Inter-dependencies between emissions of CO_2, NO_X & noise from aviation

Policy Discussion Paper
2017 Update

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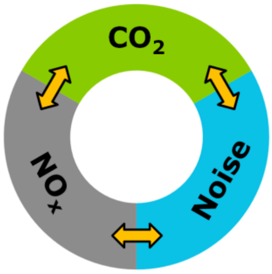
Executive Summary

In the context of local environmental concerns such as community noise and local air quality and of global environmental issues such as climate change, the industry is pursuing many opportunities to reduce emissions of CO_2, NO_X and noise from aircraft. Nonetheless there are inherent inter-dependencies which mean that in some cases achieving an improvement in one of these three areas may come at the expense of another. Understanding the implications involved in these inter-dependencies is crucial in the decision-making process.

This paper therefore explores the nature of inter-dependencies between aviation's emissions of CO_2, NO_X and noise[1], focussing on technological, operational and regulatory issues. Trade-offs[2] against capacity are also discussed. We present a largely qualitative view of the inter-dependencies described, as their quantitative character is dependent on specifics at a level of detail beyond the paper's scope.



We identify situations in which measures to reduce noise can increase fuel-burn, and circumstances in which measures to reduce fuel-burn may present challenges to meeting noise and NO_X regulations. It is the purpose of this paper to raise awareness of these trade-offs and their implications for regulatory decisions, rather than to propose solutions to the difficulties they may present.

This paper also discusses "win-win" opportunities related to reduction of aircraft thrust requirements through a variety of design and technology measures. Additionally, we identify operational measures that - for certain phases of the flight-cycle - are also able to reduce CO_2, NO_X and/or noise with little or no trade-off. We report briefly on progress towards their development and/or deployment.

We emphasise that in this highly regulated industry safety is paramount and will never be compromised for technical, operational or environmental advantage. However, subject to that overarching priority, much is being done to improve efficiency and emissions as this document describes. The aviation industry takes extremely seriously its responsibility to reduce its environmental impact, and has worked tirelessly in this regard for many decades. Over the last half-century, fuel-burn per passenger-kilometre has been reduced by some 70% against a backdrop of progressively tightening noise and NO_X regulations.

Key messages arising from this document are as follows:

General

1. All parts of the aviation industry take their environmental responsibilities seriously, as demonstrated by significant improvements in environmental performance over many years.

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[1] The impact of these emissions on climate or on local air quality is outside the scope of this paper.

[2] In this paper we use the term "inter-dependency" to refer to a situation where a change in quantity A results in a change to quantity B. The more specific term "trade-off" is used to describe an inter-dependency where the changes in quantities A and B are in mutually opposing directions with respect to desirability i.e. if A is made "better", B is likely to become "worse".

2. Inter-dependencies between noise, NO_X and CO_2 emissions are complex and require careful evaluation prior to regulatory, operational or design decisions. As regulations become more stringent, the relevant trade-offs become more difficult to address.

3. Many of the trade-offs involve decisions by more than one section of the industry, making it essential that the various stakeholders work closely together to identify and promote good practice.

4. In general, it is not possible to express an inter-dependency in terms of a universally applicable metric, since its strength and character depend on the particular design point or operating point at which it is evaluated.

5. Regular dialogue between regulators and industry stakeholders will be essential in ensuring that the complexities of the topic, and the delicate balances required, are adequately accounted for in the decision-making process.

Technological Inter-Dependencies

6. Reductions in an aircraft's thrust requirement can enable "win-win" situations in which CO_2, NO_X and noise can all be reduced. Thrust requirements can be reduced through reductions in aircraft/engine drag and weight, by improvements in engine efficiency, and through the adoption of novel drag-reducing propulsion configurations.

7. Engine fuel-efficiency can be improved by designing the core of the engine to run at increased temperatures and pressures. However, this presents challenges for managing NO_X emissions. Successive generations of combustor designs have incorporated technologies to limit the peak gas temperatures and the duration of exposure, with the aim of limiting NO_X emissions.

8. Compared with conventional turbofan configurations, open-rotor engine architectures offer significant potential for reduced fuel-burn and CO_2 emissions. Although open-rotor engines are likely to be quieter than today's turbofans, a trade-off exists between their fuel-burn advantages and the noise-reduction potential of future turbofan designs.

9. More generally, noise regulations strongly influence the design of engines, effectively narrowing the design space and impacting on fuel-burn.

10. Noise regulations have not up to this point directly influenced airframe design to such an extent as to increase fuel-burn. However, looking forwards, more stringent noise regulations could lead to fuel-burn penalties arising from the need to incorporate additional airframe noise-reduction design features which result in increased weight and/or drag.

Operational Inter-Dependencies

11. Local noise regulations can in some cases result in increased fuel-burn and CO_2 emissions arising from operational choices necessary to achieve compliance. Limitations in airspace or airport capacity can increase noise and emissions through holding, or through non-optimal cruising speeds or flight altitude profiles.

12. Some operational techniques have the potential to reduce noise, NO_X and/or CO_2 emissions with no trade-offs. These include Continuous Descent Operations (CDO), Reduced-Engine Taxiing, and the use of Fixed Electrical Ground Power (FEGP) and/or Pre-Conditioned Air (PCA).

Contents

1 Introduction

The aviation industry has worked for many decades to reduce emissions of carbon dioxide (CO_2), noise, oxides of nitrogen (NO_X) and other substances. Whilst NO_X and noise[3] are subject to regulatory limits, carbon dioxide emissions are directly related to fuel-burn and so a very strong commercial incentive has continued to drive greater efficiency through technological and operational improvements. Over the last half-century, fuel-burn per passenger-kilometre has been reduced by some 70 percent against a backdrop of progressively tightening noise and NO_X regulations. More recently, a CO_2 certification standard for aircraft has been agreed at the international level.

The industry remains resolute in its drive to reduce emissions even further, as shown by significant investment in ongoing research and development and improvement activities [SA, 2015], and by the European aviation industry's commitment to achieving challenging targets

[3] and also smoke, unburned hydrocarbons and carbon monoxide

set by *ACARE*. By 2050 we aim to develop technologies and operational practices which, when deployed in the subsequent years, will reduce aircraft CO_2 emissions per passenger kilometre by 75%, reduce noise by 65%, and reduce NO_X emissions by 90%. These achievements will be benchmarked against typical new aircraft in 2000.

Achievement of any one of these three targets would be challenging, but to achieve all three simultaneously will require considerable ingenuity and a clear understanding of the inter-dependencies between these three key drivers. This paper investigates these inter-dependencies, and catalogues the impact on each driver of potential technologies or operational practices.

We emphasise that safety is the number one priority of the aviation industry and will never be compromised for technical or operational advantage.

Emissions from aviation also include water-vapour, particulates, carbon monoxide, unburned hydro-carbons, soot and oxides of sulphur (SO_x). The climate impacts of NO_X, SO_X, particulates, soot and water-vapour emissions are discussed in a separate paper [SA, 2014]. The current paper focuses on the inter-dependencies between emissions of CO_2, NO_X and noise.

In this paper, we start by exploring technological inter-dependencies, identifying for airframe and engine technologies the nature of the interactions between NO_X, noise and CO_2 emissions. We then focus on operational aspects and the various techniques that may be employed to reduce noise or emissions, identifying the relevant inter-dependencies. We close the paper with a discussion in which we highlight “win-win” technologies or operational practices, and assess progress towards their development and/or deployment.

As an aid to the reader, a glossary of terms is provided in Appendix E. Terms explained therein appear in italics in the main text.

2 Technological Inter-Dependencies

In this section we explore inter-dependencies related to engine and airframe design choices. In general terms, reductions in weight or drag reduce the requirement for thrust and are therefore beneficial with respect to noise, CO_2 and NO_X emissions. However, significant trade-offs between CO_2 and NO_X, and between CO_2 and noise, are evident in engine design choices, whilst future options for reducing airframe noise may carry fuel-burn penalties, as described below.

2.1 “Win-Win” Opportunities

In general, reduced fuel-burn, NO_X emissions and noise are made possible by lower thrust requirements, enabled by lower aircraft weight and reduced drag, and by higher engine fuel-efficiency. Lower thrust requirements in turn reduce the amount of fuel that must be carried, which further reduces weight, thus reducing thrust requirements and so on.

Reducing airframe and engine weight and drag has been a key driver of research and development over many decades. Below we briefly describe some of the technologies being developed to enable further reductions into the future. For more details see [SA, 2016].

2.1.1 Reducing Aircraft Weight

Composite materials based on carbon fibre or glass fibre have seen increasing use in aircraft in recent decades. Aircraft such as the Boeing 787 or the Airbus A350 XWB feature a high percentage of such materials. For future aircraft, NASA is developing a method of "*sewing together layers and rods of composite material*" which could allow entirely new aircraft shapes to be built[4].

Rolls-Royce has developed composite carbon/titanium (CTi) fan blade technology which delivers lighter fan blades while retaining aerodynamic performance. "*The CTi fan system includes carbon/titanium fan blades and a composite casing that reduce weight by up to 1,500lb per aircraft, the equivalent of carrying seven more passengers at no cost.*"[5]

A key manufacturing technology receiving much research attention at present is additive layer manufacturing (ALM), sometimes referred to as 3D printing. ALM offers the prospect of manufacturing components of 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, working with a new material entitled Scalmalloy® specially designed for use with 3D printing, to manufacture a prototype cabin partition with a structure "*created with custom algorithms that generated a design that mimics cellular structure and bone growth*"[6]. This enables the required strength of the component but saves 45% of the component's weight.

2.1.2 Reducing Aircraft Drag

Conventionally, engines are mounted to the aircraft such that the air they ingest has not interacted with any part of the aircraft structure prior to ingestion. However, drag associated with the ingestion of stationary air by an engine moving forward at high speed can be reduced by arranging for the engine to ingest air that has already interacted with the aircraft fuselage or wings, reducing the speed difference between the engine and the air entering it. For example Bauhaus Luftfahrt's "*Propulsive Fuselage*" concept, which uses a propulsive fan encircling the aft section of the aircraft fuselage and driven by a co-located gas turbine engine, was shown in initial analyses to offer some 10% improvement in range relative to an equivalent twin-engined aircraft, even after the weight of the third engine is taken into account[7]. The collaborative project "DisPURSAL"[8] explored this and other arrangements aimed at making use of boundary layer ingestion.

In Europe, the Smart Fixed Wing Aircraft (SFWA) integrated technology demonstrator will develop and validate technologies with the aim of reducing aircraft drag by 10% through the

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4 http://www.nasa.gov/aero/prseus-composite-survives-torturous-testing, viewed 21st Sept 2016

5 http://www.rolls-royce.com/country-sites/northamerica/news/yr-2014/010914-rolls-royce-tests-composite-fan-systems.aspx

6 http://www.airbusgroup.com/int/en/story-overview/Pioneering-bionic-3D-printing.html, viewed 29th Sept 2016

7 http://www.bauhaus-luftfahrt.net/research/system-und-flugzeugtechnologien/propulsive-fuselage, viewed 31st August 2016

8 http://www.dispursal.eu/doc/20140515_BHL_ILA_2014_DisPURSAL.pdf, viewed 31st August 2016

use of laminar flow employing both passive and active flow control[9]. The BLADE project[10], led by Airbus and involving an additional 16 partners, is a flight test demonstrator programme - due to begin in 2017 using an Airbus A340-300 flight test aircraft - which aims to show that wings smooth enough to sustain drag-reducing natural laminar flow (NLF) can be manufactured and maintained economically.

Another method of reducing drag is to increase the aspect ratio of the wing. However, with a conventional cantilever wing arrangement there are limits to how far this approach can be pursued. One potential solution is to use a "truss-braced wing" (TBW) in which the wing is supported part-way along its length by a strut which carries part of the load to the fuselage, allowing the wing to be made longer and thinner. Wind-tunnel testing by Boeing and NASA has shown the supported wing arrangement can reduce fuel use "*by 5 to 10 percent over advanced conventional wings*"[11]

2.1.3 Improving Engine Efficiency

Clearly, the more efficient are an aircraft's engines, then less weight of fuel is needed, reducing the thrust requirement throughout the flight, and particularly at take-off conditions. Requiring less thrust at take-off has the potential to reduce engine noise and NO_X emissions. However, depending on the manner in which engine fuel-efficiency improvements have been achieved, trade-offs discussed in section 2.2 below may also need to be taken into account.

The industry continues to invest in research and development to achieve improvements in fuel-efficiency alongside many other attributes including emissions, noise, reliability and total cost of ownership. For example, the Rolls-Royce UltraFan™, "*a geared design with a variable pitch fan system, is based on technology that could be ready for service from 2025 and will offer at least 25 per cent improvement in fuel burn"*, compared to the first generation of Trent engine.[12]

2.1.4 New Propulsion Concepts

The use of hybrid gas-turbine/electric propulsion offers new opportunities for reductions of noise and emissions as well as improvements in fuel–efficiency. For example, in 2013 Rolls-Royce and EADS (now Airbus) presented E-Thrust[13], a new concept for future airliners, featuring a serial hybrid propulsion system comprising a single large gas-turbine, an advanced energy storage system, and six electrically driven fans. "*During climb the distributed fans draw power from the energy storage system, but during descent, they act like wind turbines to generate electrical energy which re-charges the batteries…..A major benefit of the distributed propulsion system is that it can be integrated into the airframe's structure to*

[9] http://www.cleansky.eu/content/page/sfwa-smart-fixed-wing-aircraft, viewed 11th Oct 2016

[10] http://www.cleansky.eu/content/interview/blade-makes-significant-progress-towards-natural-laminar-flow-wing-technology, viewed 11th Oct 2016

[11] http://www.nasa.gov/feature/nasa-aeronautics-budget-proposes-return-of-x-planes, viewed 21st Sept 2016

[12] http://www.rolls-royce.com/media/press-releases/yr-2014/260214-next-generation.aspx

[13] http://www.airbusgroup.com/int/en/corporate-social-responsibility/airbus-e-fan-the-future-of-electric-aircraft/technology-tutorial/E-Thrust.html, viewed 31st August 2016

maximise aerodynamic efficiency and optimise the airflow around it. This reduces the aircraft's weight, drag and the amount of noise it makes."[14]

A migration towards purely battery-electric propulsion may also offer opportunities to reduce CO_2 and NO_X due to the absence of on-board combustion and the possibility of charging batteries with low-carbon electricity. Although the deployment of battery-electric propulsion for commercial aircraft is unlikely to take place for some time, nonetheless progress in both concept development and technology demonstrations is being made. For example, Boeing's SUGAR[15] Volt concept aircraft has a hybrid electric propulsion system which allows for "*typical short-range flights to use mostly electric power while keeping a supply of jet fuel on board for longer-range flights*"[16], while in 2015 the Airbus E-Fan technology demonstrator programme completed a manned crossing of the English Channel using an all-electric aircraft. The E-Fan 2.0 is planned "*to be the world's first all-electric plane certified to international airworthiness standards...scheduled to take its maiden flight in late 2017*"[17]. The E-Fan Plus "*incorporates an internal combustion engine as a range extender in addition to the aircraft's on-board lithium-ion batteries.*"[18]

2.2 Engine-Related Trade-Offs

Although lower weight and reduced drag are generally advantageous for fuel-burn, NO_X emissions and noise, many technological options for improving engine fuel-efficiency have different impacts on each of these three main drivers.

The efficiency of a jet engine can be characterised by two main factors. Firstly, the engine's thermal efficiency describes the effectiveness with which the available chemical energy in the fuel is turned into mechanical energy. Secondly, the propulsive efficiency indicates how well the mechanical energy is turned into thrust. Higher values for both of these factors are desirable in the drive to reduce fuel-burn and CO_2 emissions.

Thermal efficiency is influenced primarily by the increase in pressure experienced by the air as it travels through the compressor, and by the temperature of the gas stream as it enters the turbine. A higher *overall pressure ratio* (OPR) and a higher *turbine entry temperature* (TET) both drive greater thermal efficiency. However, assuming a constant level of combustor technology, they also involve higher peak temperatures and chemical reaction rates during combustion, enhancing NO_X formation.

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14 http://www.rolls-royce.com/media/press-releases/yr-2013/18062013-works-with-eads.aspx, viewed 31st August 2016

15 SUGAR = Subsonic Ultra Green Aircraft Research

16 http://www.boeing.com/aboutus/environment/environment_report_14/2.3_future_flight.html, viewed 31st August 2016

17 http://www.airbusgroup.com/int/en/corporate-social-responsibility/airbus-e-fan-the-future-of-electric-aircraft/Programme.html, viewed 31st August 2016

18 http://www.airbusgroup.com/int/en/corporate-social-responsibility/airbus-e-fan-the-future-of-electric-aircraft/Programme.html, viewed 31st August 2016

Achieving higher thermal efficiencies without increasing total NO_X emissions represents a significant challenge to engine designers, who must also ensure combustor operability under a wide range of conditions. Successive generations of combustor designs have incorporated technologies to limit the peak gas temperatures and the duration of exposure, against a backdrop of steadily rising overall pressure ratios. Mitigation options include the use of intercooling - in which air is cooled before entering the final compressor stages, resulting in a lower combustor inlet temperature – and lean-burn combustion, in which the air-fuel ratio is higher than in more conventional arrangements. However, in comparison with more conventional combustor designs, the lean-burn concept is characterised by slightly lower efficiency and slightly higher weight, leading to slightly increased CO_2 emissions.

Propulsive efficiency is influenced primarily by the engine's bypass ratio. Air entering the engine is split between the hot core and the cool bypass duct. A higher bypass ratio indicates that a smaller proportion of the total air intake is used within the core of the engine, and results in higher propulsive efficiency.

However, for a given thrust rating, a higher bypass ratio typically requires a larger fan and its associated low-pressure turbine system, as well as a larger *nacelle*. Collectively these introduce extra weight and drag, potentially offsetting some or even all of the gains in propulsive efficiency. This trade-off between propulsive efficiency and weight/drag gives rise to an optimum bypass ratio - from the point of view of fuel-burn - for a given application.

One route to avoiding the weight penalty of a large low-pressure turbine system is to design the engine without it, instead using a geared architecture in which the fan is driven by the intermediate pressure turbine, such as in the Rolls-Royce UltraFan™ concept[19].

The open-rotor architecture is an alternative engine configuration in which 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*. As well as its potential for improved fuel-burn, the open-rotor architecture offers benefits for lower NO_X emissions, as it allows for a large increase in thrust without a corresponding increase in combustor temperatures.

However, the open-rotor configuration raises some challenges for the designer with respect to noise. For instance, the absence of fan-intake and bypass duct reduces 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.

Significant research has determined that the worst effects of these noise challenges can be overcome, and that future open-rotor engines are likely to be quieter than today's turbofans. Nonetheless, a trade-off exists between the fuel-burn advantages of a future open-rotor engine configuration, and the noise-reduction potential of future turbofan designs.

More generally, noise regulations strongly influence the design of engines, effectively narrowing the design space and potentially impacting on fuel-burn. For example, noise

[19] http://www.rolls-royce.com/media/press-releases/yr-2014/260214-next-generation.aspx

constraints may drive the choice of fan diameter to a larger size than would be chosen if fuel-burn were the sole driver, with additional implications for airframe configuration, as discussed in section 2.3 below. The design of the low-pressure turbine is also strongly constrained by noise considerations.

2.3 Airframe-Related Trade-Offs

Reducing the environmental impacts of aircraft has long been a priority for the aviation industry. Aircraft manufacturers have worked to ensure that each new generation of aircraft has a lower environmental impact than previous generations. Noise levels, emissions (impacting both local air quality and CO_2 levels) and fuel-burn have all improved over the past years, though not necessarily at the same rates, or over the same timescales due to the changing emphasis on the individual environmental impacts from regulators and other stakeholder groups.

The initial airframe design is constrained not only by trade-offs between CO_2, NO_X and noise, but also by market requirements such as design-speed, design-range, size and capacity. The aircraft manufacturer's own vision of societal, including environmental, expectations over the aircraft's lifetime – up to 30 years from entry into service – must also be factored in.

Based upon these considerations, manufacturers perform an evaluation starting well before a programme is launched, with a feasibility phase identifying design requirements and their potential solutions. An understanding of the environmental inter-dependencies at the earliest opportunity during an aircraft's development is imperative for the aircraft manufacturer, in order to avoid any unintended consequences at a later stage. Many different aspects need to be considered to select the optimal aircraft configuration, for example: environmental impacts, performance, operability, reliability, system/component integration, operations, economics, market acceptance etc. All these aspects are inter-related and trade-offs will occur working towards an adequate and complex balance between them, subject to the over-arching requirement of safety.

When integrating technologies that deliver improved efficiency, the aircraft's overall fuel-burn saving potential is not equal to the sum of the individual technologies, due to interactions between components. Consequently, the design of individual components or sub-systems must be guided by their net benefits after integration effects and trade-offs have been taken into account. For example, an innovative new system may reduce drag at the expense of increased weight or power requirements.

Many trade-offs at the engine level also have an impact on the airframe. For example, achievement of QC/2 departure noise levels at London airports resulted in a stronger weighting of noise within the overall design requirements of the A380 aircraft**,** with consequences for engine design choices. The availability of novel technologies and noise prediction capabilities allowed the achievement of the required acoustic performance of the aircraft with a limited trade against the potential range performance, acceptable to the market.

Airframe design up to now has not been <u>directly</u> affected by noise regulations to the detriment of fuel-burn. In general, the airframe has been designed for low fuel-burn and then low noise features have been incorporated if they do not cause a significant impact on performance. However, as noise regulations become progressively tighter, future options for reducing airframe noise still further may involve increased weight and/or drag. For example:

- In comparison with leading-edge slats used on today's aircraft, alternative high-lift devices with lower noise characteristics may be less efficient at generating lift, and may lead to a requirement for a larger wing, with increased weight and drag.
- Shielding landing gear to reduce airframe noise, or using novel low-noise drag devices to improve steep approach capability in an effort to reduce noise impact, could increase aircraft weight.
- The airframe could be used to provide some kind of shielding to the engine noise, which may penalise the fuel-burn performance of the aircraft due to increased weight, increased drag, or impact on airflow into the engine.
- If noise regulations lead to engines with a larger-than-optimum bypass ratio, the engines may no longer be easily installed on to the airframe in the optimum position (under the wing with the wing beneath the fuselage floor). This may cause small fuel-burn penalties by affecting the length and weight of the landing gear or by increasing installation drag due to mounting the engine closer to the wing. Larger penalties may be caused if the engines need to be installed elsewhere (for example, high wing or rear fuselage mounted).

3 Operational Inter-Dependencies

The manner in which aircraft are operated has a significant bearing on noise impact, fuel-burn and NO_X emissions. Trade-offs between these three drivers are relevant to many aspects of operational decision-making. Regulatory constraints – often driven by the need to minimise noise-impact – can bring these trade-offs into sharp focus. Appendix A describes some concrete examples of trade-offs in which noise-driven regulation has the potential to increase emissions of CO_2 and/or NO_X.

For some phases of flight, such as descent and approach, appropriate operational choices can result in environmental and other benefits without any trade-offs. However, for other phases such as take-off there are significant trade-offs, which must be carefully considered before following a particular procedure or technique. Capacity issues must also be taken into account.

To help identify and promote good practice within the aviation community, "Codes of Practice" have been developed both for arriving aircraft and for departures.

- The Arrivals Code of Practice [SA, 2006] focuses on two techniques - *Continuous Descent Approach (CDA)* and *Low Power, Low Drag (LPLD)* - as methods for reducing noise on approach. The additional benefits of these techniques are that they also reduce carbon dioxide and NO_X emissions. Indeed, CDA was originally developed as a fuel conservation technique. The Code of Practice is aimed specifically at air traffic controllers, flight crew and airports, and brings together advice for promoting these techniques from the combined expertise of the *DfT*, *NATS*, airports, airlines and the *CAA*.
- The Departures Code of Practice [SA, 2012] focuses on four areas: gate operations (the use of *Fixed Electrical Ground Power (FEGP)* and *Pre-Conditioned Air (PCA)*); taxi-out with less than all engines operating; *Continuous Climb Operations (CCO)* and *Airport – Collaborative Decision Making (A-CDM)*, as ways to maximise all operational efficiencies.

3.1 Air Traffic Management

For air traffic management the principal environmental trade-off is between noise and CO_2 emissions. The existing UK aviation policy that discourages, where possible, the over-flight of towns and cities and sensitive areas such as National Parks and Areas of Outstanding Natural Beauty in order to reduce noise exposure often results in additional track miles being flown with a resulting increase in fuel consumption and CO_2 emissions.

Further examples of environmental trade-offs in air traffic management are included in the relevant operational sections below.

The UK aviation industry is calling for urgent modernisation of UK airspace[20] to enable increased capacity for the future and to support reductions in environmental impact through minimisation of delays and enablement of many of the techniques identified in the following sections.

3.2 Airport Management

3.2.1 Airport Capacity

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 which result in less favourable environmental performance.

Ground holding and airborne holding are particular practices necessary to achieve the required throughput at major airports constrained by runway capacity. Maximising throughput requires skilful sequencing of aircraft to minimise the separation distances between each movement and therefore necessitates a 'reservoir' of aircraft - both on the ground and in the air - to ensure that there is always a suitable mix of aircraft available to sequence for take-off or landing with minimum gaps between. Clearly any delay incurred involves additional noise, NO_X and CO_2 emissions from the holding aircraft.

Contrary to popular perception, there is therefore an environmental argument for increased airport and runway capacity at capacity-constrained airports, to minimise holding requirements for a given level of aircraft throughput. In the absence of additional runway capacity, options for minimising ground-based holding at a given level of capacity constraint are discussed in section 3.3.3 below.

3.3 Ground Operations

Ground operations at airports include a number of activities that offer opportunities for environmental efficiencies in terms of minimising CO_2, NO_X and noise emissions, as detailed in this section, and with additional information provided in Appendix D. We also explore the issue of capacity, in particular the impact on environmental performance of inadequate system capacity.

[20] http://theskysthelimit.aero/

3.3.1 Aircraft Operations on Stand

Aircraft require electrical power whilst on stand to support avionic systems, lighting, cabin air-conditioning, galley chillers etc. This electrical power would typically be provided from the aircraft's Auxiliary Power Unit (APU). However, where available, the provision of electrical power and/or pre-conditioned air to the aircraft from airport infrastructure provides the opportunity to reduce not only CO_2 emissions but also NO_X and noise, with no significant trade-offs. SA is working with airport members to promote the further deployment of *Fixed Electrical Ground Power* (FEGP) and *Pre-Conditioned Air* (PCA) in place of APU usage where appropriate through application of the industry Departures Code of Practice [SA 2012].

3.3.2 Taxiing

Taxiing on fewer than all engines is employed by some operators of some aircraft types at UK airports and has been shown to offer significant fuel and CO_2 reductions. It is estimated that through use of this technique, ground-level aircraft fuel-burn can be reduced by 20-40% and ground-level aircraft NO_X emissions by 10-30% [SA, 2012]. SA and others are working to realise these savings identified by the industry code of practice [SA, 2012]. However, in some cases taxiing on a reduced number of engines may not be appropriate for safety reasons, particularly for aircraft with large engines from which jet blast may be a safety issue, for instance where there is work in progress within the airport boundary, or when there is a need to cross an active runway.

Trials of electric tugs to facilitate "engineless" taxiing have been promising from an operational perspective - demonstrating that the procedure itself could be made to work, potentially reducing ground-level noise, NO_X and CO_2 emissions with no trade-offs. However, it also identified some practical issues with towing aircraft, notably the potential to damage aircraft nose-gear over time. Work is ongoing to examine what potential exists to adapt aircraft to make them more resilient to towing.

In recent years, electric taxiing systems have been demonstrated which drive the aircraft using in-wheel electric motors mounted in the aircraft's main landing gear or in the nose-wheel. Power for the motors is provided by the aircraft's APU, meaning that the main engines need not be used for taxiing operations, reducing fuel-burn, emissions and noise. The additional weight of such systems means that they are best suited to short-range flights and are currently only available for single-aisle aircraft.

3.3.3 Ground Holding

It is usual at capacity-constrained airports for aircraft to hold on the ground prior to departure to allow the efficient management of runway capacity. Technological improvements in managing and sharing ATC information offer potential in the future to reduce holding times and move towards gate-to-gate management of the flight cycle. The European coordinated *SESAR* programme is actively pursuing this goal through its development of the concept of *Airport – Collaborative Decision Making (A-CDM)*. Reducing the pre-departure holding time offers the opportunity to reduce CO_2, NO_X and noise emissions without any trade-offs. It also increases the ability to operate reduced engine taxi-out due to more accurate target take-off times.

Several UK airports have implemented A-CDM resulting in significant improvements. For example, London Heathrow implemented A-CDM in 2013 and since then has seen take-off time accuracy improve from an average of 8.3 minutes to 30 seconds per flight. It also has vastly improved recovery rates in periods of disruption and can now let 60 aircraft depart with an average of 20 minutes sooner than it could prior to implementation.

British Airways has implemented a single engine taxi procedure that is based on the TTOT (Target Take-Off Time) which is delivered directly to the flight deck via ACARS (Aircraft Communications, Addressing and Reporting System) while the aircraft is at the stand. This saves several minutes of engine running time per flight and is estimated to have generated annual savings (based on 2015 traffic levels) of 5,000 tonnes of fuel, equivalent to saving around 16,000 tonnes of CO_2 emissions per year.

Nonetheless, if delay is to be incurred it is clearly preferable, from the point of view of fuel-burn, to absorb delay through holding on the ground rather than in the air.

3.4 Departure

A number of techniques can be applied in an attempt to reduce the environmental impact of aircraft during departure. It should be noted that some of the impacts will be highly dependent on the specific aircraft performance and the airport and runway characteristics, and legal constraints may limit what is actually available for use. There are significant trade-off issues here between noise, NO_X and CO_2, primarily related to the thrust-settings that may be employed at various stages of the departure procedure in an effort to minimise noise. Furthermore, improvements in noise levels may not be universal – even though noise levels may for instance be reduced under the flight path, the overall noise footprint may increase. Alternatively some techniques may reduce noise near the airport at the expense of increased noise further from the airport, coupled with increased fuel-burn. New software with increased aircraft capabilities can reduce noise at specific highly noise-sensitive locations. Appendix B lists the potential measures and the consequences of each in terms of noise, NO_X and CO_2 emissions.

3.5 En-Route

The three principle operational variables that can influence en-route fuel-burn are flight-level (i.e. altitude), cruising speed/*Mach number*, and the directness of the route followed after taking account of headwinds or tailwinds[21]. Direct trade-offs between CO_2 and NO_X emissions arising from these operational choices during the en-route phase of flight are not present. However, there are trade-offs between the choice of flight cruising speeds - driven in part by fuel-burn and airspace management considerations - and slot-timing constraints at airports driven both by airport capacity and by the need to minimise the noise disturbance caused by aircraft departures and arrivals. There are also trade-offs between airspace capacity and the ability to follow optimal speed and/or altitude profiles to minimise fuel-burn. Safety-driven constraints also play a role here. These issues are discussed below.

In the UK, the current airspace structure was developed many decades ago, since when aviation activity has expanded considerably, presenting challenges for capacity and

[21] The concept of “least air distance” takes account of distance travelled through a moving medium (air). A route benefitting from tailwinds may involve a lower air distance even if the route appears on the map to be geographically less direct.

efficiency. The Civil Aviation Authority (CAA) has set out its future airspace strategy, with the vision to establish "*safe, efficient airspace, that has the capacity to meet reasonable demand, balances the needs of all users and mitigates the impact of aviation on the environment*" [CAA, 2011].

The Borealis Alliance aims to "*create a single area of high altitude free route airspace covering nine northern European countries*" and "*will provide significant savings in fuel and* CO_2 *emissions to customers*" [NATS, 2016].

The Prestwick Lower Airspace Systemisation (PLAS) project will improve the efficiency and capacity of en-route airspace controlled by the Prestwick air traffic management centre. Its goals include a reduction in CO_2 emissions of some 105,000t of CO_2 per year, and noise mitigation of the impact of overflights below 7000ft[22].

3.5.1 Flight Level vs Airspace Capacity

On-board flight management systems and ground based flight planning software are used to identify the optimum cruising flight level, which will depend amongst other things on payload and mission-range, and varies as an aircraft burns fuel and reduces weight during its flight. Following a trajectory that differs from the optimum will result in increased fuel-burn and CO_2 production[23]. By way of example, the fuel-consumption, at a speed of Mach 0.8, of an A340-600 aircraft flying 4,000 feet below its optimum flight level is around 2% higher than at the optimum flight-level [Airbus, 2004].

Due to air-navigation rules, the ideal cruise-climb trajectory must be approximated by a sequence of step-climbs between flight-levels. Delaying a step-climb beyond its optimum point in the flight results in increased CO_2 emissions. In addition, ATM capacity restrictions and the requirement to protect ATC sectors from over-delivery of traffic can sometimes result in uneconomic flight-levels being allocated to operators, particularly in cases where the optimal flight-level profile has not been requested in flight-plans.

3.5.2 Cruise Speed vs Airport Capacity and Noise Disturbance

Aircraft have an optimum cruise speed or *Mach number* above or below which fuel efficiency is reduced. However, in response to a trade-off between fuel-costs and time-related costs (represented in the aircraft flight management system by a "cost-index"), operators will often fly slightly faster than the fuel-optimised cruise speed. Time related costs can include those associated with maintenance (where components have to be replaced at given time-use intervals), crew wages, engine warranty costs, and costs incurred if passengers miss connections to other flights, etc. Operators can program a specific cost index into the aircraft flight management system which will calculate a recommended cruise speed/Mach to minimise total cost, and this is often slightly higher than the fuel-optimal cruise speed. The exact fuel-burn penalty will vary by aircraft type and journey length, as illustrated in [Airbus, 2004].

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22 https://www.caa.co.uk/uploadedFiles/CAA/Content/Standard_Content/Commercial_industry/Airspace/Files/20151111PLASFrameworkBriefingNotesAndPresentation.pdf, viewed 01 March 2017

23 This has relevance for some proposed contrail-avoidance strategies involving lower cruising altitudes.

Airport landing slots are based heavily on the expected flight times, which in turn are dependent to a great extent on cruise speed. As a result, variations in cruise speed can have a significant impact on the whole slot management system, especially at the most capacity constrained airports such as Heathrow and Gatwick.

There is also a trade-off between local noise issues and flight-cycle fuel-burn. Many airports (including UK airports) have night restrictions or curfews in place in order to reduce noise impacts on local communities. Under these restrictions, changes to aircraft cruise speeds can result in holding or diversions due to arriving before a curfew ends, or after a curfew has commenced. Motivated by a requirement to arrive before the commencement of a curfew, aircraft sometimes have to be flown at a faster than fuel-optimal cruise speed, leading to increased CO_2 emissions.

Until recently, another reason to fly faster than fuel-optimal cruise speed has been to arrive as soon as possible after the 06:00 London airports night quota period arrivals restriction, motivated by a wish to reduce or eliminate airborne holding by securing an advantageous place in the queue for landing. However, the implementation of XMAN (Cross Border Arrival Management) [NATS, 2016] enables aircraft to be slowed down up to 350 nautical miles from London without losing their place in the queue for landing, resulting in reduced holding times and eliminating the incentive for higher-speed flight, with benefits for both CO_2 emissions and noise incurred in the holding pattern.

3.5.3 Safety Constraints

From an air traffic control perspective, flight levels and cruise speeds are also important issues in managing the interaction of different aircraft flows. In some cases, a requested flight level cannot be offered due to the need to ensure safe separation from other aircraft. Similarly an air traffic controller may be required to instruct non-optimal speed in order to maintain safe separation and effectively manage flows, particularly when streaming aircraft ready for descent. The environmental 'trade-off' here is therefore with airspace capacity, driven by safety-related constraints.

3.6 Approach

Techniques such as *Continuous Descent Operations (CDO)*, steeper, segmented, curved or decelerating approaches, and *Low-Power-Low-Drag (LPLD)*, have been devised and tested by the industry. There are limits to aircraft capabilities, and speed control will dictate if these approaches reduce localised noise. In general, the trade-offs between noise, NO_X and CO_2 are less manifest for arrivals than they are for departures. Indeed, measures such as CDO have the potential to reduce all three simultaneously[24]. Appendix C provides more details.

It should be noted that in some areas airspace capacity constraints may place limits on the simultaneous deployment of more environmentally efficient departures and arrivals techniques, resulting in the requirement for a balance between the two.

[24] However, CDO differs from conventional arrivals only at altitudes above 1000ft *aal*, and changes in NO_X emissions above 1000ft *aal* have minimal impact on local ground-level NO_X concentrations [ICAO, 2008].

During 2015, 77% of UK arriving flights under NATS control used CDO, representing an additional saving of 1740 tonnes CO_2 relative to 2013, as well as reducing community noise [NATS, 2016]. Work is underway to increase the level of deployment of this and other methods listed in Appendix C, alongside efforts to understand remaining barriers to implementation of the full spectrum of options.

4 Discussion and Summary

The UK aviation industry continues its active pursuit of opportunities to reduce its environmental impact. This paper has described many of the techniques that may be employed in the drive to reduce NO_X, noise and carbon dioxide emissions from aircraft. However, as we have seen, the impact of an individual technique is not always beneficial with respect to all three of these often-competing drivers. For example:

- Noise regulations can stipulate or incentivise operational practices - such as alternative thrust profiles during take-off and climb - which may result in higher NO_X emissions and/or fuel-burn.
- Some airport noise regulations present design constraints for aircraft engines in particular, driving design choices that are not necessarily optimal in terms of fuel-burn.
- Avoiding the overflight of populated areas in order to reduce noise exposure may result in increased fuel-burn arising from an increase in the actual distance flown.

Consequently the need for clear priorities must be borne in mind when proposing guidance or regulations.

Implications for cost and capacity must also be taken into account when identifying suitable mitigation techniques. For example, in a capacity-constrained system, holding forms an essential part of maximising throughput by ensuring the availability of an aircraft for each landing or take-off slot, or en-route airway. Whilst reduced holding is desirable from an environmental point of view, its achievement depends on the availability of adequate capacity for the whole system.

However, a number of operational techniques have the potential to reduce one or more of NO_X, noise or carbon dioxide without significant detriment to the remainder or to cost and capacity. These include reduced-engine taxiing, towed-taxiing, e-taxiing, *fixed electrical ground power*, continuous descent operations, steeper approaches and *low-power-low-drag* approaches. Recent progress on these items includes the following:

- Reduced engine taxiing, already in use by many UK operators, is estimated to have the potential to reduce ground-level aircraft fuel-burn by 20-40% and ground-level aircraft NO_X emissions by 10-30% [SA, 2012]. SA and others are working to realise this saving [SA, 2015].
- *CDO* has been adopted more widely across the UK over the past few years, as its benefits have been recognised and the relevant technological and procedural issues have been addressed. Further information can be found in SA's 2015 Progress Report [SA, 2015].

- The use of *FEGP* and *PCA* in place of aircraft-mounted *APU*s has the potential to save CO_2, NO_X and noise with no significant trade-offs. SA is working to promote this practice [SA, 2012].

- eTaxiing, in which the aircraft is powered by electric motors embedded in the nose-gear or main landing gear, has the potential to reduce emissions of noise, NO_X and CO_2. It is best suited to aircraft performing short range flights since the weight of the system must be carried the full distance of the flight but the advantages are only gained during the taxi phase.

Improved aircraft aerodynamics, the reduction of aircraft weight, and improvements in engine fuel-efficiency all represent substantial opportunities to reduce thrust requirements, potentially leading to reduced noise, NO_X and carbon-dioxide emissions ("win-win"), subject to trade-offs presented in section 2. Significant technological progress continues to be made in these areas, as we have discussed in this document. Small reductions in weight can also result from operational choices e.g. installation of lighter seats, or loading lower volumes of potable water.

In the UK, the local environment agenda for aviation is largely driven by noise and occasionally by local air quality impacts, whereas the national and international agenda is primarily focused on climate change. This presents a challenge for the aviation industry in addressing the often-competing demands of each of these issues. Greater awareness among policy makers of the potential down-stream effects of certain measures designed for environmental protection offers a starting point to addressing these. Environmental trade-offs should be considered early in any policy-making process in setting medium to long-term objectives to avoid unintended consequences.

This paper has largely avoided attempting to quantify the inter-dependencies that it has explored, on the grounds that to do so would require a detailed exposition of the particular technology levels, design choices and operational choices to which a particular trade-off applied.

Put more simply, the nature and strength of an inter-dependency typically varies according to the baseline from which it is evaluated, and so there is no single number expressing for instance the fuel-efficiency penalty arising from a desire to improve noise by 1dB, say. We therefore encourage regulators and policymakers to engage with industry stakeholders where appropriate to characterise and explore specific trade-offs relevant to proposed legislation.

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APPENDIX A: Operational Trade-off Issues in Practice

To illustrate the impact of trade-offs and the extent to which they are relevant to day-to-day decision-making across the industry, below we highlight some practical instances in which noise-driven regulation has the potential to increase emissions of CO_2 and/or NO_X.

London airports - 1,000ft rule

UK regulations for London airports state that after take-off, aircraft must achieve a height no less than 1000 ft *aal* at 6.5 km from start of roll (SoR), as measured along the departure track [NAR-LHR, 2010], [NAR-LGW, 2004], [NAR-STN, 2007]. This is to ensure that aircraft pass over the relevant noise monitor at "cut-back" power, whilst complying with international safety regulations concerning the minimum allowed "cut-back" height.

However, in order to reach 1,000ft *aal* at 6.5 km from SoR, some four-engined aircraft may in some circumstances have to increase power above that normally used for take-off, resulting in greater NO_X emissions and higher noise levels close to the airport. Engine maintenance costs may also be increased.

London airports - departure noise limits

UK regulations for London airports stipulate noise limits at specific monitor locations. In order to meet them, some operators have specified the use of higher than normal, or full rated, take-off power for departures at sensitive times of the day, to ensure that the aircraft is at a height where power cut-back (from that used for take-off) can legally be performed before reaching the relevant noise monitor.

As a result, although noise levels recorded by the monitor may be reduced, those close to the airport can be increased (especially to the side of the airport), and the noise contour area may be larger, depending on the noise characteristics of the aircraft. Additionally, the use of the maximum power setting increases NO_X emissions significantly.

Although this example is specific to London airports, the same issues could be observed at other airports where departure noise limits apply, depending on the location of noise monitors and the compliance policies adopted by aircraft operators.

Zurich - departure procedure

At Zurich airport, the departure procedure is a legal requirement, intended to reduce noise by maintaining take-off power and a high-drag configuration for longer than would be the case under normal airline operating practice. Specifically, take-off power is stipulated until 2900 ft *aal*, and take-off flap setting is stipulated until 4500 ft *aal* [AIP-ZRH, 2005]. The higher thrust setting enables higher climb rates, moving the noise source to a higher altitude more quickly as the aircraft leaves the airport.

However, keeping the aircraft in a high-drag configuration until 4500 ft *aal* (vs. the more commonly used 1500 ft *aal*) results in higher fuel-burn than would otherwise be the case.

Curfews

Some airports such as Sydney [SACA, 1995] and Orange County [OCAIR] impose night-time curfews to limit noise impact on local communities. However, aircraft scheduled to arrive at such airports shortly after the curfew's end risk increased fuel-burn if they arrive early. In such cases, aircraft may be held (resulting in additional fuel-burn and noise over the holding area), or diverted to another airport.

Noise Preferential Routes

Noise Preferential Routes (*NPR*s) are in common use at many airports for managing the noise impacts from aircraft departures. They were designed to concentrate aircraft over less populated areas, thereby reducing the noise impact on areas of higher population density. In the UK, Government policy is to concentrate the aircraft noise along these routes, but airports in other countries may choose to adopt a "multiple tracks" approach, which spreads the effects more evenly. In both instances, where routes have been designed where they involve flying additional track miles, the potential for higher fuel burn and emissions will be greater, and those with sharp turns at low altitudes will also result in higher noise levels due to the increased thrust requirements.

There is also a trade-off between areas affected by noise. A concentration approach may result in fewer people being affected by aircraft noise, but may lead to a loss of tranquillity in areas where populations are sparser, such as wilderness areas.

Similar issues for arrivals may arise from the choice of *ILS* intercept location, and the noise associated with any manoeuvres that may be necessary to join *ILS*.

Discussion

As the above examples show, trade-offs between noise and fuel-burn or NO_X are real and require careful attention when setting regulations in order to avoid unintended outcomes. Section 3 above discusses operational trade-offs in detail.

APPENDIX B: Operational Inter-Dependencies - Departure

Technique	Noise Impact	CO_2 Impact	NO_X (LAQ) Impact	Comments
Increasing take-off power	Reduces under flight-path, but footprint area can be increased	Slightly altered Note 1	NO_X increases with power	Note 2. Adverse impact on engine maintenance costs
Reducing take-off flap setting	Reduces noise if lift-to-drag ratio improved - dependent on aircraft & runway characteristics	May be slightly reduced	Slightly changed, dependant on aircraft & runway characteristics	Note 2. Possible implications for tail strike under certain conditions
Reduce acceleration altitude	Noise increased close to airport, reduced further out	Reduced	Note 3	Note 4. Actual differences depend upon the difference in selected acceleration altitude versus standard airline practice.
Delayed flap retraction in the climb	Noise reduced close to airport, slight increase further out	Increased	Note 3	Note 4.
Increased cut-back altitude	Noise increased at some parts close to airport, reduced further out	Slightly reduced or increased, depending on flap retraction schedule.	Note 3	Note 4.
Reduce power, retract flaps, then accelerate	Reduced noise under flight-path, after normal acceleration point.	Increased	Note 3	Note 4. Aircraft in high-drag configuration with low power set may concern regulators.
Increase *VR*, *V2* and climb speeds	Noise slightly increased close to airport, reduced further out	Minimal change	May increase or decrease depending on take-off thrust setting method	Not applicable to some aircraft types and some operators. Depends upon take-off performance limitations
Increasing climb power settings	Noise increases after cutback closer to the airport, reduces further out	Slightly reduced	Note 3	Note 4. Adverse impact on engine maintenance costs
Novel Power Management (Managed Noise)	Reduced at specific points identified as sensitive for noise.	Dependant on procedure, aircraft and airport requirements.	Note 3	Note 4.Currently only feasible with latest aircraft such as A380, A350, B787

Note 1: Although fuel flow is greater at the higher power setting, the time at that setting will be shorter, resulting in slight differences in overall fuel-burn that can be either positive or negative and will not be the same for all aircraft.

Note 2: Legal constraint: Noise Abatement Departure Procedures (*NADP*s) are not allowed below 800 ft (PANS-OPS/EU-OPS).

Note 3: Changes in NO_X emissions above 1000ft *aal* have negligible impact on local ground-level NO_X concentrations [ICAO, 2008].

Note 4: Will have an impact on flight path and speeds, so will need to keep ATC advised, and may affect adherence to Noise Preferential Routes with low level turns.

<u>APPENDIX C:</u> Operational Inter-Dependencies - Arrival

Technique	Noise Impact	CO_2 Impact	NO_X (LAQ) Impact	Comments
Continuous Descent Operations (CDO)	Reduced	Reduced	Little or no difference	Note 5, Note 6 Procedures need to be set up. Greatest benefit will occur when initiated at higher altitudes with more advanced navigation equipment, though might impact airspace capacity.
Low Power/Low Drag (LPLD)	Reduced closer to the runway *threshold*	Reduced.	Slight reduction	Note 6, Note 7, Note 8 *ICAO*-stabilised approach criteria may also act as a constraint.
Steep Approach	Reduced overall, though there may be some changes in the geographical distribution of noise, due to different flap and landing-gear extension points	Reduced.	Note 9.	Note 7, Note 8 Legal constraint: Steep approach cannot be implemented solely for noise abatement purposes. [ICAO]. *LVP* considerations may also limit application.
Curved Approach	Reduced, though dependant on the distribution of local populations	Dependent on difference in track miles.	No difference below 1,000 ft *aal*	Note 5, Note 7 Procedures need to be set up, and more advanced navigation equipment will be required.
Displaced or Inset *Threshold* (Note 10)	Note 9	No difference	Note 9.	Note 6, Note 8

Note 5: Reductions arising from these techniques are achievable above the ILS capture altitude. Below ILS capture, there is no noise or emissions benefit relative to standard approach.

Note 6: Safety considerations might preclude reductions in flap setting if runway is short or wet/contaminated.

Note 7: May require specialist aircraft and/or ground equipment to be installed, as well as additional training for aircrews

Note 8: May result in increased use of reverse thrust, potentially eroding some of the benefits of the technique.

Note 9: Slight reduction in area impact, since low-level noise/emissions take place closer to (or within) the airport boundary

Note 10: Moving the threshold along the runway so that it is further within the airport boundary

APPENDIX D: Operational Inter-Dependencies - On Ground

Technique	Noise Impact	CO_2 Impact	NO_X (LAQ) Impact	Comments
Taxi-Out with engine(s) not operating	Reduced, though may be masked by higher power from operating engine(s) Note 11	Reduced	Reduced	Safety issues may limit the extent of deployment – i.e. not suitable for all flights in all conditions. Operational requirements may mean that the APU has to be running which will reduce the benefits. Use may in some cases conflict with airport efficiency considerations.
Taxi-in with engine(s) shut down	Reduced, though may be masked by higher power from operating engine(s) Note 11	Reduced	Reduced	Safety issues may limit the extent of deployment – i.e. not suitable for all flights in all conditions. Operational requirements may mean that the APU has to be running which will reduce the benefits.
E-Taxiing	Reduced Note 11	Reduced	Reduced	Trade-off between on-ground fuel-burn saving and in-air fuel-burn penalty due to system weight – best suited to short-to-medium range flights.
Towed taxiing	Reduced Note 11	Reduced	Reduced, though the type and/or technology standard of the aircraft tug will determine the extent of the reduction	Nose wheel leg strength, and taxiway congestion may be an issue at some airports – some aircraft may need specialist tugs. Instances of *FOD* will be reduced.

Note 11: In most cases, changes in noise levels beyond airport boundary are expected to be minimal, being masked by higher noise levels from aircraft in flight (arriving/departing)

APPENDIX E: Glossary

aal - above aerodrome level – the height above the aerodrome runway datum

ACARE - Advisory Council for Aeronautics Research in Europe

A-CDM – Airport – Collaborative Decision Making – a process of sharing the right information at the right time in the right place so leading to reduced airport delays and enhanced punctuality

ATC – Air Traffic Control

ATM – Air Traffic Management

APU - Auxiliary Power Unit – a unit installed on the aircraft. Provides electrical and pneumatic power to the aircraft on the ground

CAA - Civil Aviation Authority – the UK's aviation regulator

CO_2 - Carbon Dioxide – a greenhouse gas emitted by the burning of fossil fuels, including jet fuel

CCO - Continuous Climb Operations – the use of a departure climb profile without level flight segments, allowing reductions in noise and fuel-burn/CO_2 compared with "stepped" climb departures

CDO - Continuous Descent Operations – the use of a descent profile without the level flight segments of the more traditional "stepped" descent. Has the potential to reduce noise and fuel-burn where used

DfT - Department for Transport – the UK Government department with responsibility for air transport

EU-OPS – The EU regulations specifying minimum safety and related procedures for commercial passenger and cargo fixed-wing aviation, published as Council Regulation (EEC) No 3922/91

FEGP - Fixed Electrical Ground Power – electrical power supplied from airport infrastructure rather than from an aircraft's APU

FOD – Foreign Object Damage – damage caused to aircraft or engine by debris colliding with the aircraft or being ingested by the engine

ICAO – **International Civil Aviation Organisation -** the body that sets international standards and recommended practices for civil aircraft operations

ILS - Instrument Landing System – the electronic system giving guidance to the aircraft operating crews for the vertical (glide-slope) and horizontal (localiser) approach path at an airport

Landing and Takeoff Cycle – a phrase used to encapsulate the following phases of a flight: approach (from 3000 ft) and landing, taxi to/from the airport terminal, takeoff, and climb-out to 3000ft

LP/LD - Low Power/Low Drag – refers to the configuration and thrust of the aircraft while descending, i.e. in a low drag configuration (reduced flap and landing gear lowered as late as feasible) requiring low thrust levels to keep the required descent angle

LVP - Low Visibility Procedures – procedures put in place where the aerodrome wishes to continue operating instrument approaches where poor visibility or low cloud conditions are present

Mach number (Mach, or M) – the ratio of the velocity of the aircraft to the local speed of sound

Nacelle – the structure around the engine that forms its visible outer surface when on the aircraft

NADP - Noise Abatement Departure Procedure – the procedure used during take-off and initial climb to reduce the noise impacts beneath the aircraft

NATS – provider of air navigation services in UK airspace and the eastern part of the North Atlantic

NPR - Noise Preferential Route – the departure route from an airport's runway that allows for the minimum noise impact to local communities on the ground. Sometimes called Minimum Noise Routes

OPR - Overall Pressure Ratio – a measure of the extent to which air entering the engine is compressed before entering the combustor

NO_X - Oxides of Nitrogen – gases produced when air is raised to very high temperatures. NO_X emissions have consequences for local air quality, and are also believed to impact the atmospheric concentrations of methane and ozone (both of which are greenhouse gases)

PANS-OPS – Procedures for Air Navigation Services - Aircraft Operations - outlines the principles for airspace protection and procedure design to which all ICAO signatory states should adhere. Published as ICAO Doc 8168

PCA - Pre-Conditioned Air – a source of heated or cooled air for aircraft cabin air-conditioning supplied from airport infrastructure rather than from an aircraft's APU

SES - Single European Sky – a European initiative putting forward a legislative approach to solving the ATM issues currently affecting air transport, as well as enabling ATM to cope with future demands

SESAR - Single European Sky ATM Research

Steep Approach – an approach to landing at an airport that requires a descent along a glideslope angle above 4.5°, though the term is sometimes used to refer to an approach greater than the normal maximum of 3.25°

Threshold – the start of the portion of the runway that is available for landing aircraft

TET - Turbine Entry Temperature – the temperature of the gases exiting the engine's combustor and entering the turbine

VR – the speed at which an aircraft is rotated to lift off the runway, preserving all the necessary safety margins for take-off speed

V2 – the Take-off safety speed that is, the speed which the aircraft has to attain at the end of the take-off phase at the 35ft screen height