

Potential for reducing
aviation non-CO₂
emissions through
cleaner jet fuel



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Potential for reducing aviation non-CO₂ emissions through cleaner jet fuel

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Summary

Next to the impacts of CO₂ emitted by aircraft on the climate, aviation has so-called non-CO₂ climate impacts. One of the main non-CO₂ impacts is the formation of contrails; by some measures, its contribution to global warming is larger than that of aviation CO₂ emissions.

Contrails form when aircraft engines emit particulates in ice-supersaturated regions and act as condensation nuclei for ice crystals. Particulates form in the exhaust when a share of the fuel is not fully oxidised. Fuels with a high concentration of aromatics and especially naphthalenes (a bicyclic aromatic compound) cause higher particulate emissions because aromatics burn slower than other hydrocarbons.

Therefore, one of the ways in which contrail formation and non-CO₂ climate impacts can be reduced is by reducing the concentration of aromatics in jet fuel.

Jet fuel contains aromatics because crude oil from which it is produced contains aromatics. Sustainable aviation fuels which are on the market today do not contain aromatics because they are hydrotreated. Jet fuel standards set a maximum limit for aromatics of 25% by volume and a maximum limit of naphthalene of 3% by volume. In practice, the aromatics concentration is lower, at 15-20% by volume. The naphthalene concentration is probably between 2 and 3%.

One of the ways to reduce the average aromatics concentration in the fuel mix is to blend SAFs in increasing volumes, while not increasing the concentration of aromatics in the fossil part of the blend. Because lowering the aromatics concentration in the refinery is costly, there is a possibility that refineries will blend aromatics in jet fuel up to the applicable limit in order to reduce costs, thus eliminating the non-CO₂ climate benefits of blending SAFs.

This report explores three ways in which the aromatics content could be monitored or controlled.

The first builds upon the European Commission's so-called ReFuelEU Aviation proposal, which envisages mandatory blending of SAFs in fuel supplied to aircraft departing from EU airports. If ReFuelEU Aviation (or other EU legislation such as the FQD) were to be amended in such a way that it ensures that the aromatic content of jet fuel decreases, it would also ensure that the non-CO₂ climate impact of aviation is reduced.

ReFuelEU Aviation can be amended to keep track the concentration of aromatics and naphthalenes. A monitoring requirement could be included in ReFuelEU Aviation so that fuel suppliers will report the aromatics and naphthalene concentrations to the Union Database in addition to volumes of aviation fuel, sustainable aviation fuel and lifecycle emissions of the fuel. If the obligation applies to batches of fuel containing SAFs, the additional administrative burden of this requirement would be small, because these fuels are always tested. If the monitoring requirement would apply to all aviation fuels, additional testing of pure fossil aviation would be required, thus increasing the costs.



Second, the EU could regulate the concentration of aromatics and naphthalenes. The EU has the power to mandate a new aviation fuel standard across the EU and could do so in any of a number of existing legislative vehicles such as the Fuel Quality Directive, the Emissions Trading System or in the proposed ReFuelEU Aviation.

The third option is to develop a standard for aviation fuel or amend an existing standard. ASTM and DEF are bodies that currently set the main standards for aviation fuel around the world. They could set a new standard which would reduce the non-CO₂ climate impact of aviation but these bodies act using consensus. The EU or a Member State could suggest a new global standard for aviation fuel but there would be no guarantee it would be adopted by ASTM or DEF, or that airlines would demand fuel that meets the new standard.



1 Introduction

1.1 Background of the study

The impacts of aviation on the climate are complex; next to the impacts of fossil CO₂ emitted by aircraft, there are several so-called non-CO₂ impacts which have a warming effect in combination. The largest non-CO₂ impact stems from contrails and contrail cirrus, which had a warming effect in 2018 of 57 (range 17-98) mW.m⁻² (Lee et al, 2021). Contrail formation is induced, primarily by soot emissions from aircraft engines, which result from incomplete combustion of aromatic compounds (and especially naphthalenes) in the fuel (EASA et al., 2020).

One way to reduce the contrail cirrus non-CO₂ climate impact of aviation would be to lower the concentration of aromatics in the fuel. The most widely used standard for jet fuel, ASTM D1655 - 21a, limits the concentration of aromatics to maximally 25.0 % v/v and naphthalene to 3.00% v/v for Jet A-1.

Most sustainable aviation fuels have negligible concentrations of aromatics, so blending these fuels is expected to lower the concentrations of these compounds. In principle, it is also possible to lower the aromatic content in fossil jet fuels by further hydrotreatment or extractive distillation. However, when fuels meet the standard, there is no incentive to do so.

A report by EASA et al. (2020) has identified reducing the aromatic content of fuel as one of the ways in which non-CO₂ climate impacts can be reduced and has analysed several policy options that can achieve this. It has identified the current uncertainty about the aromatic content of fuels as one of the main barriers to monitoring the effectiveness of such a policy.

The European Commission has proposed to require fuel suppliers at European airports to supply fuels with a minimum amount of sustainable aviation fuel and, from 2030, a minimum share of synthetic aviation fuels. The minimum share increases from 2% in 2025 to 5% in 2030 (of which 0.7%-points synthetic aviation fuels) and up to 63% in 2050 (of which 28%-points synthetic aviation fuels). These fuels are generally considered to contain negligible amounts of aromatics and sulphur, so that the concentrations of these compounds in the fuel would be reduced proportionally. This would have a beneficial impact on contrail formation and hence on the climate. However, if the aromatic content of the fossil share of the blend would increase, e.g. in order to lower the costs of hydrotreatment for refineries, the climate benefit could be smaller than anticipated.

There is currently little information on the aromatic content of aviation fuels. As a result, it is challenging to assess the non-CO₂ climate benefits of ReFuelEU Aviation. This study analyses what the potential impacts of ReFuelEU Aviation could be on contrail formation, how the impact could be monitored and how the aromatic content could be regulated.

1.2 Aim of the study

The project aims to analyse which advantages and barriers exist for lowering the aromatic content of jet fuels, and which policies can be developed to monitor the effectiveness of the policies identified in EASA et al. (2020).



1.3 Outline of the report

In Chapter 2 we summarise the evidence on the link between the share of sulphur, aromatics and especially naphthalenes in jet fuel, nvPM emissions, contrails, and climate impacts. In Chapter 3 the evidence on the link between nvPM emissions and local air quality is presented.

In Chapter 4 we present information on the concentration of aromatics and especially naphthalenes in jet fuel and sustainable aviation fuels. In Chapter 5 we assess the costs of reducing the share of aromatics and especially naphthalenes in jet fuel and the barriers for doing so. Chapter 6 discusses potential policies to monitor and to reduce the share of sulphur, aromatics and especially naphthalenes in jet fuel.



2 Evidence on the link between aviation fuel composition and contrail formation

This chapter presents the scientific evidence on the link between the chemical composition of aviation fuel and contrail formation. The nature of this chapter is scientific. For the non-scientific reader, a summary is provided below.

Chapter summary

There is evidence (albeit limited) that naphthalenes in aviation fuel cause a large fraction of the emissions of soot:

- Soot is primarily formed in aircraft gas turbines and emitted as very small particles of around 10 nm in diameter.
- Aviation fossil-based jet fuel (kerosene, Jet A/Jet A-1) is made up of a mixture of n-alkanes, iso-alkanes, cyclo-alkanes, and aromatics. The speciation of the aromatic fraction is not well documented but the available evidence suggests that the aromatic fraction largely comprises mono and bicyclic aromatic compounds. Naphthalene and naphthalene derivatives (e.g., branched methyl, ethyl components) are the major bicyclic components. The aromatic content is currently limited to a maximum of 25% by volume, and a minimum of 8% (for drop-in biofuels).
- Extensive measurement campaigns of aircraft exhaust gases that include fuel substitution experiments provide robust evidence that aromatic compounds are largely responsible for soot emissions from fossil fuel kerosene. More limited fuel substitution experiments indicate that the principal aromatic compound responsible for soot emissions are naphthalenes.
- Measurements at ground and altitude of the combustion of (usually) bio-based kerosene alternative fuels with reduced aromatic content show greatly reduced emissions of soot particles by mass and number.
- However, low-naphthalene fuels do not entirely remove soot. Better and more quantitative data are needed to formulate robust emission reduction strategies with known outcomes.

Soot emissions cause contrail formation under specific atmospheric circumstances.

- Many measurements and model experiments show that contrails are formed on soot particles emitted from aircraft engines.
- Modelling suggests that at temperatures below the threshold for contrail formation, ice crystal number reduces linearly with soot number emission to a certain point but that ice crystal number also depends on temperature (i.e., not just soot number concentration).
- Many measurements show that a lower aromatic content of fuel (from SAF) produces smaller soot number concentrations. Recent in-flight measurements show that these smaller soot number concentrations produce fewer ice crystals of larger size (as expected from prior modelling).
- Fewer and larger ice crystals from low-aromatic SAF fuel are modelled to result in a smaller global effective radiative forcing (ERF) - a smaller impact on the climate.
- The dominant ERF term from the formation of contrails is from persistent contrails, developing into contrail cirrus, under cold atmospheric conditions of ice-supersaturation.
- To a first order, the ERF of contrail cirrus depends on ice crystal number and size, and ice crystal number depends on soot emission number.
- The contrail cirrus ERF term remains highly uncertain, even for conventionally formed contrails from fossil kerosene soot.



Other combustion emissions have a much smaller or no impact on contrail formation

- Sulphur is present in fossil-based kerosene at concentrations thought to be around 600 ppm (the upper limit is 3,000 ppm). The sulphur in the fuel is largely converted to sulphur dioxide gas (SO₂), emitted in the exhaust and a small fraction (approximately 2%) is emitted directly as sulphuric acid. This sulphuric acid can be taken up on the surface of soot particles but in the presence of soot does not nucleate to form discrete particles, even at greater concentrations in the fuel.
- Water from the exhaust initially condenses on soot particles formed in the engine, such that the soot is ‘activated’ and the droplets grow to around 100 nm in diameter. After a second or so, if the atmosphere is supersaturated with respect to ice and is below 233K, these water droplets freeze and grow from water in the ambient atmosphere to around 1,000 nm and larger. Sulphur plays a minimal role in the formation of contrail ice crystals at present fuel S levels, and lower. Larger concentrations than currently prevalent may trigger contrail formation sooner (seconds) but do not affect whether or not a contrail is formed, thus not affecting the radiative effect.

Reducing the naphthalene content of jet fuel is likely to be the most effective way to reduce persistent contrail climate impacts

- Overall, there are clear indications from measurements that reducing naphthalene content would reduce soot number emissions from aircraft exhaust and result in fewer and larger ice crystals. The degree to which this would reduce ERF is less clear, relying on a limited number of modelling studies. Moreover, the whole study area is still hampered by large uncertainties over the current day magnitude of the contrail cirrus ERF, a recent study indicating it could be 7 times smaller than assessed with models (i.e., 8 mW m⁻² for 2019, cf approximately 60 mW m⁻²).
- Other strategies for reduction of the contrail cirrus ERF have been suggested. These include the scheduling of traffic to avoid night-time flights and their resultant positive forcing -on best available knowledge this is unlikely to have much success because of the long lifetime (10+ hours) of persistent contrails. Navigational avoidance of the formation of contrails is also widely discussed. This approach suffers from complications of an inability of current meteorological forecast models to predict ice supersaturation, and therefore persistent contrails on an operational basis, the poorly known magnitude of the contrail cirrus ERF term to justify the approach, and the lack of a robust agreed metric to compare potential reduction in contrail cirrus ERF with increased CO₂ emission, under most scenarios of ‘avoidance’, since most flights are cost and therefore fuel optimised.
- It is noteworthy that any changes (reductions) in the production of persistent contrails and particularly contrail cirrus on a large scale would be difficult or impossible to detect. This is because the variation in cirrus cloud is thought to be larger than the signal of contrail cirrus from global aviation. Thus, environmental improvement from changes designed to reduce contrail cirrus would be (at present) unverifiable.

2.1 Introduction and definition of fuels, and their composition

In this section, the definition of ‘sustainable aviation fuels’ (SAFs) is taken, as per Chapter 1, to refer to liquid paraffinic fuels that have lower life-cycle carbon footprints than fossil-based kerosene, primarily Jet A/Jet A-1. The derivation of these fuels is potentially from either bio-based feedstocks, or synthesized fuels. The latter have a range of terminologies, including synthetic fuel, e-fuel, and power-to-liquid fuels (P-T-L). Here, what is referred to as synthetic SAF, is taken to mean a liquid paraffinic fuel, synthesized by some process (such as Fisher Tropsch), where the hydrogen source is produced from renewable energy, and the carbon source is from direct air capture (DAC). Both bio- and synthetic-SAFs have low-aromatic and sulphur (S) content than fossil-based kerosene.

Petroleum based aviation fuels contain a highly complex cocktail of hydrocarbons whose constituent parts change with the source of the original crude oil. Fuel specifications define a range of physiochemical properties and not the detailed chemical composition. Globally, a



number of regional specifications and fuel types are in use, including Jet A-1 (Europe), Jet A (North America), TS-1 (Russia), and No.3 Jet Fuel (China).

The majority of aviation turbine fuel (by volume) is certified under Defence Standard 91-091 (Jet A-1) and ASTM standard D1655 (Jet A). It is however also worth noting the primary SAF specifications incorporated under Def. Stan. 091-091/issue 12 and ASTM D7566. Fuel certified under these specifications represent a small fraction of current aviation fuel usage.

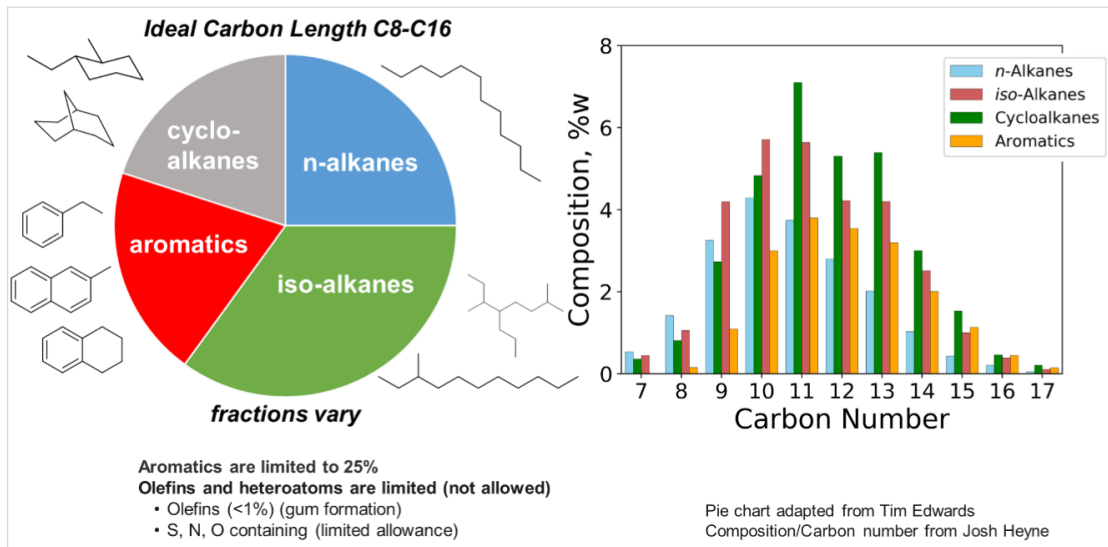
The composition of aviation jet fuel typically contains a range of different molecules in different proportions from the following chemical families: n-alkanes¹ (straight chain alkanes), iso-alkanes (branched chain alkanes), cyclo-alkanes (or naphthenes, saturated ring), and aromatics (unsaturated rings), see Figure 1. Alkenes (or olefins, unsaturated chains) are not normally present, except under conditions of severe cracking. Within the aviation fuel specifications, the aromatic family is the only group to have specifically identified control limits (max 25% v/v, of which max 3% v/v naphthalene). Other chemical families are not explicitly restricted but are effectively constrained by the required conformity to an array of physiochemical properties such as density; freeze point; distillation range; and thermal stability within the finished product.

The exact composition of the aromatic fraction of conventional fossil-based (e.g. Jet A/A-1) aviation fuel is not well documented. It is considered to be largely made up of benzene structures with added alkyl (e.g. methyl, ethyl) structures. There appears to be no formal reporting requirement of speciation, and since fossil fuel composition is diverse by nature, this speciation is largely undocumented with presentations such as those in Figure 1 being typical. However, Narayanaswamy et al. (2016) attempted to summarise this quantitatively from various sources (see Figure 2). Of the bicyclic structures, the dominant 'parent' molecule is naphthalene, a two-ringed aromatic structure (C₁₀H₈), along with other minor species being occasionally identified, such as indane, indene, tetralin with very small amounts of tri-ringed structures such as anthracene, methyl anthracene, phenanthrene, acenaphthylene being present (Bernabei et al., 2003). Naphthalene poly-aromatic hydrocarbons with additional methyl, ethyl groups are also found (Bernabei et al., 2003). Benzene is present at rather small volumetric concentrations (<0.05% or less, NAS, 2011) but it appears that alkylated benzene, toluene, xylene type structures dominate the aromatic fraction.

¹ 'Alkanes' are sometimes referred to as 'paraffins', so read 'iso-paraffins', 'cyclo-paraffins' etc. as equivalencies

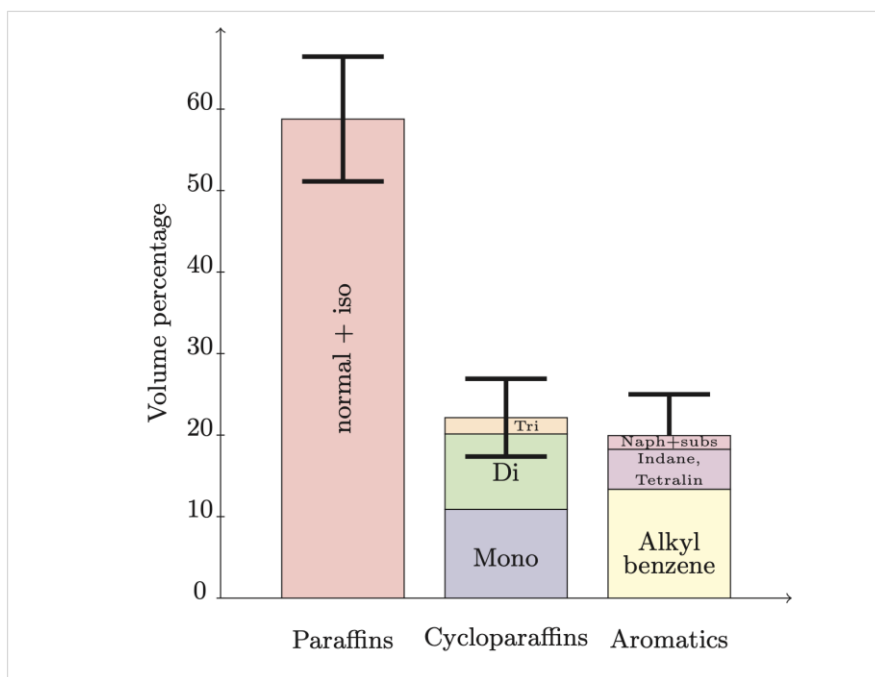


Figure 1 - Composition of average Jet A



Source: Taken from Holladay et al. (2020), based on Edwards (2017).

Figure 2 - Average composition of jet fuel



Source: Narayanaswamy et al. (2016).

One of the major issues associated with the functionality of aromatics in jet fuel is their properties of lubricity and ability to swell seals, many of these seals being ‘O rings’. When O-ring (elastomer) material is exposed to fuel for the first time, two processes occur. First, the elastomer can absorb components from the fuel such as alkanes, aromatics, etc., which causes the material to swell and soften. Second, the fuel may extract components from the elastomer such as plasticizers, which can cause the material to shrink and harden.



The balance of the effects results after the material has been in service for some time, such that the fuel-extractable components will have been removed and all subsequent changes in physical properties will result from a shifting equilibrium between the material and the overlying fuel, which in turn will depend on the composition of the fuel (Liu and Wilson, 2012). A more detailed overview of these processes is given by Annuar et al. (2021). The three types of seals frequently used in aircraft systems are fluorocarbon, fluorosilicone and nitrile seals (Annuar et al., 2021). Holladay et al. (2020) point out that the need for aromatics in SAF replacements is only for nitrile seals that have previously been exposed to aromatics and that previously unexposed seals work acceptably but offer no documentary evidence for this.

The lack of aromatics in SAF presents few problems in practice at the moment, given that only blends of SAF are certified, such that they don't fall below the 8% minimum requirement. Nonetheless, there is work ongoing in the fuels community to investigate how and what aromatic species could be added back into SAF (e.g., DeWitt et al., 2008; Al-Nuaimi et al., 2016; Annuar et al., 2021).

2.1.1 The effects of aviation on climate

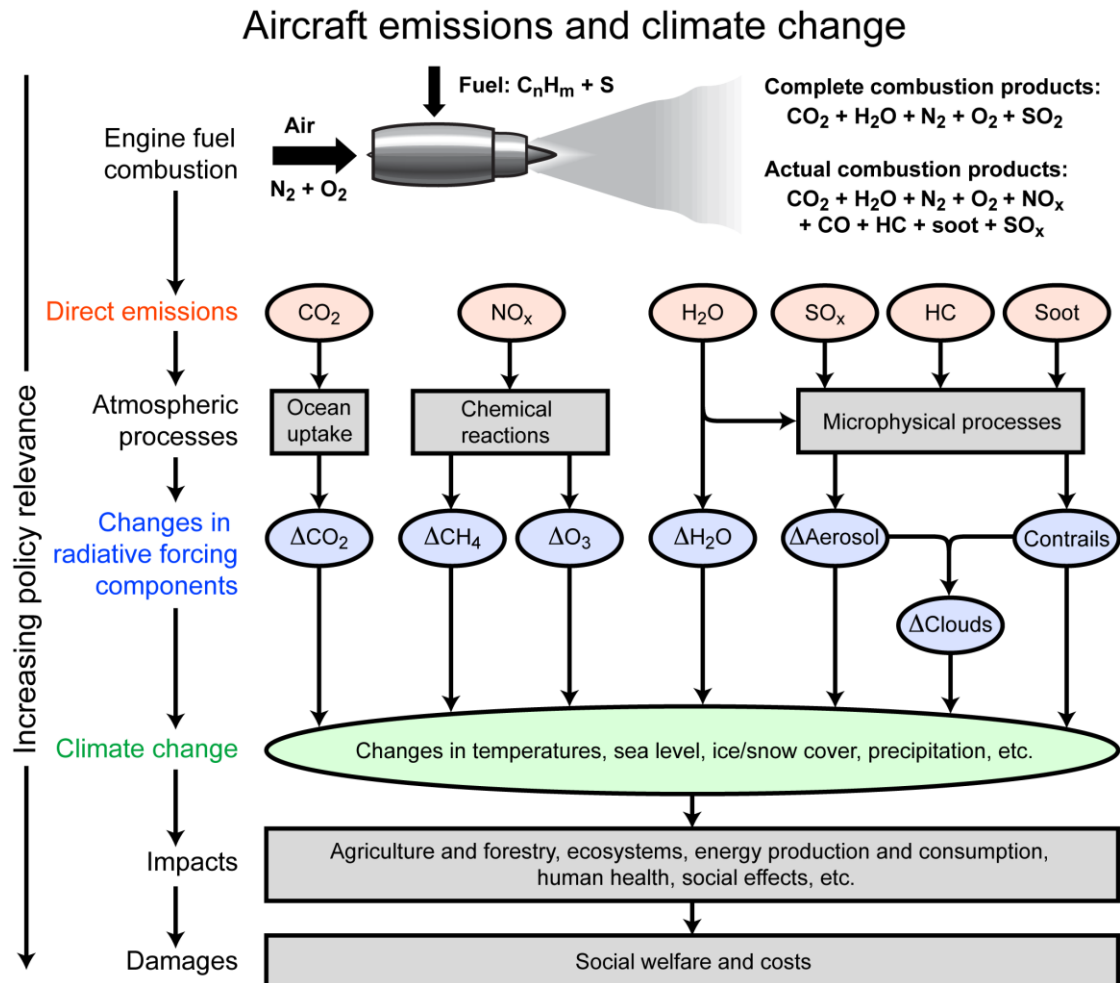
The effects of aviation on climate have been assessed for over two decades with a major international assessment first being undertaken by the IPCC in 1999 (IPCC, 1999) with updates in 2005, 2009, 2021 (Sausen et al., 2005; Lee et al., 2009; Lee et al., 2021). Aviation has been shown to have a number of effects from emissions other than CO₂, that change the radiative balance of the atmosphere, including those from NO_x, water vapour and aerosol particles. The largest calculated component, in terms of 'effective radiative forcing' (ERF) is that of contrails and contrail cirrus. Contrails are formed from the emission of soot particles and water vapour into cold ice-supersaturated atmospheres and if persistent, may spread through wind shear and further uptake of water vapour into extensive cirrus cloud-like coverages (Kärcher, 2018). A recent assessment of the 2018 ERF terms from global aviation calculated the contrail cirrus ERF to be the largest at 57 mW m⁻² (range 17- 98 mW m⁻²), larger than the CO₂ forcing of the history of aviation, and a substantial fraction of the total ERF signal, CO₂+non-CO₂ ERFs of 101 mW m⁻² (range 55-145 mW m⁻²). However, these ratios are not fixed, as pointed out by Klöwer et al. (2021), who showed that the non-CO₂ forcings from aviation were sensitive to the rate of growth of CO₂ emissions, such that the grow faster under a scenario of increasing emissions, but equally, fall more quickly if CO₂ emissions are reduced, such that the absolute and relative non-CO₂ forcings become smaller.

2.2 Combustion chemistry and non-volatile/volatile particle formation

The current subsonic fleet largely uses fossil-based kerosene as an energy source, which when combusted in the aircraft engine results in the emission of a number of products of complete and incomplete combustion, as shown in Figure 3.



Figure 3 - Schema showing the principal emissions from aviation operations and the atmospheric processes that lead to changes in radiative forcing components. Radiative forcing changes lead to climate change as measured by temperatures and sea levels, for example.



Source: Lee et al. (2009), adapted from [Prather et al. \(1999\)](#) and [Wuebbles et al. \(2007\)](#)

From Figure 3, the combustion of fossil-based kerosene (which naturally contains some S) in air ($N_2 + O_2$) results in emissions of CO_2 , H_2O , N_2 , O_2 , and SO_2 . The combustion process also results in emissions of NO_x , through fixing of atmospheric nitrogen, and incomplete combustion products of CO and hydrocarbons (HC) and soot. These products can be modified through atmospheric processes and affect the radiative forcing of climate, resulting in subsequent climate change and its impacts.



2.2.1 Non-volatile particles

In a gas turbine engine, the non-volatile particulate matter (nvPM²) is initially formed in the primary zone of the combustor and subsequently undergoes partial oxidation in the secondary and quenching zones before being emitted. This nvPM formation process is largely determined by aspects of the combustor design that control stoichiometry and mixing in the primary zone. However, combustion is a chemical oxidation process and so reaction kinetics and therefore chemical properties of the fuel also play an important role. For example, fuel aromatics have long been identified as compounds that primarily influence the tendency to form soot during combustion (Timko et al., 2010).

Nevertheless, the relationship between fuel composition and the exhaust species is not well characterised and the chemical kinetics of the combustion process are poorly understood. To better understand these processes, investigations with pure substances and mixtures of pure substances with well-defined and reproducible compositions have been undertaken. These ‘fuel surrogates’ contain a reduced number of hydrocarbon components and are designed to exhibit behaviour that is similar to the commercial fuel they are intended to represent. An extensive review of surrogate fuels designed to investigate the chemical kinetic schemes for the oxidation of fossil fuel kerosene is given by Dagaut et al. (2006). Essentially, aromatic species from the fuel condense and form addition sites for incomplete combustion that result in the formation of polyaromatic hydrocarbons (PAHs) that nucleate and agglomerate to form soot particles (e.g., Frenklach, 2002; Richter and Howard, 2000). Overall, our understanding of the soot formation process within a gas turbine combustor and for different fuel compositions is generally poor. Applying a pseudo-empirical model, it has been postulated that the formation of soot nuclei is dominated by the condensation of fuel aromatics at lower combustor temperatures (i.e., idle), as these reactions proceed at a faster rate than the condensation of paraffinic compounds, whereas at higher combustor temperatures (i.e., high power) a mechanism involving the fragmentation and polymerisation of both aromatics and paraffinic species is favoured (DeWitt et al., 2008). Hence the formation of soot nuclei is much reduced for ‘pure’ paraffinic fuels relative to Jet A-1 due to the near zero-aromatic content and this effect is particularly evident at low power.

While the aromatic content of jet fuel is widely associated with the production of soot particles, this can be specified more precisely as being the naphthalene content as being the apparent primary determinant (Chin and Lefebvre, 1990). A number of measurement campaigns with a range of strategies to determine influences of fuel composition on soot emissions from aircraft engines have been undertaken in Europe and North America (Brem et al., 2015; Moore et al., 2015).

Brem et al. (2015) ran fuel (standard Jet A-1) with added aromatic solvents, one depleted in naphthalenes and one not, for total aromatic contents ranging between approximately 18% to 24%. The effect of the naphthalene concentration on nvPM mass and on the number of particles varied by thrust setting of the engine, including the differential between fuel additives, but at 30% thrust, the naphthalene-depleted solvent additive resulted in nvPM numbers of 30% less than the standard additive. However, they noted that the differences

² Aviation emission articles 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’, terms that are sometimes used interchangeably, but incorrectly so. BC is pure elemental carbon, whereas soot usually contains impurities. Here, we will use either ‘soot’, which is taken to mean the inorganic and organic carbon in the engine exhaust and plume, or nvPM, which is strictly soot measured at the engine exit for regulatory purposes. The ‘volatile’ fraction is usually taken to be particles composed primarily of sulphate, originating from sulphur (S) in the fuel.



were indistinguishable at 100% thrust setting. Remember, however, that these experiments were conducted with standard (naphthalene-containing) Jet A-1 fuel with the aromatic content *increased* rather than a zero-aromatic SAF. Nonetheless, the measurements point to the importance of naphthalene in soot formation (here measured strictly as the nvPM regulatory measurement).

Moore et al. (2015) summarised measurement campaigns made over the previous decade from the APEX, AAFEX-I, AAFEX-II and ACCESS-I programmes (see Moore et al., 2015, for details and references), which made measurements behind the NASA Douglas DC-8 CFM56-2-C1 engines. The essential high-level conclusion from the many experiments was that the naphthalene content of the fuel determined the magnitude of the soot number and they showed that reducing both fuel sulphur and naphthalene content to near-zero would result in an approximately 10-fold decrease in aerosol number emitted per kilogram of fuel burned. In contrast to Brem et al. (2015), Moore et al. (2015) found that the 10-fold emissions reduction associated with reducing the fuel naphthalene content to near zero was similar for all engine powers but was most significant for the higher engine power settings. Moore et al. (2015) noted that the emission indices and relationships with fuel composition would be likely to be different for different engines and their thrust settings.

In a laboratory study, Richter et al. (2021) measured the sooting propensity of different fuels in an experimental combustion rig using Jet A-1 and four alternative SAF fuels. The aromatic-free synthetic paraffinic kerosene (SPK) was used to create 5 different blends, each containing a single aromatic additive of toluene, *n*-propylbenzene (both monocyclic aromatics), indane, 1-methylnaphthalene and biphenyl at concentrations of 8%, 16.5% and 25%. Richter et al. (2021) found that their measure of sooting propensity followed the order of mono-aromatics < cyclo-aromatics³ < bi-aromatics and concluded that in order to reduce soot emissions from jet fuel, it was more important to reduce the content of cyclo- and bi-aromatics than to minimise the overall concentration of aromatics, per se. These laboratory results are consistent with the field measurements of Brem et al. (2015) and Moore et al. (2015) in that they identify naphthalene as being the most important aromatic component of jet fuel for soot formation.

Based on many measurements, it is now widely accepted that SAF paraffinic fuels exhibit significantly lower nvPM (soot) emissions in comparison with Jet A-1 and that a large fraction of the soot emissions is from naphthalenes.

2.2.2 Volatile particles

In terms of volatile particulate formation, this originates primarily from S-bearing compounds. Sulphur compounds are present in aviation fuel at ppm levels (Miller et al., 2009), with the regulatory limit being specified by UK Defence Standard 91-091 and in the US by ASTM D1655 at 3,000 parts per million by mass (ppm). In practice, levels are found at around 600-800 ppm (Miller et al., 2009).

The primary emission from the engine exit is sulphur dioxide (SO₂); earlier measurements implied that up to 10% of the emitted sulphur could be gaseous sulphuric acid (Brown et al., 1997; Petzold et al., 2005). More recent work suggests that the initial sulphuric acid content directly emitted is approximately 2% (Jurkat et al., 2011). The gaseous sulphuric acid will quickly condense on existing particles from either the soot emissions or other pre-existing particles in the atmosphere. Of the larger fraction of emitted sulphur species, as SO₂, this is oxidized relatively slowly at around 1% per hour, so will form at km scale

³ Cyclo-aromatics are hydrocarbons with multiple rings, of which at least one is aromatic.



distances from the aircraft's emission (at cruise altitudes). From in-plume measurements of volatile particles, large changes in fuel S content (6 ppm to 2,700 ppm) showed increases in (volatile) particle number of between a factor of 3 to 4 (Petzold et al., 1997), thus demonstrating the 'sink' process of surface uptake of soluble sulphate on soot particles.

Emission estimates of vPM from aircraft engine emissions are harder to quantify than nvPM and the currently accepted method is the FOA3 method (Wayson et al., 2009) which provides a very approximate estimate of vPM from aircraft engine emissions based on the APEX-1 (Aviation Particle Emissions eXperiment; Kinsey et al., 2010) results. The FOA3 approximation for vPM is currently under review in ICAO-CAEP and this review will consider more recent relevant sources of data from relevant studies including from the US, APEX 2-3, AAFEX1-2, ACCESS2 ground measurements, and from the EU, AVIATOR.

2.2.3 Measurement of soot/nvPM emissions for regulation

Measurements of the emissions of soot, or nvPM for the regulatory regime, are complex, and for individual engines the soot number concentrations can vary by two orders of magnitude (Agarwal et al., 2019). Soot number concentrations from aviation vary with the assumed size of the particles emitted as well as the mass emissions. The International Civil Aviation Organization (ICAO) has developed standards and recommended practices (SARPs) to for measuring limit the mass- and number-based emissions of nvPM emitted from aircraft engines with maximum rated thrust >26.7 kN (ICAO, 2017). The SARPs for nvPM specify standardised sampling and measurement protocols (SAE, 2013, 2018), which have been extensively evaluated and validated (Lobo et al., 2015a, 2020). Robust certification measurements of nvPM mass and number for in production engines are being collected as part of the implementation of the ICAO-CAEP standards and are being made publicly available in the ICAO-CAEP Engine Emissions Databank⁴.

For other engines conversion factors from smoke number measurements to nvPM mass and number have recently been developed for the ICAO-LTO cycle (Agarwal et al., 2019). There are some additional uncertainties associated with estimating the measurement line loss element, as the certification measurement is based on measurements at the end of a relatively long sample line not at the engine emission exhaust, so adjustments are required to estimate the LTO emissions for inclusion in impact assessment studies. Furthermore, providing estimates of cruise emissions from the LTO nvPM mass and number measurements is an active area of investigation in the ICAO-CAEP community and a standardised estimation method has not yet been finalised, although other methodologies exist (Teoh et al., 2019). For the purposes of atmospheric modelling the most commonly used emission index is 0.03 g/kg fuel, or 2×10^{14} particles/kg fuel⁵ Barrett et al. (2010).

2.3 Contrail formation, effective radiative forcing, uncertainties

Extensive literature exists on the theory behind for the formation of contrails (see Schumann, 1996; 2005; Schumann and Heymsfield, 2017 for summaries). Essentially, contrails are ice crystals formed behind an aircraft on soot particles, generated from the initial 'pulse' of water vapour from the engines when conditions of temperature (<225K) and ice-supersaturation are favourable. This initial formation of contrails is well-predicted by thermodynamics and requires no direct measure of soot emissions (Schumann, 1996).

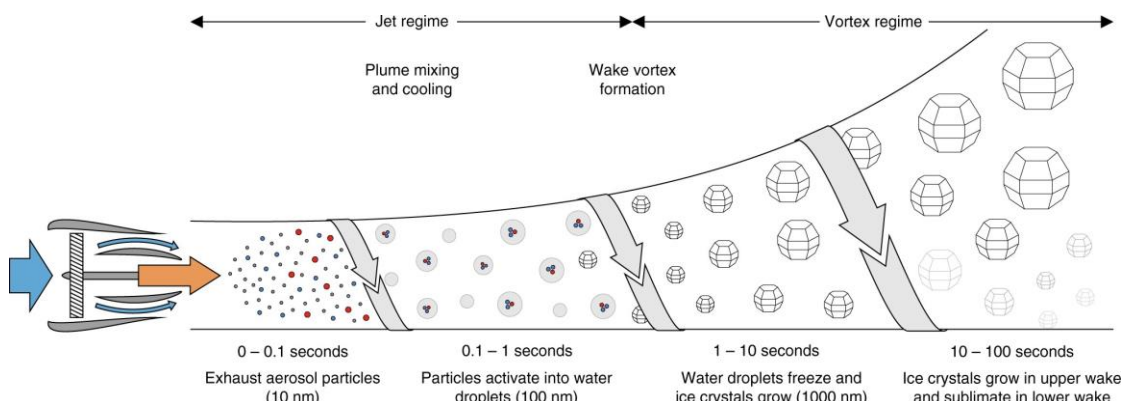
The formation of a contrail is shown in Figure 4, taken from Kärcher (2018).

⁴ www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank

⁵ Assumes mean particle size in the range of 11-79 nm diameter.



Figure 4 - Processes and timescales of contrail formation



Note: The exhaust consists of gaseous and particulate emissions. Of the particles, ultra-fine aqueous particles (UAPs) a significant fraction comes from oxidation of SO_2 (S^{IV}) to H_2SO_4 (S^{VI}), of which the conversion is of the order 2% (Jurkat et al., 2011), of less than 10 nm in aerodynamic diameter.

Source: Kärcher (2018).

Contrails formed in the jet and wake vortex regime are linear in structure and may or may not develop to be persistent. If persistent, they can spread through windshear, eventually becoming indistinguishable from natural cirrus clouds. It is considered that only persistent contrails, and particularly those that spread to form so-called ‘contrail cirrus’ are those that contribute to any warming phenomenon (Burkhardt and Kärcher, 2011). From here forwards, the term contrail cirrus will be used as being the sum of linear contrails and contrail cirrus, unless specifically discriminated between.

The degree to which contrail cirrus affects climate is usually assessed using the radiative forcing (RF) metric in W m^{-2} , and more recently, the ‘effective radiative forcing’ (ERF), which is a modified version of the RF concept that accounts for fast feedbacks in the climate system and has an improved linear relationship with global mean surface temperature response (Myhre et al., 2013). Contrail cirrus largely cools during the day as it reflects solar radiation back to space, but warms at night, when it traps terrestrial, or infra-red, radiation with a net warming response (Meerkötter et al., 1999). (Large scale ‘outbreaks’ of contrail cirrus can last of the order 10 hours (Bock and Burkhardt, 2016a) such that scheduling of air traffic for the avoidance of the night-time long wave forcing is unlikely to be successful (Newinger and Burkhardt, 2012).

The recent assessment of Lee et al. (2021) (hereafter ‘L21’) normalised and scaled a range of modelled estimates of contrail cirrus forcing to 2018 traffic and calculated an ERF of 57.4 mW m^{-2} (17-98 mW m^{-2} , 5-95% confidence interval range, assessed with a confidence level of “low”). Two of the three estimates were modified by a mean calculated efficacy factor of 0.42 to account for the change in metric from RF to ERF, while one of the estimates inherently was an ERF calculation. This substantial reduction in the RF estimate (to ERF) was the result of three different model estimates from Bickel et al. (2019); Ponater et al. (2005); Rap et al. (2010). The IPCC recently revisited the contrail cirrus ERF term, and (based upon the L21 assessment) gave a best estimate of 60 mW m^{-2} (range 20 to 100 mW m^{-2}), rounding up the L21 assessment based on “low confidence” (owing to missing or poorly quantified processes) and accounting for an additional year of traffic growth from 2018 (the L21 baseline) to 2019 (IPCC AR6, 2021, WGI, Chapter 7). A recent analysis of the impact of the COVID pandemic on air traffic was undertaken by Digby et al. (2021) who found that satellite observations of global cirrus in highly trafficked regions did not show a detectable

response to the dramatic reductions in traffic in northern hemisphere spring 2020. They also performed an approximate scaling response to ERF, which amounted to 8 (-3 to 22) mW m⁻².

2.4 The relationship between fuel composition (sulphur and aromatics) and contrails

There have been a number of measurement campaigns that have quantified reductions in soot emission behind aircraft engines at the ground, using SAF compared with conventional kerosene (Lobo et al., 2011; Beyersdorf et al., 2014; Moore et al., 2015 and references therein; Durdina et al., 2021).

Lobo et al. (2021) provide an update and overview of fuel composition effects on soot or nvPM emissions. They summarise:

- The combustion of ‘pure’/blends of SAF results in different soot emissions characteristics varying with engine type and operating condition (Beyersdorf et al., 2014; Brem et al., 2015; Corporan et al., 2011; Lobo et al., 2011, 2015, 2016; Moore et al., 2017; Schripp et al., 2018, 2019; Timko et al., 2010).
- The observed reduction in soot number (and mass) emissions is greatest at low engine thrust conditions and decreases with increasing thrust (e.g. Agarwal et al., 2019).
- In addition, SAF combustion results in changes to:
 - particle size distributions (Beyersdorf et al., 2014; Cain et al., 2013; Kinsey et al., 2012; Lobo et al., 2011, 2015, 2016; Schripp et al., 2018; Timko et al., 2010);
 - chemical composition (Elser et al., 2019; Kinsey et al., 2012; Timko et al., 2013; Williams et al., 2012);
 - morphology (Huang and Vander Wal, 2013; Kumal et al., 2020; Liati et al., 2019);
 - hygroscopic properties (Trueblood et al., 2018);
 - and optical properties (Elser et al., 2019).

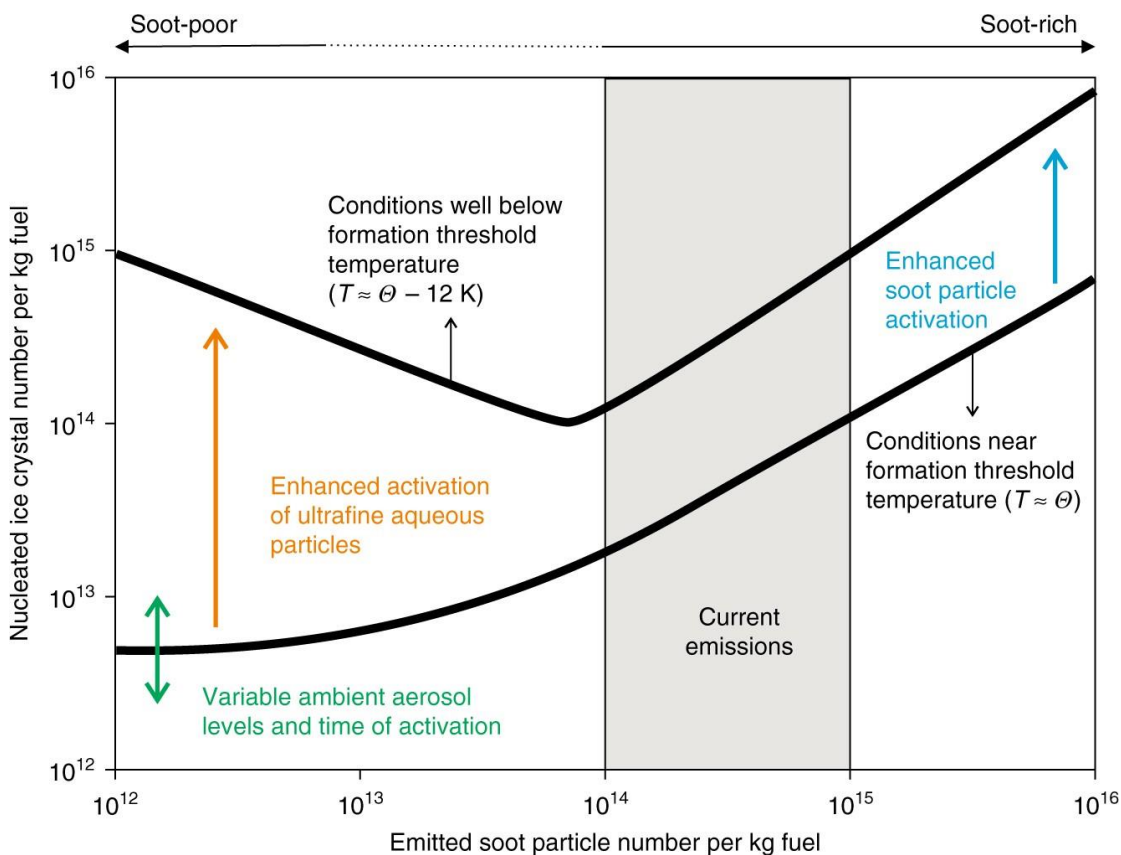
By convenience and constrained by costs, most experiments have been carried out at ground level. However, Moore et al. (2017) extended the analysis to in-flight cruise altitude-based measurements behind the NASA DC-8 aircraft using conventional Jet A and a 50:50 volume blend of Jet A and camelina-based biofuel. They found that the blend reduced particle number and mass by between 50 and 70% under non-contrail forming conditions. Tran et al. (2020) recently reported similar in-flight-based measurements of soot emissions from a Falcon aircraft with GE CF700-2D2 engines, using conventional Jet A-1, JP5 and an alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK). Total soot number emissions were reduced by 97% under contrail-forming conditions when using ATJ-SPK instead of fossil Jet A-1.

The dependence of ice particle number concentration on soot emission number concentration has been predicted with models for some time (Kärcher and Yu, 2009; Unterstrasser and Giernes, 2010; Kärcher and Voigt, 2017) and applied in the context of potentially reduced aromatic content fuels by e.g. Kärcher, et al. (2015) and large scale models of contrail cirrus forcing (Burkhardt et al., 2018; Bier and Burkhardt, 2019). Figure 5 shows the modelled dependence of ice crystal number, per unit of fuel used against the emission of soot number concentration, per unit of fuel for two example temperatures, one close to the formation threshold temperature of contrails (225K) and one at 12K less (colder). These simulations are for conventional jet fuel, with aromatic and S content. A few important features emerge. For a given emission number rate, the ice crystal number varies by temperature (i.e. there is no unique crystal number for soot number, per unit fuel) owing to incomplete activation of soot particles near the temperature threshold of formation (Kärcher and Voigt, 2017), and that the dependence between ice crystal number on soot number is linear between 10¹⁴ and 10¹⁶ soot particles



kg⁻¹ fuel. Below 10¹⁴ soot number concentrations kg⁻¹ fuel, the behaviour is different for the two temperature situations modelled. For close to formation threshold conditions, the slope of the line levels out at a value of 10¹² particles kg⁻¹ fuel, a value which is equivalent to the average background atmosphere loading of particles, i.e., a 'sootless' exhaust will still form ice crystals on background particles. For lower temperatures, condensable gases (S, organics) can start to form UAPs and *increase* the ice crystal number concentration again. If the fuel is low S, then the degree to which this may occur is thought to be less, but not confirmed.

Figure 5 - Modelled ice crystal number emission index (per kilogram of fuel burnt) in the jet regime as a function of the number emission index of emitted soot particles for two temperature conditions, one close to the contrail formation threshold temperature of approximately 225K, and a temperature 12K below this value



Source: Kärcher (2018).

The theory behind this has been recently tested and confirmed from in-flight measurements of emissions of soot number concentrations from reduced aromatic SAF and shown that ice crystal numbers are - as expected - reduced in number and are larger over conventional kerosene base case measurements (Voigt et al., 2021; Bräuer et al., 2021). Voigt et al. (2021) report measurements taken behind an Airbus A320 with International Aero Engines V2527-A5 engines, using a Jet A-1 reference fuel ('REF2'), and three low-aromatic content alternative fuel blends; a semisynthetic FT-SPK (41%), a SAF1 case (49% HEFA-SPK), and a SAF2 case (30% HEFA-SPK). Voigt et al.'s (2021) main results are reproduced for the contrail cases below (direct reproduction of their table 3).



Table 3 Summary of fuel composition and measured emissions indices for reference Jet A1 fuel (Ref2) and for low-aromatic semisynthetic (SSF1) or sustainable (SAF1 and SAF2) aviation fuel blends derived during the contrail measurement sequences at medium cruise thrust conditions.

Fuel type	Ref2 (Δ)	SSF1 (Δ)	SAF1 (Δ)	SAF2 (Δ)	Ref3 (Δ)
Aromatics (vol%) (ASTM D6379)	17.2 (± 2.5)	11.4 (± 2.5)	8.5 (± 1.5)	9.5 (± 1.5)	18.6 (± 2.5)
Naphthalenes (vol%) (ASTM D1840)	1.83 (± 0.08)	0.82 (± 0.05)	0.61 (± 0.04)	0.05 (± 0.01)	1.17 (± 0.06)
Hydrogen (mass%) (ASTM D7171)	13.73 (± 0.08)	14.36 (± 0.02)	14.40 (± 0.07)	14.51 (± 0.04)	13.65 (± 0.05)
Nonvolatile particle number Emission Index ($D_p > 10$ nm) (kg-fuel^{-1})	(4.9 \pm 0.6) $\times 10^{15}$	(2.5 \pm 0.2) $\times 10^{15}$	(2.7 \pm 0.6) $\times 10^{15}$	(2.3 \pm 0.6) $\times 10^{15}$	(3.8 \pm 0.9) $\times 10^{15}$
Apparent ice crystal number Emission Index (AEI_{ice}) (kg-fuel^{-1})	(4.2 \pm 0.6) $\times 10^{15}$	(2.0 \pm 0.2) $\times 10^{15}$	(2.3 \pm 0.2) $\times 10^{15}$	(1.1 \pm 0.4) $\times 10^{15}$	
Number of plume intercepts	29	23	46	53	30
Number of contrail intercepts	29	23	7	6	

Summary of fuel composition and emissions indices measured in 39-140 s old contrails at 9.7 to 10.7 km altitude in persistent contrail conditions. Engine settings were at medium-thrust cruise conditions and fuel flow rates as indicated in Data Table 1 and ambient conditions as detailed in Table 2. Ice particle and aerosol emissions indices are reported as the arithmetic mean ± 1 arithmetic standard deviation (a.s.d.) as described in detail in methods. Ref3 parameters are given as reference for ECLIF2/ND-MAX, while contrails were not observed at comparable ambient conditions.

From the above table, the lowest ice crystal number concentration was recorded for SAF2, for which the naphthalene content was lowest (0.05%) whereas the total aromatic content was not the lowest (9.5%, cf 17.2% for REF2), for which the ice crystal number was a factor of 3.8 times lower. Overall, Voigt et al. (2021) observed a 50 to 70% reduction in soot and ice numbers for low-aromatic sustainable aviation fuels, and larger ice crystals which are expected to sediment and sublimate more quickly, leading a reduced ice crystal lifetime.

Bräuer et al. (2021) expanded the analysis of Voigt et al. (2021) by comparison of the SAF1 and SAF2 fuels (see table above) to two further reference fuels of 100% Jet A-1, for a range of higher altitudes of contrail formation, with a focus on the similar total aromatic content of SAF1 and SAF2 but the much-reduced naphthalene content of SAF2 over SAF1. Contrail ice particle numbers are sometimes expressed as an ‘apparent emission index’ (AEI), since they are not emitted directly. Bräuer et al. (2021) found a maximum reduction in AEI of 40% between SAF and the reference Jet A-1, with reductions in contrail optical depth⁶ of 40%-52%.

Only limited efforts have been made so far, to translate reductions in soot number emissions to global contrail cirrus changes in large-scale models (Caiazza et al., 2017; Burkhardt et al., 2018; Bier and Burkhardt, 2019). The two modelling groups involved produce inconsistent results.

Caiazza et al. (2017) analyse three basic scenarios, a baseline using conventional paraffinic fossil fuel, a paraffinic biofuel, and a ‘clean burn’ technology scenario. They find competing mechanisms at play, whereby the greater water vapour emission index (EI) for the biofuel increases contrail occurrence by 8%, the contrails consist of larger crystals (+58%) and lower number concentrations (-75%) reducing contrail OD by 29% and albedo by 32%. This results in a net contrail RF change ranging between -143% and +5%. For the ‘clean there is no increase in water vapour EI, the net changes in RF range between -13% and +5%.

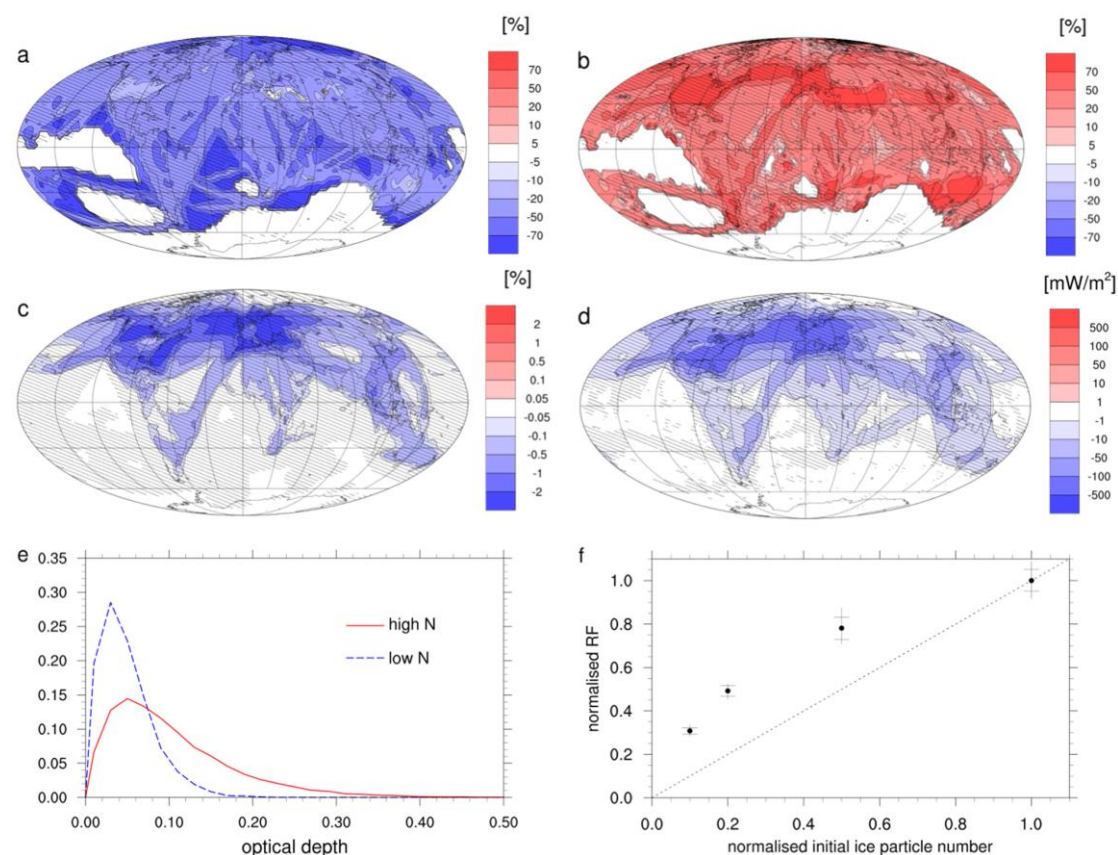
Burkhardt et al. (2018) find that (similarly), ice crystal sizes increase, contrail OD is reduced, and lifetime is reduced for an assumed reduction in soot number emission number of 80% from a 50:50 blend of biofuel. Bier and Burkhardt (2019) go on to consider details of the spatial patterns of differences, especially between the tropics and extra-tropics, where there are potentially large changes between proximity to threshold formation conditions. It is difficult to reconcile the two approaches. It is unclear whether the DLR modelling group consider changes in water vapour EI. On the other hand, since overall RF is the result

⁶ Contrail optical depth (OD) is a dimensionless measure of the reduction of radiation passing through a contrail, and the larger the OD, the larger the radiative forcing (e.g. Frömming et al., 2011).



of negative and positive forcings, the inherent radiative transfer models can make large differences to the overall results, especially the balance of short-wave to long-wave forcing, which can be quite variable between models (Myhre et al., 2009). Figure 6 from Burkhardt et al. (2018) shows the non-linear relationship between normalised AEI and RF, and that under their modelling assumptions and framework, an 80% reduction in AEI results in a decrease of contrail cirrus forcing of 50%.

Figure 6 - Normalised radiative forcing (RF) as a function of the normalised initial ice particle number concentration of contrails for which 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), their Figure 1f.

2.5 Alternative methods to changing fuel composition in order to reduce contrails

Two further principal methods for reducing the climate effect of contrails have been discussed in the literature; scheduling of air traffic to avoid warming, and contrail formation avoidance.

In researching the climate effects of contrails, it was realised very early on, that contrails have both cooling and warming effects (Meerkötter et al., 1999). Cooling mostly happens during the day from the reflection of solar radiation back to space and warming at night, from the trapping of terrestrial (infrared) radiation, the net being a positive radiative forcing (warming).

These cooling and warming effects are calculated with radiative transfer models that calculate the disruption to the earth's energy balance caused by the extra cloud cover induced from contrails and contrail cirrus. The radiative forcing is calculated at the top of the atmosphere with such models, which can be either offline or online from global climate models. Such radiative transfer models can be complex, and for contrail radiative forcing calculations, the balance of short wave and long wave forcing varies by time of day, latitude, season, cloud cover, the nature of the surface over which the forcing occurs, along with a necessity for detailed treatment of the size distribution and habit (shape) of the ice crystals (Myhre et al., 2009). Given that warming occurs exclusively at night, some attention has been given to the possibility of reductions in net forcing by avoiding night flights (e.g., Myhre and Stordal, 2001; Stuber et al., 2006). However, these studies considered linear contrails only, which contribute only a relatively small component to the total forcing (Burkhardt and Kärcher, 2011). It is thought (although not well quantified) that most of the global mean forcing comes from 'outbreaks' of persistent contrails developing into contrail cirrus (Bock and Burkhardt, 2016a) which may last of the order 10 hours. Newinger and Burkhardt (2012) concluded that avoidance of night flights to reduce contrail cirrus forcing was unlikely to be an effective strategy.

The other major mitigation strategy discussed to reduce contrail forcing has been avoidance of contrail formation by navigational means. This would involve changing route on a flight-by-flight basis and require accurate forecasting of ice-supersaturation and temperature (e.g., Matthes et al., 2017; Teoh et al., 2020). This was discussed in the recent report of the European Union Aviation Safety Agency as a potential means of future mitigation of aviation's non-CO₂ effects (Arrowsmith et al., 2020).

This mitigation strategy would involve the flight planning process avoiding low-temperature ice-supersaturated air, or possibly actively during the flight. Flight plans are filed in advance at a maximum/minimum of 120/1-3 hours in advance (depending on the nature of the flight - international/domestic). The flight plan usually aims to minimise fuel burn, based on the weather, mission distance, aircraft type, loading, and available routes. Contrail avoidance would require an extra step in the flight plan, i.e., avoidance of ice supersaturated regions (ISSRs), which are critical for contrail formation. This would require accurate prediction of ISSRs in both space and time. It is envisaged that avoidance would mostly require a change in altitude since ISSRs are broad and shallow. Schumann and Heymsfield (2017) summarise that the statistics of ISSRs are not well known but that they have a mean length of about 150 ± 250 km (Gierens and Spichtinger, 2000) and that layers are often 600-800 m thick (extreme values 25-3,000 m), with 30% of them having a depth that is less than 100 m (Dickson et al. 2010). Changes in ideal altitudes from the flight planning to minimise costs of fuel are likely to increase fuel, and therefore CO₂.

There are three issues to consider in the environmental effectiveness (not costs - these are not considered here) of taking forward such a strategy:

1. Is the ERF of contrail cirrus well enough quantified? (Part of the "*is it worthwhile?*" question).
2. Are we able to predict ISSRs well enough with meteorological forecasts?
3. How do we compare potential reductions in contrail cirrus forcing with an increase in CO₂ forcing? (Another component of the "*is it worthwhile?*" question).

Arguably, the 'best' assessment of global ERF from contrail cirrus is that of Lee et al. (2021) (L21), who combined different model estimates but were careful to scale to equal assumptions (see SI of L21) and took a mean ERF/RF scaling response from three different studies, applied to two of the three global modelling studies (one was considered to be an ERF already). The 5%/95% uncertainties to the global mean 2018 ERF of 57 mW m⁻² were 17,



98 mW m⁻² and the overall confidence level was assessed as “low”. Similarly, the IPCC recently assessed this for the year 2019 as approximately 60 mW m⁻² (range 20 to 100 mW m⁻², “low” confidence) (Forster et al., 2021). By independent analysis of observed cloud changes, Digby et al. (2021) have raised the possibility of the ERF of contrail cirrus being much smaller than these estimates. In conclusion, the overall ERF from contrail cirrus is not well quantified and any estimate judged by two international groups to have “low” confidence (using the same confidence assessment methodology).

One of the frequently overlooked aspects of potential navigational avoidance of contrails is the ability of meteorological models to predict ISSRs with sufficient accuracy in space and time. As noted above, these areas are often of the order 100+ km by <500 m deep, and evolve in matters of 10s of minutes to hours, dynamically, with the weather. As noted above, even basic knowledge of the occurrence of ISSRs is poor, let alone our predictive capability, so that even ‘good prediction’ is not easily verified. However, our predictive capability has been shown to be poor, as noted in an analysis of discrete situations by Gierens et al. (2020), for which good verification data were available from measured situations of ISSR. Gierens et al. (2020) show that as per thermodynamic theory, the threshold occurrence of contrails can be predicted well, but persistent contrails with “very low reliability”. Gierens et al. (2020) used the ECMWF weather forecasting model, which has had particular effort put into its capability to predict ISSRs (not a usual parameter for weather models) (Tompkins et al., 2007). It should also be noted that Gierens et al. (2020) used the ECMWF reanalysis data (ERA-5), not a ‘raw’ weather forecast, so predictive capability on a forecast basis from ECMWF could conceivably be worse. The essential problem with this present situation is that there is a large chance that avoidance strategies, if put into place with insufficiently verified predictive modelling capability of ISSRs, could have perverse outcomes and make the situation worse rather than better (Shine and Lee, 2021).

Lastly, if navigational avoidance of contrail cirrus involves increased fuel use and therefore CO₂, one needs to have a ‘measurement metric’ that can be used in the flight planning decision-making process (assuming that ISSRs can be predicted with sufficient accuracy). Firstly, as argued above, the contrail cirrus ERF is not well quantified enough to make such a comparison but even if it were, obstacles to the decision-making process remain. This is essentially because of the long-standing difficulties of formulating a metric for CO₂ emission equivalencies for a short-lived climate forcer like contrail cirrus vs a long-lived greenhouse gas like CO₂. There are a range of ‘natural science’ based metrics, such as the global warming potential, global temperature change potential (and their derivatives) but all require a definition of time horizon (TH). This is commonly taken as 100 years (for the GWP) in policy, but there is no robust scientific basis for such a choice. Various metrics have advantages and disadvantages but what is common to all, is that a primary determinant of their magnitude or “equivalent” CO₂ emission is the TH assumed. For example, Lee et al. (2021) illustrated that for a global mean contrail cirrus ERF of 57 mW m⁻², this could vary between 0.09 and 2.32 depending on metric and TH.

In conclusion, the concept of navigational avoidance of contrail cirrus still has many obstacles to overcome before it can be operationalised for an unequivocal clear climate benefit because of the risk of increased CO₂, either from inaccurate forecasting of ISSRs or a sound and agreed basis for quantifying the comparative benefit of reduced contrail cirrus ERF at the expense of increased CO₂.



2.5.1 The ability to observe changes

One of the important aspects of designing regulation is verification of efficacy. Evidently, for climate impacts, verification for a sector's emission reductions cannot be verified directly but only based upon robust measurements of emissions, best available science, and observations of any changes that may result. In the case of changes in contrail cirrus from aircraft soot emissions, verified base-data of the emissions by engine type are needed, generalised robust quantitative conclusions on reductions of soot by engine type, condition, and fuel type, and ideally, observations of contrail cirrus cloud change as a result. It should be noted that none of these stipulations are yet available at such a level of detail, only experimental data that are indicative and provide case-specific quantification.

In the case of contrail cirrus cloud coverage, this is unusual in that it is a directly observable quantity, unique to aviation. This is unlike, for example, ozone enhancement in the upper troposphere and lower stratosphere, from aircraft NO_x emissions, which cannot be directly observed and attributed to aviation. Line-shaped contrails are detectable by satellites and local ground observations, but it is considered that persistent contrails developing into contrail cirrus are of the greatest radiative importance. These are more difficult to track and attribute to individual flights although attempts have been made in case studies (Vazquez-Navarro et al., 2010; 2015). Attempts have been made to correlate trends in cirrus cloud coverage with air traffic, but the results have been indicative, so far, and difficult to unequivocally attribute but generally indicate positive cirrus cloud trends in trafficked regions (Boucher, 1999; Zerefos et al., 2003; Minnis et al., 2004; Stordal et al., 2005; Eleftheratos et al., 2016).

The COVID-19 pandemic and the large-scale reductions in air traffic in early 2020 gave a unique opportunity to study the potential relationship between aviation contrails, contrail cirrus and overall cirrus cloud coverage (Digby et al., 2021; Qaas et al., 2021; Li and Groß, 2021; Schumann et al., 2021a, 2021b). Qaas et al. (2021) examined MODIS satellite data for cirrus cloud coverage and reported a decrease of 9% of cirrus in the greatest 20% of traffic for northern midlatitudes in March-May 2020; however, Digby et al., (2021) note that this is not outside the variability of the previous 10 years. Li and Groß (2021) present an analysis of CALIPSO satellite data for the years 2014-2020 and show reductions in occurrence and thickness of cirrus clouds in March and April 2020 over Europe, but they assume the cause is the reduction in air traffic, whereas van Heerwaarden et al. (2021) consider air traffic reductions to be less important than the unusual weather prevailing.

Gettelman et al. (2021) modelled the effect over the course of 2020 and found a reduction of ERF to 27 (± 58) mW m⁻² over a non-COVID case of 62 (± 59) mW m⁻² in a global model simulation. Schumann et al. (2021b) modelled contrail cirrus over Europe for the period March to August 2020, a period of a 72% reduction in traffic over 2019 levels. Their computed contrail coverage for the area in 2019 was 4.6% compared with a cirrus coverage of 28%, and 1.4% in 2020 for a total cirrus coverage of 25%.

In contrast to the aforementioned studies, Digby et al. (2021) give a more cautious interpretation. Using satellite observations (three MODIS datasets) of cirrus cloud in (normally) highly trafficked regions, they could not find a statistically significant detectable global response to the reduction in air traffic, leading them to cautiously conclude that global models may overestimate contrail cirrus and hence its warming effect. They showed that the response of global aviation was within the natural range of year-to-year cirrus cloud coverage and was therefore undetectable.



On a slightly different aspect, van Heerwaarden et al. (2021) examined whether the reduction in contrails and aerosols were the cause of the increased solar irradiance in western Europe during the (spring) 2020 lockdown but concluded that the unusual weather conditions were the primary cause and that the reduced aerosols and contrails were less important.

In conclusion, it seems that the dramatic reductions in air traffic of approximately 70-80% during the COVID-19 pandemic in 2020 are not easily and robustly detectable in terms of changes in cirrus cloud coverage, Digby et al. (2021) arguing that the signal is well within year-to-year variability of cirrus cloud coverage. If this is the case, this implies that reductions in contrail cirrus from changed fuel composition, especially against a backdrop of likely increasing traffic, would be difficult if not impossible to detect from satellite observations of global cirrus cloud coverage.

2.6 Conclusions

Aviation fossil-based jet fuel (kerosene, Jet A/ Jet A-1) is made up of a mixture of n-alkanes, iso-alkanes, cyclo-alkanes, and aromatics. The speciation of the aromatic fraction is not well documented but the available evidence suggests that it largely comprises mono and bicyclic aromatic compounds. Naphthalene and naphthalene derivatives (e.g., branched methyl, ethyl components) are the major bicyclic components. The aromatic content is currently limited to a maximum of 25% by volume, and a minimum of 8% (for drop-in biofuels).

Extensive measurement campaigns of aircraft exhaust gases that include fuel substitution experiments indicate that naphthalene is the principal aromatic component responsible for soot emissions from fossil fuel kerosene.

Soot is primarily formed in aircraft gas turbines and emitted as very small particles from the combustion of the naphthalene content of the fuel, although combustion chemistry is not well characterised. These particles are initially around 10 nm in diameter.

Measurements at ground and altitude of the combustion of (usually) bio-based kerosene alternative fuels with reduced aromatic content show greatly reduced emissions of soot particles by mass and number. However, low-naphthalene fuels do not entirely remove soot. Better and more quantitative data are needed to formulate robust emission reduction strategies with known outcomes.

Sulphur is present in fossil-based kerosene at concentrations thought to be around 600 ppm (the upper limit is 3,000 ppm). The sulphur in the fuel is largely converted to sulphur dioxide gas (SO₂), emitted in the exhaust and a small fraction (approximately 2%) is emitted directly as sulphuric acid. This sulphuric acid can be taken up on the surface of soot particles but in the presence of soot does not nucleate to form discrete particles, even at greater concentrations in the fuel.

Water from the exhaust initially condenses on soot particles formed in the engine, such that the soot is 'activated' and the droplets grow to around 100 nm in diameter. After a second or so, if the atmosphere is supersaturated with respect to ice and is below 233K, these water droplets freeze and grow from water in the ambient atmosphere to around 1,000 nm and larger. Sulphur plays a minimal role in the formation of contrail ice crystals at present fuel S levels, and lower. Larger concentrations than currently prevalent may trigger contrail formation sooner (seconds) but do not affect whether or not a contrail is formed.



Many measurements show that a lower aromatic content of fuel (from SAF) produces smaller soot number concentrations. Recent in-flight measurements that show that these smaller soot number concentrations produce fewer ice crystals of larger size (as expected from prior modelling).

Fewer and larger ice crystals from low-aromatic SAF fuel are modelled to result in a smaller global effective radiative forcing (ERF).

The dominant ERF term from the formation of contrails is from persistent contrails, developing into contrail cirrus, under cold atmospheric conditions of ice-supersaturation. To a first order, the ERF of contrail cirrus depends on ice crystal number and size, and ice crystal number depends on soot emission number. The contrail cirrus ERF term remains highly uncertain, even for conventionally formed contrails from fossil kerosene soot.

Modelling suggests that at temperatures below the threshold for contrail formation, ice crystal number reduces linearly with soot number emission but that ice crystal number also depends on temperature (i.e., not just soot number concentration). At cold temperatures (12K less than threshold of 233K) modelling suggests that if soot numbers are reduced to less than $1 \times 10^{14} \text{ kg}^{-1}$ fuel, then alternative nucleation mechanisms occur of activation of ultra-fine aqueous particles (UAPs), mainly from S, and increase the ice crystal number concentration for fossil fuel. The degree to which this would happen (extent in time and space) is not known. This would imply removal of aromatics alone from fossil fuel could have counter-productive results in cold conditions.

On the other hand, if SAF is used (with zero S content), it is possible that ice crystals from UAPs may not form and that nucleation would only occur on the background aerosol, present at levels of around $1 \times 10^{14} \text{ kg}^{-1}$ fuel equivalent.

Overall, there are clear indications from measurements that reducing naphthalene content would reduce soot number emissions from aircraft exhaust and result in fewer and larger ice crystals. The degree to which this would reduce ERF is less clear, relying on a limited number of modelling studies. Moreover, the whole study area is still hampered by large uncertainties over the current day magnitude of the contrail cirrus ERF, a recent study indicating it could be 7 times smaller than assessed with models (i.e., 8 mW m⁻² for 2019, cf approximately 60 mW m⁻²).

Other strategies for reduction of the contrail cirrus ERF have been suggested. These include the scheduling of traffic to avoid night-time flights and their resultant positive forcing -on best available knowledge this is unlikely to have much success because of the long lifetime (10+ hours) of persistent contrails. Navigational avoidance of the formation of contrails is also widely discussed. This approach suffers from complications of an inability of current models to predict persistent contrails on an operational basis, the poorly known magnitude of the contrail cirrus ERF term to justify the approach, and the lack of a robust agreed metric to compare potential reduction in contrail cirrus ERF with increased CO₂ emission, under most scenarios of 'avoidance', since most flights are fuel optimised.

It is noteworthy that any changes (reductions) in the production of persistent contrails and particularly contrail cirrus would be difficult or impossible to detect. This is because the variation in ambient cirrus clouds is thought to be larger than the signal of contrail cirrus from global aviation. Thus, environmental improvement from changes designed to reduce contrail cirrus would be (at present) unverifiable.



3 Impacts of nvPM emissions on local air quality

3.1 Particulate Matter and Local Air Quality

The nvPM and vPM are constituents of total PM which affects air quality, health, and climate. Both components contribute to the concentration by mass and number of particles in the ambient air. nvPM are somewhat easier to characterise although not necessarily easy to measure and are characterised by particles in the 10-100 nm diameter size range. (Kärcher, 2018). Engine emission certification standards focus on the nvPM emissions from the engine as these are more discernible and better understood than vPM emissions⁷. Furthermore, emerging health concerns from impacts of ultra-fine PM are also tending to focus on nvPM.

In terms of ambient local air quality (LAQ) measurements these are based on the current LAQ ambient health standards for PM_{2.5} and PM₁₀ (mass of particles with aerodynamic diameter of 2.5 microns or less and 10 micron or less respectively). The EU's air quality directive (2008/50/EC Directive on Ambient Air Quality and Cleaner Air for Europe) sets pollutant concentrations thresholds that shall not be exceeded in a given period of time. In case of exceedances, authorities must develop and implement air quality management plans. These plans should aim to bring concentrations of air pollutants to levels below the limit values.

The PM EU standards and the World Health Organization (WHO) guidelines are summarised in Table 1. These apply over differing periods of time because the observed health impacts associated with the various pollutants occur over different exposure times. The WHO guideline values are set for the protection of health, and are generally stricter than the comparable politically agreed EU standards.

The ambient air quality standards for PM are expressed as PM_{2.5} and PM₁₀. There are currently no ambient air quality standards for ultra-fine particles (typically measured as particle number, rather than mass concentrations).

⁷ For the purposes of this section we consider that the volatile PM contributes to a nucleation mode and/or coatings on soot particles that form in gas-turbine engine exhaust plume and evolve in the first several km or so (minute or so) behind aircraft. Volatile species are those that are in the gas phase at engine exit plane temperatures. This is an area of ongoing research (in CAEP and in research programmes such as AVIATOR). A separate problem is the volatile contributions to PM on the regional scale (hours to days) which is dominated by gaseous emissions of NO_x, SO₂, and gaseous organic compounds that get photo-chemically processed and oxidized to contribute orders of magnitude more volatile mass than the volatile mass that is associated with the defined plume vPM described above.



Table 1 - Ambient Air Quality Standards and Guidelines for PM

Pollutant	Averaging Period	EU Air Quality Directive		WHO Guidelines	
		Objective and legal nature and concentration	Comments	Concentration	Comments
PM _{2.5}	daily			Limit value, 25µg/m ³	99th percentile (3 days/year)
PM _{2.5}	annual	Limit value, 25µg/m ³		Limit value, 10µg/m ³	
PM ₁₀	daily	Limit value, 50µg/m ³	not to be exceeded on more than 35 days per year	Limit value, 50µg/m ³	99th percentile (3 days/year)
PM ₁₀	annual	Limit value, 40µg/m ³		Limit value, 20µg/m ³	

Source: [EU Air Quality Directive \(2008/50/EC\)](#), WHO, 2006, [Air quality guidelines: Global update 2005](#)

These measurements are for total PM mass (i.e. they do not distinguish between vPM and nvPM) and are not particularly useful for determining the quantity or concentration of ultra-fine particles in ambient air as these smaller particles tend to make up a small part of the PM_{2.5} mass. For aircraft engine emissions of nvPM, which tend towards particles of around 0.1 micron or less, they are likely to be a very small contributor to these ambient mass measurements. Some studies around airports (Staffoggia et al., 2016) and in urban areas (Hofman et al., 2016) are now conducting ambient measurements of particle numbers in the ultra-fine range and research projects such as the AVIATOR H2020 research project will conduct measurements (and modelling) at various scales which will promote knowledge in this area and enable better source apportionment and attribution to aircraft engine emission sources. There are currently no ultra-fine particle LAQ regulations but 2019 amendments to Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work introduced, for the first time, exposure limits for diesel engine exhaust emissions. The exposure limit value for diesel engine exhaust emissions has been set at 0.05 mg/m³, measured as elemental carbon. This limit value becomes effective in general occupational health environments from 21st February 2023. In underground mining and tunnel construction, the limit value is applicable from 21st February 2026.

3.2 Quantifying the contribution to PM emissions from aircraft engine emissions

The absolute and relative contributions of nvPM and vPM from aircraft engine emissions to ambient concentrations are subject to large uncertainties. Issues associated with aviation emissions have, by convention, been split up into those from the Landing Take Off (LTO) cycle, with ICAO emission standards applying to them to a defined height of 3,000 ft, and those at cruise (emissions at >3,000 ft). Traditionally, only those emissions associated with the LTO would be considered relevant to local ambient air quality. However, over the last 15 years, there has been a growing body of literature, (Barret et al, 2010, Hauglustaine and Koffi, 2021, Yim et al, 2015) looking at the possibility that emissions at cruise including PM emissions may also contribute to degradation in air quality near the earth's surface.

3.3 Contribution of LTO emissions to LAQ concentrations

LTO emissions from aircraft, assumed to be those below 3,000 ft, have an impact on the ground level concentrations of pollutants including NO_x and particles. These concentrations may be determined from short-term measurement campaigns, long-term monitoring stations or from air quality modelling exercises. It should be noted that uncertainties



associated with modelling concentrations of PM are many fold but necessarily include the uncertainties of any emissions data input as described in Section 2.2.

Measurement campaigns can provide a snapshot of the aircraft contribution, whilst monitoring data provide longer term trends of the concentrations, allowing comparison with regulatory limits. However, it is often challenging to attribute the source of the contribution for the resulting PM, due to other non-aircraft airport-related sources (e.g. airside ground support vehicles, airport vehicles and tyre wear and brake dust; and from landside roadside vehicles and other sources). In order to attribute the measurements or monitoring data to aircraft emissions, the sampler would need to be located close to the runway or at a location where the contribution from other sources can be considered insignificant. The data could then be correlated to the aircraft movements and flight paths. The measurements could include information such as mass and size but may lack information on the aircraft or fuel type used without combining air traffic movements data. It should be noted that measurements, especially a single campaign, are not able to adequately describe UFP concentrations at airports in general (ACI Europe, 2012).

In terms of modelling, LTO PM concentrations can be calculated from global, regional or local scale dispersion models. Due to the spatial resolution differences in these models, the input requirement may differ, leading to differences in the concentrations estimate. A local scale dispersion model would require the most detailed input of the three types of model and will include airport specific information such as location of runway, topography and aircraft movement journals and relevant taxi times. Aircraft emissions would be better represented (e.g. as a volume source) instead of being aggregated over an area (usually larger than the airport itself) in a global model. The emissions data together with a good representation of atmospheric processes in the boundary layer, will result in better quality concentrations estimate for a local scale dispersion model when compared to a global model.

Annex A (Table 11 through Table 13) provides some selected studies that illustrate the concentration changes from aircraft emissions, based on measurements, global models and local air quality models respectively. These concentrations should be used carefully. For example, results from measurements may not be appropriate in health impact assessments due to lack of certainty in the source apportionment and the timescale as to when the measurement campaign takes place. Global modelling results provide a consistent approach as to how concentrations may increase due to aircraft emissions, however, these estimates may be uncertain due to the spatial resolution (horizontal and vertical) description of atmospheric processes at a local scale. In terms of local scale modelling, the concentration results are highly localised since dispersion characteristics is location-specific, with the atmospheric stability criteria, deposition rate and removal processes highly dependent on local meteorological conditions and topography.

The global models of Barrett et al. (2010) and Yim et al. (2015) found the peak concentration $PM_{2.5}$ change due to LTO emissions was $0.03\mu\text{g}/\text{m}^3$ and $0.0012\mu\text{g}/\text{m}^3$ respectively. A recent study (Moniruzzaman et al., 2020) found between $0.0022\mu\text{g}/\text{m}^3$ and $0.0029\mu\text{g}/\text{m}^3$ (with and without feedback respectively)⁸.

⁸ The understanding of LTO emissions on local air quality has been refined by accounting for aerosol direct feedback effects (ADFE). Over the US, Moniruzzaman et al. (2020) calculated that ADFE reduce aircraft LTO attributable O₃ and $PM_{2.5}$ changes by about 20% for the year 2005, with notable differences between global and regional model applications.



3.4 Contribution of non-LTO emissions to LAQ concentrations

Over the last 15 years, there has been a growing body of literature, starting with Tarrason et al. (2004) looking at the possibility that emissions at cruise may also contribute to degradation in air quality near the earth's surface. Barrett et al (2010) indicate an increase peak surface level PM_{2.5} concentrations of 0.15 µg m⁻³ due to LTO and cruise emissions. Similarly, Lee et al (2013) estimated that cruise emissions were responsible for an increase of ground PM_{2.5} by ~0.5% (<0.2 µg/m³) over the United States, Europe, and eastern Asia.

Two main effects have been examined in a range of studies; the effects of NO_x emissions on ambient ground level NO₂ and subsequent oxidation product ozone (O₃), a photochemical pollutant that has effects on human health and plants, and particles, primarily soot (nvPm) and sulphate (volatile particles). Other particles may also be formed in the atmosphere from NO_x emissions to form nitrate, and emissions of organic compounds to form particulate organic matter (POM) although the formation and quantification of these is far more uncertain. Whilst the topic of the contribution of non-LTO NO_x emissions to air quality is not relevant to this report, the modelling of it provides some complementary evidence to the quantification of non-LTO particulate emissions to ground level concentrations. The studies that have examined the fate and contribution of sulphate to ground level concentrations are summarised in Annex A, Table 14.

3.4.1 Basic atmospheric processes

The contribution of non-LTO emissions of particles (and NO_x) is generally calculated with global, or less commonly, regional scale (100s of km) models. Such models treat the large-scale physical and chemical processes of the atmosphere in four dimensions; latitude, longitude, altitude and time. Emissions are placed in their relevant 3D locations and tracked over time according to their physical movement (advection by winds) and chemical composition. Convection is an important physical sub-grid scale process that is usually treated as a 'parameterisation' in such models, i.e. it is simplified as the real process operates at a smaller scale than the model can treat (for a global model, the minimum usually around 0.5° latitude by 0.5° longitude by varying discretisation of height, since models generally operate on pressure levels).

Particles are ultimately removed from the atmosphere to the earth's surface in rain or deposited directly; processes referred to as wet and dry deposition. The incorporation of particles into clouds and subsequent chemistry (of S, N, POM species) is a highly complex and small-scale process (Penner et al., 2018; Righi et al., 2013). Similarly, the formation of rain droplets and location of removal is complex and cannot be represented explicitly. In order to represent wet deposition, models are usually parameterised by so-called 'scavenging coefficients'. This is simply a removal rate of the species (s⁻¹), usually determined empirically from measurements and applied in space and time in the model according to the location of clouds, and precipitation intensity, the latter again often from empirical observations.

If particles are not rained out, or 'scavenged' by wet deposition, they are ultimately removed from the atmosphere by dry deposition to surfaces. Since the particles are so small, this is not an efficient process as dry deposition of larger particles is dominated by gravitational sedimentation; smaller particles are removed depending on the size and 'roughness' of the surface to which they are deposited. Dry deposition is often described by analogy to electrical 'resistance' where the dry deposition rate is equal to the reciprocal of the sum of three terms, the 'aerodynamic resistance' (r_a), the 'quasi-laminar resistance' (of the surface) (r_b), and the 'surface resistance' (r_c). The latter, r_c , is mostly considered in terms of the chemical/physical affinity of the surface for gases in particular, e.g. as taken



up by stomata of plants, or the reactivity of the gaseous species. In practice, dry deposition rates, or in particular the term r_c , are determined from field or laboratory experiments, and parameterised in models such that the three resistance terms are prescribed by time and location, resulting in removal from the modelled atmosphere.

From the above description, it is evident that there are considerable uncertainties in determining the contribution of non-LTO emissions to ground concentrations of particles that may affect human health. For example, if we take a qualitative view of the fate of emissions of both BC and SO₂ in turn, they might be described as follows:

- **Soot particles.** As soot particles (nvPM) are emitted by aircraft at cruise, very small particles of nm-scale (10-100 nm) diameter are emitted. These may agglomerate to form larger particles, over timescales of minutes to hours, initially in the plume. If conditions of temperature and ice-supersaturation are conducive to contrail formation, the soot may form the core of ice crystals and may form a contrail cirrus cloud. If this occurs, the contrail process may enhance the uptake of SO₂ and subsequent SO₄ transformation. Ultimately, these cirrus clouds will evaporate or some of the ice crystals sediment out and evaporate. The ‘contrail-processed’ particles will then ultimately be transported by sedimentation and advection to lower levels where they may be scavenged by liquid cloud droplets, to be rained out (‘wet deposition’). If conditions at cruise altitudes are not conducive to contrail formation, then the soot particles may be transported over timescales of hours to days to lower levels of the atmosphere to be potentially scavenged by liquid cloud droplets. If the soot particles escape scavenging by cloud droplets and being wet deposited (remembering that precipitating cloud water droplets can evaporate before reaching the ground), then as they travel further towards the earth’s surface, they may then enter the planetary boundary layer (approximately <100-3,000 m, depending on location and time of day) and affect ‘air quality’ and be inhaled by humans.
- **Sulphate particles.** For S or (the largest fraction of vPM particles), the physical passage from altitude of cruise emission to the ground is very similar to that of soot but additionally involves chemical reactions. However, the primary (~98%) emission of S is as SO₂ gas. Sulphur dioxide, to a first order, is oxidized to sulphate (SO₄) at a rate of approximately 1% per hour. The sulphate is initially as gaseous or liquid-phase sulphuric acid (H₂SO₄). Gas phase H₂SO₄ may react with any ammonia (NH₃) present in the atmosphere to form ammonium sulphate; (NH₄)₂SO₄. However, NH₃ is a reactive gas and emitted primarily from agricultural sources at the earth’s surface. Ammonia is highly soluble and reactive (with acids) and observations show that NH₃ is only present at cruise-type altitudes in very small (parts per trillion mixing ratio) amounts. Oxidised SO₂ gas to sulphate (acid or neutralised form) then follows the same processes as BC of mixing in the atmosphere and incorporation into clouds and subsequent wet deposition, the ‘balance’ being sulphate particles ultimately being transported into the planetary boundary layer and then to near the earth’s surface to be available for inhalation by humans and removed by dry deposition.

Thus, in simple terms, the passage of an aircraft-derived BC/S particles from cruise emission to a few metres above the ground to be available to humans for inhalation is long and complicated.



3.5 The relationship between fuel composition (aromatics and S) and LAQ

Estimating the local air quality impact of nvPM aircraft emissions from engines burning conventional Jet A-1 kerosene as described above is clearly subject to a large degree of uncertainty including uncertainty associated with the emission indices, the dispersion and transport processes and the relative contribution from engine emissions to total concentrations. Added to this are the uncertainties associated with the exact chemical composition of the SAF and the consequent impact on the nvPM mass and number emissions. However, any reduction in emissions of nvPM during the LTO cycle due to the use of lower aromatic (or higher H content) fuels such as SAF will likely result in proportionally decreasing the LTO contribution to ambient concentrations of nvPM both in terms of number and mass.

In terms of volatile particulate formation, the low (or zero) sulphur content of SAF will result in lower contributions to vPM in the ambient air. The lower S content will also act to reduce the formation of vPM in the plume as the number of volatile particles from sulphur depends directly on the fuel sulphur content. Although the estimation of these vPM processes is less well understood and quantified.

The complexities of the atmospheric chemistry and transport processes involved in assessing the potential pathways from cruise emissions to ambient near ground level concentrations make these studies highly uncertain but a decrease in nvPM and vPM emissions at cruise from changes in fuel composition are at least likely to work in the same directional trend of decreasing their potential contributions.



4 Aromatic and naphthalenes in aviation fuels

4.1 Introduction

In order to determine the aromatics and naphthalene contents in jet fuel, the composition of jet fuel has been investigated. The term ‘jet fuel’ here refers to Jet A-1 type kerosene. In Section 4.2 the results of the literature review and interviews are presented concerning monitoring of aviation fuels and insights on shares of sulphur, aromatics and naphthalene in jet fuel sold in the Netherlands and the EU. Furthermore, the state-of-play on the handling of sustainable aviation fuels is outlined in Section 4.3.

4.2 Jet fuel aromatic content monitoring

All European sold jet fuel is tested and monitored for key properties in order to ensure the fuel meets the applicable standards. These parameters must be determined at point of manufacture and along the supply chain. For this, a certificate stating numerical values of the fuel properties is issued for every analysed batch. This is the *Refinery Certificate of Quality* (RCQ). In case different batches of fuel are commingled a new analysis and, if necessary, a new certificate is drawn up. This is a so called *Certificate of Analysis* (CA) which includes test results for a limited number of fuel properties. Fuels are not tested for their aromatics, naphthalene and sulphur content at rebatching or change of custody.⁹ An example of a certificate form for reporting monitoring data by the ASTM is given in Annex A. No detailed analysis and quantification of naphthalene is required in the fuel monitoring. These certificates are the basis for aviation fuel quality assurance (as defined in EI 1530¹⁰), and are handed over whenever there is a change of ownership of a certain jet fuel batch. It is therefore possible for a purchaser to identify whether the individual batch of aviation fuel is compliant to international standards (Zschocke, et al., 2017). However, this data is not available at public sources. Therefore, there is no overview of exact jet fuel composition for the batches sold in the EU.

Aromatics content in jet fuel depends on the composition of the crude oil used for the production of jet fuel. Depending on the location of crude oil extraction, and crude oil blending, the crude may contain a certain level of aromatics, sulphur and naphthalene¹¹. Therefore, there is likely a large variation exist in the aromatic content of internationally supplied jet fuel. Different aromatic and other component testing methods exist worldwide. This may give different results which cannot be compared directly from the globally sourced batches.

⁹ Only if a jet fuel batch is used for a SAF blend, which will be outlined later in this section.

¹⁰ [EI/JIG Standard 1530](#): published by the Energy Institute in cooperation with the Joint Inspection Group, another private institute renowned for setting industry standards. EI1530 concerns quality assurance requirements for the manufacture, storage and distribution of aviation fuels to airports.

¹¹ An interviewee indicated crudes from shale extraction (e.g. North-American tar sands) has higher contents of aromatics and other elements.



The aviation industry has adopted jet fuel standard ASTM D1655/DefStan 91-091 for safe and consistent jet fuel quality. The standard requires jet fuel to comply to a maximum of 25% aromatics by volume. CRC (2014)¹² reports a typical content of 18% aromatics by volume in Jet A-1 fuel. For the burnFAIR research project in 2011¹³, a jet fuel study for Lufthansa analysed approximately 2,000 individual batches of jet fuel (Zschocke, et al., 2017). About 75% of the batches had an aromatic content between 16% and 20%. The aromatic content of 15 batches jet fuel was analysed at lower than 8%. Benavides, et al. (2021) conducted fuel property tests on 70 Jet A-1 samples gathered in Colombia and the United States in 2018 and 2019. This resulted in a range of aromatics between 7 and 18% with a mean of 12%.

From the literature and data on fuel analyses supplied by a major jet fuel supplier we derive that a large share of jet fuel sold in Europe has an aromatic content of 15 to 20% (by volume). A refiner has shown sample data on batches Jet A-1 produced in a number of European and North-American refineries. This data showed an average of 18.7% aromatics, with a variety between 8% and 25%. This all is within the allowed range as set by the jet fuel standard. An overview of aromatic contents of jet fuel analyses found in literature is given in Table 2.

Table 2 - Overview of aromatic content by volume (v/v) in jet fuel reported in the literature

Fuel type	Min	Max	Mean	Source
Jet A-1	15%	24.4%	17.9%	PQIS (2013)
Jet A-1	-	-	18.0%	CRC (2014)
Jet A-1	5.9%	25.5%	18%-20%	Zschocke, et al. (2017)
Jet A	-	-	14.4%	Pires et al. (2018)*
Jet A-1	7.1%	17.7%	12.0%	Benavides, et al. (2021)

* These results are from one sample Jet A fuel, by mass (m/m).

Also figures on sulphur and naphthalene content in jet fuel are given by several sources. The sample data provided by the refiner indicate an average of naphthalene in Jet A-1 of 0.81% with some samples very close to zero and very few samples above 2%. These values are well within the maximum limit of 3% as stated in the standard. The CRC report states a typical weight content of 0.046% sulphur for Jet A-1 fuel measured in kerosene (CRC, 2014). Benavides, et al. (2021) reported a mean of 4% naphthalene by weight in the analysed samples. As these compounds have a lower volume to weight ratio¹⁴ (1 litre jet fuel equals 0.79 kg), the share of naphthalene by volume will be approximately 3.5%. Considering different types of naphthalene, it is possible the naphthalene content of this jet fuel batch exceeded the industry set upper limit of 3.0%. Zschocke, et al. (2017) measured sulphur values between 0.1 and 0.27% in jet fuel batches in fuel facilities of German airports. Data on sulphur and naphthalene contents in jet fuel show figures close to the allowed limit¹⁵ of 0.3% (by mass) and 3.0% (by volume) respectively. An overview of sulphur and naphthalene contents of jet fuel analyses found in literature is given in Table 3 and Table 4 respectively.

¹² Coordinating Research Council.

¹³ For details on the burnFAIR project see [here](#)

¹⁴ See [here](#) for volume and weight properties of naphthalene.

¹⁵ For sulphur and naphthalene only an upper limit is set. For aromatics as a whole the minimum is 8% and maximum is 25% by mass (m/m).



Table 3 - Overview of sulphur content by mass (m/m) in jet fuel reported in the literature

Fuel type	Min	Max	Mean	Source
Jet A-1	0.0	0.3%	0.13%	PQIS (2013)
Jet A-1	-	-	0.05%	CRC (2014)
Jet A-1	1.0%	2.7%	0.1%-0.5%	Zschocke, et al. (2017)

Table 4 - Overview of naphthalene content by volume (v/v) in jet fuel reported in the literature

Fuel type	Min	Max	Mean	Source
Jet A-1	0.2%	2.7%	1.2%	PQIS (2013)
Jet A-1	0.1%	1.2%	1.0%	Zschocke, et al. (2017)
Jet A-1	1.9%	6.2%	4.0%	Benavides, et al. (2021)*

* These results are by weight (wt%).

4.2.1 Feasibility of reducing aromatics in jet fuel

In order to expand the knowledge on the state-of-play of jet fuel monitoring and reduction options of aromatic content a number of interviews with industry experts were conducted. The focus was on the current monitoring practices of the jet fuel contents aromatics, sulphur and naphthalene. Also, the blending and SAF use practices were explored. The interviewed parties include jet fuel and SAF manufacturers, and fuel suppliers. We also contacted several airlines, but unfortunately they were not available or prone to share their insights.

From interviews with several parties involved in the production and supply chain of jet fuel we gathered the following information on the state-of-play of jet fuel monitoring. The jet fuel supply chain is a worldwide market and therefore a wide range of aromatic content in jet fuels exists. The production of jet fuel depends on refinery layout and suitability of available crudes. In Western Europe there is often a shortage of suitable crude oil available for the production of jet fuel. Therefore, a substantial share of jet fuel suitable crude and final jet fuel (A-1) is resourced globally.

All jet fuel (A-1) has to comply to the industry standards ASTM D1655 (similar to criteria of DEFSTAN 91-091, as used by the UK). At the refinery, the jet fuel is tested for compliance to the specifications of these standards of Jet A-1 fuel properties. The jet fuel supply chain is self-monitoring. This means that these tests are currently not reported to an industry or national authority in Europe. Testing of jet fuel contents takes place at the point of manufacturing in the refinery, and at every transaction in the supply chain. The last party to test the jet fuel is the airport fuelling service responsible for refuelling the aircraft.

At every transaction between fuel traders (and for transshipment within the same organisation to different locations), the buyers get the certificate which states the contents of the jet fuel batch which is subject of the transaction. The buyer tests the jet fuel to confirm the fuel is (after transport and transfer) still compliant to the specifications. For this, a new certificate of analysis is drawn. Whenever this party resells the jet fuel batch, the first buyer hands over (a copy of) their certificate to the new buyer, and the same procedures follow. This is all to ensure the jet fuel that is put into the aircraft is Jet A-1 fuel complying to the industry standards.



The standard E1530¹⁶ provides quality assurance for the supply chain of jet fuel, as this standard provides the industry with (industry-accepted) mandatory provisions and proper practice recommendations for the production, storage and distribution of aviation fuel to airports, i.e. the supply chain upstream of airports. Also included are requirements for the manufacture and handling of synthetic fuel blends. The standard is recognised by the ICAO and all companies handling aviation fuel in all aviation fuel supply chains are encouraged to conform to the requirements.

Testing is in some cases carried out by third parties, which are independent private testing firms. This can take place when a party in the supply chain finds third party testing desirable or when in-house testing capabilities and/or facilities are lacking. There is no legal requirement for airlines and fuel suppliers to document or report the data on the jet fuel content. There is no publicly available data on aromatic content shared by fuel suppliers, authorities or other stakeholders in the jet fuel supply chain. Airlines may request a test certificate from the fuel supplier, but this is not a common practice.

Airports often have a single common fuel storage, therefore all jet fuel that is accepted and tested is eventually mixed with all other batches in the storage facilities. There is no way of knowing what the exact contents are of a batch of jet fuel mix at the aircraft level when fuelled without additional testing. There is currently no need to have data on the jet fuel content at the aircraft level, as all fuel supplied to the airport fuel storage has been tested for compliance with the standard and is only used for aircraft.

As seen in the literature described in the previous section, our sources told the majority of the analysed jet fuel batches result in aromatics content far below the set limit of 25%. If the aromatic content of jet fuel were to be reduced, a gradual reduction of the upper limit(s) would be a possible way to decrease the aromatics and naphthalene content in jet fuel. Some parties indicated the market for jet fuel might experience difficulties when a strict or abrupt reduction of the upper limit would be enforced. This might lead to shortages of jet fuel at airports as a small part of the supplied jet fuel has a low-aromatic content naturally, and refineries need time and investments for the adjustments in the refinery process. Besides the financial and time investment of in refineries, a reduction of aromatics content might lead to a higher cost of jet fuel. If the maximum aromatics level were to be reduced, the cost increase of jet fuel could contribute to closing the gap in price difference between sustainable aviation fuel and conventional fossil jet fuel.

The interviewed parties indicated there are different considerations for the reduction of aromatics in jet fuel. From the refinery perspective, there is currently no incentive, financially and legally, to modify the production process to diminish the content of aromatics, sulphur and naphthalene in conventional jet fuel. The users of jet fuel, airlines, might be interested in jet fuel with lower aromatic content because jet fuel with lower aromatic content has higher energy density and therefore slightly less jet fuel is needed for flying a given distance (Boehm, 2022)¹⁷. However, this benefit is currently not articulated in the market. Moreover, less aromatics may lead to lower soot emissions, reducing the airlines' environmental footprint. However, jet fuel with a lower aromatics content is likely to be more expensive.

¹⁶ [E1530](#) published by the Energy Institute in cooperation with the Joint Inspection Group, a private institute renowned for setting industry standards.

¹⁷ [Lower heating value of jet fuel from hydrocarbon class concentration data and thermo-chemical reference data: An uncertainty quantification - ScienceDirect](#)



The effectiveness of a reduced maximum limit of aromatics depends on the details of such regulation. If the reduced upper limit applies only in small markets (e.g. only for the Dutch airports), fuel suppliers may leave these markets as the extra cost of (investing in) reducing aromatics can not be recuperated. This can lead to either shortages of suitable kerosene in the regulated markets, or higher prices if fuel producers choose to invest in the production and supply of the suitable fuel. Even if fuel suppliers charge airlines for the higher cost of fuel, airlines may choose to refuel at other airports in nearby markets. If the EU were to put a lower maximum aromatics limit for all EU airports in a regulation, with proper monitoring, reporting and verifying system there would be little room to bypass the requirements.

Because of the lack of an external authority verifying monitoring results, there may be inconsistencies in the practice of jet fuel handling. For example, it could also be possible 'new' tests are (exact) copies of the previous content monitoring certificate.

4.2.2 Perspectives on aromatic content criteria

Even though these standards are accepted and adopted by the industry - in a sense mandatory as most fuel suppliers will not accept fuel batches as jet fuel when not compliant to the content specifications, the standards are not legally enforced. For SAF jet fuel blends, a minimum aromatic content of 8% by volume is required by industry standards specifically for these aviation fuel blends.

We encountered varying expert opinions on the argument for the limits of aromatic contents in aviation fuels. The upper limits (aromatics, sulphur and naphthalene) are viewed by all interviewed parties as a non-negotiable requirement. This is mainly due to the fact the energy content of kerosene drops if a higher aromatics content is present.¹⁸ In practical terms, an airline expects an aircraft can fly a given distance with a certain amount of fuel and therefore fuels the required amount plus a margin. It could be potentially dangerous when the energy content of the fuel is lower thus used up earlier than is anticipated for.

However, there are different perspectives on the practical requirement and necessity for the lower limit of 8% (v/v) aromatics in the SAF jet fuel blend. This situation is backed by the data by Zschocke (2017), which discovered a regular use of conventional jet fuel with aromatic content below 8% in batches used for flights between Frankfurt and Hamburg (Germany).

The argument to have at least 8% of aromatics in jet fuel has historically been applied for safety considerations. This requirement stems from the role aromatics play for the swell of sealings in the aircraft fuel system. However, there are contradicting opinions on the role of a minimum content of aromatics. Several modern aircraft and engine types have sealing materials which do not require aromatics for the swell function, and research into new materials is ongoing. Moreover, in practice aircraft sometimes use fuels with an aromatics content of less than 8%, probably unknowingly. All in all, there is consensus on the requirement of the upper limit of aromatics, but there is no consensus in the industry for the necessity of a minimum level of aromatics in jet fuel. Other than on financial grounds, there are no clear reasons not to reduce the (upper) limit of aromatics. Further research is

¹⁸ Naphthalenes in aviation fuels typically have lower heating values (LHV) ranging from 39 to 41 MJ/kg; the LHV of aromatics ranges from 41 to 42.5, and other compounds such as cyclo-alkanes, iso-alkanes and n-alkanes have LHVs ranging from 42.5 to 44.5 MJ/KG. (Boehm et al., 2022)



needed to confirm or deny the role of the minimum content of aromatics for their lubrication role in aircraft.

4.3 Sustainable aviation fuels and jet fuel blends

4.3.1 SAF and aromatic content

Most sustainable aviation fuels (SAF) have zero-aromatic content. The most common industrially produced and commercially supplied SAF is HEFA¹⁹ and has no aromatics and sulphur content because it is produced by hydrotreatment. The commercially available SAF jet fuel blends therefore have a lower aromatic content than conventional jet fuel. There are however approved production processes of SAFs in which aromatics are created. This is also indicated in a number of annexes of the ASTM D7566 standard, which allows commercial use of SAF types containing aromatic content after production completion. The SAF types with aromatics produced in the production process are Fischer-Tropsch synthetic paraffinic kerosene with aromatics (FT-SPK/A, annex A4) and catalytic hydrothermolysis synthesized kerosene (CH-SK or CHJ, annex A6)²⁰.

4.3.2 SAF blend standards

The ASTM standard D7655 covers the manufacture of aviation fuel consisting of conventional and synthetic blending components. The requirements for the physical properties of the jet fuel blend are similar to those stated in the DEF STAN 91-091 for conventional jet fuel, with some extended requirements for certain properties. These properties concern a minimum aromatic content of 8% by volume.

The ASTM states the minimum aromatic contents are based on current experience with the approved synthetic fuels, i.e. those containing no aromatics, and the level was established from what is typical for refined jet fuel. Research is ongoing on the actual need for aromatics (ASTM, 2013). The minimum aromatics criteria only apply to aviation turbine fuels containing synthesized hydrocarbons. The minimum requirement for aromatics is not applicable to conventional jet fuel (as compliant to ASTM D1655).

In almost all cases, the aromatics content of fossil jet fuel will not be lower than 8%. In practice, some batches of conventional *jet fuel* may not meet the minimum aromatics criteria specified that *jet fuel SAF blends* do need to meet. There are known real-world cases where flights were performed using jet fuel having an aromatic content lower than 8%. For example, Zschocke, et al. (2017) observed no issues in aircraft using batches with very low-aromatic content. Airbus safely performed test flights with an A319neo on 100% SAF and DLR did a study (ECLIF3) in cooperation with Airbus, Rolls-Royce and Neste using an A350²¹ aircraft using 100% SAF without complications. It is however not clear what the consequence of using a fuel with low- or zero-aromatics may be over time for sealings and rings in the fuel system²². This aspects needs further investigation.

¹⁹ Hydroprocessed esters and fatty acids. See [here](#) for technical and commercial details.

²⁰ See [here](#) for an overview of SAF types and criteria for use.

²¹ See Airbus article on the test flight [here](#) and the DLR ECLIF3 study [here](#).

²² There are indications so called o-rings (sealings in the aircraft fuel piping system) may shrink without sufficient aromatics eventually damaging the system. See for example [this study](#) on seal swell.

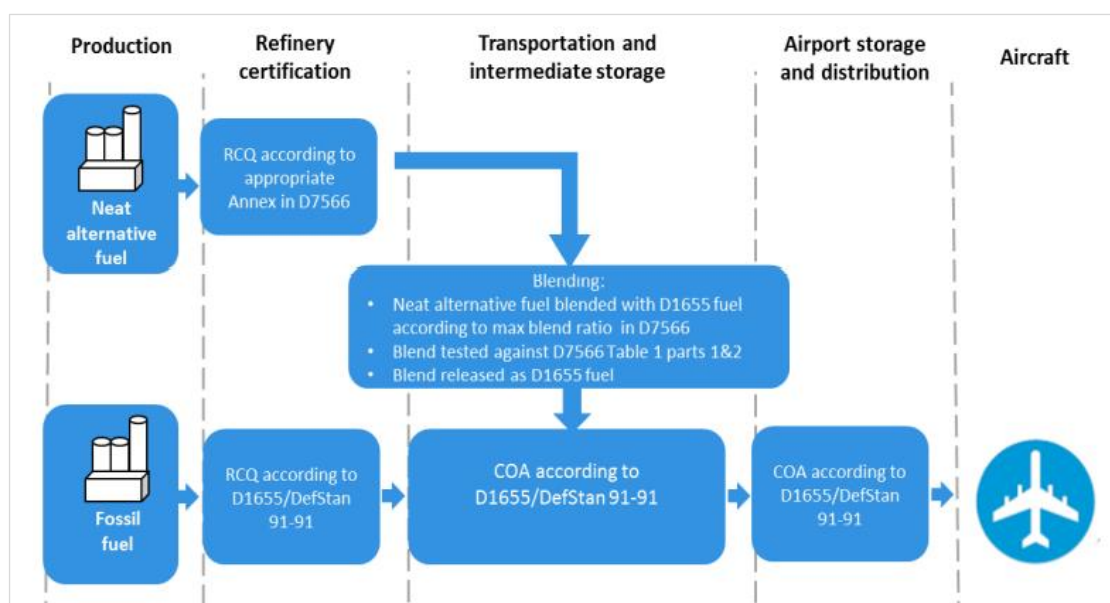


4.3.3 SAF blend monitoring

For a SAF blend both the fossil jet fuel and SAF is tested, as well as the final product of jet fuel SAF blend. SAF jet fuel blending can be performed by any party in the supply chain acquiring these batches and subsequently reselling to airports or other parties in the jet fuel supply chain. The monitoring of sustainable aviation fuels and jet fuel blends follows the same testing and procedures according to the standards for jet fuels as stated in the previous section. Thus, at the moment SAF is blended with conventional fossil jet fuel, there are three batches tested at this point of manufacture: the fossil jet fuel batch, the SAF batch and finally the SAF fossil blended jet fuel batch. All three previously mentioned jet fuel and SAF batches should have test results for aromatic content complying to the contents requirements as stated in the ASTM 1655, 7566 and DefStan 91-091. All batches should be handled according to EI1530 fuel handling standards.

The standard ASTM D7566-21 allows jet fuel-SAF blends with blending rates up to 50%, depending on feedstock and production pathway. In Europe the final product, i.e. the blended SAF jet fuel batch, should comply with the requirements as in DefStan 91-091, as all jet fuels must comply to these standards. See Figure 7 for an overview of the main steps and requirements in the jet fuel supply chain.

Figure 7 - Main steps in the jet fuel and SAF supply chain



Source: IATA (2015).

The interviewed parties state there is currently no practice to specifically opt for a jet fuel with higher aromatic content for the blending with SAF. Given the current small blending rates in aviation, there is no reason to put in additional effort to select a jet fuel with different (i.e. higher) aromatics composition. With the average aromatic content in jet fuel around 18%²³, and blending ratios up to 50%, a SAF jet fuel blend would be able to be accepted into the airport fuel storage facilities, as the aromatic content of this batch will be (maximally) around 9%. Then, this batch will be blended with other jet fuel blends in the

²³ See previous section on the average aromatic content with literature and expert interview derived range of 15-20% for the large share of Jet A-1 fuel.



airport fuel storage tanks, which leads to a significant lower blend of SAF which will enter the aircraft fuel tanks. The dilution of SAF blends in (significantly higher amounts of) jet fuel will in practice result in an aromatic content higher than 8% for the fuel actually combusted in the aircraft engines.

The current standards prescribe a minimum aromatic content of 8% v/v for the final Jet fuel-SAF blend. In principle, this is always fulfilled with the current blending rates. Given the aromatics content from the literature (on average 15-20%), it is logical SAF jet fuel blends will have aromatics content around or higher than 8%, when blending rates up to 50% are allowed. However, if in the future higher SAF blending rates would be required²⁴, fuel suppliers or SAF blending companies might choose to use a fossil jet fuel containing a higher share of aromatics, in order to comply to the prevalent industry standards.

SAF blending takes place before entering the airport fuel supply system. The common practice for jet fuel transportation to airports in western Europe is by pipeline²⁵. There is currently no practice to transport SAF by pipeline from refinery to airports as quantities are too small to be financially and technically feasible for pipeline transport. Therefore, all SAF blends are supplied to airports by either liquid tankers (ships) or fuelling trucks²⁶. All jet fuel entering the airport fuel supply system need to comply to ASTM D1655, and therefore only SAF jet fuel blends (not pure SAF batches) are supplied to airports.

4.4 Conclusions

No specific data is currently available on the properties of jet fuel supplied to airports in the Netherlands, neither does publicly available data exist for the EU in general. Also, the airlines with the largest operations at Schiphol and the fuel supply firm at Schiphol did not respond to requests to be interviewed on this topic. Results from analysis in the literature complemented by expert indications from interviews gives a rough but valuable indication of the studied properties in jet fuel. The aromatic content in a large share of Jet A-1 fuel supplied in Europe is in the range of 15 to 20%. Sulphur and naphthalene content are in most cases below the maximum limits of 0.3% (m/m) and 3.0% (v/v) respectively.

Fuel testing takes place at the point of production and at every other point of ownership change (at every transaction of a batch). The scope of considered contents in fuel tests is often limited (excluding aromatics, naphthalene and sulphur) at change of custodies, compared to full content testing (incl. aromatics, naphthalene and sulphur) at the point of manufacturer. The transaction of a jet fuel batch is accompanied by either the *refinery certificate of quality* or the *certificate of analysis*. The jet fuel can be blended at every point in the supply chain and at every rebatching a fuel property analysis is performed providing a new certificate of analysis. Every batch of jet fuel has to comply to the industry standards if the batch is to be accepted by the airport fuelling service in the airport fuel storage facilities.

From the interviews with industry experts it becomes clear there are contradicting views on how strict the compliance is concerning the limits of aromatic content in conventional jet

²⁴ This could be for example be a minimum share of SAF in the fuel blend supplied to the aircraft or a (year) average of airport fuel supply.

²⁵ The [Central Europe Pipeline System](#) (CEPS) distributes fuels to major airports and military bases in western Europe. Jet A-1 is the main product handled and stored in the system, other products may only be transported on a point-to-point basis. It is unclear whether and if so when in the future SAF would be allowed in the system.

²⁶ Sources indicate the transport of SAF blends to Amsterdam Schiphol Airport is done by ship.



fuel versus these limits for SAF blends. The requirement for a minimum level of aromatics stems from the critical role of lubrication of seals in the aircraft fuel and piping systems, while some sources indicate other materials for seals are available now, which do not require the lubrication of the jet fuel to remain intact. However, the extent to which these new type of seals are used in modern aircraft currently is unknown. This would require additional research with the aircraft manufacturing industry.

The current commercially available SAFs have zero aromatics and sulphur content, and are used in a blend with the jet fuel readily available on the fuel market. SAF blends have a lower aromatic content than fossil aviation fuel, but in practice an aircraft on SAF will only have a few percentages of SAF in their fuel tanks as a result of batch mixing in the airport fuel storage facilities. The overall level of aromatics is thus currently almost never lower than 8% when fuelled into the fuel system of aircraft.

Testing and monitoring of SAF blends follows the same standards as applicable for conventional jet fuel. Current industry standards only allow SAF blends up to 50% in the supply chain. Besides a number of test flights by SAF producers and airlines, 100% SAF is not used as of today in commercial aviation as prevailing standards and fuelling infrastructure do not allow this practice. Summarising, there are no incentives or practical considerations for producers to supply and for airlines to demand jet fuel with lower aromatic content. There is, however, no lack of practical reasons to increase or 'dump' higher aromatics jet fuel in a SAF blend. Moreover, current standards have no mechanism steering towards a reduction in these compounds in jet fuel.



5 The costs of reducing aromatic content in fuels

5.1 Introduction

Most crude oils contain considerable amounts of aromatics. Jet fuel has a distillation range of 150-300°C, so aromatics with a boiling point in this range end up in the kerosene fraction (Manchio & et al., 2018).

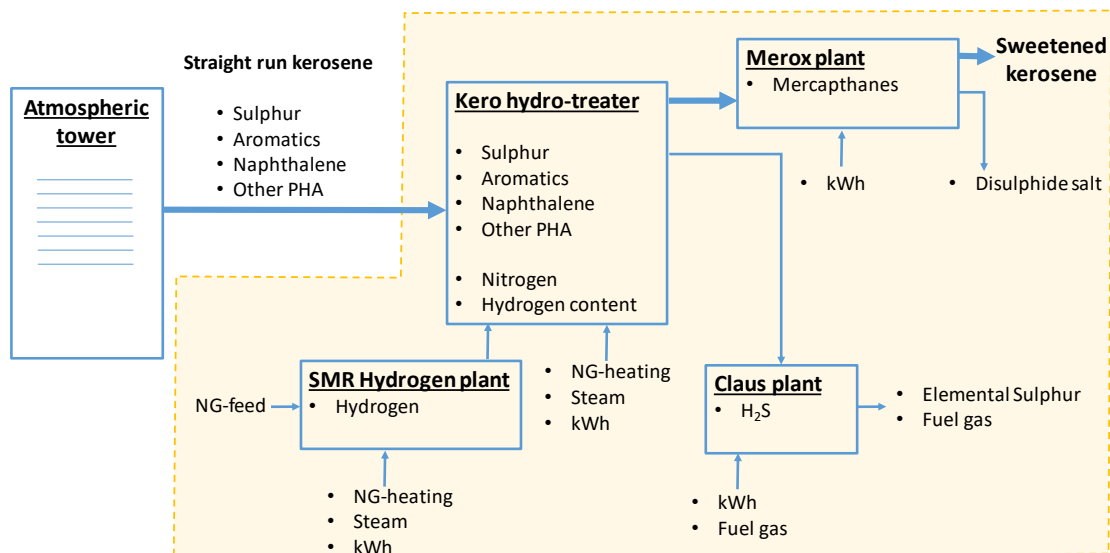
The aromatic content of straight run jet fuel can be reduced in several ways, which can be broadly grouped into conversion (in which aromatics are chemically converted into other compounds) and separation (in which aromatics are separated from the fuel) (Weibel, 2018). Of these technologies, hydrotreatment and extractive distillation are technologically mature at refinery scale and applicable with no impact on the fuel's ability to meet ASTM or DEF standards.

This chapter first presents these technologies (Section 5.2) and then assesses their costs (Section 5.4).

5.2 Hydrotreatment to reduce aromatics and sulphur from aviation fuels

To reduce the concentration of aromatics and sulphur in aviation fuels, additional processes are required compared to the conventional production process for straight run kerosene. An overview of these additional processes are shown in Figure 8.

Figure 8 - Process to remove sulphur, aromatics and naphthalene from kerosene



In general, the process to remove sulphur, aromatics and naphthalene consists of the following four steps:

- **Hydrotreatment;** this is a process of removing unwanted impurities/inorganic components (including sulphur and aromatics including naphthalenes) by processing it at high temperature and pressure in the presence of hydrogen and a catalyst. In this process hydrogen reacts with the sulphur in the fuel to form gaseous hydrogen sulphide, which is then separated from the fuel. Also for naphthalenes and other aromatics hydrotreating is considered the most common method for removal. In an industrial refinery, hydrotreatment takes place in a fixed bed reactor at elevated temperatures ranging from 300 to 400 °C 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.
- **Hydrogen production;** as input for the hydrotreatment hydrogen is required. The most common method to produce hydrogen is by steam methane reforming (SMR). In this method high-temperature steam (700 to 1,000 °C) is used to produce hydrogen from a methane source, such as natural gas (NG). Under pressure, the methane reacts with steam in the presence of a catalyst to produce hydrogen, carbon monoxide and carbon dioxide. In a next step, the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen. In a final step, carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen. In principle, other types of hydrogen could be used as well, such as *blue* hydrogen (which is produced as described above but the CO₂ is captured and permanently stored geologically) or *green* hydrogen (which is produced by electrolysis of water, using renewable electricity).
- **Merox (sweetening);** this is a process of removing a particular class of sulphur containing compounds called mercaptans²⁷ from jet fuel. This is done by oxidising the mercaptans in an alkaline environment.
- **Claus process;** the gaseous hydrogen sulphide resulting from the hydrotreatment process is further processed in the Claus plant. The Claus process consists of a thermal stage (combustion chamber, waste heat boiler) and some catalytic reaction stages (reheater, reactor and condenser). The main products of this process are elemental sulphur and fuel gas.

As indicated in Figure 8, specific inputs (e.g. natural gas, electricity) and intermediate products (H₂) are required in each of these four process steps. The use of these inputs and intermediate products result in additional production costs. The amounts of natural gas, electricity, steam and hydrogen that are required in each step of sulphur, aromatics, and naphthalene removal are taken from the detailed refinery model Prelim 1.3. The following assumptions are used in this respect:

- We consider the marginal increase of primary resources for additional hydrotreatment (compared to the conventional production process of Jet A.1 fuel) in an existing refinery assuming linearity versus removal.
- We assume that no new refinery capacity will be developed and hence no additional OPEX nor CAPEX effects are included in the assessment. This also implies that the hydrogen used is coming from existing Steam Methane Reformers (SMR).
- Cost increase exclusively by extra primary energy sources: natural gas and grid power.

²⁷ Mercaptans have a sulphur atom bonded to a hydrocarbon group and a hydrogen atom.



- Steam of SMR is used elsewhere in the refinery and equivalent distracted from the natural gas consumption.
- Hydrogen consumption for H₂S to enable processing in Claus is included in the assessment.
- Claus process with its input and output energy streams is included.
- Refinery gas for steam of Claus is used elsewhere in the refinery and equivalent distracted from the natural gas consumption.
- Heat, steam and power consumption of hydrotreatment is allocated by the amount of hydrogen consumed per component (sulphur, Claus H₂S and aromatics).
- Constant added power for Merox is assumed per amount of kerosene, independent of absolute mercaptan reduction level for polishing.
- The yield and sale of additional elemental sulphur production is deducted from the cost per ton kerosene.

Based on these assumptions, the amounts of inputs and intermediate products have been estimated by using the Prelim 1.3 refinery model. The results of this assessment are given in Table 5.

Table 5 - Overview of the amounts of inputs and intermediate products required in the various steps of the process to remove sulphur, aromatics and naphthalene per ton kerosene

	Natural gas feed	Hydrogen	Natural gas for heating	kWh	Steam	Steam
	(m ³ NG/kgH ₂)	(kgH ₂ /- or m ³ NG/ton.m% X reduced)	(m ³ NG/kgH ₂ or -/ton.m% X reduced)	(kWh/kgH ₂ or -/ton.m% X reduced)	(kg/kgH ₂)	(m ³ NG/kgH ₂ or -/ton.m% X reduced)
1. Steam methane reforming	3.5		0.38	0.31	-4.1	-0.39
2. Hydrotreatment						
a. Sulphur conversion		0.63 2.2	0.69 0.44	0.48	0.58	0.056 0.12
b. Sulphur conversion to H ₂ S for Claus		0.63 2.2	0.69 0.44	0.48	0.58	0.056 0.12
c. Aromatics		6.9 24 (as m ³ NG/ton. m% H increased)	3.9 27	2.7	3.3	0.32 0.69
d. Naphthalene		0.94 3.3 (as m ³ NG/ton.m% Naphthalene reduced)				
3. Merox				0.78 kWh/ton kero-out		
4. Claus				0.99	-29	-2.8



Based on the information from the Prelim 1.3 model, as presented in Table 5, the treatment of one tonne of fossil aviation fuel so that aromatics are reduced by approximately 50% and naphthalenes are eliminated requires the additional amounts of natural gas and electricity as presented in Table 6.

Table 6 - Additional amount of natural gas and electricity required to reduce aromatics by 50% and remove naphthalenes^a

Process steps		Natural gas (m ³ /ton kerosene)			Electricity (kWh/ton)
		Hydrogen feed	Heating	Steam	
Hydrotreatment (incl. SMR)	Sulphur conversion	0.63	0.12	0.035	0.14
	Sulphur conversion to H ₂ S for Claus	0.63	0.12	0.035	0.14
	Aromatics removal	19	22	0.56	17
	-Naphthalene removal	0.34 ^b			
Merox		-	-	-	0.78
Claus		-	-	-0.80	0.28
Total		43			18

^a The calculations are for a Jet A-1 fuel that contains 16.8% v/v aromatics, of which 1.8% v/v naphthalenes, and 300 ppm sulphur. The hydrotreated fuel contains 7.1% v/v aromatics, of which less than 0.1% v/v naphthalenes, and 14 ppm sulphur.

^b The level of reduction of aromatics is considered including naphthalene. Therefore, the amount of natural gas used to produce hydrogen to remove aromatics is assumed to include the removal of naphthalene as well.

Since the average CO₂ emissions per cubic meter of natural gas amount to 2.1 kg²⁸, and assuming an emissions factor of 0.369 kg CO₂eq per kWh²⁹, the CO₂ emissions associated with reducing aromatics by 50% and remove naphthalenes amounts to 97 kg per tonne of kerosene.

5.3 Extractive distillation of naphthalenes and other aromatics.

Extractive distillation is done by adding a solvent to a mixture which interacts differently with different compounds in the mixture. When the mixture with the solvent is distilled, some compounds remain in the residue with the solvent, these compound can then be separated from the solvent with other means (Weibel, 2018).

Extractive distillation is currently used to extract benzene, toluene and xylene in refineries, and innovation would be required to apply it to separate naphthalenes from fuels (Weibel, 2018).

In order to remove naphthalenes from jet fuel, solvents would need to be developed and extractive distillation units would need to be built or expanded. The process requires inputs of solvents, electricity, heat and cooling water. Weibel (2018) estimates the inputs to be 0.74 kWh electricity, 60 kg high-pressure steam, and 11.4 tonnes cooling water per barrel of product and the cost of replacing solvent was estimated as 0.032 US\$₂₀₁₆/barrel.

²⁸ www.co2emissiefactoren.nl/lijt-emissiefactoren/, accessed 17 February 2022.

²⁹ This is the average emission factor in the Netherlands in 2022. Other countries have different factors. www.co2emissiefactoren.nl/lijt-emissiefactoren/, accessed 17 February 2022.



5.4 Costs of treatment of aviation fuels

To estimate the additional costs of the hydrotreated aviation fuel, the additional amounts of natural gas and electricity are multiplied by the respective energy prices (see Table 7). The average energy prices are based on the average prices in the US and the EU. The global variance in natural gas and electricity prices is, however, rather large and hence may differ significantly based on the location of the refinery where the alternative aviation fuels will be produced. In addition to the costs of additional use of natural gas and electricity, the process also results in some elemental sulphur which has a market value. This benefit is monetarised by using an average global price for sulphur of € 162 per MT.

Table 7 - Energy and sulphur prices

Primary energy sources	US	EU	Average
Natural gas (€/m ³)	0.13	0.33	0.23
Electricity (€/kWh)	0.06	0.04	0.05
Elemental Sulphur (€/MT)			-162

Sources: (EIA, 2019); (Eurostat, 2019).

The additional costs of the hydrotreated aviation fuel is presented in Table 8.

Table 8 - Average additional costs of primary energy for the hydrotreated aviation fuel

	Hydrotreated Jet A-1
Natural gas (€/ton kerosene)	10
Power from grid (€/ton kerosene)	0.92
Elemental Sulphur (€/tonne kerosene)	-0.46
Total cost (€/ton kerosene)	10
Total cost (€-cents/litre kerosene)	0.823

Note: According to IATA³⁰, the average kerosene price in 2021 amounted to USD 610 per tonne, which equates to EUR 540 per tonne.

We do not have a detailed breakdown of the costs of extractive distillation. According to Weibel (2018), the costs of removing naphthalenes by extractive distillation are about 30% lower than the costs of naphthalene removal by hydrotreatment. However, hydrotreatment also reduces the content of other aromatics as well as sulphur.

³⁰ [IATA: Jet Fuel Price Monitor](#)



6 Policies to monitor and limit the concentration of aromatics in jet fuel

6.1 Introduction

This chapter analyses how a monitoring system could be set up to monitor the properties aromatics and naphthalene content of jet fuel. This is done because such a system could serve as a database to analyse whether ReFuelEU Aviation or other policies to increase the share of SAFs in the jet fuel blend would have the anticipated impact on the concentration of aromatics and naphthalene and consequently the intended impact on contrail formation.

In Section 6.2, options and implications for an aromatics and naphthalene monitoring system for jet fuel are explored. European policies to limit the concentration of aromatics and naphthalene in jet fuel are analysed in Section 6.3.

6.2 Monitoring system for aromatics and naphthalene

6.2.1 Introduction

Monitoring aromatics and naphthalene concentrations in aviation fuels would allow for the assessment of the impacts of policies like ReFuelEU Aviation on contrail formation. It would also provide for better estimates of non-CO₂ impacts of aviation in general, filling the data gap that currently exists.

The jet fuel composition of aromatics and naphthalene along the supply chain is unknown as testing on these components is not performed beyond the point of manufacturing, except for blends containing SAFs (see Section 4.2). Therefore, a new monitoring system would need to be set up to collect data on the aromatics and naphthalene content of all jet fuel sold in Europe. For such a system, there are a variety of options to consider.

One of the options could be the collection of certificates of analysis from the jet fuel manufacturer. Because of the global nature of the jet fuel market, it may be a difficult task to track down these certificates and in many cases it would be impossible to acquire these. This is because fuel traders are not always willing to share this information, due to competitive reasons, and the EU or Member States cannot legally oblige non-EU firms to deliver certain documents without additional (cooperative) legislation.

Another option is additional testing of jet fuel at a determined point in the supply chain. Details and considerations for monitoring policies are explored in the following sections.

6.2.2 Options for internalising aromatic content monitoring

In order to minimise administrative burdens, this monitoring and reporting could be integrated in existing or proposed monitoring, reporting and verifying (MRV) systems. There are a number of (proposed) EU legislations requiring MRV systems.



MRV systems for the aviation sector are currently established by the EU ETS and proposed by ReFuel Aviation and the proposed revision of the Renewable Energy Directive. In this section, the possibility of internalising monitoring aromatic content in jet fuel (blends) with the ReFuel Aviation MRV system is explored. The monitoring in ReFuel focuses on the composition of the aviation fuel blend and data on the amount of jet fuels used are reported³¹.

6.2.3 ReFuel Aviation MRV

The ReFuel Aviation regulation proposes an MRV system for the reporting of SAF use by the aviation sector in order to monitor the share of SAF used in the entire jet fuel mix. The reporting can be done by different parties in the jet fuel supply chain and in varying ways. This section discusses possible roles of fuel suppliers and airlines, as airports are not considered relevant entities in this regard.

The MRV tasks for reporting aromatic content could be performed by the same reporting entities in the jet fuel supply chain and the processing and verifying authorities as stated in the ReFuel proposal. This may minimise additional administrative efforts and cost.

This section considers several options for monitoring aromatics and naphthalenes which are aligned with the monitoring provisions contained in the ReFuel proposal. The fuel suppliers and airlines are reporting entities in the MRV policy options. The defined party 'jet fuel supplier' is defined in the ReFuel aviation proposal as '*an entity supplying fuel to the market that is responsible for passing fuel through an excise duty point*'³². In practice, these can be several commercial fuel suppliers in a Member State delivering jet fuel to the European internal market (either from EU located refineries or from extra-EU trade).

Aviation fuels are directly fuelled from airport fuelling storage into the aircraft. The point of entry into the airport fuelling storage facilities is the last point where the fuel can be checked by delivered batch for its composition. At the airport, batches of jet fuel cannot be traced back to the supplier³³ as batches are usually intermingled in large fuel storage tanks (or pipeline). Airlines are defined as all airlines operating in Europe (EU based and non-EU airlines). Apart from the reporting party (fuel suppliers and/or users), the level or scope of reporting is of relevance when setting up a monitoring and reporting system.

The fuel supplier can report by batch (every supply to the airport) or an average value per year. Reporting of aromatics and naphthalene content of aviation fuel can be performed by the airline at flight level or as an average value per year. There are several options in which the reporting of jet fuel contents can be performed. These are listed in the sections below.

³¹ See [here](#) the proposal for ReFuel Aviation, with details on monitoring, reporting and verification in annex 9.

³² As given in Directive (EU) 2018/2001, Article 2, second paragraph, point 38.

³³ In the Netherlands, this is the Central European Pipeline System (CEPS) in which jet fuel is booked into the system (from the port of Rotterdam) to supply to Amsterdam Airport Schiphol.



Reporting options for fuel suppliers

From a practical standpoint, reporting of jet fuel aromatic content by (EU) refineries is not efficient as a significant share of jet fuel used in the EU is sourced from non-EU markets. Therefore, an option in which refineries report the aromatic content is excluded beforehand. Thus, we are left with the following reporting option for fuel suppliers as listed in the ReFuel Aviation proposal:

- Suppliers must report their jet fuel supply to the Union database³⁴.

In the ReFuel aviation proposal, suppliers are required to report the total amount of jet fuel supplied to airports, the total amount of SAFs and for each type of SAF the CO₂ intensity of the supplied jet fuel, type of SAF and feedstock. In this policy option, it may be possible to add the reporting of aromatics and naphthalene content of the jet fuel. However, data on aromatics and naphthalene content of conventional jet fuel is currently unknown down the supply chain. This means an extra test is necessary for every jet fuel batch before entry into the airport fuel system. The reporting of aromatics and naphthalene content can be either per batch or by a yearly average.

With aggregate data, the reporting bodies can determine the average level of aromatic content in all aviation fuel used in the EU. In the impact assessment of the ReFuel EU proposal, the option to trade SAF certificates between fuel suppliers has been discussed. The ReFuel impact assessment states that the total amount of aromatic compounds in the total jet fuel supplied in the EU would not be influenced by a SAF certificates trading system. The place all data may be collected can be a national database linked to the EU database as suggested in the REDII³⁵.

SAF deliveries reduce additional testing requirement

The point of entry into the airport fuel storage facilities of aviation fuel is a crucial point in the supply chain. At this point, only aviation fuel compliant to the industry set standards for Jet A-1 and SAF blends are allowed to be supplied to the airport (see Section 4.2 for the standards). At this point, the aromatics content of the SAF jet fuel batches is known because at the point of manufacture all fuel batches and the final product (SAF jet fuel blend) have to be tested on these components. The certificate results of the SAF jet fuel batch analysis, as carried out by the fuel mixing party, can provide the required data for such monitoring. This results in two variants of monitoring at the supply side.

Variant 1: All jet fuel is monitored

Fuel suppliers have to report aromatics and naphthalene content of all jet fuel batches, conventional fossil and SAF jet fuel blends. This will inevitably require additional tests for these components before delivery to the airport fuel storage facilities.

Variant 2: Only SAF jet fuel blends are monitored

The aromatic content of SAF blends is tested. When the data are reported to the Union database, the aromatic content of these blends would be known and the aromatics content of the fossil part of the blend can be calculated from the percentage of SAFs blended under

³⁴ In the Netherlands, it is not yet certain exactly which party will be obliged to report the SAF supply and at which point the physical mixing of SAF and jet fuel must take place.

³⁵ See [here](#) the database set up for reporting (sustainable) fuels as in the REDII, article 28(2).



the assumption that pure SAFs do not contain aromatics, which is true for all hydrotreated SAFs.

While the costs of this option would be significantly lower than the costs of Variant 1, the resulting information of the aromatic content would not necessarily be representative for all aviation fuels sold in the EU, but only for the SAF-containing blends.

Reporting options for airlines

For airlines, the following reporting options are listed in the ReFuel Aviation proposal:

- Airlines report SAF use under ETS (article 14) with proof of jet fuel purchase and SAF sustainability certificate.
- Airlines report SAF use per intra-EEA flights as per normal under ETS (article 14).
 - For extra-EEA flights, airlines shall report SAF use as part of CORSIA MRV system (ICAO SARP Annex 16, Volume IV, Chapter 2).
- New reporting system requiring all airlines to report fuel use per flight.

Airlines can choose to receive certificates of analysis for the jet fuel bought. Under the ReFuel regulation, and depending on the policy option and reporting obligation of airlines, airlines must have composition and sustainability certificates of the SAF blends they intend to use and report this under the ETS. Internalising the reporting of aromatic content of jet fuel (blend) batches bought by the airline is a possible option.

The second option for reporting by airlines is an option in which reporting takes place to different entities than for SAF shares reporting. A new reporting system adds administrative costs compared to internalising monitoring and reporting in existing frameworks. Currently, there is no standard testing of fuel batches when refuelling aircraft. Reporting of every flight may put a large burden on airlines or airports besides the fact that new test procedures should be set up.

Effort of monitoring aromatic content

Irrespective of the scope of a future limitation of aromatic content in jet fuel, monitoring and reporting will require effort for firms acting in the aviation fuel supply chain. It makes no difference to the monitoring effort whether each batch (delivered to airport fuel systems) has to comply with lower limits or whether it is a yearly average of aromatics below the set upper limit. In both cases, each batch has to be tested to obtain the final figures on the relevant components. Annual reporting requires less effort than reporting per batch, of course.

In Table 9, the reporting options for aromatics and naphthalene content in jet fuel and SAF blends are summarised. The monitoring level indicates the point at which the jet fuel (blend) is analysed for the aromatics and naphthalene content. The reporting level presents the scope at which the reporting party has to report the data on the contents of the jet fuel. Finally, an estimation of relative administrative effort is indicated for every monitoring and reporting option.



Table 9 - Overview of jet fuel contents reporting options

Reporting party	Monitoring level	Reporting level	Administrative effort ^b
Fuel suppliers	Per delivered batch containing SAF ^a	By SAF jet fuel batch	Low to moderate
		Yearly average of all batches containing SAF	Low
	Per delivered batch of all fuels ^a	By delivered batch (all jet fuel types)	High to Moderate
		Yearly average of total supply	Moderate
Airlines	Per aircraft tank filled	By flight	High
	Per purchased batch	Yearly average use	Moderate

^a A delivered batch is an entire shipment of jet fuel to the airport fuel storage.

^b This is an indication of the relative administrative effort of the presented options. The effort is for all MRV parties (the reporting and verifying entities).

6.2.4 Conclusion

The option for MRV of aromatics and naphthalene content in which fuel suppliers monitor and report these specifications seems to be the most obvious if such policy would be initiated. The fact that SAF jet fuel blend batches are tested on these components reduce the additional testing burden in case other parties in the supply chain have to test and report. Nevertheless, it would require additional procedures and setting up conventional jet fuel batch testing, at a yet to be determined point of the supply chain. This monitoring programme may have significant impact in terms of investments and additional bureaucracy which imply increased cost for all involved parties. Thus, all benefits and cost of aromatics content monitoring should be considered before setting up such policy.

6.3 Options for standard setting for lower aromatic fuels

This section looks at how new aviation fuel specifications to reduce contrail formation could be set in the EU. It will first look to the ASTM and DEF Standards and then consider whether such standards could be set under EU legislation.

6.3.1 ASTM and DEF Standards

The ASTM (formerly the American Society for the Testing of Materials) is an international organisation that sets standards for a variety of industries, including aviation. The Aviation Fuels committee (D02.JO) has a subcommittee on Jet Fuel Specifications which has over time produced standards on topics ranging from fuel containing synthesized hydrocarbons to fuel lifecycles (ASTM, 2018). Membership of ASTM is open to all individuals and organisations that subscribe to the purposes of ASTM as set forth in its Charter (bylaw 1.1), along with the payment of an administrative fee. Members of the ASTM subcommittee on Jet Fuel Specifications include government representatives, fuel producers, fuel distributors and aircraft manufacturers. ASTM has set standards for sustainable aviation fuel (ASTM D7566) which sets which technologies, under which circumstances and characteristics are acceptable to produce SAF from a number of different feedstocks (IATA, n.d.). It is unclear whether the potential impact of SAF on contrail formation was considered as part of this process. The ASTM Board of Directors sets procedures for the development and adoption of voluntary consensus standards by following several principles such as giving adequate notice and opportunity for those interested to participate in the process (bylaw 7).



Defense Standards (DEF) are the main instruments used to define the procurement standard for fuels and lubricants used by the Ministry of Defense (MoD) in the United Kingdom. DEF are established through a consensus process between the MoD, aviation and fuel industry and academia (Ministry of Defense, 2020). The standards specify material, procedures or process guidance and use other open standard bodies as references where appropriate. Jet fuel is regulated as DEF STAN 91-091, with the standards set by DEF's Aviation Fuels Committee.

Both ASTM and DEF standards are set via consensus-driven, technical approaches. The committees set the standard for Jet A-1 fuel which is the most commonly used aviation fuel in the world. The EU (via government representatives and bodies such as EASA) is a member on the same basis as other members and thus does not have the power to set a specific outcome. While votes are taken on new standards, any participant can reject a standard 'with comments' and if the objecting comments are seen as persuasive enough, the new standard will be rejected. Similarly, when the objecting comments come from an important source, such as an aircraft manufacturer, the standard will be rejected as this is a clear signal that new aircraft cannot or will not comply with a standard.

Neither ASTM nor DEF Standards have any formal recognition in EU law currently, but both are informally relied upon for the safety of aviation fuel. The EU could propose new standards to ASTM and DEF but in both cases, it would depend on the committee accepting the proposed standards via consensus. If the EU or a Member State decided it wished to propose such standards, the first step would be to ensure that the appropriate research was done and begin an informal process of discussion with other committee members before proposing the new standard formally to the committee.

The EU could mandate new standards for aviation fuel in the EU, without ASTM or DEF approval. While this would be a departure from current practice, there are also Russian, Chinese and Canadian standards for aircraft fuel such that ASTM and DEF are not truly worldwide standards. Indeed, in the past many countries had their own individual standards but these died away due to inaction or merged with other standard bodies. The multiple standards that exist today do not generally conflict and IATA sets checklists to ensure that all the different fuels specifications can be complied with by following the checklist (IATA, n.d.).

6.3.2 Establish an EU equivalent to existing jet fuel standards

There is no EU or international law that would prevent the EU establishing a new standard for aviation fuel to reduce contrail formation and/or air pollution. There are several different legal avenues open to the EU if they wished to do so. As setting such standards would be done with an environmental purpose, the EU has competency under Articles 191 and 192 of the Treaty on the Functioning of the European Union which gives the EU power to act for environmental protection purposes. Setting such standards would be better done at an EU level rather than a Member State level due to the international nature of aviation and the fuel market, ensuring the principles of subsidiarity (that any regulation should be enacted at the level most appropriate i.e. Member State vs EU level) and proportionality (the EU should take no more action that is required to achieve the objective) are respected.

An EU standard could be implemented via establishing a new body (i.e. an EU equivalent to ASTM and/or DEF) or delegating the authority to an existing body such as EASA. Either of these options would require either amending existing legislation or agreeing new legislation to establish the authority and their powers. Indeed, there are already European



standardisation bodies such as EN which set standards across a number of products, though not yet on aviation, or EUROCAE which sets aviation standards but not yet on fuels. However, as neither EN nor EUROCAE are EU bodies nor run by EU institutions or Member States, the EU could not mandate them to set such a standard.

6.3.3 EU Emissions Trading System

The EU already regulates fuels to the extent that it allows certain fuels to be ‘zero rated’ for ETS purposes. In order to gain this advantage, airlines must show a proof of sustainability. While synthetic aviation fuels generally have negligible amounts of aromatics and sulphur, it could be that standards could be put in place even for fossil fuel use via the requirement of a certificate for those fuels as well. This could be done by establishing a hierarchy of certificates of sustainability as shown in Table 10, where the highest would be zero rated, with fossil fuels that meet appropriately set standards for contrail formation to be neutrally rated (i.e. submit allowances as usual) and for fuels that do not meet such standards of aromatics and sulphur content to be double rated (i.e. require the submission of double the allowances per tonne of CO₂).

Table 10 - Illustrative examples of potential sustainability multipliers in the ETS

Fuel	Fossil Fuels	Fossil Fuels with low-sulphur & low-aromatics	SAF with low-sulphur & low-aromatics
Number of allowances per tonne of CO ₂ to be submitted (to be adjusted for accuracy as further research becomes available)	2	1	0

If a proposal like this was implemented, a thorough study should be done to ensure the numbers are set at the right level that would most accurately reflect the GHG impact of the fuels. In addition, how such a system might create a competition between the incentive to reduce CO₂ against the incentive to use SAF should be considered.

Niklaß et al. (2019) considered the use of a multiplier to account for the non-CO₂ impacts of aviation and concluded there were multiple drawbacks including:

- uncertainty as to what the multiplier should be;
- risk of setting wrong incentives for manufacturers and aircraft operators (that would focus on CO₂ instead of NO_x); and
- the conceptual - and potentially legal - challenge whereby the principle of equal treatment (‘a tonne is a tonne’) would no longer apply; instead, greenhouse gas (GHG) emissions would be allocated to polluters in a potentially arbitrary way not based on exact science and not respecting the exact degree of responsibility.

The question was further discussed in EASA et al. (2020) where the conclusion was that a multiplier in the ETS for aviation non-CO₂ might not be appropriate because there is no linear correlation between CO₂ and non-CO₂ aviation impacts. A multiplier would not incentivise reduction of non-CO₂ independently of CO₂ emissions. Actions taken to reduce CO₂ emissions may not also reduce non-CO₂ emissions and vice versa.

However, the climate impact of aviation is not yet adequately accounted for nor addressed in the EU to date. The precautionary principle would strongly support the use of some policy instrument that would begin to account for the non-CO₂ climate impacts of aviation. This also mitigates against the third concern of Niklaß et al., but currently there is no



requirement that all tonnes of GHGs are treated equally in the EU. Some sectors such as shipping have not yet been subject to any requirement (though it is now proposed to add shipping to the ETS). Indeed, even in the aviation sector to date, the use of biofuels is zero rated but whether the use of such fuels really amounts to zero tonnes of CO₂ released depends on the lifecycle of the fuel's production, which is not fully accounted for in the zero rating. However the remaining lifecycle emissions take place in other sectors (industry, terrestrial transport). Further, if other sectors of the ETS do not cause similar non-CO₂ impacts and/or their non-CO₂ impacts are accounted for in some way, it is unlikely a legal challenge could succeed.

Additional funds generated from the inclusion of non-CO₂ for aviation (either through additional allowances sold if the emissions cap is increased or through an increased price generated if the cap is not increased) could be used for more research into non-CO₂ impacts and technological solutions that would reduce those impacts. Thus, with time the accuracy of the multiplier in the ETS could be improved.

6.3.4 ReFuelEU Aviation Regulation

Under ReFuelEU Aviation, the Commission is proposing mandatory supply and use of sustainable aviation fuel, part of which is synthetic aviation fuel. SAF could require new standards for aromatics and sulphur content, even if just to confirm the same standards that kerosene has today. ASTM sets standards for mixes of SAF with kerosene, providing an opportunity for the aromatics and sulphur content to be reviewed, even for these mixes. Some of this work is happening in ASTM already and the Regulation proposes to use ASTM standards and the Renewable Energy Directive II sustainability framework to set which fuels can be used to meet the SAF targets within the legislation.

Therefore, ensuring the ASTM standards minimise the impact of non-CO₂ emissions for SAF is an opportunity currently open to the EU. The proposed regulation requires operators to provide yearly information on the characteristics of the sustainable aviation fuels purchased such as the nature and origin of the feedstock, conversion pathway and lifecycle emissions. All of this information is to be verified. There is no reason the EU couldn't set sulphur and aromatic content standards as part of this requirement on operators in order to comply with the ReFuelEU Aviation Regulation. It would be important as part of this process to note that SAF and kerosene can be mixed and consider the impact of that mixing on the sulphur and aromatic content standards.

6.3.5 The Fuel Quality Directive (FQD)

The Fuel Quality Directive sets minimum specifications for petrol and diesel fuels for use in road and non-road mobile applications for health and environmental reasons. It does not address aviation fuels. The FQD has not yet been opened for a full revision under the Fit for 55 package. However, some elements of the Fit for 55 package do contain amendments to the FQD.³⁶ There is in principle, no reason specifications for aviation fuel could not be introduced into the FQD. The FQD already contains some elements aimed at addressing climate change and the sulphur content of other fuels.

³⁶ The proposed amendments to the Renewable Energy Directive deletes a 6% target for reducing the GHG content of transport fuels that was in the Fuel Quality Directive.



6.3.6 Voluntary Standard

A voluntary standard for aviation fuel specifications would be unlikely to have much effect. The impact assessment to the ReFuelEU Aviation legislation looked into the question with regard to a voluntary increase in sustainable jet fuel use which is equivalent to a voluntary new specification for jet fuel which would reduce non-CO₂ impacts as both require the use of fuels that have additional processes and so additional costs compared to standard jet fuel. The conclusion was that there was little merit in a voluntary standard as there are “no reasonable grounds to believe that market forces alone would achieve the desired level of SAF production and uptake”. Chapter 5 analyses the potential costs of producing low-sulphur and low-aromatic fuel in detail. While treating fuel in this way would be cheaper than producing SAF, it is still an additional cost to airlines and without regulation requiring it, they would have little incentive to produce.

6.3.7 Conclusion

The main barrier to a requirement that aviation fuel contain less sulphur and aromatics is not legal but technical. Once clear technical standards that would reduce the non-CO₂ impact of aviation are available there are multiple legal routes to their implementation as shown here. Both ASTM and DEF Standards could be used, however neither of these standard bodies will necessarily adopt any such new standard as they are bodies that operate by consensus. If the route of ASTM or DEF Standards proves unsatisfactory, the EU could use a number of different legislative vehicles such as the ETS, ReFuelEU Aviation or the FQD for standard implementation. Finally, it is important to note that any changes in fuel specifications will need to be carefully analysed with regards to impacts on safety.

Monitoring of aromatics and naphthalene content can be internalised with the reporting of SAF shares by the fuel suppliers. This approach involves the lowest possible additional cost for the sector and for authorities to monitor, process data and verify. However, the exact design of such monitoring and reporting system should follow policy or legal requirement for SAF or a lower aromatic content in jet fuel blends.

7 Conclusions

The project aims to analyse which advantages and barriers exist for lowering the aromatic content of jet fuels, and which policies can be developed to monitor the effectiveness of the policies identified in EASA et al. (2020).

In short, the conclusions are that policies which incentivise or mandate blending in sustainable aviation fuels will probably contribute to a reduction of the climate impact of contrails. However, the impact can only be assessed when the aromatics content of jet fuels are reduced, which requires additional monitoring. Monitoring provisions can be included in the ReFuelEU Aviation Regulation with small or modest administrative burden.

7.1 Aromatics in aviation fuel

Aviation fossil-based jet fuel (kerosene, Jet A/Jet A-1) is made up of a mixture of n-alkanes, iso-alkanes, cyclo-alkanes, and aromatics. The speciation of the aromatic fraction is not well documented but the available evidence suggests that it largely comprises mono and bicyclic aromatic compounds. Naphthalene and naphthalene derivatives (e.g., branched methyl, ethyl components) are the major bicyclic components. The aromatic content is currently limited to a maximum of 25% by volume, and a minimum of 8% (for drop-in biofuels).

The aromatic content of aviation fuels sold in Europe are not known in detail, as the aromatic content is generally only tested at the refinery gate and when batches of SAF-fossil fuel blends are made. The available evidence suggests that most Jet A-1 fuel supplied in Europe has an aromatics content in the range of 15 to 20% v/v, of which 1 to 2 percentage points naphthalene. Sulphur is in most cases below the maximum limit of 0.3% (m/m).

Fuel testing takes place at the point of production and at every other point of ownership change (at every transaction of a batch). The scope of considered contents in fuel tests is often limited (excluding aromatics, naphthalene and sulphur) at change of custodies, compared to full content testing (incl. aromatics, naphthalene and sulphur) at the point of manufacturer. The transaction of a jet fuel batch is accompanied by either the *refinery certificate of quality* or the *certificate of analysis*. The jet fuel can be blended at every point in the supply chain and at every rebatching a fuel property analysis is performed providing a new certificate of analysis. Every batch of jet fuel has to comply to the industry standards if the batch is to be accepted by the airport fuelling service in the airport fuel storage facilities.

7.2 The advantages of lowering the aromatics concentration in jet fuel

Extensive measurement campaigns of aircraft exhaust gases that include fuel substitution experiments indicate that naphthalene is the principal aromatic component responsible for soot emissions from fossil fuel kerosene.

Soot is primarily formed in aircraft gas turbines and emitted as very small particles from the combustion of the naphthalene content of the fuel, although combustion chemistry is not well characterised. These particles are initially around 10 nm in diameter.



Measurements at ground and altitude of the combustion of (usually) bio-based kerosene alternative fuels with reduced aromatic content show greatly reduced emissions of soot particles by mass and number. However, low-naphthalene fuels do not entirely remove soot. There are clear indications from measurements that reducing naphthalene content would reduce soot number emissions from aircraft exhaust and result in fewer and larger ice crystals. This would also reduce the effective radiative forcing (ERF), although the degree to which is less clear, relying on a limited number of modelling studies. Moreover, the whole study area is still hampered by large uncertainties over the current day magnitude of the contrail cirrus ERF.

Next to the climate benefits, any reduction in emissions of nvPM during the LTO cycle due to the use of lower aromatic fuels such as SAF will likely result in proportionally decreasing the LTO contribution to ambient concentrations of nvPM both in terms of number and mass.

7.3 Barriers to lowering the aromatics concentration in jet fuel

In principle, the aromatics concentration of fossil aviation fuel can be reduced further through hydrotreatment. Doing so would increase fuel prices by a few percent. Since there is no incentive to reduce the aromatics concentration, it is not generally done.

SAF containing aviation fuel blends have a minimum aromatics content of 8%. This limit was introduced to ensure compatibility with fuel systems on board aircraft.

7.4 Mandating lower aromatic fuels

The main barrier to a requirement that aviation fuel contain less sulphur and aromatics is not legal but technical. Once clear technical standards that would reduce the non-CO₂ impact of aviation are available there are multiple legal routes to their implementation as shown here. Both ASTM and DEF Standards could be used, however neither of these standard bodies will necessarily adopt any such new standard as they are bodies that operate by consensus. If the route of ASTM or DEF Standards proves unsatisfactory, the EU could use a number of different legislative vehicles such as the ETS, ReFuelEU Aviation or the FQD for standard implementation. Finally, it is important to note that any changes in fuel specifications will need to be carefully analysed with regards to impacts on safety.

7.5 Monitoring the aromatic content of aviation fuels

ReFuelEU Aviation can be amended to keep track the concentration of aromatics and naphthalenes. A monitoring requirement could be included in ReFuelEU Aviation so that fuel suppliers will report the aromatics and naphthalene concentrations to the Union Database in addition to volumes of aviation fuel, sustainable aviation fuel and lifecycle emissions of the fuel. If the obligation applies to batches of fuel containing SAFs, the additional administrative burden of this requirement would be small, because the aromatic content of these fuels are always tested. If the monitoring requirement would apply to all aviation fuels, additional testing of pure fossil aviation would be required, thus increasing the costs.



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A Standard form for reporting jet fuel inspection data


D 1655

INSPECTION DATA ON AVIATION TURBINE FUEL

(Items in bold type are referenced in the specification)

MANUFACTURER/SUPPLIER _____ PRODUCT CODE/GRADE _____ SPECIFICATION _____ SAMPLE NUMBER _____ DATE SAMPLED _____ SAMPLING LOCATION _____ BATCH NO. _____ QUANTITY LITERS @ 15°C _____ QUANTITY U.S. GALLONS @ 60°F _____ LABORATORY _____	DATE SAMPLED _____ DATE RECEIVED AT LAB _____ CONTRACT NO. _____ ORDER NO. _____ TANK NO. _____ DESTINATION _____ CRUDE SOURCE _____ PROCESSING METHOD _____ REMARKS _____
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<u>Method</u>	<u>Result</u>	<u>Method</u>	<u>Result</u>
APPEARANCE			
010 D 156	Color (Saybolt).....	000	
020 D 4176	Visual ("Pass" or "Fail").....	0000	
COMPOSITION			
100C D 3242	Acidity, Total (mgKOH/g).....	0+000	
110 D 1319	Aromatics (vol %).....	00+0	
115 D 1319	Olefins (vol %).....	0+0	
120 D 1840	Naphthalene (vol%).....	0+00	
130 D 3227	Sulfur, Mercaptan (mass %).....	0+0000	
140 D 4952	Doctor Test (P = pos, N = neg).....	0	
150A D 129	Sulfur, Total (mass %).....	0+00	
150B D 1266	Sulfur, Total (mass %).....	0+00	
150C D 1552	Sulfur, Total (mass %).....	0+00	
150D D 2622	Sulfur, Total (mass %).....	0+00	
150E D 3120	Sulfur, Total (ppm).....	00+00	
150F D 4294	Sulfur, Total (mass %).....	0+00	
150G D 5453	Sulfur, Total (ppm).....	0000	
160A D 3343	Hydrogen Content (mass %).....	00+00	
160B D 3701	Hydrogen Content (mass %).....	00+00	
VOLATILITY			
200A D 86	Distillation by Auto/Mannual (°C).....	0	
200B D 2887	Distillation by GC (°C).....	0	
201	Initial BP(°C).....	000+0	
202	10 % Rec(°C).....	000+0	
203	20 % Rec(°C).....	000+0	
204	50 % Rec(°C).....	000+0	
205	90 % Rec(°C).....	000+0	
206	95 % Rec(°C).....	000+0	
211	Final BP(°C).....	000+0	
213	Residue (vol %).....	0+0	
214	Loss (vol %).....	0+0	
220A D 56	Flash Point, Tag Closed (°C).....	00+00	
220B D 93	Flash Point, PM Closed (°C).....	00+0	
220C D 3828	Flash Point, Setaflash (°C), Meth A.....	00+00	
220D D 3828	Flash Point, Setaflash (°C), Meth B.....	00+0	
221 D 3828	Flash Point, Setaflash (Flash/No Flash).....	0	
230A D 1298	Density @ 15°C (kg/m ³).....	000+0	
230B D 4052	Density @ 15°C (kg/m ³).....	000+0	
231A D 1298	API Gravity @ 60°F.....	00+0	
240A D 323	Vapor Pressure, Reid (kPa).....	00+0	
240B D 4953	Vapor Pressure, Dry Method (kPa).....	00+0	
240C D 5190	Vapor Pressure, Automatic Method (kPa).....	00+0	
240D D 5191	Vapor Pressure, Mini Method (kPa).....	00+0	
FLUIDITY			
300A D 2386	Freezing Point (°C).....	-00+00	
300B D 5901	Freezing Point (°C).....	-00+00	
300C D 5972	Freezing Point (°C).....	-00+00	
300D D4305	Freezing Point (°C).....	-00+00	
310 D 445	Viscosity @ -20°C (mm ² /s).....	00+000	
311 D 445	Viscosity @ other Temp (mm ² /s).....	00+000	
312 D445	Temp (°C) of Item 311.....	0000	
COMBUSTION			
400A D 240	Net Heat of Combustion (MJ/kg).....	00+000	
400B D 1405	Net Heat of Combustion (MJ/kg).....	00+000	
400C D 3338	Net Heat of Combustion (MJ/kg).....	00+000	
400D D 4529	Net Heat of Combustion (MJ/kg).....	00+000	
400E D 4809	Net Heat of Combustion (MJ/kg).....	00+000	
410 D 1740	Luminometer No.	00	
420 D 1322	Smoke Point (mm).....	00+0	
CORROSION			
500 D 130	Copper Strip.....	00	
510 IP 227	Silver Strip.....	0	
STABILITY			
601A D 3241	JFTOT AP (mm Hg) @ other Temp.....	00+0	
602A D 3241	JFTOT Tube Deposit @ other Temp.....	0000	
603A D 3241	JFTOT TDR Spun Rating @ other Temp.....	00	
604A	Temperature (°C) of above JFTOT.....	0000	
601B D 3241	JFTOT AP (mm Hg) @ 260°C.....	00+0	
602B D 3241	JFTOT Tube Deposit Rating @ 260°C.....	0000	
603B D 3241	JFTOT TDR Spun Rating @ 260°C.....	00	
CONTAMINANTS			
700 IP 225	Copper Content (mg/kg).....	0+00	
710 D 381	Existent Gum (mg/100 mL).....	000	
720A D 2276	Particulate (mg/L).....	0+00	
720B D 5452	Particulate (mg/L).....	0+00	
730	Filtration Time (minutes).....	00	
740 D 1094	Water Reaction Interface Rating.....	00	
750 D 3948	MSEP (With SDA).....	000	
751 D 3948	MSEP (Without SDA).....	000	
ADDITIVES			
800	Antioxidant (mg/L).....	[] 00+0	
810	Metal Deactivator (mg/L).....	[] 0+0	
820	Static Dissipator Additive (mg/L).....	[] 0+0	
830A (D5006) FSII (vol%).....		[] 0+000	
830B (FTM5327) FSII (vol%).....		[] 0+000	
830C (FTM5340) FSII (vol%).....		[] 0+000	
840	Corrosion Inhibitor (mg/L).....	[] 00+0	
OTHER TESTS			
900 D 2624	Conductivity (pS/m).....	0000	
901 D 2624	Conductivity Test Temperature (°C).....	000	
Comments and/or Additional Tests:			

CERTIFIED BY _____			

FIG. X3.1 Standard Form for Reporting Inspection Data on Aviation Turbine Fuels

Source: ASTM 2019.



B Annex I

Table 11 - Concentrations near and at airports from selected studies with measurements and monitoring data

Study	Measurement details	Key findings	Notes
ACI Europe (2012)	London Heathrow Airport: 1-day at Terminals 3 and 5 ramps. Measured UFP, PM ₁ , PM _{2.5} and PM ₁₀ .	Baseline: T3: 10,000 UFP/cm ³ , T5: 20,000 UFP/cm ³ Peak levels: 70,000 UFP/cm ³ , returned to baseline quickly. Average levels: 31,000 (T3) UFP/cm ³ , 42,000 (T5) UFP/cm ³ .	Correlate to aircraft taxiing and GSE. No correlation between PN and PM mass since the latter came from different sources.
ACI Europe (2012)	Stockholm Arlanda Airport: 3 weeks in Aug-Sep 2012; 1 week ramp at Gate 5 (T5); 2 weeks at Gate 32 (T4). Measured UFP.	Average concentration: T5: 50,700 UFP/cm ³ T4: 35,600 UFP/cm ³	Variation over 24-hr period, highest concentration 7-9 am, 5-7 pm. Peaks correlate to aircraft arrivals/departures.
ACI Europe (2012)	Los Angeles World Airport: Real-time monitoring: 140 m from TO position (blast site), 5 downwind sites up to 600 m TO runway. Measured UFP, BC, PM _{2.5} .	High PN concentrations, 100x difference between highest and lowest. Total > 10 ⁷ PN/cm ³	Correlated to aircraft TO.
ACI Europe (2012)	Santa Monica Airport: Real-time measurements with electric vehicle mobile platform. Spring/Summer 2008, Measured UFP, BC, PB-PAH.	Average UFP increased by 10x (100 m downwind) and 2.5x (600 m downwind). BC, PB-PAH no appreciably elevated levels. Peaks 60s average at 100 m downwind of TO up to 2.2 × 10 ⁶ UFP/cm ³ (440x background), 440 ng/m ³ (PB-PAH, 90x background), 30 µg/m ³ (BC 100x background).	Peaks correlated to TO. UFP remained elevated for extended period associated to taxi and idle.
ACI Europe (2018)	London Heathrow Airport: Oct-Nov 2016 at 170 m north Northern runway (LHR2), 600 m south of Southern runway (Oaks Rd). Measured UFP, PM _{2.5} , PM ₁₀ , BC.	Concentrations of 14.6 nm particles 50% lower at landing than TO.	Emissions can still reach ground level under some conditions.
ACI Europe (2018)	Brussels Airport: Oct-Nov 2015. Locations on a transect aligned with runway. Measured UFP, BC, PM ₁₀ .	UFP number concentrations of 10-20 nm > 50,000 UFP/cm ³ . Effects measurable at 7 km from airport.	
ACI Europe (2018)	Zurich Airport: Locations transect north-south on main long-haul departure runway. Measured vPM and nvPM.	Range between monitoring stations: Hourly average: 16,000 particle/cm ³ to 139,000 particle/cm ³ . Range in single station: Hourly average: 1,400 to 786,000 particle/cm ³ .	High variability. Lowest at night-time and highest during day.



Study	Measurement details	Key findings	Notes
		<p>Mean: 104,000 particle/cm³.</p> <p>At background station: Hourly average: 1,300 to 100,000 particle/cm³.</p> <p>Mean: 12,000 particle/cm³.</p>	
ACI Europe (2018); Ellermann et al. (2011)	Copenhagen Airport: Real-time monitoring from 2009 to 2011. Measured PM _{2.5} .	<p>Apron PM_{2.5} concentrations < busiest street in Copenhagen (~60,000 veh/day).</p> <p>PN: Hourly average: 75-95% with diameter of 6-700 nm, 2-3x than busiest street.</p>	UFP originated from jet fuel combustion and diesel at apron.
ACI Europe (2010)	Paris Airports Zurich Airport	<p>Paris: Meteorology shows dominance over pollutant dispersion. Air traffic impact on concentration is not detectable.</p> <p>Zurich: Little to no influence visible from aircraft PM emissions.</p> <p>In general: PM₁₀ measurements in Switzerland indicate the impact of aviation on fine particle concentration in the air is extremely small.</p>	LAQ assessment at European airports based on airspace closure in Europe during volcano eruption in Iceland in April 2010.
AQEG (2018)	Review of measurements	<p>Emissions higher than previous future estimates.</p> <p>UFP measurements suggest that aircraft plumes mix downwards to a sufficient extent to be detected at ground level with concentrations similar in magnitude to road vehicle sources.</p>	Future projections show increasingly important contribution of UFP from aviation. Consists of nvBC and nucleated sulphurous particles (dependent of fuel sulphur content). It would be more difficult to detect elevated UFP concentrations, due to influence of other sources (particularly road traffic) than at many other airports where there are fewer sources upwind of the airport.



Study	Measurement details	Key findings	Notes
EASA (2010)		Reduction from 600 to 10 ppm sulphur content would result in a 0.07% decrease in aircraft LTO PM-based mortality.	
Hudda and Fruin (2016)	Mobile Monitoring Measurements downwind of LAX.	Large increases over local background in PN concentrations extending 18 km downwind, mostly of UFP < 40 nm. At least 2-fold increase in PN concentrations over baseline during most hours of the day in area ~60 km ² that extended 16 km downwind. 4- to 5-fold increase, 8-10 km downwind.	Increase lung deposition fractions to 0.7-0.8 (from 0.5-0.7). 5-fold increase in alveolar-lung deposited surface area (ALDSA) concentrations 2-3 km downwind from airport, decreasing to 2-fold increase 18 km downwind. Ratio of elevated surface over background were lower than corresponding ratio for elevated PN concentrations, but spatial patterns were similar. PN concentration can serve as nonlinear proxy for lung deposited surface area downwind of major airports. Long-term exposure from 12.2-16.3 m ³ /day in adults, 8 hr daytime exposure would increase ALDSA dose by 183-261 mm ² .
Keuken et al.,	Measurements at Adamse Bos, 7 km from Schiphol and 2012 at Cabauw, regional background site 40 km south of Schiphol.	PNC increased during periods wind direction was from Schiphol, at Cabauw by 20% and at Adamse Bos by a factor of three, from 14,100/cm ³ (other wind directions) to 42,000/cm ³ between 0600 and 2300 hrs.	Size distribution dominated by UFP from 10 to 20 nm. Emission sources identified for the elevated PNC levels at Adamse Bos: Takeoff, climbout, planes waiting at gates and landing. PH emissions from road traffic at and near airport were less important than air traffic.
Liati et al. (2014)	UFP distributions dominated by soot particles (10-40 nm). Nucleation mode particles present in exhaust.		
Masiol et al. (2017)	Winter and summer measurement campaigns at Harlington site, 1.2 km north of northern runway of LHR.	Receptor modelling study with Positive Matrix Factorization found a factor with size mode < 20nm associated with the airport, 32% PN count in warm campaign, 33% in cold.	



Study	Measurement details	Key findings	Notes
Riley et al. (2016)	Downwind measurements under landing approach near U.S. airports (LAX and ATL) using mobile monitoring platform.	3-5 fold increase in UFP concentrations in transects under landing approach path to airports, relative to surrounding urban areas with similar ground traffic characteristics (as far as 5-10 km away).	Particle number concentrations suggests significant emissions of UFPs, under low load conditions.
Stacey (2017)	Particle size distribution measurements at 2 sites within and adjacent to LHR: LHR2 within airport perimeter close to northern runway and Oaks Rd, just outside perimeter, close to southern runway. Measurement campaign in Oct 2016.	Showed substantial elevation in particles of 16-30 nm diameter at both sites relative to kerbside, urban background and rural monitoring sites. Elevation originate from runway direction and most pronounced during aircraft take-off.	
Wong et al. (2008); Dakhel et al. (2007)		Highest mass concentrations of BC per unit fuel are emitted during higher engine power (climbout/ take-off), with number concentrations vs power less consistent across all engine modes.	
Zurich Airport (2017): Ultrafine Particle Measurements at Zurich Airport	Measurement campaign over 5 weeks and a network of 10 stations.	Particle number, diameter, LDSA, met parameters (wind, temperature, precipitation). Aircraft emissions tend to produce larger numbers of particles at lower sizes. High variability dependent on wind speed/direction, significant decrease of number concentrations with increasing distance. Short-term measurements at single locations drastically over/underestimate average UFP concentrations.	Must not be used to relate UFP concentration results to health effects. This is an inventory of UFP concentrations observed at and near airport.

Notes: PN particle number; UFP ultra-fine particles (< 5 nm), BC black carbon or 'soot' nvPM.



Table 12 - Concentrations due to aircraft engine emissions from selected studies from global models

Study	Model & resolution	Pollutant modelled/Key finding	Notes
Barrett et al. (2010)	GEOS-Chem at 4° × 5°, 600 ppm S (EI SO ₂ = 1.2 g/kg fuel), EI BC 0.04 kg/kg fuel, EI OC 0.02 g/kg fuel	Primary BC, OC; secondary S/N particles. Secondary S/N dominates PM _{2.5} by 99%.	Estimates of premature ~8,000, mortality, 80% attributable to non-LTO. Fig 1 indicates peak Δ concentrations of 0.15 μg m ⁻³ , LTO+cruise PM _{2.5} , and 0.03 μg m ⁻³ LTO only.
Barrett et al. (2012)	GEOS-Chem at 4° × 5° (nested 0.5° × 0.667° within US) CMAQ, p-TOMCAT 600 and ultra-low 15 ppm S.	Secondary PM _{2.5} from S/N particles under 600 ppm/15 ppm. Increase in lifecycle CO ₂ of 2% (from fuel processing).	They note that ULSJ could have reduced aromatics and therefore reduced BC but neglect this as insignificant to CBA. They note increased climate warming results from ULSJ. Costs of desulphurisation estimated at 3.7-6.6 c/gal. Δ concentrations could not be extracted from the paper (although depicted).
Cameron et al. (2017)	5 global models; GATOR-GCMOM, GEOS-5, NASA-GISS, CAM5, GEOS-Chem	Ground PM _{2.5}	Average PM _{2.5} (μg/m ³) 0.0772 (8.9-6.5) 0.42% (GOCART) 0.17 (1.8-2.3) 1.86% 0.0062 (0.004-0.008) 0.42% 0.0165 (0.015-0.071) 1.12% 0.0034 (0.0014-0.007) 0.21% 0.0133 (0.022-0.039) 1.18% 0.0070 (0.0018-0.014) 0.14%
Jacobson et al. (2013)	GATOR-GCMOM	Ground PM _{2.5}	Increased PM _{2.5} by ~83 ng/m ³ increased human mortality globally by ~620 (-240 to 4770) deaths per year, with half due to O ₃ and the rest to PM _{2.5}
Kapadia et al. (2016)	TOMCAT CTM with GLOMAP-mode	Impact of varying aviation fuel sulphur content (FSC) on premature mortality from long-term exposure to aviation-sourced PM _{2.5}	FSC of 600 ppm result in increase of global mean surface PM _{2.5} concentrations by 3.9 ng m ⁻³ and ~ 3,600 [95 % CI: 1310-5890] annual premature mortalities globally. ULSF (FSC=15ppm) reduces global annual mean surface aviation-induced PM _{2.5} concentrations by 35.7 % and the global aviation-induced mortality rate by ~620 [95 % CI: 230-1020] mortalities per annum.
Lee et al. (2013)	CAM-Chem	emissions near cruise altitudes (9-11 km in altitude) rather than emissions during landing and take-off are responsible for most of the near ground perturbations.	Cruise emissions responsible for an increase of ground PM _{2.5} by ~0.5% (<0.2 μg/m ³) over the United States, Europe, and eastern Asia.



Study	Model & resolution	Pollutant modelled/Key finding	Notes
Morita et al. (2014)	NASA-GISS ModelE2	Global excess mortality attributable to the aviation sector in the present (2006) and in the future (three 2050 scenarios) is analysed.	3 ng/m ³ global increase in surface PM _{2.5} ; aviation PM _{2.5} global average concentration increases to 0.018 µg/m ³ at 2050 under the ref scenario, the Tech & Op and Alt Fuel scenarios yield 0.008 µg/m ³ and 0.006 µg/m ³ , respectively.
Yim et al. (2015)	GEOS-Chem and CMAQ	Concentration-response functions are used to estimate premature deaths due to population exposure to aviation-attributable PM _{2.5} and ozone.	Increase in ground level PM _{2.5} : 6.2 ng m ⁻³ - Global, 9.0 ng m ⁻³ - North America 18.2 ng m ⁻³ - Europe 15.1 ng m ⁻³ - Asia 3.8 ng m ⁻³ - Other Aviation emissions result in ~16 000 early deaths each year, PM _{2.5} and cruise emissions cause 87% and 75% of early deaths, respectively
Vennam et al. (2017)	CMAQv5.0.2 model and AERO6 aerosol module	Ground PM _{2.5}	0.013 µg/m ³ - Northern Hemisphere 0.021 µg/m ³ - North America 0.031 µg/m ³ - Europe 0.021 µg/m ³ - East Asia



Table 13 - Concentrations aircraft emissions from selected studies from local air quality models

Study	Model & resolution	Pollutant modelled/Key finding	Notes
ACI Europe Environmental Strategy Committee, 2010: Effects of Air Traffic on Air Quality in the Vicinity of European Airports	Frankfurt (LASPORT)	Frankfurt: Impact of meteorology more important than aircraft emissions variation. In general: PM ₁₀ measurements in Switzerland indicate the impact of aviation on fine particle concentration in the air is extremely small.	LAQ assessment at European airports based on airspace closure in Europe during volcano eruption in Iceland in April 2010.
Ellerman et al. (2011)	Emissions inventory indicates high sulphur content of 900ppm in aircraft fuel led to up to 50% of particle emissions. Modelling for PM _{2.5} (5x5 m resolution).	PM _{2.5} at apron from background (91%), handling (5.5%), APU (3.4%), main engines (0.4%), apron traffic (0.1%). PN contribution mainly from handling, APU and main engines.	Model results empirically adjusted based on measurements to identify relative source contributions. UFP from aircraft engines/APU spread over long distances under windy conditions.
EASA (2010)		Reduction from 600 to 10 ppm sulphur content would result in a 0.07% decrease in aircraft LTO PM-based mortality.	
European Aviation Environmental Report (2016)	Projections of vPM and nvPM from European aircraft < 3,000 ft from IMPACT modelling and EIs from ICAO Database and Manual.	Low tech improvement: vPM increase by 50% cf 2005 levels by 2035 and nvPM by 11%.	
Zurich Airport (2012): Air Quality Assessment Sensitivities	LASPORT with 4 emissions approaches (B: Representative fleet + ICAO LTO certification, C: Detailed fleet + ICAO LTO cycle, D: Detailed fleet + actual taxi times, E: Detailed fleet + performance based). PM emissions considerably lower when using scenario E. Scenario B varies with E by -12%. Increasing level of modelling sophistication leads to lower PM emissions. PM ₁₀ emissions 2.2% of total emissions in 2005.	Emissions > 300 m above ground don't contribute directly to ground concentration because they rapidly spread over a wider area, diluted and transformed. Calculation using reference LTO cycle, in order to reflect the effects of emissions on concentrations can be adjusted by -50% (application of emissions as indicator for concentrations is reasonable).	Demonstrate sensitivities in AQ assessments using different approaches and described in ICAO Doc 9889. Results do not give indication for concentrations. It is not appropriate to use the emissions of the whole LTO cycle to determine concentrations but only the part <300 m above ground.



Table 14 - Global modelling studies that have examined the contribution of cruise emissions of S to ground level concentrations

Study	Emissions	Concentrations modelled	Key finding
Barrett et al. (2010)	FSC ^a 600 ppm	Ground SO ₄	0.25 - 0.5 × 10 ⁻² µg/m ³ - North Atlantic, North Pacific 0.75 × 10 ⁻² µg/m ³ - West US 1.0 × 10 ⁻² µg/m ³ - East US 0.75 - 1.25 × 10 ⁻² µg/m ³ - Europe 0.25 - 0.75 × 10 ⁻² µg/m ³ - Asia 0.75 - 1.5 × 10 ⁻² µg/m ³ - SE Asia 1.5 - 2.0 × 10 ⁻² µg/m ³ - North Africa, Middle East 0.0 - 0.1 × 10 ⁻² µg/m ³ - Southern Hemisphere
Barrett et al. (2012) ^b	FSC 15 ppm (ultra-low-sulphur jet fuel standard, ULSJ)	Ground SO ₄ (numbers are the result of “ULSJ aircraft” (15 ppm S) and “aircraft” (600 ppm S) simulations)	-9.6 × 10 ⁻⁴ µg/m ³ - global average -4.0 - -6.0 × 10 ⁻³ µg/m ³ - West US -3.0 - -4.0 × 10 ⁻³ µg/m ³ - East US -2.0 - -3.0 × 10 ⁻³ µg/m ³ - Europe -8.0 - -10.0 × 10 ⁻³ µg/m ³ - North Africa, Middle East
Kapadia et al. (2016) ^b	FSC 15 ppm (ultra-low-sulphur jet fuel standard, ULSJ)	Ground SO ₄ (numbers are the result of “ULSJ aircraft” (15 ppm S) and “aircraft” (600 ppm S) simulations)	-2.0 - -5.0 ng/m ³ - 15° - 45° N -3.4 ng/m ³ - Europe -2.9 ng/m ³ - North America
Yim et al. (2015)	FSC 600 ppm	Ground SO ₄	37.6 ng/m ³ - Global 12.7 ng/m ³ - North America 7.0 ng/m ³ - Europe 20.0 ng/m ³ - Asia 55.5 ng/m ³ - Other

^a FSC = Fuel Sulphur Content.

^b The negative numbers indicate reductions in concentration over a base case of -600 ppm FSC.

