Climate Change Mitigation in the Aviation Industry: An Analysis of the Climate Impact Attributed to Aircraft in Flight to Enable Climate Optimization

Manon Garde

Student Number: 20785762

University of Waterloo

Master of Climate Change Internship Practicum Research Report

Supervisor: Professor David Zingg

University of Toronto Institute for Aerospace Studies

Wednesday, August 31, 2022

Table of Contents

List of Abbreviations & Chemical Formulae

Abbreviations	Meaning
AGWP	Absolute Global Warming Potential
AIC	Aviation-Induced Cloudiness
CCA	Climate-Charged Airspace
ERF	Effective Radiative Forcing
EPR	Engine Pressure Ratio
FAA	Federal Aviation Administration
ft	Feet
GHG	Greenhouse Gas
GPS	Global Positioning System
GTP	Global Temperature Change Potential
GTP_P (or PGTP)	Global Temperature Change Potential for a pulse emission
GTP_S (or SGTP)	Global Temperature Change Potential for a sustained emission change
GWP	Global Warming Potential
HO_X	Hydroxyl Radicals
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISSR	Ice-Supersaturated Region
km	Kilometers
LASR	Large Aircraft for Short-Range
LUC	Land-Use Change
nm	Nanometres
NO_X	Nitrogen Oxides
PMO	Primary Mode Ozone
ppm	Parts Per Million
redox	Oxidation-Reduction Reaction
RF	Radiative Forcing
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
SMR-CCS	Steam Methane Reforming with Carbon Capture and Storage
SWV	Stratospheric Water Vapour

Chemical Formulae	Meaning
$C_{(s)}$	Black or Elemental Carbon
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CH_3^-	Methanide
CH_4	Methane
H_2	Hydrogen
$H_2O_{(g)}$	Water Vapour
H_2SO_4	Sulphuric Acid
$O_{2(g)}$	Oxygen Gas
O_3	Ozone
$O(^3P)$	Atomic Oxygen
OH	Hydroxide
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
SO_2	Sulphur Dioxide
SO_3	Sulphur Trioxide
SO_4^{2-}	Sulphate

Abstract

Ever since the maiden flight of the Wright Flyer in 1903, powered aircraft have been contributing to anthropogenic climate change through the emission of gaseous and particle species into the atmosphere. The global aviation industry is responsible for a considerable portion of historical and present carbon dioxide and other species emissions from the operation of aircraft on the ground and in flight. Efforts to meaningfully reduce the emission of these climate forcing species, a term commonly used in the climate change community to delineate emissions that produce an imbalance in the Earth's energy system, are therefore vital to ensure the continued operation of this industry in accordance with international climate and sustainability targets. This report aims to compare the climate metrics currently in use to quantify short-lived climate forcing species relative to long-lived greenhouse gases (GHGs) relevant to aviation. This will enable a deeper understanding of the overall climate impact caused by these species and the compromises involved with mitigating them. Various alternatives to current technologies and practices will be described in order to reduce the climate impact of this industry and address any associated trade-offs.

1. Introduction

Up until the onset of the COVID-19 pandemic in early 2020, the aviation industry supported 87.7 million jobs around the world (of which 11.3 million were directly employed) and supported $3.5 trillion in global economic activity (Oxford Economics, 2021). Industry studies indicate that while air transport is responsible for less than 1% of the total goods shipped around the world by volume, for a total of 58 million tonnes of cargo transported in 2018, this comprises almost 35% by value (Industry High Level Group, 2019). Air connectivity is crucial to our modern globalized society as it enables worldwide travel with regular passenger transport and facilitates trade through timely cargo shipments (Asquith, 2020). Connectivity is also strongly linked with economic development, which is paramount to the economic vitality of remote communities and Small Island Developing States by creating job opportunities and sustaining the livelihoods of those in other related industries, such as tourism (Fageda et al., 2019; Uniting Aviation, 2017). According to Forbes magazine, if the aviation industry were a country, it would hypothetically place 20th in size by GDP (Asquith, 2020).

Revenue-passenger-kilometers (RPK), which are commonly used to measure air transport demand, is the product of the number of revenue-generating passengers on board an aircraft and the distance travelled per passenger (Rashad & Zingg, 2015). The pre-COVID-19 growth rate of the aviation industry in RPK was 5% annually, with global aviation – including international and domestic passenger-carrying flights – reaching 4.56 billion passengers carried in 2019 (International Civil Aviation Organization [ICAO], n.d.; Niklaß et al., 2021). This value does not distinguish individual passengers from repeat or frequent fliers, and studies have estimated that the actual portion of the world's population that flew commercially in 2018 is between 11 and 26% (Gössling & Humpe, 2020). The latest global pandemic provoked a sudden and dramatic disruption of global aviation that severely affected the daily operations and growth of this industry; however, the impacts of this public health crisis are expected to be largely temporary (Grewe et al., 2021).

While the services provided by the aviation industry are clearly vital to the day-to-day lives of billions of people, whether through travel, trade, or in supporting other industries, its climate impact is substantial and rising. In 2005, it was estimated that the overall anthropogenic warming attributed to the aviation industry (including aircraft-induced cirrus clouds) was 4.9%, within an uncertainty range of 2 to 14% (Lee et al., 2009). Despite advancements in aircraft fuel efficiency of 1 to 2% each year, carbon dioxide (CO_2) emissions have risen by 130% since 1990 due to the rising demand for air travel and were persistently climbing up until the disturbance of the COVID-19 pandemic (Niklaß et al., 2021). As of 2018, CO_2 emissions from the aviation industry constituted approximately 2.4% of the global anthropogenic total (including land-use change) (Lee et al., 2021). This proportion is anticipated to rise relative to other sources, given the industry's predicted business-as-usual expansion while other industries decarbonize (Grewe et al., 2021). Moreover, of this 4.9% share of the global climate impact, between half and three quarters of this warming is caused by non-CO_2 climate forcing species, which is often underestimated, thereby misrepresenting the true extent of this industry's impact (Niklaß et al., 2021).

Carbon sequestration and carbon offsetting programs are expected to comprise approximately 19% of the International Air Transport Association's (IATA) plan for net-zero carbon emissions by 2050 through the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (IATA, 2021). This will hopefully assist in stabilizing aviation carbon emissions, but the effectiveness of carbon capture and offsets in meaningfully addressing the climate impact from the aviation industry is unclear at this time and these strategies will not be examined in this report. Furthermore, decarbonizing aviation practices will be insufficient to reduce the overall climate impact of this industry, and non-CO_2 emissions must be addressed and mitigated as well. Current market-based mechanisms that address climate forcing emissions, such as carbon pricing and emissions trading systems, are not targeted towards non-CO_2 emissions and will also not be discussed in this report (Rashad & Zingg, 2015). Given that some emissions tend to be excluded from consideration in many climate change mitigation approaches, a re-evaluation of more appropriate strategies is required.

This report will first describe the contribution of the aviation industry to anthropogenic climate change, specifically characterizing the climate forcing species emitted by aircraft in flight and their influence on the local atmosphere and the global energy balance. A detailed comparison of the climate metrics that can be used to quantify the impact of these emissions will then be conducted, with a careful consideration of the merits of each when evaluating both short-lived climate forcing species and long-lived GHGs. A key priority of this report is to establish the most appropriate use of metrics for evaluating aircraft emissions in order to develop effective climate change mitigation strategies for aviation. Through the recommendation of various climate-optimized operational adjustments, alternative fuels, and technologies, this report aims to better inform aircraft design and industry practices to reduce the overall climate impact associated with commercial flight. It will conclude with a brief discussion of considerations into policy and industry dynamics, as well as several recommendations areas for further inquiry.

2. Climate Forcing Species Emitted by Aircraft in Flight

This Section will evaluate the climate forcing species emitted by aircraft in flight and their influence on the Earth's climate in order to achieve a sufficient understanding of the overall climate impact of the aviation industry. With a central focus on the effect of these emissions at altitude, informed mitigation strategies can be devised to address these impacts more precisely. Emissions from aircraft propulsion systems, whether gas-turbine or reciprocating piston engines, consist of approximately 70% CO_2, less than 30% water vapour, and less than 1% each of nitrogen oxides, particulate matter, sulphur oxides, carbon monoxide, and volatile organic compounds by mass (Federal Aviation Administration [FAA], 2005). Most of these species are primarily emitted at altitude, with only an average of 10% being released near the ground during the taxi, take-off, and landing phases of flight (FAA, 2005). While CO_2 evidently comprises a major proportion of aircraft emissions, studies indicate that the total climate impact of the aviation industry is as much as three times greater than the impact of CO_2 emissions alone (Lee et al., 2021).

Additionally, unlike CO_2, many non-CO_2 species emitted by aircraft at altitude produce regionally specific effects due to their shorter perturbation lifetimes in the atmosphere. As a result of the uneven global geographic distribution of air traffic, with flights predominantly taking place in mid-latitude regions of the Northern Hemisphere, net positive climate forcing (i.e., warming) is greatest over North America, Europe, and the North Atlantic Ocean (Köhler et al., 2013; Lund et al., 2017). Many of the impacts arising from the emission of these species are proportional to fuel burn. The division of fuel consumption by subsector is displayed in Figure 1, which was adapted from Gössling and Humpe (2020). Although there is significant uncertainty associated with military and private aviation due to a lack of available data, commercial passenger transport clearly accounts for the largest share of fuel use in aviation (Gössling & Humpe, 2020).

2.1 Carbon Dioxide

CO_2 is a long-lived GHG, with a highly contested atmospheric lifetime of approximately two hundred to as much as two thousand years (Archer et al., 2009). It is difficult to assign an exact lifetime to CO_2 owing to the substantial variation in natural carbon uptake processes and rates (Inman, 2008). This long lifetime allows for sufficient atmospheric mixing such that the ensuing climate impacts are independent of the perturbation location, altitude, and season, and this gas does not result in regionally specific consequences. Hence, aircraft CO_2 emissions can be treated identically to any other source of CO_2, as an emission at ground level will produce the same outcome as an emission at cruise altitude (Stevenson & Derwent, 2009). CO_2 is emitted as a product of the complete combustion of petroleum-based hydrocarbon fuels, including jet fuel (i.e., kerosene, also known as Jet A-1) and aviation gasoline (i.e., avgas) used to drive gas-turbine and piston engines, respectively (Kurniawan & Khardi, 2011). The complete combustion reaction that takes place in an aircraft's engine is represented by the following equation, whereby the carbon in the fuel reacts with atmospheric oxygen gas to produce CO_2 gas: $C_XH_{Y(l)} + O_{2(g)} \rightarrow CO_{2(g)} + H_2O_{(g)}$ (Kurniawan & Khardi, 2011). The emission index for CO_2 is 3.16 kg/kg of fuel, meaning that for every kilogram of kerosene that is burned, 3.16 kilograms of CO_2 is emitted into the atmosphere (Proesmans & Vos, 2021). A cumulative total of 32.6 billion tonnes of CO_2 have been emitted by aircraft between 1940 and 2018 (Lee et al., 2021).

2.2 Nitrogen Oxides

Nitrogen oxides, commonly referred to as NO_X (including NO and NO_2), are emitted from jet engines during combustion as a result of the synthesis of atmospheric nitrogen and oxygen gas under high temperatures and pressures in the combustor (Kurniawan & Khardi, 2011). While some natural sources of NO_X are known to exist, such as lightning, wildfires, and bacterial reactions in soils, anthropogenic practices are primarily responsible for the atmospheric abundance of these species (Blaszczak, 1999). Once emitted by an aircraft into the atmosphere at cruise altitudes, NO_X are responsible for initially increasing the rate of production of short-lived ozone, as well as gradually reducing the lifetime of methane (Dessens et al., 2014). These species are both potent GHGs, and as such, NO_X emissions serve as indirect climate forcing species due to their ability to chemically modify the atmospheric concentration of these GHGs (Köhler et al., 2008). NO_X have an increased lifetime at altitude, and with roughly 60% of aircraft emissions of this species occurring between 9 and 12 km above ground level, their

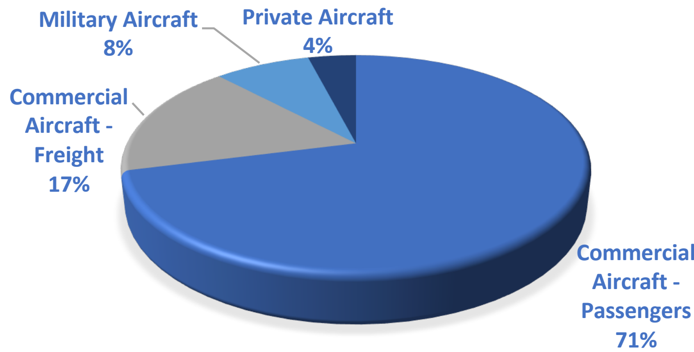

Figure 1: Global Distribution of Fuel Consumption within the Aviation Sector (Gössling & Humpe, 2020)

impacts tend to be more significant here than near the Earth's surface (Dessens et al., 2014; Lee et al., 2010).

The climate impact resulting from a pulse emission of NO_X is net positive, including both warming and cooling terms. The associated temperature response is greatest within a year of its emission and subsequently decreases over time to produce a net negative forcing approximately 15 years after the initial perturbation and eventually disperses completely after 60 years (Skowron et al., 2021). Unlike CO_2, the lifetime and climate impact of NO_X is dependent on the latitude and altitude at which these species are emitted (Dessens et al., 2014; Skowron et al., 2021). Regionally specific impacts occur along flight routes, where NO_X concentrations of 30 to 40% greater than ambient conditions can be found (Lee et al., 2010). The magnitude of the climate forcing is also contingent on the background NO_X setting, whereby short-lived ozone generation dominates in high NO_X environments (Freeman et al., 2018). The emission index for NO_X is variable, owing to the influence of atmospheric conditions and engine configuration (i.e., combustor inlet temperature, engine pressure ratio (EPR), etc.) on aircraft NO_X emissions; however, it has been estimated to be approximately 14 g/kg of fuel (Lee et al., 2010; Proesmans & Vos, 2021).

2.2.1 Short-Lived Ozone

NO_X emissions from aircraft at altitude promote chemical reactions and atmospheric processes which result in the formation of ozone (O_3) (Niklaß et al., 2021), among other relevant outcomes which will be discussed in Section 2.2.2. At altitudes between 8 and 12 km above ground, short-lived ozone production efficiency is four times greater than it is near the Earth's surface and its radiative efficiency (or potency) increases with altitude as well (Dessens et al., 2014; Skowron et al., 2021). Short-lived ozone is estimated by various authors to decay within the time frame of approximately one to three months, thereby producing an important yet short-term positive climate forcing component (Azar & Johansson, 2012; Fuglestvedt et al., 2010). In the upper troposphere and lower stratosphere, precursors for short-lived ozone formation include methane, carbon monoxide, and other hydrocarbons, which react with oxygen gas to produce hydroxyl radicals (HO_X) (Grewe et al., 2019; Lee et al., 2010).

When nitric oxide (NO) is emitted by an aircraft, it is rapidly oxidized through an oxidation-reduction (redox) reaction with HO_2 present in the surrounding atmosphere to produce nitrogen dioxide (NO_2) and hydroxide (OH) via the following chemical reaction: $HO_2 + NO \rightarrow OH + NO_2$ (Lee et al., 2010; Matsumoto et al., 2006; Zhang et al., 2004). NO_2 then undergoes a decomposition reaction called photolysis, which is driven by either solar or radiant energy, resulting in direct or indirect photolysis, respectively (Speight, 2017). This causes the bonds in the NO_2 molecule to break, thereby producing atomic oxygen ($O(^3P)$) and NO through the following reaction: $NO_2 \xrightarrow{hv} O(^3P) + NO$ (Lee et al., 2010). Here, Planck's constant ($h = 6.626 \times 10^{-34}$ J · s) is multiplied by the wavelength (v in Hz) to give the total energy of a single photon, which enables the reaction. Subsequently, the atomic oxygen reacts with atmospheric oxygen gas ($O_{2(g)}$) to form ozone, as depicted in the following reaction: $O(^3P) + O_2 + M \rightarrow O_3 + M$, where M is any additional species present in the reaction that utilizes any surplus energy (Lee et al., 2010).

Ozone is continuously produced and photolyzed through natural formation and loss cycles until a photostationary state (also known as photochemical equilibrium) is reached (Matsumoto et al., 2006). However, aircraft NO_X emissions lead to an enhanced rate of the reaction pathways that produce short-lived ozone, thereby increasing ozone generation beyond that which natural processes can account for (Lee et al., 2010). The climate impact of short-lived ozone therefore involves a positive forcing component, which is the net outcome of natural ozone cycles and the anthropogenic aircraft-induced rise in ozone production (Gilmore et al., 2013). Owing to the greater levels of incident solar radiation present at the equator, this aircraft-induced short-lived ozone generation is most prevalent at this latitude (Lee et al., 2010). However, as much as half of the climate impact from ozone forcing is estimated to be offset by longer-term negative forcing impacts of NO_X emissions (Lee et al., 2010).

2.2.2 Methane & Long-Lived Ozone

The positive forcing resulting from the production of short-lived ozone following the emission of NO_X in flight is coupled with a negative forcing caused by atmospheric methane (CH_4) degradation and an associated decline in long-lived or primary mode ozone (PMO) formation and stratospheric water vapour (SWV) (Azar & Johansson, 2012; Köhler et al., 2008). These prolonged atmospheric changes will unfold over the course of approximately a decade (Dessens et al., 2014). Photolysis of short-lived ozone, which takes place via the following reaction: $O_3 \xrightarrow{hv} O(^3P) + O_2$, naturally accompanies its enhanced production outlined in Section 2.2.1 (Lee et al., 2010). As a result, the formation of hydroxyl radicals in favour of hydroxide will ensue in accordance with the following reaction: $O_3 + HO_2 \rightarrow 2O_2 + OH$ (Lee et al., 2010; Niklaß et al., 2021). Hydroxide supports the oxidation of hydrocarbons, which allows methane to be oxidized more efficiently into its conjugate acid methanide (CH_3^-), thereby reducing the atmospheric lifetime of this GHG by 3% (Gilmore et al., 2013; Köhler et al., 2008; Lee et al., 2010). This redox reaction proceeds via the following reaction: $CH_4 + OH \rightarrow CH_3 + H_2O$ (Lee et al., 2010).

Given that methane is a key ozone precursor in the troposphere, an additional outcome of this reduction in methane lifetime is a long-term depletion of background PMO (Grewe et al., 2019). Methane oxidation is also an important source of SWV, and another less significant but nevertheless notable impact of NO_X emissions is the decline in SWV levels over time due to the reduced concentration of methane in the stratosphere (Myhre et al., 2007). This impact produces a slight negative forcing component as well, since water vapour is a GHG (Lee et al., 2021). The decreases in methane lifetime, long-lived ozone production, and SWV each result in a cooling component; however, this term does not fully compensate for the warming term from short-lived ozone, and the net forcing from NO_X emissions is therefore positive (Lee et al., 2021).

2.3 Contrails & Contrail Cirrus

Contrails (i.e., condensation trails), also known as vapour trails, are line-shaped clouds composed of ice crystals that form in the wake of jet engines (Intergovernmental Panel on Climate Change [IPCC], 1999). This occurs as a result of the mixing of hot and moist exhaust air with cool and humid ambient air, which becomes saturated with respect to liquid water (Deuber et al., 2013; Lee et al., 2010). Water droplets will then form, freeze, and persist in the structure of a contrail if the surrounding atmosphere is saturated with respect to ice (Grewe et al., 2019). Contrail formation is stimulated by the emission of water vapour during combustion in an aircraft engine, which must take place within suitable atmospheric conditions dictated by the Schmidt-Appleman criterion (Fuglestvedt et al., 2010; Lee et al., 2010). Persistent contrails, or those which persevere in the atmosphere for longer than a few minutes following their formation, can be found in ice-supersaturated regions (ISSRs) where ambient temperatures are below 235 K (-38°C) and relative humidity is greater than approximately 42% (Irvine et al., 2014; Narciso & de Sousa, 2021; Proesmans & Vos, 2021). These conditions tend to be most prevalent at high altitudes near the upper troposphere, since the frequency of ISSRs increases with altitude up to the tropopause, hence the probability of contrail formation and persistence is reduced at lower altitudes (IPCC, 1999; Irvine et al., 2012).

This formation process is also contingent on certain engine characteristics, including propulsive efficiency, and fuel specifications, such as the water vapour and particulate matter emission indices (Grewe et al., 2019). The greater an engine's propulsion efficiency, the smaller the ratio of temperature rise over moisture rise in the exhaust plume and the broader the range of conditions favourable for contrail formation (Schumann, 2000). This correlation allows contrails to form at greater ambient temperatures and therefore over a wider array of altitudes (i.e., lower than usual in the troposphere and higher in the stratosphere), meaning that aircraft are more prone to produce them in flight (Schumann, 2000). Furthermore, contrail formation is also aided substantially by the emission of aerosols (i.e., soot and sulphates), which provide a surface for condensation to occur and can also alter the contrail characteristics (Grewe et al., 2019; Kärcher, 2018). At cruise altitudes, the combustion by-product black carbon (also known as elemental carbon), which is a primary component of soot, and sulphate particles serve as effective condensation nuclei that seed contrail formation (Kärcher, 2018; Lee et al., 2010; Teoh et al., 2020). There is an approximately linear relationship between the magnitude of soot particles emitted during combustion and the number of ice crystals that constitute a contrail (Lee et al., 2010; Narciso & de Sousa, 2021). Soot and other aerosols and precursors will be further discussed in Section 2.4. Conditions suitable for contrail formation and persistence in the atmosphere are known to be less common in the tropics than the extratropics owing to the warmer cruise altitude temperatures that are not conducive for ice supersaturation (Lund et al., 2017). However, should contrails form in tropical regions, the optical depth and subsequent climate impact will be greater due to the abundance of atmospheric moisture (Lund et al., 2017).

Once formation is complete, contrails can grow to be 1 to 10 km in length (Irvine et al., 2014). Their size is influenced by the particle density and characteristics within the contrail, which increases along with the associated climate impacts with age until a maximum size and forcing is achieved within several hours (Azar & Johansson, 2012; Narciso & de Sousa, 2021). When contrails propagate into non-linear formations, they transition into contrail cirrus clouds, which are also referred to as aviation-induced cloudiness (AIC) (Lee et al., 2010). Contrails produce the shortest-lived climate forcing component relevant to aviation, with an average lifetime of just one hour, but may persist as much as 18 to 24 hours as contrail cirrus (Irvine et al., 2014; Teoh et al., 2020). Contrail persistence is determined by the level of ice saturation in the ambient atmosphere, whereby flights through areas that are not supersaturated with ice may still produce contrails, but these will dissipate through sublimation along with the wingtip vortices produced in the aircraft's wake within a matter of minutes, yielding a negligeable climate impact (Kärcher, 2018; Rashad & Zingg, 2015; Teoh et al., 2020). Accordingly, this forcing component can be essentially eliminated by avoiding flight through regions associated with persistent contrail formation through altitude and route adjustments. The introduction of these aircraft-induced clouds into the atmosphere may cause the local cloudiness to rise by a factor of 1.8, and in areas of high air traffic congestion, contrail cirrus may amass into cirrostratus layers as large as 100,000 square kilometers (Irvine et al., 2014; Kärcher, 2018).

Like other naturally occurring clouds, contrails and contrail cirrus contribute to the global energy balance by reflecting incoming solar radiation away from the surface as well as absorbing outgoing longwave radiation from the Earth and the atmosphere and re-releasing it back down to the surface (Azar & Johansson, 2012; Grewe et al., 2021). However, unlike natural clouds, this additional anthropogenic cloudiness is not a part of the Earth's natural water cycle and results in an energy imbalance, thereby producing a short-term net warming effect which is determined by the sum of the resulting day and night forcing (Kärcher, 2018; Lee et al., 2021). The extent of this ensuing climate impact depends on a contrail's coverage, optical depth, and properties, the temperature and albedo of the ground below, present meteorological conditions, as well as the diurnal and seasonal cycle at the time of formation (Azar & Johansson, 2012; Teoh et al., 2020). At night, the climate impact of contrails is most severe because the inbound solar radiation ceases, meaning that the negative forcing (or cooling) term is eliminated, and the warming effects will be strongest at this time (Azar & Johansson, 2012). A similar effect can be observed in winter, when there is less solar irradiance and the cooling benefits from contrails are consequently reduced (Azar & Johansson, 2012). Furthermore, their impacts are also highly regionally specific, with the greatest climate forcing occurring in airspaces with significant air traffic density (Matthes et al., 2021). Nevertheless, contrail cirrus clouds can be carried by various transport mechanisms, such as wind shear or turbulence, as much as 100 km from their location of formation (Kärcher, 2018).

Despite dissipating more rapidly than any other species discussed in this Section, AIC produce the greatest climate forcing over short timescales. Moreover, in certain geographic areas, their impacts can persist to approximately 15% of the forcing attributed to CO_2 as much as a century later (Lund et al., 2017). Of each of the climate forcing species relevant to aviation, contrails are undoubtedly associated with the greatest uncertainty, and they are therefore often excluded from considerations and calculations of the overall climate impact of the aviation industry. This lack of confidence in the exact impact of contrails has led to hesitation in prioritizing their mitigation and generally unambitious approaches to reducing contrail and AIC formation. Limited observational data for contrail cirrus currently exists, owing to the challenging nature of differentiating anthropogenic and naturally occurring cirrus clouds following their formation, and the climate impact of contrails produced within other natural cloud formations has been minimally examined (Kärcher, 2018; Matthes et al., 2021).

2.4 Aerosols & Aerosol Precursors

Aerosols and precursors for aerosols are solid particles and gaseous species that are emitted by aircraft in flight primarily as a result of the combustion of jet fuel (Lee et al., 2010). These species are composed of primary aerosols, which are directly emitted by the aircraft's engine, and secondary aerosols, which are formed by gaseous aerosol precursors within the exhaust plume through nucleation and condensation processes (Ervens et al., 2011). The emitted species can be found along aircraft flight routes and consist principally of particulate matter, including black carbon and organic carbon, sulphur oxides, water vapour, and chemi-ions (Lee et al., 2010; Lee et al., 2021). These emissions produce regionally specific direct positive and negative climate forcing impacts, as well as indirect impacts on the surrounding atmospheric chemistry and microphysical cloud characteristics (Dessens et al., 2014).

Carbonaceous aerosols contribute to the positive climate forcing from aviation, and of key relevance to this analysis is the emission of particulate matter at altitude through the combustion of fossil-derived jet fuel. With a pulse emission lifetime of 7.4 days, black carbon ($C_{(s)}$) is produced during the incomplete combustion of any hydrocarbon fuel via the following reaction: $C_XH_{Y(l)} + O_{2(g)} \rightarrow CO_{2(g)} + H_2O_{(g)} + CO_{(g)} + C_{(s)}$ (Fuglestvedt et al., 2010; Kurniawan & Khardi, 2011). Organic carbon is also emitted into the exhaust plume and has a pulse emission lifetime of 7.6 days (Fuglestvedt et al., 2010). Together, black and organic carbon comprise soot, which is a non-volatile aerosol produced through the condensation of unburnt aromatic compounds in the combustion chamber (Lee et al., 2021). The emission index of soot is approximately 0.025 g/kg of fuel, or 2×10^{14} particles/kg of fuel, but this is magnitude is variable with engine operating parameters (Lee et al., 2010; Schwartz Dallara et al., 2011). Particle size, which depends on both the engine power as well as the fuel type, tends to span roughly 30 to 60 nm across, but they may accumulate to form clusters as large as 100 to 500 nm (Lee et al., 2010; Narciso & de Sousa, 2021). The climate impact of soot aerosols is net positive due to their capacity to absorb short-wave radiation, resulting in a warming component (Lee et al., 2021).

While the climate forcing from soot aerosols is arguably small when compared to other aviation-related sources, comprising a mere 5% of the total forcing from the industry, the more severe impact is their tendency to influence contrail characteristics, as previously described in Section 2.3, which is inherently difficult to quantify (Grewe et al., 2019; Schwartz Dallara et al., 2011).

Volatile sulphur-containing species also comprise a significant portion of the aircraft aerosols and precursor emissions. Sulphur oxides, predominantly consisting of sulphur dioxide (SO_2), are released during combustion when fractional amounts of sulphur present in kerosene (as well as all hydrocarbon fuels) are oxidized by atmospheric oxygen (Kurniawan & Khardi, 2011; Lee et al., 2021). The perturbation lifetime of a pulse emission of SO_2 is no more than 4 days and it has an emission index of 1.2 g/kg of fuel with a sulphur content of 600 ppm (Fuglestvedt et al., 2010; Lee et al., 2021). Upon its release, this gas rapidly oxidizes in the presence of the hydroxyl radical OH and a catalyst to produce sulphur trioxide (SO_3) via these reaction pathways: $SO_2 + OH + M \rightarrow HSO_3 + M$ and $HSO_3 + O_2 \rightarrow SO_3 + HO_2$ (Brown et al., 1996; Dessens et al., 2014). SO_3 is a precursor for sulphuric acid (H_2SO_4), which is then formed through the following reaction: $SO_3 + H_2O \rightarrow H_2SO_4$ (Brown et al., 1996).

Gas-phase sulphuric acid is known to be an important precursor of anthropogenic sulphate (SO_4^{2-}) aerosols in the troposphere (Dessens et al., 2014). Sulphate particles can form through a gas-to-particle transformation undergone by H_2SO_4 called homogenous nucleation, or using existing nuclei called heterogenous nucleation (Tilmes & Mills, 2014). Through the condensation of H_2SO_4 gas and the coagulation of particles, sulphate aerosols can combine with one another to grow to sizes greater than 1000 nm in diameter (Tilmes & Mills, 2014). In addition to their influence on contrail formation and properties, sulphate aerosols are adept at scattering inbound short-wave radiation, thereby increasing the global albedo (i.e., the ratio of the solar radiation that is reflected away from the Earth to the total insolation) (Lee et al., 2010; Tilmes & Mills, 2014). This stimulates tropospheric and surface cooling and provides the only substantial negative forcing component to the net climate forcing attributed to aerosols (Lee et al., 2021; Tilmes & Mills, 2014). The emission indices of SO_2, H_2SO_4, and SO_4^{2-} are approximately 0.8 g/kg, 0.04 g/kg, and 0.04 g/kg of fuel, respectively (Lee et al., 2010; Proesmans & Vos, 2021). The nature of these sulphur species emissions is determined by the composition of the fuel in use (Dessens et al., 2014).

As previously mentioned, water vapour ($H_2O_{(g)}$) is one of the main products of combustion within an aircraft engine, where the hydrogen in the fuel undergoes a synthesis reaction with atmospheric oxygen, with an emission index of 1.231 kg/kg of fuel (Kurniawan & Khardi, 2011; Lee et al., 2021). While water vapour itself is considered a volatile aerosol precursor and a strong GHG, its main contribution to climate forcing in this context is in stimulating the formation of contrails (Grewe et al., 2019). Since the atmospheric lifetime of water vapour is a function of pressure – with the greatest pressure resulting in the lowest lifetime – the climate impact of such emissions at altitudes less than 6 km (or roughly 19,700 ft) above ground are assumed to be negligible. However, at cruise altitudes (particularly within the stratosphere), the accumulation per unit of H_2O emitted during combustion and resultant contribution to climate forcing will be larger (Fuglestvedt et al., 2010). As such, the climate impact of supersonic jets is predominantly from water vapour, given that they travel primarily through the stratosphere during cruise (Lee et al., 2010).

Furthermore, chemi-ion gases are produced during combustion through chemical reactions among radicals, which serve as volatile aerosol precursors in the exhaust plume. Chemi-ions stimulate the development of H_2SO_4 and H_2O aerosols through various pathways, including the electrostatic aggregation of molecules, and may activate particulate matter aerosols as well (IPCC, 1999; Lee et al., 2010). Each of the aerosol and aerosol precursor species described in this section are distributed and dissipated through atmospheric circulation pathways, such as Hadley cell circulation (Lee et al., 2010). Their tropospheric residence time is determined by the relevant transportation mechanisms, competing chemical removal processes, seasonal cycles, as well as the local dry and wet deposition rates (Lee et al., 2010).

2.5 Other

Carbon monoxide (CO) and volatile organic compounds known as hydrocarbons are also emitted as a product of incomplete combustion, with emissions indices of approximately 3 g/kg and 0.4 g/kg, respectively (Kurniawan & Khardi, 2011; Lee et al., 2010). Their emission is largest at low engine power settings and is contingent on the combustion properties of the fuel in use (Dessens et al., 2014; Kurniawan & Khardi, 2011). Contrary to most other emitted species under consideration in this report, a smaller proportion of CO and hydrocarbon emissions occur at altitude, with 30% of these emissions occurring near the surface (FAA, 2005). Similar to the effect of NO_X at ground level, these species are of greater concern for local air quality and human health considerations in the areas surrounding airports than for climate impacts (Lee et al., 2010), and will not be further investigated in this report.

3. Climate Metrics

A climate metric is a mechanism used to evaluate the impacts of different climate forcing species on a common scale (Fuglestvedt et al., 2010). Metrics are vital components in effectively navigating and addressing the trade-offs associated with mitigating emissions of varying lifetimes. Those considered in this report consist of physical metrics including Radiative Forcing, Global Warming Potential, and Global Temperature Change Potential. Selection among these metric options depends heavily on the purpose for the comparison, which guides the choice of timeline and the outcome that is prioritized (Fuglestvedt et al., 2010). There are also numerous considerations for timescale selection that must be addressed, whereby the length of the time horizon determines the course of action for confronting the climate impact. Longer time horizons, for example, can encourage systemic changes towards lasting sustainability within the industry rather than merely achieving climate targets, but this brings into question broader considerations of emissions accountability and intergenerational climate justice (Niklaß et al., 2021). The nature of a climate policy, treaty, or regulation being developed may also have an important influence on the selection criteria. For instance, metrics chosen in accordance with the Paris Agreement's aim to limit global temperature rise to a maximum of 2°C beyond pre-industrial levels by 2050 must take temperature change into account to allow for climate stabilization (Dessens et al., 2014). However, the strictness of this timeline may result in disregard for any persisting climate impact in the decades to follow this target year, and there are consequently many necessary considerations involved in determining the most suitable metric for the task at hand.

3.1 Radiative Forcing

Radiative Forcing (RF or ΔF in $mW \cdot m^{-2}$) is a measure of the immediate energy imbalance resulting from the emission of GHGs and climate forcing species from anthropogenic and/or natural sources per unit area, which can be taken locally or globally (Andrews et al., 2021; Teoh et al., 2020). This is an instantaneous and backward-looking metric that represents the difference in net inbound short-wave solar radiation and outbound long-wave terrestrial radiation (Dessens et al., 2014; Lee et al., 2021). It can be determined by calculating the change in the atmospheric concentration of these species at the top-of-the-atmosphere at two distinct points in time, often taken as the overall impact of current emissions relative to pre-industrial times (Fuglestvedt et al., 2010; Lee et al., 2021). A positive RF value indicates net warming, whereas a negative value indicates net cooling (Agarwal, 2009).

There is a linear relationship between the global average RF and mean surface temperature response that serves as an indicator of the estimated equilibrium temperature following a climate forcing perturbation; however, this correlation is only relevant when RF is constant with respect to time (Lee et al., 2010). RF can also be represented as Effective Radiative Forcing (ERF), which is a similar evaluation of the energy imbalance resulting from such an emission but is generally accepted to be a more useful metric than RF due to its inclusion of climate responses that are independent of surface warming (Andrews et al., 2021; Lee et al., 2021). ERF is taken following a period where atmospheric temperatures, moisture levels, and cloudiness are permitted to adapt to the impacts of this climate forcing species, while surface conditions (i.e., land and sea surface temperatures) remain unchanged (Andrews et al., 2021).

As a climate metric, RF is robust and commonly used by the scientific community, but it has several limitations which may reduce its effectiveness in quantifying the climate impact from aviation (Lee et al., 2010). As a result of a methodological disagreement in the literature, significant discrepancies in RF data values for NO_X exist. Grewe et al. (2019) observe that simplifications in RF calculations concerning methane and short-lived ozone have led to flawed results that underestimate the overall impact of NO_X emissions by aircraft. These authors believe that inconsistencies have partly arisen from the assumption that fluctuations in methane lifetime and concentration resulting from NO_X influences occur in steady state conditions, where these changes really occur as a temporary response to a NO_X perturbation (Grewe et al., 2019). When calculated as such, the extent of the negative forcing from the decrease in methane lifetime is reduced by 35%, meaning that the net RF from NO_X is a greater positive value overall (Grewe et al., 2019). Additionally, assuming a linear relation between NO_X emissions and the atmospheric concentration of short-lived ozone has also been deemed a flawed method, as this association is distinctly nonlinear. This produces results for ozone RF that are almost half as large as would be expected using a purportedly more suitable nonlinear approach (Grewe et al., 2019). Consequently, the reported contribution of aircraft NO_X to the aviation industry's overall climate impact varies in magnitude in the literature on the order of 6 to 7 times (Grewe et al., 2019). An undervalued approximation of the contribution of NO_X to the net aviation RF has the potential to lead to misguided mitigation measures that overemphasize the contribution of CO_2 and contrail impacts. This issue must therefore be further investigated and considered going forward when implementing industry sustainability measures.

In addition to these inconsistencies, a key issue with RF as a metric is that it neglects any consideration of the timescales of the global mean surface temperature response associated with gradual thermal absorption by the oceans, thereby disregarding any lasting impacts of short-lived climate forcing species following the termination of their emission (Lee et al., 2010). Additionally, given that RF is only able to characterize impacts at a specific moment in time, it is known to underrepresent the total lifetime impacts from historical emissions (Lee et al., 2010; Schwartz Dallara et al., 2011). It also fails to provide an appropriate estimation of the future impacts of present-day emissions as a result of the varying lifetimes of the species under consideration (Köhler et al., 2013). Finally, RF poorly represents the relative significance of short- and long-lived climate forcing species, since emissions of the former may have been released within the past several weeks, whereas the latter could be from the preceding decades or centuries (Agarwal, 2009; Fuglestvedt et al., 2010). Time integration can assist in gaining a more accurate understanding of the overall lifetime impacts of the species under consideration by eliminating some of these issues (Schwartz Dallara et al., 2011).

3.2 Global Warming Potential

Global Warming Potential (GWP) represents the time-integrated RF resulting from a single pulse emission of a particular gas over a designated time horizon – often taken to be 20, 50, or 100 years from the time of emission – relative to an emission of equal unit mass of CO_2 (Allen et al., 2016; Shine et al., 2005). This allows the climate impacts of various forcing species to be weighed against one another in order to ascertain the equivalence of different gaseous species and prioritize the actions required to mitigate them (Shine et al., 2005). The GWP of these species is typically expressed as a unitless ratio, where a positive sign indicates a positive climate forcing component, but it can also be conveyed as the Absolute Global Warming Potential (AGWP in $W \cdot m^{-2} \cdot kg^{-1} \cdot yr$) of a species when CO_2 is not considered (Fuglestvedt et al., 2010). Despite several limitations to its use, this metric is widely used by many international policymaking bodies and academics due to its straightforwardness and transparency (Shine et al., 2005). GWP has largely become the default for comparing emissions by the IPCC and the United Nations Framework Convention on Climate Change and has most notably been used in the Kyoto Protocol (Fuglestvedt et al., 2010).

An important shortcoming of this metric is that it tends to misrepresent the relative strength of the species under evaluation. For example, a potent but short-lived species could have an identical GWP value as a weaker long-lived species for the same pulse mass emitted; however, the temperature change resulting from these two emissions would be vary substantially at any given time (Shine et al., 2005). Consequently, it is difficult to determine the climate impact of each gas at a specific point in time, resulting in a lack of understanding regarding the relative importance of these species. GWP is also incapable of offering regionally specific data or responding to any deviations in the background atmosphere at the point of emission and it does not account for the surface temperature response associated with these emissions (Dessens et al., 2014; Shine et al., 2005). Lastly and perhaps most importantly, GWP is not intended to be used for quantifying very short-lived climate forcing species, such as short-lived ozone precursors and contrails, and therefore has limited applicability in measuring the non-CO_2 climate impacts of the aviation industry on its own (Shine et al., 2005).

3.3 Global Temperature Change Potential

Global Temperature Change Potential demonstrates the surface temperature change at a given time resulting from either a pulse emission (GTP_P or PGTP) or a sustained emission change (GTP_S or SGTP) of a climate forcing gas relative to an identical pulse emission of CO_2 (Shine et al., 2005). This is an endpoint metric (also known as a snapshot metric), meaning that the temperature response is taken for the final year in the time horizon instead of being integrated over time, which takes on more of a climate modelling approach than the other metrics described in this Section (Azar & Johansson, 2012; Dessens et al., 2014; Fuglestvedt et al., 2010). Like GWP, GTP is also usually expressed as a unitless ratio and is commonly evaluated at a specific instant 20, 50, or 100 years from either the time of the pulse emission or the initial introduction of the sustained emission, which assists in the comparison of these two metrics.

Pulse-based metrics, such as GWP or GTP_P, are beneficial in evaluating the net difference between various emission scenarios, particularly pertaining to time-varying emissions (Fuglestvedt et al., 2010; Lund et al., 2017). However, the usefulness of GTP_P is largely restricted to long-lived species because of the prompt decay period of the climate impacts associated with pulse emissions of short-lived species (Deuber et al., 2013; Shine et al., 2005). Conversely, GTP_S has been proven effective under a large variety of species lifetimes and it is also less sensitive to uncertainties than GTP_P (Shine et al., 2005). Additionally, while behaving similarly to GWP and GTP_P, GTP_S data is strictly based on physical science and it does not rely on potentially biased value judgements regarding timeline selection (Fuglestvedt et al., 2010). One drawback the GTP_S metric is that it presumes that all future emissions will be consistent with present day emissions (Fuglestvedt et al., 2010). Overall, of these two metrics, GTP_S is more favourable for use when quantifying the impacts of non-CO_2 species than GTP_P; however, this metric is not currently in use within climate policy and there is limited data available that quantifies emissions using this metric (Lee et al., 2021).

3.4 Metric Comparison & Selection

When examining the in-flight emissions associated with conventional aircraft, the comparison of short-lived emitted species with long-lived GHGs is of vital importance. A challenge associated with this comparison is that a pulse emission of a long-lived species may appear to be approximately equal to a sustained emission of a short-lived species; however, the true impacts imposed on the climate at any given time may be very different and difficult to relate (Allen et al., 2016). Moreover, the choice of metric and time horizon tends to favour certain emitted species, which may result in their prioritization over others when implementing climate change mitigation measures. Selecting an appropriate metric is therefore imperative to gaining a complete understanding of the overall climate impact attributed to the operation of aircraft and better inform aircraft design and operational practices. For each of the metrics under consideration in this Section, there is an inherent bias towards either long-lived GHGs or short-lived climate forcing species, which will be emphasized in the analysis. This is contingent on the applied time horizon, as short timescales result in the prioritization of short-lived species (being primarily NO_X and contrails) over others in mitigation discussions (Azar & Johansson, 2012). Simultaneously, since the effects of short-lived species become less pronounced over time, longer timescales can appear to suggest that there is little cause for mitigating these emissions (Deuber et al., 2013).

Similarly, metric selection itself may misdirect the relative priority of emitted species. Some metrics, such as GWP or GTP_P, tend to overstate the long-term cooling benefits associated with NO_X impacts, since the positive climate forcing resulting from short-lived ozone production will deteriorate quickly following a pulse emission, leaving only negative forcing (Deuber et al., 2013). Hence, the day-to-day influence of these species on the climate is understated and can seemingly encouraging a misguided increase in their emission to mitigate other emissions. Conversely, sustained emissions changes (as with GTP_S) are able to more realistically represent the climate impact from short-lived species because these emissions are more closely related to a change over time than a pulse release in practice (Lund et al., 2017). Thus, the impacts of non-CO_2 species will be represented as constant or rising slightly while the impacts of CO_2 will accumulate more gradually (Deuber et al., 2013). Overall, when RF or GWP are used to quantify the contribution of aviation to anthropogenic climate change, long-lived CO_2 will be favoured over shorter-lived non-CO_2 species, while non-CO_2 species will be represented with greater relative importance when GTP_S is used.

Of significance to aircraft design when selecting an appropriate metric are the implications on climate forcing species prioritization which determines the required operational and technological measures required to mitigate these impacts. This will guide aircraft design decisions related to wing dimensions and features, such as the wing area, thickness-to-chord ratio, aspect ratio, and level of sweepback, as well as engine characteristics and fuel type, including EPR and bypass ratio (Green, 2009; Proesmans & Vos, 2021). Generally, none of the metrics under consideration in this report provide a flawless approach for understanding and mitigating aircraft emissions effectively. RF is widely used in academia to measure the magnitude and sign of individual GHGs and climate forcing species, but limited comparisons can be drawn among different species. Likewise, while GWP is currently in use by many international climate policy frameworks, it has been criticized as being fundamentally incompatible with long-term climate targets (Collins et al., 2020). Owing to the extensive disadvantages associated with these current metrics, as discussed in Sections 3.1 and 3.2, they may prove to be less reliable and less applicable to aviation on their own. One advantage of RF over GTP_S is that it has a greater signal-to-noise ratio (i.e., the strength of a desired signal relative to any background interference), meaning that there is less uncertainty associated with this metric (Matthes et al., 2021). Added uncertainty is unquestionably a disadvantage for GTP_S, but this may prove to be a necessary trade-off to allow for increased relevance (Schwartz Dallara et al., 2011).

GWP and GTP have some common characteristics, with several key exceptions. These two metrics utilize similar data input values, and over timescales greater than a century, they have shown to provide results of similar magnitudes (Fuglestvedt et al., 2010; Shine et al., 2005). However, being related to global-mean surface temperature response resulting from the emission of a climate forcing species, GTP offers a new approach and a different conceptual understanding of the relative impacts of each species than traditional metrics (Fuglestvedt et al., 2010). It is being increasingly understood that GTP_S may be more appropriate metric than RF or GWP for industry decisions and policy discussions related to aviation as it is better equipped to handle the temperature response for multiple timescales (Shine et al., 2005). Accordingly, GTP_S may offer the most suitable method to represent the relative climate impact of short-lived species, and this more recent metric may prove to be increasingly valuable in aviation contexts. This report recommends the use of a weighted average of the values given by the GWP and GTP_S metrics to develop an accurate emissions equivalence factor that is specifically applicable to aviation. This averaging will account for the favouring of long-lived species by GWP and the uncertainty of GTP_S, thereby enabling the combined benefits of these metrics to provide more effective quantification of the overall contribution of each climate forcing species to aircraft-induced climate change. An advantage of this method is that different weightings can be applied to each term to evaluate the short- or long-term effects more precisely.

4. Climate Optimized Flight

4.1 Operational Measures

Due to the industry's primary focus on mitigating CO_2 emissions (rather than overall emissions), operational efficiencies – aggregated with infrastructure improvements – comprise just 3% of IATA's plan towards net-zero. However, climate change mitigation strategies involving adjustments to current operational measures have significant potential to play an important role in addressing non-CO_2 emissions. This can be approached by implementing universal measures to global aircraft fleets, applying precise interventions to specific flights, or a combination of the two. The strategies described in this Section are certainly not exhaustive, but they serve as examples of promising options that can be employed to improve operational efficiency beyond 3% of the industry's efforts.

4.1.1 Cruise Altitude & Mach Number Reductions

As previously discussed, non-CO_2 species emitted by aircraft tend to have elevated impacts when released at conventional cruise altitudes (between 30,000 and 40,000 ft) in comparison with emissions closer to the Earth's surface (Schwartz & Kroo, 2009). Accordingly, short-lived ozone production is generally less efficient at lower altitudes and the conditions suitable for contrail formation and associated climate forcing are also less prevalent due to the greater ambient temperatures and reduced abundance of ice crystals in the atmosphere (Kärcher, 2018; Proesmans & Vos, 2021). This relation is effectively demonstrated in Figure 2 using the GTP_S metric to assess the relative surface temperature change resulting from a sustained emission of various species in flight as they vary with altitude with respect to that imposed by CO_2, which remains constant. Cooling benefits from aircraft aerosol emissions have also been estimated to increase when flying at lower altitudes (Matthes et al., 2021). Additionally, the rate of NO_X formation during combustion rises with overall EPR, which is reduced at lower cruise altitudes due to the lower flame temperature during combustion (Agarwal, 2009). Therefore, one promising mitigation strategy for non-CO_2 emissions is to adjust aircraft flight levels through the implementation of cruise altitude reductions, where a small CO_2 trade-off will allow for the net climate forcing associated with these species to decrease (Matthes et al., 2021).

Modern aircraft design allows for flexibility in cruise flight level of as much as 3,000 ft; however, for any altitudes beyond this range, further aerodynamic changes in fleet design will be required (Teoh et al., 2020). When optimizing for climate, other relevant measures of effective flight operations are often rendered sub-optimal, such as fuel usage and direct operating costs (Proesmans & Vos, 2021). Flying at lower altitudes incurs a fuel penalty due to the increased parasite drag and reduced engine efficiency that accompanies the greater air density at lower flight levels, which causes the CO_2 emissions to rise slightly (Schwartz & Kroo, 2009). Measures proposed by Matthes et al. (2021) reveal that lowering the average cruise altitude by 2,000 ft below a fuel-optimized 2006 reference case would be accompanied by a rise in fuel consumption and associated CO_2 emissions of just 1%, but this penalty will increase with more ambitious altitude reductions. Furthermore, to achieve a more favourable lift-to-drag ratio at lower altitudes, a reduced Mach number – being the aircraft's true airspeed relative to the local speed of sound – is also necessary, meaning longer flight times for the same distance travelled (Proesmans & Vos, 2021).

By designing aircraft to operate in regions of the atmosphere where the climate forcing from NO_X emissions is less severe and/or where the temperature and humidity are unsuitable for contrail formation, the climate impact associated with cruise flight can be reduced (Fichter et al., 2005). While these atmospheric conditions do not always coincide, it is generally agreed that flying lower than the current average cruise altitudes will address both impacts and reduce the imposed climate forcing. A study conducted by Schwartz & Kroo (2009) concluded that the global mean temperature response in terms of GTP_S for a 100-year time horizon attributed to these non-CO_2 species can be reduced by half when aircraft are operated at 25,000 ft at Mach 0.72, which would impose a mere 1.5 to 3% increase in operating costs (Schwartz & Kroo, 2009). With more radical measures, the non-CO_2 temperature response can be almost entirely eliminated when cruising at 17,500 ft at Mach 0.45, leaving the remaining climate forcing from

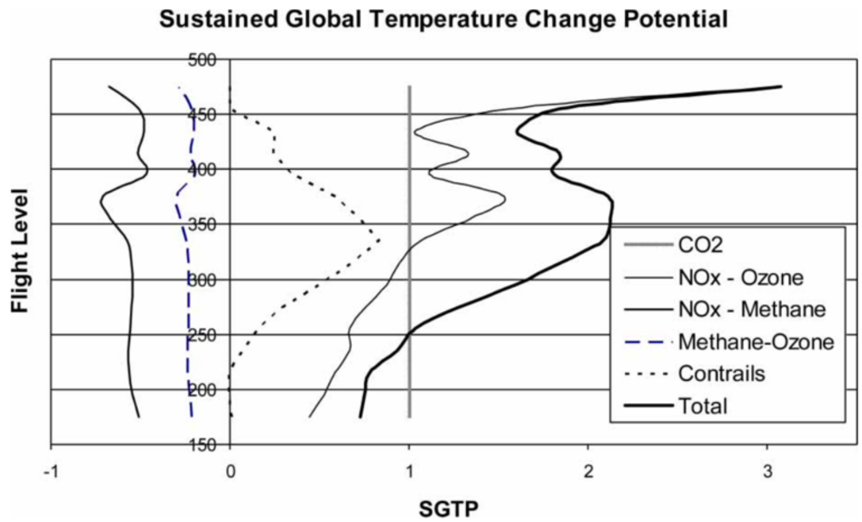

Figure 2: GTP_S Variation of Aviation Climate Forcing Species with Flight Level (Conveyed in Hundreds of ft) (Egelhofer et al., 2007)

CO_2 alone, although this approach would consequently incur more significant fuel penalties and a substantial increase in operating costs (Schwartz & Kroo, 2009). Furthermore, studies have shown that a 6,000 ft altitude reduction below average cruise levels would yield a reduction in the annual average global contrail coverage by 45 to 50% (Fichter et al., 2005; Mannstein et al., 2005).

A focus on mitigating non-CO_2 emissions in accordance with this strategy has several implications for designing the next generation of aircraft. One associated co-benefit to lowering the cruise Mach number is that wing area and sweepback can be reduced while the wing thickness can be increased, thereby also reducing the weight of the wing (Green, 2009). This will assist in offsetting some of the added weight from the greater fuel required to compensate for the increased drag at these lower altitudes, resulting in a less significant fuel burn penalty (Proesmans & Vos, 2021). An additional design adjustment that must be made to lessen the induced drag experienced in flight is to increase the aspect ratio (i.e., the ratio of the wingspan to the mean chord), as a larger wingspan becomes optimal at slower airspeeds (Proesmans & Vos, 2021). These climate-optimized changes are made apparent in Figure 3 in comparison with fuel- and direct operating cost-optimized designs. This Figure utilizes the Average Temperature Response metric, which will not be further considered in this report. It represents the mean surface temperature response to a perturbation over a pre-determined time horizon (taken to be 100 years in this case) and has the advantage of accounting for the thermal inertia of the ocean and atmosphere (Dahlmann et al., 2021).

A key challenge related to the development of effective mitigation strategies for aircraft emissions is the inherent trade-off that exists when addressing short-lived climate forcing species and long-lived GHG emissions, as an increase in the emission of one species is often necessary for the sake of reducing another. In this case, as previously mentioned, this is because the impacts of NO_X and contrails are strongest at operational altitudes and airspeeds most favourable

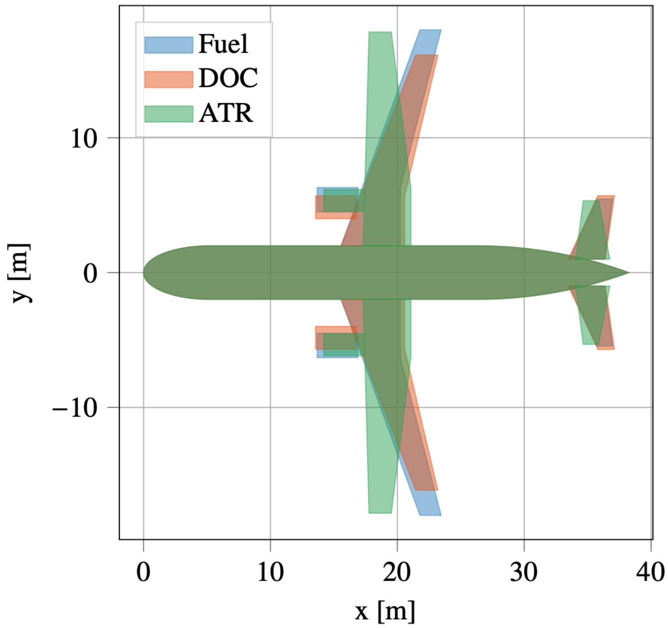

Figure 3: Planview of an Aircraft Optimized for Fuel (Blue), Direct Operating Costs (Red), and Average Temperature Response (Green) (Proesmans & Vos, 2021)

for low fuel burn (hence low CO_2 emissions). The clear compromise between mitigating non-CO_2 emissions and inciting a rise in fuel burn and CO_2 emissions involved with this proposed measure highlights the importance of an appropriate metric when developing mitigation strategies. Furthermore, justifying this trade-off and finding a balance between different species emissions requires careful consideration and a robust understanding of the consequences of each available option. As displayed in Figure 2, the net GTP_S observed within current average cruise altitudes greatly surpasses the forcing resulting from CO_2 alone and the climate benefits of this measure largely outweigh the consequential rise in CO_2 emissions. This trade-off can therefore be justified, unless other measures can be implemented that address these impacts more effectively. Further analysis will be required to determine the extent of the altitude and airspeed reductions that are required to achieve the desired effect from this strategy.

There are also several socio-economic implications for this climate change mitigation strategy which must be considered as well. For instance, from a cost-optimized perspective, flight at a reduced cruise altitude – with its associated greater fuel consumption and necessary lower Mach number – makes little economic sense. Any operational or aerodynamic changes that require slower cruising speeds will also likely result in the need for larger fleet sizes and more aircraft in the air at any given time to meet the demand for passenger travel (Proesmans & Vos, 2021). This may lead to airspace congestion, which imposes the potential for air safety issues and more frequent in-flight delays (Rashad & Zingg, 2015). Moreover, longer flight times and the potential for greater turbulence at lower flight altitudes may disincentivize travel and decrease passenger comfort while on board (Rashad & Zingg, 2015). The accompanying rise in costs and challenges with air traffic management brings the practicality and realism of this strategy into question; however, these considerations are beyond the scope of this report. While this strategy may prove to be highly effective once implemented, it is crucial to pursue other methods to mitigate the climate impact from aviation simultaneously to avoid trade-offs where possible, such as advanced combustor design to reduce NO_X emissions.

4.1.2 Flight Re-Routing

A promising operational strategy aimed specifically at mitigating the climate impact from non-CO_2 species emissions is to re-route flights either vertically or horizontally around the areas of the atmosphere most vulnerable to these species, known as climate-sensitive regions (Deuber et al., 2013). This climate change mitigation method is likely to produce the most effective outcome by diverting flights around ISSRs, thereby eliminating contrail forcing. An example of this approach is displayed in Figure 4, where two sample lateral re-routing options around an ovular ISSR are provided between New York City, USA and London, England. There are several trade-offs associated with flight re-routing for the sake of contrail avoidance, the most important being the rise in fuel consumption and CO_2 emissions due to these diversions, which increase flight distance and time (Agarwal, 2009). This strategy may also increase air traffic in certain areas, create delays and disturbances in airline schedules, and increase costs (Agarwal, 2009). A complex understanding of contrail formation, properties, and climate impact, as well as the local meteorological conditions is required to determine the advantages and compromises associated with any deviation from the existing fuel- or cost-optimized routing. If implemented effectively, the mitigation benefits of this measure are expected to compensate for these trade-offs.

As described in Section 2.3, persistent contrails are known to form most effectively in large-scale ISSRs within appropriate atmospheric temperatures (Kärcher, 2018). These climate-sensitive areas can be either mapped daily by air traffic services or detected by pilots in flight with meteorological instruments and avoided in order to largely eliminate this short-lived forcing component from the net climate impact of aviation (Mannstein et al., 2005; Niklaß et al., 2021). Accordingly, the need for onboard hygrometers to measure the atmospheric humidity and levels of ice-supersaturation outside the aircraft may arise to allow for contrail detection by pilots (Mannstein et al., 2005). Aside from this additional instrumentation, an advantage of this strategy is that it does not impose implications on aircraft design, as it can be implemented immediately with present aircraft technology. A simultaneous co-benefit of any reduction in cruise altitudes through vertical diversions in accordance with this strategy is a reduction in NO_X emissions as well. Another significant benefit is that it is unnecessary to implement fleetwide measures because effective operational contrail avoidance is highly context specific.

A highly targeted approach to mitigating contrail impacts involves addressing the specific flights that result in the greatest climate forcing from contrails, known as Big Hits (Gierens et al., 2020). A 2013 study conducted by Teoh et al. (2020) determined that only 2.2% of flights within Japanese airspace accounted for 80% of the total contrail forcing, which is anticipated to hold true for to other mid-latitude regions. Owing to the global variation in the elevation of the tropopause, contrail formation is dependent on the geographic location and altitude of the flight path (Lee et al., 2010). Accordingly, aircraft will be more likely to produce contrails following

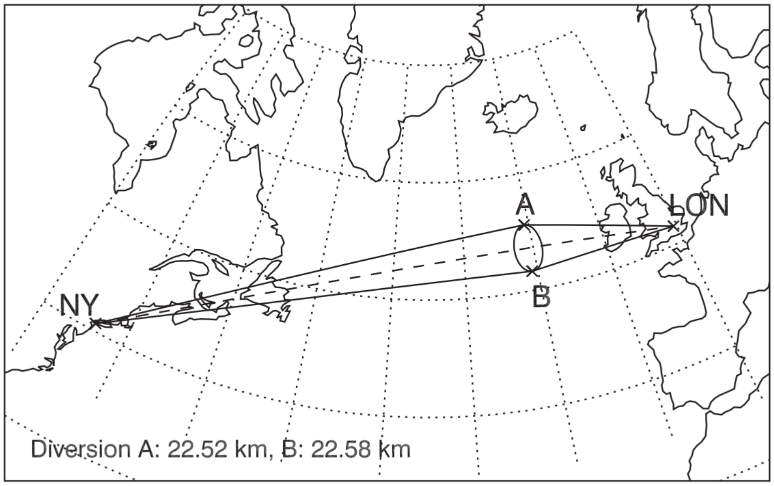

Figure 4: Great circle route for a sample flight between New York City (NY) and London (LON) (dashed line) and lateral flight re-routing options around an ISSR via point A or B (solid lines) with distances added to the overall route due to the diversion (Irvine et al., 2014)

certain flight routes than others, for example, through extratropical regions (Lund et al., 2017). Moreover, larger aircraft would generally benefit more from flight re-routing than smaller aircraft because they may be responsible for generating thicker contrails, thereby producing greater contrail forcing. They are also required to fly less significant distances beyond the most direct flight routing to avoid contrail formation (Irvine et al., 2014). Diversions must therefore be prioritized for specific flights and not universally applied to all aircraft in the fleet to allow for the most optimal outcome from a climate perspective (Teoh et al., 2020). This strategy may provide the simplest and most effective near-term approach to contrail avoidance that eliminates the largest climate forcing for the smallest trade-offs in CO_2 emissions and cost.

4.1.3 Climate-Charged Airspace Framework

A substantial trade-off associated with climate change mitigation in aviation is the added expense of introducing and maintaining these strategies. This compromise may serve as an impediment towards the effective implementation of these measures and disincentivize action, as there is often a clear trade-off between cost- and climate-optimization. For example, cruising at lower-than-average altitudes or re-routing around ISSRs necessitates longer flight times and a corresponding increase in operating costs, as previously discussed. Since a cost-benefit analysis would typically rule against the implementation of the strategies outlined in Sections 4.1.1 and 4.1.2, policy or market-based measures will be required to stimulate climate action among commercial air operators. Where climate change mitigation efforts interfere with cost-optimized operations, policy measures may also be required to ensure that passengers are not entirely responsible for these additional expenses and that aviation operators are accountable for their own climate impact (Niklaß et al., 2021).

An interesting approach that has been proposed to incentivize optimizing for overall climate impact in flight rather than for fuel burn (which often aligns with flight time and operating costs) is the Climate-Charged Airspace (CCA) framework. This promising market-based measure was introduced by Niklaß et al. (2021) to provide financial motive for avoiding climate-sensitive areas within the atmosphere related to non-CO_2 emissions, such as ISSRs, following the polluter pays principle in order to stimulate climate action within the aviation industry. The CCA mechanism effectively addresses the trade-off between cost- and climate-optimized operations by implementing tolls and aligning flight paths such that it makes the most economic sense to re-route around these regions of airspace, which allows commercial air operators to internalize the costs of their climate impact (Niklaß et al., 2021). CCAs are intended to be defined and overseen by air traffic control, which alleviates the need for individual airlines and other operators to make complicated climate-related and metric-dependent decisions when flight planning (Niklaß et al., 2021).

This framework can primarily be used to mitigate contrail and AIC impacts, as well as NO_X to a certain degree, as it has the potential to be applied to three-dimensional airspace, with vertical and horizontal routing adjustments as needed to avoid daily designated climate-sensitive regions of the atmosphere. Thus, the strategies discussed in Section 4.1.2 (and 4.1.1 to an extent) would be effectively incentivized. Figure 5 depicts a theoretical example of a CCA framework for flights between JFK International Airport in New York City (JFK) and Hamburg Airport in Germany (HAM). These specific tolls would only be valid in this region for the duration of the atmospheric conditions that produce the climate-sensitive areas shown in part a). Three options for flight routing through CCAs are presented, which depends on the optimization goals of the operator.

4.1.4 Further Potential Operational Adjustments

Beyond those previously described in this Section, there are several additional operational changes that can be made to further reduce the climate impact of the aviation industry. While these do not offer drastic emission reductions, they provide an effective intermediate step towards climate mitigation (Zingg & Gülder, 2016). For instance, close formation flying is a promising prospective modification to commercial practices that can be employed almost immediately to current global fleets using existing military procedures and current Global Positioning System (GPS) technology. There are several advantages associated with formation flight with as few as two or three aircraft, although these benefits tend to increase with every additional aircraft in the formation (Agarwal, 2009; Zingg & Gülder, 2016). This strategy results in a reduction in induced drag and allows for any trailing aircraft to utilize the energy produced by the leading aircraft's wake vortex, as is displayed in Figure 6, thereby enabling increasing either aircraft range or endurance, or permitting fuel savings (Marks et al., 2021). Including considerations for added fuel burn from re-routing aircraft into the formation, the universal implementation of close formation flying will result in a global reduction in net fuel consumption (Unterstrasser, 2020). A decrease in contrail formation and climate impact is also expected due to the competition for atmospheric water vapour availability among aircraft exhaust plumes and saturation of the local atmosphere (Unterstrasser, 2020).

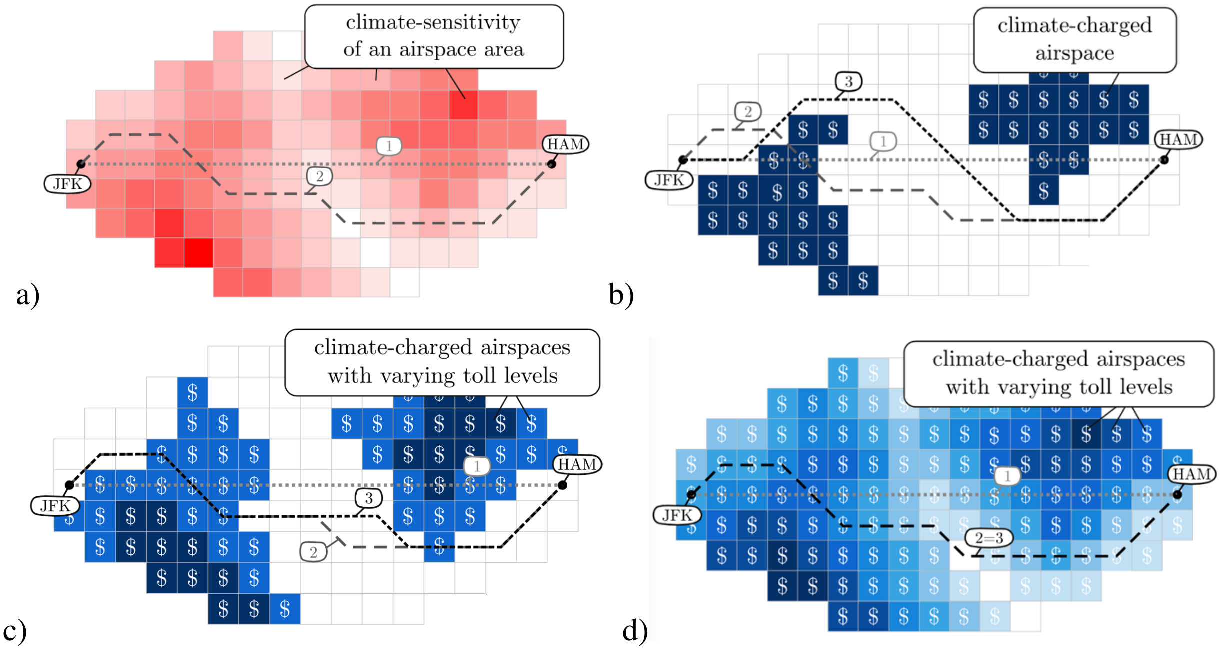

Figure 5: CCA framework for a sample route between JKF and HAM where the b) short-, c) medium-, and d) long-term approaches for airspace charging are in accordance with the climate-sensitivity along the route (a), giving air operators the choice of following the 1. time-optimized, 2. climate-optimized, or 3. cost-optimized routing with respect to the CCA tolls (Niklaß et al., 2021)

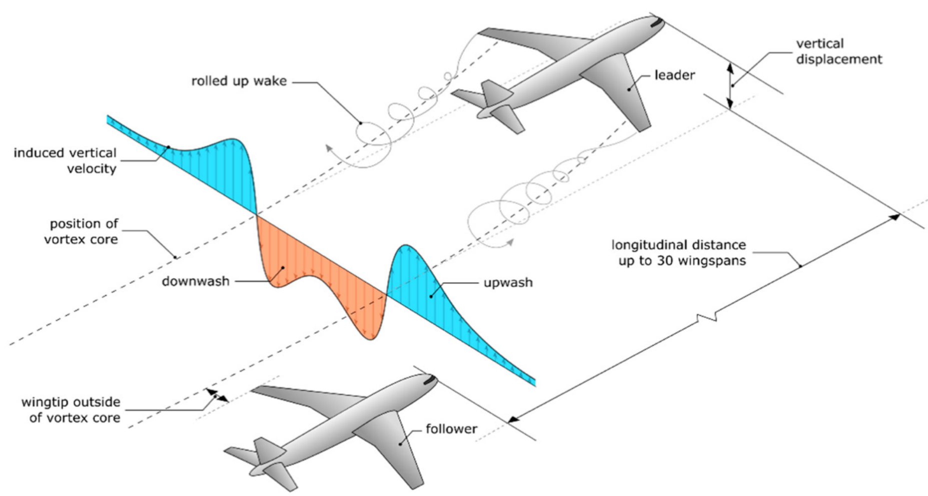

Figure 6: Principle of Two-Aircraft Close Formation Flight (Marks et al., 2021)

Moreover, multi-stage long-distance travel has been proposed as a method to improve fuel efficiency where a long-haul flight is divided into several short-haul flights to reduce the quantity of fuel required onboard (Agarwal, 2012; Zingg & Gülder, 2016). This approach decreases the aircraft's take-off weight, thereby reducing the fuel consumption and associated emissions. These operations can be further supported with air-to-air refuelling to eliminate the need for multiple stops to be made throughout the route, which will save time and additional fuel burn from the take-off, climb, and decent phases for each stop (Agarwal, 2009). Air-to-air refuelling offers a 30 to 40% reduction in fuel consumption, including the refuelling aircraft, and allows for the use of smaller and more fuel efficient short- and medium-range aircraft for long-distance routes (Nangia, 2008). The use of large aircraft for short-range (LASR) flight can also save fuel by increasing the volume of passengers that can be carried on each flight, thus decreasing the number of aircraft required to meet travel demands (Kenway et al., 2010). Multi-stage long-distance travel and LASR flight would require aircraft reconfiguration of seating arrangements and fuel tanks to trade the reduced fuel weight for additional passenger and cargo, thereby necessitating fleet replacement.

Continuous descent approaches provide an effective replacement for traditional step-down approaches (colloquially known as dive and drive). These two approach types are illustrated in Figure 7, where the former eliminates the need for power applications to maintain altitude when leveling off during the descent (as is the case with the latter), allowing for a constant low power descent (Coppenbarger et al., 2009). The sole use of this strategy over other approach methods could reduce aircraft fuel consumption by approximately 40% for the arrival phase of flight (Agarwal, 2012). A shift away from outdated ground-based navigational aids towards performance-based navigation using Global Navigation Satellite Systems (GNSS) will enable enhanced in-flight operational efficiency, particularly during the climb and descent phases of flight, thereby allowing for fuel savings (NAV CANADA, 2013). Finally, ground handing techniques, such as single-engine taxiing or the use of electric Ground Power Units to provide power to aircraft systems (rather than kerosene-consuming Auxiliary Power Units), can also improve efficiency during ground operations (Green, 2009; Transport Canada, 2012).

4.2 Alternative Fuels

4.2.1 Biofuels

Biofuels offer a promising solution to mitigate a portion of the climate impact caused by aviation and set the industry on track for low carbon – and eventually carbon neutral – growth (Zhao et al., 2021). They fall within the larger umbrella of Sustainable Aviation Fuel (SAF), which consist of a wide variety of jet fuel alternatives, such as power-to-liquid or synthetic fuels, that are not fossil fuel-based (Cabrera & de Sousa, 2022). SAF is an integral component of IATA's net-zero strategy, comprising 65% of the emissions reductions (IATA, 2021). Biofuels are produced through thermochemical or biochemical processes where biomass is converted into fuel that can be used as a substitute for kerosene (Hari et al. 2015). This approach is not yet a carbon neutral strategy, and the emission intensity of biofuels can vary substantially depending on the feedstock type and source, production process, and transportation methods (Zhao et al., 2021). It may even provoke a knock-on rise in carbon emissions in other areas as a result of land-use change or deforestation (Timperley, 2017). However, estimates indicate that biofuel use in aircraft has the potential to reduce lifecycle carbon emissions by as much as 80% in comparison

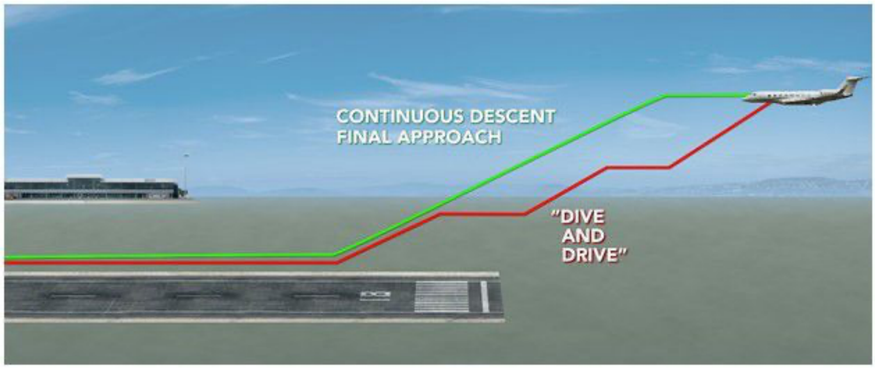

Figure 7: Comparison of the Conventional Step-Down Approach (or "Dive and Drive", in red) with the Continuous Descent Final Approach (in green) (Rogers, 2019)

with conventional jet fuel and lessen the effects of some non-CO_2 emissions as well (Cabrera & de Sousa, 2022).

Furthermore, the use of plant and waste matter for energy enables carbon recycling and circumvents the need to continue excavating and burning harmful fossil fuels (Hari et al., 2015). The universal adoption of this alternative would ideally allow for the acceleration of the Earth's natural carbon cycle to cease by eliminating the exploitation of long-term subsurface carbon storage deposits, thereby reducing anthropogenic carbon emissions significantly. A significant advantage of the use of many types of biofuels is that they are "drop-in," meaning that they replicate the chemical and combustion characteristics of kerosene and can therefore be implemented into current aircraft fleets without the need for engine modifications (Rashad & Zingg, 2015). Biofuels are therefore likely to provide an effective solution for mitigating the climate impact of the aviation industry related to CO_2 emissions. The intent of this Section is to highlight the significant potential for the successful implementation of this strategy while recognizing that biofuels are not a panacea for decarbonizing the aviation industry and that other options should continue to be investigated simultaneously.

Biomass-based fuels fall under three different categories, being first-, second-, and third-generation, depending on their feedstock. First generation biofuels are composed of edible sugars, starches, plant oils, and other food crops such as soybean, corn, wheat, etc., or those that can be used to feed livestock (Timperley, 2017). At present, this is widely used for ground vehicles, for example, sugar- or corn-based ethanol is commonly blended with gasoline. The sudden expansion in production of this type of biofuel to replace fossil-based jet fuel and avgas to maintain pace with the demands of the aviation industry will impose several ethical implications that should be avoided. Of particular concern is the risk of driving up food prices and aggravating global food insecurity by diverting food supplies away from those in need (Timperley, 2017). While first-generation biofuels have similar climate change mitigation benefits to other biofuel types, it is generally agreed that these do not uphold the sustainability requirements for SAF, and they are not viable substitutions for fossil-based fuel use in this industry (Cabrera & de Sousa, 2022).

Conversely, second-generation biofuels are produced from plant and waste matter consisting entirely of inedible material and are considered to be a sustainable alternative to kerosene (Cabrera & de Sousa, 2022). Designated energy crops including camelina, jatropha, and halophytic plants, as well as waste materials such as sewage and municipal waste, forest and sawmill residue, inedible agricultural waste, animal waste, used cooking oil, etc. are key feedstock sources (Hari et al., 2015; Timperley, 2017). The use of these biofuel feedstock options tends to be highly advantageous because they can be used as rotational crops, they are often capable of growth within areas where other vegetation struggles (e.g., salt marshes, infertile land, deserts), and some sources accumulate year-round (Hari et al., 2015). Furthermore, third-generation biofuels consist of algae, which may eventually prove to be exceedingly useful in biofuel production due to their rapid growth rates, superior carbon sequestration capability, and limited land required for accumulation (Cabrera & de Sousa, 2022). However, this feedstock source remains in early stages of its development and is not currently economically viable (Timperley, 2017).

Of these three categories, second-generation biofuels are likely to provide the most effective near-term option, but the means of acquiring the feedstock for this fuel is of vital importance to its sustainability. To meet the staggering and growing demands of the industry's fuel needs, feedstock must be produced at a massive scale, which risks a consequential rise in GHG emissions associated with LUC (Cabrera & de Sousa, 2022). Induced LUC results from any farmland conversion or deforestation related to energy biomass production (direct LUC), as well as any additional changes brought about elsewhere to supplement lost production of the original crops or materials (indirect LUC) (de Jong et al., 2017). This can considerably reduce the extent of the mitigation benefits gained from biofuel use due to the knock-on CO_2 emissions associated with unsustainable feedstock production, and this is an important distinguishing factor in determining the emission intensity relative to other biofuels (Zhao et al., 2021). Furthermore, to be deemed sustainable, it is also necessary that these feedstocks do not create a competition with edible crops for arable land, as this may place food security into question, particularly in the Global South (Cabrera & de Sousa, 2022; Lee et al., 2010). These considerations must be taken into account throughout the adoption of biofuels within commercial aviation to ensure that additional sustainability issues do not arise as a consequence of biofuel production and use.

In addition to mitigating a substantial portion of the industry's CO_2 emissions, the replacement of kerosene with biofuels will enable several co-benefits that contribute to mitigating the non-CO_2 impacts from aviation as well. For example, biofuels that undergo the Fischer-Tropsch, Hydrotreated Renewable Jet, or Hydroprocessed Esters and Fatty Acids processes during their production emit less NO_X than kerosene when burned (Hari et al., 2015). Biofuels also contain almost zero sulphur species and aromatic compounds when used unblended with conventional fuels; however, aromatics may need to be added to biofuels to avoid fuel leakage (Kärcher, 2018; Narciso & de Sousa, 2021). The implementation of drop-in biofuels in aviation would substantially reduce the emission of soot and sulphur aerosols in flight in comparison with kerosene, and the positive forcing associated with soot will therefore be almost eliminated (Lee et al., 2010). This will also have a significant influence on contrail formation, given the diminished abundance of condensation nuclei emitted in the exhaust plume, thereby potentially reducing the initial quantity of ice crystals in the contrail (Narciso & de Sousa, 2021).

Simultaneously, most SAF has a greater water vapour emission index than kerosene, which may lead to more frequent contrail formation of larger size (Narciso & de Sousa, 2021).

A computational model developed by Narciso and de Sousa (2021) sought to quantify this trade-off between the potentially contradictory influences of these changes in soot and water vapour emission indices. Simulations indicate that the most favourable outcomes tend to result from flight through regions with atmospheric conditions characterized by the ability to form persistent contrails. These contrail structures were shown to have lifetimes as much as 76% shorter and optical depths up to 37% smaller than would be expected from kerosene (Narciso & de Sousa, 2021). In regions with less ambient moisture available but near threshold conditions for contrail formation, the opposite was true, with thicker and slightly longer-lived contrails (in the order of minutes) observed (Narciso & de Sousa, 2021). The authors conclude that while the effects of biofuels on contrail formation and characteristics are clearly context specific, the climate impact imposed by any increase in contrail forcing is marginal at most, and the benefits largely outweigh the drawbacks.

Despite the clear advantages of using biofuels as a substitute for kerosene, SAF comprise less than 0.1% of global jet fuel consumption as of 2021 (International Energy Agency [IEA], 2021). Blending these fuels with conventional jet fuel, as is the current practice, has shown to significantly limit their climate change mitigation benefits (Kärcher, 2018). While seven types of SAF have been approved for use in commercial aircraft, these must be combined with kerosene to comprise no more than 10 to 50% of the fuel mixture (IEA, 2021). Furthermore, a significant obstacle to the widespread implementation of these fuels in aviation is the considerable scale of the feedstock needed to supplement the vast quantities of kerosene required to fuel global fleets (Cabrera & de Sousa, 2022). The expense of biofuels will also initially impose a barrier, since SAF currently costs at least twice as much as kerosene, meaning that airlines and other aviation operators will be highly unlikely to take initiative in implementing this solution (Grewe et al., 2021). It is estimated that this greater expense will produce demand-suppressing repercussions on the aviation industry of as much as 10 to 15% by 2050 due to increasing airline ticket prices (Grewe et al., 2021).

Finally, stringent industry fuel standards are in place to ensure continued safe operations, which pose an additional challenge to the production and utilization of biofuel within aviation, as SAF quality must meet specific criteria before it can be certified for use in commercial aircraft (Cabrera & de Sousa, 2022). While there are several processes that can be used in the production of biofuels, many produce fuels that are unsuitable for use in aircraft due to the high energy density and low freezing point requirements, such as ethanol and biodiesel (Hari et al., 2015; Lee et al., 2010). Further research into sustainable biofuel production for aviation and consideration into policy and industry-level regulatory measures to incentivize this potentially cost-prohibitive strategy (e.g., carbon pricing mechanisms) is therefore recommended.

4.2.2 Liquid Hydrogen Fuel

Liquid hydrogen fuel is another up-and-coming low carbon alternative to conventional jet fuels that has the potential to eliminate in-flight carbon and aerosol emissions. While this technology is in early stages of its development, it is ultimately expected to contribute towards achieving the industry's net-zero goal, although not to the same extent as SAF (IATA, 2021). As low temperatures are required to maintain hydrogen in a liquid state (i.e., cryogenic hydrogen), hydrogen-powered aircraft are often referred to as cryoplanes (Agarwal, 2009). The primary benefit of this strategy is that no CO_2, particulate matter, sulphur species, carbon monoxide, or volatile hydrocarbons are emitted during this reaction, as the main species emitted when liquid hydrogen is burned in flight is water vapour (Hari et al., 2015; Lee et al., 2010). Despite an increase in water vapour emissions, the use of hydrogen as a replacement for kerosene also has the potential to mitigate contrail impacts as a result of the elimination of aerosols. Contrails arising from cryoplane emissions are projected to be optically thinner, less persistent in the atmosphere, and contain 1 to 2 times less ice crystals (Lee et al., 2010).

In a controlled environment of pure oxygen gas, the combustion of liquid hydrogen takes place via the following reaction: $2H_2 + O_2 \rightarrow 2H_2O$ (Lewis, 2021). In practice, this reaction takes place in the presence of the ambient nitrogen-containing atmosphere and will result in the emission of NO as a minor by-product, leading to the production of NO_2. These emissions occur in the same manner as NO_X production from burning kerosene or any fossil-based fuels, as described in Section 2.2, and can potentially be mitigated similarly through operational changes or technological advancements (Lewis, 2021). Since there are no CO_2 emissions associated with liquid hydrogen combustion, the carbon footprint of hydrogen fuel is heavily contingent on the production process technology in use. Each of the processes discussed in this Section require sizeable energy inputs, so the associated carbon emissions are highly dependent on the local electricity grid mix (Hermesmann & Müller, 2022). There are varying degrees of production-related emissions, yielding what is known as grey, blue, turquoise, or green hydrogen in order of most to least climate impact.

Steam methane reforming (SMR), known as grey hydrogen, involves the breakage of carbon-hydrogen bonds in fossil hydrocarbon feedstocks (typically natural gas) under high temperatures and pressures in the presence of steam to produce hydrogen (H_2) and CO (Hermesmann & Müller, 2022; Lewis, 2018). This process is currently the most commonly used process to generate hydrogen, which is undergone via the following reaction: $CH_4 + H_2O \rightarrow CO + 3H_2$ (Hermesmann & Müller, 2022). SMR also produces the highest GHG emissions by releasing CO_2 as a by-product in addition to any GHGs associated with resource extraction or the substantial process-related energy demands (i.e., using natural gas to produce thermal energy) (Hermesmann & Müller, 2022). Furthermore, SMR with carbon capture and storage (SMR-CCS or blue hydrogen) ideally results in fewer emissions by sequestering as much as 53 to 95% of the CO_2 released during the SMR process, which is then permanently stored in appropriate geologic structures (Hermesmann & Müller, 2022). This method allows for the direct climate impact of SMR to be reduced for a 5 to 14% production efficiency trade-off, but the emissions resulting from energy use will be consistent (Hermesmann & Müller, 2022).

Methane pyrolysis (or turquoise hydrogen), on the other hand, entails the separation of methane (also usually from natural gas) into hydrogen gas and solid black carbon, which does not directly release CO_2 (Hermesmann & Müller, 2022). This process proceeds through the following decomposition reaction: $CH_4 \rightarrow 2H_2 + C$ (Hermesmann & Müller, 2022). This process has a lower climate impact than SMR and SMR-CSS, although it does still rely on fossil fuel feedstocks, thereby implicating any emissions related to resource extraction in its lifecycle impact as well. However, biofuels may eventually be used as a lower carbon alternative, allowing for a reduction in the accompanying net carbon emissions (Hermesmann & Müller, 2022). Finally, water electrolysis (or green hydrogen) is considered a promising carbon-free hydrogen production method that is likely to provide the most sustainable option for supplying liquid hydrogen for aviation practices in the future. This process involves the electrochemical cleavage of water molecules to produce hydrogen and oxygen gas following this decomposition reaction: $H_2O \rightarrow H_2 + \frac{1}{2}O_2$ (Hermesmann & Müller, 2022). No carbon is emitted or produced as a by-product, and it is usually assumed that renewable energy is used (Lewis, 2018). As such, the climate impact can be almost entirely attributed to the hydrogen plant manufacturing and water supply (Hermesmann & Müller, 2022). While this type of hydrogen production is currently commercially available, it is not yet competitive with other manufacturing processes or accessible at a sufficient scale to fill the needs of the aviation industry (Hermesmann & Müller, 2022).

Unfortunately, hydrogen is not a drop-in option as it cannot be used in current jet engines. While hydrogen has a greater energy density than kerosene by mass, it requires significantly more space due to its lower energy density by volume, taking up 4.2 times more volume for an identical amount of energy (Agarwal, 2009). The application of hydrogen fuel technology would therefore require engine modifications and larger on-board fuel tanks, meaning that aircraft fleet replacement would be necessary (Hari et al., 2015). This may consequently raise the lifecycle climate impact of current aircraft by imposing additional emissions due to aircraft manufacturing. Thus, cryoplanes are unlikely to offer a realistic near-term approach due to the vast expense and sustainability concerns associated with retiring and replacing commercial aircraft earlier than their operational lifespan dictates, as well as the difficulties in sourcing sustainable hydrogen at scale (Hermesmann & Müller, 2022). Cryoplanes are also unlikely to be capable of flight as fast as or over equal distances to current aircraft due to the increased aircraft weight and drag associated with larger fuel tanks; however, they have significant potential to provide a promising long-term solution with effective applications for short- to medium-range routes (Agarwal, 2009).

4.3 Technological Measures

New aircraft technology is another fundamental component of IATA's plan to reach net-zero emissions, including engine upgrades, aircraft efficiency improvements, and potentially unconventional aircraft for future commercial fleets (IATA, 2021). However, thorough consideration of the potential technological measures related to climate change mitigation is beyond the scope of this report. For additional information, please refer to Appendix M3: Technology Sub Group Report of the Report on the Feasibility of a Long-Term Aspirational

Goal (LTAG) for International Civil Aviation CO_2 Reductions from ICAO (2022a) and the Independent Expert Integrated Technology Goals Assessment and Review for Engines and Aircraft by Cumpsty et al. (2019).

4.3.1 Engine Advancements

Generally, aircraft NO_X emissions arising from combustion can be mitigated by increasing the air-to-fuel ratio to enable lean-burn conditions, reducing the combustion temperature, or effecting exhaust after-treatment for a slight operational trade-off in engine performance and increased costs (Lewis, 2021). One emerging combustor technology focused on NO_X mitigation involves lean premixed combustion, whereby the fuel and air are combined before combustion takes place and the fuel is able to evaporate completely (Rashad & Zingg, 2015). This advancement will allow for lower combustion temperatures, hence lower NO_X emissions, as well as the eradication of carbonaceous aerosol emissions (Zingg & Gülder, 2016). Furthermore, the replacement of single annular combustors with double annular combustors is predicted to lessen the emission index of particulate matter, thereby reducing the formation of contrails, as well as their ice crystal content and persistence in the atmosphere (Teoh et al., 2020). Additionally, the use of engine bypass air to cool and condense the gases in the exhaust plume has been proposed as a method for addressing contrail impacts, as this would reduce the emission index of water vapour significantly (Lee et al., 2010).

There is an unfortunate technological trade-off between efforts to mitigate CO_2 emissions through engine design and an associated rise in NO_X emissions and contrail formation. An increase in jet engine thermal efficiency though greater EPR or high bypass ratio engine design often produces conditions more favourable for NO_X formation through greater temperatures and pressures in the combustor (Freeman et al., 2018; Lee et al., 2010). Similarly, engine modifications aimed at reducing NO_X have been shown to increase CO_2 emissions (Freeman et al., 2018). Moreover, the increased likelihood of contrail formation that accompanies greater engine propulsive efficiency, as described in Section 2.3, presents yet another trade-off to be contended with (Lund et al., 2017). Nevertheless, when paired with operational measures, these technological trade-offs can be reduced. For example, the introduction of open rotor engines has the potential to considerably reduce fuel consumption through enhanced propulsive efficiency (as much as 90% greater than current jet engines), which may consequently result in a rise in contrail formation (Lee et al., 2010; Rashad & Zingg, 2015). However, this can perhaps be offset when implemented in conjunction with the operational measures outlined in Section 4.1. Simultaneously, should these engine design advancements be successfully employed to global aircraft fleets, certain operational strategies – such as cruise altitude and Mach number reductions targeted towards mitigating NO_X emissions – may become redundant. Thus, a re-evaluation of the effectiveness and associated trade-offs of various mitigation strategies would be required.

4.3.2 Aircraft Efficiency Improvements & Unconventional Aircraft

Climate change mitigation through aircraft efficiency can be approached using several different methods through reductions in aircraft weight and/or drag, improving airflow over the aircraft surfaces, or a combination of these measures. Natural laminar flow, for example, can reduce parasite drag resulting from skin friction of the aircraft with the surrounding air (i.e., viscous drag) by enabling more favourable pressure gradients (Green, 2009). Similarly, active flow control aims to stabilize the boundary layer and maintain laminar flow to reduce viscous drag by providing suction along the wing for a small trade-off in aircraft weight, intricacy, and engine performance (Zingg & Gülder, 2016). Unconventional aircraft configurations, such as the strut-braced wing, closed- or box-wing, blended wing-body, or double bubble, provide promising approaches to aerodynamic optimization for future generations of aircraft (Zingg & Gülder, 2016). However, this report will not further elaborate on these unique approaches.

5. Discussion & Conclusions

5.1 Further Considerations into Aviation Policy & Industry Dynamics

Where aviation is concerned, many climate policy gaps exist. For instance, the Paris Agreement excludes international aviation from Nationally Determined Contributions and nationwide emissions inventories (Ritchie, 2020). It is instead classified with maritime shipping as an international bunker fuel, which leaves the associated climate change mitigation, goalsetting, and accountability to industry leaders who likely have more economically centred priorities. The Paris Agreement also does not recognize non-CO_2 impacts from aviation, which constitute a large share of the overall climate impact from aviation, leaving little motivation to mitigate these emissions (Ritchie, 2020). Revisions in policy and regulations are thereby required to fully account for the climate impact caused by the aviation industry to allow for effective mitigation strategies.

The impacts of the global COVID-19 pandemic on near- and long-term aviation operations also require consideration to gain a complete understanding of the influence of shifting industry trends and projections on its climate impact. During the worst of the lockdowns in April 2020, RPK fell by about 94% (compared with April 2019) grounding 64% of global commercial fleets at the time and temporarily reducing CO_2 emissions from aviation by 60% (Le Quéré et al., 2021; Oxford Economics, 2021). Moreover, the average number of global flights in 2020 was reduced by 45% relative to 2019 levels (Klöwer et al., 2021). This extreme disturbance is made evident in Figure 8 with a graphical representation of the decrease in passenger travel as a result of the pandemic in comparison to several other significant world events that have influenced air travel in the past. While domestic and international air travel is expected to return to 2019 levels by 2025 at the latest, the lasting impacts of the pandemic on aviation operations and associated emissions remain unclear, as some aspects of aviation may have undergone permanent changes (IATA, 2022). For example, owing to the sudden and effective shift to virtual

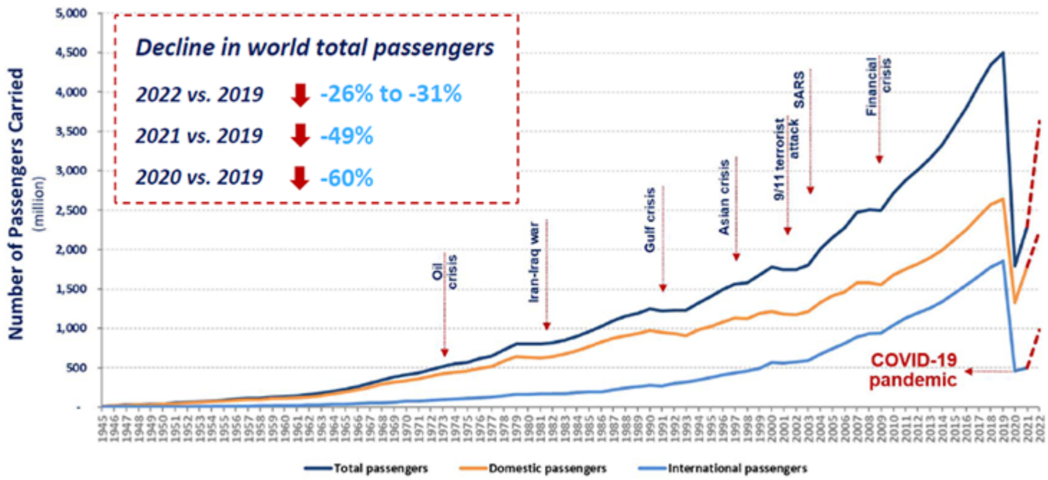

Figure 8: World Passenger Transport from 1945 to 2022 Projections (ICAO, 2022b)

platforms for business meetings and conferences, business travel may not recover to pre-pandemic levels (Dichter & Riedel, 2021, 5:15). Accordingly, there is an anticipated decline in air passenger traffic of 8% relative to pre-pandemic estimations for 2050 (Air Transport Action Group, 2021). However, this irregular reduction in air traffic and associated emissions brought on by the pandemic and potential for minor permanent effects are insufficient to adequately curb the impact of aviation on climate change, and the need to mitigate this impact remains pressing.

In addition to the many trade-offs mentioned throughout this report, there may also be a compromise between the immediacy of the actions implemented for the sake of climate change mitigation and overall sustainability. For instance, early retirement of planes that are still currently operational will be required to allow for immediate climate-optimization in commercial fleets through more climate-conscious and modern aircraft design, as even present best-in-class aircraft can be made more efficient. This has the potential to incite a rise in the lifecycle climate impact of international fleets, which may prove necessary from a climate perspective despite the accompanying environmental issues arising from increased aircraft manufacturing and disposal (Proesmans & Vos, 2021). However, the likelihood of commercial air operators voluntarily retiring fully functional aircraft is questionable due to the associated expense and this would require substantial financial assistance or incentive.

5.2 Conclusions

Owing to the lack of consideration for relevant climate metrics in aviation, the contribution of non-CO_2 species to the climate impact from this industry has largely been underestimated at the policy- and industry-levels, leading to misinformed climate action and inaction towards mitigating these emissions. The development and use of a weighted climate metric and associated equivalence factor using GWP and GTP_S is therefore required to minimize the drawbacks associated with each of these metrics when used on their own and precisely quantify the climate impact attributed to these short-lived species. This recommendation will allow for a deeper understanding of the comparison between short- and long-lived forcing species and more accurate estimations of their combined influence on the global climate in order to guide climate change mitigation decisions going forward.

Of the measures proposed in Section 4, re-routing specific flights around climate-sensitive regions of the atmosphere may offer the most promising near-future strategy for reducing a portion of the aviation industry's climate impact attributed to non-CO_2 species emissions. This strategy can be implemented with current aircraft fleets, requires minimal procedural changes, can be incentivized relatively easily with the CCA framework, and is considered the "low-hanging fruit" of these climate change mitigation options. Nevertheless, a combination of approaches to climate action that address both CO_2 and non-CO_2 emissions is generally expected to yield the most successful outcome and will allow for the trade-offs associated with any one measure to be reduced. When implemented in conjunction with policy incentives and regulatory measures, these recommended alternatives to current practices have significant potential to meaningfully mitigate the industry's climate impact. A weighted metric may also assist in driving this simultaneous use of multiple strategies by emphasizing the importance of addressing aircraft emissions beyond merely decarbonizing aviation practices.

5.3 Recommended Areas of Further Research

Several gaps in the industry and academic literature were exposed during the research process for this report, which must be addressed in order to best inform aircraft design and operational measures aimed at reducing the climate impact from aircraft in flight. It is imperative that an agreement in the methodology for calculating the climate impact attributed to NO_X emissions is achieved among authors, and efforts to reduce the level of uncertainty associated with contrails and AIC impacts must also be undertaken. Closing these research gaps will likely motivate the implementation of more ambitious mitigation strategies targeted towards non-CO_2 emissions and will provide further evidence to justify any accompanying trade-offs. Additionally, there is limited data availability for the impact of each emitted species in terms of GTP_S, which will be necessary for the development of a weighted metric to effectively quantify the overall impact of the aviation industry, as discussed in Section 3.4. Further quantitative evaluation into aircraft emissions using this metric is therefore recommended.

6. References

Agarwal, R. K. (2009). Sustainable (green) aviation: Challenges and opportunities. *SAE International Journal of Aerospace*, *2*(1), 1–20. https://doi.org/10.4271/2009-01-3085

Agarwal, R. K. (2012). *Recent advances in aircraft technology*. InTech.

Air Transport Action Group. (2021). *Waypoint 2050: An Air Transport Action Group Project*. (pp. 1-103). Air Transport Action Group: Geneva, Switzerland.

Allen, M. R., Fuglestvedt, J. S., Shine, K. P., Reisinger, A., Pierrehumbert, R. T., & Forster, P. M. (2016). New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change*, *6*(8), 773–776. https://doi.org/10.1038/nclimate2998

Andrews, T., Smith, C. J., Myhre, G., Forster, P. M., Chadwick, R., & Ackerley, D. (2021). Effective radiative forcing in a GCM with fixed surface temperatures. *Journal of Geophysical Research: Atmospheres*, *126*(4). https://doi.org/10.1029/2020jd033880

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A., & Tokos, K. (2009). Atmospheric lifetime of fossil fuel carbon dioxide. *Annual Review of Earth and Planetary Sciences*, *37*(1), 117–134. https://doi.org/10.1146/annurev.earth.031208.100206

Asquith, J. (2020, April 6). *If aviation was a country it would be the world's 20th largest by GDP*. Forbes. Retrieved July 19, 2022, from https://www.forbes.com/sites/jamesasquith/2020/04/06/if-aviation-was-a-country-it-would-be-the-worlds-20th-largest-by-gdp/?sh=eb5c0d4e5b5a

Azar, C., & Johansson, D. J. (2012). Valuing the non-CO2 climate impacts of Aviation. *Climatic Change*, *111*(3-4), 559–579. https://doi.org/10.1007/s10584-011-0168-8

Blaszczak, R., Nitrogen Oxides (NOx): Why and how they are controlled. 1–48 (1999). Research Triangle Park, North Carolina; Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency.

Brown, R. C., Anderson, M. R., Miake-Lye, R. C., Kolb, C. E., Sorokin, A. A., & Buriko, Y. Y. (1996). Aircraft exhaust sulfur emissions. *Geophysical Research Letters*, *23*(24), 3603–3606. https://doi.org/10.1029/96gl03339

Cabrera, E., & de Sousa, J. M. M. (2022). Use of sustainable fuels in aviation—A Review. *Energies*, *15*(2440), 1–23. https://doi.org/10.3390/en15072440

Collins, W. J., Frame, D. J., Fuglestvedt, J. S., & Shine, K. P. (2020). Stable climate metrics for emissions of short and long-lived species—combining steps and pulses. *Environmental Research Letters*, *15*(2). https://doi.org/10.1088/1748-9326/ab6039

Coppenbarger, R. A., Mead, R. W., & Sweet, D. N. (2009). Field evaluation of the tailored arrivals concept for datalink-enabled continuous descent approach. *Journal of Aircraft*, *46*(4), 1200–1209. https://doi.org/10.2514/1.39795

Cumpsty, N., Mavris, D., Alonso, J., Catalano, F., Eyers, C., Goutines, M., Gronstedt, T., Hileman, J., Joselzon, A., Khaletskii, I., Ogilvie, F., Ralph, M., Sabnis, J., Wahls, R., Zingg, D. (2019). Independent Expert Integrated Technology Goals Assessment and Review for Aircraft and Engines (ICAO Doc 10127), Montreal.

Dahlmann, K., Grewe, V., Matthes, S., & Yamashita, H. (2021). Climate assessment of single flights: Deduction of route specific equivalent CO_2 emissions. *International Journal of Sustainable Transportation*, 1–12. https://doi.org/10.1080/15568318.2021.1979136

de Jong, S., Antonissen, K., Hoefnagels, R., Lonza, L., Wang, M., Faaij, A., & Junginger, M. (2017). Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnology for Biofuels*, *10*(1). https://doi.org/10.1186/s13068-017-0739-7

Dessens, O., Köhler, M. O., Rogers, H. L., Jones, R. L., & Pyle, J. A. (2014). Aviation and climate change. *Transport Policy*, *34*, 14–20. https://doi.org/10.1016/j.tranpol.2014.02.014

Deuber, O., Sigrun, M., Robert, S., Michael, P., & Ling, L. (2013). A physical metric-based framework for evaluating the climate trade-off between CO2 and contrails—the case of lowering aircraft flight trajectories. *Environmental Science & Policy*, *25*, 176–185. https://doi.org/10.1016/j.envsci.2012.10.004

Dichter, A., & Riedel, R. (Hosts). (2021, May 20). How air travel is evolving postpandemic. [Audio podcast episode]. In *The McKinsey Podcast*. McKinsey & Company. https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/how-air-travel-is-evolving-postpandemic

Egelhofer, R., Bickerstaff, C., & Bonnet, S. (2007). Minimizing impact on climate in aircraft design. *SAE Technical Paper Series*. https://doi.org/10.4271/2007-01-3807

Ervens, B., Turpin, B. J., & Weber, R. J. (2011). Secondary organic aerosol formation in cloud droplets and aqueous particles (aqSOA): A review of Laboratory, field and model studies. *Atmospheric Chemistry and Physics*, *11*(21), 11069–11102. https://doi.org/10.5194/acp-11-11069-2011

Fageda, X., Suárez-Alemán, A., Serebrisky, T., & Fioravanti, R. (2019). Air Transport Connectivity of remote regions: The impacts of public policies. *Regional Studies*, *53*(8), 1161–1169. https://doi.org/10.1080/00343404.2018.1556391

Federal Aviation Administration, Aviation & Emissions: A Primer (2005). Washington, D.C.; Office of Environment and Energy.

Fichter, C., Marquart, S., Sausen, R., & Lee, D. S. (2005). The impact of cruise altitude on contrails and related radiative forcing. *Meteorologische Zeitschrift*, *14*(4), 563–572. https://doi.org/10.1127/0941-2948/2005/0048

Freeman, S., Lee, D. S., Lim, L. L., Skowron, A., & De León, R. R. (2018). Trading off aircraft fuel burn and NOx emissions for optimal climate policy. *Environmental Science & Technology*, *52*(5), 2498–2505. https://doi.org/10.1021/acs.est.7b05719

Fuglestvedt, J. S., Shine, K. P., Berntsen, T., Cook, J., Lee, D. S., Stenke, A., Skeie, R. B., Velders, G. J. M., & Waitz, I. A. (2010). Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment*, *44*(37), 4648–4677. https://doi.org/10.1016/j.atmosenv.2009.04.044

Gierens, K., Matthes, S., & Rohs, S. (2020). How well can persistent contrails be predicted? *Aerospace*, *7*(12), 1–18. https://doi.org/10.3390/aerospace7120169

Gilmore, C. K., Barrett, S. R., Koo, J., & Wang, Q. (2013). Temporal and spatial variability in the aviation NOx-related O3 impact. *Environmental Research Letters*, *8*(3). https://doi.org/10.1088/1748-9326/8/3/034027

Gössling, S., & Humpe, A. (2020). The global scale, distribution and growth of aviation: Implications for climate change. *Global Environmental Change*, *65*, 1–12. https://doi.org/10.1016/j.gloenvcha.2020.102194

Green, J. E. (2009). The potential for reducing the impact of aviation on climate. *Technology Analysis & Strategic Management*, *21*(1), 39–59. https://doi.org/10.1080/09537320802557269

Grewe, V., Matthes, S., & Dahlmann, K. (2019). The contribution of aviation NOx emissions to climate change: Are we ignoring methodological flaws? *Environmental Research Letters*, *14*(12). https://doi.org/10.1088/1748-9326/ab5dd7

Grewe, V., Gangoli Rao, A., Grönstedt, T., Xisto, C., Linke, F., Melkert, J., Middel, J., Ohlenforst, B., Blakey, S., Christie, S., Matthes, S., & Dahlmann, K. (2021). Evaluating the climate impact of aviation emission scenarios towards the Paris Agreement including Covid-19 Effects. *Nature Communications*, *12*(1). https://doi.org/10.1038/s41467-021-24091-y

Hari, T. K., Yaakob, Z., & Binitha, N. N. (2015). Aviation biofuel from renewable resources: Routes, opportunities and challenges. *Renewable and Sustainable Energy Reviews*, *42*, 1234–1244. https://doi.org/10.1016/j.rser.2014.10.095

Hermesmann, M., & Müller, T. E. (2022). Green, turquoise, blue, or grey? environmentally friendly hydrogen production in transforming Energy Systems. *Progress in Energy and Combustion Science*, *90*. https://doi.org/10.1016/j.pecs.2022.100996

Industry High Level Group. (2019). (rep.). *Aviation Benefits Report* (pp. 1–71). International Civil Aviation Organization.

Inman, M. (2008). Carbon is forever. *Nature Climate Change*, *1*(812), 156–158. https://doi.org/10.1038/climate.2008.122

Intergovernmental Panel on Climate Change. (1999). *Aviation and the global atmosphere: Special report of the intergovernmental panel on climate change*. (J. E. Penner, D. H. Lister, D. J. Griggs, D. J. Dokken, & M. McFarland, Eds.). Cambridge University Press.

International Air Transport Association. (2021, October 4). *Net-Zero Carbon Emissions by 2050*. [Press release]. Retrieved July 22, 2022, from https://www.iata.org/en/pressroom/2021-releases/2021-10-04-03/.

International Air Transport Association. (2022, March 1). *Air Passenger Numbers to Recover in 2024*. [Press release]. Retrieved June 13, 2022, from https://www.iata.org/en/pressroom/2022-releases/2022-03-01-01/.

International Civil Aviation Organization. (2022, March). (rep.). *Report on the Feasibility of a Long-Term Aspirational Goal (LTAG) for International Civil Aviation CO_2 Reductions*. ICAO Committee on Aviation Environmental Protection.

International Civil Aviation Organization. (2022, January 17). *2021 global air passenger totals show improvement from 2020, but still only half pre-pandemic levels*. [Press release]. Retrieved June 14, 2022, from https://www.icao.int/Newsroom/Pages/2021-global-air-passenger-totals-show-improvement.aspx#:~:text=Montr%C3%A9al,%2017%20January%202022%20-%20Global,percent%20drop%20seen%20in%202020.

International Civil Aviation Organization. (n.d.). *Air Transport, passengers carried*. The World Bank. Retrieved June 13, 2022, from https://data.worldbank.org/indicator/IS.AIR.PSGR

International Energy Agency. (2021, November 1). *Aviation*. IEA, Paris. Retrieved July 13, 2022, from https://www.iea.org/reports/aviation

Irvine, E. A., Hoskins, B. J., & Shine, K. P. (2012). The dependence of Contrail Formation on the weather pattern and altitude in the North Atlantic. *Geophysical Research Letters*, *39*(12). https://doi.org/10.1029/2012gl051909

Irvine, E. A., Hoskins, B. J., & Shine, K. P. (2014). A simple framework for assessing the trade-off between the climate impact of aviation carbon dioxide emissions and contrails for a single flight. *Environmental Research Letters*, *9*(6). https://doi.org/10.1088/1748-9326/9/6/064021

Kärcher, B. (2018). Formation and radiative forcing of Contrail Cirrus. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-018-04068-0

Kenway, G., Henderson, R., Hicken, J., Kuntawala, N., Zingg, D., Martins, J. R., & McKeand, R. (2010). Reducing aviation's environmental impact through large aircraft for short ranges. *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, 1–11. https://doi.org/10.2514/6.2010-1015

Klöwer, M., Allen, M. R., Lee, D. S., Proud, S. R., Gallagher, L., & Skowron, A. (2021). Quantifying aviation's contribution to global warming. *Environmental Research Letters*, *16*(10). https://doi.org/10.1088/1748-9326/ac286e

Köhler, M. O., Rädel, G., Dessens, O., Shine, K. P., Rogers, H. L., Wild, O., & Pyle, J. A. (2008). Impact of perturbations to nitrogen oxide emissions from Global Aviation. *Journal of Geophysical Research*, *113*(11). https://doi.org/10.1029/2007jd009140

Köhler, M. O., Rädel, G., Shine, K. P., Rogers, H. L., & Pyle, J. A. (2013). Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics. *Atmospheric Environment*, *64*, 1–9. https://doi.org/10.1016/j.atmosenv.2012.09.013

Kurniawan, J. S., & Khardi, S. (2011). Comparison of methodologies estimating emissions of aircraft pollutants, environmental impact assessment around airports. *Environmental Impact Assessment Review*, *31*(3), 240–252. https://doi.org/10.1016/j.eiar.2010.09.001

Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C. N., Lim, L. L., Owen, B., & Sausen, R. (2009). Aviation and global climate change in the 21st Century. *Atmospheric Environment*, *43*(22-23), 3520–3537. https://doi.org/10.1016/j.atmosenv.2009.04.024

Lee, D. S., Pitari, G., Grewe, V., Gierens, K., Penner, J. E., Petzold, A., Prather, M. J., Schumann, U., Bais, A., & Berntsen, T. (2010). Transport impacts on atmosphere and climate: Aviation. *Atmospheric Environment*, *44*(37), 4678–4734. https://doi.org/10.1016/j.atmosenv.2009.06.005

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., Gettelman, A., De León, R. R., Lim, L. L., Lund, M. T., Millar, R. J., Owen, B., Penner, J. E., Pitari, G., Prather, M. J., … Wilcox, L. J. (2021). The contribution of Global Aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, 1–29. https://doi.org/10.1016/j.atmosenv.2020.117834

Le Quéré, C., Jackson, R. B., Jones, M. W., Smith, A. J., Abernethy, S., Andrew, R. M., De-Gol, A. J., Willis, D. R., Shan, Y., Canadell, J. G., Friedlingstein, P., Creutzig, F., & Peters, G.

P. (2020). Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nature Climate Change*, *10*(7), 647–653. https://doi.org/10.1038/s41558-020-0797-x

Lewis, A. C. (2021). Optimising air quality co-benefits in a hydrogen economy: A case for hydrogen-specific standards for NOx emissions. *Environmental Science: Atmospheres*, *1*(5), 201–207. https://doi.org/10.1039/d1ea00037c

Lund, M. T., Aamaas, B., Berntsen, T., Bock, L., Burkhardt, U., Fuglestvedt, J. S., & Shine, K. P. (2017). Emission metrics for quantifying regional climate impacts of Aviation. *Earth System Dynamics*, *8*(3), 547–563. https://doi.org/10.5194/esd-8-547-2017

Mannstein, H., Spichtinger, P., & Gierens, K. (2005). A note on how to avoid contrail cirrus. *Transportation Research Part D: Transport and Environment*, *10*(5), 421–426. https://doi.org/10.1016/j.trd.2005.04.012

Marks, T., Dahlmann, K., Grewe, V., Gollnick, V., Linke, F., Matthes, S., Stumpf, E., Swaid, M., Unterstrasser, S., Yamashita, H., & Zumegen, C. (2021). Climate impact mitigation potential of formation flight. *Aerospace*, *8*(1), 1–18. https://doi.org/10.3390/aerospace8010014

Matthes, S., Lim, L., Burkhardt, U., Dahlmann, K., Dietmüller, S., Grewe, V., Haslerud, A. S., Hendricks, J., Owen, B., Pitari, G., Righi, M., & Skowron, A. (2021). Mitigation of non-CO2 aviation's climate impact by changing cruise altitudes. *Aerospace*, *8*(2). https://doi.org/10.3390/aerospace8020036

Matsumoto, J., Kosugi, N., Nishiyama, A., Isozaki, R., Sadanaga, Y., Kato, S., Bandow, H., & Kajii, Y. (2006). Examination on Photostationary State of nox in the urban atmosphere in Japan. *Atmospheric Environment*, *40*(18), 3230–3239. https://doi.org/10.1016/j.atmosenv.2006.02.002

Myhre, G., Nilsen, J. S., Gulstad, L., Shine, K. P., Rognerud, B., & Isaksen, I. S. (2007). Radiative forcing due to stratospheric water vapour from CH4 oxidation. *Geophysical Research Letters*, *34*(1). https://doi.org/10.1029/2006gl027472

Nangia, R. K. (2008). Air to air refuelling in civil aviation: An opportunity & a vision. *Royal Aeronautics Society Greener by Design Conference*, 1–19.

Narciso, M., & de Sousa, J. M. M. (2021). Influence of sustainable aviation fuels on the formation of contrails and their properties. *Energies*, *14*(5557), 1–19. https://doi.org/10.3390/en14175557

NAV CANADA (2013). (rep.). *The Air Navigation System Plan: Charting the Future*.

Niklaß, M., Grewe, V., Gollnick, V., & Dahlmann, K. (2021). Concept of climate-charged airspaces: A potential policy instrument for internalizing aviation's climate impact of non-

CO Effects. *Climate Policy*, *21*(8), 1066–1085. https://doi.org/10.1080/14693062.2021.1950602

Oxford Economics. (2021, September). *COVID-19 Analysis Fact Sheet*. Aviation Benefits Beyond Borders. Retrieved July 12, 2022, from https://aviationbenefits.org/media/167482/abbb21_factsheet_covid19-1.pdf

Proesmans, P.J., & Vos, R. (2021). Airplane design optimization for minimal global warming impact. *American Institute of Aeronautics and Astronautics, Inc*., 1–25. https://doi.org/10.2514/6.2021-1297

Rashad, R., & Zingg, D. W. (2015). (rep.). *Actions to Reduce the Climate Change Impact on the Aviation Sector* (pp. 1–65). Toronto.

Ritchie, H. (2020, October 22). *Climate change and flying: What share of Global CO2 Emissions Come From Aviation?* Our World in Data. Retrieved May 29, 2022, from https://ourworldindata.org/co2-emissions-from-aviation#:~:text=Aviation%20accounts%20for%20around%202.5,number%20of%20more%20complex%20ways.

Rogers, D. (2019, August 17). *Eliminating dive and drive*. Honeywell Aerospace. Retrieved July 27, 2022, from https://aerospace.honeywell.com/us/en/about-us/news/2019/08/eliminating-dive-and-drive

Schumann, U. (2000). Influence of propulsion efficiency on Contrail Formation. *Aerospace Science and Technology*, *4*(6), 391–401. https://doi.org/10.1016/s1270-9638(00)01062-2

Schwartz, E., & Kroo, I. (2009). Aircraft design: Trading cost and climate impact. *47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*. https://doi.org/10.2514/6.2009-1261

Schwartz Dallara, E., Kroo, I. M., & Waitz, I. A. (2011). Metric for comparing lifetime average climate impact of aircraft. *AIAA Journal*, *49*(8), 1600–1613. https://doi.org/10.2514/1.j050763

Shine, K. P., Fuglestvedt, J. S., Hailemariam, K., & Stuber, N. (2005). Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change*, *68*(3), 281–302. https://doi.org/10.1007/s10584-005-1146-9

Skowron, A., Lee, D. S., De León, R. R., Lim, L. L., & Owen, B. (2021). Greater fuel efficiency is potentially preferable to reducing NOx emissions for aviation's climate impacts. *Nature Communications*, *12*(1). https://doi.org/10.1038/s41467-020-20771-3

Speight, J. G. (2017). Chemical Transformations in the Environment. In *Environmental Organic Chemistry for Engineers* (pp. 305–354). Butterworth-Heinemann.

Stevenson, D. S., & Derwent, R. G. (2009). Does the location of aircraft nitrogen oxide emissions affect their climate impact? *Geophysical Research Letters*, *36*(17). https://doi.org/10.1029/2009gl039422

Teoh, R., Schumann, U., Majumdar, A., & Stettler, M. E. (2020). Mitigating the climate forcing of aircraft contrails by small-scale diversions and technology adoption. *Environmental Science & Technology*, *54*(5), 2941–2950. https://doi.org/10.1021/acs.est.9b05608

Tilmes, S., & Mills, M. (2014). Stratospheric sulfate aerosols and planetary albedo. *Global Environmental Change*, 771–776. https://doi.org/10.1007/978-94-007-5784-4_11

Timperley, J. (2017, July 19). *In-depth: The challenge of using biofuels to cut transport emissions*. Carbon Brief. Retrieved from https://www.carbonbrief.org/in-depth-the-challenge-of-using-biofuels-to-cut-transport-emissions.

Transport Canada. (2012). (rep.). *Canada's Action Plan to Reduce Greenhouse Gas Emissions from Aviation*. Government of Canada.

Uniting Aviation. (2017, February 23). *Aviation is at the heart of sustainable development for Small Island countries*. Uniting Aviation. Retrieved July 20, 2022, from https://unitingaviation.com/news/economic-development/aviation-is-at-the-heart-of-sustainable-development-for-small-island-countries/

Unterstrasser, S. (2020). The contrail mitigation potential of aircraft formation flight derived from high-resolution simulations. *Aerospace*, *7*(170), 1–22. https://doi.org/10.3390/aerospace7120170

Zhang, J., Dransfield, T., & Donahue, N. M. (2004). On the mechanism for nitrate formation via the Peroxy Radical + NO reaction. *The Journal of Physical Chemistry A*, *108*(42), 9082–9095. https://doi.org/10.1021/jp048096x

Zhao, X., Taheripour, F., Malina, R., Staples, M. D., & Tyner, W. E. (2021). Estimating induced land use change emissions for sustainable aviation biofuel pathways. *Science of The Total Environment*, *779*. https://doi.org/10.1016/j.scitotenv.2021.146238

Zingg, D. W., & Gülder, Ö. L. (2016). Technology developments and renewable fuels for Sustainable Aviation. *Sustainable Development, International Aviation, and Treaty Implementation*, 17–31. https://doi.org/10.1017/9781316594216.002