Contrails

A policymaker's guide to reducing aviation emissions

SMALL WORLD CONSULTING

A report by

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Contents

Top 5 things to know about contrails

1. Contrails cause 35% of the warming effects of flights, measured over 100 years. But because they are short-lived, acting to reduce them now could reduce flight climate emissions by half by 2040.

2. Contrail management is far cheaper than 'sustainable' aviation fuel. Reducing contrails costs just \$5-\$25 per tonne of CO_2 equivalent. The best-case cost for sustainable aviation fuel is \$185 per tonne of CO_2 equivalent, and sustainable fuels are unlikely to meet demand at the scale and cost needed by 2050.

3. Very few flights need to change anything to address contrails. Small adjustments to just 1.7% of flight paths could reduce contrail impact by over 60%.

4. Even with very conservative assumptions, research has shown significant reductions in contrail warming can be achieved for less than €4 per flight ticket.

5. The aviation industry, technology providers, and academics are already working in partnership, researching and trialling solutions. They want to engage with policymakers to move to actionable, impactful policies fairly across the industry.

Top 5 actions to reduce contrail impact

1. The aviation industry must be compelled to focus on contrail management as the greatest priority for reducing its climate impact now. Any emission reduction enabled by switching to Sustainable Aviation Fuels will only be realised in decades to come. We do not have the luxury of decades to wait – or waste – before we address the climate crisis.

2. For all flights – particularly international ones, which have the greatest climate impact – it must become mandatory for the aviation industry to monitor non-CO_2 emissions and to collect and analyse data on weather conditions, particularly high-altitude humidity measurements.

3. Contrail management must become a mandatory part of the planning technology for all flights. Solutions are already being trialed by some companies within the aviation industry, which have made small adjustments to the flight paths, timings and fuel costs of a very small % of flights, resulting in dramatic contrail reductions.

4. Set fair payments for emissions impact by taxing frequent flyers, private aircraft use and damaging long-haul flights, and use these funds to support the aviation industry in effective contrail management.

5. Engage with the best-practice partnerships, such as the Contrail Impact Task Force, to bring policymakers together with the aviation industry, technology providers, aircraft and engine manufacturers, and academics who are already researching and trialling contrail avoidance.

Executive Summary

Reducing contrails – those silver streaks that form across cold, humid skies - is the closest thing we have to a silver bullet to dramatically reduce the climate impact of aviation.

Reducing contrail clouds and their warming effect can be actioned now, will only need to reroute less than 2% of flights, has technological solutions available, and already has the support and co-operation of key players in the aviation industry such as academics, flight-path providers as well as some airlines.

We can easily decrease contrail formation by around 60%. As contrails are responsible for 35-50% of a flight's climate warming effect, this means a 20-30% reduction of aviation's climate impact.

The policy landscape is forming around aviation's CO_2 emissions, including emissions trading and fuel standards. However, the main area is 'Sustainable Aviation Fuel' (SAF). This is highly unlikely to meet the industry's supply requirements by 2050, and the large land requirement for producing many SAFs casts serious doubt on their sustainability credentials, especially with increasingly extreme weather events and the resulting pressure on land.

Conversely, policies for aviation's non-CO_2 emissions aren't ambitious enough. The EU has implemented a monitoring, reporting and verification framework (MRV) for non-CO_2 emissions from 1 January 2025 but only for flights within the European Economic Area (EEA) and from the EEA to the UK and Switzerland. Long-haul flights won't be required to monitor until 1 January 2027. But emission reductions are possible now. Effective policies are the final part of the solution.

Policies needed for contrail reduction

Monitoring of the non-CO_2 impacts of all flights, including long-haul flights which have a bigger climate impact than short-haul ones due to their distance, duration and altitude. Monitoring provides more data to strengthen the models on which contrail management technologies are based, and lays the groundwork for future reporting on reductions.

All flight planning needs to include **contrail management** as standard. Technological solutions already exist, and the small number of flight adjustments needed to implement these solutions result in dramatic contrail reductions for very little cost.

Taxation of the whole aviation industry needs to reflect the cost of tackling the damaging impacts of contrails combined with CO_2 emissions. The UK and EU emissions trading scheme and any air passenger taxes need to include non-CO_2 emissions.

Even with efforts to reduce both CO_2 and non-CO_2 emissions, policy is needed to force a **reduction** in the number of flights taken. Here policymakers must recognise the disproportionate impact of frequent flyers and private aircraft, and place sufficient levies on them to force a reduction in this kind of flying. Such levies would also raise funds to help decarbonise other areas of the aviation industry and support climate vulnerable countries.

Effective **partnerships** across the aviation industry: technology providers, manufacturers and academic researchers are driving forward monitoring, modelling, planning and reporting. They are ready to engage with policymakers as the last piece of the puzzle needed to galvanise the whole industry towards action.

Introduction

The fossil fuel use underlying and propelling the global aviation industry has resulted in a buildup of CO_2 in the Earth's atmosphere, together with high levels of short-lived climate forcers such as contrails and nitrogen oxides which have resulted in extensive damage to the climate. The combined effect of these long- and short-lived climate forcers (SLCFs) is that aviation today accounts for at least 4% of global warming (Klöwer, et al., 2021) and potentially as much as 9% depending on the metric used to compare CO_2 and non-CO_2 effects. In 2023 there were 37.7 million passenger flights globally, up 17% from 2022 (International Air Transport Association, 2024) and, despite declining significantly during the COVID-19 pandemic, the industry has fully bounced back in some markets and is predicted to recover globally, and continue to grow, in the coming years (Sun, Wandelt, & Zhang, 2023). This paper will discuss the issues faced by the industry, assess the current proposed solutions, and help steer policymakers to make informed decisions that will enable the aviation industry to transition as part of the future green economy. Key to this is the massive potential offered by contrail management for creating significant and cost-effective reductions in aviation emissions over a relatively short period of time, which is critical if humanity is to stay within global targets on emissions levels.

The statistics around who is flying, and where to and from, are also critical in the process of highlighting the easiest path to reducing emissions. It is important to recognise that in 2018 only 11% of the global population travelled by air, and only 4% travelled internationally (Gössling & Humpe, 2020). Most of these flights were within the Global North, highlighting that while the climate crisis is happening worldwide, the actions required to tackle aviation emissions are much more localised and achievable. This is reinforced by the reality that only 1% of the world's population contribute around 50% of aviation CO_2 emissions, through frequent flying and long-haul flights. Studies have also shown that the probabilities of contrail formation are highest in the North Atlantic, followed by Europe, which adds to the weight of responsibility for action incumbent on a small demographic (Teoh, et al., 2024). Immediate actions targeting the worst-offending flights and routes could help bridge the gap between the current situation and the rollout of long-term decarbonisation strategies. This could be achieved through taxing flight distances, fuel consumption (from which, astonishingly, international aviation fuels are currently exempt) or frequent flyer levies. Recent research shows that within Europe, such measures could reduce the number of flights by 26% while raising €63.6bn in net tax revenues (Stay Grounded; New Economics Foundation; CE Delft; AdaStone Law, 2024).

As is the case in most industries, many factors are contributing to the delay in action. While the emissions relating to fuel burn in aviation are well established, other emissions associated with the flight parameters are much more complicated and an ongoing field of study. Accessing relevant data on the climate impacts of flying can be difficult, and often no data are collected at all. While some airlines are open to the prospect of stricter reporting regulations, strong policy will be critical in galvanising action from the various stakeholders in the industry.

What problems does the industry face, and what solutions are available?

The impacts of aviation are not limited to CO_2 emissions; several SLCFs are also cause for concern. The size of these impacts varies drastically, as do the methods available to reduce them. The three primary contributors to global warming from aviation are CO_2 (55%), contrail effects (35%) and NO_x (9%) based on the GWP100 metric typically used in reporting emissions (Lee, et al., 2021). It is important to analyse the solutions for tackling each of these within the context of their relative impact and unique properties. The remaining warming comes from the emission of soot (product of incomplete combustion), and water vapour with a slight cooling effect produced by sulphur dioxide (SO_2) reacting with the atmosphere. Given the small contribution these last two components represent, they are not discussed in detail here. However, their associated emissions (apart from water vapour) will be reduced through cleaner, more efficient fuels and engines in future generations of planes.

It is worth noting that the metric used has significant implications for the resulting picture characterising aviation emissions, particularly when considering contrails and other SLCFs. For example, using GWP20 (which assesses impacts over 20 years, rather than 100) suggests that the figure for non-CO_2 warming is twice that for CO_2. This issue is not unique to aviation and is prevalent throughout climate discourse, notably with agriculture and methane emissions. Despite this, a comprehensive analysis on the impacts of various metrics for aviation concluded that uncertainty on the choice of metric is not an obstacle for implementing contrail avoidance policies (Borella, et al., 2024).

CO_2

The harmful impacts of CO_2 emissions in the Earth's atmosphere are well documented and reasonably well understood by a general audience, and as such won't be elaborated upon here. Regarding the durability of these impacts, a proportion of CO_2 emissions in the atmosphere remains there for over 1000 years. The warming effects of CO_2 are cumulative as emissions build up over time, which is why mitigation methods often refer to keeping within a budget of CO_2 emissions over a given period. Achieving these budgets requires the successful implementation of long-term decarbonisation strategies. When discussing aviation, the primary discussion centres around sustainable aviation fuels (SAFs) such as biofuels and synthetic aviation fuels produced capturing carbon from the air.

In principle, these alternative fuels offer a lower-carbon alternative to traditional jet fuels. However, there are nuances between the fuel types and between the methodologies of refining those fuels. The claimed reduction in emissions primarily comes from a lifecycle assessment of the production supply chain; the process of combustion for alternative fuels – with some exceptions such as hydrogen – is often similar to traditional jet fuels. The method used to produce the fuel, and the source of the material (feedstock), are the basis for defining the overall reduction in emissions. The best production methods such as the Fischer-Tropsch synthesis (FT) have nearly 100% emissions-saving potential, on average, while the worst, for example hydro-processed fermented sugars to synthetic Isoparaffins (HFS–SIP) (also known as 'direct sugars-to-hydrocarbon', DSHC), hover around 50% emissions savings (Braun, Grimme, & Oesingmann, 2024). The largest variation comes from the feedstocks, where the best options such as municipal waste or agricultural and forestry residues can have upwards of 80-90% savings, while palm oil and corn grain can sometimes be worse than traditional jet fuel. In fact, when the full lifecycle for these biofuels is considered, many biofuel alternatives fall short of theoretical emissions savings due to indirect land use change (ILUC). The additional demand for agricultural land, which is already high to ensure future food security, will also be another lever contributing to the biodiversity crisis. The resulting habitat loss and pollution from growing these feedstocks will further reduce the ability of SAFs to contribute to a more sustainable aviation industry. The European Commission found that all vegetable-based biodiesel produced more emissions than fossil fuels – even 2-3 times more in the case of the biggest culprits: palm and soy oil – driving a demand for divestment from the worst-performing fuels (Rangaraju, 2021). With such variation, there is a need for clarity and strong regulation on which alternative fuels are considered sustainable. The EU's Renewable Energy Directive stipulates that in order to be defined as SAFs, alternative fuels must reduce emissions by 50-70% (relative to traditional aviation fuels) over their complete lifecycle, with the added requirement of avoiding negative environmental and socioeconomic consequences arising from changes to land use.

Synthetic fuels have similar considerations, mainly centring around high costs, the availability of renewable hydrogen and the feasibility of carbon capture technology. Research has shown that it is currently unlikely that carbon capture will reach the scale currently envisioned by existing decarbonisation pathways (Kazlou, Cherp, & Jewell, 2024) and as a result, relying on even more carbon capture for fuel production is unlikely to be feasible when attempting to decarbonise the sector. Provided the energy used is 100% renewable, synthetic fuels produced using green hydrogen have some of the highest potential reductions. There are, however, logistical challenges related to producing, transporting and utilising hydrogen in supply chains in general, not just within aviation. Fuels whose manufacture requires large quantities of renewable energy may also prove difficult to bring onstream at scale, due to the energy demand represented by a myriad of sustainable technologies – such as heat pumps and electric cars – which is already high and will grow, impacting on both local and international energy grids. In the long term, hydrogen stocks may naturally increase as a better way to utilise the excess energy characteristic of renewable energy systems may be to direct it towards hydrogen production, rather than dissipating this surplus energy as heat or selling it to neighbouring countries (Al-Ghussain, Ahmad, Abubaker, & Hassan, 2022).

These considerations culminate in the key questions of cost and the current capability of all the relevant strands that feed into aviation fuel supply chains to achieve the necessary emission reductions reflected by decarbonisation targets. The costs of these alternative fuels are currently much higher than those of traditional jet fuel, and even with projected policy support, most sustainable fuels cannot compete with traditional jet fuels on cost (O'Malley, Pavlenko, & Kim, 2024). Looking at the United States as a reference case for feedstock availability, in 2021 the Biden Administration introduced the U.S. Sustainable Aviation Fuel Grand Challenge, which set SAF production targets of 3 billion gallons by 2030 and 35 billion by 2050, which would be sufficient to meet aviation fuel demand. As it stands, projections suggest that production of environmentally positive SAFs may just meet the 2023 target of around 3.3 billion gallons by 2030, but is unlikely to meet the required 2050 levels. The key limiting factor is the availability of the right types of feedstock, and scenarios that could increase production to around 6.7 billion gallons by 2030 are nearly four times more carbon-intensive.

While the potential for CO_2 reductions through SAFs is immense, the feasibility of bringing production up to scale in a way that retains this reduction potential is uncertain, and implementation will require significant investment, policy engagement and time. **If the aviation industry is to successfully decarbonise, SAF will be a key piece of the puzzle. However, it is essential that this is not the only strategy implemented if we are to stay within our climate targets, not least due to the significant non-CO_2 components of aviation emissions**.

Contrails

While white streaks in the sky are a familiar sight for individuals living in areas of high air traffic, there is often very little understanding around contrail formation and the resulting impacts. As jet fuel is burnt during an aircraft's flight, CO_2 is emitted. A mixture of water vapour, soot and other particles (including NO_x) is also left in a trail behind the aircraft before dispersing. When local atmospheric conditions are sufficiently cold and humid, the water vapour can condense around the emitted particles, forming ice crystals. These contrail clouds typically disappear shortly after being produced; however, when conditions are particularly cold and humid they can persist, spread and form contrail cirrus clouds. It is these contrail cirrus (now referred to as contrails) that are the main concern, as they are the source of most of the non-CO_2 climate impacts.

When a contrail persists for several hours, the exact effect it has on the planet is driven by two opposing processes. Albedo is the measure of how much incoming radiation, such as that from our Sun, is reflected by an object like the Earth. Certain features of our planet, such as its polar icecaps and clouds, reflect some incoming solar radiation and create a cooling effect, raising the overall albedo. Through this, contrails can, given the right conditions, have negative warming potential by reflecting incoming sunlight. However, this only occurs during the day, when there is solar radiation to reflect. In contrast, clouds, including contrails, act like a blanket to trap some of the thermal energy being emitted by the Earth, which then warms the planet. The balance, at global level, between these albedo and blanket effects leads to overall warming close to or exceeding the impacts associated with CO_2 emissions themselves, depending on the metric used. Given that GWP100 generally underestimates the impacts of SLCFs, the impacts of contrails are understood to be comparable to that of CO_2 from aviation, one of the most carbon-intensive industries, and one that is projected not to shrink but to grow in the coming years, posing tremendous climate-related risks for the future.

Since contrails are an example of an SLCF, the warming effects they generate are instantaneous and relatively short-lived. This means that unlike when trying to tackle the cumulative effects of CO_2, techniques for managing contrails could significantly reduce global temperature rise in the short term, even while long-term decarbonisation strategies are scaling up. The current landscape on this, from research to implementation of contrail management, is explored below in 'Where are we with action on contrails?'.

NO_x

The contribution of nitrogen oxides to climate impacts compared with CO_2 and contrails, while notably smaller, are still significant enough to warrant mitigation actions. Low-NO_x combustor technology has existed for some time in an aviation fuel context, and can reduce the associated emissions by at least 60%, but due to the additional weight and cost of these technologies, they have not seen significant rollout across the global air fleet. In fact, engines that are more fuel-efficient (which are preferable, since they reduce CO_2 emissions and contrail formation) have often been found to emit more NO_x than less efficient ones (National Research Council, 2002). More recent research has shown that focusing on advances in fuel efficiency may be more beneficial for the climate than targeting NO_x reductions (Skowron, Lee, León, Lim, & Owen, 2021). When considering timescales of action, NO_x is unlikely to be reduced significantly in the short term, but this area will naturally come into sharper focus when other critical measures have been implemented.

Where are we with action on contrails?

The discussion around contrails has been active for many years; the significance of these impacts relative to the CO_2 emissions has been discussed by the IPCC since the start of the millennium (IPCC, 1999). Since then, as the global sustainability agenda has progressed and started to be adopted by the airline industry, the science of contrails has begun to influence both new and existing industries, as well as becoming a question for policy at various scales of government.

The last 20 years have seen huge advances in scientific understanding around contrails: their impacts, formation and the ability to predict them through modelling. There is no single model that is universally applicable to all the needs of the industry, but instead several models serve distinct roles. Generally, most models require varying degrees of data on flight trajectories, meteorological detail, aircraft properties and fuel properties. A notable exception would be using AI to analyse primarily satellite imagery, and training these machines to identify where contrails have been formed and might form in the future. This approach bypasses the otherwise considerable data requirements, although comes with its own limitations relating to contrail identification and the availability of high-quality satellite data, as well as the general concerns around the use of AI and its sustainability.

One of the most widely used models is the Contrail Cirrus Prediction Tool (CoCiP) released in 2009 (Schumann, 2009). More recently, through a collaboration with Imperial College and Breakthrough Energy, this model has been adapted to a package called Pycontrails (pycontrails, 2024). The success of the model is characterised by its requiring small amounts of computing power, allowing for many simulations to run over short periods of time, in a way that matches the requirements of the industry for day-to-day operations. Pycontrails also has more parameters than any other model on the market, allowing the user to drastically improve the accuracy of modelling when the data quality and quantity are high. Like many models, it depends heavily on the quality of weather data, particularly high-altitude humidity measurements. The availability of this data is a current limitation in the industry, and any progress on this front would deliver far more accuracy in contrail predictions.

Thanks to advances in modelling of contrails, several companies have incorporated them into either new or existing software. Flight plan providers such as FLIGHTKEYS have implemented Pycontrails in their existing suite of services, and other providers are working on similar solutions. Likewise, some airlines work with third-party providers such as SATAVIA and Estuaire, who use their software to suggest alternate flight paths, in parallel with quantifying avoided emissions post-flight. All these solutions are part of the pre-flight procedures typical to everyday operation of airlines. However, they are limited by an inability to react to real-time changes in conditions during the flight. These flight plans generally consist of identifying areas of high contrail risk and deviating either horizontally or vertically to avoid them. These plans and decisions need to consider whether the extra fuel used to deviate has a greater warming effect than the contrails avoided. Studies have shown that in some areas as little as 2% of flights are responsible for 80% of the global warming effect of contrails, which means that tactically diverting just 1.7% of flights could reduce effective forcing by around 60% (Teoh, Schumann, Majumdar, & Stettler, 2020).

Practical trials such as Google Research's Project Contrails, working with American Airlines over 70 flights, demonstrated a 54% reduction in contrails at a cost of only 2% fuel, showing good agreement with the models. The study also found costs of around \$5-25/tCO_2e, while SAF was estimated to cost around \$185/tCO_2e of reduction in the best-case scenario (Capaz, Guida, Seabra, Osseweijer, & Posada, 2020) highlighting how cost-efficient contrail management can be as an emission reduction technique. Contrail management and the rollout of SAFs are not competing, but in fact they complement each other in tackling aviation's overall footprint. There is, however, a cost incentive to reducing warming as soon as possible, given that in 2023 nearly all indicators of progress on climate action (41 out of 42, covering power, buildings, land, agriculture etc.) were not on track to reach 1.5°C-aligned targets. The climate breakdown likely to ensue from this failure to reduce emissions will only make decarbonisation harder, result in more damages, and wreak disastrous consequences for people all over the world. It is here that contrail management, implemented now, can enable a smoother transition for the industry at a comparatively low price.

There have been fewer in-flight trials for live contrail management, with EUROCONTROL's Maastricht Upper Area Control (MUAC) collaboration with The German Aerospace Centre (DLR) being the notable exception. The trial showed that it was feasible for air traffic control to implement contrail management with low impact on the capacity of flights and will likely be a reference case as the technology advances with further trials in the coming years.

The policy surrounding contrails is currently relatively limited compared to the research and industry activity in the sector. Typically, policy around emissions follows a monitoring, reporting and verification framework (MRV), followed by allowance trading. The EU Emissions Trading System (EU ETS) includes measures around reporting and measuring CO_2 emissions from flights within the EEA. This scheme does not include any flights to and from the EEA to an outside destination, which is a serious downfall given that long-haul international flights are often the worst offenders for creating contrails. The current exclusion is due to the existence of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which is projected to cover 128 states and aims to standardise regulation aimed at offsetting and reducing aviation-related CO_2 emissions. The effectiveness of this scheme remains uncertain, with a full review due in 2026 by the European Commission to determine whether the EU ETS needs extending to include extra-EEA CO_2 monitoring. A similar MRV for intra-EEA non-CO_2 emissions will be implemented from 1 January 2025; meanwhile the requirement to report on non-CO_2 or CO_2 emissions for all flights to and from Europe to an outside destination (except for flights to the UK and Switzerland) are postponed from having to report on non-CO2 emissions until 2027. The European Commission will report on the results of the MRV by 31 December 2027, and, where appropriate, create a legislative proposal to address non-CO_2 emissions from aviation by expanding the scope of the ETS to include non-CO2 aviation effects. The exclusion of extra-EEA non-CO_2 from the ETS would introduce unnecessary and climate damaging delays to the tackling of these emissions given that we know contrail warming per mile is 71% higher in the North Atlantic than Europe (García & Toth, 2024).

Overall, a large chunk of the data needed is still missing, and filling the gap will require policy. Likewise, policy for financing and encouraging the technological developments required for a successful transition of the industry to meet climate targets is currently lacking. This includes industry-funded price support mechanisms for the production of SAFs; such systems have also been shown to help reduce the effects of contrails, and will complement the active management of contrails in the future (Voigt, et al., 2021). To ensure that responsibility is not shifted to consumers, policy implementing a cap on fare increases could make sure costs are met primarily by the aviation industry. When considering just contrail management, research has shown that meaningful reductions can be achieved for less than €4 per flight ticket (García & Toth, 2024).

While the potential for contrail management to reduce non-CO_2 emissions within the industry is being recognised across the sector, there is insufficient cohesion between all the relevant stakeholders, particularly regarding policy. Some notable exceptions exist, such as the Contrail Impact Task Force which recently released a very comprehensive overview of the whole industry, bringing together research, airlines, contrail management providers and some policymakers (Contrail Impact Task Force, 2024).

Where we can be: a policymakers' action plan

The scale of change required to bring aviation into line with the Paris agreement is immense, and is simply not achievable without co-operation between all stakeholders. When assessing the decarbonisation pathway for aviation, the International Council on Clean Transportation (ICCT) determined, in its most optimistic 'breakthrough' pathway for CO_2 emissions, that aviation would consume a proportional carbon budget equivalent to 1.75°C of global temperature change. To stay within 1.5°C would require net-zero emissions by 2030, a level of ambition far beyond any existing commitments (Graver, Zheng, Rutherford, Mukhopadhaya, & Pronk, 2022). Failure to stay within the 1.5°C limit will be catastrophic for people, planet and the industry itself, which will be impacted just as much as any other by changes in the global climate. It is clear, then, that the reduction of non-CO_2 emissions is not just complementary to reducing CO_2, but integral to minimising the climate impacts of the industry.

Yet non-CO_2 emissions remain largely overlooked in policy frameworks, despite the availability of relatively straightforward and well-researched methods to address them, if given the right support. The European Union has taken some steps forward: starting in 2025, member states will monitor and report non-CO_2 emissions under measures introduced by the EU Emissions Trading System Directive, which recognised that ignoring non-CO_2 effects is no longer tenable. However, this falls short of capturing the real scope of contrail emissions due to its omission of extra-EEA monitoring. This omission risks undermining the EU's broader efforts to decarbonise its aviation sector, and could weaken its international leadership on climate action.

Policies to manage and mitigate contrails

In the short term, contrails management is the clear path that should be taken by the industry. Strong policies are urgently needed to **monitor** and quantify contrail formation, to better understand the scale of the problem and to assess the effectiveness of mitigation strategies. Transparent and accurate data collection is essential, and policymakers must push for comprehensive international monitoring frameworks. While the EU has made strides forward with its upcoming non-CO_2 monitoring framework, there is a chance to lead by implementing more ambitious policies that include action in relation to long-haul international flights, where contrail formation has even stronger climate impacts.

Monitoring and reporting, however, are only the foundation. To effectively mitigate contrails, proactive measures must be incorporated into flight operations. One priority is to embed contrail management into all flight **planning** as a standard procedure, whether managed internally by airlines or through third-party companies. This would require the development of clear, standardised guidelines for assessing net-positive flight path deviations. These guidelines should emphasise principles such as flying the most fuel-efficient routes, and making small altitude adjustments (e.g. +/- 600m) only when there is a high likelihood of forming warming contrails, and when the additional fuel burn is minimal compared to the avoided warming. Studies have demonstrated that such measures can prevent over 50% of flights becoming contrail-forming without compromising safety or significantly increasing CO_2 emissions (Roosenbrand, Sun, & Hoekstra, 2023).

Additionally, **scheduling** policies to reduce contrails during night flights offers significant potential for climate benefits. Night-time contrails are exclusively warming, as the absence of sunlight negates their cooling effects. Policies that incentivise daytime flights or discourage night-time operations in contrail-prone conditions would deliver clear emission reductions. While changes to scheduling can involve complications for maintaining fleet safety, this just highlights the need for more data to identify which key flights to modify in order to achieve optimum emission reductions while balancing other industry concerns.

Finally, attention must be focused on high-impact parts of the world such as Europe and the North Atlantic, which experience heavy flight traffic and frequently-favourable conditions for contrail persistence. Policies targeting these regions could include mandatory adjustments to flight altitudes, rerouting under specific atmospheric conditions, or even broader strategies such as reductions in the volume of flights. With coordinated action, these measures could significantly reduce contrail-induced warming, complementing efforts to reduce CO_2 emissions and enabling the aviation sector to take meaningful steps toward aligning with global climate goals. **Recent studies have shown that even with very conservative estimates, there is potential to halve contrail emissions by 2040 (García & Toth, 2024)**.

Policies for equitable and effective aviation emission reductions

Given the projected growth in flight numbers, **reducing** flights will be essential wherever possible. A disproportionate share of emissions is being produced by a relatively small portion of the global population. Frequent flying will become harder to justify in a world with greater virtual connectivity than ever, and that offers more ecologically friendly ways of working and communicating over large distances. Policy centred around equity of flight emissions, and limiting access to flying for those who currently abuse the system, could help greatly to ease pressure on the whole system without large investments of capital and time. This could be achieved through a frequent flying levy, which would discourage excessive flying as well as raise valuable funds required to decarbonise the economy.

Further **funding** could be achieved through making taxation of the industry proportional to the damages it is causing, and calculating tax based on the impact of both CO_2 and non-CO_2 emissions. This could be achieved through a duty on jet fuel or through a distance-based system such as the UK's Air Passenger Duty (APD). The success of these measures will be linked to policy ensuring that the funds raised go towards decarbonising the industry, ensuring that charges are commensurate with the impact of the flight involved, and that costs are not forced entirely onto the consumer. A perfect example of policy falling short of this would be the UK and EU emissions trading schemes, which both currently exclude non-CO_2 when considering aviation.

These funds can be used for **developing** an industry capable of achieving the change required to stay within existing climate targets. While some of this should be directed to support the development of SAFs, they are only one part of the solution. Funding toward improving the efficiency of engines in new generations of planes would result in less fuel burn and produce smaller quantities of SLFs. Equally, there is a need to ensure that all flights are working toward a common goal of reducing emissions. This can be achieved by ensuring that funds are used to develop and install sensors on flights capable of collecting data (such as humidity) which will be essential for advancing our understanding of the climate impact of aviation and steering actions to where they will have the most impact.

While the challenges faced by the industry are enormous, this potential for innovation, collaboration and radical change should be the focus for the international community. Strong governance will be the critical factor in ensuring a successful 'breakthrough'. **Contrail management has the potential to set the standard for how the transition can and should be handled in the short term, while long-term measures – such as the adoption of cleaner jet fuels, sustainable aviation fuels, zero-emission technologies, and reductions in damaging high-impact flights – will work in tandem to create a comprehensive pathway toward our climate goals.**

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