9. Annex A Academic study

9.1. Annex A Executive Summary

The primary assumption of ANIMA is that communities living around airports are the key stakeholders with respect to understanding, minimising, managing and mitigating the impact associated with aircraft noise and exhaust emissions. This therefore requires an understanding and appreciation of non-acoustical factors and air quality issues that go beyond the traditional aircraft noise vs emissions debate. However, an objective of ANIMA is to also consider such interdependencies and seek out insights in to how airports or airlines address these potentially competing issues.

This Annex provides a first step in this process and undertakes a detailed review of archived peer reviewed academic literature to present a snap shot of current knowledge and understanding of the interdependencies between aircraft noise and exhaust emissions and subsequent impact on communities. It is clear from the literature that the focus of academic, and perhaps also industry, studies has been overwhelmingly one dimensional. A wide range of studies have considered aircraft noise and related these to operational factors and impact on community annoyance and health. By way of contrast, there have been a relatively smaller number of studies that have considered aircraft exhaust emissions and impact on air quality in and around airports. Only relatively recently have these studies started to embrace the impact of aircraft emissions on the health outcomes of residents who live around airports. Therefore, it is perhaps unsurprising that a holistic approach which considers any interdependencies between aircraft noise and exhaust emissions and subsequent impact on communities have a very limited coverage in the literature. This clearly reflects the regulatory approach which generally considers noise and emissions separately.

The academic study does not seek to offer further insight in to the impact of aircraft noise on communities as this is the prime focus of the ANIMA project. However, it does set out an overview of aircraft exhaust emissions during the LTO cycle and identifies the role that changes to operational procedures can make to the quantitative and qualitative make up of engine exhaust. It also sets out an argument that the impact of emissions on local air quality and subsequent possible health outcomes of residents in communities neighbouring airports is of importance. Until quite recently, the main pollutant of concern for Airports, industry and regulators was NOx (NO_2) given its known health impacts and the need to meet air quality standards. However, within the literature there is increasingly attention being focussed on particulate matter (PM) and specifically ultrafine particles (UFP). This also reflects an increasing number of air quality studies that are seeking to better understand and offer insights into the role of aircraft exhaust emission on the concentration and size of PM in and around airports. In addition, the proposed CAEP/11 standards for LTO nvPM mass and number, the first standards of their kind, will be agreed at CAEP/11 in February 2019. It will also be proposed that the Smoke Number (SN) regulation can be retired (for engines greater than 26kN) and that a maximum concentration limit for nvPM mass agreed. Consequently, it is likely that industry and stakeholders will see nvPM (and possibly total PM) as being a key pollutant of concern particularly in the context of local impacts. As such ANIMA should consider including nvPM within its interdependencies and trade off analysis.

9.2. Annex A.1 Introduction and purpose

The key assumption of ANIMA is that communities living around airports are: i) the main stakeholders associated aircraft noise as they are directly impacted by this problem; and ii) that mitigating and managing the impact of aviation noise requires non-acoustical factors to be taken into account.

A specific objective of ANIMA is to also understand and consider interdependencies and how airports or airlines address competing environmental issues. However, by understanding and valuing the unique position of communities whose lives are affected by aircraft operations, such interdependencies should focus upon environmental issues which have local importance and impact on health outcomes and quality of life. These are primarily aircraft noise and gaseous and particulate emissions from aircraft engine exhaust[14].

Aviation in Europe is forecast to grow by 2.3% per annum[15]. Such growth whilst significantly contributing to wealth creation and offering greater global connectivity also has the potential to impact of European citizen lives and wellbeing through exposure to aircraft noise and exhaust emissions. By 2050 the number of commercial flights landing and taking off in Europe is forecast to be 18.6-26.1 million per annum which is 2-2.7 times the number of 2012[16]. Much of this growth is likely to be accommodated by existing large hub airports, however where aircraft operators are faced with capacity constraints they will grow their business where capacity is available. In doing so, new communities may be exposed to an enhanced level of aircraft noise and exhaust emissions.

The challenge for the regulators and industry is how to minimise, manage and mitigate its future impacts on communities living close to airports and ensure compliance with existing environmental guidelines, standards and limits.

Conventionally, the Committee on Aviation Environmental Protection (CAEP) within ICAO has addressed aircraft noise and emissions impacts independently of each other through measures such as engine NO_x emissions certification

[14] Fuel efficiency and carbon emissions are globally important as part of the climate change debate and have to be factored into the interdependencies equation, but at a local level emissions and noise are the predominant issues of concern for communities impacted by aircraft operations in and around airports.

[15] IATA(2017). Air Passenger Forecast

[16] Eurocontrol Challenges for Growth 2013. Available at: www.eurocontrol.int/sites/default/files/content/documents/official-documents/reports/201307-challenges-of-growth-summary-report.pdf

standards or aircraft noise certification standards[17]. This separation of issues is not isolated to ICAO but is also embedded across many stakeholders and industry bodies. For example, ACARE Flightpath 2050[18] goals also separate aircraft noise and emissions. To a large extent this is a logical and reasonable approach - as the objective is to reduce the environmental burden of aviation across the twin environmental issues of noise and emissions. Although, by not adopting a holistic approach industry and regulators could be criticized by not considering interdependencies. OEMs would, perhaps, argue that in the real world, manufacturers have a heightened awareness of understanding of the issues and seek to minimise or adopt as far as possible a reasonable balance.

On the whole, aircraft noise (and impacts) is the most widely reported environmental issue to be addressed by European airports and described in the recent academic literature (for example during 2016-2018 approximately 500 articles were published detailing studies of aircraft noise in and around airports and annoyance, compared with approximately 40 articles which detail studies focused on the impact of aircraft exhaust emissions on air quality in and around airports)[19].

This focus on noise is reflected in the historic response of the regulators. Since 2001 the International Civil Aviation Organisation (ICAO) has required Member States to adopt a 'balanced approach' to aircraft noise management[20,21]. This consists of identifying the noise problem at an airport and then analysing the various measures available to reduce noise through the exploration of four principal elements with the goal of addressing noise problems on an individual airport basis and to identify the noise related measures that achieve maximum environmental benefit in the most cost-effective way. The four elements are:

- Reduction at source (e g quieter aircraft).
- Land-use planning and management.
- Noise abatement operational procedures.
- Operating restrictions.

These principles also underpin The European Community adopted Regulation (EU) No 598/2014 on the procedures concerning the introduction of noise-related operating restrictions[22].

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[17] Mahashabde, A. (2011) Assessing the environmental impacts of aircraft noise and emissions. *Progress in Aerospace Sciences* 47. 15-52.

[18] Flight path 2050 available at www.acare4europe.org/sria/flightpath-2050-goals

[19] SCOPUS. Key words: i) *aircraft* and *noise* limited to *airport* and *annoyance*; and ii) *aircraft* and *exhaust* and *emissions* limited to *airport* or air *quality*.

[20] ICAO (2008). Guidance on the balanced approach to aircraft noise management. 2nd edition (Doc 9829)

[21] Scatolini, F. et al (2016). Easing the concept "Balanced Approach" to airports with densely busy surroundings – The case of Congonhas Airport. *Applied Acoustics* 105. 75-82.

[22] See for example: www.easa.europa.eu/easa-and-you/environment/policy-support-and-research/balanced-approach-regulation

Concern regarding air quality in and around airports has been recognised by *The Advisory Council for Aviation Research and Innovation in Europe (ACARE)* who identify within Action Area 3.5[23] the need for airport development to be sustainable, stating *"assessment of air quality impact at or near airports must be based on accurate measures or prediction of air vehicle emissions combined with sound atmospheric transport models"*. These challenges, which are further elaborated within Flightpath 2050[18], amplify the societal and industrial requirement for an enhanced qualitative and quantitative understanding of aircraft engine emissions, physicochemical interactions, and dispersion, with specific reference to pollutants that may have significant health impacts.

However, there is no analogous policy instrument or regulations related to the reduction of emissions from aircraft which embraces the principles of the balanced approach. Nonetheless, a number of academic and industry studies[24,25,26] have shown the potential of changes to aircraft operational procedures to lead to a marginal reduce in emissions (including circulars issued by ICAO)[27].

This brief Annex provides an overview of aircraft engine exhaust emissions in and around airports. It is structured to provide the ANIMA community with an overview of aircraft emissions and impact on local air quality and includes; i) operational procedures for emission reduction; ii) trade-offs and interdependencies between noise and emissions; iii) technological developments and implication for emissions.

9.3. Annex A.2 Airport air quality and health

Health impacts from aviation emissions have been quantified at various scales from national to global[28,29,30,31]. Estimates for premature mortalities attributable

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[23] ACARE Strategic Research and Innovation Agenda, Volume 1. Available at www.acare4europe.org/sria

[24] Koudis, G. S. et al., (2017). Airport emissions reductions from reduced thrust takeoff. *Transport Research Part D*: 52.15-28

[25] Koudis, G.S. et al., (2017). The impact of aircraft takeoff thrust setting on NOx emissions. *Journal of Air Transport Mnagement*: 65: 191-197.

[26] Flughafen Zurich (2010). Sensitivity of Aircraft Operational Improvements. LAQ modelling of landing and take-off cycles. Available at: https://www.zurich-airport.com/~/media/flughafenzh/dokumente/das_unternehmen/laerm_politik_und_umwelt/luft/2010_zrh_laq modelling_sensitivities.pdf

[27] ICAO circular 303 -AN/176.

[28] Yim, S.H.L. (2015). Global, regional and local health impacts of civil aviation emissions. *Environ. Res. Lett*. 10. 034001

[29] Morita, H. et al (2014) Global health impacts of future aviation emissions under alternative control scenarios. *Environ. Sci. Technol*. 48(24): 14659-14667.

[30] Penn, S.L. et al. (2017). Modelling variability in air pollution health damages from individual airport emissions. *Environmental Research*. 156. 791-800.

[31] Levy, J.I. et al (2012). Current and future particulate matter related mortality risks in the United States from aviation emissions during landing and take-off. *Risk Analysis* 32 (2). 237-249

to aviation have been estimated as 8,000 associated with cruise emissions[32] and a total of about 5000 people who live within 20 km of airports are estimated to die prematurely each year due to long-term exposure to aviation-attributable $PM_{2.5}$ and O_3[28,33].

There is a developing consensus of understanding about the possible health effects of aircraft engine emitted pollutants, other than NO_x (as NO_2), this is driving airport operators needs for a quantitative and qualitative understanding of aircraft engine emissions of PM (specifically UFP), VOC and SVOC. Scientists and regulators have an increasingly informed understanding of the complex nature of Particulate Matter (PM) in ambient air, in terms of particle size and chemical composition from different sources both natural and anthropogenic. What is less certain, is how PM species and precursors evolve and interact within the atmosphere, and which characteristics of the PM are most harmful to public health. Within this context, it is considered that Ultra Fine Particles (UFP), defined as particles of aerodynamic diameter less than 100 nm, may have greater toxicity on an equal mass basis than currently regulated larger particles ($PM_{2.5}$/PM_{10})[34] because their vast numbers and small diameters provide a high surface area which is a potentially important toxicological interface[35]. These UFP's are relevant to civil aviation, and recent studies have shown that aircraft engines emit primary aerosol as non-volatile Particulate Matter (nvPM)[36,37,38,39] as well as secondary aerosol precursor gases such as organic gases and sulphates[40] that nucleate within the exhaust plume within this size range. The contribution of UFP from aircraft operations to the emissions inventory in and around airports is therefore largely unknown, and could be significant[41].

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[32] Barrett, S.H. (2010). Global mortality attributable to aircraft cruise emissions. *Environ. Sci. Technol*. 44 (19) 7736-7742.

[33] Harrrison, R. et al. (2015). Civil Aviation, air pollution and human health. *Environ. Res Lett*. 10: 041001

[34] Air quality in Europe – 2017 report, (p 58), European Environment Agency

[35] RIVM, (2016). Explorative study into health risks of UFPs from aviation around Schiphol airport and proposal for follow-up

[36] Kinsey, J.S. et al (2011). Chemical characterisation of the fine particle emissions from commercial aircraft engines during the aircraft particle emissions experiment (APEX) 1 to 3. *Environ. Sci. Technol*. 45. 3415-3421.

[37] Hudda, N. et al (2014). Emissions from an International airport increase particle number concentrations 4 fold at 10km downwind. *Environ. Sci. Technol*. 48. 6628-6635.

[38] Hudda, N and Fruin, S.A. (2016). International Airport Impacts to air quality: size and related properties of large increases in ultrafine particle number concentrations. *Environ. Sci. Technol*. 50. 3362-3370.

[39] Winther, M. et al. (2014) Emissions of NOx, particle mass and particle numbers from aircraft main engines, APU's and handling equipment at Copenhagen Airport. *Atmospheric Environment*. 100. 218-229.

[40] Kilic, D. et al. (2018). Identification of secondary aerosol precursors emitted by an aircraft turbofan. *Atmos. Chem. Phys*. 18, 7379-7391

[41] Jannsen N. et al., Verkenning gezondheidsrisico's ultrafijnstof luchtvaart rond Schiphol en voorstel vervolgonderzoek. RIVM Briefrapport 2016-0050

9.4. Annex A.3 Pollutants of concern for airports – a change of focus?

NO_x has historically been viewed as the primary aircraft exhaust emission of concern though it is the concentration of NO_2 at receptors that is associated with adverse health effects, not NO_x. There have been many studies on estimating the NO_x burden on an airport and relating these to health based NO_2 standards[42,43]. In the more recent academic literature (2016-18) emissions of PM (and secondary formation) has been identified as important pollutant that has the potential to impact on the health of airport workers and adjacent communities (see above). A number of airports across Europe share this concern and it is reasonable to speculate that PM is likely to occupy a more dominant space in the operator agenda. This is evidenced by the recent focus placed on understanding the spatial and temporal concentration of ultra-fine particles (UFP) in and around airports[44,45]. A number of airports across Europe have put in place detailed measurement studies in an attempt to quantify the issue. In addition, a number of academic based studies[46,47,48,49,50,51,52] have also provided additional insight into the magnitude and impact of aircraft PM emissions.

9.5. Annex A.4 PM Emission Index

Given the increased importance that is focused on PM as a major pollutant of concern for the airport community it is important to appreciate: i) there is not a direct emissions Index (EI) for PM; and ii) the significant effort by ICAO and aviation stakeholders to develop a robust approach in estimating emissions.

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[42] Herndon, S.C. et al. (2004) No and NO2 emission ratios measured from in use commercial aircraft during taxi and take-off. *Environ. Sci. Technol*. 38. 6078-6084.

[43] Carslaw, D.C. et al. (2006) Detecting and quantifying aircraft and other on-airport contributions to ambient nitrogen oxides in the vicinity of a large international airport. *Atmos. Environ*. 40. 5424-5434

[44] ACI (2018) Ultrafine particles at airports – current understanding of ultrafine particle emissions and concentrations at airports in 2018

[45] ACI (2012) Ultrafine particles at Airports – discussion and assessment of ultrafine particles (UFP) in aviation and airports in 2012. http://dit.cph.dk/wp-content/uploads/2015/06/ACI-study-on-ultrafine-particles-at-airports.pdf

[46] Maisol, M. et al. (2017). Sources of sub-micrometer particles near a major international airport. *Atmos. Chem. Phys.* 17, 12379-12403

[47] Hudda, N. et al. (2016). Aviation emissions impact ambient ultrafine particle concentrations in the greater Boston area. *Environ. Sci. Technol*. 50. 8514-8521.

[48] Hudda, N. et al. (2018) Aviation-related impacts on ultrafine particle number concentrations outside and inside residences near an airport. *Environ. Sci. Technol.* 52, 1765-1772

[49] Woody, M.C. and Arunachalan, S. (2013). Secondary organic aerosol produced from aircraft emissions at the Atlanta Airport: An advanced diagnostic investigation using process analysis. *Atmospheric Environment*. 79 101-109.

[50] Masiol, M. et al. (2016). Source apportionment of wide range particle size spectra and black carbon collected at the airport of Venice (Italy). *Atmospheric Environment* 139, 56-74.

[51] Riley, E.A. et al. (2016) Ultrafine particle size as a tracer for aircraft turbine emissions. *Atmospheric Environment*. 139, 20-29

[52] Ren, J. et al. (2016). A study of ambient fine particles at Tianjin International Airport, China. *Science of the Total Environment*. 556, 126-135

To address the lack of an EI a simple methodology (FOA3)[53,54] was established in 2007 to estimate aircraft PM mass emissions based on Smoke Number. However, more recently in conjunction with the findings of the SAMPLE and A-PRIDE studies, a new regulatory framework for the sampling and measurement of nvPM mass and number emissions was agreed and adopted by ICAO (CAEP/10, Annex 16 Vol II)[55]. Since adoption of the nvPM methodology, numerous independent OEM tests and collaborative 'parallel' measurements with an EU, North American and Swiss reference systems, have populated an ICAO database for aircraft engine nvPM mass and number emissions. This is currently being used to develop a nvPM mass and number CAEP/11 regulatory standard[56]. In the future engine emissions will be regulated for both nvPM mass and number, and if scientifically established for local air quality assurance, a measure of total PM, including secondary PM evolved in the exhaust plume from gas precursors or condensed vPM may also be required. As an interim step a revised methodology for estimating nvPM has been developed known as Smoke Correlation for Particle Emissions – CAEP11 (SCOPE11). This new methodology revises the PM EI and predicts ~32% higher BC mass emissions than FOA3[57].

It should also be noted that emissions from APU (e.g. NO_x and PM) are not currently regulated by ICAO, but may contribute noticeably to air quality issues particularly on and around the apron[58].

9.6. Annex A.5 -Emissions or air quality the importance of understanding the difference

The process used to estimate gaseous emissions (SO_2, NO_x, CO) and non-volatile PM within the exhaust of aircraft engines is well understood within the aviation community and across stakeholders. A comprehensive description is detailed in the ICAO Doc 9889[54] and more recently elsewhere[59]. However, airports do not have to comply with standards based on emissions, though a number of airports have adopted a NO_x charging scheme based on a cost per kilogram of NO_x

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[53] Wayson, R. et al. (2009). Methodology to estimate particulate matte remissions from certified aircraft engines. *Journal of the Air and Waste Management Association*. 59. 91-100

[54] ICAO Doc 9889. Airport Air Quality Manual. (2011)

[55] The latest version of Annex 16, Vol II is the 4th edition, published in July 2017

[56] The CAEP10 nvPM standard regulates the LTO nvPM maximum mass concentration and requires reporting of LTO EIs for nvPM mass and number. The future CAEP11 nvPM standard will regulate engine nvPM emissions over the LTO cycle for mass and number

[57] Agarwal, A. et al (2019) The SCOPE11 method for estimating aircraft black carbon mass and particle number emissions. Submitted to: *Environ. Sci. Technol*. (in review)

[58] Masiol, M. and Harrison, R.M. (2014). Aircraft engine exhaust emissions and other airport related contributions to ambient air pollutant: A review. *Atmospheric Environment*. 95. 409-455.

[59] Zaporozhets, O. and Synylo, K. (2017). Improvements on aircraft engine emission and emission inventory assessment inside the airport area. *Energy*. 140 (2) 1350-1357

emitted per landing and take-off cycle[60,61] in order to incentivise airlines to use aircraft which meet CAEP6 standard[62].

Given the primacy of NO_2 and PM for European airports (O_3 is important in the US) primary and secondary emissions (NO_x, NO_2, VOC, PM etc) have to be modelled to account for any chemical transformation and dispersion to estimate the concentration of regulated pollutants (NO_2, $PM_{2.5}$/PM_{10}) to ensure compliance with health-based standards.

NO_2: Aircraft NOx emissions are made up primary NO_2 and NO but conventionally termed NO_x. To calculate the concentration of NO_2 at a receptor requires a detailed understanding of i) the magnitude of NO and primary NO_2 emissions; ii) concentrations of oxidants (principally NO_2 and O_3) in the air; iii) the magnitude of incoming solar radiation and; iv) travel time.

PM: It is widely recognised that the current International Civil Aviation Organization (ICAO) regulatory requirement for the measurement of gases, nvPM and Smoke Number at engine exit, may not be sufficient to accurately predict total PM formed in the exhaust of an aircraft engine.

Aircraft engines emit volatile precursors of PM and non-volatile PM in form of soot or black carbon with diameter below 100 nm (UFP) and volatile material. In the process of dilution of the exhaust with ambient air, the particles are coated by volatile species and new volatile particles are created from a range of gaseous sulfates and organic precursors[63,64]. Superimposed on these processes is the overall physical dynamics of the exhaust flow. While there is an increasing amount of measurement data and theoretical estimates of the mass and number emission of nvPM, major gaps exist in understanding and modelling the subsequent aging processes and formation of particles from volatile and semi-volatile PM. For the exhaust dynamics, major uncertainties exist in describing the effects of exit turbulence, buoyancy and wingtip-vortex interactions[65] as a function of meteorological conditions, LTO segment, and aircraft size. These processes can have strong impact on the resulting pollutant concentration in and around an airport.

Airports have to comply within the EU include the Ambient Air Quality Directives[66] and the National Emission Ceilings Directive[67], which includes a new

[60] CAA (2017). Environmental charging- review of impact of noise and NOx landing charges. Update 2017. CAP 1576.

[61] Boeing (2015). Airport noise and emission regulations. www.boeing.com/commercial/noise/

[62] www.icao.int/environmental-protection/Pages/technology-standards.aspx

[63] See e.g. Kärcher, B. et al., (2000), Journal of Geophysical Research. 105/D24:29,379-29,386

[64] Timko, M.T. et al., (2013): *Environ. Sci. Technol.* 37:3513-3520

[65] See e.g. Unterstrasser, S. et al., (2014): Atmospheric Chemistry and Physics 14: 2713-2733

[66] Ambient Air Quality Directives. (2004, 2008). Available at: ec.europa.eu/

[67] National Emissions Ceiling Directive NECD (2016). Available at: eur-lex.europa.eu

emission reduction commitment for fine particulate matter (PM2.5). Many European airports are located in or close to air quality management zones/agglomerations where statutory bodies are required to adopt measures to improve air quality and meet EU ambient air quality directives (specifically NO_2 and $PM_{10}/PM_{2.5}$). For many airports this requires the development of a detailed emissions inventory of airport activity (aircraft, landside traffic, airside traffic, boiler plan etc). This is then layered on to other local and regional sources to produce the input data for detailed dispersion modelling. After accounting for background concentrations, the impact of aircraft emissions to receptors can be readily estimated. For example, at Heathrow it is estimated that the contribution of all emission sources at the airport to NO_x pollutant levels is about 30% at the boundary and significantly less at distances less than 1km away[68].

There is a clear analogy between the impact associated with aircraft noise and exhaust emissions. With aircraft noise there are also complex relationships between noise, the annoyance response and non-acoustical factors (for example fear and individual noise sensitivity). Whilst for gaseous or PM pollutants there are also complex relationships between the magnitude of the emission release, atmospheric transformation and exposure. A simple noise vs emissions approach to assessing trade-offs or interdependencies is perhaps a simplistic approach which disregards actual impact and down plays the importance for the industry and stakeholders.

9.7. Annex A.6 CO2 – an important driver for airlines

In October 2016, the International Civil Aviation Organization (ICAO) agreed on a Resolution for a global market-based measure to address CO_2 emissions from international aviation from 2021[69].

The Carbon Offsetting and Reduction Scheme for International Aviation, or CORSIA, aims to stabilise CO_2 emissions at 2020 levels by requiring airlines to offset the growth of their emissions after 2020.

Airlines will be required to:

- monitor emissions on all international routes;
- offset emissions from routes included in the scheme by purchasing eligible emission units generated by projects that reduce emissions in other sectors (e.g. renewable energy).

During the period 2021-2035, and based on expected participation, the scheme is estimated to offset around 80% of the emissions above 2020 levels.

[68] Carslaw, D. C. et al. (2006). Detecting and quantifying aircraft and other on-airport contributions to ambient nitrogen oxides in the vicinity of a large international airport. *Atmos. Env*. (40). 5424-5434

[69] ICAO (2018). Annex 16 Vol IV Carbon offsetting and reductions scheme for international aviation (CORSIA).

Emissions of CO_2 from aircraft engines are directly related to fuel burn and can be estimated relatively easily[70]. Fuel efficiency is important for airlines in terms of economic savings and environmental (global) impacts. It is estimated that the annual average RTK fuel efficiency from 2009-2014 stands at 2.4% compared to the 1.5% industry target[71]. This trend in fuel efficiency is likely to increase in the short term as CORSIA and the rising cost of fuel drive the industry to reduce costs including the a wider uptake of fuel efficient aircraft including Boeing 787-9 and Airbus A350-900 and A320neo. In addition, airlines routinely employ a variety of operational measures to gain fuel savings including reduced thrust/de-rated take-offs, CDA, reduced engine taxi etc. A number of academic studies have described these in detail[72,73,74,75,76,77,78,79].

9.8. Annex A.7 Interdependencies/trade-offs between emissions and noise within the LTO

The potential for trades-offs between noise and emissions have been qualitatively summarised elsewhere[80]. The academic peer reviewed literature provides details of possible or potential trade-offs or interdependencies associated with some aircraft operations in the LTO, but there appears to be limited recent peer reviewed and archived studies that provide a detailed analysis of the array of the trade-offs or interdependencies between noise and emissions. Likewise, those studies which have isolated one operational procedure (such as CDO or reduced thrust take-off) have not taken into account the full suite of emissions. Most studies focus on the trade-off or interdependency between CO_2 (fuel) or NO_x with noise but do not consider other primary

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[70] Ashok, A. et al. (2014). Quantifying the air quality CO_2 trade-off potential for airports. *Atmos. Env*. (99). 546-555.

[71] IATA (2018). Economic performance of the airline industry – semi-annual report. www.iata.org/publications/economics/Reports/Industry-Econ-Performance/IATA-Economic-Performance-of-the-Industry-mid-year-2018-report-final-v1.pdf

[72] Clarke, J.P. (2013). Optimised profile descent arrivals at Los Angeles International Airport. *Journal of Aircraft* 50 (2) 360-369

[73] Nikoleris, T. et al. (2011) Detailed estimation of fuel consumption and emissions during aircraft taxi operations at Dallas/Fort Worth International Airport. *Transportation Research Part D*. 16, 302-308.

[74] Koudis, G.S. et al. (2017). The impact of aircraft take-off thrust setting on NOx emissions. *Journal of Air Transport Management*. 65, 191-197

[75] Turgut, E. T. et al. (2013). Estimation of vertical and horizontal distribution of take-off and climb NO_x emissions for commercial aircraft. *Energy Conservation and Management*. 76, 121-127.

[76] Solveling, G. et al. (2011). Scheduling of runway operations for reduced environmental impact. *Transportation Research Part D* 16, 110-120.

[77] Ashok, A. et al. (2017). Reducing the air quality and CO_2 climate impacts of taxi and take-off operations at airports. *Transportation Research Part D* 54, 287-303.

[78] Turgut, E. T. and Usanmaz, O. (2012). NO_x, fuel consumption and time effects of flight path angle during descent. *Journal of Aerospace Engineering*. 227(5), 737-750

[79] Hao, L. et al. (2017). Estimating fuel burn impacts of taxi-out delay with implications for gate hold benefits. *Transportation Research Part C* (80) 454-456

[80] Sustainable Aviation (2017) Inter-dependencies between emissions of CO_2, NO_x and noise from aviation. www.sustainableaviation.co.uk/wp-content/uploads/2018/06/FINAL__SA_InterDependencies_2017.pdf

emissions including nvPM or the formation of secondary pollutants which potentially have health related impacts. Equally, there appears to be little in the literature which considers the trade-off between the impact of aircraft noise alongside the impact of exhaust emissions which arguably is as important, and perhaps more crucial, than focusing on primary emissions. Clearly, this will be important for ANIMA to acknowledge and set out a pathway for it to be addressed in the future.

As described above, there are a number of studies which have considered fuel burn and emissions across the whole of the LTO. These studies illustrate the importance of accessing data from FDR in order to estimate emissions as the operational values are generally found to differ from the ICAO databank values in a statistically significant manner.

For completeness this report briefly summarises the main aircraft manoeuvres or operational procedures associated with trade-offs or interdependencies and which are widely reported in industry and academic literature.

Arrival

CDO: When an aircraft follows a Continuous Descent Operation (or Continuous descent approach) procedure it stays higher for longer, descending continuously and avoids extended level segments of flight prior to intercepting the 3-degree glide path. Consequently, a continuous descent also requires significantly less engine thrust than required for level flight. Details of CDO/CDA have been discussed widely and the noise and emission impacts described in regulator, industry and academic literature[81,82,83,72]. There are both fuel (and CO_2) and NO_x savings associated with CDO/CDA[72,78]. However, NO_x emissions savings within the LTO cycle are relatively minimal and will not contribute greatly to improved air quality.

Low power/Low drag: Low power/low drag is the collective term used for describing the lowest noise configuration for a given speed and/or altitude during the approach. If pilots select more flap than is required for a given speed it will typically lead to more airframe noise, increase fuel burn due to higher engine power to compensate for the increased drag and thus lead to higher noise – typically in the order of 1 dB. The deployment of the landing gear also significantly increases aircraft drag and airframe noise, and necessitates an increase in engine power to maintain the flight path. This can lead to increased noise in the order of 5 dB[84,85]. Procedures to optimise flap and landing gear

[81] Wubben, F.J.M and Busink, J.J. (2000). Environmental benefits of continuous descent approaches at Schiphol Airport compared with conventional approach procedures. NLR-TP-2000-275

[82] ICAO Doc 9931

[83] Eurocontrol (2011) Continuous Descent – a guide to implementing continuous descent. www.eurocontrol.int/sites/default/files/publication/files/2011-cd-brochure-web.pdf

[84] CAA (2017). Review of aircraft noise controls (CAP1554).

[85] ECAC.CEAC Doc29

deployment would have an impact on noise and fuel (CO_2) and gaseous emissions. However, as with CDO procedures emission reductions within the LTO would be minimal and have limited impact on local air quality.

Reduced landing flap: Reduced landing flap requires an aircraft on approach to be flown at higher speeds. This is likely to increases the touchdown speed, which in some circumstances may lead to an increased use of reverse thrust to slow the aircraft. However, overall it can reduce fuel burn and engine emissions (NO_x). Noise reductions could be in the order of 0.5-1.5 dB.

Take-Off procedures

Reduced or flexible thrust: Most operators prefer to reduce the level of take-off thrust as much as possible to reduce engine maintenance, minimise operational costs and reduce noise close to an airport. This common practice is referred to as using *reduced* or *flexible* thrust. The take-off phase is an important generator of emissions. For example, at Heathrow the take-off roll is estimated to produce 60% of total ground level NO_x emissions and 50% of black carbon. Consequently, for airport operators, airlines and regulators this is a phase of aircraft operations that provides a major opportunity to reduce emissions. Recent work using FDR data from an airline operating at Heathrow indicate that using reduced thrust take-off reduces fuel consumption, NO_x and black carbon BC emissions by 1.0–23.2%, 10.7–47.7%, and 49.0–71.7% respectively relative to 100% thrust take-off [24]. Consequently, when appropriate and subject to safety and other operational conditions the use of reduced thrust take-off offers emissions savings, however this may reduce the height of cutback and at least beyond the cutback point create more noise at ground level.

Taxi in/out procedures

A number of recent studies have sought to model aircraft LTO emissions and quantify the benefits of adopting reduced pollutant- emitting operations, primarily during taxiing activities[86]. Through optimising operations including pushback, gate location and taxiway orientation fuel consumption reductions of between 19 and 31% were identified. However, as with other phases of operation the robust estimation of fuel burn and pollutant emissions is highly dependent upon the availability of data from FDR rather than reliance on ICAO databank assumptions for TIM and EI. Studies have shown that using FDR[87] to determine taxi fuel consumption illustrates lower engine thrust and the importance of the number of accelerations events (stop/start). In general fuel

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[86] Zurich Airport (2017). Taxi emissions at Zurich Airport – calculation, analysis and opportunities. www.zurich-airport.com/~/media/flughafenzh/dokumente/das_unternehmen/laerm_politik_und_umwelt/taxi_study_zurichaireport_20171207.pdf

[87] Khadilkar, H. and Balakrishan, H. (2012) Estimation of aircraft taxi fuel burn using flight data recorder archives. *Transportation Research Part D* 17 (7) 532-537.

flow fuel flow estimates using the ICAO method over predicted fuel burn by up to 35% compared to the FDRs. However, variations to taxi procedures will have marginal benefits for the overall noise contour of an airport.

Reduced engine taxi: Taxi operations with less than all engines operating is often known as single engine operation. Though for four engine aircraft the two inner engines may be turned on or off sooner or later. Single taxi operations are used by many airlines and at numerous airports. However, there appear to be few academic studies which seek quantify the fuel savings and impact on pollutant emissions from the use of reduced engine taxi procedures and which seek to quantify impact on PM emissions and secondary formation. However, industry is taking a lead and an analysis at Zurich Airport[86] provides a comprehensive analysis of the fuel savings and impact on pollutant emissions including NO_x and nvPM. Recent work which could have a significant bearing on the understanding of aircraft emissions on air quality in and around airports highlights the importance of secondary aerosols[88]. A reduction in engine idling thrust from circa 7% to 3% could lead to an increase in the formation of secondary organic aerosols by 30%.

9.9. Annex A.8 Future technological developments impacting on emissions

This section of the report provides a brief overview of likely technological developments which will have an impact upon emissions and will potentially factor in future trade-off/interdependency analysis. The emission reduction derived from step changes in technology and the availability of alternative drop-in fuels will deliver significant emission and subsequently impact benefits leading to improved air quality in and around airports.

The ACARE flight path 2050 targets are... "procedures available allow a 75% reduction in CO_2 emissions per passenger kilometer and a 90% reduction in NO_x emissions. The perceived noise emission of flying aircraft is reduced by 65%. These are relative to the capabilities of typical new aircraft in 2000". In addition, aircraft are expected to be emission free during taxi and the Europe will be a centre of excellence for sustainable fuel.

Aircraft engine emission improvements are created primarily through step change and through incremental technology insertions. WP6 will unpick the technological roadmap further and examine possible emission reductions. For the purposes of WP2 this brief introduction highlights that future developments will most likely be significantly more important than any marginal gains made through addressing trade-offs or interdependencies.

[88] The dominant source of airport aerosol is aircraft engine exhaust and is classified as either directly emitted primary aerosol or secondary aerosol. Primary aerosol from aircraft engines and contains mainly black carbon whereas secondary aerosol is formed by the oxidation of emitted precursor gases.

Engine: Technological developments to reduce emissions have historically been focussed on NO_x production. Specifically, OEMs have adopted two main strategies in combustor architecture design to address NOx production. These approaches are the Lean combustor and the Rich Burn-Quick Quench-Lean Burn (RQL) combustor. Lean combustor designs burn at a low fuel-air ratio to drive NO_x production down. The Lean technique allows for combustion at a lower temperature and the staging of piloted chambers and nozzles to adapt to each LTO cycle and reduce residence time.

RQL combustor designs begin by burning fuel in a rich environment, where the free O2 and N2 particles are scarce compared to fuel. Following that, bypass air is quickly mixed to quench the fuel-air ratio and shortcut the transition to a final lean combustion, essentially avoiding combustion at the stoichiometric ratio.

However, when a CAEP12 nvPM (mass and number) stringency limit is agreed then OEMs will be seeking to manage the interdependencies between NO_x, PM and VOC. With both Lean and RQL technology emissions of nvPM and VOC may increase or decrease (there may also be a trade-off between nvPM and VPM) across some operational procedures within the LTO. This may be an issue for OEMs particularly if the formation of secondary aerosols in the plume is considered.

Alternative drop in fuel: The connectivity between fuel chemistry and combustion exhaust emissions has long been established in sectors such as automotive. In recent years, the introduction of alternative into the aviation sector (ASTM D7566; DefStan 91-91) has similarly led to a growing body of evidence to suggest that the wider benefits of these engineered fuels can be realised in commercial operations. Furthermore, these benefits are not limited to the headline reduction in fossil CO_2 of up to 60%:

Classes of predominantly paraffinic fuels have been shown to greatly reduce the emission of nvPM, particularly in the idle and lower thrust range. Moreover, the near zero levels of fuel sulphur inevitably lead to significant reductions in emissions of vPM. Hence the potential to reduce the proportion of total PM from aircraft sources has been established, and the possible transference of these emission reductions to improvements in local air quality is credible.

In contrast, current research suggests that the perturbation in the acoustic signature from aircraft using alternative fuels is small to negligible, and any reduction in the emission of noise is unlikely to be discerned within impacted communities.

9.10. Annex A.9 Conclusion

This review has provided an overview of possible interdependencies or trade-offs between aircraft noise and exhaust emissions associated with operational procedures in the LTO. The study primarily confirms the view that noise and emissions are frequently considered independently and not in a holistic way.

Indeed, it appears only a few academic studies have sought to quantify the trade-offs though a number have provided a qualitative/hypothetical assessment. This reflects the approach of regulators who also set independent standards for noise and emissions. This approach and the increasingly stringent noise and emission standards have been successful in reducing the overall environmental impact of aviation. Given the regulatory separation it is of little surprise, therefore, that the recent peer review and accessible industry literature contains little evidence of a comprehensive noise/emission trade-off analysis.

Generally published studies which have examined the effect of changes to how aircraft operate in and around airports have focused on savings to CO_2 or NO_x. Only recently has PM been factored into the equation primarily through the application of FOA3 rather than the actual emission of nvPM (mass and number). There is also little evidence that existing work has considered the formation of secondary PM which could be an order of magnitude larger than the primary emission. This may have profound implications when considering operations with low thrust setting (taxi).

The existing literature is also relatively silent on examining any trade-offs or interdependencies between the impact of noise and emissions. Arguably, it is the impact of aircraft noise and emissions which is important and should be factored in to future trade-off/interdependency analysis. Though it is recognised that this is not a simple or straight forward task and may beyond the capability of many airports.

9.11. Annex A.10 Recommendations

The following recommendations have been set out to help guide the development of D2.3.3.

1. Scope11 methodology should be used to estimate the concentration of PM as a key in any trade-off or interdependency analysis.
2. Keep a watching brief on the development of new insights into primary emission of PM and precursors.
3. Consider how to factor environmental impact (nuisance vs air quality) into future analysis of interdependencies.
4. Consider how to layer into the interdependency debate health impacts. How do health outcomes differ between exposure to noise and emissions?
5. Obtain a better understanding of the potential emission benefits that may be derived from new technology and fuel formulation.