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PART 1/3

COMMISSION STAFF WORKING DOCUMENT

Full-length report

Accompanying the document

Report from the Commission to the European Parliament and the Council

Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4)

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European Union Aviation Safety Agency
SAFE AND SUSTAINABLE AVIATION

FINAL REPORT

Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4)

Contract reference: MOVE/E1/SER/2019-475/SI2.817062
Date: September 2020

Disclaimer

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Project Team

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For further information linked to matters on aviation and environmental protection, we invite you to visit the EASA website (www.easa.europa.eu/environment).

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EXECUTIVE SUMMARY

The EU Emissions Trading System (ETS) currently regulates aviation CO_2 emissions, although it is recognised that there are other aviation emissions that contribute to the sector's climate impact. In 2006, the Impact Assessment for the EU ETS Directive 2003/87/C analysed the possibility of regulating Oxides of Nitrogen (NO_x), and this was subsequently followed up in 2008 by a DG MOVE study '*Lower NO_x at Higher Altitudes: Policies to Reduce the Climate Impact of Aviation NO_x Emission*'. At that time, scientific understanding in this field was not considered to be sufficiently mature to indicate a clear course of action from a policy perspective. There have been many scientific developments over the last decade and consequently the co-legislators provided the following mandate within Article 30(4) of the revised EU ETS Directive 2018/410:

> *'Before 1 January 2020, the Commission shall present an updated analysis of the non-CO_2 effects of aviation, accompanied, where appropriate, by a proposal on how best to address those effects.'*

In response to this mandate, the European Commission commissioned a study to EASA covering three main elements:

Task 1: What is the most recent knowledge on the climate change effects of non-CO_2 emissions from aviation activities?
Task 2: What factors/variables have had an impact on these effects (e.g. technology / design, operations, fuel, market based measures)? What is the level of that impact? Do these factors/variables exhibit trade-offs or interdependencies between different emissions?
Task 3: What research has been undertaken on potential policy action to reduce non-CO_2 climate impacts? What are the pros and cons of these options in terms of implementation? What knowledge gaps exist?

An initial project team meeting of key European experts was held on 17th September 2019, followed by a workshop on Tasks 1 and 2 on 20th November with a wider group of experts covering different perspectives within the scientific community. An interim report was delivered on 6th December, with initial thoughts on the three tasks. This report was used to focus the subsequent work, with a further project team meeting on 20th February 2020 and an additional expert workshop on Task 3 on 12th March.

TASK 1: Aviation non-CO_2 impacts – current status of science and remaining uncertainties

Aviation Radiative Effects

- There are significant scientific uncertainties remaining in quantifying aviation's non-CO_2 impacts on climate. The non-CO_2 impacts arise from emissions of oxides of nitrogen (NO_x), soot particles[1], oxidised sulphur species, and water vapour. These emissions result in changes in the chemical composition of the global atmosphere and cloudiness, perturbing the earth-atmosphere radiation budget. The net impact of aviation non-CO_2 emissions is a positive radiative forcing (warming), although there are a number of individual positive (warming) and negative (cooling) forcings arising from respective aviation non-CO_2 emissions, for which large uncertainties remain.
- The largest aviation non-CO_2 impacts that can be calculated with 'best estimates' are those from 'net-NO_x[2]' and contrail cirrus[3], both of which have significant uncertainties in their magnitude, particularly contrail cirrus.
- The Effective Radiative Forcing (ERF) from the sum of non-CO_2 impacts yields a net positive (warming) that accounts for more than half (66%) of the aviation net forcing in 2018.
- The uncertainty distributions (5%, 95%) show that non-CO_2 forcing terms contribute about 8 times more than CO_2 to the overall uncertainty in the aviation net forcing in 2018.
- The scientific understanding on the net effect of NO_X climate forcing has evolved over the last decade. Research has shown that there is high non-linear chemistry of the interaction of NO_X with background concentrations of other emissions at cruise altitudes, and the effect of NO_X is dependent on the location it is emitted. While the confidence level on the magnitude of the impact of NO_X remains low, the current scientific understanding is that NO_X still has a net positive climate forcing effect (i.e. warming).
- If surface emissions of tropospheric ozone precursors (NO_x, CH_4, CO, non-methane hydrocarbons) decrease significantly and aviation emissions increase, as envisaged by various scenarios, it is possible that the net aviation NO_x Effective Radiative Forcing (ERF, see Metrics below) will decrease or even become negative (i.e. cooling) in the future, even with increasing total emissions of aviation NO_x. This highlights one of the problems of formulating NO_x mitigation policy based on current emissions/conditions.

[1] 'Soot' refers to combustion particles that exist in the engine plume and ambient environment, that may undergo chemical (e.g. oxidation and surface adsorption of gas phase molecules) and physical processes (e.g. agglomeration, coagulation)

[2] NO_x is not a climate warming agent per se, but its emission results in changes in the chemical balance of the atmosphere to ozone and methane which have radiative impacts, quantified as a 'net-NO_x' effect.

[3] Contrail cirrus is an artificial cirrus-like cloud produced in the upper atmosphere (~ 8 to 12 km above ground) as a result of aircraft emissions of water vapour and soot particles into very cold atmospheres that are supersaturated with respect to ice. Conditions of the atmosphere (temperature and ice supersaturation) dictate whether linear contrails form behind the aircraft and persist to produce larger-scale spreading of the linear contrails into contrail cirrus.

- Soot particle number emissions show a dependency on the aromatic content of aviation fuels. A decrease in soot particle number emissions reduces the number of ice particles formed, increases the mean crystal size, reduces contrail lifetime and reduces optical depth. This leads to a net reduction in the positive Radiative Forcing (i.e. warming). One study has shown that a ~50% reduction of the number of initial ice particles formed on emitted soot resulted in a ~20% reduction in Radiative Forcing.
- Aerosol-cloud interactions, which are separate to contrail cirrus, also have a potentially large non-CO_2 impact from changes in high-level cloudiness from soot particle emissions, and changes in low-level clouds from sulphur emissions. Best estimates of these effects cannot be given at present. The impact of changes in high-level cloudiness has been calculated to be either a positive or negative forcing (warming or cooling), whereas the impact on low level clouds is highly likely to be cooling but with very uncertain magnitude. Greater understanding of the indirect cloud effects of soot particles and sulphur, through aerosol-cloud interactions, is urgently required to formulate effective policy.

Metrics

- The scientific community has adopted the metric 'Effective Radiative Forcing' (ERF) as a better metric of an absolute impact when compared to Radiative Forcing (RF). This is because it shows better proportionality to changes in global mean surface temperature response particularly for short-lived climate forcing agents such as clouds and aerosols.
- The usage of ERF rather than RF is potentially significant for aviation NO_X and contrail cirrus impacts. Aviation ERFs are less well quantified than RFs for net NO_x impacts (only one estimate at present), but better quantified for contrail cirrus forcing effects. The available studies suggest that that the aviation net NO_x ERF > net NO_x RF (by possibly factor ~2) and the contrail cirrus ERF < contrail cirrus RF (by factor 0.3–0.6). Irrespective of which metric is used, ERF or RF, the largest aviation non-CO_2 impacts remain 'net-NOx' and contrail clouds.
- In terms of comparing aviation CO_2 emissions with non-CO_2 emissions and their impacts on a common scale, 'equivalent emissions metrics' are required (CO_2-e). The CO_2-e metric that is currently widely used, including within the EU ETS, is the Global Warming Potential for a time-horizon of 100 years (GWP100).
- Formulating aviation emissions equivalencies for short-lived climate forcers (e.g. non-CO_2 impacts) with the long-lived greenhouse gas (e.g. CO_2) [4], presents scientific and policy challenges. In addressing this, the scientific community has proposed a number of alternatives to the GWP100. There is no exclusively 'correct' choice of a CO_2 equivalent emissions metric, as the choice depends on the policy (e.g. temperature target, emissions reduction target), and also the subjective choice of time horizon of interest. A particular challenge is associated with the use of emissions metrics to assess policy options that involve a reduction of a short-lived climate forcer with a possible CO_2 penalty.

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[4] CO_2 has multiple lifetimes in the atmosphere because of different sink timescales, but a significant fraction (~20%) accumulates and remains in the atmosphere for millennia.

- A simple approach to account for the climate effects of non-CO_2 emissions would be to formulate a single CO_2 equivalent emissions 'multiplier' (for example a net GWP100 based multiplier for aviation non-CO_2 impacts), averaged across the aircraft fleet and all atmospheric conditions. However, adopting a single multiplier may not be appropriate because:
    - The magnitude of the multiplier depends on the metric chosen, and mostly, the time horizon considered.
    - The use of a multiplier does not incentivise reductions of non-CO_2 emissions independently of CO_2 emissions, neither at the global/regional fleet level nor on an individual flight-by-flight basis.
- Another option, would be to calculate the total climate impact of individual flights and then determine the CO_2 equivalent emissions on a flight-by-flight basis. Such equivalents could be used as the basis for a policy instrument, but once again, the magnitude of the equivalency depends on the choice of metric and time horizon. Also, a flight-by-flight basis would require calculating climate impacts of individual flights in space and time, which would be a challenge, even on a statistical or average basis.

Mitigation Opportunities

- Technological or operational measures to mitigate aviation's non-CO_2 impacts that involve a reduction of a short-lived climate forcer (e.g. NO_x or contrail cirrus), but result in increased CO_2 emissions, need to be considered carefully to ensure that the net impact is beneficial. Since CO_2 has a very long lifetime in the atmosphere, the ratio between benefits and disbenefits will change with the time horizon being considered. As such, a reduction of short-lived climate forcers might make it easier to achieve climate change targets in the next decades and up to a century. Nevertheless, conservative mitigation approaches that ensure benefits on a wide range of timescales may be possible.
- Aviation emissions of NO_x are currently calculated to have a positive RF (warming) and represent a potential mitigation opportunity. However, mitigation of aviation NO_X would require a careful consideration of:
    - the regulatory approach taken as the ICAO NO_x emissions regulations allow for increasing emission index of NO_x (g NO_x per kg fuel) with engine pressure ratio;
    - technological trade-offs that might increase fuel consumption and CO_2 emissions;
    - the possibility of technological 'lock in' of decreasing NO_x over the longer term, when NO_x emissions may eventually have an overall cooling effect.
- Reducing the climate impact of aviation by avoiding the formation of contrail cirrus could be achieved by operational means whereby contrail cirrus-forming regions of the atmosphere are avoided. The atmospheric conditions that produce contrail cirrus are associated with ice-supersaturated regions (ISSR) being of the order of tens to hundreds of kilometres wide and hundreds of metres thick. There is some evidence that most of the total forcing comes from a few events, where contrail cirrus formation is large and long-lasting – sometimes termed 'Big Hits'. It would therefore be advisable that flights impacting these events should be 'targeted' for avoidance, rather than all flights, and that research into reliably forecasting such 'Big Hits' is undertaken.

- Avoidance of contrail cirrus would require that:
    - the inherent uncertainties of the contrail cirrus effect are much better quantified (including a better understanding of the differences between the ERF and RF);
    - the potential impacts of trade-offs from increased CO_2 emissions are more thoroughly understood to ensure 'no regrets policies', and;
    - regions of ice-supersaturation can be predicted in a sufficiently accurate manner, at least 24 hours in advance.
    - meteorological forecast modelling be improved as the capability to forecast persistent contrails is limited.
- Reducing soot particle emissions (by number) from aviation, in particular by means of sustainable low carbon footprint aviation fuels, would be a 'win-win' situation for improving air quality and reducing contrail cirrus impact on climate, but by an uncertain amount that requires better quantification from measurements and modelling. This would not require any modification of flight trajectories or incur any additional fuel consumption/CO_2 penalty.

TASK 2: Technological and operational options for limiting or reducing non-CO_2 impacts from aviation and related trade-off issues

Technology

- EASA environmental certification standards already exist for aircraft engine emissions. These include Oxides of Nitrogen (NO_x) as well as the mass and number of non-volatile Particulate Matter (nvPM)[5] emissions.
- NO_X and nvPM emissions are measured during the engine type certification process at various power settings and duration that simulates a reference Landing and Take-Off (LTO) cycle. Uncertainties, and the variability between engine types, of nvPM emissions are greater than for NO_X.
- Cruise NO_X and nvPM emissions are generally considered to be related to LTO emission trends (i.e. reductions in LTO emissions leads to reductions in cruise emissions), but are less well characterised for newer staged combustion technology. However, work in the ICAO environmental committee is ongoing to provide better cruise emission estimation methods using LTO data.
- A reporting point for NO_X and nvPM emissions at cruise thrust settings in the engine emissions certification requirements may allow better inventory quantification and incentivise reductions of NO_X and PM emissions in this flight phase.
- The global aircraft fleet NO_X performance, in terms of certified data, will improve as older high-NO_X engine designs are replaced with combustion technologies such as Rich-Burn, Quick-Mix, Lean-Burn (RQL) and Lean Burn combustors[6]. Emissions of NO_x on a per passenger kilometre basis will also show a reduction over time.
- However, the general trend for increased engine overall pressure ratios to provide better specific fuel consumption means that emission indices (g NO_x per kg fuel burnt) are likely to increase. Significant overall NO_x reductions from new technology beyond Lean Burn and advanced RQL may also be limited.
- Advanced alternative aircraft technology, including electrified aircraft propulsion, is not considered likely to be in service in the next 20 years. Beyond 2040-2050, hybrid/electric aircraft and revised configurations could offer significant reductions in NO_x emissions.
- nvPM emissions (mass and number) are likely to improve as engines with technology designed for NO_X control enter the fleet (i.e. Lean Burn and advanced RQL). However, technologies to mitigate nvPM are less well understood than NO_X.
- Improvements in aircraft fuel efficiency for a given engine combustor technology generally provide a win-win situation for both fuel burn and engine emissions, as well as noise.

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[5] Non-volatile particulate matter (nvPM) refers to particles measured at the engine exit and is the basis for the regulation of engine emissions certification as defined in ICAO Annex 16 Volume II, *"emitted particles that exist at a gas turbine engine exhaust nozzle plane, that do not volatilize when heated to a temperature of 350°C"*.

[6] Lean Burn and RQL (Rich-burn, Quick-mix, Lean-Burn) combustion technologies have been developed to control NOx emissions. These combustor designs are differentiated by their different strategies for NOx control, specifically different approaches to fuel-air-mixture control through the combustor.

- Emissions indices of CO_2 (kg CO_2 / kg fuel burnt) are derived directly from fuel use estimates, or measured data, and are well understood.
- There are commercial pressures to incentivise fuel burn improvements up to the point where they cease to lower overall costs. This incentive has been reinforced by the introduction of the EASA aeroplane CO_2 certification standard
- Potential trade-offs would need to be taken into account between fuel burn/CO_2, NO_X and nvPM control technologies if more stringent standards are considered for aircraft engine emissions or aeroplane CO_2 emissions.

Operations

- The Single European Sky (SES) has various environmental performance indicators linked to the fuel efficiency / CO_2 emissions of the air traffic management system. This could be further developed to potentially consider the impact of non-CO_2 emissions and added to the route-charging concept.
- Improvements in air traffic management that result in a reduction of fuel burn / CO_2 emissions will generally reduce non-CO_2 emissions.
- Contrail avoidance by changing flight paths horizontally or vertically generally have fuel burn penalties as this involves flying longer distances or at sub-optimum altitudes.

Fuel

- International fuel standards contain limits on chemical composition requirements, but are not currently defined with environmental concerns in mind.
- Use of sustainable aviation fuels (biofuels and 'Power to Liquid') has shown a reduction in nvPM emissions in LTO and cruise due to their lower aromatic and sulphur content.
- There is scope for improving emission characteristics through the hydrotreatment of conventional fossil fuels to reduce aromatics and sulphur. However, the overall costs and energy requirements need to be examined carefully in order to balance the differential environmental benefits (e.g. reduced soot emissions and contrail climate impact but extra energy for fuel processing, and therefore increased CO_2 unless renewable energy is utilized).

TASK 3: Potential policy action to reduce non-CO_2 climate impacts

Following a review of scientific literature, and expert workshop discussions, a range of potential mitigation measures were identified to reduce the non-CO_2 climate impacts of aviation[7]. Based on various criteria in line with EU climate policy goals, the below six options were shortlisted to be considered in greater detail in terms of design, administration, incentives, caveats and constraints, and further research needs. These six options were considered representative of similar considerations and details exhibited by an original longer list of options.

Type of Measure			Main non-CO_2 effect(s) addressed by the measure
Financial	1.	NO_X charge	NO_X
	2.	Inclusion of aircraft NO_X emissions in EU ETS	NO_X
Fuel	3.	Reduction in maximum limit of aromatics within fuel specifications	Soot particulates and contrail-cirrus
	4.	Mandatory use of Sustainable Aviation Fuels (SAF)	Soot particulates and contrail-cirrus
ATM	5.	Avoidance of ice-supersaturated areas	Contrail-cirrus
	6.	A climate charge	All (NO_X, water vapour, soot, sulphates, contrails)

1. NO_X charge

- This measure is defined as a monetary charge on the total NO_X emissions over an entire flight, approximated by certified Landing Take-Off (LTO) NO_X emissions data, the distance flown and a factor accounting for the relation between LTO and cruise emissions.
- A legal analysis from 2009 suggested that neither ICAO's Chicago Convention nor ICAO's recommended policies on taxes and charges should prevent the implementation of such a measure.
- This option would incentivise engine manufacturers to reduce LTO NO_X emissions during their engine design process, and airlines to minimise NO_X emissions in operation, while taking into account associated trade-offs.
- Further research would be needed in these key areas:
    - Under certain future scenarios of declining emissions of tropospheric ozone precursors from surface sources, combined with increasing aviation emissions, aviation NO_X may lead to a net negative climate forcing (i.e. cooling). As such, there

[7] These options would be in addition to those already in place, such as the aircraft engine NO_X and nvPM emissions standard and airport NO_X charging schemes.

is a need to monitor the scientific understanding of this issue as it further evolves over time.

  - Existing analytical methods, such as the Boeing fuel flow method (BFF2) and the DLR fuel flow method, have been used in the past to estimate cruise NO_X emissions based on LTO NO_X data. However, the robustness of these methods when applied to recent technological developments, such as lean burn staged combustion, is still being assessed and the methods may need to be updated. Research to develop and agree on an accurate, internationally recognised methodology for estimating cruise NO_X emissions will be important for the implementation of this measure.
  - In order to compare the climate change impact of NO_X emissions to CO_2 emissions, an appropriate CO_2 equivalent emissions metric and time horizon would need to be agreed politically. In doing so, it is important to ensure that the trade-off between NO_X and CO_2 emissions in engine design does not result in unintended consequences and a resulting net warming effect.
  - The level of the charge should reflect the climate damage costs of aircraft NO_x emissions. Using the aforementioned metric, these costs could be related to the damage costs of CO_2, which are an on-going point of discussion.
- The necessary legislation and implementation of this option would need to be considered within the context of the regulatory framework of the Single European Sky Performance and Charging Scheme[8], as well as other financial policy options (including those already in place).
- If the outstanding research issues linked to this measure are addressed, and there is the political will to take the option forward, then the measure could potentially be implemented in the mid-term (5 to 8 years)[9].

2. Inclusion of aircraft NO_X emissions in EU ETS

- The EU Emissions Trading System (ETS) is a 'cap and trade' scheme in which emission allowances for CO_2 emissions are traded among incumbent operators in a number of different sectors, including aviation. The system allows opt-ins for emissions of N_2O and PFCs for stationary installations.
- This measure would see the extension of the scope of the EU ETS by incorporating aviation NO_X emissions.
- As the EU ETS legislation uses the CO_2 equivalent emissions metric 'GWP100' to convert other greenhouse gases to CO_2 equivalents, it is assumed that including aircraft NO_X into EU ETS would also require using GWP100.
- This option would incentivise engine manufacturers to reduce NO_X emissions during their engine design process, and airlines to minimise NO_X emissions in operation, while taking into account associated trade-offs.
- Further research would be needed on the same issues as the '*NO_X charge*' measure.

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[8] COMMISSION IMPLEMENTING REGULATION (EU) 2019/317 of 11 February 2019 laying down a performance and charging scheme in the single European sky and repealing Implementing Regulations (EU) No 390/2013 and (EU) No 391/2013.

[9] Rough estimates of timescales to implement policy options have been provided, but are dependent on addressing the identified research needs and the political will to take the options forward. For the purpose of this study, short-term is defined as 2-5 years, mid-term as 5-8 years and long-term as 8+ years.

- In contrast to other measures outlined in this report, this measure could be implemented by adjusting existing ETS legislation and building on existing administrative processes and precedents (e.g. monitoring, reporting, verification and accreditation - MRVA; baseline; cap and auctioned allowances).
- The same EU ETS geographical scope for aviation could be applied to NO_X as that for CO_2 emissions.
- The uncertainty about the climate impact of NO_X, and the potential unintended consequences, introduces a political risk for the integrity of the EU ETS which needs to be taken into account when considering it as an opt-in non-CO_2 gas in the EU ETS. In this sense, the measure differs from the '*NOx charge*'.
- If the outstanding research issues linked to this measure are addressed, and there is the political will to take the option forward, then the measure could potentially be implemented in the mid-term (5 to 8 years).

3. Reduction in maximum limit of aromatics within fuel specifications

- This measure would entail reducing the maximum volume concentration of aromatics within fuel uplifted at European airports.
- Lower aromatics in fuels provide a cleaner burn and reduced non-volatile Particulate Matter (nvPM) emissions, which are directly linked to contrail cirrus formation and radiative properties. In addition, the reduction in aromatics improves the energy density of the fuel, which reduces the mass of fuel needed for a specific flight and results in a small reduction in overall fuel burn / CO_2 emissions (approx. 1%).
- The aromatics concentration could be reduced through blending certain sustainable aviation fuels (SAF) with conventional Jet A-1 fuel, through hydro-treatment of Jet A-1 fuel or through changes in production processes by refineries.
- Jet A-1 fuel is the most commonly used aviation fuel in the world. Its fuel specifications are managed through the four main standardisation committees, including US ASTM (D1655) and UK DEF STAN (91-091). Engagement with these committees to discuss the climate benefits of low aromatic fuels will be crucial.
- This measure would require fuel producers to adapt their production processes to meet the new standard, which may result in higher CO_2 emissions in refineries.
- Further research would be needed in these key areas:
    - The scientific understanding of the contribution of nvPM to the formation of contrail cirrus is evolving, but confidence level in the magnitude of the net positive climate forcing effect (i.e. warming) is low. As such, there is a need to monitor the scientific understanding of this issue as it further develops over time.
    - A cost-effectiveness assessment is needed to assess options for reducing the aromatics limit. While the maximum volume concentration of aromatics is 25 volume percent, the actual content in Jet A-1 fuel currently used within the aviation sector is not well known. Studies have revealed that it can vary extensively. As such, the specifications of fuels being used in Europe will need to be monitored in order to be able to assess the impact of a reduced maximum limit of aromatics.
    - Special consideration will need to be given to the effect on military aircraft, which can be relatively old compared to commercial aircraft, and the use of lower aromatics fuels may have airworthiness consequences for parts of the engine (e.g. rubber seals) where the fuel supply is shared. For this reason, ASTM and DEF STAN

are currently considering an 8% minimum aromatics limit for fossil based fuels, though this is currently just guidance.
    - A system to monitor the aromatics content of fuels used in the aviation sector would need to be set up to ensure that the policy delivers the anticipated benefits.
- Existing fuel specification committees use a consensus-driven, technical approach. While a legally imposed EU standard would ensure a specific outcome, it would disrupt the current global approach to managing fuel quality standards.
- An alternative option to this measure could be an incentive for the sale of fuel with low aromatics.
- If the outstanding research issues linked to this measure are addressed, and there is the political will to take the option forward, then the measure could potentially be implemented in the mid- (5 to 8 years) to long- term (+8 years).

4. Mandatory use of Sustainable Aviation Fuels (SAF)

- This measure would entail the mandatory use of SAF, for instance through an EU blending mandate specifying that a certain percentage of the total Jet A-1 fuel sold in Europe over a set time period would have to be SAF.
- Within the European regulatory framework, SAF would be defined as per the criteria in the new Renewable Energy Directive (RED II) 2018/2001/EU.
- SAF typically have lower aromatic concentrations and thus the same benefits as summarised in the '*Reduction in maximum limit of aromatics within fuel specifications*' measure, as long as the aromatics content in the fossil part of the blend does not increase and offset the benefits. In addition, SAF also have lower lifecycle CO_2 emissions compared to conventional fossil based fuels and lower sulphur content resulting in lower SO_4 emissions.
- This measure would incentivise the use of SAF in the single market by providing certainty to SAF producers and an impetus to up-scale their production and benefit from economies of scale. It may also increase airline operational costs, depending on the size of the mandate and subsequent supply-side response from the SAF market.
- Further research would be needed in these key areas:
    - Blending mandates have already been introduced or announced in individual European states. A cost-benefit assessment would be needed to inform a decision on the level of an EU blending mandate. This assessment would need to consider realistic yet ambitious levels, the impact on stakeholders and potential implementation processes (e.g. a dynamic blending mandate that increases over time in order to provide certainty to the market for long-term investments).
    - As per option (3), a system to monitor the characteristics of SAF being used in operation within Europe would be needed to ensure compliance with the mandate and provide valuable oversight on the environmental benefits from this measure.
- A 'control point' will need to be identified (e.g. blending location), where the total SAF going to the aviation sector in Europe can be identified and hence compliance with the blending mandate can be monitored. This could build on existing legislation (e.g. RED II, FQD).

- The mandating of SAF results could be considered as a holistic approach with simultaneous reductions in CO_2, nvPM and sulphur emissions, although it does not address NO_x emissions.
- If the outstanding research issues linked to this measure are resolved, and there is the political will to take the option forward, then the measure could potentially be implemented in the short- (2 to 5 years) to mid- term (5 to 8 years).

5. Avoidance of ice-supersaturated areas

- This measure involves optimizing flight trajectories to avoid climate-sensitive regions, such as ice-supersaturated areas, in order to reduce the climate impact of aviation. This can be considered a potential first step towards full optimisation of flight profiles for climate impacts.
- Contrails are largely formed in ice-supersaturated and low-temperature areas, and thus avoiding these regions reduces contrail cirrus occurrence that have a net positive radiative forcing effect (i.e. warming).
- Prior to a flight plan being filed, Air Navigation Service Providers (ANSPs) and airline operators would need to have all the relevant information (e.g. temperature, humidity) in order to identify the ice-supersaturated areas. The route network would also have to be designed to allow such deviations based on this pre-flight tactical planning.
- Further research would be needed in these key areas:
    - A pilot project involving ANSPs, ICAO, meteorological institutes and airlines operating over the Atlantic would be needed to assess the feasibility and benefits of this measure. This should include the effect of such a measure on existing Single European Sky operational initiatives such as Free Route Airspace. Implementation over mainland European airspace would be a challenge as this region already faces capacity constraints during daily peak periods.
    - Flight detours (horizontal and vertical) to avoid ice-supersaturated areas are likely to have an impact on airlines in terms of costs, and will also lead to trade-offs with regard to fuel burn and emissions (e.g. CO_2 and NO_X). An appropriate CO_2 equivalent emissions metric that permits a comparison between the climate change impact of contrail-cirrus and other aviation emissions will be required to determine the maximum detour that still ensures an overall reduction in climate impact from a flight.
    - Most of the contrail cirrus forcing that results in significant warming is believed to be due to a few large-scale events. It would therefore be advisable to 'target' flights that impact these events, rather than all flights. Identification of these few large-scale events should be a topic of further research as meteorological forecast models presently have only limited capability to predict persistent contrails correctly in time and space.
- Demonstration and communication on the environmental benefits would be needed, as well as potentially additional incentives, to ensure buy-in from stakeholders.
- If the outstanding research issues are addressed, including positive results from a pilot-phase project in the short-term, and there is the political will to take the option forward, then the measure could potentially be implemented in a more complete form in the mid-term (5-8 years).

6. A climate charge

- The concept of this policy measure is to levy a charge on the full climate impact of each individual flight. This makes it both the measure with the broadest coverage and the one that is likely to be the most complicated to implement.
- The introduction of a charge requires a good estimate of the climate costs at a flight level. Currently, there is no scientific consensus on the methodology to calculate these costs.
- It could be argued that a levy that aims to internalise the external costs would be considered a charge and not a tax. In this case, the charge would be related to recover the external costs of the climate impact of aviation
- Further research would be needed on the same issues as the '*Avoidance of ice-supersaturated areas*' measure, but with a larger geographical scope and including the level of the charge to be set for the climate damage costs of CO_2, which is an on-going point of discussion.
- The necessary legislation and implementation of this option will need to be considered within the context of the regulatory framework of the Single European Sky Performance and Charging Scheme[10].
- Significant more research is needed to develop and define this measure. If there is the political will to take this forward, then the measure could potentially be implemented in the long-term (+8 years).

[10] COMMISSION IMPLEMENTING REGULATION (EU) 2019/317 of 11 February 2019 laying down a performance and charging scheme in the single European sky and repealing Implementing Regulations (EU) No 390/2013 and (EU) No 391/2013.

CONCLUDING REMARKS

The latest scientific understanding on the climate change effects of non-CO_2 emissions from aviation activities has advanced over the last 10 years. While uncertainties remain with regard to these impacts, and how to assess them in terms of CO_2 equivalent emissions metrics, there are a range of policy options with associated pros and cons that the European Commission could evaluate. Specific research issues, which are identified this report, would need to be addressed in order to take these options forward.

[placeholder for aviation-related illustration]

1. INTRODUCTION

In order to achieve the Paris Agreement global temperature goals, it is recognised that the aviation sector will need to provide a contribution to reductions in Greenhouse Gas (GHG) emissions. In this respect, in addition to the actions aimed at reducing or mitigating the climate change impact from CO_2, measures to address non-CO_2 climate effects (e.g. NO_x, SO_2, sulphate aerosols and soot particles) need to be investigated.

There have been several requests by the co-legislators, particularly the European Parliament, for aviation's non-CO_2 emissions to be scrutinised and possibly addressed through policy/legislative means. In 2006, the Impact Assessment for the EU ETS Directive analysed the possibility of also regulating NO_x, and this was subsequently followed up in 2008 by a DG MOVE study '*Lower NO_x at Higher Altitudes: Policies to Reduce the Climate Impact of Aviation NO_x Emission*'.

At that time, scientific understanding of the impact of NO_X emissions was not considered to be sufficiently mature to indicate a clear course of action from a policy perspective. There have been many scientific developments over the last decade and consequently the co-legislators provided the following mandate within Article 30(4) of the revised EU ETS Directive[11] in 2018:

> *'Before 1 January 2020, the Commission shall present an updated analysis of the non-CO_2 effects of aviation, accompanied, where appropriate, by a proposal on how best to address those effects.'*

In response to this mandate, DG MOVE and DG CLIMA initiated discussions with EASA during spring 2019 to perform this analysis. The tasks specifications (Appendix 1) included three main elements:

Task 1: What is the most recent knowledge on the climate change effects of non-CO_2 emissions from aviation activities?

- 1A. Which metric and time horizon may be used to measure these effects?
- 1B. What is the level of scientific understanding of these effects and what are the related uncertainties?

Task 2: What factors/variables have had an impact on these effects (e.g. technology / design, operations, fuel, market based measures)? What is the level of that impact? Do these factors/variables exhibit trade-offs or interdependencies between different emissions?

Task 3: What research has been undertaken on potential policy action to reduce non-CO_2 climate impacts? What are the pros and cons of these options in terms of implementation? What knowledge gaps exist?

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[11] Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2915/1814

In order to meet the ambitious timescales of an interim report in December 2019 and a final report by April 2020, significant outreach was made to key European experts in this field, and provisional telecons / meetings agreed (Appendix 2), in order to secure their participation and availability prior to the start of the contract in August 2019.

An initial project team meeting was held on Tuesday 17 September 2019 at the EASA offices in Brussels, with the objective of taking forward discussions on all three tasks and development of the overall project schedule.

As per the task specifications, it was agreed to hold a workshop on Tasks 1 and 2 on Wednesday 20th November at the EASA office in Brussels with a wider group of experts covering different perspectives within the scientific community. Initial thoughts on the three tasks were provided by the project team in order to place the project in context and stimulate an interactive discussion. The output from this workshop was subsequently taken into account when developing the Interim Report that was completed on Friday 9th December 2019 (Appendix 3).

The Interim Report provided an overview of the work done up to that point, and the evolving views based on these initial discussions. It also provided an indication of the future work to finalise the report, including the shortlisted potential policy options to be considered in more detail under Task 3.

A further project team meeting was held on Wednesday 20th February 2020 to discuss the Task 3 policy options, and an additional workshop focused on Task 3 was organised on Thursday 12th March to obtain feedback from experts in the relevant fields. The presentations and output from this workshop (Appendix 4) fed into this Final Report that was delivered on Friday 3rd April.

[placeholder for aviation-related illustration]

2. TASK 1: Aviation Non-CO_2 Impacts – Current status of science and remaining uncertainties

2.1 Aviation emissions in context

The climate impact of aviation emissions has been recognized for many years with the Intergovernmental Panel on Climate Change's (IPCC, 1999) Special Report 'Aviation and the Global Atmosphere' being a landmark. This IPCC report highlighted aviation's impacts on climate using the metric 'radiative forcing of climate[12]' through its CO_2 and a range of non-CO_2 impacts. Updated assessments since then have been published by Sausen et al. (2005) and Lee et al. (2009; L09), and a further update has recently been published (Lee et al., 2020; L20 – see Appendix 5). Aviation's non-CO_2 emissions of importance to climate include water vapour, SO_2, soot particles, and oxides of nitrogen (NO_x, where $NO_x = NO + NO_2$).

The main climate forcing agents from aviation emissions include:

Emissions of carbon dioxide (CO_2) from civil aviation in 2018 represented around 2.4% of annual CO_2 emissions from total global fossil fuel emissions and land-use change emissions using data from the International Energy Agency and Le Quéré et al. (2018). The cumulative amount of emissions of CO_2 is more important than any given year's emissions (IPCC, 2013). Aviation's long-term cumulative emissions between 1940 and 2018 amount to ~33 billion (10^9) tonnes (IEA and other data, L20), of which ~9.5 billion tonnes have been emitted since 2005 (29%).

Emissions of water vapour (H_2O) have a well-quantified emission index (g H_2O/kg fuel burnt) for current fossil-fuel based kerosene, so can be easily calculated if the fuel burn is reliably known. The direct climate effect of water vapour is relatively small for the current subsonic fleet at current cruise altitudes[13] (2.8 mW m^{-2} of a total aviation signal of 78 mW m^{-2}, see Figure 2), but emitted water vapour plays an important role in the initial formation of contrails (see section 2.2).

Emissions of oxides of nitrogen (NO_x) from current-day subsonic civil aviation result in (i) the formation of ozone (O_3, a greenhouse gas) in the upper troposphere and lower stratosphere, where today's fleet of subsonic aircraft cruise, and (ii) the destruction of a small amount of ambient methane, another greenhouse gas, originating largely from natural, agricultural, waste and industrial sources[14]. The emission of NO_x from global aviation is estimated to be around 1.4 Tg N yr^{-1}, compared with around 42 Tg N yr^{-1} from surface anthropogenic sources[15]. While aviation emissions appear to be a small fraction of total

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[12] A change in the Earth-atmosphere's radiation budget caused by the accumulated emissions/effects since 1750, measured in watts per square metre (W m^{-2}), see section 2.2.1.

[13] Emissions of water vapour from potential supersonic aircraft have a larger effect as water vapour is emitted directly into the dry stratosphere, which has a strong warming impact (IPCC, 1999; Grewe et al., 2010).

[14] See section 2.2 for a more detailed explanation of aviation's climate impacts.

[15] There are other natural sources of NO_x from lightning (6 Tg N yr^{-1}), soil emissions (4 – 5 Tg N yr^{-1}), natural fires (4 – 5 Tg N yr^{-1}) stratospheric decomposition of N_2O (<1 Tg N yr^{-1}).

emissions, they have a larger specific radiative forcing (W/m^2 per unit emission) than surface sources of NO_x. Aviation NO_x emissions are relatively well quantified compared with other anthropogenic and natural sources, although there are uncertainties regarding scaling of ground-level to cruise altitude emission indices for some modern engine types (see section 3.4.3).

Emissions of sulphur dioxide (SO_2) are the result of the combustion of kerosene whose composition includes hydrocarbons containing sulphur (S). Most of the S is emitted as gaseous sulphur dioxide (SO_2), but a small fraction of about 5% is fully oxidised within the engine to form gaseous sulphuric acid (H_2SO_4), which subsequently condenses on the surfaces of other ambient or soot particles. The larger fraction of emitted SO_2 goes on to form condensed particles as sulphate in the plume and ambient atmosphere. The fuel S content can be easily measured and has a regulatory limit of 3,000 parts per million by volume (ppm by mass). In practice, S is thought to be present in fuel at levels averaging ~600 – 800 ppm(m) (Miller et al., 2010), but data are not readily available. The global emissions of S from aircraft are estimated to be small at ~0.2 Tg S yr^{-1} (compared with surface anthropogenic sources of ~53 Tg S yr^{-1}).

Emissions of soot particles from aircraft are largely the result of incomplete combustion of fuel from the aromatic and naphthalene content (Ebbinghaus and Wiesen, 2001). Soot particles are present in large number concentrations in the initial plume (milli-seconds to seconds) and, under certain ambient conditions of ambient temperature and water vapour, they play a role in the formation of contrails (see section 2.2). The global emissions from aviation are estimated to be ~0.01 Tg (range 0.001 to 0.02 Tg y^{-1}) soot particles yr^{-1} compared with surface anthropogenic sources of around 4.8 Tg (range 3.6 to 6.0) soot particles yr^{-1} (IPCC, 2013). Emissions of soot particles during the landing and takeoff cycle are becoming better understood through the engine type certification process (see section 3.3) although emissions at cruise conditions are poorly quantified as emissions indices (mg soot particles per kg fuel burnt) for soot particulate mass and number can vary according to the particular combustor design in the engine type. In addition, high-quality reference data are not publicly available, and the scaling from ground-level to cruise-level emission indices is not well quantified (see section 3.4.3).

Key points from 2.1:

- Aviation emissions of NO_x are relatively well quantified and amount to ~1.4 Tg N yr-1 in 2018 or ~3% of anthropogenic sources.
- Emissions of SO_2 are not well quantified because of poor availability of fuel sulphur content data, but are likely to be below 0.2 Tg S or 0.4% of global sulphur emissions.
- Soot particle number and mass emissions for individual current aircraft are not as well quantified[16] as NO_x LTO emissions and poorly quantified for cruise conditions. The fleet emissions are thought to be ~0.01 Tg or some 0.2% of global anthropogenic emissions.
- Despite relatively low emissions compared to other sources, aviation emissions in relatively clean parts of the atmosphere can have a disproportionally large impact.

[16] It should be noted that the ICAO Engine Emissions Databank is expected to be populated with certified nvPM mass concentration data by the end of 2020.

2.2 The effects of aviation on climate

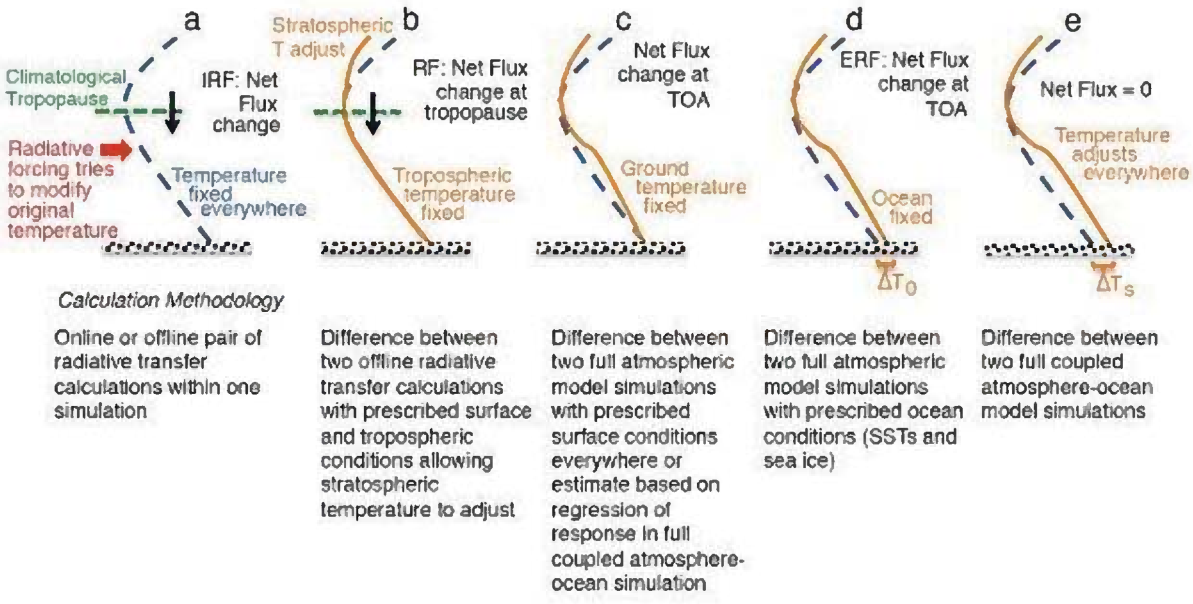
2.2.1 Radiative forcing of climate

The metric '*radiative forcing*' (RF) of climate has been used by the scientific community and the IPCC for many years as a useful proxy for expected global mean surface temperature change. This is because there is an approximately linear relationship between the RF (watts per square metre W m^{-2}) since the onset of industrialization that is taken to be 1750, and the expected equilibrium change in global mean surface temperature (ΔT_s in kelvin), with the climate sensitivity parameter[17] (λ, in kelvin per Wm^{-2}) as the multiplying factor, i.e.:

$$\Delta T_s = \lambda \ RF \qquad [1]$$

There are a number of definitions of RF. In its simplest form, it is the instantaneous change in total irradiation (incoming short wave solar radiation minus the outgoing long wave terrestrial radiation) at the top of the atmosphere since 1750 due to a climate forcing mechanism with everything else being fixed. For most climate forcers, a better definition is the '*stratosphere-adjusted radiative forcing*', in which the stratosphere is allowed to reach a new radiative equilibrium upon the introduction of a climate forcing agent while other climate variables are held constant. The stratosphere-adjusted RF allows a better approximation of the linear relationship in [1].

More recently, there has been a shift away from RF, particularly for forcing agents that are either horizontally or vertically inhomogeneously distributed, such as aerosols, contrails or aviation-induced ozone. The metric '*effective radiative forcing*' (ERF) was introduced by the IPCC (2013) in their Fifth Assessment Report as it is a better predictor of the equilibrium change in global mean surface temperature to a forcing, by accounting for rapid adjustments in the atmosphere (e.g. thermal structure of the atmosphere, clouds, aerosols etc.) but maintaining sea surface temperatures constant. This is illustrated as case (d) in Figure 1 (IPCC, 2013).



[17] Climate sensitivity is the change in surface air temperature per unit change in radiative forcing, and the **climate sensitivity parameter** is therefore expressed in units of $K/(W/m^2)$

Figure 1. Schema comparing (a) instantaneous RF, (b) RF, which allows stratospheric temperature to adjust, (c) flux change when the surface temperature is fixed over the whole Earth (a method of calculating ERF), (d) the ERF calculated allowing atmospheric and land temperature to adjust while ocean conditions are fixed and (e) the equilibrium response to the climate forcing agent. The methodology for calculation of each type of forcing is also outlined. ΔT_o represents the land temperature response, while ΔT_s is the full surface temperature response. (Updated from Hansen et al., 2005.) From AR5 WG1, Chapter 8, Figure 8.1 (Myhre et al., 2013).

The ERF is relevant to aviation non-CO_2 effects as potentially significant differences exist for the net-NO_X effect through responses to ozone and methane atmospheric chemistry (estimates of ERF > RF, Ponater et al., 2005) and contrails (estimates of ERF < RF, Bickel et al., 2019; Ponater et al., 2006; Rap et al., 2010[18]). In all cases, it is emphasised that the nature of RF, in any form, is 'backward looking' and informs on the current perturbation of the radiation budget from historical and current-day emissions. It does not inform on potential future changes, nor does it directly provide any emission equivalence on the climate impact of CO_2 and non-CO_2 emissions. As such, RF or ERF are of relevant for understanding science, but are unsuited for direct use in policy or regulation that considers emissions equivalency.

2.2.2 Aviation radiative effects

Aviation emissions have a number of radiative effects. These are summarized in the bullet points below and described in more detail in following sub-sections, illustrated by the latest available assessment of Lee et al. (2020) using the ERF metric, shown in Figure 2.

- **CO_2** – a positive RF (warming effect) as a long-lived greenhouse gas (LLGHG) that is a direct result of burning fossil fuel kerosene.
- **Water vapour** – a positive RF (warming effect) as a short-lived climate forcer (SLCF) that is a direct result of burning fossil fuel kerosene.
- **Sulphate particles** – a negative direct RF (cooling effect).
- **Soot particles** – a positive direct RF (warming effect).
- **NO_x** – a net positive RF (warming effect). Net effect is the sum of the rapid formation of ozone (warming effect), the slower destruction of ambient methane CH_4 (cooling effect), and the indirect effects on stratospheric water vapour and long-term background ozone (cooling effect). There are less well quantified effects on aerosols.
- **Contrails and contrail cirrus** – a net positive RF (warming) from the formation of linear contrails and their spreading into contrail cirrus clouds.
- **Aerosol-cloud interactions from soot, sulphate, and nitrate** – the indirect effect on high altitude ice cloud formation has an RF effect of uncertain sign and magnitude, and likely a negative RF (cooling) from lower level warm clouds (no best estimate included in Figure 2).

[18] Ponater et al., 2006 and Rap et al., 2010 estimated the climate 'efficacy' of forcings (Hansen et al., 2005), which to a first order can be multiplied by the RF to obtain an ERF.

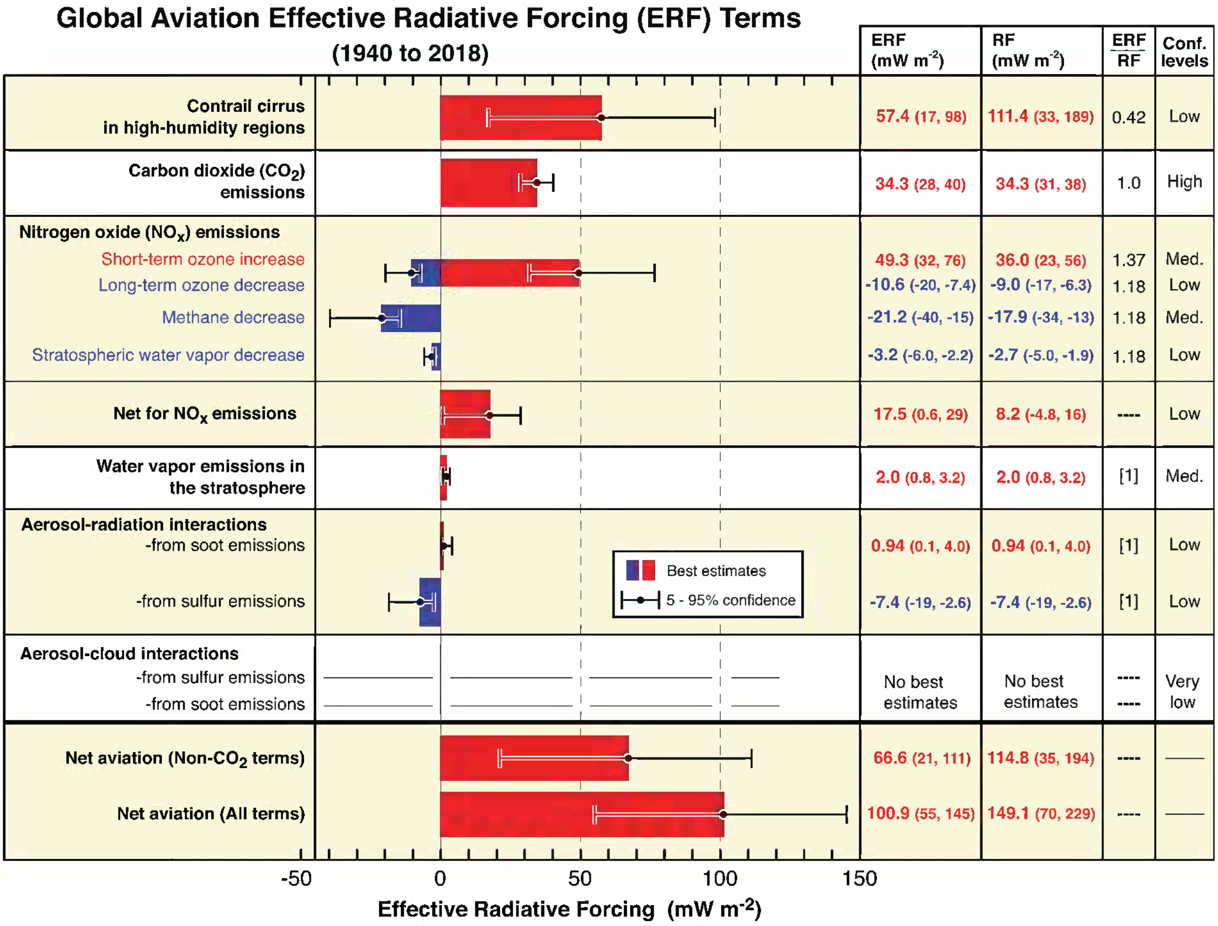


Figure 2. Best-estimates for climate forcing terms from global aviation from 1940 to 2018. The bars and whiskers show ERF best estimates[19] and the 5–95% confidence intervals, respectively. Red bars indicate warming terms and blue bars indicate cooling terms. Numerical ERF and RF values are given in the columns with 5–95% confidence intervals along with ERF/RF ratios and confidence levels. RF values are multiplied by the respective ERF/RF ratio to yield ERF values. ERF/RF values designated as [1] indicate that no estimate is available yet.. Taken from Lee et al. (2020).

The two largest quantifiable non-CO_2 effects, which have much shorter atmospheric timescales than CO_2, are the net NO_x effect and contrail cirrus. In addition, aerosol-cloud interactions represent potentially large effects although there are no consensus best estimates of these effects. These are all described in a little more detail below.

NO_X Emissions result in the production of ozone (O_3) through gas-phase chemistry in the upper troposphere and lower stratosphere (a positive RF – warming effect) with impacts on timescales of weeks and the destruction of ambient CH_4 (a negative RF – cooling effect) with impacts on timescales of decades, with a net positive balance of warming for current day conditions. These effects are well known, and many studies have confirmed this over the last 20 years.

[19] Best estimate is used to express a value to which 95% uncertainty intervals can be attributed, which is the range of values for which there is a 95% likelihood of covering the true value that is being estimated. A best estimate can be a median or a mean, depending on the distribution assumed.

During the last 10 years, additional secondary effects associated with the NO_x effects on CH_4 have been quantified, including the decrease in stratospheric water vapour resulting from decreased CH_4 abundance[20] (Myhre et al., 2011), and a decrease in the long-term background O_3 in the troposphere from reduced background CH_4 (Holmes et al., 2011). These additional effects have contributed to a decrease in current estimates of the net positive RF (warming effect) from NO_x.

Another recent development has been the reformulation of the basic CH_4 forcing according to Etminan et al. (2016), who showed that the 1750 – 2011 RF is about 25% greater than estimated in the IPCC (2013) AR5 assessment by inclusion of the shortwave forcing. For aviation, this means that the cooling impact of CH_4 reduction from aircraft NO_x is stronger (greater negative RF).

A recent study (Grewe et al., 2019) indicates that a more advanced consideration of the longer lifetime of the methane effect, and a more accurate attribution of the aviation NO_x emissions using the so-called 'tagging' technique to the abundance of short-term O_3, results in a smaller cooling from methane and a larger warming from ozone, which both increase the net warming from aircraft NO_x emissions. The reduction in the CH_4 effect is somewhat offset by a revised formulation of the forcing of CH_4 by Etminan et al. (2016). The net effect is to increase the net NO_x forcing by ~71%, including the revised formulation and steady-state of CH4 with a further increase of a factor of 1.26 of the net NO_x forcing. Both the reformulation of the CH_4 forcing of Etminan et al. (2016) and the steady-state to equilibrium correction were included in the net NO_x assessment of Lee et al. (2020), shown in Figure 2. The assessment of Grewe et al. (2019) does not include any consideration of the ERF, which may increase the net NO_x forcing effect further (Lee et al., 2020).

The net-NO_x effect of aviation is the result of highly non-linear atmospheric chemistry and is also inextricably linked to the state of the background atmosphere. Thus, the net NO_x climate effect from aviation emissions is dependent on background conditions. In other words, the magnitude of the aviation net NO_x effect can be different for the same magnitude of aviation emissions due to different magnitudes of background concentrations from precursor emissions emitted by other sources. Under future emission scenarios of declining emissions of tropospheric ozone precursors, including CH_4 (e.g. RCP4.5) from surface sources, combined with "business as usual" increasing aviation emissions, a net negative RF (cooling) of aviation NO_x may result (Skowron et al., 2020; Hauglustaine, pers. comm., 2020). However, it should also be recalled that for current day conditions, the net-NO_x forcing is positive, (i.e. warming) by somewhere between ~15 to 30 mW m^{-2}.

Contrail and contrail-cirrus modelling of radiative effects have improved markedly over recent years with incorporation of process-based modelling into regional and global models (Burkhardt and Kärcher, 2011; Chen and Gettelman, 2013; Schumann et al., 2015). Contrails predominately cool[21] if the zenith angle is large, i.e. the sun is close to the horizon, and they

[20] The principal destruction route of CH_4 in the atmosphere is by reaction with OH, producing CO_2 and water vapour. In the naturally dry stratosphere, the water vapour product of CH_4 destruction, is a positive RF, so that any reduction in CH_4 in the atmosphere (e.g. from aviation NO_x emissions, resulting in OH production) represents a secondary cooling effect from the aviation NO_x reduction of CH_4.

[21] 'Cooling' in terms of a negative radiative forcing from contrails often depends on where it is specified; at the surface, the top of the atmosphere (~50 km) or top of the troposphere (~12 km).

warm if the zenith angle is small, i.e. the sun is high in the sky. However, contrails exclusively warm at night by reducing the outgoing infra-red radiation flux, thereby resulting in a net positive (warming) RF (Meerkötter et al., 1999). More recently, it has been observed that air traffic appears to increase the optical thickness of pre-existing cirrus clouds, which would likely be a net cooling effect (Tesche et al., 2016). A normalized figure of the radiative forcing by contrails and contrail-cirrus was estimated by the IPCC (2013) to be 50 mW m^{-2} (90% uncertainty range, 20 to 150 mWm^{-2}) for 2011.

Contrail and contrail cirrus process models show a dependence of RF on soot particle number emissions, to varying degrees. As such, a decrease in soot particle number emissions reduces the number of ice particles formed, increases the mean crystal size, reduces contrail lifetime and reduces optical depth. Consequently this leads to a net reduction in the positive RF warming effect (Bier and Burkhardt, 2019). However, the reduction in the associated RF is less than that of the decrease in soot particles, e.g. a ~50% reduction of the initial ice particles (formed on emitted soot) results in a ~20% reduction of the positive RF. In addition, when estimating the impact of contrail cirrus on surface temperatures it is important to switch to the ERF metric (Ponater et al., 2005; Rap et al., 2010, Bickel et al., 2019) which is reduced relative to the RF estimates by ~50% or more. Bickel et al. (2019) showed that the largest factor at play reducing the forcing was the negative feedback that decreased natural clouds as contrail cirrus dehydrates the surrounding atmosphere, as earlier observed in the model simulations of Burkhardt and Kärcher (2011).

There are several elements to the forcings shown in Figure 2 that will be updated in the new assessment of aviation ERF (see Appendix 5). These include: accounting for increased emissions from the baseline year of 2005 to 2018; reassessment of direct radiative effects of particles and water vapour; inclusion of the secondary negative effects of NO_x on CH_4 in the net-NO_x effect (reductions in stratospheric water vapour and long-term background ozone); updated assessment of the CH_4 RF term from Etminan et al. (2016); updated assessment of a combined linear contrail plus contrail cirrus effect; depiction of the indirect aerosol-cloud interactions and accounting for ERFs vs RF of net-NO_x and contrail-cirrus terms.

Aerosol-cloud interactions. The indirect radiative effects of S, N and soot are potentially large, relative to the effects of other aviation emissions, but current estimates are highly uncertain. The radiative effect on low-level clouds is likely to be negative (cooling) and potentially of a large magnitude (tens of mW m^{-2}), relative to other aviation RF effects (Gettelman and Chen 2013; Kapadia et al., 2014; Righi et al., 2013). The radiative indirect effect of soot on upper tropospheric (cirrus) clouds has been estimated to potentially be relatively very large (hundreds of mW m^{-2}), but current estimates range from negative, to near zero, through to positive values (Gettelman and Chen, 2013; Pitari et al., 2015; Zhou et al., 2014; Zhou and Penner, 2014; Penner et al., 2018) by approximately -350 to +210 mW m^{-2} in this literature. The ranges of potential forcings for aerosol cloud interactions was examined by Lee et al. (2020) and is illustrated in that paper (see Appendix 5).

2.2.3 Uncertainties

This section considers some of the uncertainties associated with the main RF effects from aviation emissions. The principal uncertainties associated with the CO_2 ERF[22] term lies in the history of emissions and the usage of CO_2 ERF.

Aviation CO_2 emissions are well quantified from 1971 onwards through International Energy Agency (IEA) data on aviation kerosene usage. However, there is greater uncertainty (±20%) for the period 1940 to 1970, which is taken as the start of 'significant' aviation activity (Sausen and Schumann, 2000).

Estimates of the uncertainties of the net NO_x ERF of 17.5 mW m^{-2} still remain large (0.6 – 29 mW m^{-2}, for 95% confidence interval, Lee et al., 2020) because of model-to-model variability in results. This may be associated with the set-up and assumptions of models, in terms of aviation and surface emissions, or other treatments of atmospheric processes including boundary-layer schemes, convection, chemical mechanisms and large-scale meteorological processes. One of the uncertainties is the way attribution of climate impact is made to a sector or emission source. Since the chemistry is non-linear, removal of a source to determine the magnitude of its impact is not necessarily the best way to quantify this, although it is the most practical in many circumstances.

Alternative techniques are available, such as 'tagging' of NO_x molecules to sources (Grewe, 2013), or computing smaller perturbations of the source of interest, which are then linearly scaled (Myhre et al., 2011). However, there is no single method that solves this non-linear attribution problem. For example, NO_x can be 'tagged' to avoid non-linearities invoked by differencing techniques to assess the short term ozone effect (i.e. the model runs 'with' and 'without' aviation), but the CH_4 reduction has *only* been determined by differencing so far. Linear scaling of small perturbations may also lose the non-linear characteristics that the technique is attempting to capture. In terms of the ERF (cf RF) of aviation NO_x impacts, these are particularly poorly researched with only one study being available for aviation perturbations (Ponater et al., 2005).

There is considerable uncertainty with the aviation net NO_x effect for future scenarios. As the chemistry is highly non-linear, the size of the aviation RF effect varies with the associated future changes in surface emissions of ozone precursors. To put it another way, the size of the net NO_x RF effect can vary for the same aviation NO_x emissions, depending on background conditions (Skowron et al., 2020).

The principal uncertainties around the contrail cirrus effect are linked to the dependence on soot particle number emissions, the contrail optical properties, the time evolution of the contrail cirrus and the ERF (vs RF).
Indirect aerosol-cloud interaction radiative effects from soot, S, and N have very large uncertainties that preclude any best estimates. This is an important area for future research as these effects could be significant and are currently poorly understood.

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[22] CO_2 ERF uncertainties are around ±20% *cf* CO_2 RF, which are ±10% (Myhre et al., 2013).

Key points from 2.2:

- Effective radiative forcing (ERF), which takes fast adjustments to a RF into account, is an improved metric of climate change relative to RF, in that it better quantifies the relationship between forcing and a change in global mean surface equilibrium temperature response. ERF is being widely adopted across the scientific community, and notably by the IPCC.
- A number of aviation non-CO_2 emissions have an effect on climate. The largest of these effects are the forcing from the current-day net NO_x effect and contrail cirrus. However, these effects are quantified with low confidence and still subject to considerable uncertainty (see Appendix 5).
- It has been found in recent years that the net-NO_x RF has additional associated negative (cooling) terms, although the current overall net signal is still one of warming. The ERF of net-NO_x is poorly known, with only one study that allows a correction from RF to ERF. However, this change in metric may increase the climate impact by a factor of ~2. Future forcing from aircraft NO_x is not well understood as the aviation effect is greatly affected by changes in background composition of the atmosphere, potentially even to a change in sign of the effect, i.e. from warming to cooling.
- Modelling of contrail cirrus has vastly improved in recent years with incorporation of the formation process into global and regional models. Nevertheless, the uncertainties remain large (see Appendix 5). The ERF/RF of contrail cirrus has been estimated to be somewhere between 0.35 and 0.7, with a mean of 0.42.
- There are potentially large effects from the impact of soot particles on ice clouds, but the sign of the forcing is not known with confidence. There are also potentially large effects of S, N, and soot on lower-level clouds. This is likely to be a negative forcing (cooling), but there is low confidence in the magnitude. Both are important areas for future research.

2.3 CO_2 equivalent emissions metrics

The concept of **Global Warming Potentials (GWP)** was introduced in the First Assessment Report of the IPCC (IPCC, 1990) as an illustration of difficulties related to comparing the climate impacts of emissions of different gases. It was later adopted as the metric for calculating so called "CO_2-equivalent emissions" (CO_2-e) in order to provide a flexible mechanism to signatories of the United Nations Framework Convention on Climate Change (UNFCCC) to reduce their emissions of long-lived GHGs[23]. Emissions equivalence metrics were also supposed to be able to be used in policy measures such as emissions trading schemes; once again, to give flexibility to participants. The Global Warming Potential (GWP) for a time horizon of 100 years, despite much discussion and debate, has remained the metric of choice within UNFCCC and adopted within the EU. This choice is still in discussion for the implementation phase of the Paris Agreement. The calculation of GWP has

[23] More precisely, the Absolute Global Warming Potential (AGWP) is the metric for comparing emissions on a common basis, while the Global Warming Potential (GWP) is the factor for calculation of the CO_2-e of a species *i*, i.e., $GWP_i = AGWP_i / AGWP_{CO2}$.

progressively been extended to short-lived climate forcers such as NO_x, soot, sulphate, etc. and applied to aviation forcing agents (e.g. Fuglestvedt et al., 2010; Lee et al., 2010). As discussed below, there are important limitations to GWP as a metric to aggregate forcing agents with very different temporal behaviour. In the case of aviation, emissions metrics have been of interest in order to determine CO_2 emission equivalencies of its non-CO_2 forcing agents. A method to place emissions on a common scale is also needed for determining whether technological or operational trade-offs between reductions in aviation non-CO_2 SLCFs and corresponding CO_2 penalties produce net benefits or disbenefits at particular time horizons (Freeman et al., 2018).

There are many emission-equivalence metrics available to approximate non-CO_2 emissions to CO_2 emissions. There is a wealth of literature on the merits and history of emission equivalency metrics, but the assessments of Fuglestvedt et al. (2003; 2010) provide much of this background. Emission metrics were also the subject of assessment in the IPCC Fifth Assessment Report, within its Chapter 8 of WGI (Myhre et al., 2013). Here we outline some of the key points.

All metrics entail subjective user choices, such as time horizon and none are true 'equivalents' to CO_2, because of its unique behaviour[24]. The biogeochemical cycle of CO_2 gives it a unique behaviour amongst LLGHGs in that it accumulates in the atmosphere, a fraction of it for millennia (Archer and Brovkin, 2008). To illustrate the complexity of this without a 'textbook' explanation of the carbon cycle, a convenient quote may be taken from the IPCC in the Fourth Assessment Report summary of Chapter 7 of WGI (IPCC, 2007; Denman et al., 2007):

> *"Carbon dioxide cycles between the atmosphere, oceans and land biosphere. Its removal from the atmosphere involves a range of processes with different time scales. About 50% of a CO_2 increase will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% may stay in the atmosphere for many thousands of years."*

Most equivalent emissions metrics have an underlying physical basis. Figure 3, taken from the IPCC WG1 Fifth Assessment Report, Chapter 8 (Myhre et al., 2013), illustrates the definition of the two most commonly discussed and used emission metrics, the GWP and the **Global Temperature change Potential (GTP)** (Shine et al., 2005). The GWP gives the response of the climate system to a change in a non-CO_2 climate forcing agent over a selected time horizon in terms of the integrated radiative forcing (the 'absolute' or AGWP represented by the area under the red and green fields), which is divided by the same AGWP for an equal mass emission of CO_2 (area of the blue field). The GTP is the resultant change in global mean surface temperature at a given time horizon, again expressed as a dimensionless ratio to the same response (absolute GTP) from an equivalent amount of CO_2 emission. Whereas the GWP is an integrating metric, the GTP is an 'end point' metric[25]. Both

[24] "Ideally, the climate effects of the calculated CO_2 equivalent emissions should be the same regardless of the mix of components emitted. However, different components have different physical properties, and a metric that establishes equivalence with regard to one effect cannot guarantee equivalence with regard to other effects and over extended time periods." (IPCC AR5, Chapter 8).

[25] RFs are used within GTPs but they are used to calculate a temperature response, usually from a simplified climate model (SCM) and are not integrated in the same way as within the GWP.

the GWP and GTP are designed to provide a 'conversion currency' for climate forcing agents although the original intent was for LLGHGs.

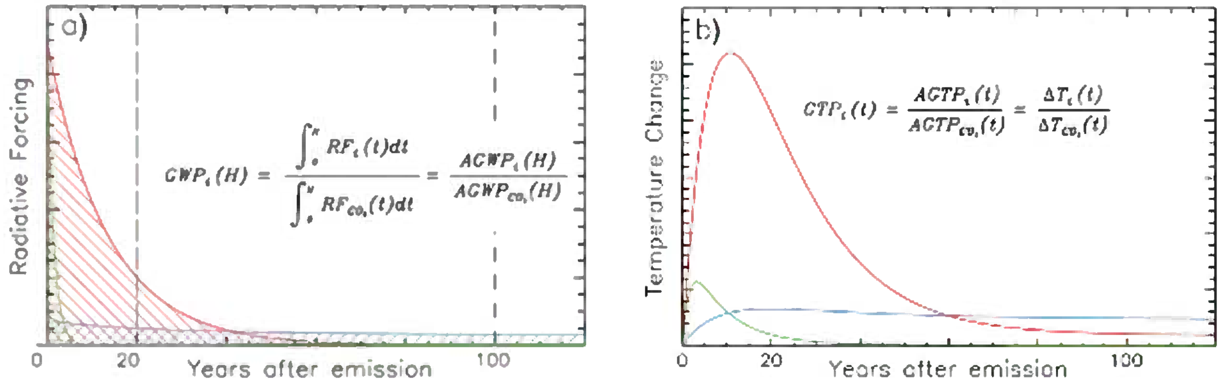

Figure 3. (a) The Absolute Global Warming Potential (AGWP) is calculated by integrating the RF due to emission pulses over a chosen time horizon; for example, 20 and 100 years (vertical lines). The GWP is the ratio of AGWP for component i over AGWP for the reference gas CO_2. The blue hatched field represents the integrated RF from a pulse of CO_2, while the green and red fields represent example gases with 1.5 and 13 years lifetimes, respectively. (b) The Global Temperature change Potential (GTP) is based on the temperature response at a selected year after pulse emission of the same gases; e.g., 20 or 100 years (vertical lines) (taken directly from Figure 8.28 of Myhre et al., 2013).

There are a range of derivative metrics from GWP and GTP that express the changes in different ways, for example:

- **ATR_H:** Average Temperature Response over a defined time horizon H (Schwartz Dallara et al. 2011; Grewe and Dahlmann, 2012), an application of GTP;
- **MGTP(H)**: Mean Global Temperature Potential = iAGTP(H)/H (Gillett and Matthews 2010);
- **iAGTP(H):** Integrated Absolute Global Temperature change Potential (Peters et al. 2011);
- **GWP*:** An alternative usage of GWP that equates an increase in the emission rate of an SLCF with a one-off "pulse" emission of CO_2. (Allen et al., 2018; Cain et al., 2019).

It is possible to formulate regional metrics, based on the AGTP, that provide additional insight into the geographical distribution of temperature change beyond that available from traditional global metrics (Lund et al., 2017). In addition, there are a number of other metrics that overlay an economic dimension to the physically based metrics, for example the Global Cost Potential, Global Damage Potential, Global cost Effective Damage Potential (Manne and Richels, 2001; Fuglestvedt et al., 2003; Johannson, 2012).

The integrative nature of GWP causes particular issues when used for comparing short-lived climate forcers (such as aviation non-CO_2 impacts) with CO_2, as it maintains an 'artificial memory' (due to the integration) and hence indicates a larger importance of short-lived climate forcers than is 'felt' by the climate system in terms of temperature (Fuglestvedt et al., 2010). Put another way, for a pulse of a short lived climate forcer (SLCF), the climate system has forgotten most of this input after about 20 – 30 years (roughly approximating to the thermal equilibrium time of the surface ocean, although the deeper ocean has a longer but smaller response (Boucher and Reddy, 2008). The time-variant nature of the GWP is illustrated in Figure 4 for the simple case of CH_4 emissions (not aviation-related), again taken from the IPCC Fifth Assessment Report, Chapter 8 (Myhre et al., 2013).

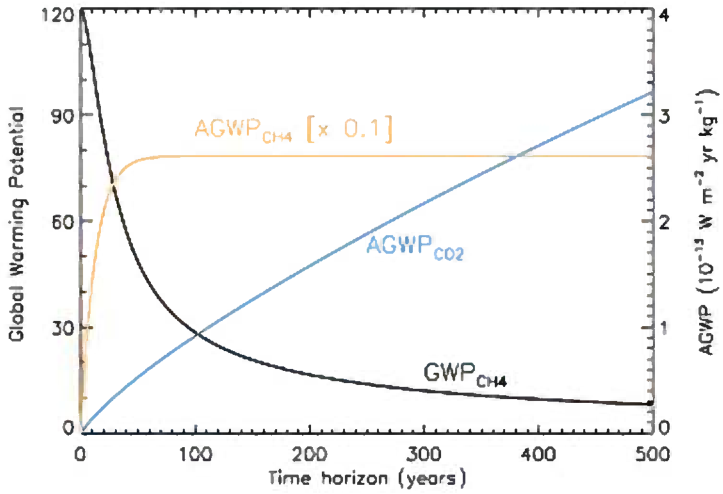

Figure 4. Development of AGWP-CO_2, AGWP-CH_4 and GWP-CH_4 with time horizon. The yellow and blue curves show how the AGWPs changes with increasing time horizon. Because of the integrative nature the AGWP for CH_4 (yellow curve) reaches a constant level after about five decades. The AGWP for CO_2 continues to increase for centuries. Thus, the ratio which is the GWP (black curve) falls with increasing time horizon (taken directly from Figure 8.29 of Myhre et al., 2013).

The fundamental differences between emission metrics is clearly illustrated by calculations of 'net' GWP- and GTP-weighted emissions (i.e., net CO_2-equivalent emissions) for aviation effects (Lee et al., 2020)[26] for a 100-year time horizon, where the net GWP-weighted emissions was 1.7 and the GTP-weighted emissions was 1.1[27]. A 'net' CO_2-equivalent emission, as derived from weighting by either GWP or GTP, represents what is commonly referred to as an 'emissions multiplier' to account for aviation non-CO_2 effects (noting that RFI, see footnote, is an incorrect 'emissions multiplier'). Additionally, GWP_{100} can result in negative CO_2 equivalent emissions in the case of pulse emissions of aviation NO_x for short time horizons (Fuglestvedt et al., 2010), while sustained emissions produce positive CO_2 equivalent emissions.

A relatively new application of the GWP, referred to as 'GWP*', produces a better temperature-based equivalence of short-lived non-CO_2 climate forcers than the traditional use of GWP by equating an increase in the emission rate of a Short Lived Climate Forcer with a one-off "pulse" emission of CO_2. The GWP* is an example of a 'flow-based' method that represents both short-lived and long-lived climate forcers explicitly as 'warming-equivalent' emissions that have approximately the same impact on the global average surface temperature over multi-decade to century timescales (Allen et al., 2016; 2018; Cain et al.,

[26] No uncertainty ranges given for emission metrics (e.g. GTP, GWP, GWP^*_{100}).

[27] The metric 'Radiative Forcing Index' (RFI) introduced by the IPCC (1999) to illustrate aviation's net current-day non-CO_2 radiative impacts, relative to its historical and current day CO_2 radiative impacts was never designed to be an emissions metric and has been widely misused as such, despite scientific literature, including the IPCC Fifth Assessment Report (Myhre et al., 2013) pointing this out.

2019). GWP^*_{100} for net aviation impacts was calculated by Lee et al. (2020) for recent conditions. The CO_2-warming-equivalent emissions based on this method indicate that aviation emissions are currently warming the climate at approximately three times the rate of that associated with aviation CO_2 emissions alone.

It could be argued that temperature-based metrics, and the GWP*, are potentially more useful for temperature-based policy objectives such as the temperature targets of the Paris Agreement. They also provide a more physical basis of actual impacts than GWPs for SLCFs.

Niklaß et al. (2019) addressed whether non-CO_2 climate impacts from aviation could be incorporated into the EU-ETS and CORSIA. In Part A of the report, Dahlmann et al. (2019) recommended the usage of the ATR with a 100 year time horizon to be used for emission trading or additional non-CO_2 impacts to be incorporated into CORSIA. Their conclusion was based upon a particular mitigation approach of a range of complexity of spatially and temporarily adjusted factors. The potential mitigation options considered in Sections 4 and 5 are wider in approach.

Key points from 2.3:

- In considering mitigating aviation non-CO_2 impacts, one of the key considerations is how to formulate emission equivalences between its non-CO_2 impacts, which are all short lived climate forcers, and emissions of CO_2, a long-lived greenhouse gas. Equivalent emissions metrics are also needed in considering any trade-offs that may arise between the shorter timescale non-CO_2 impacts and longer timescale impacts of CO_2.
- Temperature-based metrics, and the GWP*, are potentially more useful for temperature-based policy objectives such as the temperature targets of the Paris Agreement.
- All metrics produce different magnitudes of equivalence (or even sign, positive or negative), based on the user's choice of either metric or time-horizon. The GWP* and Average Temperature Response (ATR) minimise some dependency of time horizon. Additionally, the ATR provides the same sign for pulse and sustained emissions if it takes an average of the last *n* years that excludes any negative response (e.g. in the case of aviation net-NO_x).
- Metrics differ in their applicability, with standard metrics comparing pulse emissions as this approach is more adapted to standard policy instruments as discussed in 2.3 and illustrated in Figure 3.
- This report does not recommend one specific metric, or choice of time horizon. These choices partly depend on the suitability of the metric to a particular mitigation strategy, and partly upon the user's choices which may be influenced by socio-economic factors, such as equity valuation.
- IPCC (2013) provides a succinct summary of the problems associated with comparing short lived climate forcers with long-lived greenhouse gases: *"Ideally, the climate effects of the calculated CO_2 equivalent emissions should be the same regardless of the mix of components emitted. However, different components have different physical properties, and a metric that establishes equivalence with regard to one effect cannot guarantee equivalence with regard to other effects and over extended time periods."* (IPCC AR5, Chapter 8, Myhre et al., 2013).

2.4 Mitigation opportunities

The mitigation of aircraft **NO_x emissions**[28] can potentially be achieved by technological or operational means. The development of more fuel-efficient aircraft engines has increased the pressure ratio and combustor temperatures, leading to an increase in the average NO_x emission index (EI_{NOx} – g NO_x/kg fuel burn) during the recent decades. The introduction of low-NO_x combustion technology has mitigated this increase in EI_{NOx} for a given engine pressure ratio. EASA regulations allow a larger EI_{NOx} for higher pressure ratio engines. Decreasing NO_x emissions for increased pressure ratio engines may involve a fuel-burn penalty (see section 3), although it is thought not to have happened so far (IEIR, 2019). Comparisons of NO_x reductions with fuel penalties are difficult and the use of different emissions-equivalency metrics can be invoked to explore the impacts, which can reveal that large emission reductions of NO_x, e.g. a 50% reduction for a 2% fuel penalty can actually imply a net climate disbenefit in terms of net forcing over a 100 year timescale (Freeman et al., 2018).

Operational options exist for reducing impacts of NO_x by modifying cruise altitudes (e.g. Frömming et al., 2012), but if these involved systematic changes (generally lowering) in cruise altitude of current-day aircraft, it would involve a fuel burn penalty, and therefore a CO_2 penalty with net RF changes dependent upon the time horizon used.

Mitigation options for **contrail-cirrus** can also be technological or operational. Contrail cirrus ERF can be reduced by reducing the emission index for soot particle number[29], but at very small soot number emission indices ($<10^{14}$ kg^{-1} fuel) well below contrail formation threshold conditions, ultrafine aqueous particles can be activated and form large numbers of ice crystals thereby increasing ERF (Kärcher, 2018) (see Figure 5)[30].

Figure 5. Taken from Kärcher (2018). Dependency of nucleated ice crystal number/kg fuel on emitted soot particle number/kg fuel for two contrail threshold formation conditions.

[28] Regulation of aircraft engine NO_x emissions is undertaken by EASA, but is focused on the Landing Take-Off (LTO) cycle in order to protect air quality. It has previously been assumed that reductions of LTO NO_x emissions scale to altitude emissions, which is less certain for more modern staged combustors.

[29] This can be achieved with fuels with less aromatic content and less naphthalene.

[30] See the following quote (reference numbering is from the paper) from an explanatory Box (1) in Kärcher, 2018): *"As mixing and associated cooling of jet plumes with surrounding air progresses, ambient aerosol particles are gradually mixed into them and exposed to moister and warmer plume air. Ultrafine aqueous particles (UAPs) are generated from gaseous emissions before ice crystals form. UAPs partition into a larger mode that formed on ionised molecules (chemi-ions)[41,128] and an electrically neutral mode too small to contribute significantly to ice nucleation. Fuel combustion produces condensable vapours including water vapour, sulphuric acid, nitric acid, and low-volatile hydrocarbons. Sulphuric acid is produced by oxidation of emitted sulphur oxides and is highly water-soluble. Nitric acid is produced by oxidation of emitted nitrogen oxides and is only taken up by UAPs that are sufficiently diluted (water rich)[129]. The chemical nature of organic compounds from emissions of unburned hydrocarbons in aircraft exhaust is poorly characterised. The number of UAPs in the chemi-ion mode, exceeding 10^{17} per kg of fuel burnt[41], is insensitive to variations of, and UAP sizes (1–10 nm) increase with, the sulphur content in the fuel[130,131]"*

For moderate decreases in the soot particle number index, the number of nucleation sites for ice crystals is reduced, resulting in fewer larger crystals, and reducing the optical thickness of the clouds, and also the lifetime of clouds (Bier et al., 2017; Burkhardt et al., 2018). The effect is a reduction of RF (see Figure 6, from Burkhardt et al., 2018), but the real-fleet change is not well known because of large uncertainties in the emissions quantification of soot particle number emissions at cruising conditions, and the microphysical and optical properties of contrail cirrus. Lower aromatic fuels are also an option to reduce soot number emissions and represent a mitigation opportunity with no CO_2 penalty (assuming that the fuels are either lower carbon footprint biofuels or synthetic fuels manufactured from renewable energy). The reduction in soot particle number emissions both at ground level and cruise altitudes from lower aromatic content fuels is well established from measurements (see Moore et al., 2015; 2017 and references therein).

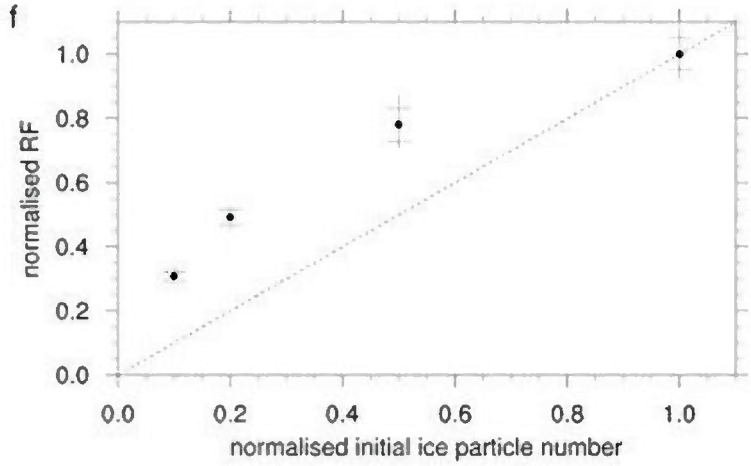

Figure 6. Global net radiative forcing (RF), given as a fraction of the radiative forcing for the 'present-day soot number scenario', as a function of the initial ice particle number concentration of contrails, given as a fraction of the initial ice crystal number concentration for the 'present-day soot number scenario'. Initial ice crystal numbers were reduced to 0.5, 0.2, and 0.1 of the present-day values (taken from Burkhardt et al., 2018).

Changes to more day-time only flights have been suggested, thereby avoiding the larger net warming at night and reducing the impact of linear contrails (Stuber et al., 2006). However, modelling of contrail cirrus shows no net benefit because of the longer lifetime (observed to be up to 18 hours) of the contrail cirrus (Newinger and Burkhardt, 2012).

Changing flight paths to avoid low-temperature ice-supersaturated regions is feasible in order to reduce the positive radiative effects of contrail cirrus, especially as a small proportion of flights produce a large proportion of contrail cirrus. This would require accurate forecasting of ice-supersaturation and temperature (Matthes et al., 2017; Teoh et al., 2020). However, on most occasions, this would involve a fuel burn penalty and therefore additional CO_2 emissions (Teoh et al., 2020). Changing route could potentially be environmentally beneficial, even with some additional CO_2 emission but there are some important qualifications to this. Gierens (GBD, 2019; 2020 pers. comm.) and more recently Teoh et al. (2020) have shown that potentially much of the annual forcing from contrail cirrus originates from a small number of events, described as 'Big Hits'. Thus, the argument is that avoidance of ice supersaturated regions (ISSRs) need only be done selectively, which represents a potential mitigation opportunity.

If ISSR avoidance were to be applied in European air space, there are a number of scientific considerations to be made (practical air traffic management considerations are outlined in Section 5). Most importantly, ISSRs would need to be accurately predicted in horizontal and vertical extent. While statistics of ISSRs have been made that indicate average horizontal extents are of the order of 100s km and vertical extents of 100 – 200 m (Spichtinger et al., 2003), the statistics of ISSRs that cause 'Big Hits' are not well known. This could be problematic from a practical point of view because a rather accurate definition of the vertical extent of ISSR would be required for contrail avoidance. Recent work by Gierens et al. (2020) provides the first comprehensive analysis of the ability of a meteorological model to forecast persistent contrails by comparing reanalysis data from the European Centre for Medium-Range Weather Forecast (ECMWF) model, the 'ERA-5' data, with aircraft observational data (MOZAIC/IAGOS; Petzold et al., 2015) and satellite data of persistent contrails (Vázquez Navarro et al., 2015). Contrail formation could be predicted quite reliably from thermodynamic conditions, but the weather model had only a poor ability to predict ice supersaturation at the right time and place (Gierens et al., 2020). The weather data were deemed to have "only limited capabilities for estimating real-world contrail formation along an aircraft trajectory". From the analysis of Gierens et al. (2020), it is clear that much more work is needed to examine the abilities and shortcomings of meteorological models to predict persistent contrail formation correctly in time and space.

The other consideration, from an environmental/scientific point of view, is how to assess the net benefit of contrail avoidance. Teoh et al. (2020) have suggested that there could be a net benefit with the RF avoided in the short to medium term by outweighing the consequential long-term CO_2 additional RF. Whether this is a 'benefit' or 'disbenefit', depends on the time horizon over which the additional CO_2 'effect' eventually becomes larger than the avoidance 'effect' from contrail cirrus. The 'effect' can also differ depending on the emissions equivalency metric, e.g. AGWP or AGTP. As has been outlined earlier, there are also significant uncertainties over the magnitude of contrail cirrus RF and ERFs, which would place additional uncertainties on the assessment of 'benefit/disbenefit'.

In case studies, it has been demonstrated that flight planning according to trajectories with minimal climate impact can substantially (up to 50%) reduce the aircraft net climate impacts despite additional CO_2 emissions (e.g., Niklaß et al., 2017). However, where trade-offs exist between reduced non-CO_2 forcing and increased CO_2 forcing, the net benefit or disbenefit depends upon the choice of metric and time-horizon applied. There is a tendency for additional CO_2 to cause a net disbenefit for all metrics when very long time horizons are considered. Conservative mitigation approaches (i.e. focusing on a limited number of favourable cases) may be possible in order to ensure a net climate benefit on a wide range of timescales.

Key points from 2.4:

- Mitigation of NO_x emissions has been achieved historically through technological means, although the fleet emission index (g NO_x per g fuel burnt) has increased due to the nature of the regulatory metric, which allows increasing NO_x emissions with increasing pressure ratio of engines.
- If NO_x emissions are reduced by technological means, this may be at the expense of improved fuel consumption and could ultimately lead to a climate dis-benefit from increased CO_2 over longer time horizons.

- Contrail cirrus *Effective* Radiative Forcing is between 0.35 and 0.5 of previously calculated RF (see Section 2.2). The uncertainties on the forcing term still remain large.
- Contrail cirrus forcing could be decreased by up to 50% with an 80% reduction in soot particle emission number. This could be achieved by reducing aromatic content of the fuel through the use of either biofuels or synthetic fuels from renewable energy. Further research is needed to address uncertainties in this quantification, but there would be no CO_2 penalty.
- Contrail cirrus can be reduced by avoiding regions that are conducive to contrail formation. For most cases, this will involve a flight path deviation and fuel burn penalty, and the net benefit (or disbenefit) will depend on the contrail cirrus reduction vs CO_2 increase, and time horizon of computation. For contrail cirrus, there seems no benefit in targeting night-time flights since contrail cirrus has a longer lifetime than linear contrails (up to 18 hours) and modelling indicates little variation over day/night even with night-time traffic removed. Nonetheless, avoidance should be studied further, including the degree to which 'Big Hits' (large contrail outbreaks, responsible for a large fraction of annual mean forcing) can be accurately forecast.
- Meteorological forecast models need to be analysed further for their ability to predict persistent contrail formation which, at present, is poor.
- The total climate impact of aviation could be reduced by choosing climate-optimized flight trajectories.

[placeholder for aviation-related illustration]

3. TASK 2: Technological and Operational factors for limiting or reducing non-CO_2 impacts from aviation and related trade-off issues

3.1 Introduction

Aviation emits a wide variety of gases and aerosols with distinctly different characteristics, which influence climate directly and indirectly via chemical and physical processes as described in Task 1.

The principle non-CO_2 climate impacts identified in Task 1 are as follows:

- Contrail formation i.e. contrail and contrail cirrus impacts arising from the jet exhaust in particular local atmospheric conditions (temperature and moisture);
- The complex impacts arising from NOx emissions during cruise;
- The complex impacts arising from PM emissions (primary and secondary) during cruise especially their potential links to contrail/cirrus formation.

Technological and operational factors determining the emissions/impacts, and potential trade offs between these factors, are presented in this section. In the absence of supersonic civil aircraft in the current fleet, the focus of this report is on subsonic aircraft only.

Current policies designed to reduce non-CO_2 emissions and their impacts are identified in this section, and consideration is given as to how these existing policies and their likely future direction may impact CO_2 and non-CO_2 emissions/impacts.

Potential future directions for technology will also be discussed, particularly in terms of how these factors may interact with each other.

3.2 Emissions and Impacts

3.2.1 NO_x oxides of nitrogen (NO_x = NO and NO_2)

Aviation NO_x emissions are formed in the engine combustor at the heart of the aircraft engine. The NO_X formation rate is dependent upon the temperature of the flame and system pressure (higher temperature and pressure result in acceleration of NO_X formation), the fuel to air ratio in the primary combustion zone and the residence time spent at the flame temperature. Most aviation engine NO_x emissions are formed by the thermal route where the nitrogen (N_2) and oxygen (O_2) molecules dissociate to their atomic states at high temperature and react with N_2 and O_2 to form NO (nitric oxide). NO is the primary NO_x species produced in the flame and subsequent oxidation of NO to NO_2 occurs in the engine and in the ambient environment by O_3.

Emissions of NO_X from a reference aircraft Landing and Take Off (LTO) cycle are measured as part of the engine type certification process (see section 3.4), and hence the emission indices (g NO_X as NO_2 per kg fuel burn) during LTO are therefore fairly well known. Full flight emissions of NO_X are less well known and estimation methods have been developed (e.g. Boeing Fuel Flow Method BFFM2, DLR fuel flow method) to predict NO_X emissions during cruise from the LTO NO_X data. However, the suitability of these estimation methods is less certain for newer technologies developed to control NO_X such as staged lean burn combustion. Consequently, work is ongoing to establish whether these methods can be applied to this technology. In terms of in-production engines within the current fleet, their NO_X emission indices during the LTO varies between around 5 and 65 grams of NO_x per kilogram of fuel burnt. Emissions of NO_x in the LTO cycle are highest during take-off (i.e. highest thrust settings) and lowest during idle (i.e. lowest thrust settings). For the 2015 global fleet in the ICAO Trends Analysis (ICAO, 2019) the fleet full flight average EINOx was approximately 15.6 grams of NOx (as NO_2) per kilogram of fuel burnt. EINOx for the overall LTO cycle are similar to the average EINOx for cruise phase, while EINOx for the climb phase (top of the LTO to cruise altitude) are higher due to the higher thrust levels.

3.2.2 Particulate matter

Aviation emission particles can be roughly divided into two categories; non-volatile particulate matter (nvPM) and volatile particulate matter (vPM). The former, nvPM, is usually interpreted as 'black carbon' (BC)' or 'soot', which are terms that are sometimes used interchangeably. Here, the term nvPM refers to particles measured at the engine exit and is the basis for the engine emissions certification regulation[31]. The volatile fraction (vPM) is composed of compounds that are in the gas phase at engine exit plane temperatures such as organic compounds. Gaseous emissions from engines can also condense to produce new particles, or coat the emitted soot particles. Additionally, gaseous emissions species react chemically with ambient background chemical constituents in the atmosphere to produce the so-called secondary particulate matter[32]. Volatile particulate matter is dependent on these gaseous precursor emissions, which are controlled by aircraft engine gaseous emissions certification standards and fuel standards (e.g. sulphur content).

At the engine exhaust, particulate emissions mainly consist of nvPM. They are present in the high temperature regions at the engine exhaust, and they do not change in mass or number as they mix and dilute in the exhaust plume near the aircraft. The geometric mean diameter of these particles is much smaller than 2.5 µm, which is the operational cut-off used for air quality relevant total PM concentration $PM_{2.5}$ (particular matter mass smaller than 2.5 µm) and ranges roughly from 15 to 60 nm (0.015 to 0.060 µm). These are classified as ultrafine particles (UFP), and the mass and number of nvPM emissions is primarily dependent on the engine technology. The aircraft engine LTO nvPM mass and number certification standards seek to ensure continuous improvements over time through the introduction of cleaner combustor technologies. LTO nvPM mass and number emission rates for lean burn staged

[31] Non-volatile particulate matter (nvPM) is defined in ICAO Annex 16 Volume II as *"emitted particles that exist at a gas turbine engine exhaust nozzle plane, that do not volatilize when heated to a temperature of 350°C"*. 'Soot' refers to combustion particles that exist in the engine plume and ambient environment, that may undergo chemical (e.g. oxidation and surface adsorption of gas phase molecules) and physical processes (e.g. agglomeration, coagulation).

[32] The primary emission from the engine exit is sulphur dioxide (SO_2); it is thought that up to 10% of the emitted sulphur could be gaseous sulphuric acid (Petzold et al., 2005). The gaseous sulphuric acid will quickly condense on existing particles from either the nvPM emissions or other pre-existing particles in the atmosphere. Of the larger fraction of SO_2, this is oxidized relatively slowly at around 1% per hour, so will form at km distance from the aircraft's emission (at cruise altitudes).

combustor technologies are much lower than for conventional non-staged combustion. Synthetic fuels with low aromatics content can also help to reduce nvPM mass and number emissions, especially at low thrust conditions.

Measured LTO nvPM mass and number emissions data, using consistent certification measurement procedures, is being collated as engines come forward for certification against the new nvPM mass and number standard (see section 3.5). LTO emissions of nvPM mass and number are not as well understood as NO_X LTO emissions due to greater uncertainties in the sampling and measurement procedures.

Emissions of nvPM during cruise are not well characterised, with very little measured data available. As such, work is ongoing to develop suitable estimation methods for cruise nvPM emissions. Emissions Index (EI) of nvPM mass vary from 1-400 mg/kg (i.e. 0.001-0.4 grams per kilogram of fuel burnt) and EI nvPM number are in the range between $5x10^{13}$ – $5x10^{15}$ particles per kilogram of fuel burnt during the LTO, although for lean burn combustion engines the EIs are much lower. Unlike for NO_x emissions, the range in values is large between engine types, the variation of EI nvPM (mass and number) is less predictable and EI versus thrust setting varies considerably between engines.

3.2.3 Fuel burn/Carbon dioxide

The emission of carbon dioxide (CO_2) is directly proportional to the fuel burnt, and for aviation kerosene the Emission Index is 3.16 kilograms of CO_2 per kilogram of fuel burnt (IPCC, 2006). Unlike for NO_x and nvPM, the CO_2 emissions are directly related to fuel consumption.

Key points from 3.2:

- Emissions of NO_X for the LTO cycle are well defined through engine certification data. Cruise NO_X emissions are less well defined, especially for newer staged combustion technology, although work is ongoing to provide better estimation methods using LTO measurements.
- The Emission Index (EI) of NO_x during LTO vary between around 5 and 65 grams of NO_x (as NO_2) per kilogram of fuel burnt for in-production engines within the current fleet.
- Emissions of nvPM mass and number during the LTO cycle are reducing and are expected to continue to reduce. This trend can be monitored through approved engine certification data. Sampling and measurement uncertainties and variability of nvPM mass and number emissions are greater than for NO_X.
- The Emissions Index (EI) of nvPM mass during LTO vary from 1-400 mg/kg (i.e. 0.001-0.4 grams per kilogram of fuel burnt) and EI of nvPM number are in the range between $5x10^{13}$ – $5x10^{15}$ particles per kilogram of fuel burnt, although for lean burn combustion engines the EIs are much lower.
- Emissions of CO_2 are derived directly from fuel burn estimates or measured data, and are well understood. The EI of CO_2 for aviation kerosene is 3.16 kg per kg of fuel burnt.

3.3 Current policies

3.3.1 Technology-Design Standards

The environmental certification standards are developed internationally within the ICAO environmental committee (CAEP), promulgated by national legislation and implemented by the Certification Authorities. The European Aviation Safety Agency (EASA) certification standards for aircraft engine emissions include NO_x, nvPM (mass and number), Carbon Monoxide (CO), Unburnt Hydrocarbons (UHC) and Smoke[33], and are based on the ICAO Annex 16 Volume II. Likewise, the EASA aeroplane CO_2 emissions standard is based on ICAO Annex 16 Volume III. These EASA standards are technology-design standards that compare the environmental performance of different products. They are not designed to promote any specific technology, but to provide regulatory pressure to improve the overall environmental performance of the global fleet over time.

The emission standards of most relevance to aviation non-CO_2 climate change impacts are the NO_X and nvPM aircraft engine emissions standards. These standards are focused on local air quality concerns and based on the emissions during the Landing and Take-Off (LTO) cycle. Past analysis has concluded that reductions in emissions of NO_X and nvPM at LTO will also lead to reductions at cruise.

EASA standards have been set to follow the latest available technology in order to prevent backsliding and to provide a regulatory pressure for improvement over time through the integration of best available technology. This has given rise to the need to have a separate set of technology goals focused on leading edge technology, to guide subsequent regulations, and to which industry and ICAO may aspire.

In 2016, ICAO's CAEP commissioned a study from a group of independent experts to establish long-term technology goals for aircraft fuel burn, engine NOx and nvPM emissions and aircraft noise in a so-called Independent Expert Integrated Review (IEIR)[34]. The time periods to be considered were medium term (2027, 10 years from baseline) and long term (2037, 20 years from the baseline). The report of the Independent Experts was presented and accepted at the CAEP/11 meeting in February 2019, and a summary was subsequently published in the ICAO Environmental Report (ICAO, 2019)

The ICAO Technology Goals defined by the Independent Experts (IE) needed to be "challenging but achievable", which is the same definition as that adopted by previous groups of Independent Experts established by ICAO CAEP.

The NO_x, nvPM and CO_2 standards are considered separately in the following sections (3.4 to 3.6), together with the ICAO CAEP technology goals that provide an assessment of the direction for future technology developments over the next 20 years.

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[33] The Smoke Number regulation is a visibility criteria for the engine exhaust plume which will be replaced by the CAEP/10 nvPM mass concentration regulation for engines with rated thrust >26.7kN from 1 January 2023.

[34] Previous CAEP Technology Reviews had worked in one area only with some consideration of trade-offs but setting the goals in separate reviews.

3.3.2 Operational Regulatory Instruments

There are no specific operational regulations currently in place that are aimed at reducing non-CO_2 impacts, i.e. emissions of NO_x, nvPM or the formation of contrail-cirrus. The Single European Sky (SES) has various environmental performance indicators linked to the fuel efficiency of the air traffic management system, but none on non-CO_2 climate impacts at the present moment.

3.3.3 Fuel Standards

As jet fuel supply arrangements have become more complex, involving co-mingling of product in joint storage facilities, a number of fuel suppliers developed a document that became known as the Aviation Fuel Quality Requirements for Jointly Operated Systems, or AFQRJOS, Check List. The Check List represents the most stringent requirements of the following specifications:

(a) UK Ministry of Defence Standard - DEF STAN 91-91

(b) The American Society for the Testing of Materials - ASTM D1655 Kerosene Type Jet A-1 (Jet A)

By definition, any fuel meeting these Check List requirements will also meet either DEF STAN or ASTM specifications.

Jet A and Jet A-1 are kerosene-type fuels. The primary physical difference between the two is the freeze point (the temperature at which wax crystals, which form in the fuel as it cools, completely disappear when the fuel is rewarmed). Jet A, which is mainly used in the United States, must have a freeze point of -40 °C or below, while Jet A-1 must have a freeze point of -47 °C or below. The fuel freezing point is the temperature at which wax crystals, which form in the fuel as it cools, completely disappear when the fuel is rewarmed

The fuel standards are currently in place to ensure that safety and operational requirements are met. In terms of chemical composition, the fuel standards currently specify an allowable range of aromatic content by volume and sulphur by weight. Both aromatic content (naphthalene) and sulphur have impacts on emissions of nvPM and vPM, respectively.

3.3.4 Other Policies

Other policies for CO_2 emissions reduction include market-based measures such as the EU Emissions Trading System (ETS) and the recently agreed ICAO Carbon Offsetting and Reduction Scheme for International Aviation (the CORSIA).

Key points from 3.3:

- Technology/Design: There are certification standards for aeroplane CO_2 emissions as well as aircraft engine NO_X and nvPM (mass/number) emissions. There are discussed in more detail, together with the future technology goals, in section 3.4 to 3.6.
- Operational: The Single European Sky (SES) has various environmental performance indicators linked to the fuel efficiency / CO_2 emissions of the air traffic management, but none on non-CO_2 emissions at the present moment.
- Fuel standards: International fuel standards (DEF STAN and ASTM) contain limits on chemical composition requirements, but may not be currently defined with environmental concerns in mind.

3.4 NO_x Standard and Technology Goals

3.4.1 EASA NO_x Engine Emission Standard

The first Landing and Take-Off (LTO) NO_x emissions standard became effective in 1986 (CAEE[35]). The next standard, which reduced the associated regulatory limits, came in to force in 1996 (CAEP/2 meeting) when a 20% reduction was agreed against the original CAEE standard. Since then further reductions have been made over time, including CAEP/4 with an effective date of 2004 (-16% versus CAEP/2); CAEP/6 with an effective date of 2008 (-12% below CAEP/4 at overall pressure ratio, OPR, 30); and CAEP/8 with an effective date of 2014 (-15% below CAEP/6 at OPR 30).

Until CAEP/4 the standard was a simple straight line of permitted NO_x rising with increasing overall engine pressure ratio (OPR). However, from CAEP/4 onwards a steeper slope was introduced above OPR 30, which permitted engines with higher OPR to produce more NO_x. This recognised the technical challenges in mitigating NO_X emissions for larger aircraft engines with higher combustor temperatures and pressures to increase fuel burn efficiency (i.e. CO_2 reduction) through improvements in thermal and cycle efficiency. This steeper slope above OPR 30 was maintained in the CAEP/6 and CAEP/8 NO_X standards.

These NO_X regulations apply to engines with a rated thrust above 26.7kN. The LTO NO_x metric used for all of these ICAO standards was Dp/Foo which is defined as the mass of emissions produced (Dp) during a static sea level engine test for a simulated idealized LTO normalised against maximum engine thrust (Foo). Figure 7 below illustrates the NO_x standard regulatory levels together with certified engine emissions data over various time periods.

[35] The Committee on Aircraft Engine Emissions (CAEE), which was the predecessor of the ICAO Committee on Aviation and Environmental Protection (CAEP)

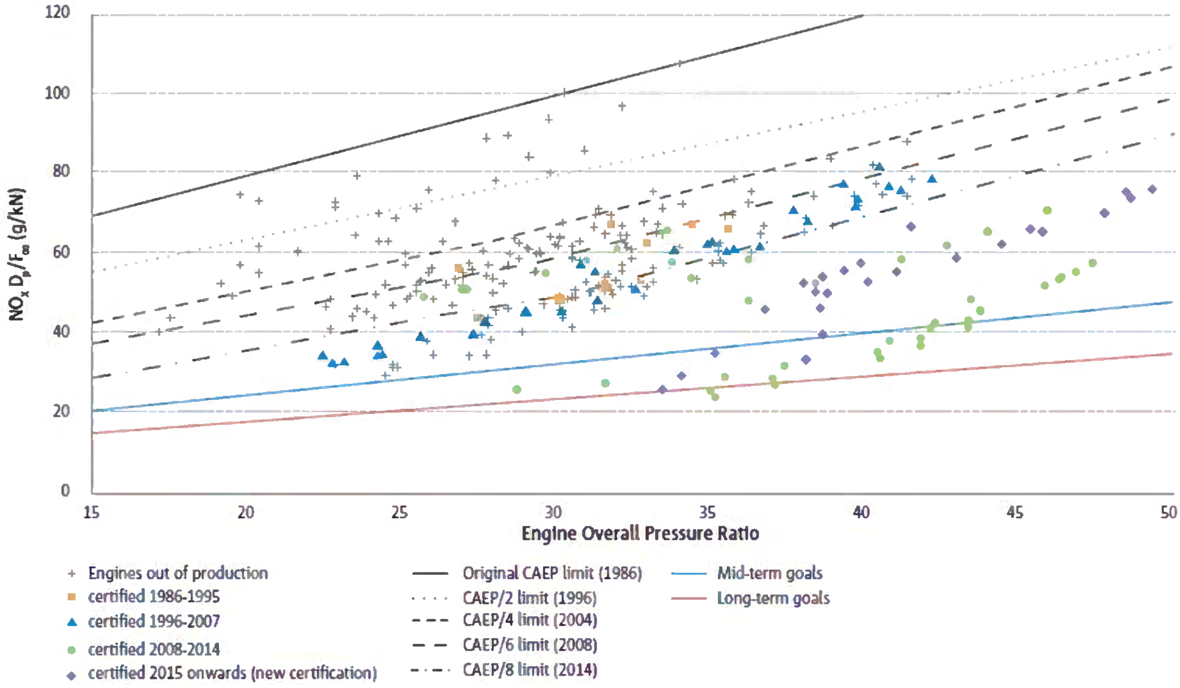

Figure 7. Engine emissions certification data (EASA, 2019)

Despite the significant increases in the stringency of NO_X standards over the years, the overall NO_X emissions from the global fleet has not been reduced. This is due to the increased use of aircraft engines with higher OPR engines that are permitted to produce more NO_X, as well as fleet growth and slow fleet rollover.

The NO_X standards are not generally technology forcing. However, it is important to note that the standards prevent backsliding and provide market incentives by permitting the environmental performance of competitor engines to be compared via their % margin to the NO_X limit. It is estimated that over 98% of engines to be produced in 2020 for international civil purposes will comply with the CAEP/8 NO_X standard.

When designing new products, particularly the first of a new family of engines, manufacturers aim to provide a NO_x compliance margin to the limit in order to guard against any shortfall in expected performance and to meet customers' expectations of 'future proofing' against increases in stringency. Moreover, several manufacturers have stated that their research has been influenced by the expectation that standards would be further tightened in the future. These compliance margins are evident from the most recent certifications, where new engines were certificated at between 6 to 50% below the CAEP/8 standard.

3.4.2 NO_x Technology Goals

The recent Independent Experts Integrated Review (IEIR) was tasked with reviewing current NO_X performance along with other emissions and noise; potential outcomes from current research programmes; longer-term potential reductions and local air quality and climate impact evidence.

The IEIR reported that NO_X control technology had plateaued with only a few percentage points improvement expected over the next 20 years from the best of today's technology. In view of the lack of emerging new technology beyond Lean Burn and advanced RQL[36], they declined to set a long-term technology goal for 2037 (20 years from the 2017 base line technology). However, they did set a medium term goal for the 10 year period up to 2027 and this goal is shown as a red line in Figure 7. This new medium term 2027 goal is set in the same place as the previous long-term (2026) goal from the earlier CAEP NO_X technology goals review. The medium term goal is 54% below CAEP8 at OPR=30 and it is set just below the best certified engine at the time of the IEIR, reflecting the increasing difficulty of obtaining further improvements in NO_X during this period.

An additional aspect of the new NO_X medium term 2027 technology goal is that it is only met when the 50th engine of a goal-compliant type enters service. This is to avoid low-thrust versions of engines with small production possibilities being taken to achieve the goals rather than the higher thrust products with higher NO_X, improved fuel burn performance and better market realisation prospects. The IEIR panel concluded that for any consideration of a long term goal in 2037, a new metric may need to be considered and must be based on a methodology which reflects combustors where emissions alter strongly with T_{40} (the combustor exit temperature). The IEIR panel also concluded that advanced alternative aircraft technology including electrified aircraft propulsion was not likely to be in service before 2037.

The NO_X 2027 goal lies well below current CAEP/8 standard (-54% at OPR=30), and by a larger margin than when compared with the difference between successive changes to standards (CAEP/8 is 15% below CAEP/6 at OPR30). While there may be an opportunity to reduce the NO_X regulatory limit to levels below CAEP/8 in the coming years, it should be noted the higher rated thrust variants of the same engine have a lower margin to the NO_x limit and that there may be trade-offs with increased fuel burn / CO_2 emissions.

3.4.3 LTO NO_X and Cruise NO_X

The LTO NO_X certification standard exists principally for the purposes of reducing the engine emission impacts on air quality in the vicinity of airports. However, past analyses have concluded that a reduction in LTO NO_X will also result in a reduction of NO_X emissions at cruise and, based on the premise that the impacts of NO_X emissions at cruise are overall warming, this will thereby help reduce the climate change impacts of aviation.

Based on the discussion in Task 1, this premise has evolved over the last decade and a recent study (see Appendix 5) indicates that climate warming impacts of cruise NO_X emissions remain highly uncertain. In addition, there is also uncertainty in the relationship between LTO NO_X and cruise NO_X for more recent engine technology developments such as staged combustion, e.g. Lean Burn. On-going work in ICAO CAEP is assessing whether the current methods for estimating cruise NO_X from LTO NO_X, (i.e. Boeing fuel flow method and the DLR fuel flow method) are applicable to staged combustors such as lean burn combustors. The IEIR conclusions on cruise NO_X are provided as follows:

> *To reflect the potentially increasing importance of altitude NO_X relative to LTO NO_X, consideration should be given to the development of a cruise-based NO_X goal. This should use a climb/cruise (or full flight) metric system, ideally developed by CAEP, as*

[36] RQL Rich burn, Quick quench (or Quick Mix), Lean burn

part of cruise NO_X certification. Development of such a goal was too ambitious for this integrated review.

Further research, including altitude testing, is required to obtain data for climb and cruise NO_X emission rates, especially on staged combustion engines, in order to validate any analytical modelling methodology. Setting a cruise-based NO_X goal would take full account of interdependencies, in particular the technical trade-offs with fuel burn resulting from higher combustor exit temperatures (T40) and the emerging understanding of the environmental impacts from nvPM and NO_X.

Cruise NO_X emissions are not currently measured or certified as past analyses concluded there was a correlation between LTO and cruise NO_X emissions. As such, there is no direct incentive for an engine manufacturer to specifically improve cruise NO_X emissions. Lean burn engines currently have the potential to emit significantly less NO_X at cruise by ensuring that the rich burn pilot stage, which causes the higher NO_X at low thrust settings, is switched off or at a lower power setting during cruise. Introduction of a cruise NO_X reporting point as part of the LTO engine emissions certification requirements would potentially allow subsequent policy action to target cruise NO_X, if emerging research and climate science provides direction on whether this is a priority from a climate impact point of view.

Key points from 3.4:

- The global aircraft fleet NO_X performance will improve at a fixed overall pressure ratio (OPR) as older high NO_X engine designs are retired and replaced with designs incorporating lower NO_X technology such as Lean Burn and advanced Rich burn-Quick quench-Lean burn (RQL) combustion. However, the increase in engine design OPR to improve specific fuel consumption has somewhat counterbalanced this with higher overall NO_X per LTO (at a constant rated thrust output).
- Further significant NO_X performance from new technology beyond lean burn and advanced RQL may be limited.
- A review of the correlation between reductions of LTO NO_X and that of NO_X in cruise for new engine technology/designs would be helpful in order to consider how well cruise NO_X is controlled.
- Introduction of a cruise NO_X reporting point as part of the LTO engine emissions certification requirements would potentially allow subsequent policy action to target cruise NO_X, if emerging research and climate science provides direction on whether this is a priority from a climate impact point of view.
- Increases in the stringency of the NO_X standard beyond CAEP/8 may come at the expense of some specific fuel consumption improvements.

3.5 nvPM Standards and Technology Goals

3.5.1 EASA nvPM Engine Emission Standards

The first engine nvPM emissions standard was agreed to at the CAEP/10 meeting in 2016 and was a peak Mass Concentration standard designed to ultimately replace the older

Smoke Number regulation based on statistical correlation[37]. An important additional purpose of the CAEP/10 nvPM standard was the mandatory reporting of nvPM mass and number emissions at the specified four LTO measurement points, acquired through a certification process for in-production engines. The CAEP/10 nvPM standard is applied to engine types with a rated thrust greater than 26.7 kN that are produced on or after 1 January 2020. The certified data permits a comparison of engine type design and technology in terms of nvPM emissions. Furthermore, the maximum nvPM Mass Concentration obtained from the nvPM certification measurement helps maintain the non-visibility criteria of the exhaust emissions and provides a pathway for ending the applicability of the Smoke Number standard for engines of rated thrust greater than 26.7 kN. The Smoke Number regulation will be replaced by the CAEP/10 nvPM mass concentration regulation for engines with rated thrust >26.7kN from 1 January 2023.

Following the development of the CAEP/10 nvPM Mass Concentration standard in 2016, CAEP continued the development of the LTO nvPM Mass and Number standards. Approximately 25 engine types that represented the range of in-production engine combustor technologies, and a full range of engine sizes, were tested to characterize nvPM mass and number emissions. Using these datasets, metric systems for LTO nvPM mass and number emissions were developed to provide an effective way to characterise and reduce real-world LTO nvPM emissions. As noted earlier, the nvPM mass and number emissions show a much wider range with more variability between engine types than NO_X emissions, and with different relationships between nvPM emissions and thrust across different engine types.

At the CAEP/11 meeting in February 2019, new engine LTO nvPM mass and number emission standards were agreed for in-production and new aircraft engines. This standard is a mitigation measure to control the ultrafine nvPM emissions emitted at the engine exit, directly related to the combustion technology and fuel burn. As with the NO_X standards, the guiding principle for these new standards is to improve air quality and human health. EASA is currently working to integrate these new standards into European legislation.

The purpose of emission certification is to compare engine technology-designs, and to ensure that the engines produced comply with the prescribed regulatory limits. Test data was used to develop a methodology to correct measured nvPM emissions to reference conditions in order to directly compare the environmental performance of different engine types. The nvPM sampling and measurement system requirements also standardises the particle losses. For emission inventories and impact assessments, nvPM emissions at the engine exit plane should include the particle size dependent losses in the sampling and measurement system calculated using a standardized methodology. It is worth noting here that some uncertainties regarding the measurement of nvPM emissions remain subject to further work, including characterising the impact of ambient conditions during emissions measurements. As nvPM emission rates are also affected by aromatics in the fuel, the certification test fuel specifies a small range of total aromatics, including naphthalenes.

[37] Noting that the nvPM mass concentration measurement performed with the new much more sensitive measurement method can be related to the smoke number standard to control non- visibility of exhaust plumes. The CAEP/10 standard was introduced with a maximum nvPM mass concentration limit.

The research and data collected during development of the CAEP nvPM standards has allowed emission estimation methods for nvPM mass, and to a lesser extent number, to be improved for the LTO cycle. The ICAO Doc 9889 airport local air quality manual contains the improved methods based on the SCOPE11 methodology (Agarwal *et al.*, 2019), now named FOA4.

3.5.2 nvPM Technology Goals

Historically aircraft gas turbine engines have not been designed for low nvPM emissions. With the implementation of CAEP/11 LTO nvPM Mass and Number standards in EU legislation, future engine designs will need to consider the full interdependencies between all pollutant emissions and fuel burn. While there may be trade-offs and constraints, these engine emissions standards will encourage cleaner technologies to be included in future engine designs. Significant reductions in nvPM mass and number, in addition to NO_X, have are already been achieved with lean-burn staged and advanced rich-burn combustors (e.g. EASA, 2014).

In view of the large uncertainties of nvPM mass and number control technology, the IEIR declined to set medium or long term technology goals.

3.5.3 LTO nvPM and Cruise nvPM

The engine certification standards for LTO nvPM emissions are focused on health and airport air quality issues. As with the NO_x LTO certification standards, there is a premise that reducing LTO nvPM emissions will also lead to reductions of nvPM in cruise, which mitigates the contribution of the aviation sector to climate change. Initial development work on methods to estimate cruise nvPM emissions from LTO measurements has been initiated, but these methods do not provide sufficiently accurate results at this point in time. It is expected that during the CAEP/12 cycle (2019-2022), an acceptable method for estimating cruise nvPM emissions from the LTO data will be finalised.

Key points from 3.5:

- There is increasing knowledge of LTO nvPM emissions by mass and number for engine certification regulatory purposes, but nvPM emissions at cruise conditions are not well characterised. Further work is required on developing methods to estimate cruise emissions from nvPM LTO data, and this may require additional engine emissions measurement campaigns.
- nvPM emissions (mass and number) are likely to be reduced as engine types with technology designed for NO_X control enter the fleet (i.e. lean burn and advanced RQL). However, nvPM control technologies, especially for nvPM number, are less well understood than NO_X.
- Climate science outlined in Task 1 suggests that particulate number, rather than mass, emitted during cruise is the driver for contrail and cirrus formation.
- Significant reductions in the aviation nvPM emissions (mass and number) can be achieved with the use of recent advanced rich burn and lean burn combustors.
- Similar to NO_X, a cruise nvPM reporting point as part of the LTO engine emissions certification requirements may allow better inventory quantification and incentivise reductions of PM emissions in cruise.

3.6 CO_2 standard and Technology Goals

General improvements in fuel burn efficiency lead to overall reductions in both CO_2 and non-CO_2 emissions.

3.6.1 EASA aeroplane CO_2 Standard

The first aeroplane CO_2 emissions certification standard was agreed at ICAO in 2016. The standard was subsequently integrated into EU legislation and implemented within EASA certification specifications. The technology-based CO_2 Standard has been developed at the aeroplane level, and therefore has considered all fuel efficiency technologies associated with the aeroplane design (e.g. propulsion, aerodynamics and structures). The standard applies to new type subsonic jet and turboprop aeroplane designs from 2020. It will also apply to in-production aeroplanes from 2023 that are modified and meet a specific change criterion. This is subsequently followed up by a production cut-off in 2028, which means that in-production aeroplanes that do not meet the standard can no longer be produced beyond 2028 unless the designs are modified to comply with the standard. The CO_2 standard provides added regulatory pressure, on top of the existing commercial pressure, to optimize the design for fuel burn improvements both at the engine and aircraft level.

3.6.2 CO_2 Technology Goals

The ICAO independent technology review (IEIR) recommended a 2027 medium term goal for overall fuel efficiency improvements (and therefore reductions in CO_2 emissions) of around 1.3% per annum for single aisle aircraft and 1.0% per annum for twin aisle aircraft. For the following decade, 2027 to 2037, improvements of around 1.2% per annum for single aisle and 1.3% per annum for twin aisle were provided as the long term goal. Beyond 2037, the IEIR concluded that there is the possibility of more novel technology, for example, hybrid electric aircraft providing more significant improvements.

It should be noted that the most recent IEIR review concluded that potential alternative aircraft configurations (e.g. hybrid wing-body; transonic truss-braced wing; double bubble; boundary layer ingesting propulsion; and electrified aircraft propulsion), were unlikely to enter into the fleet in the next twenty years. Nonetheless, electrified aircraft propulsion research related activities are expanding, including hybrid electric propulsion components and architecture. In the next couple of decades, the most likely initial application of electric propulsion could be on regional jets or perhaps single aisle, and is likely to be the turbo-electric approach whereby the energy source remains jet fuel and the configuration does not rely on battery storage. For longer range and larger aircraft, electric propulsion is not currently likely in the first half of this century. The focus of this report is for the next 10 to 20 years and, reflecting the IEIR conclusions, it does not consider in detail the potential alternative aircraft configurations.

Key points from 3.6:

- Technological improvements in aircraft fuel efficiency are pursued through reduced engine specific fuel consumption, aerodynamic improvements and weight reduction. These generally provide a win-win situation for fuel burn, engine emissions and noise for a given combustor technology.
- Advanced alternative aircraft technology, including electrified aircraft propulsion, is not considered likely to be in service before 2037. Beyond 2040-2050, hybrid/electric aircraft and revised airframe configurations could offer significant reductions in NO_X and nvPM.
- Commercial considerations provide strong incentives for continuous fuel burn improvements, and this has been reinforced by the introduction of the aeroplane CO_2 emissions certification standard.

3.7 Aircraft Technology Issues and Potential Trade offs

Design and development of new aircraft technology, and its incorporation within new designs that are more fuel efficient and/or have lower emissions, is one key way of reducing the environmental impact of aviation. However, the fuel burn and emissions performance is only one of the key requirements to be considered in aircraft and engine combustor developments with safety being the prime concern. There are also some technological advances that lead to improvements in the performance of one emission at the potential expense of another, so-called 'trade off' issues. Emissions of CO_2 and water are determined by the fuel burn performance and therefore the design of the aircraft and engine. Emissions of NO_X and nvPM, as well as CO and HC, are mainly determined by the design and operation of the combustor.

These trade-offs are considered in more detail in the following sections.

3.7.1 NO_X emissions vs Fuel Burn

The NO_X formation rate is dependent upon the temperature of the flame and system pressure (higher temperature and pressure result in acceleration of NO_X formation), the fuel to air ratio in the primary combustion zone and the residence time spent at the flame temperature. The specific fuel combustion of the engine for a specific rated thrust can be improved by increasing the thermal efficiency and/or the propulsive efficiency of the engine. Improvements in both of these factors are sought by combustion engineers in order to drive down specific fuel consumption and therefore lower CO_2 emissions. The technology driving thermal efficiency improvements in aero engines has trade-offs with NO_X formation and this inherent tension is discussed in this section.

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 temperature 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, accelerating NO_X formation. This illustrates the main trade-off issue between NO_X and CO_2 emissions at the engine level. Successive generations of combustor designs have incorporated technologies to limit the peak gas temperatures and the duration of exposure, set against the background of a trend of increasing OPR for fuel efficiency, with the aim of limiting NO_X emissions. Within the overall annular combustor design there are two main approaches to controlling NO_X emissions: Rich burn, Quick quench, Lean burn (RQL) and Lean Burn.

Within the context of pressure on fuel burn improvements and NO_X control, industry has been working on improving both these parameters concurrently. In response to the question, "*To what extent could fuel efficiency improvements have been taken further in the absence of NO_X controls?*", industry representatives to the IEIR considered that the one was not holding the other back. Manufacturers indicated to the IEIR that in terms of meeting the certification requirements, NO_X technology would be developed to meet the needs of the most fuel-efficient technically feasible cycle and, for the foreseeable future, would not prevent fuel-efficient technology being pursued.

In previous reviews, independent experts (IE) explored mass penalties as a result of advances in combustor technology to reduce NO_X (e.g. Dual Annular Combustors). The additional mass of advanced combustors clearly results in a small but necessary trade-off in order to achieve the overall NO_X benefits. This trade-off was considered to be weak. In this latest IEIR review, the IEs were informed that for CAEP modeling purposes the fuel burn penalty resulting from minimizing NO_X at a given overall pressure ration (OPR) and combustor exist temperature (T40) has been assumed to lie in the range between 0.0% and 0.5%, the upper limit assuming a worst case. Manufacturers indicated that generally the cost of the combustor technology is not a critical issue for larger engines.

Commercial pressure to reduce fuel burn, and environmental pressure to reduce CO_2 emissions, will ensure that the focus remains on fuel efficiency of aircraft and aircraft engines in the future. The establishment of a long-term goal for CO_2 emissions in ICAO may further prioritise this view. In view of the potential trade-offs between NO_X and fuel burn at the engine level, and if the thermal efficiency of the engine is improved through higher core pressures and temperature while all else is held equal, then there will be a resulting rise in the mass of NO_X emitted. This NO_X:CO_2 trade-off has NO_X regulation pressing down on one side with CO_2 regulation and commercial pressures bearing down on the other. However, the past ten years has shown that both these emissions can be mitigated concurrently through improved NO_X control technologies being used in more fuel efficient higher OPR engines (as well as higher bypass ratio and higher fan pressure ratios). It should be borne in mind that engines with higher OPRs have higher regulatory limits within the NO_X certification standard.

The trends in air traffic and emissions data from 2005 to 2017 are shown in Figure 8 for all flight departures from the EU28+EFTA (EASA, 2019). This illustrates about a 10% increase in fleet wide full flight EINOx in the period between 2005 and 2017, although the rate of increase has been slower in the last 4 or 5 years. Overall there has been about a 20% decrease in NO_X emissions per passenger kilometre over the period 2005 to 2017, while NO_X emissions per available seat-km (ASK) are estimated at 0.44g/ASK in 2005 and 0.41g/ASK in 2014.

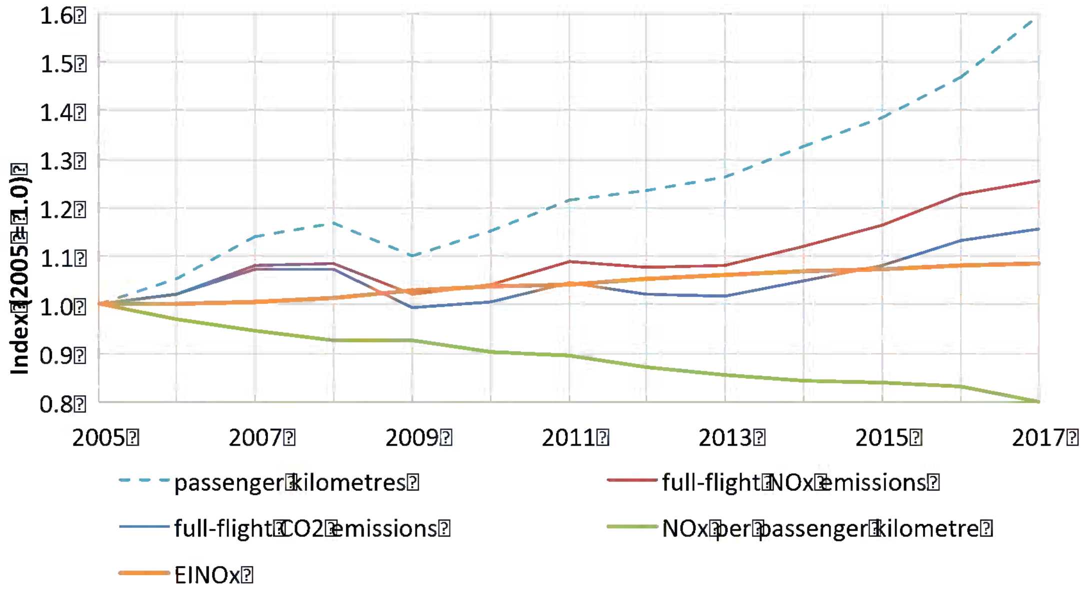

Figure 8. Trends in Air Traffic and Emissions from European Flight Departures (EASA, 2019)

3.7.2 nvPM vs NO_X emissions

In theory the reduction of nvPM emissions requires the combustion process to be at a high temperature and for as long as possible in the presence of abundant oxygen. However, for lower NO_X emissions, the conditions are not the same and reducing NO_X emissions requires avoiding high temperatures or limiting the residence time during when high temperature is unavoidable. In some ways the design options for low NO_X are therefore opposite of those for low nvPM. However, the mechanisms determining nvPM emissions are more complicated and less well understood than those for NO_X.

The nvPM mass production process is much more complicated that for NO_X. The way in which complex aerodynamics and mixing interact in the process to form in a particular combustor design is still being determined, although nvPM mass formation is better quantified than nvPM number. In addition to the combustor design conditions defined by the engine cycle (T30, P30 and the overall fuel to air ratio) the local fuel to air ratio within the different parts of the combustor define the formation of nvPM in the primary zone. Subsequent oxidation (and destruction) of the formed particles in the downstream part of the combustor is then dependent on the high temperature and long residence time. The nvPM number production is not always linked to mass so it is currently not possible to say what the main drivers of nvPM number are.

With Lean Burn and advanced RQL technology innovations, significant reductions in nvPM mass emissions have been seen in addition to reduced NO_X emissions when compared with earlier rich burn combustors. However, despite these already demonstrated order of magnitude improvements, industry advised the IEIR that early difficulties in service are likely to result in trade off issues between nvPM and NO_X emissions at higher OPRs and T40. As a result, development issues with lean burn and advanced rich burn may not deliver the full order of magnitude reduction in nvPM being achieved, though reductions are still expected to be substantial. The technology is not yet mature enough, and the design trades not necessarily well defined, to provide any quantification for the likely nvPM reduction. Further significant improvements would require a step change in combustor technology driven by low nvPM design parameters, but no such step change appears to be forthcoming.

One important aspect for climate science is that within a given combustor design nvPM and NO_X can be traded with each other, perhaps around 10% NO_X for up to an order of magnitude nvPM mass. Within the bounds of certification limits, policy indication to manufacturers is needed as to where to place combustor designs within this trade space. From information provided to the workshop, a greater emphasis on nvPM reduction at the expense of NO_X reduction would appear to be the correct direction to trade, conveniently mirroring the increased air quality concerns over nvPM ultrafine particles. Due to the limited knowledge on nvPM mitigation technologies, potential trade-offs with fuel burn are not well understood.

In summary, the lean burn and advanced RQL NO_X-reduction combustor technology appear to offer major reductions in nvPM emissions for the next 10-20 years. However, further work is needed to quantify nvPM emissions in cruise, the quantity of below-detection-threshold-particles and the prioritisation between nvPM and NO_X reductions. Beyond 2040-2050, hybrid/electric aircraft and novel airframe configurations could offer further significant reductions in both nvPM and NO_X emissions.

3.7.3 Fuel burn: propulsive efficiency, aerodynamics and weight reduction

Laminar flow, wing tips devices, fuselage shape, new materials and drag reduction are all being integrated into aircraft and engine designs to make further fuel efficiency improvements. These reductions in fuel burn generally provide a win-win situation without trade-offs for other emissions. Some potential impact on contrail formation from fuselage shape changes has been mentioned by climate science/contrail modelling contributors.

Another potential trade-off is that the formation of aircraft contrails has some dependence on increased overall propulsive efficiency of the aircraft/engine combination. Higher propulsive efficiency may cause contrails at higher ambient temperatures and over a larger range of flight altitudes. However, this factor was not considered as a significant effect for current contrail-cirrus formation by the climate scientists at the Task 1 workshop on 20 November 2019.

Key points from 3.7:

- NO_X vs Specific Fuel Consumption: Simultaneous reductions in overall NO_X emissions and specific fuel consumption have been achieved in the past. However, there is an acknowledged trade-off between fuel consumption and NO_X at the combustor level. The general trend in the global fleet to use engines with higher overall pressure ratios to provide better specific fuel consumption, means that emission indices of NO_X (kg of NO_X per kg of fuel burnt) are not reducing over time. However, emissions of NO_X per passenger kilometre do show a reduction over time. An increase in the stringency of the engine NO_X emissions certification standard may have fuel burn penalties.
- NO_X vs nvPM: There are potentially important trade-offs that need to be taken into account between NO_X and nvPM control technologies if more stringent regulation for either is considered. However, the lean burn and advanced RQL NO_x-reduction combustor technology appears to offer the potential for major reductions in LTO

nvPM emissions. Improved understanding of cruise NO_X and nvPM emissions are required to assess trade-offs in this flight phase.

- Aerodynamic and weight saving technologies that improve fuel efficiency generally lead to a simultaneous reduction in NO_X and nvPM emissions.

3.8 Operational /ATM Measures and Potential Trade-Offs

The focus of Task 2 in this area is to provide generic commentary on operational means to reduce non-CO2 impacts, and the associated CO2 trade-offs, rather than on the conclusions of the studies which to some degree already include interpretations of relative importance of individual forcing agents, time horizons and climate metrics.

The overall climate impact of NO_X emissions during cruise is dependent on the altitude and other factors such as background concentrations (see Task 1). For contrail and contrail-cirrus formation, the location of the flight in terms of altitude latitude/longitude as well as time of day are important as the contrail is only formed by the jet exhaust in cold and dry atmospheric conditions.

As both the climate impacts of NO_X and contrail formation have a dependence on the flight path location, it is best perhaps to consider these factors together. Operational measures to reduce the climate impacts of NO_X emissions, and to avoid the formation of contrails, has been the subject of European research through the Tradeoff, REACT4C and ATM4E studies (Grewe *et al,* 2014 and Matthes *et al*, 2018).

In both the REACT4C and the ATM4E studies, climate cost functions were developed whereby a climate impact, using a particular metric or set of climate metrics, is determined on a route by route basis. This would allow the most 'climate-friendly' route, or in the case of ATM4E the most 'environmentally-friendly' route, to be identified at operational flight planning level.

A climate cost function incorporates the climate impacts of a particular flight, principally NO_X, contrail-cirrus and CO_2 impacts. It is based on an agreed relative importance of individual emissions species for a reduction of the climate impact from air traffic, as well as an agreed metric and time scale. Potential reductions in climate impacts were demonstrated to be possible on some routes based on the assumptions embedded in the data.

The above studies concluded that, for a 1% fuel penalty, the formation of contrail-cirrus could be avoided leading to a 50% reduction in Average Temperature Response (ATR_{ref}) from aerosol induced cloudiness (AIC). Reductions in the impact of NO_X emissions were much smaller with a reduction in ATR_{ref} of 1 or 2%. For a fuel penalty of 5%, the calculated reduction in ATR_{ref} from AIC avoidance is around 65%.

Subject to the science in Task 1, and consideration of feasibility in Task 3, these types of operational measure warrant further consideration.

Key points from 3.8:

- Contrail avoidance by changing flight paths, horizontally or vertically, generally have fuel burn penalties as this involves flying further or at sub-optimum altitudes. Further research is required to identify mitigation options that ensure an overall reduction in climate impact.

3.9 Fuels and Potential Trade-Offs

There is a known impact of fuel composition on emissions of nvPM. Naphthalenes, a type of aromatic compound, in jet fuel have been identified as disproportionate contributor to nvPM emissions compared to other fuel species (DeWitt et al. 2008; Moore et al. 2015, Brem et al. 2015). On average, naphthalenes constitute less than 2% of the total composition of jet fuel, and less than 10% of the total aromatic content (PQIS, 2013).

Aviation fuels from biogenic wastes and residues (i.e. biofuels) tend to have naturally low levels of aromatics and sulphur compared to conventional fossil fuel-based kerosene. Alternatively, the composition and therefore emission characteristics can be changed through the hydrotreatment (see 3.9.1) of conventional fossil fuels to reduce aromatics and sulphur.

Data on the actual specifications of fuel uplifted, including sustainable aviation fuel and the geographical variation, are not well known and is the subject of ongoing work.

3.9.1 Processing of fossil fuels

There are refinery processes that can be used to eliminate naphthalenes in jet fuel feedstocks, namely hydrotreating and extractive distillation. Hydrotreating is the main method and involves reaction with hydrogen at mild conditions in order to saturate aromatics and removes sulphur components. The process is designed to semi-saturate naphthalenes (Gary et al., 2007) that would result in a decreased aromatic content in the fuel and subsequently lower emissions of both nvPM mass and nvPM number. A second process is extractive distillation where di-aromatics such as naphthalene are selectively removed from jet fuel using a polar solvent (Meyers, 2004). The extracted naphthalene is either used elsewhere in the refinery, or burned for process heat.

Both these processes entail an economic and energy cost, and increased CO_2 emissions from hydrogen production for the hydrotreating and utilities for both. There would have to be careful consideration as to the emissions involved in the processing to understand the life cycle emissions involved. Initial work in this area would suggest that the CO_2 emissions from the additional processing would be significant unless renewable energy is utilised.

3.9.2 Sustainable aviation fuels (from biogenic wastes and residues)

As noted above, aviation biofuels tend to be lower in aromatic/naphthalene and sulphur content. It has been shown from measurements at both the ground and at altitude that utilization of biofuels reduced nvPM emissions from gas turbine engines. (e.g. Beyersdorf *et al*, 2014 and Lobo *et al*, 2012)

The well-to-tank fuel processing steps for sustainable biofuels has come under considerable scrutiny, and standard values of the GHG life cycle (in terms of CO_2 equivalents) for a number of feedstocks are defined in the EU Renewable Energy Directive (RED) as well as in ICAO's Carbon Offsetting and Reduction scheme for International Aviation (CORSIA). One of the largest potential factors in determining life cycle analysis (LCA) reductions of CO_2 over fossil kerosene is the land use change from bio-feedstocks.

Key points from 3.9:

- Utilization of sustainable aviation fuels (biofuels and PtL) has been shown from measurements at both the ground and at altitude to reduce soot particulate emissions from gas turbine engines as they have reduced aromatics and sulphur content.
- There is scope for improving emission characteristics through the hydrotreatment of conventional fossil fuels to reduce aromatics and sulphur components. However, the overall costs and energy requirements need to be examined carefully in order to balance the differential environmental benefits (e.g. reduced soot emissions but extra energy of processing the fuel requirements, and therefore increased CO_2 emissions unless renewable energy is utilized).

[placeholder for aviation-related illustration]

4. TASK 3: What research has been undertaken on potential policy action to reduce non-CO_2 climate impacts?

4.1 Introduction

This chapter aims to identify measures to address the non-CO_2 climate impacts of aviation and present initial thoughts on those that could be further developed.

The method in section 4.2, which was used to identify mitigation measures, combines potential policy aims with types of policy measures and subjects the results to feedback from a wider audience.

The criteria in section 4.3 were developed in order to select the measures. Some criteria were used to eliminate measures from the list, while others are used to categorize measures according to the time it would take to develop them, given data requirements and other issues.

Following extensive discussions, both within the consortium and in two stakeholder meetings, section 4.4 identifies six potential policy options to address the non-CO_2 climate impacts of aviation that were shortlisted for further consideration

4.2 Identification of measures to address non-CO_2 climate impacts of aviation

As discussed in section 2.1, the climate impacts of aviation stem from emissions of CO_2, NO_x, water vapour, SO_2 and soot particles, as well as from the formation of contrails and cirrus, other aerosol-cloud interactions, the formation of O_3 and reduction of CH_4 lifetime in the atmosphere. Of these impacts, the ones resulting from the emissions of CO_2, NO_x and the formation of contrails and cirrus are considered to be the largest in terms of radiative forcing. Aerosol-cloud interactions (of sulphur on low-level clouds and soot on high-level ice clouds, see section 2.2.2) could also be potentially large, but there is still significant uncertainty associated with the magnitude of these impact and even the sign (warming/cooling) of soot effects on ice clouds. Consequently this study has focused on measures that aim to address emissions NO_x, the formation of contrails and cirrus, or the overall climate impact of aviation.[38]

Many of these impacts are interdependent, and technological or operational changes that can reduce one or more impacts may result in synergies or trade-offs between impacts. For example, as discussed in Chapter 3, contrails and cirrus formation can be reduced by avoiding flying in areas of ice supersaturated air. However, doing so may result in greater

[38] With the development of new aircraft designed for operations at supersonic speed and higher cruise altitudes in the dry stratosphere, water vapour emissions are likely to become more important in the future. However, the scope of the current research focusses on mitigating the non-CO_2 effects of aircraft flying at subsonic speed.

fuel consumption and thus larger CO_2 emissions. Likewise, policies aimed at reducing NO_X emissions may in some instances result in the development of new engine types that have lower NO_x emissions at the expense of greater fuel burn and CO_2 emissions. Synergies exist between reducing soot and SO_2 emissions on the one hand and contrails and cirrus formation on the other hand, as reducing soot particle emissions would also result in reduced contrail formation.

Keeping in mind that impacts can be interdependent, and that they cannot be addressed in isolation, the following potential policy aims were identified:

1. Reduce the overall climate impact of aviation;
2. Reduce the climate impacts of NO_x emissions, either
    a. Not at the expense of CO_2 emissions; or
    b. Possibly at the expense of CO_2 emissions as long as the overall climate impact is not increased.
3. Reduce the climate impact of contrails and cirrus clouds, either:
    a. While simultaneously reducing CO_2 emissions;
    b. Not at the expense of CO_2 emissions; or
    c. Possibly at the expense of CO_2 emissions as long as the overall climate impact is not increased.

Note that the other non-CO_2 climate impacts are very small in comparison to NO_x and contrails / cirrus, and are therefore not considered in isolation.

The following policy types are considered:

1. Standards:
    a. Aircraft technology standard;
    b. Engine technology standard; or
    c. Fuel quality standard.
2. Market-based measures:
    a. Emissions trading; or
    b. Taxes and charges.
3. Changes in air traffic management procedures.

An initial matrix was developed of possible aims and the types of policy measures to achieve these aims (see Table 1).

	Policy Measure					
	Standards			**Market-based measures**		**Operations**
Policy Aim	**Aircraft standard**	**Engine standard**	**Fuel standard**	**Emissions trading**	**Taxes and charges**	**ATM procedures**
Reduce overall climate impact	-	-	-	Include overall climate impact in EU	Differentiate ATM route charges with respect to climate	Optimise ATM for lowest climate impact

				ETS	impact Charge departing flights for overall climate impacts	
Reduce NO_x emissions	-	Introduce new standard for LTO NO_x emissions Develop engine cruise-NO_x standard	-	Include aircraft NO_x emissions in the EU ETS	Introduce a cruise-NO_x charge Introduce an LTO-NO_x charge with a distance factor	
Reduce contrail and cirrus formation	-	Introduce new LTO-nvPM standard Develop cruise-nvPM standard	Reduce aromatics and sulphur content of fuels	Include nvPM emissions in EU ETS	Introduce a nvPM emission charge Introduce a charge on the aromatics content of the fuel	Avoid ice-supersaturated areas

Table 1. Overview of conceivable policy measures to address the most significant non-CO_2 climate impacts of aviation.

For each of the measures included in Table 1, potential impacts on the climate effects of aviation are evaluated based on the trade-offs and synergies identified in Chapters 2 and 3. The trade-offs and synergies are summarised in Table 2.

Policy Measure	Short-term trade-offs and synergies (constant technology)	Long-term trade-offs and synergies (taking technology development into account)
Include overall climate impact in EU ETS	No trade-offs or synergies expected if the overall climate impact can be accurately measured.	
Differentiate ATM route charges with respect to climate impact		
Charge departing flights for		

Policy Measure	Short-term trade-offs and synergies (constant technology)	Long-term trade-offs and synergies (taking technology development into account)
overall climate impacts		
Optimise ATM for lowest climate impact		
Develop aircraft cruise-NO_x standard	None	Potentially higher CO_2 emissions as future engines may reduce NO_x emissions at the expense of fuel consumption and, assuming that fossil fuels continue to be used, CO_2 emissions.
Introduce new standards for LTO NO_x emissions		
Develop engine cruise-NO_x standard		
Include aircraft NO_x emissions in the EU ETS		
Introduce a cruise-NO_x charge		
Introduce an LTO-NO_x charge with a distance factor		
Introduce new LTO-nvPM standard		
Develop cruise-nvPM standard		
Standard for the maximum aromatics content of fuels	Lower aircraft CO_2 emissions because of the higher energy density of low-aromatics fuels, but potentially higher lifecycle CO_2 emissions because the energy required to reduce the aromatics content	Impact on CO_2 is independent of aircraft or engine technology
Mandatory use of sustainable aviation fuels	Lower tank-to-wing CO_2 emissions because the energy density of aromatics is lower than the energy density of alkanes. Lower lifecycle CO_2 emissions.	Impact on CO_2 is independent of aircraft or engine technology
Include nvPM emissions in EU ETS	None	Potentially higher NO_x emissions as future engines may reduce nvPM emissions at the expense of NO_x emissions and, assuming that fossil fuels continue to be used, CO2 emissions
Introduce a nvPM emission charge		
Introduce a charge on the aromatics content of the fuel		

Avoid ice-supersaturated areas	Higher CO_2 emissions because of change in flight levels and/or larger deviations from great circle distance (shortest distance from origin to destination).	Impact on CO_2 is independent of technology

Table 2. Impacts of policy measures to reduce specific non-CO_2 climate impacts of aviation on other non-CO_2 climate impacts

4.3 Criteria for the selection and classification of measures

In order to select a short-list of measures that would be developed further in the next stages of the project, criteria have been developed for the selection and classification of measures.

As the policy context of measures to address the non-CO_2 climate impacts of aviation is climate policy, measures which are not in line with overall climate policy goals are discarded.

Criteria 1: The measure is effective, i.e. in line with the Paris Agreement and Europe's Nationally Determined Contributions

Article 2 of the Paris Agreement expresses a temperature goal, i.e. to hold "*the increase in the global average temperature to well below 2°C above pre-industrial levels and [to pursue] efforts to limit the temperature increase to 1.5°C above pre-industrial levels*". According to the IPCC Special Report *Global Warming of 1.5°C* (IPCC 2018), the temperature goal implies reducing CO_2 emissions to net zero by around 2050 and to reduce the emissions of non-CO_2 emissions (including short-lived climate forcers).

Because Article 2 does not set a target date for the temperature goal, we understand that the temperature should remain well below 2°C indefinitely. This means that any policy should also take into account the impacts over time periods beyond 2100.

Criteria 2: The measure is based on science while taking the precautionary principle into account

As an environmental policy measure, the measure has to be based on science and in line with the current scientific understanding. In line with Article 191 of the Treaty, the measure has to be in line with the precautionary principle, as explained also in Communication COM(2000) 1 final .

If the science is not sufficiently clear due to uncertainty about the sign of the effect (e.g. whether the effect can be expected to remain positive or become negative in the future), a measure can be categorised as requiring further scientific research before it can be designed and implemented.

Criteria 3: The measure is implementable

The measure has to result in a reduction in the climate impact of aviation. This requires a change in technology or operational practice of actors involved. It should therefore be clear which actors will be responsible for fulfilling the requirements, and which requirements they have to fulfil. The requirements should also be measurable in order for them to be enforceable.

If a requirement cannot be formulated in a measurable way (e.g. because a certain indicator has yet to be developed), then it can be categorised as requiring further regulatory development.

Criteria 4: The measure is in the scope of competence of the EU or of its Member States

The policy action should be able to be formulated at the EU or MS level.

Policy Measure	Criteria 1. Effective in reducing climate impact	Criteria 2. Based on science and precautionary principle	Criteria 3. Implementable	Criteria 4. EU or MS policy
Include overall climate impact in EU ETS	The effectiveness depends on the accuracy of the climate indicator.	Although uncertainties remain in the exact magnitude of the Radiative Forcing of non-CO_2 climate impacts, the science is sufficiently clear that net non-CO_2 climate impacts of aviation are currently warming.	The development of climate impact indicators requires more work, including a decision on the choice of a climate metric.	EU ETS is an EU policy and currently includes intra-EEA flights.
Differentiate ATM route charges with respect to climate impact	The effectiveness depends on the accuracy of the climate indicator.	The science is sufficiently clear that net non-CO_2 climate impacts of aviation are currently warming.	The development of climate impact indicators requires more work, including a decision on the choice of a climate metric.	To be evaluated
Charge departing flights for overall climate impacts	The effectiveness depends on the accuracy of the climate indicator.	The science is sufficiently clear that net non-CO_2 climate impacts of aviation are currently warming.	The development of climate impact indicators requires more work, including a decision on the choice of a climate metric.	To be evaluated

Policy Measure	Criteria 1. Effective in reducing climate impact	Criteria 2. Based on science and precautionary principle	Criteria 3. Implementable	Criteria 4. EU or MS policy
			The introduction of a climate impact charge would require setting up a new charging system.	
Optimise ATM for lowest climate impact	The effectiveness depends on the accuracy of the climate indicator.	The science is sufficiently clear that net non-CO_2 climate impacts of aviation are currently warming.	The development of climate impact indicators requires more work, including a decision on the choice of a climate metric.	To be evaluated
Develop aircraft cruise-NO_x standard	The effectiveness depends on the stringency of the standard, the rate of fleet renewal, and the relation between NO_x emissions and warming, which may change in the future.	The net radiative forcing from aircraft NO_x is currently positive (warming) but this may change in the future, depending on the background concentration of other substances in the atmosphere.	The development of a cruise-NO_x standard requires gathering data on the cruise-NO_x emissions of current engines.	To be evaluated
Introduce new standards for LTO NO_x emissions	The effectiveness depends on the stringency of the standard, the relation between NO_x emissions and warming, which may change in the future, and on the relation between LTO NO_x and cruise	The net radiative forcing from aircraft NO_x is currently positive (warming) but this may change in the future, depending on the background concentration of other substances in the	LTO NO_x emissions are currently regulated.	EU Regulation 2018/1139

Policy Measure	Criteria 1. Effective in reducing climate impact	Criteria 2. Based on science and precautionary principle	Criteria 3. Implementable	Criteria 4. EU or MS policy
	NO_x.	atmosphere. The relation between cruise NO_x and LTO NO_x is not well understood for modern engines.		
Develop engine cruise-NO_x standard	The effectiveness depends on the stringency of the standard, the rate of fleet renewal, and the relation between NO_x emissions and warming, which may change in the future.	The net radiative forcing from aircraft NO_x is currently positive (warming) but this may change in the future, depending on the background concentration of other substances in the atmosphere.	The development of a cruise-NO_x standard requires gathering data on the cruise-NO_x emissions of current engines.	To be evaluated
Include aircraft NO_x emissions in the EU ETS	The effectiveness depends on the stringency of the standard, the rate of fleet renewal, and the relation between NO_x emissions and warming, which is uncertain, depending on timescales considered, and may change under future atmospheric conditions.	The net radiative forcing from aircraft NO_x is currently positive (warming) but this may change in the future, depending on the background concentration of other substances in the atmosphere.	The introduction of NO_x emissions would require the establishment of a monitoring system for NO_x.	EU ETS is an EU policy.

Policy Measure	Criteria 1. Effective in reducing climate impact	Criteria 2. Based on science and precautionary principle	Criteria 3. Implementable	Criteria 4. EU or MS policy
Introduce a cruise-NO_x charge	The effectiveness depends on the level of the charge, and the relation between NO_x emissions and warming, which may change in the future.	The net radiative forcing from aircraft NO_x is currently positive (warming) but this may change in the future, depending on the background concentration of other substances in the atmosphere.	The inclusion of cruise NOx emissions would require a robust data on the cruise-NOx emissions of current engines. The introduction of a cruise-NOx charge would require setting up a new charging system.	To be evaluated
Introduce a cruise-NO_x charge, approximated by LTO-NO_x emissions and a distance factor	The effectiveness depends on the level of the charge, the relation between LTO and cruise NO_x, and the relation between NO_x emissions and warming, which may change in the future.	The net radiative forcing from aircraft NO_x is currently positive (warming) but this may change in the future, depending on the background concentration of other substances in the atmosphere.	The introduction of an LTO-NO_x charge would require setting up a new charging system.	To be evaluated
Introduce new LTO-nvPM standard	The effectiveness would depend on the relation between LTO-nvPM and cruise-nvPM and on the stringency of the standard.	The relation between nvPM emissions and contrails and cirrus is sufficiently well established to conclude that a reduction of nvPM emissions would result in fewer contrails and less induced	LTO nvPM emissions are currently regulated, although the standard is being improved.	EU Regulation 2018/1139

Policy Measure	Criteria 1. Effective in reducing climate impact	Criteria 2. Based on science and precautionary principle	Criteria 3. Implementable	Criteria 4. EU or MS policy
		cloudiness.		
Develop cruise-nvPM standard	The effectiveness would depend on the stringency of the standard and the rate of fleet renewal.	The relation between nvPM emissions and contrails and cirrus is sufficiently well established to conclude that a reduction of nvPM emissions would result in fewer contrails and less induced cloudiness.	The development of a cruise-nvPM standard requires gathering data on the cruise-nvPM emissions of current engines.	To be evaluated
Lower the standard for the maximum aromatics content of fuels	The effectiveness depends on the reduction of cruise-nvPM emissions as a result of reduced aromatic content of aircraft fuels.	The relationship between aromatics content and nvPM emissions is well established. The relation between nvPM emissions and contrails and cirrus is sufficiently well established to conclude that a reduction of nvPM emissions would result in fewer contrails and less induced cloudiness.	The baseline of the aromatic content of aviation fuels would need to be established. Minimum aromatic contents would also need to be established.	To be evaluated
Mandate the use of blending of Sustainable Aviation Fuels	The effectiveness depends on the reduction of cruise-nvPM emissions as a	The relationship between aromatics content and nvPM	The baseline of the aromatic content of aviation fuels would need to	RED and FQD to be evaluated

Policy Measure	Criteria 1. Effective in reducing climate impact	Criteria 2. Based on science and precautionary principle	Criteria 3. Implementable	Criteria 4. EU or MS policy
	result of reduced aromatic content of aircraft fuels.	emissions is well established. The relation between nvPM emissions and contrails and cirrus is sufficiently well established to conclude that a reduction of nvPM emissions would result in fewer contrails and less induced cloudiness	be established. Minimum aromatic contents would also need to be established.	
Include nvPM emissions in EU ETS	The effectiveness would depend on the incentive to reduce nvPM emissions and the costs of fuel changes.	The relationship between nvPM emissions and contrails and cirrus is sufficiently well established to conclude that a reduction of nvPM emissions would result in fewer contrails and less induced cloudiness.	The introduction of an nvPM emissions charge would require the establishment of a monitoring system for nvPM.	EU ETS is an EU policy.
Introduce an nvPM emission charge	The effectiveness depends on the reduction of cruise-nvPM emissions as a result of the charge.	The relationship between nvPM emissions and contrails and cirrus is sufficiently well established to conclude that a reduction of nvPM emissions would result in	The introduction of an nvPM emissions charge would require setting up a new charging system and the establishment of a monitoring system for nvPM.	To be evaluated

Policy Measure	Criteria 1. Effective in reducing climate impact	Criteria 2. Based on science and precautionary principle	Criteria 3. Implementable	Criteria 4. EU or MS policy
		fewer contrails and less induced cloudiness.		
Introduce a charge on the aromatics content of the fuel	The effectiveness depends on the reduction of cruise-nvPM emissions as a result of reduced aromatic content of aircraft fuels.	The relationship between aromatics content and nvPM emissions is well established. The relationship between nvPM emissions and contrails and cirrus is sufficiently well established to conclude that a reduction of nvPM emissions would result in fewer contrails and less induced cloudiness.	The introduction of a charge on the aromatics content of aviation fuel would require setting up a new charging system. It is debatable whether a charge on the aromatics content of a fuel would be allowed under Air Service Agreements that mutually grant tax exemptions for aviation fuels.	To be evaluated
Avoid ice-supersaturated areas	The effectiveness depends on the additional fuel required to avoid ice-supersaturated areas.	It is well established that avoiding ice-supersaturated areas would reduce contrails and cirrus. However, the relative climate impacts of contrails and CO_2 depend on the metric chosen.	To be evaluated based on ATM system constraints. It is not clear whether ice-supersaturated areas can be predicted with sufficient accuracy.	To be evaluated

4.4 Shortlist of measures for further development

Based on Section 4.3, the measures can be categorised as follows:

Measures that can be implemented based on existed legislation or regulatory systems:

- Introduce a cruise-NO_x charge, approximated by LTO NO_x emissions and a flight distance factor;
- Include aircraft NO_x emissions in the EU ETS;
- Introduce new standards for LTO NO_x emissions
- Introduce new LTO-nvPM standard

Measures that require the development of monitoring systems or other regulations:

- Measures that require monitoring of aromatics content
  - Reduce aromatics contents of fuels via maximum fuel specifications limit;
  - Introduce a charge on the aromatics content of the fuel;
  - Mandatory use of sustainable aviation fuels
- Measures that require monitoring of cruise nvPM emissions
  - Include nvPM emissions in EU ETS
  - Introduce an nvPM emission charge
- Measures that require monitoring of cruise-NO_x emissions
  - Include cruise NO_x emissions in the EU ETS;
  - Introduce a cruise-NO_x charge
- Measures that require the development of a new type of standard:
  - Develop aircraft cruise-NO_x standard
  - Develop engine cruise-NO_x standard

Measures that require further scientific research:

- All measures relating to holistic optimisation of the climate impact:
  - Include overall climate impact in EU ETS
  - Differentiate ATM route charges with respect to climate impact
  - Charge flights for overall climate impacts
  - Optimise ATM for lowest climate impact
  - Avoid ice-supersaturated areas

In general, the climate impact of contrails and induced cirrus cloudiness is less sensitive to changes in background concentrations than the impacts of NO_x emissions. While the sign of the NO_X impacts may change when background concentrations change, the net climate impact of contrails and cirrus is typically positive (warming). Moreover, there are solutions to reducing nvPM emissions, and thereby contrails, that do not lead to increases in CO_2 emissions. These are related to fuel changes, and it is therefore proposed to further consider measures that require improvements in fuel quality.

Measures based on LTO-NO_x emissions have the advantage that they can be introduced without the further development of standards or monitoring systems. With the current trend in background concentrations reducing the positive radiative forcing of NO_x emissions, and the continued correlation between LTO NO_x and cruise NO_x, it is proposed to select measures based on LTO-NO_x emissions for further consideration while keeping an eye on the possible impact these measures may have on CO_2 emissions.

Although they require further scientific research, measures based on indicators that capture the total climate impact of flights would be the most effective because all trade-offs and synergies would be captured by the indicator.

Following extensive discussions, six potential policy options to address the non-CO_2 climate impacts of aviation were shortlisted for further consideration (see Table 3).

Type of Measure	**Main non-CO_2 effect(s) addressed by the measure**	**Report Section**
NO_X charge	NO_X	5.1
Inclusion of aircraft NO_X emissions in EU ETS	NO_X	5.2
Reduction in maximum limit of aromatics within fuel specifications	Soot particulates and contrail-cirrus	5.3
Mandatory use of Sustainable Aviation Fuels (SAF)	Soot particulates and contrail-cirrus	5.4
Avoidance of ice-supersaturated areas	Contrail-cirrus	5.5
A climate charge	All (NO_X, water vapour, soot, sulphates, contrails)	5.6

Table 3 – Overview of considered policy options

Section 5 presents a high-level design of these six short-listed policy options to address the non-CO_2 climate impacts of aviation. For each of the options considered, a proposal is made on the design and administration of the measure.

Furthermore, important caveats and constraints that need to be considered for each measure are identified, as are the stakeholders that would need to be involved for a successful and effective implementation of the measure. Areas for further research are suggested in order to fill gaps that are needed to implement the options, and initial thoughts are provided on the timescale over which the measure can be implemented. Some measures may be suited for implementation in the short-term, whereas others may only be feasible in the mid to long-term.

The reference scenario, against which each of these measures is held, is the current situation. This implies that all measures are considered in addition to the measures currently in place (e.g. aviation under EU ETS but limited to all intra-EEA flights).

Finally, it is important to note that there are a number of measures already in place to address the non-CO_2 impacts of aviation. Most of these are of a technical nature and are hence already addressed in Task 2 (e.g. aircraft engine NO_X and nvPM emissions standard, airport NO_X charging schemes).

5. TASK 3: Potential policy options

5.1 NO_X charge

5.1.1 Definition of the measure

The NO_X charge is defined as a monetary charge on the accumulated NO_X emissions over the course of the whole flight, by approximating cruise NO_X emissions from Landing Take-Off (LTO) NO_X emissions and the distance flown (Figure 9). The charge would be aircraft- and route-specific, and would be based on the LTO cycle NO_X emissions by assuming a linear factor between LTO NO_X emissions and cruise NO_X emissions. Hence, it is a policy measure that addresses a subset of the non-CO_2 climate impacts of aviation and the local air pollution impacts, as it takes into account NO_X emitted during both LTO and cruise. Earlier studies have previously investigated this measure (CE Delft et al., 2008), and more recently the DLR investigated a distance dependent CO_2 factor, which shows some similarities to the NO_X charge with a distance factor (DLR, 2019).

The LTO NO_X emissions per aircraft engine type can be found in the ICAO Aircraft Engine Emissions Databank (EASA, 2020). This databank contains information on various exhaust emissions of aircraft engines measured according to the certification requirements in ICAO Annex 16, Volume II.

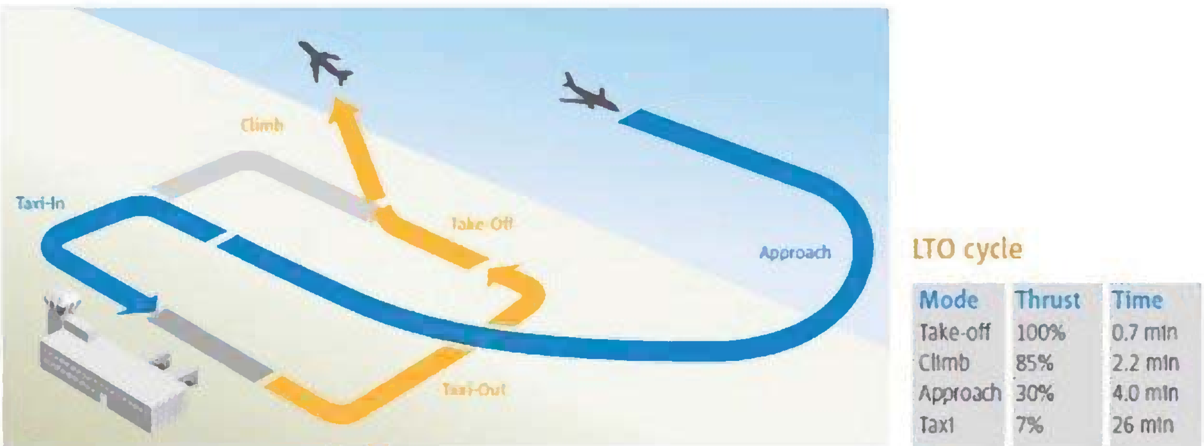

Figure 9 - Standard engine emissions LTO cycle[39]

Although data about LTO NO_X emissions are available, there are uncertainties regarding the scaling of LTO NO_X to cruise NO_X emissions, especially for new technologies such as lean burn combustors (see section 3.4.3). However, in order to adequately address the climate impacts of aviation during cruise, an approximation of the cruise NO_X emissions can be made based on LTO NO_X emissions, and this has been done in a number of studies. Such studies have shown that, at the time, LTO NO_X and cruise NO_X were correlated when looking at a

[39] European Aviation Environmental Report – Appendix D.

range of engines and planes. Past analyses have concluded that a reduction in LTO NO_X will also result in a reduction of NO_X emissions at cruise and, based on the premise that the overall impacts of NO_X emissions at cruise are warming, this will help reduce the climate change impacts of aviation. However, it is acknowledged that there is greater uncertainty with regard to the relationship between LTO NO_X emissions and cruise NO_X emissions for new technology (e.g. lean burn staged combustors).

Currently, a number of EU airports have already implemented an LTO NO_X charge as a part of their emission charging scheme, e.g. London Heathrow (Civil Aviation Authority, 2017), Copenhagen (Copenhagen Airport, 2010), Stockholm (Swedavia, 2018) and Zurich (Zurich Airport, 2010). However, EU-wide implementation, and the addition of the flight 'distance factor' to also incorporate climate impact during cruise, would be a new aspect of this measure. There are other charges (e.g. UK Air Passenger Duty) that work with distance bands, but these are not NO_X related charges.

An LTO NO_X charge with a distance factor would be a new legal instrument at EU level. In order to maximise the effect of this measure the geographical scope would need to be set at all flights departing the European Union, regardless of their destination (intra- or extra-EU).

5.1.2 Design of the measure

Analytical methods exist that characterise the relationship between emissions of NO_X per unit of fuel burnt during the LTO phase and the emissions of NO_X that occur during the cruise phase (CE Delft et al., 2008). While the relationship between LTO NO_X and cruise NO_X may not be as robust for new technologies, these methods are still considered to provide the best estimates for cruise NO_X.

Earlier work by CE Delft et al. (2008) revealed that approximately 90% of the variance in trip NO_X emissions can be explained by LTO NO_X * distance. Based on this data, we assume that fuel burn in LTO is correlated with fuel burn in cruise[40], and that fuel burn is related to distance flown. From this, and other factors, the total NO_X emissions of the flight could be approximated according to the formula below.

$$Total\ NOx_{i.j} = \beta \times LTONOx_i \times D_j$$

Where:

- $Total\ NOx_{i.j}$ is the total NO_X emissions for aircraft i on route j in mass units (kg).
- β is the factor that transforms the total NO_X LTO emissions to cruise emissions per kilometre. It can be either a fleet average of an engine specific factor.
- $LTONOx_i$ is the aircraft i engine NO_X emissions per LTO cycle in mass units (kg) taken from the ICAO Aircraft Engine Emissions Database.
- D_j is the distance of the route flown in kilometres (km). This would ideally be a continuous distance metric based on great circle distance (shortest distance) between the two airports.

[40] It is important to note that this assumption is based on data, although this is relatively old data from before large scale introduction of staged combustion in aircraft.

Once the total NO_X emissions of the flight have been calculated according to the formula above, the emissions can be multiplied with the NO_X charge per kg, in order to reach the total size of the charge, which is aircraft- and route-specific.

$$Charge_{i,j} = \alpha_{Clim\ NOx} \times Total\ NOx_{i.j}$$

Where:

- $Charge_{i,j}$ is the charge for aircraft i on mission j in Euro.
- $\alpha_{Clim\ NOx}$ is the charge level in Euro per unit of emitted NO_X mass (€/kg), set at the monetary value of the climate impact of NO_X

α, the level of the charge per kg of NO_X emitted, could be set at the global warming potential (GWP) of aviation NO_X (NO_X emissions x GWP) multiplied by the climate damage costs of CO_2 [41]. Alternatively, the GWP could be replaced by GWP* or the global temperature change potential (GTP), over some time horizon. Task 1 provides insight into the current GWP, GWP* or GTP of NO_X compared to CO_2. However, which of these metrics to use is an issue that deserves further research (see section 5.1.6). In contrast to the measure in section 5.2, where aircraft NO_X emissions are included in EU ETS, one can still choose which metric to use to compare the climatic impact of NO_X to CO_2 for this measure. In the current EU ETS, nitrous oxides (N_2O) and perfluorocarbons (PFCs) are translated to CO_2-equivalents using GWP100. Note, however, that these substances are longer-lived than the greenhouse gases influenced by emissions of NO_X. For this new measure, one could potentially choose alternative metrics (e.g. GTP or GWP*). A full discussion on metrics and how the different metrics compare to each other is provided in Task 1.

The level of the charge should be set at the climate damage costs of CO_2, which are an on-going point of discussion (CE Delft et al., 2019; Botzen & van den Bergh, 2012; Burke et al., 2016; ExternE, 2005; Watkiss et al., 2005a). From a theoretical perspective, the damage costs of CO_2 correspond to the marginal social costs of CO_2. While the social costs of carbon could be used in principle, the risk is that aviation pays a different price for CO_2, in comparison to the EU ETS price, which reflects the marginal prevention costs. If there is a misalignment of the two prices, either NO_X reduction or CO_2 reduction is over-incentivised. An alternative would be to approximate the climate damage costs of CO_2 using the price of emission allowances in the EU ETS. Over the year 2018, the average emission allowance price was €15.50 per tonne of CO_2 (EEA, 2019). The climate damage cost figure would have to be adjusted annually to take into account changes in the EU ETS allowances.

It is important to note that this measure could potentially also be applied on an nvPM emissions or full climate impact basis. However, it is more challenging to predict analytically the cruise nvPM emissions from LTO emissions data, while the full climate impact basis would require a decision on an appropriate CO_2 equivalent emissions metric and a more complex methodology.

5.1.3 Administration of the measure

[41] Please note than in theory the charge level α can be changed into a subsidy if the sign of the climate impact of NO_X changes.

The administration of the measure can be delegated to three different levels, each having their own advantages. The administration of the measure could be placed with individual airports, at the level of the Member State level or be delegated to an appropriate body at the European level.

Airports

Arguably, airports are well placed to handle the administration of the measure. The basis of the charge is the great circle distance of each flight, and the LTO NO_X emissions of the aircraft type. Airports already knows the routes flown by aircraft and can hence calculate the great circle distance per flight. They also already have information on the aircraft engine configuration that is used, and can hence look up the LTO engine NO_X emissions per aircraft type in the ICAO Aircraft Engine Emissions Databank.

However, airports are legally speaking not permitted to levy charges other than those for the use of airport facilities. Any charges that are levied by airports have to be related to landing, take-off, lighting, parking of the aircraft and the processing of passengers and freight according to Directive 2009/12/EC of the European Parliament and of the Council (European Parliament, 2009). Therefore, the airports, although well-placed, do not currently have the jurisdiction to levy the charge.

Member States

Member States have the legal jurisdiction to administer the charge, and can enforce the legislation on occasions when the charge has not been paid. However, Member States themselves may not have information on all flights departing the country. This information that airports have, in terms of flight destinations and aircraft type used, would need to be communicated to the Member States. Member States would then need to use the ICAO Aircraft Engine Emissions Databank so that they can hence look up the LTO NO_X emissions per aircraft type. Alternatively, this could also be done by the airports, so that only the task of actually levying the charge would be done by the Member State.

Regardless of whether the Member States administer the charge themselves or whether they delegate the responsibility to another organisation, the Member States will need to agree to the implementation of this measure at the EU level. Depending on whether the measure qualifies as a tax, it could require unanimity, as opposed to qualified majority in the European Council.

European Union

The necessary legislation and implementation of this option will need to be considered within the context of the regulatory framework of the Single European Sky Performance and Charging Scheme[42], as well as other financial policy options (including those already in place) and notably within the DG TAXUD intended review of taxation of aviation kerosene.

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[42] COMMISSION IMPLEMENTING REGULATION (EU) 2019/317 of 11 February 2019 laying down a performance and charging scheme in the single European sky and repealing Implementing Regulations (EU) No 390/2013 and (EU) No 391/2013.

To keep the administrative burden as low as possible, it would be ideal if all the steps of the administrative arrangements are handled within the same organisation as every exchange of information or funds between organisations adds administrative complexity to the issue.

The basis of the charge is the great circle distance of each flight, and the LTO NO_X emissions of the aircraft type. Access to relevant databases would be needed on routes flown by aircraft-engine configuration and what aircraft is being used. The LTO NO_X emissions per aircraft engine type can be found in the ICAO Aircraft Engine Emissions Databank.

5.1.4 Incentives from the measure

Engine manufacturers

With the implementation of the LTO NO_X charge with a distance factor, engine developers will indirectly have an incentive to reduce NO_X emissions from aircraft engines. However, due to the NO_X-CO_2 trade-off in engines, and depending on the size of the charge, manufacturers could start reducing NO_X emissions in engines at the expense of increased fuel burn / CO_2 emissions. As such, the NO_X charge needs to be set at the right level, otherwise it could lead to an undesirable outcome where the climate impact of this measure is positive (i.e. warming) due to the increased CO_2 emissions more than offsetting the environmental benefit created by the reduction in NO_X emissions (Freeman et al., 2018). This can be avoided if the design of the measure is well thought out, and the price incentives are accurately set to reflect the relative impacts of NO_X and CO_2 emissions on global warming.

A similar trade-off exists between NO_X emissions and nvPM emissions. Optimising engines to minimise NO_X emissions may lead to increases in nvPM, which in turn enhances contrail formation and has a net warming effect.

Care should be taken in the design of this measure so that both of these trade-offs do not lead to a detrimental effect on the climate.

Airlines

Through this measure, airlines would need to pay for the NO_X emissions. As a result, they will be incentivised to invest in aircraft with lower NO_X emissions. If this measure were to be implemented at all European airports, this would provide a larger scale stimulus for the use of low NO_X emitting aircraft. In the short run, this could imply some tactical switching of aircraft on certain routes (e.g. routes to and from the European Union vs. rest of the world), whereas in the longer run, the charge may provide enough incentive to invest in lower NO_X emitting aircraft engines.

5.1.5 Caveats and constraints

There are four notable caveats or constraints associated with this measure.

LTO NO_X - cruise NO_X relation

Although aviation NO_X emissions are relatively well quantified compared to other sources, there are uncertainties regarding the scaling of LTO NO_X to cruise NO_X. LTO NO_X emissions are relatively well quantified through engine certification data. Cruise NO_X emissions are not as well characterised for many of the new staged combustion technology. Past analyses have concluded that a reduction in LTO NO_X will also result in a reduction of NO_X emissions at cruise.

Recent developments, such as staged combustion (e.g. lean burn), has led to questions regarding this correlation. The Boeing Fuel Flow Method (BFFM2) and the DLR fuel flow method have been applied to staged combustors. However, obtaining additional data about the cruise NO_X emissions of aircraft would permit a more accurate NO_X charge to be levied over distance.

Impact of NO_X and how it will evolve in the future

As noted in section 2, the current scientific understanding is that the net effect of NO_X forcing is positive, i.e. warming. However, under future emission scenarios of declining emissions of tropospheric ozone precursors (e.g. RCP4.5) from surface sources, combined with a 'business as usual' aviation scenario (i.e. increasing aviation emissions), this may result in a net negative RF effect (cooling) from aviation NO_X emissions (Skowron et al. 2020).

Metrics

Establishing accurate factors that compare the climate change impact of NO_X emissions to CO_2 emissions is of crucial importance to this measure, due to the different timescales on which these pollutants operate. While GWP, GWP* or GTP metrics could be used, the impact of using one these measures compared to the others should be captured before a definitive decision is made. For a full discussion on CO_2 equivalent emissions metrics, see section 2.3.

ICAO policies and international law

According to past studies (CE Delft et al., 2008), a NO_X charge would comply with ICAO policies such as those laid down in (ICAO, 2000) and (ICAO, 2012) because they would internalise an external cost. As such, they are not considered to be a tax. Subjecting all flights to and from EU airports to such a charge was also considered to be compatible with relevant international law.

5.1.6 Further research

Further research should be conducted before a NO_X charge with a distance factor can be implemented. Based on the sections above, two major areas have been identified where further research would be particularly useful.

Firstly, efforts should be made such that a good metric and method for identifying cruise NO_X emissions can be established. With increasingly widespread use of new developments such as staged combustion (e.g. lean burn), the previous method for estimating cruise NO_X based on LTO NO_X may need to be updated. It is of vital importance for the implementation of this measure that an internationally recognised methodology for measuring/estimating cruise NO_X emissions is established.

Secondly, we have identified that the charge level of the NO_X emissions should be set at the monetary value of the climate impact of NO_X. However, there are remaining questions to be addressed on which relevant metric to use, e.g. GWP, GWP* or GTP, and over which timescale. Establishing accurate factors that compare the climate change impact of NO_X emissions to CO_2 emissions is of importance to this measure in order to ensure that the trade-off in engine technology between NO_X and CO_2 does not result in unintended consequences and a net warming effect.

5.1.6 Conclusion

In conclusion, there are two areas that are crucial to this measure that deserve further research, the relationship between LTO NO_X and cruise NO_X with staged combustion engines and which climate metric should be used to ensure that the CO_2-NO_X trade-off in engine design is not exploited to the disadvantage of the climate.

The data needed to implement this measure is available, and the administration may not require a significant amount of additional effort. A legal analysis from 2009 revealed that neither ICAO's Chicago Convention or ICAO's recommended policies on taxes and charges should prevent the implementation of this measure.

The research issues are not considered to pose a major challenge, although the measure would require the development of a new policy instrument. If the issues linked to this measure are addressed, and there is the political will to take the option forward, then the measure could potentially be implemented in a mid-term timescale (5 to 8 years)[43].

[43] Rough estimates of timescales to implement policy options have been provided, but are dependent on addressing the identified research needs and the political will to take the options forward. For the purpose of this study, short-term is defined as 2-5 years, mid-term as 5-8 years and long-term as 8+ years.

5.2 Inclusion of aircraft NO_X emissions in EU ETS

5.2.1 Definition of the measure

The current EU ETS is a ‘cap and trade’ scheme in which emission allowances for CO_2 are traded among companies in a number of different sectors, including aviation. In addition to CO_2, other greenhouse gases are occasionally included in the EU ETS, such as nitrous oxide from the production of nitric, adipic and glyoxylic acids and glyoxal.[44]

This measure would entail extending the scope of the EU ETS and incorporating aviation NO_X emissions. This can be done if one can ‘translate’ the climate impact of NO_X into “equivalent CO_2” as the units traded in the EU ETS are CO_2 emission allowances (Scheelhaase, 2019).[45] Currently, N_2O and perfluorocarbons (PFC)[46] are converted into CO_2 equivalents using GWP100. Based on the fact that the original EU ETS legislation uses GWP100 to convert substances to CO_2 equivalents, it is assumed that including aircraft NO_X into EU ETS would also require using GWP_{100}. However, it is important to note that this will not always provide for a positive number (i.e. warming effect) due to the differences between short-lived NO_X and the longer-lived gases currently included in EU ETS. In that case, one may need to conduct further research in whether or not a different metric should be used.

As a result of the expansion of the scope of EU ETS, the cap of the EU ETS would have to be increased accordingly and a linear reduction factor would need to be applied to the aforementioned cap. In addition, adjustments to the free allocation would need to take place.

The inclusion of aviation NO_X emissions in the EU ETS would allow for a higher rate of internalisation of the full climate impact of aviation engine emissions. This would subsequently incentivise aircraft operators and engine manufacturers to design and operate engines that have the minimal combined CO_2 and NO_X impact on the climate (CE Delft et al., 2008). The measure has previously been investigated in (CE Delft et al., 2008) and (Niklaß, et al., 2019).

This measure addresses the same non-CO_2 issue as the LTO NO_X charge with a distance factor (section 5.1), and hence suffers from the same limitations in data regarding cruise NO_X emissions. It also has the benefit of addressing both the climate impact of aviation and the air quality levels near airports.

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[44] https://ec.europa.eu/clima/sites/clima/files/factsheet_ets_en.pdf

[45] Following this reasoning, all climate relevant species (e.g. nvPM, water vapour, contrails and contrail formation) could be compared to each other and included in the EU ETS. For the purpose of this measure, we only consider incorporating NO_X emissions into EU ETS.

[46] Not all N_2O and PFC emissions fall under EU ETS. Only (N2O) emissions from all nitric, adipic, glyoxylic acid and glyoxal production, and perfluorocarbons (PFC) emissions from aluminium production are currently regulated under EU ETS.

In contrast to many other measures outlined in this report, this measure could be implemented by adjusting existing legislation, e.g. amending the EU directive on the EU ETS. The measure would then be implemented with the same geographical scope as the current EU ETS for CO_2 emissions. Currently this would imply that all flights within the European Economic Area (EEA) would be subject to this scheme. Under the original scope of the EU ETS, all flights to, from and within the EEA would be subject to this scheme. In absence of a new amendment, the EU ETS would revert back to its original scope from 2024 onwards (European Commission, 2020).

5.2.2 Design of the measure

In general, much of the design of the measure to include aviation NO_X emissions in the EU ETS can draw on the existing system processes. For instance, the monitoring, reporting and verification (MRV) requirements would be the same or very similar to that of aviation's CO_2 emissions under the EU ETS (CE Delft et al., 2008). However, four issues will need to be addressed before NO_X emissions can be incorporated under the EU ETS.

- ***Monitoring emissions***: In the EU ETS, aircraft operators monitor and report CO_2 emissions on the basis of fuel use, multiplied by the CO_2 emission factor of the fuel. Whereas NO_X emissions cannot be accurately measured over the course of the flight, they can be approximated through existing modelling methodologies using certified emissions data from ICAO Aircraft Engine Emissions Databank.

$$Total\ NOx_{i.j} = EINOx_i\ \times Fuel_j$$

Where:

- $Total\ NOx_{i.j}$ is the total NO_X emissions for aircraft *i* on route *j* in mass units.
- $EINOx_i$ is the emission index for NO_x at the cruise condition (g/g_{fuel}). It is dependent on the engine types of the aircraft.
- $Fuel_j$ is the amount of fuel used on flight j in mass units. This is already monitored under the EU ETS.

- ***Establishing the amount of NO_X per allowance***: EU ETS directive 2003/87/EC, and its subsequent amendments, allows for the inclusion of gases other than CO_2 into EU ETS. Specifically, Directive 2003/87/EC creates allowances 'to emit one tonne of carbon dioxide equivalent' (article 3.a.), with the latter defined as 'one metric tonne of carbon dioxide (CO_2) or an amount of any other greenhouse gas [...] with an equivalent global-warming potential'. This means that the amount of NO_X that may be emitted per allowance can be established by the following formula, and is dependent on the CO_2 equivalence 'emission metric' (GWP) of aviation NO_X.

$$Mass\ of\ NO_X = \frac{1000}{Emission\ metric_{NO_x}}\ (kg)$$

If aviation NO_X emissions were to be included in the EU ETS Directive, then the list of gases in Annex II would need to be extended to include those with indirect climate impacts such as NO_X.

- ***Setting a baseline***: The inclusion of aviation in the EU ETS uses a historical baseline on the basis of which the total amount of allowances allocated to the sector is calculated. A baseline for NO_X could be set in the same way, provided that a calculation method for NO_X emissions is established and that the necessary data are available. The data necessary to establish a baseline is a comprehensive set of flights and aircraft-engine configurations for a baseline year or set of years (CE Delft et al., 2008). The European Union should have access to this data and be able to calculate a baseline either for a year or for a set of years. From this baseline, a certain amount of allowances will need to be taken off the market annually to ensure an incentive to continuously reduce NO_X emissions.

- **Percentage auctioned:** In the current EU ETS for CO_2, 85% of allowances do not require auctioning and are allocated for free (grandfathering). It has been argued that the same rate can also be used for non-CO_2 impacts in EU ETS, such as NO_X (Scheelhaase, 2019). Baselines can then determine the amount of permits allocated free of charge to individual airlines. A political decision will need to be made on the amount of permits that are auctioned.

The environmental impacts of the inclusion of aviation NO_X emissions in the EU ETS are similar to the impacts of the LTO NO_X charge with a distance factor. The reason for this is that the inclusion in the ETS can be based on the same methodology, so at a given GWP and at a given EU ETS price, both the amount of charge paid and the costs of the allowances to be surrendered would be equal (CE Delft et al., 2008). The advantage of integrating both NO_X and CO_2 into the same system is that one will not be able to take advantage of the trade-off between NO_X and CO_2 to the detriment of the climate, provided the climatological impacts are accurately weighed and reflected in the allowance price. The fundamental difference between both systems (i.e. NO_X charge with distance factor or NO_X in EU ETS) lies in achieving a set amount of NO_X emissions at an uncertain cost (EU ETS) or having a certain cost as a result of the NO_X charge, but an uncertain amount of NO_X emissions (NO_X charge with distance factor).

As this measure would entail amending a legal instrument that is currently in place, there is a relatively low administrative legal burden associated with it. From a legal perspective the inclusion of aviation NO_X emissions in the EU ETS would require changing the ETS Directive. With respect to international law, the inclusion of aviation NO_X emissions would not be fundamentally different to the inclusion of aviation CO_2 emissions (CE Delft et al., 2008). However, the uncertainty regarding the climate impact of NO_X emissions is larger than the uncertainties regarding the climate impact of CO_2 emissions. Hence, when fungibility between the two impacts is introduced in the EU ETS, care should be taken to maintain the overall credibility of the EU ETS.

It is important to note that this measure could potentially also be applied on an nvPM emissions or full climate impact basis. However, it is more challenging to predict analytically the cruise nvPM emissions from LTO emissions data, while the full climate impact basis would require a decision on an appropriate CO_2 equivalent emissions metric and a more complex methodology.

5.2.3 Administration of the measure

Under the current EU ETS, emissions of CO_2 from fossil fuel combustion in the aviation sector are regulated by the Member States' national emissions authorities. For each tonne of CO_2 emitted, one allowance unit must be surrendered by the aircraft operator to the competent national authority. This scheme covers intra-European flights (i.e. departure and arrival in EEA Member States) and has required since 2013 that relevant fuel consumption and CO_2 emissions data be monitored, reported and verified. It is anticipated that including NO_X into the EU ETS would not affect this existing structure of Member States and their individual national emissions authorities.

5.2.4 Incentives from measure

Airlines

Airlines will be the stakeholders largely affected by this measure. Incorporation of NO_X into the EU ETS raises the costs to airlines in two ways. Firstly, it demands effort from their side in terms of administration and secondly, airlines will need to pay for a part of their allowances. However, literature on including aviation in EU ETS has revealed that in the intra-EU market the aviation industry passes on 100% of the cost increase to passengers (CE Delft, 2008; CE Delft, 2007; Infras, CE Delft & TAKS, 2016; Frontier Economics, 2018).

Modelling studies in the literature indicate that the cost of including other greenhouse gases in EU ETS will be larger than under the current scheme (Scheelhaase, 2019). This is logical as the climatic effects of the EU ETS addressing CO_2 and non-CO_2 emissions will also be larger. However, because the length of the flight and the engine setting in operation impacts the NO_X emissions, the scheme may have consequences for the competitive environment of airlines. For instance, full service airlines operating mainly on long-haul flights will be at a competitive disadvantage compared to those operating mainly short- and medium-haul flights (Scheelhaase, 2019). This is due to the shorter cruise flight phases of short- and medium-haul flights, and the fact that long-haul aircraft typically have larger engines operating at higher pressures and temperatures.

Airlines will additionally need to keep in mind that only optimising on fuel efficiency will not be rewarded. If both NO_X and CO_2 are incorporated into the EU ETS, it would be important to keep the trade-off between fuel efficiency and NO_X in mind (Scheelhaase, 2019).

Complying with the EU ETS demands that aircraft operators establish defined processes to collect the relevant data, continuously retrieve this data throughout the compliance period and then report it to the competent authority. This data collection cycle and process involves various discrete steps and is known as monitoring, reporting and verification (MRV). The MRV compliance cycle is based on the calendar year. Initially an Emissions Monitoring Plan (EMP) describing all relevant processes to collect the required data is created. At the end of the monitoring period, the data is reviewed, data gaps are closed and an Annual Emissions Report (AER) is generated. External verification of the AER is performed before it is submitted to the competent authority, together with the required allowances. Improvements to the EMP may be made on an annual basis following the results of the reporting process. In addition, for their own benefit, aircraft operators also keep track of ongoing regulatory changes and manage the administrative requirements of participating in the scheme (Plohr, et al., 2019).

The MRV process imposes a financial burden on airlines, not only in terms of their own staff resources, but also in terms of direct costs paid to third-parties for relevant services delivered. The size of the overall administrative effort and cost is dependent on the specifics of an individual airlines' operations. By expanding the scope of the EU ETS, it is certain that the compliance costs will also increase. Overall, the administrative costs currently incurred by aircraft operators are non-negligible. However, in most cases, the cost of the actual price placed on their emissions will be significantly larger (Plohr, et al., 2019).

5.2.5 Caveats and constraints

The three caveats and constraints associated with this measure are the same as for the measure 'LTO NO_X charge with a distance factor' as they tackle the same problem. These include:

LTO NO_X - cruise NO_X relation

Although aviation NO_X emissions are relatively well quantified compared to other sources, there are uncertainties regarding the scaling of LTO NO_X to cruise NO_X. LTO NO_X emissions are relatively well quantified through engine certification data, but cruise NO_X emissions are not as well characterised, especially for many of the new staged combustion technology. Past analyses have concluded that a reduction in LTO NO_X will also result in a reduction of NO_X emissions at cruise.

However, recent technological developments such as staged combustion (e.g. lean burn) has led to questions regarding this conclusion. The Boeing fuel flow method (BFF2) and the DLR fuel flow method have been applied to staged combustors, but the robustness of using these methodologies to calculate NO_X emissions in cruise is currently being assessed. Obtaining additional data about cruise NO_X emissions of aircraft would permit a more accurate determination of the NO_X charge.

Impact of NO_X and how it will evolve in the future

As noted in section 2, the current scientific understanding is that the net effect of NO_X forcing is positive, i.e. warming. Recent research has shown that there is high non-linear chemistry of the interaction of NO_X with background concentrations, and the effect of NO_X is dependent on the location of emission. As such, under future emission scenarios of declining emissions of tropospheric ozone precursors (e.g. RCP4.5) from surface sources, combined with a "business as usual" aviation scenario (i.e. *increasing* aviation emissions), a net negative RF (cooling) of aviation NO_X may result (Skowron et al. 2019).

Metrics

Establishing accurate factors that compare the climate change impact of NO_X emissions to CO_2 emissions is of crucial importance to this measure, due to the different timescales on which these pollutants operate. In this Chapter we have suggested that While GWP, GWP* on GTP could be used, the impact of using one these measures compared to the others should be captured before a definitive decision is made on which metric should be used. For a full discussion on CO_2 equivalent emissions metrics we refer to section 2.3.

5.2.6 Further research

As this measure addresses the same climate impact as the measure in section 5.1 the avenues for further research are identical. These include an appropriate CO_2 equivalent emissions metric for translating NO_X to CO_2, and a method to accurately estimate cruise NO_X emissions for new technology (e.g. lean burn staged combustion engines).

5.2.7 Conclusion

In conclusion, there are two areas that are crucial to this measure that deserve further research. This includes the relationship between LTO NO_X and cruise NO_X for new technology (e.g. lean burn staged combustion engines), and which climate metric should be used to ensure that the CO_2-NO_X trade-off in engine design is not exploited to the disadvantage of the climate. Hence, there are clear synergies between this measure and the NO_X charge.

EU legislation could be adapted to expand the EU ETS to include aviation NO_X emissions, and the data needed to implement this measure is available. However, the uncertainty about the climate impact of NO_X , and the potential unintended consequences, has a higher political risk than the 'NO_X charge' and this needs to be taken into account when considering it as an opt-in non-CO_2 gas in the EU ETS.

If the outstanding research issues linked to this measure are addressed, and there is the political will to take the option forward, then the measure could potentially be implemented in the mid-term (5 to 8 years) as it builds on existing legislation.

5.3 Reduction in maximum limit of aromatics within fuel specifications

5.3.1 Definition of the measure

Jet A-1 fuel is the most commonly used aviation fuel in the world. Its fuel specifications are managed through the US ASTM (D1655) and UK DEF STAN (91-091) standardisation committees, where the maximum volume concentration of aromatics is 25 volume percent (UK Ministry of Defence, 2015; ICAO, UNDP & GEF, 2017). This measure would entail adjusting the maximum aromatics content standard for the fuel used at all European Union airports to a value that is lower than 25 volume percent. In practice, Jet A-1 fuels already tend to have an aromatics content that is lower than the legal maximum (DLA Energy, 2013; Brem et al., 2015; Edwards, 2017; Zschocke, et al., 2012).

Aromatics are hydrocarbons characterised by a ring of resonance bonds which implicate that the ratio of hydrogen to carbon is lower than for alkanes and that the heating value is lower (Chen, et al., 2019). They therefore increase the fuel density (mass per volume), without adding energy density (energy content per volume). Removing aromatics reduces the mass of fuel required for a specific flight and hence improves aircraft fuel efficiency.

When aromatics are present in fuels, they also encourage particulate matter formation upon combustion, hence, lower aromatics fuels provide a cleaner burn (Chen, et al., 2019). Reducing the aromatics content of the fuels therefore reduces the formation of nvPM emissions (ICAO, UNDP & GEF, 2017; Brem et al., 2015).[47]

The aromatics content in fuels can be reduced through blending certain sustainable aviation fuels (SAF) with conventional Jet A-1 fuel, or through hydro-treatment of Jet A-1 fuel.

There are currently six production pathways of SAF that have been certified for blending with conventional fossil based aviation fuel. These are summarised in Table 4 below. In addition, Power-to-Liquid (PtL) fuels could also be considered SAF when they use renewable hydrogen (produced by electrolysis of water with renewable electricity) and CO_2 extracted from the atmosphere to form liquid hydrocarbons.

[47] Soot, black carbon and non-volatile particulate matter (nvPM) are often used interchangeably.

Name of production pathway	Description of production pathway	Maximum blending ratio
FT-SPK: Fischer-Tropsch synthetic Paraffinic Kerosene	Biomass is converted to synthetic gas and then into bio-based aviation fuel	50%
FT-SPK/A: Fischer-Tropsch synthetic Paraffinic Kerosene derived by alkylation of light aromatics	A variation of FT-SPK, where alkylation of light aromatics creates a hydrocarbon blend that includes aromatic compounds	50%
HEFA: Hydroprocessed Fatty Acid Esters and Free Fatty Acid	Lipid feedstocks, e.g. vegetable oils and used cooking oils are converted using hydrogen into green diesel, and this can be further separated to obtain bio-based aviation fuel	50%
HFS-SIP: Hydroprocessing of Fermented Sugars – Synthetic Iso-Paraffinic kerosene	Sugars are converted to hydrocarbons using modified yeasts	10%
ATJ-SPK: Alcohol-to-Jet Synthetic Paraffinic Kerosene	Dehydration, oligomerisation and hydroprocessing are used to convert alcohols, such as iso-butanol, into hydrocarbon	50%
Co-processing	Biocrude up to 5% by volume of lipidic feedstock in petroleum refinery process	

Source: (EASA, 2020; ICAO, UNDP & GEF, 2017; EEA, EASA & EUROCONTROL, 2019; SkyNRG, 2020)

Table 4 – SAF production pathways

Hydro-treatment is a common method to saturate aromatics and thus reduce their concentration in conventional Jet A-1 fuel. In the process, other unwanted impurities/inorganic components such as sulphur and nitrogen are also removed by processing it at high temperature and pressure in the presence of hydrogen and a catalyst (CE Delft, Forthcoming). In an industrial refinery, hydro-treatment takes place in a fixed bed reactor at elevated temperatures ranging from 300 ºC to 400 ºC and elevated pressures ranging from 30 to 100 kPa, in the presence of a catalyst consisting of an alumina base impregnated with cobalt and molybdenum (CE Delft, Forthcoming). This process diminishes the aromatics content of conventional Jet A-1 fuel although it requires extra energy in the refinery process. Unless renewable energy is used, this extra energy would lead to increased CO_2 emissions on a fuel lifecycle basis. If the fuel is produced in Europe, this could be addressed through the EU ETS cap on refinery emissions. Nonetheless, it is important to balance the different environmental benefits (e.g. reduced soot and contrail and increased aircraft fuel efficiency through higher fuel density by mass, but possibly increased CO_2 during the refinery process).

Studies have shown that SAFs have lower black carbon emissions (Chan, et al., 2015). For 100% synthetic kerosene containing aromatics[48], a 28-50% reduction in black carbon emissions was observed (dependent on engine load[49]) compared to the use of Jet A-1 fuel (Chan, et al., 2015). A 58-86% reduction in black carbon emissions was observed for the 50% HEFA-fuel compared to Jet A-1 fuel (Chan, et al., 2015). For the 100% Fischer-Tropsch

[48] Please note that this fuel is not certified for 100% use. The maximum blending ratio up to 50% (see **Error! Reference source not found.**).

[49] Engine load was measured as “take-off condition”, “idle” or “cruise”.

synthetic kerosene with reduced aromatics[50] black carbon (or nvPM) mass emissions were observed to be 70-98% lower than for Jet A-1 (Chan, et al., 2015). nvPM number emissions from this fuel were also lower by a comparable magnitude when compared to that from Jet A-1.

Non-volatile particulate matter (nvPM) mass and number emissions are directly linked to contrail cirrus formation. Condensation trails (contrails) are line-shaped ice clouds generated by aircraft cruising at 8-13 km altitude (Kärcher, 2018). They are formed when jet engine exhaust plumes mix with surrounding ambient air, such that particles are activated into water droplets, which in turn freeze and grow into ice crystals (Burkhardt, et al., 2018). The impact of contrail cirrus on radiation is dependent on the number and size of these ice crystals. Reducing the soot (nvPM) number emissions reduces the initially formed ice crystal numbers which in turn reduces the radiative forcing of contrail cirrus (Burkhardt, et al., 2018). Although there is a lot of uncertainty around the magnitude of the climate change impact of contrail formation, it exerts on average a warming effect at the top of the atmosphere. Contrails therefore have a net global warming effect. The GWP_{100} of all aircraft induced cloudiness[51] is 0.63 (Lee, et al., 2010), although the level of scientific understanding around this figure is very low. Compared to CO_2, the lifetime of contrails is much shorter (hours vs. centuries-millenia) which makes it amenable to rapid mitigation. Hence, setting a maximum standard for the aromatics content of fuels could contribute to reducing the non-CO_2 climate impact of aviation.

The ASTM and DEF STAN standards are two of the four main aviation fuel standards used globally.[52] If this measure was to be implemented, these standards would need to be adjusted.

5.3.2 Design of the measure

For this measure to be effective, the maximum aromatics content of the fuel needs to be lower than the aromatics content of Jet A-1 fuels currently used in operation. At the present moment, the aromatics content of Jet A-1 fuels can vary up to the legal maximum (25 volume %), although it is unclear what the 'normal' aromatics content of Jet A-1 fuel is in operation. Studies have suggested the typical volume % of aromatics in Jet A-1 fuel may be somewhere between 11% and 18% (Edwards, 2017) or 8% and 20%, with most values falling within the range 16-20% (Zschocke, et al., 2012). According to the Petroleum Quality Information System 2013 report the mean aromatics content of Jet A-1 fuel was 17.94 volume %, with a minimum of 15.00 volume %, and a maximum of 24.40 volume % (DLA Energy, 2013), although this study focusses on fuel purchased by the US government, and may therefore not be representative of the European situation. Other point estimates of proposed reference average volume percentages of 17.8% (Brem et al., 2015) or 17% (Edwards, 2017) have been made. For the measure to be effective, one would recommend a

[50] Please note that this fuel is not certified for 100% use. The maximum blending ratio up to 50% (see **Error! Reference source not found.**).
[51] This is an umbrella-term for all long-lived (>10mins) contrails, regardless of whether or not they retain their linear shape.
[52] The other two standards are Russian and Chinese.

maximum aromatics content that is at least lower than current average (i.e. lower than ca. 18 volume %).[53] The precise content will need to be established at a later date, and all relevant stakeholders would need to be involved in the process of determining the new maximum volume percentage.

The design of the measure itself is relatively complicated. One of the main global fuel specifications is set by ASTM, which is not directly managed by regulatory bodies, but by groups of stakeholders from both regulators and industry. Members of the ASTM aviation fuel subcommittee (ASTM D02.J) therefore also include aircraft manufacturing companies (e.g. Airbus, Boeing), engine manufacturing companies (e.g. General Electric, Rolls-Royce and Pratt & Whitney), fuel producers and operators. Any change to the current standards will need to be accepted by all the stakeholders. If the EU wanted to reduce the limit for the aromatics content, it would need to promote such a change within the fuel specification committees, via EASA who is a member as a regulating body. However, this could be a long process, and would need to involve a regulatory impact assessment to ensure consensus across the committees and maintain harmonised global fuel specifications. A similar procedure is applicable to changes of DEF STAN 91-091 that is managed by the Aviation Fuels Committee (AFC).

As an alternative, the EU could provide an incentive for selling lower aromatic fuels in European countries, so long as they still comply with the current ASTM and DEF STAN specifications. However, it may lead to issues with military aircraft who also utilise ASTM and DEF STAN fuels so that they are not restricted in their fuel uplift locations and have operational flexibility. With this in mind, military aircraft are on average older, and the use of lower aromatics fuels may have consequences for parts of the engine (e.g. rubber seals).

5.3.3 Administration of the measure

The administration of the measure is dependent on which of the options one follows: lobbying for adjustment of the ASTM standards or providing a European incentive for selling lower aromatics fuels. Both options have their own advantages and disadvantages.

ASTM/DEF STAN
The adjustment of the worldwide fuel standards is up to the ASTM/AFC members. These consist of industry representatives and regulators. Any adjustment to the standards will need to be agreed upon by the ASTM aviation fuel subcommittee or AFC. It is important to note that both ASTM and DEF STAN are consensus standards.

European Union
If the EU chooses to provide an incentive for the sale of low aromatics aviation fuel in Europe, this could be implemented and administrated through legislation at the European level. Potentially, one could use the Fuel Quality Directive or Renewable Energy Directive as a basis for a monitoring system. The maximum aromatics content of aviation fuels sold in Europe would need to be in line with the global ASTM/DEF STAN standards, such that they

[53] It is important to note that there are currently ongoing discussions in the ASTM committee and the Aviation Fuel Committee about the introduction of a minimum aromatics content of Jet A-1 fuel. This is being considered with regards to safety in older aircraft. See section 0 for more information.

are not undermined. However, a financial incentive could be provided to fuel producers if the fuel produced contains an aromatics content lower than x%. Whether the lower aromatics content is obtained through blending of SAF or through hydro treatment would be up to the fuel producers.

5.3.4 Incentives from measure

Fuel producers

If the EU chooses to promote changes in the fuel specifications, and this is successful, fuel producers will need to adapt to these changes. If the EU opts for the financial incentive for lower aromatics content in aviation fuels sold in Europe, the fuel producers have the choice of whether or not they want to change their production processes. The ultimate decision they will make will depend on the business case, and the extent of the financial incentive.

If fuel producers decide to adjust production processes such that a lower aromatics content is reached, this measure should not specify how this is done. Whether fuel producers do so by hydro-treating conventional Jet A-1 fuel or by blending conventional Jet A-1 fuel with SAF would be up to them. This measure will provide a stimulus for additional investment in SAF or hydro-treatment, and lead to an increase in the cost of producing aviation fuel.

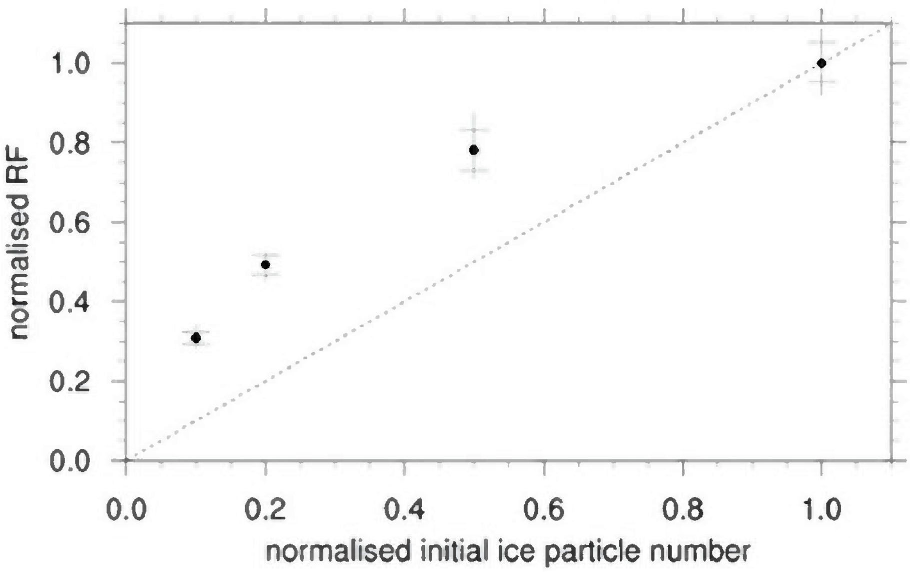
European Union

The European Union has an important regulator role to play in securing a consensus on a proposed adjustment of the ASTM/DEF STAN standards for the maximum aromatics content of the fuel, or the implementation of an incentive for lowering the aromatics content of the aviation fuel.

5.3.5 Caveats and constraints

Relationship between nvPM and contrail formation

While there is a linear relation between aromatics content and emissions soot/black carbon/nvPM, the relation between nvPM emissions and contrail formation is not linear. Recent scientific literature has shown that reducing nvPM number emissions by 50% compared to present day emissions reduces the radiative forcing of contrail cirrus by 20% (Burkhardt, et al., 2018). Further reductions are likely to have a more drastic effect on radiative forcing (**Error! Reference source not found.**0). Reducing the soot emissions from fuel (and thereby also initial ice particle numbers) by 80% leads to a reduction in radiative forcing of contrail cirrus by 50%, and reductions in soot emissions from fuel of 90% lead to 70% reduction in radiative forcing.



Source: (Burkhardt, et al., 2018)

Figure 10 – Global net radiative forcing as a function of the initial ice particle number concentration of contrails

However, this relationship breaks down at very low levels of nvPM number emissions. In those cases, the contrail formation could actually be increased when lowering the number of nvPM emissions (see Figure 5, Section 2.4, taken from Kärcher (2018). While those cases are far removed from the present level of emissions, it should be borne in mind when designing this measure that the aim should not be to completely eliminate nvPM emissions from jet engines.

In addition, the percentage reduction of nvPM emissions and the relationship outlined above are based on scientific understanding, but do not inform us of the reductions that are technically possible with blending SAF. Further research on a viable maximum aromatics standard will need to be conducted before legislation can be designed and implemented.

Minimum aromatics content

Secondly, while the reduction of aromatics has a positive effect on climate, it also has other side-effects, for instance on the performance of elastomer seals. This is particularly important when considering the lifespan of the fleet in the aviation industry. Over the last 20 years there have been significant changes in technology, and many of the aircraft that are being flown first today will still be in circulation in 20 years' time. This means that any adjustments to fuel standards need to be compatible with all aircraft that are currently still being operated without impacts on the safety of the aircraft. Hence, changes in fuel specifications will need to be carefully analysed with regards to impacts on safety. This is one of the reasons why the ASTM aviation fuel subcommittee and AFC have agreed a minimum aromatics limit of 8% for SAF, and are also considering a similar limit for fossil based fuels that is currently just guidance (Chevron, 2006; ASTM, 2007).

5.3.6 Further research

Further research will need to be conducted before this maximum aromatics content standard can be implemented. Based on the sections above, we have identified four major areas that would be particularly useful.

A first step would be to discuss the climate benefits of low aromatics fuels (taking into account the environmental impact of increased processing) with members of the ASTM and DEF STAN committees. This is crucial to start the process of negotiations to reduce the aromatics limit within these specifications.

Secondly, a cost-effectiveness assessment would need to be conducted with regard to options for reducing the maximum aromatics content standard. Currently, the level of aromatics content in Jet A-1 fuel used within the aviation sector is not well known. While the maximum content is 25 volume %, studies have revealed that the volume % of aromatics in fuel can vary extensively. More information on the distribution of aromatics content in aviation fuels will first need to be collected, before the impact of a reduced maximum standard can be evaluated. This collation of data of the specification of fuel used in operation is ongoing in ICAO CAEP, however it has to date been unsuccessful in retrieving the desired information.

Thirdly, further research would need to look into the legality of choosing to provide an incentive for all fuel sold in the EU to have a lower aromatics content.

Lastly, the effects on relevant stakeholders (e.g. fuel producers, military) from promoting lower aromatics fuels will need to be further investigated. This is especially so for the military who operate relatively older aircraft compared to commercial aircraft operators, and the use of lower aromatics fuels may have consequences if they share the same fuel supply.

5.3.7 Conclusion

Various areas of further research have been identified for this measure that are crucial to the success of its implementation. This includes the need for cost-effectiveness assessment on the options for reducing the maximum aromatics content standard, including potential increases in CO_2 emissions in the refinery process and the impact of lower aromatics fuel on relevant stakeholders (e.g. airlines, fuel producers, military). In addition, the legality of an EU incentive for the sale of fuels with lower aromatics content within the specifications of the ASTM of DEF STAN standards would need to be considered.

There are two ways in which this measure can be considered, that are not necessarily mutually exclusive. If the outstanding research issues linked to this measure are addressed, and there is the political will to take the option forward, then an initiative to change the ASTM of DEF STAN standards could potentially be implemented in the mid- (5 to 8 years) to long- term (+8 years).

Simultaneously, the EU could consider ways to incentivise the sale of lower aromatics fuel. As the measure does not require scientific research, it could be implemented on a relatively shorter time scale, although the incentive would need to be developed and agreed upon.

5.4 Mandatory use of Sustainable Aviation Fuels

5.4.1 Definition of the measure

Jet A-1 is the standard fuel specification used globally and is widely available (Shell, 2020). Sustainable Aviation Fuels (SAFs) are a cleaner and more environmentally friendly alternative to fossil-based fuels, but there are different definitions of SAF within different regulatory systems. In the European regulatory framework, sustainability is defined in the new Renewable Energy Directive (RED II) 2018/2001/EU. These fuels typically have a lower aromatics content and also a lower sulphur content, as well as lower lifecycle CO_2 emissions. Hence, these fuel result in lower PM and SO_4 emissions.

This measure would entail the mandatory use of SAF, for instance through a blending mandate which requires fuel producers to add a minimum amount of SAF to conventional fossil-based Jet A-1 fuel. There are currently six production pathways of SAF that have already been certified for blending with conventional aviation fuel. These are summarised in **Error! Reference source not found.**4 in Chapter 5.3.1. In addition, fuels produced through a Power-to-Liquid (PtL) pathway that combines renewable electric energy with water and CO_2 to form liquid hydrocarbons are also considered SAF.

An additional benefit of SAF is that the energy density is higher by mass (albeit lower by volume) (Kinder & Rahmes, 2009; Blakey, Wilson, Farmery, & Midgley, 2011; ITAKA, 2015). In total this implies less fuel weight will need to be taken on board for a given route. Estimates are that an efficiency gain of approximately 1% can be obtained as a result of this property of SAF.

Blending mandates have already been introduced in individual European countries. For instance 0.5% of the annual volume of aviation fuel sold by fuel suppliers in Norway will have to be SAF from 2020 onwards (Norwegian Government, 2018). In Sweden, a blending mandate has been proposed, which would involve an increasing blend ratio from 1% by volume in 2021, 5% in 2025 up to 30% in 2030 (Biofuels Flight Path, 2019; AINonline, 2019).

This proposed measure would entail an EU-wide blending mandate for all fuel sold in European countries.

5.4.2 Design of the measure

This measure entails the setting of an EU-wide blending mandate through EU legislation. This could involve specifying that a certain percentage of the total Jet A-1 fuel sold in Europe over a set time period would have to be SAF. The level of the blending mandate is yet to be determined. It is possible to opt for a dynamic blending mandate, of which the percentage SAF to be blended increases over time. This is to provide certainty to the market for long-term investments. To ensure support of the blending mandate, it is important to involve all stakeholders early and throughout the entire process, including in the discussions on the size of the mandate.

In countries where current blending mandates are already in place (e.g. Norway) it is up to the market players to decide where and when the biofuel is mixed, and these players may adapt the blending requirement as appropriate for individual clients (BioEnergy International, 2018). In a European scheme, it may be preferable to have a bit more guidance, due to the sheer volume of the market. A 'control point' will need to be identified, where the total fuel going to the aviation sector in Europe can be identified and hence compliance with the blending mandate can be measured (IATA, 2015). For road fuel, this control point is set at the fuel duty point. However, as international jet fuel is not subject to fuel duty, there is currently no established equivalent of the fuel duty point for aviation fuel (IATA, 2015). From a practical point of view, a logical control point could be the point where SAF is blended with fossil fuel as a final ASTM D1655 or DEF STAN 91-091 certified fuel.

An important part of this measure is monitoring, reporting and verification (MRV). If the control point is set where the fuel is blended, the fuel blenders will need to monitor, report and verify their SAF consumption to prove that the fuel used complies with the mandate. A link could be made with the wider EU regulatory framework, including the RED directive, to facilitate the monitoring of SAF usage by Member States that would then be reported to the European level through the RED Union Database. Alternatively, it is possible that a scheme could be created that is similar to the MRV guidelines for aviation under the EU ETS.

The fact that current ASTM/DEF STAN specifications allow for the blending of SAF for up to 50% implies that this measure can be designed and implemented on a relatively shorter timescale than the measure to reduce the maximum aromatics content of aviation fuels. However, there are potential synergies between the two measures. Only when the aromatics content of the fuel blends are actually lower than the current aromatic content of jet fuels would the measure reduce nvPM emissions and contrails.

5.4.3 Administration of the measure

This measure could be administrated at the EU level or by Member States. Once a point of control has been established at the fuel blenders, and a monitoring and reporting process put in place, a competent authority would be responsible for verifying the blending content of the fuel at the point of control. An MRV scheme could be built on existing processes to verify the sustainability characteristics of SAF (e.g. use of SCS) and reporting (e.g. RED II) in order to monitor use of SAF within Europe and associated emissions reductions. This scheme could also be used to monitor the aromatics content of the blends in order to ensure that the measure has the intended impact on nvPM emissions.

5.4.4 Incentives from measure

Fuel producers & fuel blenders
Fossil fuel producers will not be directly affected by this measure, yet SAF producers will. With this measure a certain demand of SAF is guaranteed, providing a huge impetus for up-scaling production of SAFs, leading to potential economies of scale.

For verification of the blending percentage, a point of control will need to be established at the fuel blending locations, as one can then directly measure the total amount of fuel that used in the aviation sector (and hence verify the percentage of SAF).

Airlines
This measure will affect the operational costs and fuel management systems of aircraft operators, and so they need to be involved in the discussion regarding the size of the blending mandate. With SAFs currently priced at higher levels than fossil-based aviation fuel, this measure could increase operating costs for airlines, depending on the size of the blending mandate.

European Union / Member States
The European Union has a key role to play in setting the blending mandate to stimulate the single market in this area, as well as involving all stakeholder parties such that they can inform the decision-making process and buy-in to the final proposal. Depending on the choices that are made regarding enforcement of the Directive, an EU level and/or Member State body could be tasked with ensuring compliance.

5.4.5 Caveats and constraints

In mandating the use of SAF one needs to ensure that SAFs are safe to use in the aviation system and sustainable in order to deliver environmental objectives. There are a number of important caveats and constraints to be considered.

Feedstock supply
In theory, there is high potential availability of sustainable feedstock, but its collection is accompanied with problems. For instance, crop and forestry residues must be harvested carefully to avoid loss of soil carbon and health; there may not always be enough time to harvest crop residues before planning the next crop; the feedstocks are contaminated with soil and are difficult and bulky to transport and store. In addition mature supply chains of these products are not usually in place (ICCT, 2019).

Cellulosic energy crops are a large potential future source of biomass production, but have a different challenge related to the high investment required upfront: the 'chicken-and-egg' problem. Farmers are unwilling to invest in these crops without mature demand market, and vice versa the biofuel producers cannot scale up their production without solid feedstock supply chains in place (ICCT, 2019).

For some feedstocks there are additional sustainability concerns. One example is palm oil, which has been responsible for rainforests destruction, as well as swamps and peatland drainage (Transport & Environment, 2018), leading to a release of significant amounts of CO_2 emissions. Hence, in the Norwegian blending mandate, these 'problematic feedstocks' are ineligible for use as SAFs in Norway (BioEnergy International, 2018).

Production capacity
The production capacity of bio-based aviation fuel in the EU relies on a small number of plants, which could account for a maximum potential output of 2.3 million tonnes per year.

This corresponds to roughly 4% of the total EU conventional fossil fuel demand. However, considering the relatively low profitability of producing aviation fuels, a more moderate output scenario of 0.355 million tonnes is deemed more realistic (EASA, 2020).

Costs of production
Production costs of SAF are relatively high compared to fossil-based kerosene, which is one of the major barriers to greater market penetration. The major component of the price of SAF is the feedstock price (EASA, 2020). High price volatility of these feedstocks on the EU market can also create supply problems for fuel producers. While conventional fossil-based aviation fuel typically costs €600/tonne, the price of SAFs produced from used cooking oil can be 60-70% higher (EASA, 2020).

In the future, we may witness increased competition between the road and the aviation sector for feedstocks that comply with sustainability requirements, such as used cooking oil and tallow used in the HEFA process. This is likely to increase prices for SAFs further. However, this point may be redundant if e-mobility for light and heavy goods vehicles takes off in the near future.

Simultaneously there are various on-going initiatives at the European level with the intention of increasing the market penetration of SAFs. However, despite the presence of these initiatives, the current consumption in Europe is very low when compared to the potential production capacity (EASA, 2020). A blending mandate would spur demand for SAFs, which could lead to a greater use of the potential production capacity, economies of scale and lower prices.

SAFs, aromatics and PM emissions
Most SAFs have a lower aromatic content compared with conventional fossil Jet A-1 fuel. Due to the fact that a reduction in the aromatics content of the fuel leads to a cleaner burn, SAFs lead to lower soot / nvPM emissions than conventional fuel (ICAO, UNDP & GEF, 2017). nvPM emissions are closely linked to contrail formation, although this relationship is not linear.

Hence, the impact of the measure depends on the aromatics content of the blend. Contrail formation will only be reduced if the aromatics content of the blend is lower than the current fossil fuel reference. A monitoring programme on the specifications of fuel used in Europe, including aromatics content, is required in order to analyse whether the measure has the intended impact.

Condensation trails (contrails) are line-shaped ice clouds generated by aircraft cruising at 8-13 km altitude (Kärcher, 2018). They are formed when jet engine exhaust plumes mix with surrounding ambient air, such that particles are activated into water droplets, which in turn freeze and grow into ice crystals (Burkhardt, et al., 2018). The impact of contrail cirrus on radiation is dependent on the number and size of these ice crystals. Reducing the soot number emissions reduces the initially formed ice crystal numbers which in turn reduces the radiative forcing of contrail cirrus (Burkhardt, et al., 2018).

Recent scientific literature has shown that reducing soot emissions by 50% compared to present day emissions reduces the radiative forcing of contrail cirrus by 20% (Burkhardt, et al., 2018). Further reductions are likely to have a more drastic effect on radiative forcing, although this relationship breaks down at very low levels of emissions. In those cases, the contrail formation could actually be increased when lowering emissions (Kärcher, 2018). While those cases are far removed from the present level of emissions, it should be borne in mind when designing this measure and setting the size of the blending mandate.

5.4.6 Further research

Further research should be conducted on the share of SAF to be blended with fossil fuels and associated timeframe, taking into account the current low production capacity of these fuels. This should be set at a level that is realistic with respect to production capabilities, yet ambitious, and possibly be dynamic in the sense that flexibility is built in to let it increase over time (as biomass supply and SAF technologies become more mature).

In addition, the aromatics content of blended fuels should be monitored to demonstrate that the volume % of aromatics indeed goes down and that the low aromatics content of SAFs is not offset by an increase in the aromatics content of fossil fuels. The relevant stakeholders (fuel producers, fuel blenders and airlines) should be closely involved in this process.

5.4.7 Conclusion

There are areas that require further research before this measure could be implemented. This concerns the share of SAFs to be blended in particular. A blending mandate would provide certainty to fuel producers that there will be demand for their product, hence providing an important stimulus to the SAF industry.

The mandating of SAF results could be considered as an holistic approach with simultaneous reductions in CO_2, nvPM and sulphur emissions resulting in a more favourable cost-effective outcome. This approach is similar to the previous introduction of car Denox catalytic convertors to reduce NO_X emissions, and which also needed lower sulphur fuel to work properly leading to changes in road fuel specifications. Compared to adjusting the standards for maximum aromatics content, this measure is also simpler in the sense that it doesn't involve a lengthy international negotiation process within the fuel specification committees that may result in limited environmental benefits in operation. A downside is the geographical scope being limited to all fuel uplifted in Europe, which could provide an extra incentive for fuelling from outside of the EU if fuel becomes more expensive in Europe.

A system to monitor the specifications of fuel being used in operation within Europe would provide valuable oversight on the environmental benefits from the implementation of this measure. The measure may require a new regulatory framework, or it may be possible to build on existing legislation (e.g. RED, FQD) to incorporate an aviation blending mandate.

If the outstanding research issues linked to this measure are resolved, and there is the political will to take the option forward, then the measure could potentially be implemented in the short- (2 to 5 years) to mid- term (5 to 8 years) as a number of European states currently have a blending mandate in place, or are planning one soon.

5.5 Avoidance of ice-supersaturated areas

5.5.1 Definition of the measure

The climate impact of a flight depends not only on the quantity and type of emissions, but also on where the flight takes place, e.g. altitude, geographical location, time and local weather conditions (Yin, et al., 2018). Therefore, optimizing flight trajectories such that climate-sensitive regions are avoided is a mitigation option to reduce the climate impact of aviation (Matthes et al., 2017; Rosenow et al., 2017; Lim, et al., 2017). Avoidance of ice-supersaturated areas is a potential first step towards full optimisation of flight profiles for climate impacts (section 5.6).

Contrail cirrus could potentially be the largest individual contributor to total aviation RF (Grewe et al., 2017). Contrails are largely formed in ice-supersaturated and low-temperature regions (Yin, et al., 2018). Avoiding these regions would reduce contrail cirrus occurrence. However, current flight paths are designed to minimise flight time and/or fuel cost, therefore any deviation from this trajectory will incur a time penalty or a fuel penalty (and hence a climate penalty). Implementation of this measure in mainland European airspace would be a challenge as this region already faces capacity constraints during daily peak periods (Rosenow, et al., 2018). As aviation demand is expected to increase further in the future, capacity may become even more constrained.

This measure entails deviating either horizontally or vertically from current flight trajectories such as to minimise passing through ice-supersaturated areas. Studies have shown that a 40% reduction in contrail distance can be achieved throughout all seasons with an increase in flight time of less than 2% (Yin, et al., 2018)[54]. If the contrail coverage of a flight is reduced, then its climate impact is too. A recent paper looking at flights in Japanese airspace concluded that diverting 1.7% of the flights could reduce the energy forcing from contrails by 59.3% with only a 0.014% fuel burn penalty (Teoh, et al., 2020), although it is important to note that this study was conducted with a focus on the Japanese airspace and therefore findings may not transfer to the European context. (Teoh et al., 2020) also concluded that a low-risk strategy of diverting flights only if there is no fuel penalty at all would reduce contrail energy forcing by 20%. Hence recent scientific evidence suggests that avoiding ice-supersaturated areas could reduce the non-CO_2 climate impact of aviation.

There is currently no incentive for airlines or air traffic control to avoid ice-supersaturated areas. Therefore, making the avoidance of these areas mandatory would constitute a new legal instrument.

[54] Contrail distance reductions of up to 90% can be achieved with an increase of flight time of less than 2% depending on the season. Contrail formation is lower in the summer months, hence avoiding ice-supersaturated areas is more effective in winter months than in summer months.

5.5.2 Design of the measure

Conversations with stakeholder experts suggest this measure could first be implemented as a pilot over the Atlantic airspace, jointly under the jurisdiction of appropriate Air Navigation Service Providers (ANSPs). Compared with the European continental airspace, where traffic flows in all directions, the airspace across the Atlantic occurs in only two directions. In addition, Atlantic traffic arrives in flows, making it relatively easy to restrict access to a certain area. If pilot studies are proven successful, it may be possible to upscale the measure over the entire Atlantic airspace.

The measure consists of deviating from current flight trajectories such as to minimise the passing through of ice-supersaturated areas. This deviation can either be vertical or horizontal. Ice-supersaturated areas can have a maximum horizontal size of 500 kilometres, whereas on average the vertical size of ice-supersaturated areas is only 200-300 metres. Due to this, and due to the structure of the flight levels flown in the airspace above the Atlantic which are strictly adhered to, vertical deviations are the preferred option. However, for vertical deviations to be successful, information is needed on the depth of the ice-supersaturated areas.[55]

This measure should be designed such that air navigation service providers and airline operators have all the relevant information (e.g. temperature and humidity) prior to a flight plan being filed in order to identify the ice-supersaturated areas and design, pre-tactically, the route network allowing flights to deviate from these areas. This could be provided through close liaisons with meteorological institutes, such as the World Area Forecast Centres (WAFC) in London (Met Office) and Washington (NOAA) or the European Centre for Medium-Range Weather Forecasts (ECMWF). These institutes already provide meteorological information necessary for flights according to Annex 3 of the ICAO convention in the form of gridded global forecasts covering a number of parameters, including air temperature, humidity, wind, turbulence and icing (Dahlmann, et al., 2019)[56]. The ECMWF routinely produces this data every 12 hours, and has even demonstrated its capability of predicting ice-supersaturated regions with high accuracy up to three days in advance (Rädel & Shine, 2010). For this measure to be tactically implemented, the weather forecasts will need to be shared with air traffic control and airlines before the airlines file their flight plan. This is usually done 12 hours in advance of the flight for European and North-American airlines crossing the Atlantic in order to ensure predictability such that the network capacity can be managed efficiently.

Based on the information of the meteorological institutes, airlines will file their flight plans. Air traffic control will then create the tracks across the Atlantic such that as many airlines as possible get their preferred route while avoiding ice-supersaturated areas, which are then

[55] This can be done based on ECMWF data, but is a step that is currently not yet undertaken.

[56] To contribute towards the safety, regularity and efficiency of international air navigation WAFCs prepare gridded global forecasts of: 1) upper wind; 2) upper-air temperature and humidity; 3) geopotential altitude of flight levels; 4) flight level and temperature of tropopause; 5) direction, speed and flight level of maximum wind; 6) cumulonimbus clouds; 7) icing and; 8) turbulence, for operators, flight crew members, air traffic services units, etc.

defined as Climate-Restricted Areas (CRA). The airlines will then fly the routes based on the allocated route received by air traffic control.

The concept of Climate-Restricted Areas is inspired by military exclusion zones (Dahlmann, et al., 2019).[57] Areas that are ice-supersaturated are then classified as CRA for a period of time (hour, day etc.). Air navigation service providers would then divert the traffic to avoid the ice-supersaturated areas, this can either be a horizontal or a vertical diversion.

To avoid significant trade-offs with fuel burn / CO_2 emissions a maximum limit in terms of detour (time or flight kilometres) could be determined. This maximum time or flight kilometre limit needs to be set in order to avoid having a net warming climate impact due to the extra distance flown. The precise limit will still need to be determined, and it should balance climate concerns with airlines' commercial concerns (e.g. it would be complicated to sell a twelve-hour flight from Amsterdam to New York, when the same flight normally takes less than eight hours).

The design of the measure itself is entirely new. Currently, the main task of air navigation service providers is to ensure adherence to rules for the safe operation in airspace, which involve maintaining a safe distance from other aircraft. It would be a first to adjust these rules to incorporate climate concerns, in addition to the core task of safety.

5.5.3 Administration of the measure

As this measure is entirely new, it is recommended to first implement a pilot version of the measure, in a relatively uncomplicated environment, such as the airspace over the Atlantic. This will require the cooperation and agreement of relevant ANSPs, as well as ICAO as it concerns international airspace. In addition, all airlines making use of this airspace will need to be involved, although in the pilot stage it is possible that only one airline participates in this measure or that airlines volunteer. Lastly, the air navigation service providers will need to liaise closely with meteorological institutes as enhanced meteorological data will be required in order to identify these climate-restricted areas.

5.5.4 Incentives from measure

There are a number of key players in the implementation of this measure.

Air Navigation Service Providers

In the pilot stage of this measure, ANSPs will need to work closely together to divert traffic away from the climate-restricted areas. These organisations are key players because of their

[57] We have also considered a charging scheme for these Climate-Restricted Areas, rather than a total flight ban. However, to minimise the contrail cirrus in ice-supersaturated areas no flights should be flying through the area. A mere reduction in the number of flights is not likely to be effective, as the effect is non-linear. If, with a charging scheme, even one or two flights choose to fly through the area, the effectiveness of the Climate-Restricted Area is drastically reduced. Hence, we have only considered a total restriction on flying through the Climate-Restricted areas.

role in coordinating flight plans and actual traffic in their regions. However, ANSPs currently do not possess all the information needed to identify ice-supersaturated areas, and will need to liaise with meteorological institutes to identify the climate-restricted areas.

Meteorological Institutes
Literature has shown that meteorological forecast models can predict the general occurrence of ice-supersaturated areas with high accuracy three days before departure (Rädel & Shine, 2010). However, this methodology used visual observations from the ground made at four times per day and were compared with corrected radiosonde data of humidity profiles as well as grid-box averaged data from ECMWF. A more specific comparison was made by Gierens et al. (2020) using satellite observations of persistent contrails and dedicated in-flight data of humidity compared with ECMWF predictions, and this found only a poor space/time correspondence. If this predictive capability can be enhanced, and found to be reliable across a range of meteorological forecast models, meteorological institutes could pass this information to air navigation service providers in the form of Pre-Flight Information Bulletins (PIB), who could then adjust flight trajectories for those flights that would normally fly through these ice-supersaturated areas.

Airlines
Airlines will need to adjust their flight routes to avoid these ice-supersaturated areas, and are likely to incur costs as a result.

5.5.5 Caveats and constraints

Airlines
One of the major constraints in the implementation of this measure is that airlines may currently be unwilling to participate in a pilot stage due to the fact that their flights will be diverted to avoid the climate-restricted areas, thereby leading to time and fuel penalties. A first hurdle for implementation is therefore finding airlines that are willing to participate, or else mandating airlines to participate.

Measuring the effectiveness of the measure
A second caveat associated with this measure is how to ensure the detour around the climate restricted area, and the extra fuel burn incurred by this detour, does not outweigh the climate benefit created by avoiding the area. Further research should be conducted to determine a realistic detour amount that does not undo the climate benefit. It is likely this will be dependent on the size or volume (area and thickness) of the ice-supersaturated area.

Impacts on Air Traffic Managers
Conversations with experts highlighted the need for predictability in order to manage the network capacity. This is particularly relevant in terms of safety over the Atlantic region where there is no radar coverage. Therefore, this measure would require deviations around ice-supersaturated areas to be included in the filed flight plan, such that in-flight requests for changes are avoided.

5.5.6 Further research

From conversations with stakeholder experts, it has been concluded that there are technical, operational or logistical challenges in the implementation of a pilot measure (i.e. over the Atlantic only), but that these are all solvable. The most important area for further research is how to determine the maximum detour that may be permitted to avoid ice-supersaturated areas such that the net climate impact of this measure is not negative (i.e. warming). All in all, with the current scientific knowledge, there remain uncertainties as to whether this measure would have a long term climate benefit. This is due to the fuel burn penalty of deviating from an optimised route in order to avoid ice-supersaturated areas and the inherent uncertainties of the contrail cirrus forcing.

In addition, it is important to note that this measure complicates air navigation services, and that the safety, capacity and efficiency aspects, in addition to the potential environmental benefits, should be analysed further prior to implementation. This includes the effect of such a measure on existing Single European Sky operational initiatives such as Free Route Airspace.

There is some evidence that most of the total forcing comes from a few events, where contrail cirrus formation is large and long-lasting – sometimes termed 'Big Hits'. It would therefore be advisable that flights impacting these events should be 'targeted' for avoidance, rather than all flights. Therefore, it is recommended that research into reliably forecasting such 'Big Hits' is undertaken. This would require further research into the relevant time/space forecasting ability of meteorological models to predict ice supersaturation and persistent contrail formation.

5.5.7 Conclusion

It is acknowledged that there are significant areas that require further research before this measure can be implemented. In particular, an appropriate CO_2 equivalent emissions metric that permits a comparison between the climate change impact of contrail-cirrus and CO_2 emissions. This will be required to determine the maximum detour that flights can take, and the associated fuel burn trade-off, that still ensures an overall reduction in climate impact from a flight.

As this measure is likely to significantly impact industry in terms of costs (flight detours), their involvement in the design and development of this measure would be essential. Clear demonstration and communication on the environmental benefits would also be needed to ensure buy-in.

If the outstanding research issues are addressed, including positive results from a pilot-phase project in the short-term, and there is the political will to take the option forward, then the measure could potentially be implemented in a more complete form in the mid-term (5-8 years).

5.6 A climate charge

5.6.1 Definition of the measure

The concept of this policy measure is to levy a charge on the full climate impact of each individual flight. This makes it both the measure with the broadest coverage and the one that is likely to be the most complicated to implement.

It is important to note the ICAO definition of a charge: this is a levy that is designed and applied specifically to recover the costs of providing facilities and services for civil aviation (ICAO, 2012). A tax is a levy that is designed to raise national or local government revenues, which are generally not applied to civil aviation in their entirety or on a cost-specific basis (ICAO, 2012). According to (CE Delft, 2002), it could be argued that a levy that aims to internalise the external costs would be considered a charge and not a tax. In this case, the charge would be related to recover the external costs of the climate impact of aviation.

5.6.2 Design of the measure

There are numerous ways in which the full climate impact of individual flights can be assessed, each differing in complexity (Niklaß, et al., 2019). Niklaβ et al. (2019) suggests three different calculations methods:

1. A relatively simple distance dependent CO_2 equivalence factor;
2. A climatological latitude-height dependent CO_2 equivalence factor; and
3. A detailed weather and spatial dependent CO_2 equivalence factor.

These methods differ in their accuracy in calculating the climate impact, which is traded-off against the additional administrative burden required to implement it (e.g. provision of necessary input data and calculation of the climate impact).

The **distance dependent CO_2 equivalence factor** has a relatively low administrative burden, but is the least accurate of the three in calculating the climate impacts of a flight. Niklaβ et al. (2019) do not recommend this calculation method, as important factors such as actual route taken or specific weather conditions are ignored. The administrative burden is expected to be 10-20% higher for authorities than currently under EU ETS. This is the result of the required monitoring, reporting and verification procedures (Niklaß, et al., 2019), where aircraft operators would be required to provide information on airport pairs (origin-destination), the number of flights per airport pair and the total fuel consumption of the fleet per airport pair.

The **latitude-height dependent CO_2 equivalence factor** requires 3D emission inventories to check the non-CO_2 emissions reported by operators. This in turn requires tools to model and verify the reported emissions because fuel consumption and exact waypoints are not immediately available to the authority responsibly for MRV. Administrative burdens are expected to at least double compared with current MRV efforts for EU ETS (Niklaß, et al., 2019). Aircraft operators would be required to provide information on airport pairs (origin-destination), the number of flights per airport pair, the aircraft type per flight, (flown) 3D trajectory per flight, fuel consumption per flight and the 3D emission inventory (CO_2, NO_X) per flight.

Detailed weather and spatial dependent CO_2 equivalence factors would require meteorological data on top of the data requirements needed under the latitude-height dependent CO_2-equivalence factor. This would imply an increase in the administrative burden of more than 100% compared with current MRV efforts (Niklaß, et al., 2019). Aircraft operators would be required to provide information on airport pairs (origin-destination), the number of flights per airport pair, the aircraft type per flight, (flown) 4D trajectory per flight, fuel consumption per flight and the 4D emission inventory (CO_2, NO_X) per flight. The 4D flights profiles are documented for each flight by the aircraft flight recorder and the Air Navigation Service Providers.

The level of the climate charge would be set by multiplying the climate impact of an individual flight (dependent on which of the three calculation methods is chosen from above) expressed in tonnes of CO_2-equivalents, by the social cost of carbon.

Comparing multiple types of non-CO_2 impacts with each other, and with CO_2, represents a major issue that leads to choices that are non-scientific by nature. This is due to the fact that different species persist over different time periods and that the quantification of their impact depends on the emission metric chosen. Non-scientific choices that need to be made include: what climate change variable (e.g. RF or temperature) should be used for comparing the different impacts; whether impacts are integrated over time or considered for a specific point in time and the time horizon over which impacts are to be assessed.

If a consensus on the method to calculate the full climate impact of individual flights could be reached, this would open the door to its inclusion in existing market-based instruments or charging mechanisms, as well as the introduction of new climate policy instruments.

The full climate impact of aviation could alternatively be included in the EU ETS (similar to the measure described in section 5.2, but expanded to incorporate other non-CO_2 effects beyond just NO_X). However, this measure considers a climate charge that is separate from the EU ETS scheme.

Lastly, it is important to note that Member States will need to agree to the implementation of this measure. Depending on whether the measure legally qualifies as a tax, it could require unanimity amongst all EU Member States, as opposed to a qualified majority.

5.6.3 Administration of the measure

The necessary legislation and implementation of this option will need to be considered within the context of the regulatory framework of the Single European Sky Performance and Charging Scheme[58]. Successful administration of the measure would include:

- the registration and calculation of emissions in EU airspace;
- operation of the charging and invoicing procedure; and
- the collection and disbursement of revenues.

5.6.4 Incentives from measure

Airlines

Depending on which calculation method is ultimately chosen, airlines will be incentivised to adjust their flight plans to mitigate the overall climate impact.

Member States

Member States will need to reach consensus on how to administer such a climate charge levy.

European Union

Dependent on the calculation method that is chosen for the climate charge, the EU will need to introduce the necessary legislation in order to implement this option within the context of the regulatory framework of the Single European Sky Performance and Charging Scheme. Close contact with the relevant meteorological institutes, airline operators, ANSPs and Network Manager will be essential for successful implementation.

5.6.5 Caveats and constraints

Comparing different non-CO_2 climate impacts

In this climate charge, multiple climate impacts are combined into one charge. This requires a manner of equivalency between the different impacts, as some effects occur over a shorter time-frame and others over a longer time-frame. Decisions should hence be made with regards to intergenerational equity as to how to value these different effects.

Perverse incentives

In designing this measure it is important to ensure that there are no perverse incentives in the technological developments of aircraft engines. A notable example is the NO_X-CO_2 trade-off in engine design. If the different climate costs are not accurately reflected in the charge, a perverse incentive may exist, and the charge could potentially lead to a warming effect. As such, the design of the measure needs to be well thought through and the price accurately set to reflect the different impacts and create the right incentives.

[58] COMMISSION IMPLEMENTING REGULATION (EU) 2019/317 of 11 February 2019 laying down a performance and charging scheme in the single European sky and repealing Implementing Regulations (EU) No 390/2013 and (EU) No 391/2013.

5.6.6 Further research

Climate impact and cost function

Further research should be conducted on which of the three calculation methods mentioned in 0 should be used to estimate the climate impact and costs of each flight. Particular attention should be paid to maximising the effectiveness of the measure without unnecessarily burdening stakeholders.

Metric for CO_2 equivalence

As mentioned with previous measures, care should be taken in the choice of emission metric to calculate the equivalence of different emissions emitted at different latitudes and longitudes and under different weather conditions to each other. This is particularly relevant here as this measure incorporates all non-CO_2 climate impacts of aviation with time horizons ranging from very short to very long. Hence, scientific and political consensus on the metric and time horizon considered would be needed. A full discussion on climate metrics is provided in Task 1. An accurate weighing of these different impacts is crucial to achieve the desired effect of the measure, which is to reduce the global warming effect from aviation emissions.

5.6.7 Conclusion

The advantage of this measure compared to all other measures investigated in this report is that it is the only measure that internalises the costs of all the CO_2 and non-CO_2 emissions from aviation. However, there is no scientific consensus on which social cost of carbon function or impact calculation method to use, and the measure needs a clear CO_2 equivalent emissions metric which effectively compares the climate impact from different non-CO_2 emissions.

Significant more research is needed to develop and define this measure. If there is the political will to take this forward, then the measure could potentially be implemented in the long-term (+8 years).

5.7 Overview of potential policy options

An overview of the different policy options considered and how they compare to each other is presented in **Error! Reference source not found.**5.

Name of measure	Advantages	Disadvantages	Timescale for implementation[59]
A NO_x charge	— Internalises the external costs of a well-understood non-CO_2 climate impact in the cost of flying; — Reduces demand and consequently also CO_2 and other emissions; — nvPM and full climate impact could be addressed in a similar manner but would be more complicated.	— Could incentivise technological development that leads to increased CO_2 emissions — Uncertainty about the direction of climate impact of NOx in the future (warming/cooling is dependent on background concentrations of other pollutants)	Mid-term
Include aircraft NO_x emissions in EU ETS	— Internalises the external costs of a well-understood non-CO_2 climate impact in the cost of flying; — Reduces demand and consequently also CO_2 and other emissions; — Legislative framework already in place; — nvPM and full climate impact could be addressed in a similar manner but would be more complicated.	— Could incentivise technological development that leads to increased CO_2 emissions — Uncertainty about the direction of climate impact of NOx in the future (warming/cooling is dependent on background concentrations of other pollutants) — Uncertainty about climate impact of NO_x emissions is larger than for CO_2 emissions. Care should be taken to maintain the credibility of the EU ETS	Mid-term

[59] Rough estimates of timescales to implement policy options have been provided, but are dependent on addressing the identified research needs and the political will to take the options forward. For the purpose of this study, short-term is defined as 2-5 years, mid-term as 5-8 years and long-term as 8+ years.

Reduction in maximum limit of aromatics within fuel specifications	— Reduction in contrail formation; — If ASTM and/or DEF STAN standards are adjusted, then the measure has a global impact. — Lowers PM emissions: positive impact on local air quality and climate change.	— Uncertain what the current aromatics content is and hence what the new standard should be to have an effect — initiatives to change fuel standards could be a long process and the outcome is uncertain — Legality of EU incentive for the sale of low-aromatics fuels next to existing fuel standards unclear	Mid- to long-term
Mandatory use of Sustainable Aviation Fuels	— Reduction in contrail formation and SO_x emissions — Reduction in fuel lifecycle CO_2 emissions — Reduction in nvPM emissions. — Potential increase in aircraft fuel efficiency.	— Smaller geographical scope (fuel uplifted in Europe) compared to standard for maximum aromatics content of fuel — Increased incentive for tankering from outside EU	Short- to mid-term
Avoidance of ice-supersaturated areas	— Reduction in contrail cirrus	— Trade-offs in detour (extra CO_2) versus reduced contrail effect — Limited scope because the measure cannot be implemented in crowded airspace	Mid-term
A climate charge	— Internalises the costs of all the CO_2 and non-CO_2 emissions from aviation	— No scientific consensus on the cost function — Involves weighting impacts of different pollutants that are active across different time periods	Long-term

Table 5 – Main conclusions of the considered policy options

[placeholder for aviation-related illustration]