alternative of slats for a natural laminar flow wing or hybrid laminar flow control for medium and long-range aircraft.

I.4 FLAP NOISE TECHNOLOGIES

Numerous CFD computations and detailed experimental flow surveys have been performed to characterize the complex three-dimensional vortex structure that develops at flap side edges. A primary vortex is developing from the flap pressure side close to the flap leading edge. A secondary vortex then is formed from the edge toward the flap suction side. Both vortices merge and finally separate from the flap suction side surface typically around a 70% flap chord position. Therefore, flap side-edge noise is assumed to be a composition of the classical trailing-edge noise source mechanism, noise from the interaction of the vortex flow with the flap upper surface and noise originating from accelerated free turbulence in the vortex flow. Broadband flap side edge noise scales on a Strouhal number basis and levels increase with a flow velocity corresponding to a fifth power law. The radiation directivity is found to be quite complex and frequency dependent.

I.4.1 Flap Noise Reduction

Flap side edges are an important noise source of high-lift devices, and almost in parallel to research into slat noise reduction technologies, efforts were undertaken to develop means of reducing flap side-edge noise. Corresponding edge modifications comprised both added-on side-edge fences and flow transparent edge replacements, for example, porous metal foam or brushes. The latter proved to be very effective but such material has not yet been approved for aircraft applications Aerodynamic tests with either side-edge fences or a flow transparent edge design showed that the side-edge vortex diameter is increased and shifted outboard (at constant overall vortex strength), which is assumed to be the reason for the observed noise reduction.

A still more drastic approach is the elimination of the edge through the so-called moldline technology providing a significant noise reduction potential. Here, the former single edge vortex breaks up into a spanwise distribution of weaker vortices due to a more continuous spanwise variation of the wings' circulation. The practical application of this solution, however, would require quite complex flap structures and hinge mechanisms.

APPENDIX J. ENVIRONMENTAL DESIGN SPACE COMPONENTS

J.1 INTRODUCTION

This appendix provides a further discussion of the components of the Environmental Design Space (EDS); the modelling and simulation environment utilized to assess the technology baskets for the IEIR goal study. EDS is comprised of a number of NASA developed analysis tools for the evaluation of the engine and airframe performance characteristics. Each of the tools are described herein with the connectivity of the tools described in later sections.

J.2 CMPGEN

CMPGEN is a NASA Glenn analysis tool used to generate component maps for the fan, LPC, and HPC[124]. The user-defined inputs for each component include the design point pressure ratio, the corrected flow, corrected flow per area, and stall margin. The program uses these design point values along with built-in empirical relationships to calculate off-design data for corrected flow, efficiency, and pressure ratio as a function of corrected speed and pressure ratio. The ranges of corrected speed and pressure ratio for use in component map generation are also specified by the user.

J.3 NUMERICAL PROPULSION SYSTEM SIMULATION (NPSS)

The Numerical Propulsion System Simulation (NPSS) is an aerothermal-mechanical computer simulation that is capable of modelling physical interactions within an engine model. NPSS is under continuing development by the NPSS Consortium, hosted at Southwest Research Institute and is supported by the U.S. aeropropulsion industry and the Department of Defense in hopes of lowering concept-to-production development time and reducing the need for full-scale tests or more sophisticated analysis tools[125,126]. Version 1.6.5v is currently integrated into EDS. NPSS is an object oriented simulator which performs steady state and transient off-design performance prediction by calling upon a number of varying fidelity tools which are controlled using the NPSS solution algorithm. At this time, NPSS offers the following capabilities:

- Complete model definition through input files(s)
- NIST (National Institute of Standards and Technology) compliant thermodynamic gas-properties package
- Analytical solver with auto-setup, constraints, and discontinuity handling
- Steady-state and transient system simulation
- Flexible report generation
- Built-in object-oriented programming language for user-definable components and functions
- Support for distributed running of external code(s)
- Support for test data matching analysis

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[124] Converse, G.L.; and Giffin, R.G., "Extended Parametric Representation of Compressors Fans and Turbines. Vol. I - CMGEN User's Manual," NASA CR-174645, 1984

[125] "NPSS User Guide." Software Release: NPSS_1.6.4; REV: Q; Doc. #: NPSS–User; Doc Revision: W in progress; Revision Date: November 5, 2006

[126] "NPSS Reference Sheets." Software Release: NPSS_1.6.4 V; Doc. #: NPSS–Ref Sheets; Doc Revision: W in progress; Revision Date: January 05, 2007

J.4 WEIGHT ANALYSIS OF TURBINE ENGINES (WATE)

Weight Analysis of Turbine Engines (WATE) was developed by the Boeing Military Airplane Development group as a subprogram for the NASA Engine Performance Program (NEPP) in 1979 in an effort to provide weight and dimension estimates for propulsion systems for use in conceptual design. EDS currently utilizes an updated version, WATE++, which has been moved to the same language as NPSS. WATE++[127] estimates the weight and dimensions of both large and small gas turbine engines. Approximations made within WATE++ are based on historical correlations, material properties, geometric characteristics, and component parameter information. Sizes and weights for the inlet, fan, compressor, turbine, burner, mixers, nozzles, ducts, splitters, and valves are calculated.

J.5 FLIGHT OPTIMIZATION SYSTEM (FLOPS)

The FLight OPtimization System (FLOPS) is a multidisciplinary computer program developed for conceptual and preliminary design and evaluation of advanced aircraft concepts[128]. EDS currently runs FLOPS version 8.11, which consists of eight modules:

- Weights, aerodynamics
- Engine cycle analysis – Not utilized for EDS
- Propulsion data scaling and interpolation
- Mission performance
- Take-off and landing
- Noise – Not utilized for EDS
- Cost analysis – Not utilized for EDS
- Program control

Through the program control module, FLOPS may be used to analyze a point design, parametrically vary certain design variables, or optimize a configuration. The weights and aerodynamics modules use statistical and empirical methods to estimate respective metrics, i.e., component weights and aerodynamic performance. The engine cycle analysis module is based on a modified version of NEPCOMP designated QNEP. This module is capable of internally generating an engine deck (thrust, fuel flow, etc.) at various Mach-altitude combinations. Following the engine deck module, the propulsion module sizes the engine by making use of scaling laws. The mission performance module takes the information calculated in the previous modules and determines the performance characteristics of the aircraft. The take-off and landing module calculates the requirements necessary to meet the performance demands at take-off and landing and with the available data calculated attempts to ensure that the aircraft meets all FAR 25 requirements. The noise footprint module based on the FOOTPR program generates take-off and climb-out profiles for the aircraft and computes the noise footprint contour data and/or noise levels at user specified or FAA locations. From the cost analysis module, discussed in more detail in the next section, the airframe RDT&E and production cost, engine RDT&E and production costs and direct and indirect operating costs are estimated to provide a life cycle cost for subsonic transport aircraft. Most of the input data required for these modules is contained in a Namelist formatted input file. Many values have default settings to provide reference values for new users. FLOPS also has the capability of using data from external tools, specifically engine performance decks, and higher fidelity weight and aerodynamic prediction tools. In lieu of the internal engine deck generation capabilities, EDS generates the performance deck within NPSS and the propulsion weight and dimensions in WATE++ and passes the data to FLOPS.

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[127] Tong, M., Naylor, B., "An Object-Oriented Computer Code for Aircraft Engine Weight Estimation," NASA/TM-2009-215656

[128] "Flight Optimization System, Release 8.11, User's Guide." L. A. (Arnie) McCullers, Revised 9 October 2009

J.6 AIRCRAFT NOISE PREDICTION PROGRAM (ANOPP)

The NASA Aircraft Noise Prediction Program (ANOPP[129,130]) was developed by the NASA Langley Research Center and provides a capability to predict noise from aircraft in flight, accounting for the effects of the aircraft configuration, its airframe, its engines, its operations, and the atmosphere. This is accomplished by computing the source noise from each aircraft component that comprises the engine and airframe and propagating these results through the atmosphere to far-field observers. ANOPP computes the acoustic power of aircraft noise sources as a function of polar and azimuthal angles, frequency, and time along a user defined flight path. The observer receives the noise signal from the direct ray and, for observers above the ground, can also receive a ray reflected by the local ground surface. The noise source models in ANOPP have been developed over decades and largely represent semi-empirical and empirical models for a wide range of aircraft technologies. An analytical method based on Fresnel diffraction theory is also included to provide an initial prediction of the effects of shielding and reflection. User defined tables of data can be input to directly represent the effects of noise reduction technologies or other effects. New noise source models continue to be developed to provide better prediction of future aircraft technology. In addition, new modelling development continues to provide more general methods for the effects related to propulsion airframe aeroacoustic interactions including from shielding and reflection.

The outputs from ANOPP are divided in two main groups: certification noise levels and noise power distance curves. The first are calculated using the geometric and cycle information of the engine from NPSS and the trajectory provided by FLOPS, which ANOPP uses to define where to start the propagation of the noise produced. ANOPP then calculates the noise perceived at the 3 certification observers, following FAR part 36 requirements. ANOPP calculates the effective perceived noise levels for each individual component, as well as the overall aircraft noise level. The NPD's are calculated in a similar way, but only for the whole aircraft, not individual components. Instead of using a trajectory, ANOPP calculates the noise levels at different distance from the aircraft and at different thrust settings, for both approach and landing configurations.

J.7 EDS FUNDAMENTAL ARCHITECTURE

The fundamental architecture of EDS is based on a multiple point design (MPD) for the engine based on airframe thrust requirements and a design loop is iterated until convergence is reach between the engine capability and airframe requirements. The base logic for EDS revolves around NPSS simultaneously solving four design points. The Aero Design Point (ADP) is considered the component design point, with fan pressure ration (FPR), low pressure compressor pressure ratio (LPCPR), and high pressure compressor pressure ratio (HPCPR) specified at this point. The bypass ratio (BPR) at the ADP is determined by specifying an Extraction Ratio. The ADP T4 is set by specifying a maximum T4 and an engine lapse rate. The airflow is determined by specifying the thrust required at top of climb (TOC). Turbine cooling flows are determined at the Take-off condition (max T4). Design and Power Management variables are included in addition to variables provided by Auto Solver Setup for continuity and work balance. Finally, solver variables are added to specify the scaling points for the fan and compressor maps and to determine the turbine cooling flows using the Coolit algorithm[131]. The independent variables used for convergence in the MDP are

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[129] Lopes, L.V., Burley, C.L.,"ANOPP2 User's Manual, Version 1.2", NASA/TM-2016-219342, October 2016.

[130] William E. Zorumski, "Aircraft Noise Prediction Program Theoretical Manual", NASA Technical Memorandum 83199. Revised December 2006

[131] Gauntner, J., "Algorithm for Calculating Turbine Cooling Flow and the Resulting Decrease in Turbine Efficiency," NASA-TM-81453

provided in Schutte, while the flow of information is depicted in Figure J-1[132]. The convergence criteria for the design case is a thrust and fuel balance of the engine and airframe.

The convergence architecture is based on the following logic:

- Generate initial component maps
- Perform the MPD based on an initial guess of the four thrust requirements
- Create engine flowpath
- Generate the engine performance deck through the flight envelope (Flt Env)
- Fly the aircraft through FLOPS to obtain actual thrust requirements at the four points
- Iterate until thrust available equals thrust required

Table J-1. EDS Multi-point Design List of Varied Independents

Parameter to Vary	To Satisfy
ADP BPR	ADP Extraction Ratio (= 1.0)
ADP Airflow	TOC Thrust
ADP FAR	ADP T4
TOC FAR	TOC Airflow
Take-off FAR	Take-off T4
SLS T4	SLS T4
Fan design point Rline	Fan design point surge margin
LPC design point Rline	LPC design point surge margin
HPC design point Rline	HPC design point surge margin
HPT vane percent flow	Coolit calculation at take-off
HPT blade percent flow	Coolit calculation at take-off
LPT vane percent flow	Coolit calculation at take-off
LPT blade percent flow	Coolit calculation at take-off

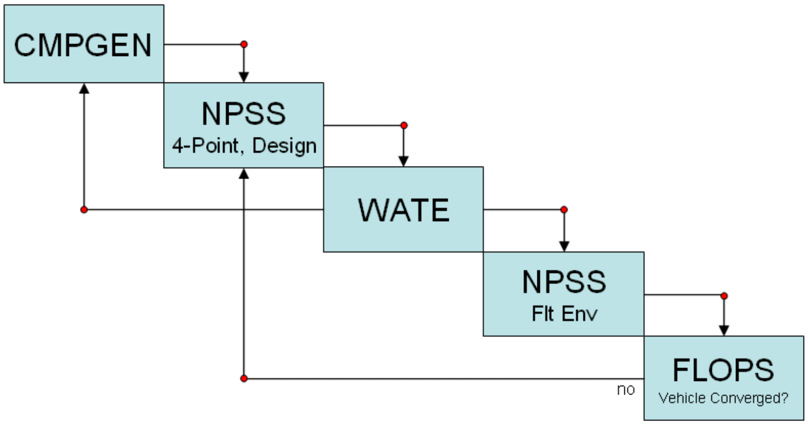

Figure J-1. EDS Vehicle Convergence Architecture

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[132] Schutte, J., Tai, J., Mavris, D., "Multi-Design Point Cycle Design Incorporation into the Environmental Design Space," 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA 2012-3812

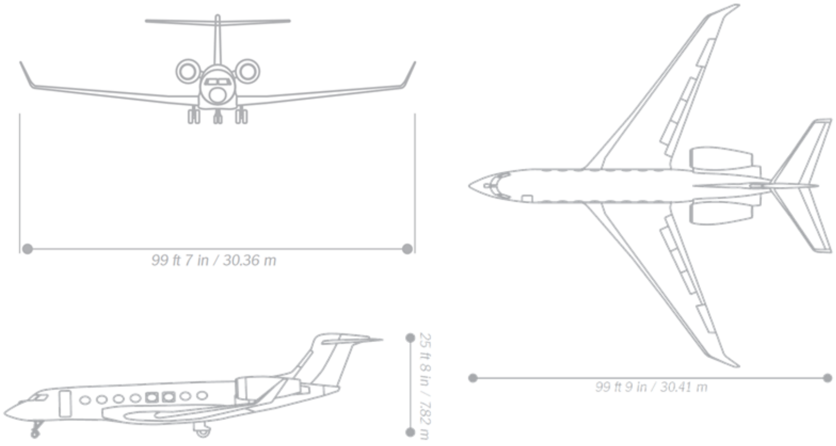
APPENDIX K. TECHNOLOGY REFERENCE AIRCRAFT MODELLING DETAILS

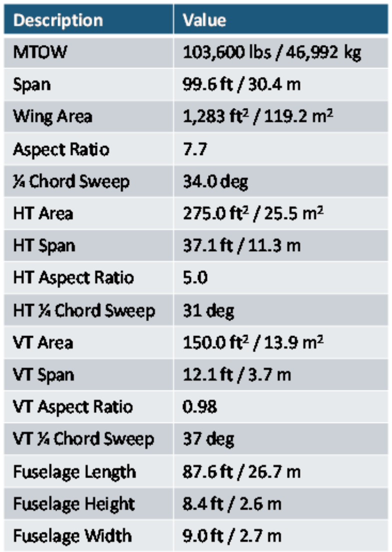
K.1 BUSINESS JET TRA

K.1.1 Assumptions

BJ Technology Reference Aircraft (TRA) is based on a technology level in line with state-of-the-art of the vehicles in production today:

- Notional Gulfstream G650ER
- Assumed payload of 1,800 lbm (817 kg)
    - 8 passengers @ 102 kg each (@ design range including baggage)
- Design range of 7,500 nm
- Metallic main components (wing, fuselage, empennage)
- 2 turbofan engines (notional Roll-Royce BR725 A1-12)
    - Created notional engine model from publically available information and ICAO databank
    - Match ICAO fuel flow and thrust levels



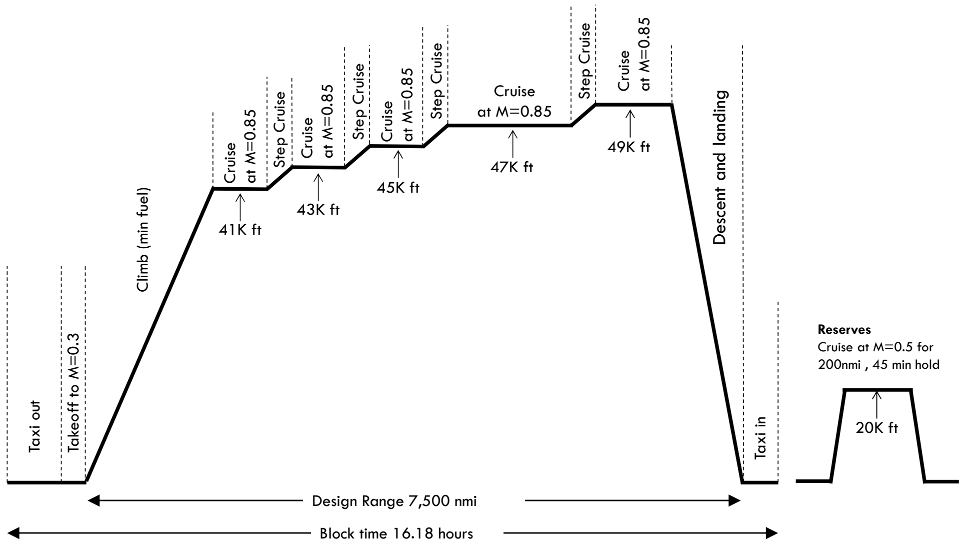


Description	Value
MTOW	103,600 lbs / 46,992 kg
Span	99.6 ft / 30.4 m
Wing Area	1,283 ft² / 119.2 m²
Aspect Ratio	7.7
¼ Chord Sweep	34.0 deg
HT Area	275.0 ft² / 25.5 m²
HT Span	37.1 ft / 11.3 m
HT Aspect Ratio	5.0
HT ¼ Chord Sweep	31 deg
VT Area	150.0 ft² / 13.9 m²
VT Span	12.1 ft / 3.7 m
VT Aspect Ratio	0.98
VT ¼ Chord Sweep	37 deg
Fuselage Length	87.6 ft / 26.7 m
Fuselage Height	8.4 ft / 2.6 m
Fuselage Width	9.0 ft / 2.7 m

*Drawings not to scale

Images taken from http://www.gulfstream.com/images/uploads/brochures/aircraft/G650_Details_ENG.pdf

K.1.2 Mission Profile



K.1.3 Vehicle Performance

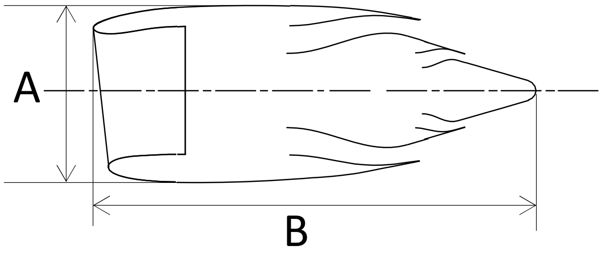
Parameter	Acronym	Units	Value
Approach Speed	V_{app}	mps	53.5
Aspect ratio	AR	~	7.7
Bypass ratio (SLS)	BPR	~	4.32
C_{Lmax} Landing	$C_{LmaxLdg}$	~	2.1
C_{Lmax} Take-off	C_{LmaxTO}	~	1.9
Cockpit crew	~	~	2
Design cruise speed	M_{des}		0.85
Design fuel	~	kg	20,493
Design Payload at R_2		Kg	817
Design Range at R_2	R2	nm	7,500
Fuselage height	DF	m	2.6
Fuselage length	XL	m	26.7
Fuselage width	WF	m	2.7
Initial Cruise Altitude	~	ft	41,000
Landing field length	LdgFL	m	1,247
Manufacturer's empty weight	MEW	kg	22,984
Maximum L/D at cruise	~	~	19.13
Maximum landing mass	MLM	kg	26,452
Maximum SLS thrust per engine	F_n	kN	75.7
Maximum take-off mass	MTOM	kg	46,992
Number of passengers	# pax		8
Operating empty weight	OEW	kg	24,494
Overall pressure ratio (SLS)	OPR	~	26.1
Ramp gross weight	~	kg	47,174
Reference geometric factor	RGF	m2	45.6
Service ceiling	~	ft	51,000
Take-off field length	TOFL	m	1,079
Wing area	SW	m2	119.2
Wing span	~	m	30.4
Wing ¼ chord sweep	~	degrees	34

Mass and Balance Summary	***lbs***	**kg**
WING	12,943	5,871
HORIZONTAL	1,570	712
VERTICAL TAIL	889	403
FUSELAGE	8,543	3,875
LANDING GEAR	3,517	1,595
NACELLE	1,183	537
STRUCTURE TOTAL	28,645	12,993
ENGINES	8,173	3,707
FUEL SYSTEMS/ PLUMBING	637	289
PROPULSION TOTAL	8,810	3,996
SURFACE CONTROLS	1,375	624
AUXILIARY POWER	84	38
ELECTRICAL & INSTRUMENTS	1,345	610
HYDRAULICS	747	339
AVIONICS	767	348
FURNISHINGS & MISC SYSTEMS	8,822	4,002
AIR CONDITIONING & ANTI-ICING	77	35
FIXED EQUIPMENT TOTAL	13,217	5,995

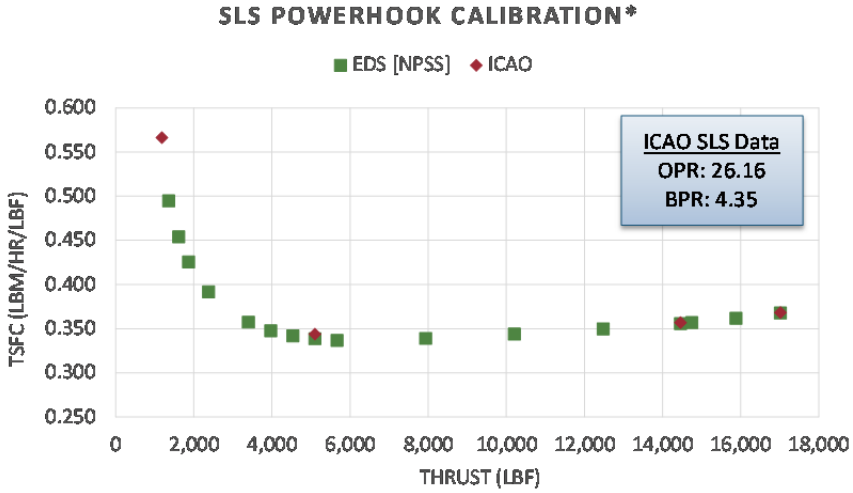
Mass and Balance Summary	***lbs***	**kg**
WEIGHT EMPTY	50,672	22,984
OPERATOR ITEMS	3,328	1,510
OPERATING WEIGHT EMPTY (OWE)	54,000	24,494
PAYLOAD 8 Passengers + baggage (225 lbs each)	1,800	816
ZERO FUEL WEIGHT	55,800	25,310
TOTAL FUEL	48,200	21,863
TRIP FUEL **(TOTAL w/o RESERVES, TAXI IN & OUT)**	45,180	20,493
RAMP GROSS WEIGHT	104,000	47,174
Taxi Out Fuel Weight	400	181
MAXIMUM TAKE-OFF WEIGHT	**103,600**	**46,992**

K.1.4 Engine Performance

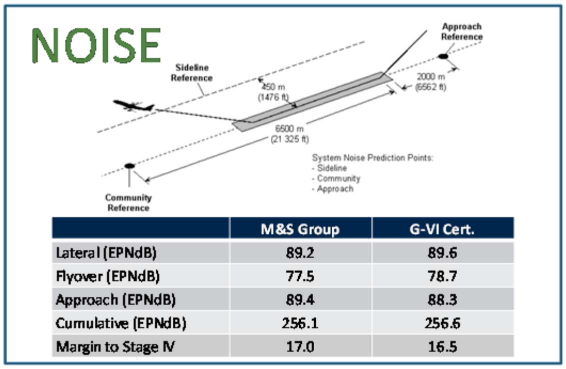
Description	**Units**	**Value**
SLS Thrust	kN	75.7
Fan Diameter	m	1.3
Dry Weight	kg	1,696
Turbomachinery Arrangement	~	1-10-2-3
SFC @ beginning of cruise	lbm/hr/lbf	0.6698
Max Diameter (A)	m	1.5
Max Length (B)	m	2.4



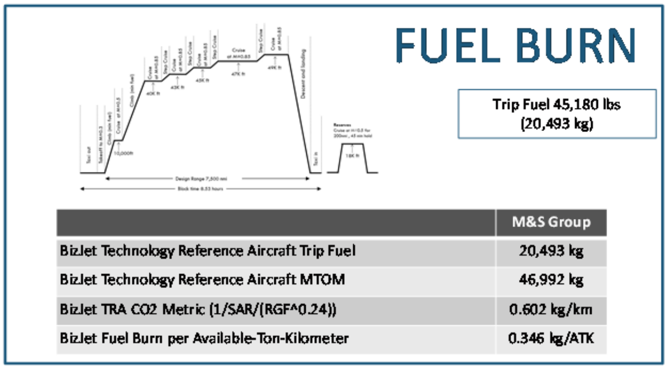
Description	**Sea Level Static**	**Max Climb**	**Cruise**
Net Thrust	75.7 kN	16.6 kN	14.8 kN
OPR (SLS uninstalled)	26.1	34.0	31.3
FPR (SLS uninstalled)	1.63	1.80	1.75
BPR (SLS uninstalled)	4.32	4.03	4.15



K.1.5 Top Level Metrics

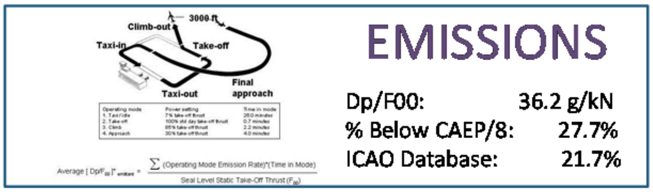


	M&S Group	G-VI Cert.
Lateral (EPNdB)	89.2	89.6
Flyover (EPNdB)	77.5	78.7
Approach (EPNdB)	89.4	88.3
Cumulative (EPNdB)	256.1	256.6
Margin to Stage IV	17.0	16.5



Trip Fuel 45,180 lbs
(20,493 kg)

	M&S Group
BizJet Technology Reference Aircraft Trip Fuel	20,493 kg
BizJet Technology Reference Aircraft MTOM	46,992 kg
BizJet TRA CO2 Metric (1/SAR/(RGF^0.24))	0.602 kg/km
BizJet Fuel Burn per Available-Ton-Kilometer	0.346 kg/ATK



Operating mode	Power setting	Time in mode
1. Taxi / idle	7% take-off thrust	26.0 minutes
2. Take-off	100% std day take-off thrust	0.7 minutes
3. Climb	85% take-off thrust	2.2 minutes
4. Approach	30% take-off thrust	4.0 minutes

$$\text{Average } [Dp/F_{00}]^{*}_{\text{emitted}} = \frac{\sum \text{(Operating Mode Emission Rate)*(Time in Mode)}}{\text{Seal Level Static Take-Off Thrust } (F_{00})}$$

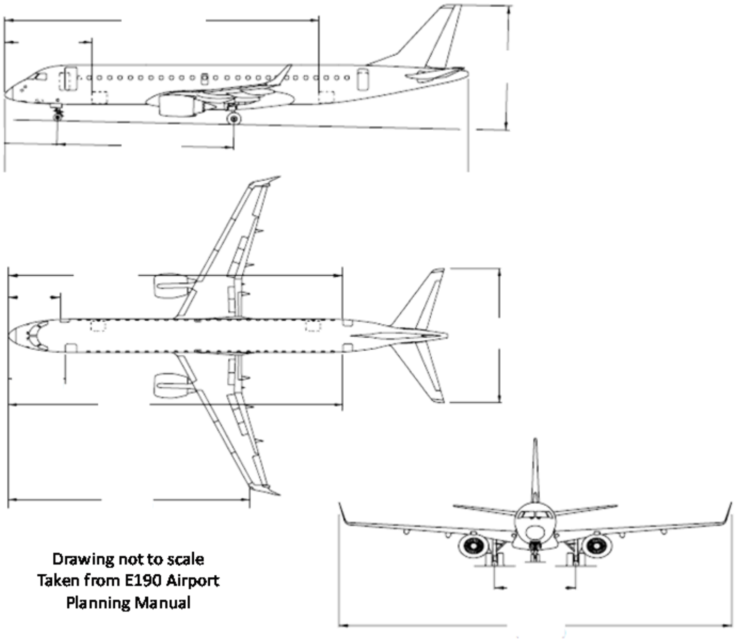
Dp/F00:	36.2 g/kN
% Below CAEP/8:	27.7%
ICAO Database:	21.7%

K.2 REGIONAL JET TRA

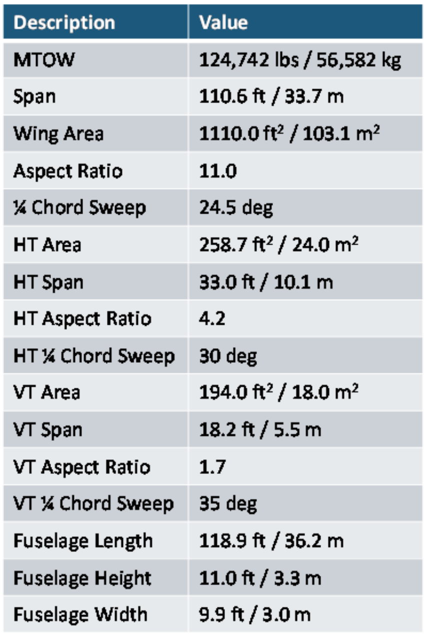
K.2.1 Assumptions

RJ Technology Reference Aircraft (TRA) is based on a technology level in line with state-of-the-art of the vehicles in production today:

- Notional Embraer E190-E2
- Assumed payload of 23,000 lbm (10,432.6 kg)
    - 106 passengers @ 100 kg each (@ design range including baggage)
- Design range of 2,850 nm
- Metallic main components (wing, fuselage, empennage)
- 2 geared fan engines (notional PW1524G) at high bypass ratio of ~11 (SLS)
    - Used PW1524G instead of PW1919G since TCDS and ICAO Databank data exist
    - PW1524G and PW1919G have exact same turbomachinery arrangement, thrust class, and bypass ratio

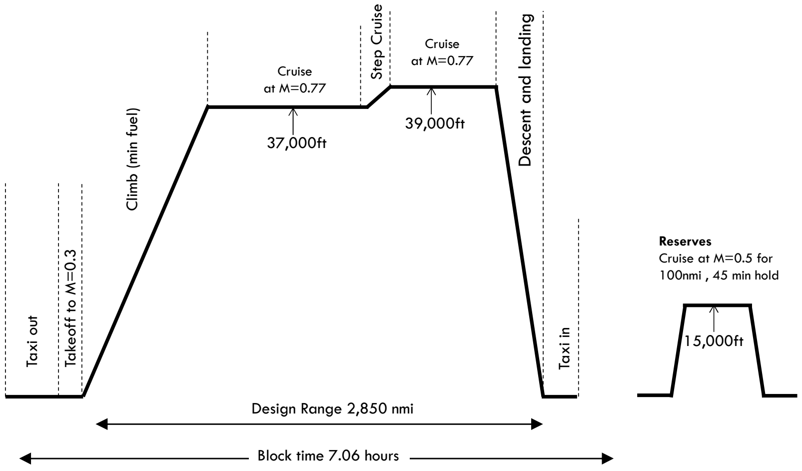


Drawing not to scale
Taken from E190 Airport Planning Manual



Description	Value
MTOW	124,742 lbs / 56,582 kg
Span	110.6 ft / 33.7 m
Wing Area	1110.0 ft^2 / 103.1 m^2
Aspect Ratio	11.0
¼ Chord Sweep	24.5 deg
HT Area	258.7 ft^2 / 24.0 m^2
HT Span	33.0 ft / 10.1 m
HT Aspect Ratio	4.2
HT ¼ Chord Sweep	30 deg
VT Area	194.0 ft^2 / 18.0 m^2
VT Span	18.2 ft / 5.5 m
VT Aspect Ratio	1.7
VT ¼ Chord Sweep	35 deg
Fuselage Length	118.9 ft / 36.2 m
Fuselage Height	11.0 ft / 3.3 m
Fuselage Width	9.9 ft / 3.0 m

K.2.2 Mission Profile



K.2.3 Vehicle Performance

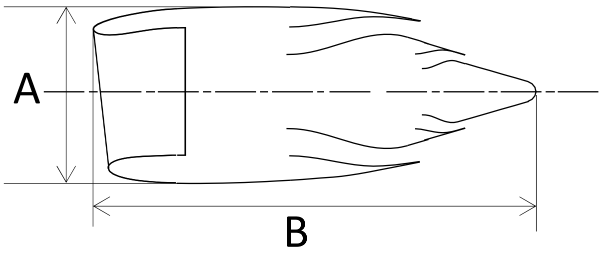
Parameter	Acronym	Units	Value
Approach Speed	V_{app}	mps	67
Aspect ratio	AR	~	11.0
Bypass ratio (SLS)	BPR	~	11.0
C_{Lmax} Landing	$C_{LmaxLdg}$	~	2.79
C_{Lmax} Take-off	C_{LmaxTO}	~	1.92
Cockpit crew	~	~	2
Design cruise speed	M_{des}		0.77
Design fuel	~	kg	10,991
Design Payload at R_2		Kg	10,581
Design Range at R_2	R2	nm	2,850
Fuselage height	DF	m	3.3
Fuselage length	XL	m	36.2
Fuselage width	WF	m	3.0
Initial Cruise Altitude	~	ft	37,000
Landing field length	LdgFL	m	1,728
Manufacturer's empty weight	MEW	kg	31,287
Maximum L/D at cruise	~	~	17.58
Maximum landing mass	MLM	kg	48,640
Maximum SLS thrust per engine	F_n	kN	108.5
Maximum take-off mass	MTOM	kg	56,582
Number of passengers	# pax		106
Operating empty weight	OEW	kg	33,185
Overall pressure ratio (SLS)	OPR	~	38.9
Ramp gross weight	~	kg	56,632
Reference geometric factor	RGF	m2	77.5
Service ceiling	~	ft	41,000
Take-off field length	TOFL	m	1,391
Wing area	SW	m2	103.1
Wing span	~	m	33.7
Wing sweep	~	degrees	24.5

Mass and Balance Summary	*lbs*	kg
WING	14,209	6,445
HORIZONTAL	1,329	603
VERTICAL TAIL	824	374
FUSELAGE	13,913	6,311
LANDING GEAR	4,974	2,256
NACELLE	3,687	1,672
STRUCTURE TOTAL	38,936	17,661
ENGINES	11,683	5,299
FUEL SYSTEMS/ PLUMBING	599	272
PROPULSION TOTAL	12,282	5,571
SURFACE CONTROLS	1,914	868
AUXILIARY POWER	724	328
ELECTRICAL & INSTRUMENTS	1,589	721
HYDRAULICS	929	421
AVIONICS	957	434
FURNISHINGS & MISC SYSTEMS	10,622	4,818
AIR CONDITIONING & ANTI-ICING	1,024	464
FIXED EQUIPMENT TOTAL	17,759	8,055

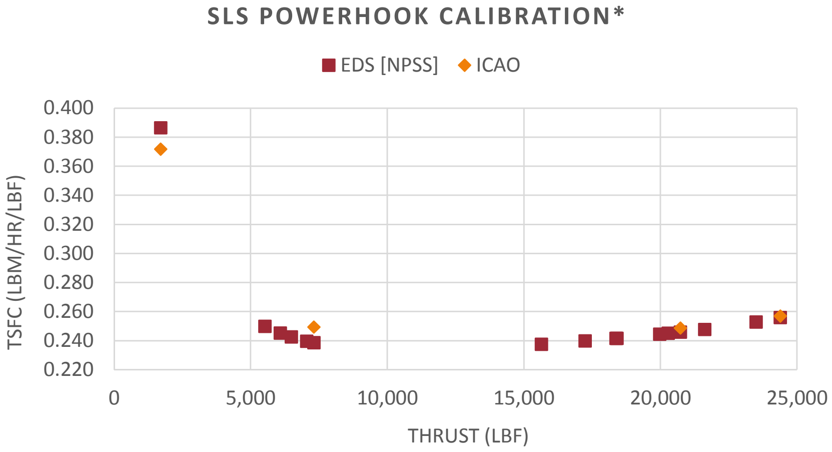
Mass and Balance Summary	*lbs*	kg
WEIGHT EMPTY	68,977	31,287
OPERATOR ITEMS	4,183	1,897
OPERATING WEIGHT EMPTY (OWE)	73,160	33,185
PAYLOAD 106 Passengers + baggage (220 lbs each)	23,320	10,578
ZERO FUEL WEIGHT	96,480	43,763
TOTAL FUEL	28,372	12,869
TRIP FUEL **(TOTAL w/o RESERVES AND TAXI)**	24,232	10,991
RAMP GROSS WEIGHT	124,852	56,632
Taxi Out Weight	110	50
MAXIMUM TAKE-OFF WEIGHT	**124,742**	**56,582**

K.2.4 Engine Performance

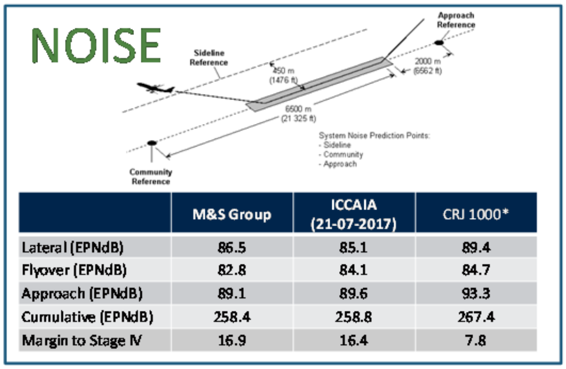
Description	Units	Value
SLS Thrust	kN	108.5
Fan Diameter	m	1.85
Dry Weight	kg	2,650
Turbomachinery Arrangement	~	1-G-3-8-2-3
SFC @ beginning of cruise	lbm/hr/lbf	0.5872
Max Diameter (A)	m	2.01
Max Length (B)	m	3.13



Description	Sea Level Static	Max Climb	Cruise
Net Thrust	108.5 kN	22.2 kN	21.9 kN
OPR (SLS uninstalled)	38.9	48.4	47.8
FPR (SLS uninstalled)	1.41	1.53	1.52
BPR (SLS uninstalled)	11.0	9.6	9.7



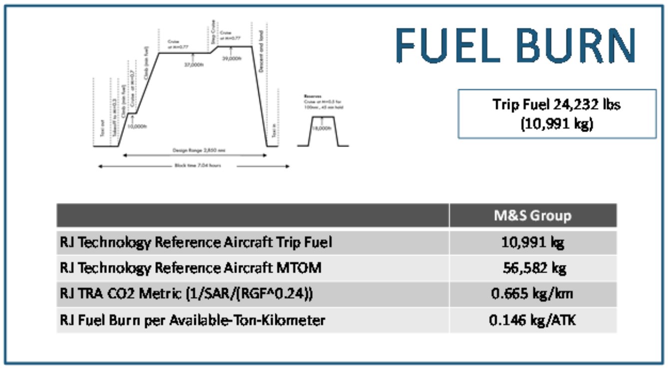
K.2.5 Top Level Metrics



NOISE

System Noise Prediction Points:
- Sideline
- Community
- Approach

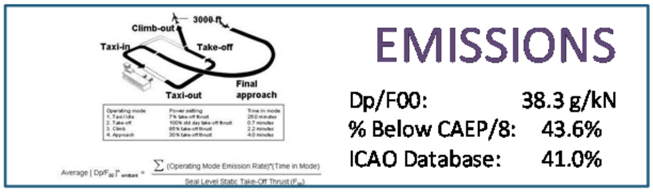
	M&S Group	ICCAIA (21-07-2017)	CRJ 1000*
Lateral (EPNdB)	86.5	85.1	89.4
Flyover (EPNdB)	82.8	84.1	84.7
Approach (EPNdB)	89.1	89.6	93.3
Cumulative (EPNdB)	258.4	258.8	267.4
Margin to Stage IV	16.9	16.4	7.8



FUEL BURN

Trip Fuel 24,232 lbs
(10,991 kg)

	M&S Group
RJ Technology Reference Aircraft Trip Fuel	10,991 kg
RJ Technology Reference Aircraft MTOM	56,582 kg
RJ TRA CO2 Metric (1/SAR/(RGF^0.24))	0.665 kg/km
RJ Fuel Burn per Available-Ton-Kilometer	0.146 kg/ATK



Operating mode	Power setting	Time in mode
1. Taxi/idle	7% take-off thrust	26.0 minutes
2. Take-off	100% std day take-off thrust	0.7 minutes
3. Climb	85% take-off thrust	2.2 minutes
4. Approach	30% take-off thrust	4.0 minutes

$$\text{Average}\,[D_p/F_{00}]^{*}_{\text{emittant}} = \frac{\sum (\text{Operating Mode Emission Rate})^{*}(\text{Time in Mode})}{\text{Seal Level Static Take-Off Thrust }(F_{00})}$$

EMISSIONS

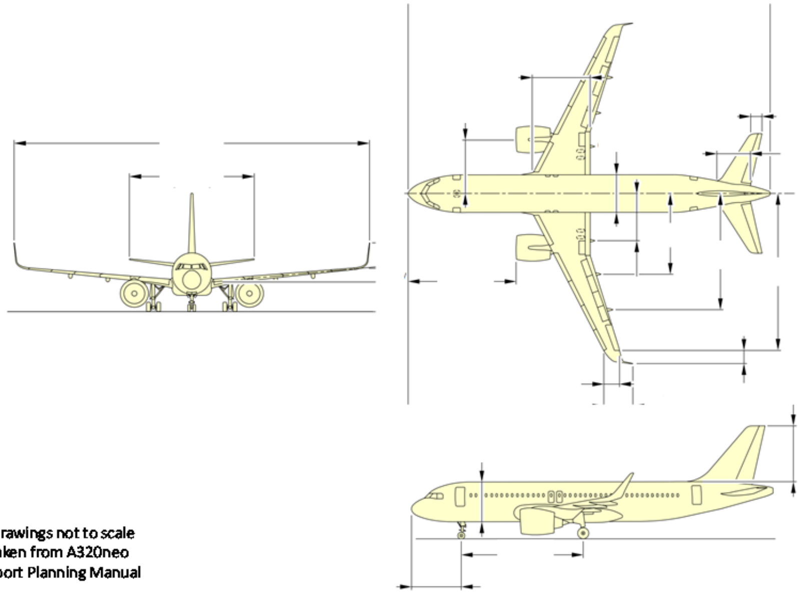
Dp/F00:	38.3 g/kN
% Below CAEP/8:	43.6%
ICAO Database:	41.0%

K.3 SINGLE AISLE TRA

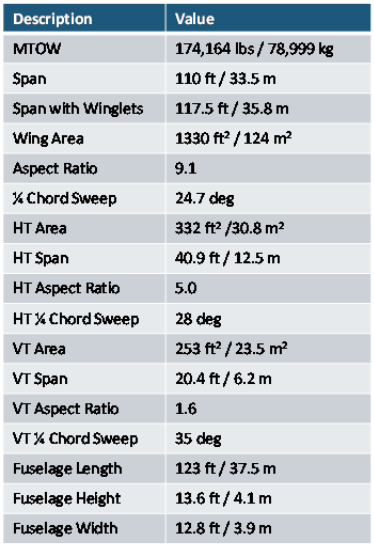
K.3.1 Assumptions

SA Technology Reference Aircraft (TRA) is based on a technology level in line with state-of-the-art of the vehicles in production today:

- ***Notional*** Airbus A320neo
    - Assumed payload of 37,125 lbm (16,840 kg)
        - 165 pax (12 Business & 138 Economy) @ 102 kg each (@ design range including baggage)
- Design range of 3,500 nm
- Metallic main components (wing, fuselage, empennage)
- 2 geared fan engines (**notional** PW1127G) at high bypass ratio of ~11 (SLS)
    - Created PW1133G model from publically available information and ICAO databank
    - De-rated PW1133G to PW1127G performance to match ICAO powerhook

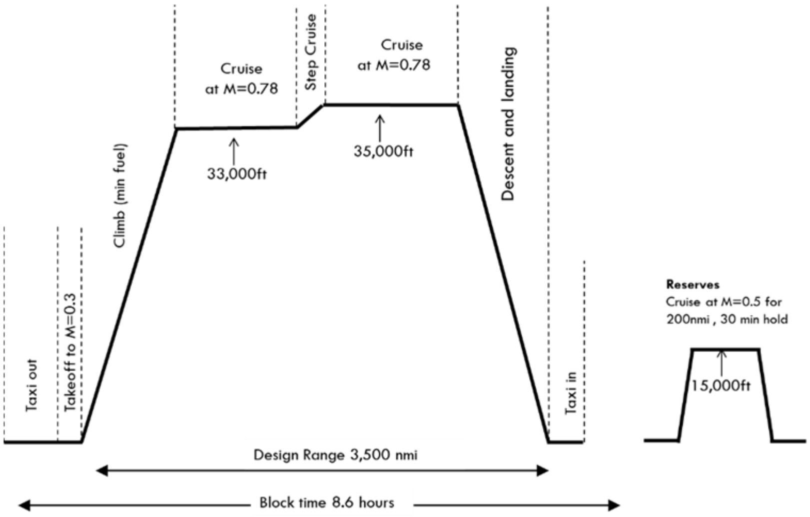


***Drawings not to scale**
Taken from A320neo
Airport Planning Manual



Description	Value
MTOW	174,164 lbs / 78,999 kg
Span	110 ft / 33.5 m
Span with Winglets	117.5 ft / 35.8 m
Wing Area	1330 ft² / 124 m²
Aspect Ratio	9.1
¼ Chord Sweep	24.7 deg
HT Area	332 ft² /30.8 m²
HT Span	40.9 ft / 12.5 m
HT Aspect Ratio	5.0
HT ¼ Chord Sweep	28 deg
VT Area	253 ft² / 23.5 m²
VT Span	20.4 ft / 6.2 m
VT Aspect Ratio	1.6
VT ¼ Chord Sweep	35 deg
Fuselage Length	123 ft / 37.5 m
Fuselage Height	13.6 ft / 4.1 m
Fuselage Width	12.8 ft / 3.9 m

K.3.2 Mission Profile



K.3.3 Vehicle Performance

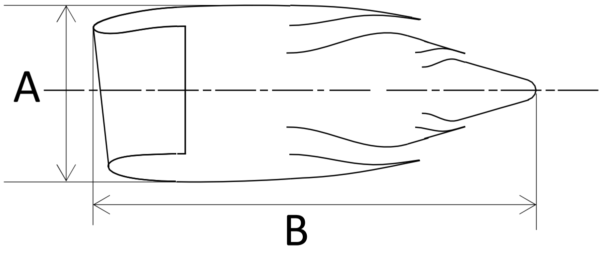
Parameter	Acronym	Units	Value
Approach Speed	V_{app}	mps	72.0
Aspect ratio	AR	~	9.1
Bypass ratio (SLS)	BPR	~	12.0
C_{Lmax} Landing	$C_{LmaxLdg}$	~	2.85
C_{Lmax} Take-off	C_{LmaxTO}	~	1.85
Cockpit crew	~	~	2
Design cruise speed	M_{des}		0.78
Design fuel	~	kg	18,015
Design Payload at R_2		Kg	16,840
Design Range at R_2	R2	nm	3,500
Fuselage height	DF	m	4.1
Fuselage length	XL	m	37.5
Fuselage width	WF	m	3.9
Initial Cruise Altitude	~	ft	33,000
Landing field length	LdgFL	m	1,917
Manufacturer's empty weight	MEW	kg	39,844
Maximum L/D at cruise	~	~	17.86
Maximum landing mass	MLM	kg	66,320
Maximum SLS thrust per engine	F_n	kN	120.4
Maximum take-off mass	MTOM	kg	78,999
Number of passengers	# pax		165
Operating empty weight	OEW	kg	41,866
Overall pressure ratio (SLS)	OPR	~	32.6
Ramp gross weight	~	kg	79,399
Reference geometric factor	RGF	m2	108.9
Service ceiling	~	ft	39,000
Take-off field length	TOFL	m	2,373
Wing area	SW	m2	124.0
Wing span	~	m	33.5
Wing ¼ chord sweep	~	degrees	24.7

Mass and Balance Summary: Empty Weight Breakout	***lbs***	**kg**
WING	17,421	7,902
HORIZONTAL	1,875	850
VERTICAL TAIL	1,020	463
FUSELAGE	17,617	7,991
LANDING GEAR	6,421	2,913
NACELLE	3,575	1,622
STRUCTURE TOTAL	47,929	21,740
ENGINES	14,718	6,676
FUEL SYSTEMS/ PLUMBING	631	286
PROPULSION TOTAL	15,349	6,962
SURFACE CONTROLS	2,323	1,054
AUXILIARY POWER	946	429
ELECTRICAL & INSTRUMENTS	1,982	899
HYDRAULICS	1,248	566
AVIONICS	1,283	582
FURNISHINGS & MISC SYSTEMS	15,331	6,954
AIR CONDITIONING & ANTI-ICING	1,449	657
FIXED EQUIPMENT TOTAL	24,562	11,141

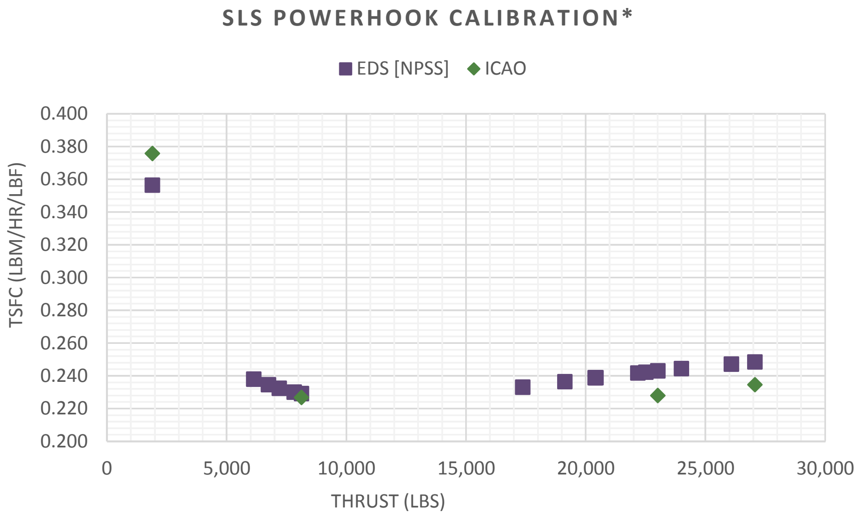
Mass and Balance Summary	***lbs***	**kg**
WEIGHT EMPTY	87,840	39,844
OPERATOR ITEMS	4,459	2,023
OPERATING WEIGHT EMPTY (OWE)	92,299	41,866
PAYLOAD 165 Passengers + baggage (225 lbs each)	37,125	16,840
ZERO FUEL WEIGHT	129,424	58,706
TOTAL FUEL	45,622	20,694
TRIP FUEL (TOTAL w/o RESERVES AND TAXI)	39,717	18,015
RAMP GROSS WEIGHT	175,046	79,399
Taxi Out Fuel Weight	882	400
MAXIMUM TAKE-OFF WEIGHT	**174,164**	**78,999**
OEW/MTOW	**0.53**	**0.53**

K.3.4 Engine Performance

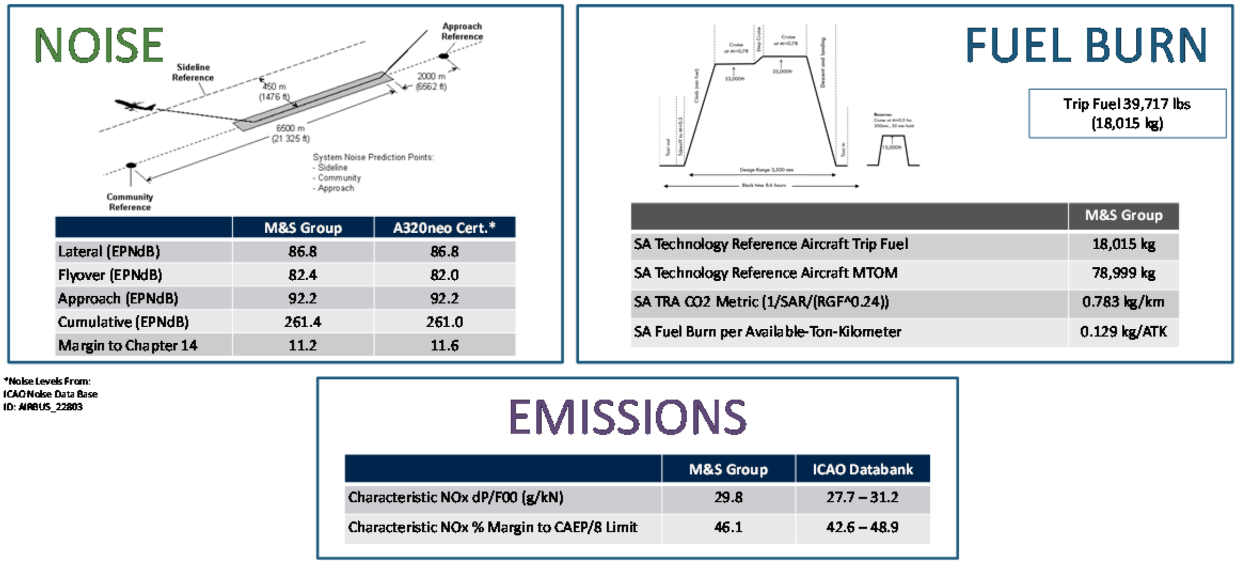
Description	**Units**	**Value**
SLS Thrust	kN	120.4
Fan Diameter	m	2.1
Dry Weight	kg	2,787
Turbomachinery Arrangement	~	1-G-3-8-2-3
SFC @ beginning of cruise	lbm/hr/lbf	0.534
Max Diameter (A)	m	2.4
Max Length (B)	m	3.6



Description	**Sea Level Static**	**Max Climb**	**Cruise**
Net Thrust	120.4 kN	31.6 kN	27.4 kN
OPR (SLS uninstalled)	32.6	47.9	42.9
FPR (SLS uninstalled)	1.37	1.52	1.47
BPR (SLS uninstalled)	12.0	11.8	12.5



K.3.5 Top Level Metrics



NOISE

System Noise Prediction Points:
- Sideline
- Community
- Approach

	M&S Group	A320neo Cert.*
Lateral (EPNdB)	86.8	86.8
Flyover (EPNdB)	82.4	82.0
Approach (EPNdB)	92.2	92.2
Cumulative (EPNdB)	261.4	261.0
Margin to Chapter 14	11.2	11.6

*Noise Levels From:
ICAO Noise Data Base
ID: AIRBUS_22803

FUEL BURN

Trip Fuel 39,717 lbs
(18,015 kg)

	M&S Group
SA Technology Reference Aircraft Trip Fuel	18,015 kg
SA Technology Reference Aircraft MTOM	78,999 kg
SA TRA CO2 Metric (1/SAR/(RGF^0.24))	0.783 kg/km
SA Fuel Burn per Available-Ton-Kilometer	0.129 kg/ATK

EMISSIONS

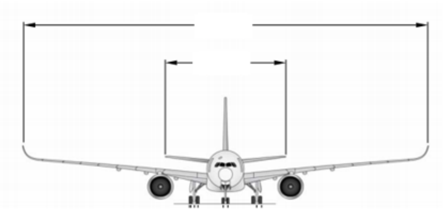
	M&S Group	ICAO Databank
Characteristic NOx dP/F00 (g/kN)	29.8	27.7 – 31.2
Characteristic NOx % Margin to CAEP/8 Limit	46.1	42.6 – 48.9

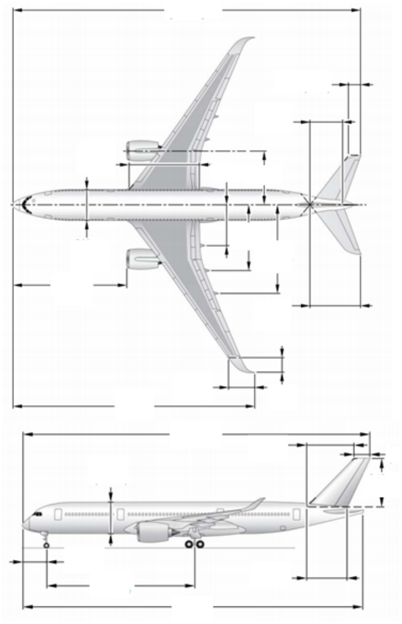
K.4 TWIN AISLE TRA

K.4.1 Assumptions

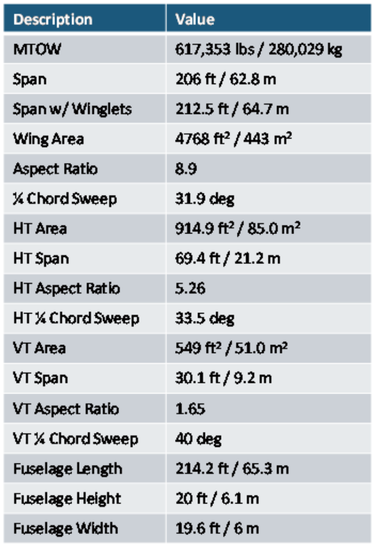
TA Technology Reference Aircraft (TRA) is based on a technology level in line with state-of-the-art of the vehicles in production today:

- ***Notional*** Airbus A350-900
    - Assumed payload of 70,875bm (32,149 kg)
        - 315 pax (38 Business & 277 Economy) @ 102 kg each (@ design range including baggage)
- Design range of 8,100 nm
- Composite main components (wing, fuselage, empennage)
- 2 three-spool engines (**notional** Rolls Royce Trent XWB-84) at high bypass ratio of ~11 (SLS)
    - Created RR Trent XWB-84 model from publically available information and ICAO databank



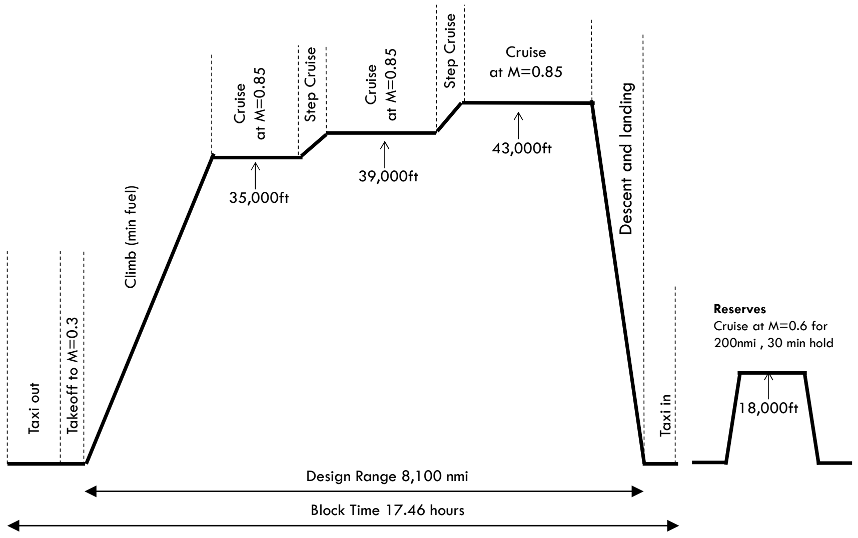


*Drawings not to scale
Taken from A350 Airport
Planning Manual



Description	Value
MTOW	617,353 lbs / 280,029 kg
Span	206 ft / 62.8 m
Span w/ Winglets	212.5 ft / 64.7 m
Wing Area	4768 ft^2 / 443 m^2
Aspect Ratio	8.9
¼ Chord Sweep	31.9 deg
HT Area	914.9 ft^2 / 85.0 m^2
HT Span	69.4 ft / 21.2 m
HT Aspect Ratio	5.26
HT ¼ Chord Sweep	33.5 deg
VT Area	549 ft^2 / 51.0 m^2
VT Span	30.1 ft / 9.2 m
VT Aspect Ratio	1.65
VT ¼ Chord Sweep	40 deg
Fuselage Length	214.2 ft / 65.3 m
Fuselage Height	20 ft / 6.1 m
Fuselage Width	19.6 ft / 6 m

K.4.2 Mission Profile



K.4.3 Vehicle Performance

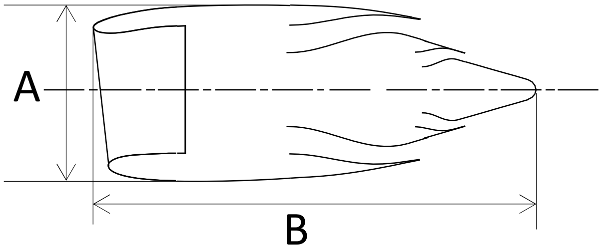
Parameter	Acronym	Units	Value
Approach Speed	V_{app}	mps	71.3
Aspect ratio	AR	~	8.9
Bypass ratio (SLS)	BPR	~	9.01
C_{Lmax} Landing	$C_{LmaxLdg}$	~	2.46
C_{Lmax} Take-off	C_{LmaxTO}	~	2.11
Cockpit crew	~	~	2
Design cruise speed	M_{des}		0.85
Design fuel	~	kg	101,865
Design Payload at R_2		Kg	32,149
Design Range at R_2	R2	nm	8,100
Fuselage height	DF	m	6.1
Fuselage length	XL	m	65.3
Fuselage width	WF	m	6.0
Initial Cruise Altitude	~	ft	35,000
Landing field length	LdgFL	m	2,005
Manufacturer's empty weight	MEW	kg	136,442
Maximum L/D at cruise	~	~	20.54
Maximum landing mass	MLM	kg	205,005
Maximum SLS thrust per engine	F_n	kN	379.0
Maximum take-off mass	MTOM	kg	280,029
Number of passengers	# pax		315
Operating empty weight	OEW	kg	139,929
Overall pressure ratio (SLS)	OPR	~	41.1
Ramp gross weight	~	kg	280,932
Reference geometric factor	RGF	m2	299.0
Service ceiling	~	ft	43,000
Take-off field length	TOFL	m	2,480
Wing area	SW	m2	443.0
Wing span	~	m	62.8
Wing ¼ chord sweep	~	degrees	31.9

Mass and Balance Summary	*lbs*	kg
WING	68,010	30,849
HORIZONTAL	6,426	2,915
VERTICAL TAIL	2,643	1,199
FUSELAGE	61,561	27,924
LANDING GEAR	21,097	9,570
NACELLE	5,108	2,317
STRUCTURE TOTAL	164,845	74,773
ENGINES	45,894	20,817
FUEL SYSTEMS/ PLUMBING	944	428
PROPULSION TOTAL	46,838	21,246
SURFACE CONTROLS	5,406	2,452
AUXILIARY POWER	1,615	733
ELECTRICAL & INSTRUMENTS	3,041	1,379
HYDRAULICS	4,431	2,010
AVIONICS	3,205	1,454
FURNISHINGS & MISC SYSTEMS	68,389	31,021
AIR CONDITIONING & ANTI-ICING	3,033	1,376
FIXED EQUIPMENT TOTAL	89,120	40,425

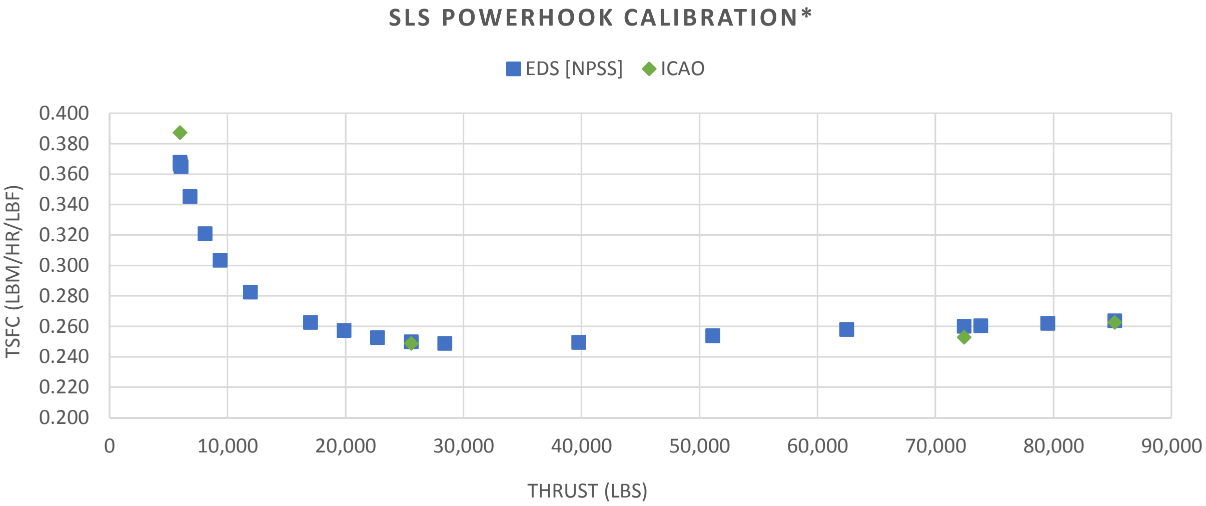
Mass and Balance Summary	*lbs*	kg
WEIGHT EMPTY	300,803	136,443
OPERATOR ITEMS	7,684	3,485
OPERATING WEIGHT EMPTY (OWE)	308,487	139,929
PAYLOAD 215 Passengers + baggage (225 lbs each)	70,875	32,149
ZERO FUEL WEIGHT	379,362	172,077
TOTAL FUEL	239,981	108,855
TRIP FUEL **(TOTAL w/o RESERVES AND TAXI)**	224,571	101,865
RAMP GROSS WEIGHT	619,343	280,932
Taxi Out Fuel Weight	1,990	903
MAXIMUM TAKE-OFF WEIGHT	**617,353**	**280,029**

K.4.4 Engine Performance

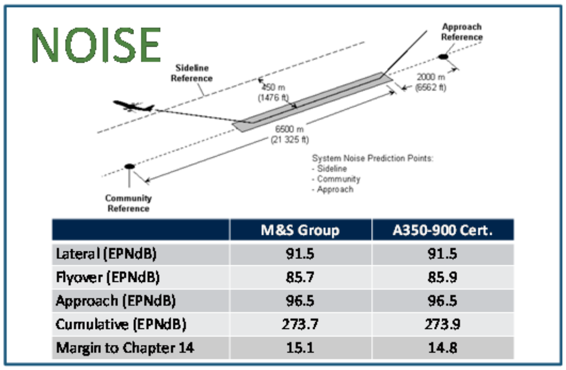
Description	Units	Value
SLS Thrust	kN	379.0
Fan Diameter	m	3.0
Dry Weight	kg	9,008
Turbomachinery Arrangement	~	1-8-6-1-2-6
SFC @ beginning of cruise	lbm/hr/lbf	0.524
Max Diameter (A)	m	3.9
Max Length (B)	m	7.4



Description	Sea Level Static	Max Climb	Cruise
Net Thrust	379.0 kN	70.8 kN	61.4 kN
OPR (SLS uninstalled)	41.1	48.7	44.6
FPR (SLS uninstalled)	1.52	1.62	1.57
BPR (SLS uninstalled)	9.01	9.3	9.5

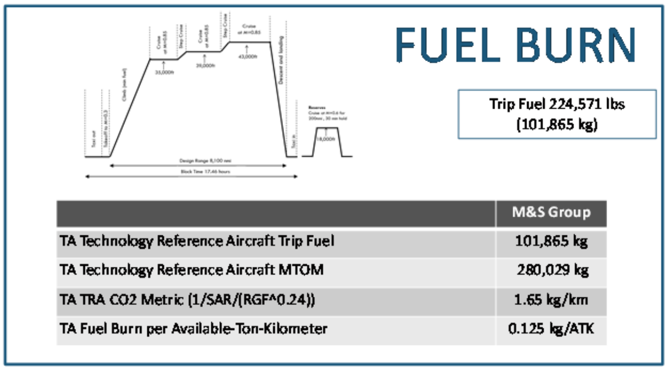


K.4.5 Top Level Metrics



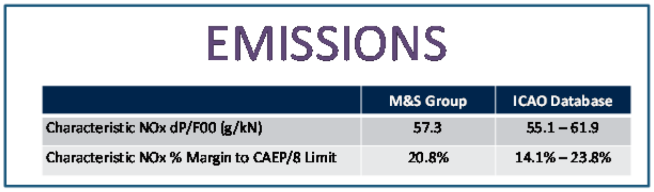
	M&S Group	A350-900 Cert.
Lateral (EPNdB)	91.5	91.5
Flyover (EPNdB)	85.7	85.9
Approach (EPNdB)	96.5	96.5
Cumulative (EPNdB)	273.7	273.9
Margin to Chapter 14	15.1	14.8

*Noise Levels From:
ICAO Certification Database
ID: AIRBUS_22758



Trip Fuel 224,571 lbs
(101,865 kg)

	M&S Group
TA Technology Reference Aircraft Trip Fuel	101,865 kg
TA Technology Reference Aircraft MTOM	280,029 kg
TA TRA CO2 Metric (1/SAR/(RGF^0.24))	1.65 kg/km
TA Fuel Burn per Available-Ton-Kilometer	0.125 kg/ATK



EMISSIONS

	M&S Group	ICAO Database
Characteristic NOx dP/F00 (g/kN)	57.3	55.1 – 61.9
Characteristic NOx % Margin to CAEP/8 Limit	20.8%	14.1% – 23.8%

APPENDIX L. TRA TECHNOLOGY TAXONOMY IMPACTS

This appendix provides the resulting 2027 and 2037 technology taxonomy impacts obtained from ICCAIA, the IEs, and prior GT studies for NASA utilized for the goal setting process for each of the TRAs.

L.1 BUSINESS JET TECHNOLOGY IMPACTS

Table L-1. 2027 BJ Technology Three Point Estimate Impacts from ICCAIA

2027	Technology Category	High Confidence	Nominal	Low Confidence
Noise	Jet Source Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Fore Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Aft Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Core (Combustor) Noise (ΔdB)	0	0	0
	Core (Turbine) Noise (ΔdB)	-1	-2	-3
	Nacelle Liner - Fan Fore Noise (ΔdB)	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*
	Nacelle Liner - Fan Aft Noise (ΔdB)	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*
	Landing Gear Noise (ΔdB)	-1	-2	-3
	Flap Noise (ΔdB)	None	None	None
	Slat Noise (ΔdB)	None	None	None
	PAI Flyover Noise (ΔEPNdB)	None	None	None
	PAI Lateral Noise (ΔEPNdB)	None	None	None
	PAI Approach Noise (ΔEPNdB)	None	None	None
Structures	Wing Weight (%)	-3.0%	-4.9%	-6.8%
	Fuselage Weight (%)	-0.8%	-2.5%	-4.2%
	Empennage Weight (%)	-1.3%	-3.3%	-5.2%
Aero	Total Drag (%)	-1.8%	-3.0 (-4.0%	-5.6% (-6.6%)

* additional to standard 2DOF nacelle efficiency

Table L-2. 2027 BJ Technology Three Point Estimate Impacts from IEs and GT

2027	Technology Category	High Confidence	Nominal	Low Confidence
Propulsion*	FPR	1.68	1.67	1.65
	OPR	29	30	31
	BPR	4.6	4.7	4.9
	HPCPR	17.4	18.1	18.9
	Fan η (Adiabatic)	90.60%	90.80%	91.10%
	HPC η (Polytropic)	90.60%	90.60%	90.60%
	HPT η (Adiabatic)	88.40%	88.50%	88.60%
	LPT η (Adiabatic)	90.00%	90.00%	90.00%
	Nacelle Drag Reduction	3.00%	4.00%	5.00%
	Nacelle Weight Reduction	2.00%	3.00%	4.00%
	Increase in Small Core Technology Efficiency	8.00%	10.00%	12.00%
	Engine Component Weights (Avg. Reduction)	0.00%	2.00%	3.00%

* values obtained from prior GT studies, with concurrence of the IEs and ICCAIA

Table L-3. 2037 BJ Technology Three Point Estimate Impacts from ICCAIA

2037	Technology Category	High Confidence	Nominal	Low Confidence
Noise	Jet Source Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Fore Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Aft Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Core (Combustor) Noise (ΔdB)	0	0	0
	Core (Turbine) Noise (ΔdB)	-1	-2	-3
	Nacelle Liner - Fan Fore Noise (ΔdB)	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*
	Nacelle Liner - Fan Aft Noise (ΔdB)	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*
	Landing Gear Noise (ΔdB)	-1	-2	-3
	Flap Noise (ΔdB)	None	None	None
	Slat Noise (ΔdB)	None	None	None
	PAI Flyover Noise (ΔEPNdB)	None	None	None
	PAI Lateral Noise (ΔEPNdB)	None	None	None
	PAI Approach Noise (ΔEPNdB)	None	None	None
Structures	Wing Weight (%)	-3.0%	-4.9%	-6.8%
	Fuselage Weight (%)	-0.8%	-2.5%	-4.2%
	Empennage Weight (%)	-1.3%	-3.3%	-5.2%
Aero	Total Drag (%)	-1.8%	-3.0% (-4.0%)	-5.6% (-6.6%)

* additional to standard 2DOF nacelle efficiency

Table L-4. 2037 BJ Technology Three Point Estimate Impacts from IEs and GT

2037	Technology Category	High Confidence	Nominal	Low Confidence
Propulsion*	FPR	1.64	1.63	1.62
	OPR	32	33	34
	BPR	5.2	5.3	5.6
	HPCPR	19.7	20.4	21.1
	Fan η (Adiabatic)	91.40%	91.70%	91.90%
	HPC η (Polytropic)	90.80%	90.80%	90.80%
	HPT η (Adiabatic)	88.90%	89.00%	89.10%
	LPT η (Adiabatic)	90.50%	90.50%	90.50%
	Nacelle Drag Reduction	6.00%	7.00%	8.00%
	Nacelle Weight Reduction	4.00%	5.00%	6.00%
	Increase in Small Core Technology Efficiency	12.00%	12.00%	12.00%
	Engine Component Weights (Avg. Reduction)	2.00%	3.00%	4.00%

* values obtained from prior GT studies, with concurrence of the IEs and ICCAIA

L.2 REGIONAL JET TECHNOLOGY IMPACTS

Table L-5. 2027 RJ Technology Three Point Estimate Impacts from ICCAIA

2027	Technology Category	High Confidence	Nominal	Low Confidence
Noise	Jet Source Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Fore Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Aft Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Core (Combustor) Noise (ΔdB)	0	0	0
	Core (Turbine) Noise (ΔdB)	-1	-2	-3
	Nacelle Liner - Fan Fore Noise (ΔdB)	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*
	Nacelle Liner - Fan Aft Noise (ΔdB)	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*
	Landing Gear Noise (ΔdB)	-1	-2	-3
	Flap Noise (ΔdB)	None	None	None
	Slat Noise (ΔdB)	None	None	None
	PAI Flyover Noise (ΔEPNdB)	2.5x(0.2+0.2668x(BPR-15))	2.5x(0.2+0.2668x(BPR-15))	2.5x(0.2+0.2668x(BPR-15))
	PAI Lateral Noise (ΔEPNdB)	1.0x(0.2+0.2668x(BPR-15))	1.0x(0.2+0.2668x(BPR-15))	1.0x(0.2+0.2668x(BPR-15))
	PAI Approach Noise (ΔEPNdB)	1.5x(0.2+0.2668x(BPR-15))	1.5x(0.2+0.2668x(BPR-15))	1.5x(0.2+0.2668x(BPR-15))
Structures	Wing Weight (%)	-3.7%	-5.7%	-7.8%
	Fuselage Weight (%)	-2.1%	-3.8%	-5.5%
	Empennage Weight (%)	-4.0%	-5.9%	-7.8%
Aero	Total Drag (%)	0.0%	-1.4%	-3.0%

* additional to standard 2DOF nacelle efficiency

Table L-6. 2027 RJ Technology Three Point Estimate Impacts from IEs and GT

2027	Technology Category	High Confidence	Nominal	Low Confidence
Propulsion*	FPR	1.48	1.45	1.42
	OPR	47	49	50
	BPR	12.1	13.3	14.7
	HPCPR	16.5	17	17.5
	Fan η (Adiabatic)	1.95	2	2.05
	HPC η (Polytropic)	92.80%	93.10%	93.50%
	HPT η (Adiabatic)	91.80%	92.10%	92.50%
	LPT η (Adiabatic)	91.80%	92.10%	92.50%
	Nacelle Drag Reduction	89.30%	89.60%	90.00%
	Nacelle Weight Reduction	91.40%	91.70%	92.10%
	Increase in Small Core Technology Efficiency	5.00%	7.00%	10.00%
	Engine Component Weights (Avg. Reduction)	5.00%	7.00%	10.00%

* values obtained from prior GT studies, with concurrence of the IEs and ICCAIA

Table L-7. 2037 RJ Technology Three Point Estimate Impacts from ICCAIA

2037	Technology Category	High Confidence	Nominal	Low Confidence
Noise	Jet Source Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Fore Noise (ΔdB)	FT:-1.5 BB:-1.5	FT:-2.5 BB:-2.5	FT:-3 BB:-3
	Fan Aft Noise (ΔdB)	FT:-1.5 BB:-1.5	FT:-2.5 BB:-2.5	FT:-3 BB:-3
	Core (Combustor) Noise (ΔdB)	0	0	0
	Core (Turbine) Noise (ΔdB)	-1	-2	-3
	Nacelle Liner - Fan Fore Noise (ΔdB)	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*
	Nacelle Liner - Fan Aft Noise (ΔdB)	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*
	Landing Gear Noise (ΔdB)	-2	-3	-5
	Flap Noise (ΔdB)	None	None	None
	Slat Noise (ΔdB)	None	None	None
	PAI Flyover Noise (ΔEPNdB)	2.5x(0.2+0.2668x(BPR-15))	2.5x(0.2+0.2668x(BPR-15))	2.5x(0.2+0.2668x(BPR-15))
	PAI Lateral Noise (ΔEPNdB)	1.0x(0.2+0.2668x(BPR-15))	1.0x(0.2+0.2668x(BPR-15))	1.0x(0.2+0.2668x(BPR-15))
	PAI Approach Noise (ΔEPNdB)	1.5x(0.2+0.2668x(BPR-15))	1.5x(0.2+0.2668x(BPR-15))	1.5x(0.2+0.2668x(BPR-15))
Structures	Wing Weight (%)	-5.7%	-9.2%	-12.5%
	Fuselage Weight (%)	-3.6%	-6.6%	-9.5%
	Empennage Weight (%)	-5.7%	-8.6%	-11.5%
Aero	Total Drag (%)	-2.1%	-4.2%	-6.7%

* additional to standard 2DOF nacelle efficiency

Table L-8. 2037 RJ Technology Three Point Estimate Impacts from IEs and GT

2037	Technology Category	High Confidence	Nominal	Low Confidence
Propulsion*	FPR	1.41	1.4	1.38
	OPR	51	52	54
	BPR	15.4	16.1	17.2
	HPCPR	18	18.5	19
	Fan η (Adiabatic)	2.03	2.04	2.09
	HPC η (Polytropic)	93.50%	93.80%	94.10%
	HPT η (Adiabatic)	92.50%	92.80%	93.10%
	LPT η (Adiabatic)	92.50%	92.80%	93.10%
	Nacelle Drag Reduction	90.00%	90.30%	90.60%
	Nacelle Weight Reduction	92.10%	92.40%	92.70%
	Increase in Small Core Technology Efficiency	12.00%	15.00%	18.00%
	Engine Component Weights (Avg. Reduction)	12.00%	15.00%	18.00%

* values obtained from prior GT studies, with concurrence of the IEs and ICCAIA

L.3 SINGLE AISLE TECHNOLOGY IMPACTS

Table L-9. 2027 SA Technology Three Point Estimate Impacts from ICCAIA

2027	Technology Category	High Confidence	Nominal	Low Confidence
Noise	Jet Source Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Fore Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Aft Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Core (Combustor) Noise (ΔdB)	-4	-6	-9
	Core (Turbine) Noise (ΔdB)	-1	-2	-3
	Nacelle Liner - Fan Fore Noise (ΔdB)	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*
	Nacelle Liner - Fan Aft Noise (ΔdB)	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*
	Landing Gear Noise (ΔdB)	-1	-2	-3
	Flap Noise (ΔdB)	-1.5	-2	-3
	Slat Noise (ΔdB)	-1.5	-2	-3
	PAI Flyover Noise (ΔEPNdB)	+2.5x(0.2+0.2668x(BPR-15))	+2.5x(0.2+0.2668x(BPR-15))	+2.5x(0.2+0.2668x(BPR-15))
	PAI Lateral Noise (ΔEPNdB)	+1.0x(0.2+0.2668x(BPR-15))	+1.0x(0.2+0.2668x(BPR-15))	+1.0x(0.2+0.2668x(BPR-15))
	PAI Approach Noise (ΔEPNdB)	+1.5x(0.2+0.2668x(BPR-15))	+1.5x(0.2+0.2668x(BPR-15))	+1.5x(0.2+0.2668x(BPR-15))
Structures	Wing Weight (%)	-7.4%	-10.1%	-12.9%
	Fuselage Weight (%)	-4.0%	-6.8%	-9.5%
	Empennage Weight (%)	-5.6%	-8.1%	-10.6%
Aero	ICCAIA Provided Total Drag (%)	0.0%	-1.2%	-2.8%
	IE Modified Total Drag for Modelling**	-3.0%	-4.2%	-5.8%

* additional to standard 2DOF nacelle efficiency

** Rationale described in Chapter 7.

Table L-10. 2027 SA Technology Three Point Estimate Impacts from IEs and GT

2027	Technology Category	High Confidence	Nominal	Low Confidence
Propulsion*	FPR	1.48	1.45	1.4
	OPR	50	51.5	52.5
	BPR	13.1	14.3	16.6
	HPCPR	18	19	20
	Fan η (Adiabatic)	1.91	1.9	1.9
	HPC η (Polytropic)	92.80%	93.10%	93.50%
	HPT η (Adiabatic)	91.80%	92.10%	92.50%
	LPT η (Adiabatic)	91.80%	92.10%	92.50%
	Nacelle Drag Reduction	89.30%	89.60%	90.00%
	Nacelle Weight Reduction	91.40%	91.70%	92.10%
	Increase in Small Core Technology Efficiency	5.00%	7.00%	10.00%
	Engine Component Weights (Avg. Reduction)	5.00%	7.00%	10.00%

* values obtained from prior GT studies, with concurrence of the IEs and ICCAIA

Table L-11. 2037 SA Technology Three Point Estimate Impacts from ICCAIA

2037	Technology Category	High Confidence	Nominal	Low Confidence
Noise	Jet Source Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Fore Noise (ΔdB)	FT:-1.5 BB:-1.5	FT:-2.5 BB:-2.5	FT:-3 BB:-3
	Fan Aft Noise (ΔdB)	FT:-5 BB:-2	FT:-8 BB:-3	FT:-10 BB:-4
	Core (Combustor) Noise (ΔdB)	-4	-6	-9
	Core (Turbine) Noise (ΔdB)	-1	-2	-3
	Nacelle Liner - Fan Fore Noise (ΔdB)	-1.5 dB per 0.1 L/D (acoustic)*	-1.5 dB per 0.1 L/D (acoustic)*	-1.5 dB per 0.1 L/D (acoustic)*
	Nacelle Liner - Fan Aft Noise (ΔdB)	-1 dB per 1 L/H (acoustic)*	-1 dB per 1 L/H (acoustic)*	-1 dB per 1 L/H (acoustic)*
	Landing Gear Noise (ΔdB)	-2	-4	-6
	Flap Noise (ΔdB)	-2	-3	-5
	Slat Noise (ΔdB)	-5	Full Cancellation	Full Cancellation
	PAI Flyover Noise (ΔEPNdB)	+2.5x(0.2+0.2668x(BPR-15))	+2.5x(0.2+0.2668x(BPR-15))	+2.5x(0.2+0.2668x(BPR-15))
	PAI Lateral Noise (ΔEPNdB)	+1.0x(0.2+0.2668x(BPR-15))	+1.0x(0.2+0.2668x(BPR-15))	+1.0x(0.2+0.2668x(BPR-15))
	PAI Approach Noise (ΔEPNdB)	+1.5x(0.2+0.2668x(BPR-15))	+1.5x(0.2+0.2668x(BPR-15))	+1.5x(0.2+0.2668x(BPR-15))
Structures	Wing Weight (%)	-9.6%	-13.6%	-17.3%
	Fuselage Weight (%)	-5.8%	-9.8%	-13.6%
	Empennage Weight (%)	-7.3%	-10.9%	-14.4%
Aero	Total Drag (%)	-1.7%	-3.4%	-5.4%
	IE Modified Total Drag for Modelling**	-8.7%	-10.4%	-12.4%

* additional to standard 2DOF nacelle efficiency

** Rationale described in Chapter 7.

Table L-12. 2037 SA Technology Three Point Estimate Impacts from IEs and GT

2037	Technology Category	High Confidence	Nominal	Low Confidence
Propulsion*	FPR	1.39	1.37	1.35
	OPR	53	54.5	56
	BPR	17.6	19	20.7
	HPCPR	20	21	22
	Fan η (Adiabatic)	1.94	1.92	1.91
	HPC η (Polytropic)	93.50%	93.80%	94.10%
	HPT η (Adiabatic)	92.50%	92.80%	93.10%
	LPT η (Adiabatic)	92.50%	92.80%	93.10%
	Nacelle Drag Reduction	90.00%	90.30%	90.60%
	Nacelle Weight Reduction	92.10%	92.40%	92.70%
	Increase in Small Core Technology Efficiency	12.00%	15.00%	18.00%
	Engine Component Weights (Avg. Reduction)	12.00%	15.00%	18.00%

* values obtained from prior GT studies, with concurrence of the IEs and ICCAIA

L.4 TWIN AISLE TECHNOLOGY IMPACTS

Table L-13. 2027 TA Technology Three Point Estimate Impacts from ICCAIA

2027	Technology Category	High Confidence	Nominal	Low Confidence
Noise	Jet Source Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Fore Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Aft Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Core (Combustor) Noise (ΔdB)	-4	-6	-9
	Core (Turbine) Noise (ΔdB)	-1	-2	-3
	Nacelle Liner - Fan Fore Noise (ΔdB)	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*	-1 dB per 0.1 L/D (acoustic)*
	Nacelle Liner - Fan Aft Noise (ΔdB)	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*	-0.5dB per 1 L/H (acoustic)*
	Landing Gear Noise (ΔdB)	-1	-2	-3
	Flap Noise (ΔdB)	-1	-1.5	-3
	Slat Noise (ΔdB)	-2	-3	-5
	PAI Flyover Noise (ΔEPNdB)	+2.5x(0.2+0.2668x(BPR-15))	+2.5x(0.2+0.2668x(BPR-15))	+2.5x(0.2+0.2668x(BPR-15))
	PAI Lateral Noise (ΔEPNdB)	+1.0x(0.2+0.2668x(BPR-15))	+1.0x(0.2+0.2668x(BPR-15))	+1.0x(0.2+0.2668x(BPR-15))
	PAI Approach Noise (ΔEPNdB)	+1.5x(0.2+0.2668x(BPR-15))	+1.5x(0.2+0.2668x(BPR-15))	+1.5x(0.2+0.2668x(BPR-15))
Structures	Wing Weight (%)	-4.0%	-6.9%	-9.9%
	Fuselage Weight (%)	-3.2%	-5.8%	-8.5%
	Empennage Weight (%)	-3.2%	-5.8%	-8.5%
Aero	Total Drag (%)	0.0%	-1.2%	-3.1%

* additional to standard 2DOF nacelle efficiency

Table L-14. 2027 TA Technology Three Point Estimate Impacts from IEs and GT

2027	Technology Category	High Confidence	Nominal	Low Confidence
Propulsion*	FPR	1.54	1.5	1.46
	OPR	48	52	55
	BPR	10.3	11.4	12.7
	HPCPR	8	8.2	8.4
	Fan η (Adiabatic)	4	4.3	4.6
	HPC η (Polytropic)	92.60%	92.90%	93.30%
	HPT η (Adiabatic)	91.80%	92.10%	92.50%
	LPT η (Adiabatic)	91.80%	92.10%	92.50%
	Nacelle Drag Reduction	89.30%	89.60%	90.00%
	Nacelle Weight Reduction	92.30%	92.60%	93.00%
	Increase in Small Core Technology Efficiency	92.30%	92.60%	93.00%
	Engine Component Weights (Avg. Reduction)	5.00%	7.00%	10.00%

* values obtained from prior GT studies, with concurrence of the IEs and ICCAIA

Table L-15. 2037 TA Technology Three Point Estimate Impacts from ICCAIA

2037	Technology Category	High Confidence	Nominal	Low Confidence
Noise	Jet Source Noise (ΔdB)	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]	[Cycle Dependent (built in Jet Noise Prediction)]
	Fan Fore Noise (ΔdB)	FT:-1.5 BB:-1.5	FT:-2.5 BB:-2.5	FT:-3 BB:-3
	Fan Aft Noise (ΔdB)	FT:-5 BB:-2	FT:-8 BB:-3	FT:-10 BB:-4
	Core (Combustor) Noise (ΔdB)	-4	-6	-9
	Core (Turbine) Noise (ΔdB)	-1	-2	-3
	Nacelle Liner - Fan Fore Noise (ΔdB)	-1.5 dB per 0.1 L/D (acoustic)*	-1.5 dB per 0.1 L/D (acoustic)*	-1.5 dB per 0.1 L/D (acoustic)*
	Nacelle Liner - Fan Aft Noise (ΔdB)	-1 dB per 1 L/H (acoustic)*	-1 dB per 1 L/H (acoustic)*	-1 dB per 1 L/H (acoustic)*
	Landing Gear Noise (ΔdB)	-2	-4	-6
	Flap Noise (ΔdB)	-1.5	-3	-4
	Slat Noise (ΔdB)	-5	Full Cancellation	Full Cancellation
	PAI Flyover Noise (ΔEPNdB)	+2.5x(0.2+0.2668x(BPR-15))	+2.5x(0.2+0.2668x(BPR-15))	+2.5x(0.2+0.2668x(BPR-15))
	PAI Lateral Noise (ΔEPNdB)	+1.0x(0.2+0.2668x(BPR-15))	+1.0x(0.2+0.2668x(BPR-15))	+1.0x(0.2+0.2668x(BPR-15))
	PAI Approach Noise (ΔEPNdB)	+1.5x(0.2+0.2668x(BPR-15))	+1.5x(0.2+0.2668x(BPR-15))	+1.5x(0.2+0.2668x(BPR-15))
Structures	Wing Weight (%)	-5.7%	-9.8%	-13.7%
	Fuselage Weight (%)	-4.7%	-8.4%	-12.0%
	Empennage Weight (%)	-4.7%	-8.4%	-12.0%
Aero	Total Drag (%)	-2.0%	-4.4%	-7.2%

* additional to standard 2DOF nacelle efficiency

Table L-16. 2037 TA Technology Three Point Estimate Impacts from IEs and GT

2037	Technology Category	High Confidence	Nominal	Low Confidence
Propulsion*	FPR	1.45	1.4	1.35
	OPR	54	58	62
	BPR	13.1	15.5	18.1
	HPCPR	8.5	8.7	8.9
	Fan η (Adiabatic)	4.5	4.9	5.3
	HPC η (Polytropic)	93.30%	93.60%	94.00%
	HPT η (Adiabatic)	92.50%	92.80%	93.10%
	LPT η (Adiabatic)	92.50%	92.80%	93.10%
	Nacelle Drag Reduction	90.00%	90.30%	90.60%
	Nacelle Weight Reduction	93.00%	93.30%	93.70%
	Increase in Small Core Technology Efficiency	93.00%	93.30%	93.70%
	Engine Component Weights (Avg. Reduction)	12.00%	15.00%	18.00%

* values obtained from prior GT studies, with concurrence of the IEs and ICCAIA

APPENDIX M. DESIGN VARIABLE RANGES AND CONSTRAINTS

M.1 2017 DESIGN VARIABLES RANGES AND CONSTRAINTS

Table M-1. 2017 Design Variable Ranges

2017 Ranges		Wing Loading (lb/ft^2)	AR	FPR	OPR	T40 (R/K)
BJ	Min	81.1	7.5	1.65	26	2560 / 1422
	TRA Base Value	81.1	7.7	1.7	28	2587 / 1437
	Max	81.1	8.25	1.75	31	2610 / 1450
RJ	Min	112.1	10.5	1.42	42	2915 / 1619
	TRA Base Value	112.1	11.03	1.5	44	2940 / 1633
	Max	112.1	11.25	1.6	52	2965 / 1647
SA	Min	130.0	9.0	1.4	45	3065 / 1703
	TRA Base Value	131.5	9.1	1.52	48.5	3091 / 1717
	Max	133.0	11	1.6	52.5	3115 / 1730
TA	Min	129.9	8.5	1.46	45	2860 / 1589
	TRA Base Value	129.9	8.9	1.585	46	2884 / 1602
	Max	129.9	11.0	1.6	56	2910 / 1617

Table M-2. 2017 Optimization Constraints

2017 Constraints		T3max Limit (R/K)	Gate Constraint (ft / m)	Fan Diameter Constraint (ft / m)
BJ	TRA Base Value	1505 / 836	99.6 / 30.4	4.2 / 1.28
	Constraint	1505 / 836	N/A	N/A
RJ	TRA Base Value	1649 / 916	110.6 / 33.7	6.2 / 1.88
	Constraint	1649 / 916	118.1 / 36.0	6.4 / 1.95
SA	TRA Base Value	1644 / 913	117.5 / 35.8	6.8 / 2.08
	Constraint	1644 / 913	118.1 / 36.0	7.2 / 2.20
TA	TRA Base Value	1668 / 927	212.5 / 64.7	9.9 / 3.02
	Constraint	1668 / 927	213.3 / 65	10.9 / 3.33

M.2 2027 DESIGN VARIABLES AND CONSTRAINTS

Table M-3. 2027 Design Variable Ranges

2027 Ranges		Wing Loading (lb/ft^2)	AR	FPR	OPR	T40 (R/K)
BJ	Min	81.0	7.5	1.65	26	2560 / 1422
	TRA Base Value	81.1	7.7	1.7	28	2587 / 1437
	Max	82.0	8.25	1.75	31	2655 / 1475
RJ	Min	112.0	10.5	1.42	42	2915 / 1619
	TRA Base Value	112.1	11.03	1.5	44	2940 / 1633
	Max	113.0	11.5	1.6	52	3050 / 1695
SA	Min	130.0	9.0	1.4	45	3065 / 1703
	TRA Base Value	131.5	9.1	1.52	48.5	3091 / 1717
	Max	133.0	11.0	1.6	52.5	3200 / 1778
TA	Min	129.0	8.5	1.46	45	2800 / 1556
	TRA Base Value	129.9	8.9	1.585	46	2884 / 1602
	Max	131.0	11.0	1.6	56	2940 / 1633

Table M-4. 2027 Optimization Constraints

2027 Constraints		T3max Limit (R/K)	Gate Constraint (ft / m)	Fan Diameter Constraint (ft / m)
BJ	TRA Base Value	1505 / 836	99.6 / 30.4	4.2 / 1.28
	Constraint	1620 / 900	N/A	N/A
RJ	TRA Base Value	1649 / 916	110.6 / 33.7	6.2 / 1.90
	Constraint	1800 / 1000	118.1 / 36.0	6.4 / 1.95
SA	TRA Base Value	1644 / 913	117.5 / 35.8	6.8 / 2.08
	Constraint	1800 / 1000	118.1 / 36.0	7.2 / 2.20
TA	TRA Base Value	1668 / 927	212.5 / 64.7	9.9 / 3.02
	Constraint	1800 / 1000	213.3 / 65	10.9 / 3.33

M.3 2037 DESIGN VARIABLES AND CONSTRAINTS

Table M-5. 2037 Design Variable Ranges

2037 Ranges		Wing Loading (lb/ft2)	AR	FPR	OPR	T40 (R/K)
BJ	Min	81.0	7.5	1.62	26	2560 / 1422
	TRA Base Value	81.1	7.7	1.7	28	2587 / 1437
	Max	84.0	9.0	1.75	34	2720 / 1511
RJ	Min	112.0	10.5	1.38	42	2915 / 1619
	TRA Base Value	112.1	11.03	1.5	44	2940 / 1633
	Max	115.0	13.5	1.6	56	3115 / 1730
SA	Min	130.0	9.0	1.35	45	3065 / 1703
	TRA Base Value	131.5	9.1	1.52	48.5	3091 / 1717
	Max	135.0	13.0	1.6	56	3300 / 1833
TA	Min	129.0	8.5	1.35	45	2800 / 1556
	TRA Base Value	129.9	8.9	1.585	46	2884 / 1602
	Max	133.0	13.0	1.6	62	3070 / 1706

Table M-6. 2027 Optimization Constraints

2037 Constraints		T3max Limit (R/K)	Gate Constraint (ft / m)	Fan Diameter Constraint (ft / m)
BJ	TRA Base Value	1505 / 836	99.6 / 30.4	4.2 / 1.28
	Constraint	1710 / 950	N/A	N/A
RJ	TRA Base Value	1649 / 916	110.6 / 33.7	6.2 / 1.90
	Constraint	1836 / 1020	118.1 / 36.0	6.4 / 1.95
SA	TRA Base Value	1644 / 913	117.5 / 35.8	6.8 / 2.08
	Constraint	1836 / 1020	118.1 / 36.0	7.2 / 2.20
TA	TRA Base Value	1668 / 927	212.5 / 64.7	9.9 / 3.02
	Constraint	1836 / 1020	213.3 / 65	10.9 / 3.33

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