Competing Priorities

Technology's Influence on the Levels of Environmental Emissions from Aircraft and the Trade-Offs Involved – Review and Future Prospects

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Contents

Glossary

ALM	Additive Layer Manufacturing What is normally referred to as “3d printing”
APU	Auxiliary Power Unit Small gas turbine fitted to most aircraft and used to generate electricity whilst on the aircraft is on the ground
BWB	Blended Wing Body One of several proposed concepts for next generation aircraft. The military equivalent is often called a delta wing.
CAEP	Committee on Aviation Environmental Protection A technical committee of ICAO. Composed of various working groups of which WG1 is on noise issues – they are advised by an Independent Expert Panel (IEP).
EIS	Entry into Service Actual or expected date that an aircraft type is first used commercially.
HLD	High Lift Device(s) Components of aircraft wing designed to increase lift – normally during take-off and landing – and include flaps and slats.
ICAO	International Civil Aviation Organisation
IEP	Independent Expert Panel – see CAEP.
LAQ	Local Air Quality
SSBJ	Super-sonic Business Jet
TRL	Technology Readiness Level A series of nine levels that describe how close to be employed commercially a particular technology is. TRL1 is concept observed ranging to TRL9 where the system has been proven in an operational environment.
VAN	Variable Area Nozzle A means of ensuring that High Bypass Ratio engines work efficiently at both high altitude (low air pressure) and at low altitudes (high air pressure).

Executive Summary

In the future, aircraft will become less noisy and only the extent and rate of improvement is influenced by trade-offs.

While there are some forms of technology that offer an obvious trade-off between noise and other emissions, this is not generally the case. The complex inter-dependencies between noise, NO_X and CO_2 emissions mean that target reductions need to be set at an early design stage. For this reason, continuing dialogue between regulators and industry stakeholders is necessary.

An aircraft's thrust requirement is the main driver of all emissions and is set to decrease in the future. This will come about through reductions in aircraft/engine drag and weight, by improvements in engine efficiency (leading to less fuel payload), and through the adoption of novel drag-reducing propulsion configurations.

Engine fuel-efficiency can be improved by increasing the operating pressure ratio and temperature of the core. However, this presents a challenge for managing NO_X emissions which, if prioritised, will lead to increased weight and higher CO_2 emissions.

Improved attenuation of engine noise using variable frequency bypass liners and ceramic hot core liners must be traded against increased weight.

Open rotor engines offer significant potential for reduced fuel-burn, CO_2 and NO_X emissions if these are prioritised. However, while future designs of open rotor are likely to be quieter than present day turbofans, they will be significantly noisier than future turbofans.

Modern composite materials and manufacturing methods such as ALM offer the possibility to substantially reduce weight and drag. They also allow the realisation of low noise HLD but this would involve a trade-off with CO_2 and NO_X emissions as such devices increase drag (and possibly weight).

Apart from improved design, landing gear noise can only be tackled via shielding or using novel low-noise drag devices to improve steep approach capability. Both of these are likely to increase weight.

Novel aircraft design could entail using the airframe to provide shielding to the engine noise (such as the BWB and other lifting fuselage concepts). Compared to competing designs this is likely penalise the fuel-burn performance of the aircraft due to increased weight, increased drag, and impact on airflow into the engine.

Ground operational techniques have the potential to reduce all emissions simultaneously with no trade-offs. These include reduced engine taxiing, and the elimination of needing to use APUs at stand.

Of all the emissions, NO_X remains the hardest to tackle. Here, the use of all electric or electric assisted take-off and landing offers real potential for reducing NO_X close to airports. By greatly increasing aircraft efficiency these technologies also lower CO_2 emissions. Noise is unlikely to be any greater than equivalent future turbofan aircraft, but importantly, is unlikely to be quieter as is often supposed.

Because of increasing demand, fleet size will grow and operational noise levels will rise in the immediate future but eventually the benefits of quieter aircraft entering service will reverse this trend and operational noise levels will begin to fall. The principal driver here is the rate of aircraft replacement. Looking as far as 2050 and assuming reasonable technological advances, there is no projected scenario where operational noise does not eventually fall – only the timing of the maximum noise point and rates of decrease are affected by choice of technology, aircraft replacement rates, and trade-off considerations. Peak noise is likely to occur between 2025 and 2030.

Electric operated air taxis and drones are a new form of aviation that will not contribute to CO_2 and NO_X emissions. However, as their numbers increase they pose a serious noise challenge.

Introduction

This report has been commissioned by The Department of Transport (DfT) as part of their input to the development of the Aviation Strategy.

The Government acknowledges the benefits which growth of the aviation sector brings while also recognising the environmental challenges that it poses, both locally in the form of noise and air quality, and globally in the form of greenhouse gases. These issues need to be managed if aviation is to continue to grow, which is why the government is proposing to establish a partnership for growth. It is also the case that the UK is party to a number of targets (some advisory and some legally binding) that seek to reduce aviation emissions. For instance the 2008 Climate Change Act commits the UK to reducing GHG emissions to 20% of 1990 levels by 2050 while EU initiatives such as Flightpath 2050 seek aggressive reductions in noise, LAQ pollutants and GHG over the same time period.

In parallel with the agenda of national and international governmental bodies, the aviation industry has been developing environmental roadmaps over several years. In the UK, the Sustainable Aviation Group have published long term goals for both noise and emissions and internationally the International Air Transport Association (IATA) has set the goal of reducing CO_2 emissions by 50% (against a 2005 baseline) by 2050.

The goals set by various agencies are broadly similar in ambition and involve strategies based on a mixture of similar initiatives such as improvements in technology, operations, carbon trading, and infrastructure and land use management. However, such a mixed approach offers the potential for trade-offs between the strategies for reaching individual emission targets. For instance, a re-routed flightpath may be desired to avoid noise exposure in densely populated areas; however, by flying indirectly more fuel will be burnt and therefore the impact from CO_2 and other GHG will be greater.

This report explores the issue of trade-offs between noise and other emissions and concentrates primarily on the influence of technology. In the next section a brief description of the likely future developments in new aircraft is given, followed by a synopsis of the types and causes of aircraft emissions in section 3 and a review of recent historical progress in section 4. Whilst conventional turbofan powered tube and wing designed aircraft are set to remain central to aviation for some time, the consensus of the industry is that the longer term emission targets will not be met unless there is a step change in technology. Section 5 of the report looks at potential future technologies -- again from the perspective of emissions trade-offs. Invariably, aircraft emissions cannot be separated completely from the operational environment and the type of aircraft in service and these aspects are considered briefly in sections 6 and 7.

The main aim of the report is to summarise existing literature in a way that it is accessible to the lay reader. A list of sources used is given.

Context

The medium range aircraft class has seen significant re-engineering over the last two decades with the introduction of aircraft such the A320neo and B737 Max, while three all-new wide-body long haul models – the A380 and A350, plus the B787 – have been introduced. They have benefited from the introduction of new technologies, principally the increasing use of composites and the replacement of hydraulic and pneumatic systems by electric powered alternatives. Given these newly introduced wide-body aircraft and the fact that both manufacturers have large backlogs in their narrow body programmes, we are unlikely to see wholly new replacement aircraft in either class in the near future, probably 2030.

The increasing use of electric systems presages yet further introduction of electric technology, and the commitment of both Airbus and Boeing to electric power is clear with the E-Fan and Horizon X programmes. More broadly, there exist a host of concepts and demonstrators for hybrid electric and fully electric powered aircraft by a number of new players who have entered the field.

The notion of “on demand” (or “air taxis”) is currently seen as a likely first step for fully electric flight, with hybrid electrics replacing the current family of regional turbofan and turboprop aircraft (such as the Bombardier CRJ and Q400 Series, and the Embraer E jet series). Uber recently announced plans to introduce electric air taxis (the Uber Elevate) by 2023, but the use of hybrid electric powered regional aircraft is more likely EIS in the 2030s timeframe. It should also be noted that a new type of electrically powered aircraft already with us is the small UAV, or drone. It is likely that the use of drones will substantially increase over the years to come.

Whilst Elon Musk has suggested an electric supersonic business jet, none of the traditional manufacturers in the business jet sector show much interest in this, and instead focus on improvements to conventional turbofan technology. The main conceptual designs for future vehicles focuses on a new generation of SSBJs using turbofans.

In summary, the air taxis and drone sector is likely to see rapid development in the near future. The more traditional aviation sectors of large, medium, and regional aircraft are in a quiet period, allowing time for the development of future engine and airframe concepts that exploit new materials and manufacturing methods along with increasing the use of electrical systems and power units. Turbofans will remain the mainstay for larger aircraft, and engine manufacturers will introduce a new generation of engines to complement the new airframes.

Sources of Aircraft Noise and Emissions

Noise

Aviation noise is one of the key issues at airports. It is seen as a cause of annoyance which is detrimental to the quality of life of those living nearby. Consequently, noise from aircraft taking off and landing is regulated both internationally and locally. Internationally, the main source of regulation is the ICAO noise chapters, which prescribe limits on the amount of noise produced by new aircraft on entry into service (EIS). The ICAO chapters act as short term drivers for improvement and have proved highly successful in decreasing the noise from individual aircraft, Figure 1.

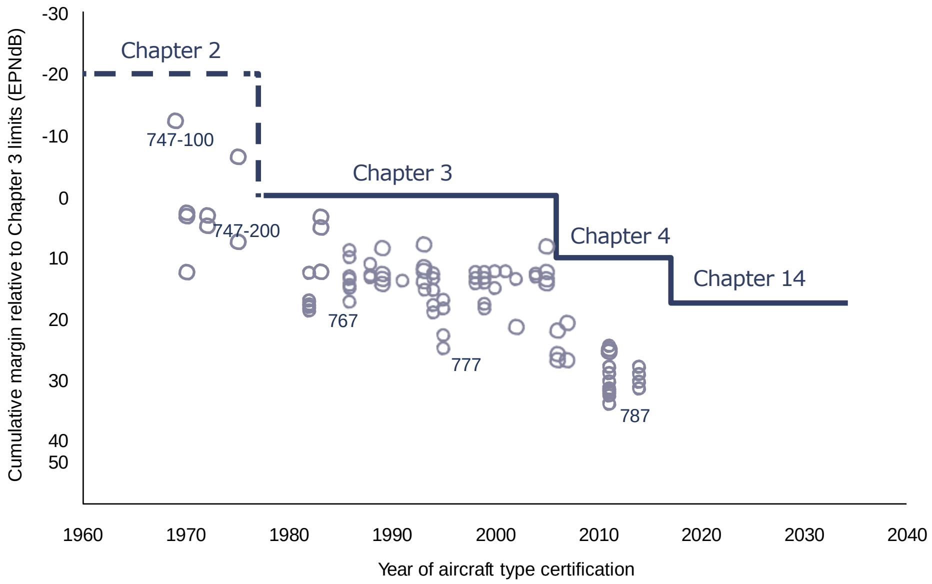

Figure 1. Improvement in aircraft noise performance. (Adapted from EASA: European Aviation Environmental Report 2016.)

Physically, noise is a form of vibrational energy consisting of pressure waves. However, if we were to measure it in purely physical units (such as say Watts/sqm) this would not accurately reflect the way it is perceived by people. To overcome these difficulties, a number of proxy metrics based on listening tests are used. The variety of proxy metrics can be confusing to the non-specialist but broadly consist of: instantaneous levels (e.g. Sound Intensity Level), event levels such as an aircraft flying overhead as measured by, for instance, the Effective Perceived Noise Level (EPNL) used in the ICAO chapters, and long term exposure levels such as the Day-Night Average Sound Level (L_{DN}) used in airport noise contours. In all cases, a decibel scale is used; this means that halving the acoustic energy from a source only results in a 3dB reduction in the perceived noise. This has the important implication that to make major advances in reducing aircraft noise, all the sources of such noise must be reduced in parallel.

Unfortunately, aircraft have a large number of noise sources, as illustrated in Figure 2. However, they can be broadly classified as engine noise sources and airframe noise sources.

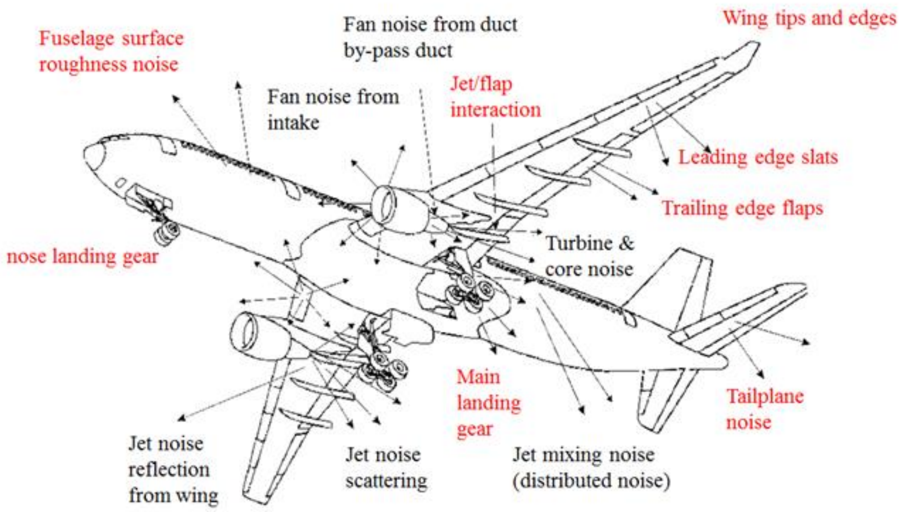

Figure 2. Main sources of engine and airframe noise.

The major sources of engine noise are the fan and jet, and to a lesser extent, the compressors, combustor, turbine and bleeds (which may actually dominate at certain times during flight). Airframe noise is generated by the airflow surrounding the moving plane. The main sources are the discontinuities of the aircraft structure, such as high-lift devices (HLD), landing gear wheels (when extended), and trailing edges which lead to speed shearing (aircraft speed versus still air). A further source of noise arises from the interaction of the engines exhaust jet with the airframe. As a general rule, engine sources dominate on take-off while airframe noise dominates on approach.

Other Emissions

Aircraft produce the same types of emissions as the internal combustion engines of cars, namely, carbon dioxide (CO_2), water vapour (H_2O), nitrogen oxides (NO_x), carbon monoxide (CO), oxides of sulphur (SO_x), unburned or partially combusted hydrocarbons (also known as volatile organic compounds (VOCs)), particulates, and other trace compounds.

Aircraft emissions, depending on whether they occur near the ground (generally below 200m ref Rogers et al) or at altitude, are primarily considered either LAQ pollutants or GHG, respectively. At altitude, water in the aircraft exhaust will have a greenhouse effect; it may also produce contrails which could lead to further greenhouse effects. The bulk of aircraft emissions (approximately 90%) occur at altitude. The largest source of NO_x near airports originates from roads as well as other traffic associated with the airport.

All gaseous emissions from aircraft arise from the combustion process, with the exception of particulates, where brake and tyre wear are factors. CO_2 and H_2O are the products of complete combustion of aviation and other hydrocarbon based fuels. Nitrogen oxides are produced when air passes through high temperature/high pressure combustion and nitrogen and oxygen present in the air combine to form NO_x. VOCs and CO are emitted due to incomplete fuel combustion. Sulphur oxides are produced when small quantities of sulphur, present in all natural hydrocarbon fuels, combine with oxygen from the air during combustion.

ICAO has established international certification limits for NO_x emissions from jet engines, with the current NOx standards being established in 2012, (the fourth change since the original standards were agreed back in 1981). New standards for engines entering service came into effect in 2013; they reflect a 12 percent NO_x reduction over the 2008 levels as baseline. ICAO's CAEP has since recommended new certification standards that represent a further 15% NO_x reduction over the 2014 levels as baseline. Aviation NO_x emissions are projected to be less than 3% of the transportation NO_x inventory by 2020 ref FAA primer ref 82.

Recent past progress in reducing aircraft noise and emissions

General considerations

Whilst technological improvements targeted at reducing noise and/or gaseous emissions have been made, the main reason for the steady progress in reducing aviation emissions over the last few decades can be directly linked to an overall improvement in aircraft fuel consumption, as illustrated in Figure 3.

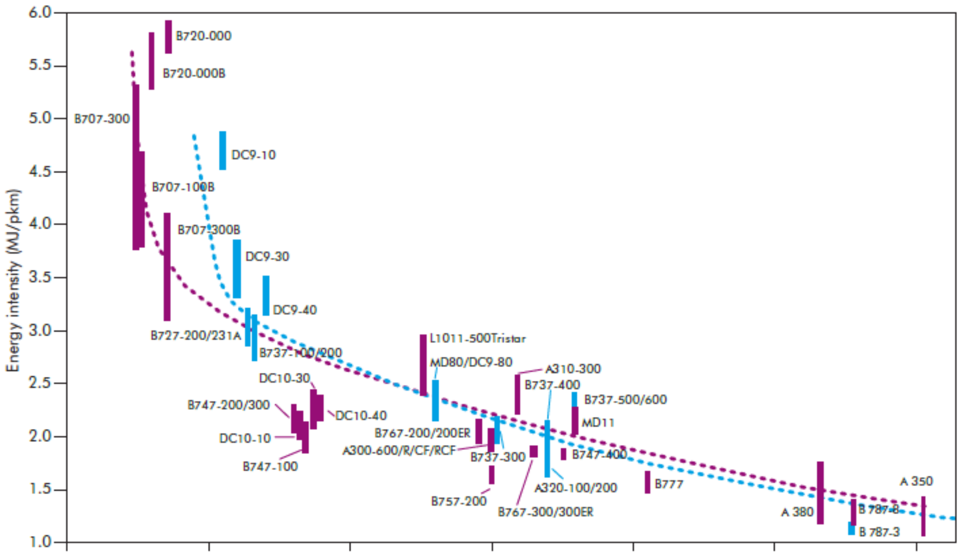

Figure 3. Improvement in aircraft efficiency. (From [16]).

It is clear why this improvement in fuel consumption should lead to lower CO_2 emissions (per passenger km), but less so why it also implies an improvement in NO_x and noise. During take-off, both NO_x and noise will vary in line with the thrust requirements of the aircraft. If the aircraft requires a smaller fuel payload, less thrust is required, resulting in less noise and NO_x emissions. This “win-win” situation was born out of a need for manufacturers to minimise operational costs of operators. Consequently, it can be argued that most of the environmental improvements in aviation over the last few decades have arisen as a by-product of the need for manufacturers to produce economically competitive products.

Aircraft Efficiency Improvements

Aircraft efficiency is a measure of how well the available energy of fuel is converted into useful forward motion for an aircraft. It is the product of the individual efficiencies of the steps involved in this overall process. The efficiency of an engine comprises two main factors. The engine’s thermal efficiency describes the effectiveness with which the available chemical energy in the fuel is turned into mechanical energy, and the propulsive efficiency of the engine indicates how well the mechanical energy is turned into thrust. Additionally, the propulsive efficiency of the airframe measures how well this thrust is converted into useful forward motion. Higher values for all of these efficiencies are desirable in the drive to reduce fuel-burn and CO_2 emissions. However, while lower fuel burn implies less NO_x emission, a higher thermal efficiency can lead to enhanced NO_x production per unit mass of fuel burn.

Improvements to engine thermal efficiency are constrained by thermodynamics and involve both increasing the overall pressure ratio of the core and increasing the turbine entry temperature. Unfortunately, this also involves a higher combustion temperature which increases NO_x production; to date, the overall fuel consumption improvement has compensated for this. To improve engine propulsive efficiency, the main approach has been one of steadily increasing the bypass ratio (BPR) – that is, the ratio of the amount of air that passes through the fan but not the engine core to the amount of air that passes through the core itself. A larger bypass flow of slower air through the fan also has the advantage of decreasing jet noise considerably. However, for a given thrust rating, a higher bypass ratio typically requires a larger fan and nacelle together with a low-pressure turbine system. These changes introduce additional weight and drag, offsetting some of the gains in propulsive efficiency. This trade-off between engine propulsive efficiency and weight/drag gives rise to an optimum bypass ratio which, at the time of writing, has been reached. This is not to say that further improvement utilising increased BPR is not possible, but simply that it implies the need for addition technological improvements as discussed below.

Historically, the greatest increase in aircraft efficiency has been made by improved engine performance. However, as engines have become more efficient, the gains to be made through airframe improvements have become more significant. There are two main points worth noting here.

Aircraft weight is a primary driver of fuel burn because a heavier aircraft requires increased lift, thereby increasing drag and the consequent need for additional thrust. To decrease weight, the use of composite materials (based on carbon fibre or glass fibre) in aircraft has increased in recent decades. A high percentage of newer aircraft such as the Boeing 787 and the Airbus A350 XWB consist of such materials.

In addition to decreasing weight, decreasing drag (for a given thrust) will improve aircraft efficiency. Winglets are the most obvious recent example of a technology that decreased drag. Adding winglets (Figure 4) that are tilted upward at the tips, either to new aircraft or as retrofits to existing models, has delivered 3-5% reductions in fuel burn, depending on the length of the flight and type of aircraft. An alternative to the winglet is the raked tip, which can produce similar drag reductions.

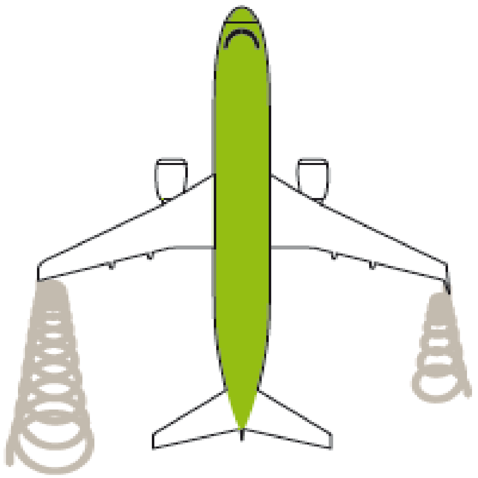

Figure 4. Winglets decrease drag. Fast moving air along the top of the wing meets slower air moving underneath at the wing's tip, creating a vortex. This illustration shows how this wake vortex can be significantly reduced by the use of wingtip devices. Reducing the vortex reduces drag. ***(From [13]).***

One may think that increasing lift would lead to an increase in aircraft efficiency, and in principle this is correct. However, any benefits gained from increased lift may well be more than offset by other factors, depending on how that additional lift is obtained. During take-off and approach, when the aircraft is moving slowly, there is definitely a need for increased lift, and this is made possible by deploying high lift devices (HLD) known as flaps and slats. These devices increase both wing area and thickness of the wing, leading to increased lift, but in doing so, they also increase airframe noise considerably and lead to increased drag which then requires extra thrust (and hence additional engine noise and emissions). If a similar strategy to increase lift (by increasing area and thickness) was employed during cruise, the additional drag would more than offset the benefits. Consequently, most gains have come about through incremental design improvements, largely due to better computational methods.

Technology Leading to Decreased Noise Levels

As well as noise improvements through increased aircraft efficiency, manufacturers have also introduced technological improvements specifically aimed at decreasing noise. To date, the primary driver for technology has been fuel burn. Noise suppression technology has been constrained for the most part, meaning that the solutions adopted have had little or no effect on other emissions. The one notable exception to this rule is the A380, where achieving the QC/2 departure noise levels at London airports resulted in noise being given a stronger weighting during the design process. Consequently, the noise requirements were met at the expense of a slightly increased fuel burn.

Engine Noise

Fan Noise

While increased BPR has decreased jet noise, it has led to larger fans, resulting in increased fan noise. To counteract this, a number of largely passive technologies have been introduced. At present, liners consist of classical honeycombs, where the outer plate is perforated (Figure 5). These liners behave like Helmholtz resonators, absorbing noise in a limited frequency range. For this reason, they are well suited to fan noise, which is tonal in character. Newer designs have more than one layer of honeycombs in order to broaden the frequency range absorbed.

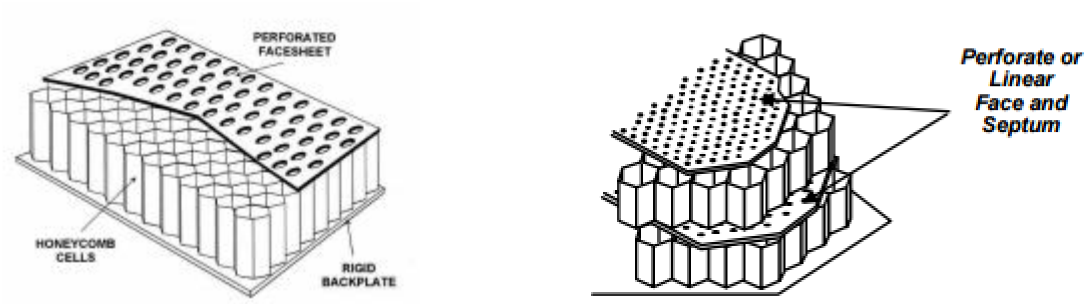

Figure 5. Illustration of a single layer liner (left) and multiple layer liner (right).

When first manufactured, intake liners were usually manufactured in sections for ease of fitting. Once in the nacelle, the sections were joined by longitudinal splices which entailed sharp azimuthal variations of acoustical impedance where the liners were spliced. This meant that tones (especially buzz-saw tones) could be scattered into other frequencies and less well attenuated. To overcome this, “zerosplice” liners were developed, and are now fitted to the A380, A350XWB and B787.

As well as attenuating fan noise, progress has been made on reducing noise at source by introducing designs that are inherently quieter. For instance, increasing the distance between fan rotor blades and stators, or sweeping the stators, results in a decrease in rotor-stator interaction tones. However, changes in the design of the blades themselves may directly affect the performance of the engine. Consequently, manufacturers reveal very little about their low noise designs since this may affect competitiveness.

Jet and Exhaust Noise
Because jet noise is produced as the engine exhaust mixes with the ambient air (i.e. it is not generated within the engine itself, but rather downstream of the nozzle), other than lowering the velocity, it is a particularly difficult factor to control. To date, the only viable technology that has been invented are chevrons (Figure 6).

Figure 6. Left: core chevrons on a A321 (from pprune.org). Right: fan chevrons on a B787 (Personal photo).

Chevrons are corrugations of the cylindrical exhaust of either the primary jet (core chevrons) or the secondary one (fan chevrons). Core chevrons primarily lower take-off noise, while fan chevrons act to reduce shock-cell noise during cruise. (The gain by using core chevrons on the A21 engine are 2EPNdB, making it compliant with chapter 4.)

Chevrons are considered optional add-ons and are not always adopted. This is because while they do provide noise benefits, the gain is not always seen as worth the aero-performance penalty that they generate when cruising. However, it is worth noting that this ambivalence is largely down to our lack of understanding of the mechanisms through which chevrons act to affect noise and performance. Indeed, it is likely that several different mechanisms may be involved.

Other Engine Sources
Historically, engine noise has been dominated by noise from the fan and the jet, but as these sources have been addressed more and more, other sources of engine noise, namely, the compressor, turbines, the combustor, and handling bleeds have become more important. Consequently, many of the benefits to be gained lie in the future, and where manufacturers have made improvements, it has been to design details that they are unwilling to make public. An exception to this is bleed noise, where simple changes to the silencer design has ensured acceptable noise levels with no performance penalty.

Airframe Noise

Historically, aircraft noise has been dominated by the propulsion system. However, success in controlling engine noise has been so successful over the past fifty years that for an aircraft deployed for landing, the airframe noise is now a major contributor. As a result, further reductions in landing approach noise is dependent on the control of noise generated by landing gear and high lift devices (slats and flaps).

Perhaps unsurprisingly, the larger the aircraft, the more significant the effect of the landing gear in comparison to that of the HLDs. For instance, noise from HLDs is dominant when discussing airframe noise for mid-range aircraft, while landing gear noise is more important for a long-haul aircraft.

Despite its size, a clean aircraft gliding through the air in its cruise configuration, with high lift devices and landing gear retracted, is surprisingly quiet. Deploying the full landing configuration typically increases the level of airframe noise by 10-15dB. There are two main reasons for this. Firstly, flow over sharp edges and other structural discontinuities (as found with landing gear and HLD) is noisier than a similar flow over a smooth surface. Secondly, the geometry of landing gear and HLDs increases the flow speed locally adding to the effect and making them strong noise sources.

Noise from the landing gear is generated by vortex shedding from all its main structural components, such as the wheels, main legs, and struts. The level of noise is significantly enhanced by the several smaller scale features such as brake pipes, cavities, clips, wheel rims and so on. In principle, these mechanisms are well understood and offer two main ways of control. The use of fairings or spoilers to reduce the flow velocity over key noise generating parts of the gear is a 'low-tech' method of noise control amenable to relatively simple engineering design methods, but does carry significant weight penalties. Alternatively, carefully designing the gear to smooth the through-flow and reduce the number of 'discontinuities' in its path can achieve good noise reductions with lower weight penalties, but in practice is very difficult to do.

Noise from high lift devices tends to be dominated by the leading edge slats, with the flaps being a significant secondary contributor. The main source mechanism is the passage of turbulent flow over the trailing edges of the slats and flaps, but other discontinuities such as support tracks and side edges are also important. In comparison to landing gear, the low noise designs of HLDs are very immature, primarily because known methods of noise control strongly reduce the performance of aircraft.

Turbulent interactions between components can also be a significant source of noise. Examples include the jets from the engines or wakes from the landing gear interacting with the flaps. An illustration of this (and the potential to make noise focused retrofit alterations) is the tonal noise often associated with A320 aircraft in approach mode. This has been identified as being due to a fuel dump orifice, for which a fix is being applied.

It is evident from the above that, apart from careful design, little has been done to address the problem of airframe noise. That said, research is ongoing, and there is the potential for improvement in the future, as discussed below.

Technology Leading to Decreased Gaseous Emissions Levels

The amount of CO_2 and water vapour emitted by aircraft is directly linked to fuel burn, and as such, improvements in emissions can be explained by the increase in overall aircraft efficiency as discussed above.

To a large extent, the same is true of other gaseous emissions such as SO_x, NO_x and VOCs, but here the combustion process itself plays a significant role. While there is research underway that will produce cleaner combustors (discussed further below), to date, progress in combustor technology has been limited to increasing the thermal efficiency of the engine, resulting in fuel saving. These improvements are incremental design enhancements that ensure more efficient mixing of fuel and air and aid complete combustion. This decreases VOCs, but, as noted above, may actually increase NO_x production.

For SO_x the situation is slightly different. If sulphur is present in fuel, very little can be done to prevent SO_x formation. In such instances, the only remedy is to use low sulphur (or sulphur free) fuels. Although demonstrations for such fuels have been conducted, they aren't yet operational.

Potential Future Technologies for Reducing Noise and Emissions

Looking towards the future, there is clear potential for a significant decrease in both noise and gaseous emissions. Improvements in system design capability mean that the aircraft can be viewed as a whole rather than separate parts, namely airframe and propulsion systems. The integration of the engine and airframe is set to increase further, bringing with it both benefits (increased aircraft efficiency) and challenges (maintaining commensurate levels of noise and emissions).

In a report of this kind there is insufficient space to give detailed timelines for all the different technologies (or indeed to list all the technologies themselves). Rather, a broad classification of near and long term will be used. By near term we mean a timeframe wherein the process of 'development to market' of existing research is completed by 2030. Long term refers to completion between the years 2030 and 2050. Broadly speaking, this means that the near term encompasses development of conventional tube and wing technology, while the long term involves more novel designs. However, the reality is that these timeframes are likely to overlap.

Near-term Technology to Improve Aircraft Efficiency and Emissions

The main improvements will derive from weight reduction to both airframe and engine. Within the engine, composite fan blades and casings will make significant savings (Rolls-

Royce estimate up to 1,500lb per aircraft); further use of composites will improve airframe weight.

Additive layer manufacturing (ALM) offers the prospect of manufacturing components that are entirely new shapes (which were previously not possible to make), opening up the design space and presenting opportunities for weight reduction. For example, Airbus has used ALM to manufacture a prototype cabin partition with a novel structure that provides the required strength but reduces its weight by 45%.

Besides weight reduction, a decrease in drag will increase aircraft efficiency. One way of doing this is to increase the aspect ratio of the wing (i.e. make it longer and thinner). With a conventional cantilever wing arrangement, there are limits to how far this approach can be pursued because of structural integrity concerns. However, with composite technology, there is now the capability to manufacture truss-braced wings (i.e. a wing supported part-way along its length by a strut which carries part of the load to the fuselage). According to NASA, such a wing can reduce fuel use by 5 to 10%. These benefits are offset by potential space related problems at airport stands as a result of the elongated wings, increasing the likelihood that such a design will fall within the longer term timeframe.

One drag reduction technology that is realistically achievable in the near term is the Natural Laminar Flow wings. The EU Clean Sky BLADE project recently conducted a demonstration to show the feasibility of introducing laminar flow wing technology on a large airliner. It is estimated that the technology can decrease aircraft drag by up to 10%.

Further efficiency gains to the engine will be made via both thermal efficiency and propulsive efficiency. Like in the past, these will be achieved by further increasing the core pressure ratio and engine BPR. However, the penalties associated with these strategies (enhanced NO_x production and increased weight, respectively) are now sufficiently large that mitigating technology will need to be employed.

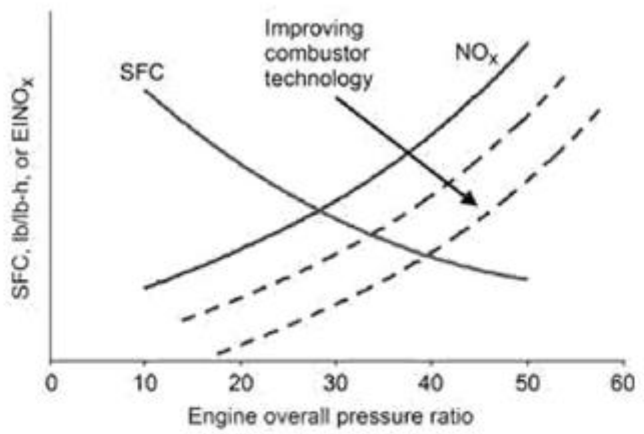

Figure 7. CO_2, NO_X trade-off for combustors, [18].

Mitigation options for NO_x include the use of intercooling - a process which involves air being cooled before it enters the final compressor stages, resulting in a lower combustor inlet temperature – and lean-burn combustion (also known as DLI or Direct Lean Injection), in which the air-fuel ratio is higher than in more conventional arrangements. These combustors are radically different to conventional designs and offer both increased fuel efficiency and lower NO_x levels (up to 65% below CAEP/8 according to Rolls-Royce). Another alternative is the Rich burn Quick quench Lean burn (RQL) combustion system.

One problem with increasing BPR further is that the increased propulsive efficiency is undone by the increased weight of the low pressure turbine. One way of avoiding this is to do away with the low pressure turbine stage, and instead use a geared architecture in which the fan is driven by the intermediate pressure turbine, Figure 8. This is the case with both the Pratt & Whitney PurePower engines and the Rolls-Royce UltraFanTM concept that is currently being developed. It is likely that UltraFan will power the B797, and Rolls-Royce estimates a 15% reduction in fuel consumption compared to the equivalent Pratt & Whitney PurePower engine, or some 25% compared to the existing Trent 700.

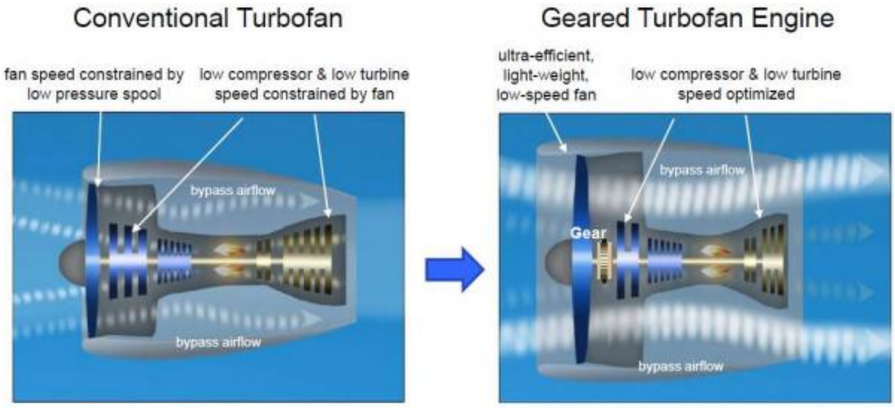

Figure 8. Principle of Geared Turbofan Engine (From [19]).

Near-term Technology to Improve Noise

There is potential for reducing noise by way of better component design and incremental improvements in existing technology, but it is not appropriate to detail all the possibilities here. (The reader is referred to reference [1] for a comprehensive listing. See also Table 1 for illustrative examples.) Instead, we highlight where new technological improvement is likely, and cases where an improvement in aircraft efficiency and gaseous emissions creates a new noise risk that will need to be addressed.

The range of liners employed to attenuate noise will be significant in the near term. Specifically, lip liners (where the intake liner is extended around the lip of the nacelle intake) are feasible now that the problem of integrating them with the de-icing system has been overcome. Modern ceramics and improved manufacturing have made core exhaust liners possible, but the problem of high temperatures and a highly curved geometry must still be solved. Equally, ALM allows for varying the depth of nacelle liners to obtain a distribution of acoustic impedance that can be optimised for maximum attenuation (Nark et al., 2016) or the use of radically new liner design (Koch et al., 2017).

A potential problem with very high BPR engines is obtaining sufficient surge margin. Essentially this is because an engine has to work well at both high and low altitudes (low and high air pressure regimes) and this is increasingly difficult when the BPR is high. One way of overcoming this is to use a Variable Area Nozzle (VAN). Such a nozzle also has benefits associated with fuel burn and noise. Fuel burn will typically reduce by about 10 % during departure and approach, leading to lower NO_x emissions. The noise reduction is in the order of 2dB. It occurs because of the increased diameter of the nozzle, leading to low exhaust velocity. Boeing recently tested a scaled variable area jet nozzle capable of a 20% area change, where shape memory alloy actuators were used to position twelve interlocking panels at the nozzle exit.

In terms of landing gear noise, most benefits will arise from increased computational design capability improvements, although some specific acoustic technologies such as perforated or porous fairings will be introduced. The same is true of HLDs, where improved optimisation of design features such as the slat gap will bring benefits. Likewise, porous edges or edges with chevrons are known to improve noise. Unfortunately, alternative high-lift devices with lower noise characteristics may be less efficient at generating lift, thereby necessitating a larger wing, leading to increased weight and drag.

Component	Technology	Estimated dB Reduction on component level	Timescale	Notes
Fan	Rotor Sweepn and Stator sweep and lean	2dB	Near term	
	Variable Area Nozzle	2dB	Near term	Complexity and weight issues
	Liner improvements	2--4dB	Near term	Manufacture & repair technologies. Integration with other systems such as de-icing.
	Active stators	Up to 8dB	Near/Long term	Highly complex. Weight & structural integrity issues.
	Active blade control	Up to 20dB	Near/Long term	
Jet	Chevrons	1 -- 3dB on TO	Near term	Potental fuel burn penalty
	Fluid injection/microjets/excitation	1--3dB	Near/Long term	Highly complex.
Landing Gear	Fairings	Up to 3dB	Near term	Weight penalty. Maintenance access.
	Low noise design	Up to 5dB	Near/Long term	
	Flow control	1dB	Near/Long term	Weight penalty.
High Lift Devices	Slat & track treatment	Up to 5dB	Near term	Potential for increased drag => fuel penalty
	Flap side edge treatment	Up to 5dB	Near term	Potential for increased drag => fuel penalty
	Low noise design	Up to 5dB	Near/Long term	Potential for increased drag => fuel penalty
Core	Hot liners	2--4dB	Near term	

Table 1. Examples of potential noise reduction through component improvements. (Based on data given in [1].)

Long-term Technology to Improve Aircraft Efficiency, Emissions and Noise

At present, there is a plethora of advanced design concepts for future aircraft, ranging from advanced turbofan powered tube and wing designs, to blended wing bodies (BWB), distributed propulsion (DP) aircraft, and hybrid electric and fully electric aircraft.

An example of the benefits that may be realised in the future is given by the SFW Northrop-Grumman 2035 Tube and Wing Aircraft, Figure 9.

Figure 9. SFW Northrop-Grumman 2035 Tube and Wing Aircraft. (From [1]).

CAEP IEP2 WG1 Final Report tells us that this is a 120 passenger, 2,600 nm range aircraft that is designed to have 64% fuel burn below the baseline B737-500 aircraft, 70 EPNdB below Chapter 4, and 75% LTO NO_x emissions below CAEP/6. The concept includes two Rolls-Royce three-shaft turbofan engines with a ultrahigh bypass ratio of 18 at cruise conditions, compressor intercooling and a cooled cooling air turbine, active compressor clearance control, a lightweight fan and fan cowl, fan blade and outlet guide vanes sweep designs, lean-burn ceramic matrix composite combustor and turbine blades, shape memory alloy nozzle, porous ceramic nozzle material, endothermic fuel system and advanced inlet acoustic liners. For the airframe, the most relevant technologies are ultrahigh performance fibre, advanced metallic, aero elastic structures, sweep-wing laminar flow, large integrated structures, landing gear fairings, 3D woven pi perform joints, and carbon nanotube electrical cables.

It is not possible in a report of this length to describe all these potential improvements to performance adequately. Rather, the aim of listing them in this way is to illustrate what can be achieved with the new generation of aircraft, and to note that there are very large improvements to be made in all areas of emissions. The individual improvements for fuel burn (hence GHG), NO_x, and noise vary from concept to concept, but reviewing the predicted performance figures (for eleven design concepts detailed in the CAEP report) does not give an identifiable pattern that would indicate an obvious trade-off between GHG, NO_x and noise emissions. Clearly, more research needs to be undertaken, and in practice it is unlikely that all these potential technologies will be developed at the same rate. Thus, the main driver behind reducing emissions will be societal ambition rather than technical feasibility.

This is not the case with newer propulsion concepts. An example is the (not so new concept) of open-rotor architecture, (Figure 10). Here, the bypass duct is omitted altogether, allowing for significantly higher bypass ratios without incurring the weight and drag penalty normally associated with a large nacelle. This offers the potential for greatly improved fuel-burn and significantly lower NO_x emissions by allowing for a large increase in thrust without a corresponding increase in combustor temperatures. In this respect it outperforms the turbofan concepts mentioned above. However, these benefits are realised at the expense of noise. The absence of a fan-intake and a bypass duct means that there are fewer opportunities for sound absorption, while the lack of intake flow-conditioning increases the likelihood that the leading rotor will experience non-uniform inflow arising from wing or airframe wake, leading to additional noise challenges. The interaction of the first rotor's outflow with the second rotor presents a further potential source of noise. Low TRL studies suggest that any future open rotor engine would in fact be quieter than present day turbofans, but would be significantly louder than the advanced turbofan concepts discussed above. It may be that over mounting the engines above a BWB would provide sufficient shielding to bring the noise down to acceptable levels, but again, this is more a matter of targets than technology.

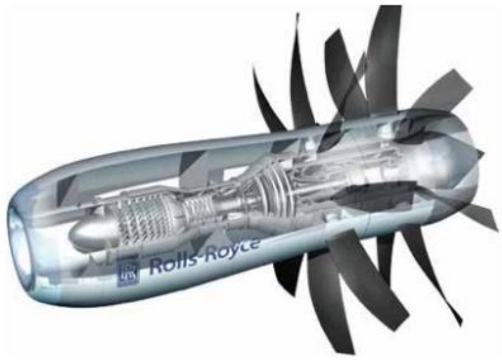

Figure 10. Open rotor concept (courtesy Rolls-Royce).

Another novel propulsion concept is hybrid electric propulsion, which offers new opportunities for reducing noise and emissions, as well as improving fuel efficiency. Its main benefits stem from the power unit (a conventional gas turbine) and the propulsion units (electric fans driven by electricity generated by the gas turbine) being separate. This allows each unit to be individually optimised, making them perform their roles better than is possible in an integrated turbofan arrangement, and with less of the coupling engineering required in an integrated unit. In the conventional design, the gas turbine is buried within the rear of the fuselage, where it ingests the boundary layer of the aircraft body, decreasing the wake energy and improving overall propulsive efficiency. Furthermore, if batteries are built into the design, a smaller gas turbine will be required as the batteries can help during take-off. One danger with this is that the distorted flow into the engine will cause noise, and at this point it is not clear if sufficient inlet duct length exists to attenuate this noise through the use of liners.

At the 2018 Farnborough Air Show, a team consisting of Airbus, Rolls-Royce, and Siemens announced the E-Fan X hybrid-electric flight demonstrator programme. The programme aims to replace one of four gas turbines on a flying testbed with a 2 MW electric motor driven by electricity generated by a buried gas turbine. The first test flight is scheduled for 2020.

The use of purely battery-electric propulsion may also offer opportunities to reduce CO_2 and NO_X emissions due to the absence of on-board combustion and the potential to charge the batteries with low-carbon electricity. While the feasibility of such technology is still debatable (mainly because it requires significantly improved battery energy and power density), progress is being made with both concept development and technology demonstrations. For example, Boeing's SUGAR15 Volt concept aircraft has a hybrid electric propulsion system which allows for short electric only flights and hybrid electric longer range flights. In 2015, the Airbus E-Fan technology demonstrator programme completed a manned crossing of the English Channel using an all-electric aircraft.

To some, the idea of an all-electric aircraft represents a panacea in that it eliminates all airborne gaseous emissions. Furthermore, it is supposed that the use of electric propulsion will greatly reduce noise. However, such high hopes are unlikely to be met. Studies by the author and others indicate that this is likely to only work for very low range, low passenger occupancy aircraft (so-called air taxis). The weight of the batteries required for longer higher capacity flights will lead to a negligible reduction in noise when compared to current turbofan equivalents. Of course, such an assessment can be characterised as unduly pessimistic, but it would be unwise to try and develop such technology without first exploring the tech behind hybrid-electric and all-electric air taxis.

Operational Effects on Noise and Emissions

How aircraft are operated has a significant bearing on noise impact, fuel-burn and NO_X emissions. Sometimes, good operational choices can result in environmental benefits without any associated trade-off. For example a Continuous Decent Approach (Figure 11) can have significant noise benefits. For other phases such as take-off, there are significant trade-offs, principally between noise and fuel burn.

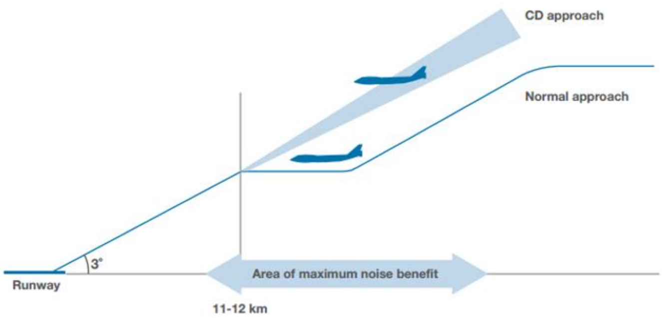

Figure 11. Traditional v. Continuous Decent Approach operation..

For air traffic management, the principal environmental trade-off is between noise and CO_2 emissions. Existing UK aviation policy discourages where possible flying over towns, cities, and sensitive areas such as National Parks and Areas of Outstanding Natural Beauty. Reducing noise exposure in this way often results in additional track miles being flown and a consequent increase in fuel consumption and CO_2 emissions.

Airport expansion and runway capacity are contentious issues that can provoke intense public reaction. However, inadequate runway capacity requires certain operating procedures to be adopted, resulting in less favourable environmental performance. The most obvious example is holding, a process which ensures the availability of an aircraft for each landing or take-off slot but which clearly generates additional emissions.

Ground operations at airports are a major source of CO_2, NO_X, and noise emissions, and there are several areas where gains may be made. Eliminating the need for aircraft Auxiliary Power Units (APU) operated through the provision of electrical power from airport infrastructure is an excellent opportunity to reduce all three major emissions (CO_2, NO_X and noise) with no significant trade-offs. Taxiing on fewer engines or the use of electric tugs are another way to reduce all three major emissions with no significant trade-offs. As an alternative to tugs, main engine-off taxiing using in-wheel electric motors mounted in the aircraft's main landing gear is an option; the in-wheel motors can be operated using power from the APU. However, this involves additional weight which would lead to fuel burn penalties that will be significant on long and medium range flights.

Table 2 gives an indication of the extent of savings obtainable through operational improvements.

	CO_2 Benefit	NO_X Benefit	In flight Noise Benefit
APU reduced use	0.60%	4.30%	-
Single-engine taxi	0.50%	10%	-
Precision Based Navigation	1.70%	Minor	-
Low Power Low Drag Approach	0.30%	Minor	1dB
Continuous Descent Approach	0.50%	Minor	4dB
Displaced Thresholds	-	-	4dB

Table 2. Reductions in emissions and noise due to various operation changes. (Based on data given in [3].)

Fleet Considerations

Newer aircraft are invariably quieter and more efficient than older aircraft, meaning that they also emit less NO_X and CO_2. The gradual turnover of fleet composition towards more modern aircraft will therefore bring significant environmental benefits, even without future innovative technology. The caveat is that these gains will, of course, be offset to some extent by growing fleet size. The Sustainable Aviation Group's analysis indicates that, despite a growing fleet size, overall noise will remain relatively constant until 2025, when it will start to decline. Their analysis of CO_2 shows a slight rise until 2025 followed by a fall to 2005 levels by 2050. These improvements could potentially be fast-tracked and increased with the use of policy measures to incentivise the renewal of UK and European fleets.

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