Contrail Impact Mitigation Task & Finish Group

A Strategic Framework for UK Contrail Impact Mitigation

Abstract

Aviation's contrail climate impact is significant, yet Contrail Impact Mitigation remains fragmented and stuck in a "project-by-project" phase. This report assesses the UK's national capability to solve this challenge, synthesising findings from seven key work-streams using a five-level Capability Impact Mitigation Framework (CIMF). The analysis reveals the UK is at Level 2 ("Reactive"), blocked from achieving a standardised (Level 3) approach by critical, cross-cutting barriers, including data gaps, scientific uncertainty, and the lack of a coordinating body. A gap analysis confirms that global trials have been too small and have overlooked the strategically vital North Atlantic airspace. This report provides a clear strategic roadmap to break this impasse through three key priorities: establishing a permanent governance body, using the CIMF to synchronise industry, and implementing large-scale UK trials, and developing the enabling policy and operational procedures.

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Foreword

I am delighted to present the conclusions and recommendations of the Contrail Impact Mitigation Task and Finish Group for the United Kingdom Jet Zero Task Force. Contrail Impact Mitigation remains a topic of exploration and understanding for scientists, industry, authorities and regulators, encompassing the fundamental study of contrails themselves and strategies for reducing their warming impacts. This creates an environment of uncertainty that naturally leads to diverse and opposed opinions, particularly concerning the extent to which contrail mitigation needs to be implemented, considering the likely impact of increased CO_2. Our group successfully embraced the range of perspectives, and combined them with the essential need to inform the UK Government decision-making, and leverage the role of the UK given its strategic geographical and airspace positioning.

The Task and Finish Group has focused on the operational capabilities, given the current status of the scientific maturity and understanding. We have not addressed the fundamentals of contrail science because this is already addressed by research projects globally and will evolve at its own pace. Our focus has been on mitigating the potential impact of contrails in a manner that can be implemented by and across the aviation stakeholder community.

Our baseline analysis of the existing landscape has highlighted the maturity of impact mitigation trials performed globally up to today. This analysis has identified the areas in contrail mitigation that have been explored and the areas (physically, operationally and scientifically) that need to be further matured. It is clear that the UK's geographic location and airspace authority over the North Atlantic becomes a focus for emphasis in the overall impact of contrail mitigation; this is due to the quantity of air traffic, the weather conditions, the greater number of night flights and the long flight durations. The analysis also highlights the need to further support the science by providing means to physically validate the reduction in contrails instead of only utilising models. A series of physical navigational avoidance trials has been identified within the NATS airspace, allowing for increased maturity and complexity.

The trials will develop the UK's operational understanding, and support the scientific evidence required for future mitigation measures. Nevertheless, these trials will only mature certain workstreams, leaving other key areas for future development. Careful trial design presents an opportunity to advance several related workstreams in parallel, including weather data and analysis, contrail observation, fuel/time/contrail trades, climate impact assessment, and technology impacts. These additional dimensions each need to mature to support an operational level of mitigation maturity.

We have collectively created a framework based on proven transformation principles that addresses all of the topics outlined above with respect to the stakeholder community that can mature them. Such a model provides a framework that allows the UK, in an international context, to map where it is today and the fundamental steps that must be achieved to implement a credible and defendable Contrail Impact Mitigation.

None of this would be possible without the key stakeholders across the aviation industry to bring their personal and organisational knowledge and experience. This has been essential to create the knowledge base upon which we have built a shared understanding. To progress this work, a permanent governance model with some additional stakeholders is recommended.

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Executive Summary

Aviation's climate impact extends beyond CO_2. Non-CO_2 effects, particularly contrails, represent a potentially significant portion of the sector's total warming influence. Recognising this, the Jet Zero Taskforce established the Contrail Impact Mitigation (CIM) Task and Finish Group to assess the UK's capability to address this challenge and recommend a strategic path forward.

This report presents a consolidated national assessment, synthesising findings from seven key workstreams across the aviation ecosystem. The assessment uses a Contrail Impact Mitigation Framework (CIMF), a five step model to benchmark capability from Level 1 ("Unknown, not practised or not controlled") to Level 5 ("Optimising").

The analysis reveals that the UK's contrail mitigation capability is currently at Level 2 ("Reactive, known, project-by-project"). A gap analysis of global trials confirms that efforts remain fragmented and small-scale. Crucially, no workstream has yet achieved Level 3 ("Proactive, standardised"), which signifies consistent, defined processes. Key barriers include a lack of standardised climate calculation methods, deficiencies in upper-atmosphere weather data, a lack of automated flight planning tools, and the absence of an enabling regulatory framework, including an agreed methodology for Monitoring, Reporting, and Verification (MRV).

Progress requires a coordinated, "whole system" approach, as each workstream's maturation is critically dependent on the others. For example, airlines cannot implement standardised avoidance without the necessary tools and procedures; climate models cannot be validated without data from real-world trials; and significant industry investment is unlikely without clear policy signals from the UK Government.

Based on these findings, the report proposes four strategic priorities:

1. Establishing a Permanent Governance Body to own the national roadmap.
2. Utilising the CIMF to guide investment and track progress.
3. Implementing phased UK trials to address gaps and build capability.

4. Developing the enabling policy and operational procedures for CIM.

This report provides a clear assessment of the current state and a strategic roadmap to accelerate the UK's capability in contrail impact mitigation. It aims to ensure efforts are coordinated, effective, and aligned with the UK's net-zero ambitions.

1.0 Introduction

This report provides a national assessment of the United Kingdom's capability to mitigate the climate impact of aviation contrails. It synthesises findings from seven key work streams to establish a collaborative framework for Government and industry, charting a course from the current reactive state to a future of optimised mitigation.

The assessment proposes a framework for assessing maturity to benchmark current UK practices for Contrail Impact Mitigation across the aviation sector. A Capability framework is a widely used management tool that breaks down a capability's development into a series of defined, sequential maturity levels. Its purpose is to provide a clear and objective measure of how an organisation's processes evolve, moving from an initial state without formal processes to one that is proactive, measured, and continuously improved. This framework allows us to evaluate contrail mitigation capability in a standardised way across five distinct levels, from Level 1 to Level 5 (see Table 1 below).

The Five Maturity Levels of the Contail Impact Mitigation Framework (CIMF)

Level	Level Name	Description within the Contrail Mitigation Context
1	Initial / Unknown	No formal processes or coordinated activity exists. Contrail impact is not a consideration in standard operational, design, or regulatory practice.
2	Managed / Reactive	Capability is developed through isolated, project-by-project trials. The focus is on gaining initial experience and understanding in an uncoordinated environment.
3	Defined / Proactive	Organisations implement formal, standardised processes and tools based on validated trial data, enabling a consistent and proactive approach to mitigation.
4	Quantitatively Managed / Measured	The performance and climate impact of the standardised processes are actively measured and monitored using agreed-upon metrics and KPIs (Key Performance Indicators).
5	Optimising	A continuous improvement loop is established, using performance data to proactively refine and optimise mitigation processes, technology, and regulations for

maximum effectiveness.

Table 1. The Five Maturity Levels of the Contrail Impact Mitigation Framework (CIMF)

The analysis reveals that the UK's contrail mitigation capability is in its early stages. The assessment placed most workstreams at Level 2, characterised by isolated, project-by-project trials. Crucially, no work stream has yet achieved Level 3, which would signify the implementation of proactive, standardised processes. The current maturity levels are:

- Aircraft/Engine OEMs: Level 2
- Airline Operations: Level 1
- Weather Data: Level 2
- Climate Impact: Level 2
- Air Navigation Service Provider (ANSP) Operations: Level 2
- Regulation: Level 1
- Fuel Standards: Level 2

This low overall maturity reflects systemic challenges, including critical data and validation gaps, the lack of standardised tools and procedures, and the absence of a dedicated regulatory framework.

This report details the methodology behind this assessment, including the CIMF (Chapter 2) and a gap analysis of existing global activities (Chapter 3). This analysis confirms that global trials to date have been small-scale and fragmented, with a key gap in large-scale validation over the North Atlantic, a region of high importance for the UK. It then elaborates on the specific findings for each of the seven key workstreams, outlining their current maturity level, justification, and a strategic roadmap required to achieve Level 5 capability, highlighting critical interdependencies (Chapter 4). Finally, the report concludes with strategic recommendations designed to accelerate the UK's progress towards effective contrail mitigation (Chapter 5).

2.0 Methodology

This section outlines a structured methodology to develop, manage, and continually improve a collaborative process for contrail impact mitigation. The CIMF is a five-level model designed to help organizations assess and improve their mitigation processes. The CIMF's staged structure is inspired by the maturity-level concepts found in established process improvement and data management frameworks like CMMI®, BPMM™ and DMM™, and informed by a survey of past industry trials and projects and the workstream findings described in sections 3 and 4.

A key feature of this structure is that it allows different workstreams to set formal requirements for each other. This creates the conditions the group needs to define and achieve the next maturity level. This provides a shared framework to move from initial disjointed efforts to a predictable, standardised, and optimised system. The core idea is to progress through the five distinct maturity levels, with each level building a more disciplined and capable foundation for the next.

2.1 Capability Impact Mitigation Framework (CIMF)

This framework breaks down the development of contrail mitigation capability into five levels.

Level 1: Unknown, not practised or not controlled.

- **Description**: The initial state with no formal processes. Contrail impact is not a consideration. Collaboration is informal and reactive. Success depends on individual efforts, not a stable, agreed process.
- **Features introduced:** None.
- **Governance**: No formal oversight.
- ***Example****: Efforts are disjointed and uncoordinated. A single airline's sustainability team might analyse public weather data to suggest a set of trial diversions. Separately, a university research group publishes a paper on improved contrail modeling. An aviation authority monitors atmospheric conditions for its own purposes. These actions remain unlinked.*

Level 2: Reactive, known, project-by-project.

- **Description**: Organisations develop capabilities through isolated, uncoordinated trials. Each organisation focuses on their own work: Planning tasks, monitoring progress and checking quality.
- **Features introduced:**
  - **Project-level Management.**
  - **Quality Control:** Within each organisation.
  - **Configuration Management:** Controlling versions of work where models, data, tools need to be shared.
- **Governance:** Project-level oversight within each organisation
- ***Example****: This level reflects some current trial schemes. For instance, an airline manages contrail mitigation through a distinct project, with its own internal plan for how its pilots and dispatchers receive and interpret contrail forecasts from a partner. They monitor their own adherence to their plan and track their own results. While they coordinate with the forecast provider, the primary focus is on each organisation managing its own internal process.*

Level 3: Proactive, standardised.

- **Description**: Organisations implement formal, standardised processes and tools based on validated trial data. The collaboration moves from project processes to shared processes. Organisations define a single shared set of standard processes for contrail mitigation
- **Features introduced:**
  - **Shared Standards**: Common processes for all organisations to follow.
  - **Organisational Improvement Working Group:** To manage and improve the shared standards/processes.
  - **Shared Capabilities:** Central repositories for models and data (e.g. pyContrails[1], ContrailNet[2]).
- **Governance:** Introduction of a Joint Governance Body.
- ***Example****: This represents an evolution of current trials into a formal, multi-party system, involving collaborations between technology providers, major airlines, and climate research groups (i.e. a formal multi-party system). All participating airlines and ANSPs agree to use a common contrail forecasting model and a single, standard procedure for*

[1] https://py.contrails.org/
[2] https://www.eurocontrol.int/news/eurocontrol-launches-contrailnet-new-network-create-common-repository-contrail-observation

requesting, verifying, and implementing flight plan adjustments across a specific airspace.

Level 4: Quantitatively Measured and controlled.

- **Description**: The collaboration actively measures and monitors the performance and impact of the standardised contrail avoidance processes..
- **Features Introduced:**
  - **Quantitative Measurements:** Shared, measurable performance data
  - **Performance Baselines:** That is the baseline against which performance measurement must occur.
- **Governance**: Joint Governance Body - develop process for measuring contrail impact mitigation in agreed, standardised units against a baseline.
- ***Example****: The collaboration focuses on meeting regulatory requirements. The group's quantitative objective is to ensure all participating airlines can report their contrail data accurately. They track required metrics required by the reporting framework, such as flight trajectory data, fuel consumption per flight, and modelled contrail distance/climate impact in agreed, standardised units. This data is compared against performance baselines and objectives to predict success, manage the collective reporting performance, and ensure regulatory compliance.*

Level 5: Optimising with active feedback.

- **Description**: A continuous improvement loop uses performance data to measure impact, identify necessary improvements, and refine and optimise processes, regulations, and technology to reduce contrail impact.
- **Features Introduced:**
  - **Ongoing Performance Management:** Setting and proactively managing contrail impact mitigation goals
  - **Causal Analysis / Resolution:** A systematic approach to fix cross organisation issues and replicate successful ways of working.
- **Governance**: Joint Governance Body - Now focuses on optimisation and iteration to achieve contrail impact mitigation goals (reducing the net warming effect caused by contrails, measured against an agreed, **standardised unit of climate impact dependent on the purpose)**

- ***Example:*** *Using aggregated data from the reporting scheme the joint governance body identifies that contrail forecasts in the North Atlantic Track system are consistently less accurate than in other regions. They perform a causal analysis, find the root cause, such as a flaw in processing humidity data. They sponsor an innovative update to the shared model, pilot it, and measure a significant accuracy improvement before deploying it to all partners.*

2.2 Joint Governance Body

A critical element for the success of this framework is the establishment of a joint governance body (from Level 3 onwards). Given the diverse and sometimes competing interests of the stakeholders, this body should operate as a neutral entity, independent of sole leadership from an existing organisation. Its primary role is to own the shared process, oversee the implementation of this framework, and progress the collaboration through the maturity levels.

To be effective this body must include representation from all key stakeholder groups representing seven key workstreams:

- **Stream 1: Aircraft & Engine Technology - Aircraft OEMs, Engine OEMs**
  - Provides data on aircraft performance, engine characteristics, and design constraints essential for contrail modelling.
- **Stream 2: Airline Operations - Airlines, Airports, Flight Planning, Pilots Association**
  - Provides the operational perspective, user requirements, and business case reality. Develop and integrate the necessary software tools for dispatchers and flight crew to plan and execute avoidance maneuvers.
- **Stream 3: Climate Impact - Academia, Research Bodies**
  - Provides independent scientific validation, ensuring the process is effective in mitigating climate impact.
- **Stream 4: Weather Data - Contrail forecast and Meteorological Service Providers**
  - Delivers core scientific models, atmospheric data, and verification capabilities.
- **Stream 5: ANSP Operations - Domestic and Transatlantic ANSPs**
  - Ensures airspace safety, manages traffic flow, and handles the operational feasibility of flight adjustments.
- **Stream 6: Regulation - Regulators, Aviation Authorities**
  - Defines the overarching safety, policy, and compliance framework.

- **Stream 7: Fuel & Standards - Fuel Producers, SAF (Sustainable Aviation Fuel) Providers**
    - Offer data on fuel properties and how different SAF blends impact contrail formation.

2.3 Gate Process

Each of the seven workstreams will have their own inherent challenges in uncertainty, data quality, availability at scale, operational feasibility, consistency. The CIMF requires that each workstream reaches maturity through a formal gate process to demonstrate both maturity of knowledge and achievement of confidence in any one level before being able to progress effectively in the next. Therefore, this framework does not stipulate a separate uncertainty management process. Instead, the governance body should place requirements on each workstream to define appropriate ways to advance through the CIMF stages, capture uncertainties, assure quality and manage risk.

2.4 Framework Benefits

With a CIMF for mapping maturity and a joint governance body in place, this could benefit the contrail impact mitigation process development by:

- **Managing complexity through sharing standards & processes:** It creates a standard structure for collaboration and promotes the development of shared processes and standards. This builds the confidence necessary to act on shared data in a complex, multi-organisation environment.
- **Delivering operational reliability:** The model is evolutionary, promoting synchronised development across multiple streams. This path allows the collaboration to mature from basic processes into a predictable and reliable system, which is essential for aviation.
- **Reducing cross organisational risks:** It requires the formal identification and management of cross-organisational risks from an early stage, reducing the chance of unexpected problems.
- **Enabling continuous improvement:** The framework moves the collaboration through maturity levels, and by Level 5 provides the structure to use data to predictably manage and continuously optimise the contrail mitigation process.

3.0 Global Gap Analysis

3.1 Introduction

Contrail avoidance trials are not new; several have been conducted in the last five years. The JZTF CIM T&F group has identified eighteen global trials since 2020, with at least 10 largely complete, six in progress, and two in an advanced stage of planning. Such work, with inputs from ANSPs, airlines, academia, leading research institutes, and technology companies, combines some or all of the following elements:

- Weather forecasting
- Integration of forecast with flight planning tools
- Identification of contrail likely zones
- Optimisation of flight plans
- Integration with operations
- Flight execution
- Analysis of results

In some cases, trials reported as contrail avoidance have this as a secondary or tertiary objective. For instance, the Contrail Optical Depth Experiment (CODEX) trial involving the National Aeronautics and Space Administration (NASA), GE Aerospace, Aerospace Carbon Solutions (previously Satavia) and the German Aerospace Centre - Deutsches Zentrum für Luft- und Raumfahrt (DLR) used NASA's Gulfstream G-III research aircraft and GE's Boeing 747 flying testbed as part of technology development.

For the Virgin 'Flight 100', a transatlantic flight operated on Zero Emissions Flight with 100% SAF, operators considered a contrail forecast during the flight planning process, assigned but the flown flight path cruised at 40,000 feet for operational reasons rather than specifically to avoid Ice Super Saturated Regions (ISSRs).

Work to date has already partly demonstrated the concept. In many cases, these trials showed fewer contrails and the potential for lower contrail-induced warming. The findings regarding CO_2 were more mixed. Rather than discussing the results, this section considers possible gaps in the work completed to date. In turn, this aims to help identify scope for more ambitious trials that deliver greater impact.

Addressing Fuel Penalties in Contrail Management

Some quarters have expressed concern that contrail management trials carry the risk of significant fuel penalties, as aircraft must fly above or (more likely) below their "optimum" flight planned altitude. This is often cited as a reason not to proceed with large-scale trials.

However, during real-world commercial air transport operations, an aircraft cannot fly at its theoretical "optimum altitude" to achieve a "minimum fuel" operation. To do this would require a "cruise-climb" flight profile. This is impossible in practice, due to the need for aircraft to fly at fixed flight levels for Air Traffic Control coordination.

Putting Fuel Figures in Context

For context, consider the relative magnitude of potential fuel penalties versus the aircraft systems' ability to register those values. An aircraft's flight management computer typically calculates its fuel predictions to the nearest 100kg.

Additionally, consider the magnitude of typical components of an aircraft's flight planned fuel load:

- A large wide-body two-engine aircraft will burn in the region of 45,000kg of fuel for a 7-hour flight. The taxi fuel allowance might be between 700kg and 1,100kg (1.5% - 2.4% of the total), depending on the complexity and congestion of the departure and destination airports.
- A medium single-aisle two-engine aircraft will burn in the region of 5,000kg of fuel for a 2-hour flight. The taxi fuel allowance might be between 200kg and 300kg (4% - 6% of the total), again depending on airport complexity.

In other words, the magnitude of any fuel penalty is likely to be significantly lower than the typical amount of fuel used during taxi. It may even be below the level of accuracy the aircraft's flight management computer is able to display to the pilots.

Operational Feasibility

A number of real-world contrail management trials have indicated that fuel penalties are minimal, especially when pre-tactical interventions are carried out. Moreover, pilot operational experience suggests that long-haul flights (e.g. trans-Atlantic) provide an opportunity to significantly reduce fuel penalties caused by flying above or below the flight planned cruise altitude.

During normal airline operations, it is common for aircraft to deviate vertically and/or laterally from the flight planned route for extended distances. This might be due to other aircraft occupying the cruise altitude, or weather phenomena such as turbulence or thunderstorms. In such circumstances, pilot Standard Operating Procedures (SOP) are designed to allow for the in-flight adjustment of flight profiles (speed, altitude, lateral route) to minimise fuel penalties and delays.

Therefore, significant additional pilot training should not be required for the implementation of contrail management trials. Tactical deviations for contrail avoidance should be handled in the same way as other weather- or traffic-related deviations, as described above.

3.2 Geography of Contrail Avoidance

A review of trials to date shows that these trials have overwhelmingly focused on two geographical areas. Considerable work has taken place in Northern Europe, centred around the Maastricht Upper Area Control Centre (MUAC), which manages the upper airspace (from 24,500 to 66,000 feet) over Belgium, the Netherlands, Luxembourg and north-west Germany.

Other trials have focused on departing European aircraft travelling further afield, beyond the Benelux area and into North Africa and the Middle East. However, these have been modest in scale and still continental in nature.

The other principal geographic focus is from a small number of North American trials that are continental or transcontinental in nature. This includes work by the US carriers Delta and American Airlines, with support from others, including Google, Breakthrough Energy and the Massachusetts Institute of Technology (MIT).

A consequence of this European and North American focus is that the trials take place in highly congested airspace. For instance, MUAC is one of Europe’s busiest and most complex airspace areas. While this airspace is highly congested, it should be noted that contrail trials have mainly taken place at night when traffic levels are significantly lower. The conventional view is that vertical manoeuvring in such congested airspace is more restricted. In turn, this may alter the dynamic between horizontal and vertical deviations and lead to a greater impact on flight-path length and fuel consumption. There is also possibly more disruption in flight and departure times, and landing schedules when compared with flights in less congested oceanic airspace.

Conducting trials in less congested airspace over the North Atlantic may demonstrate greater benefits at reduced fuel penalties, when compared with contrail trial work undertaken to date over Europe and North America.

3.3 Trial Size and Complexity

Analysis of work to date illustrates that even the largest trials have involved fewer than one thousand flights. For comparison, over 1.98 million scheduled flights departed and arrived at UK airports in 2024. Furthermore, these flights have been between a limited number of departing and arriving airports and do not adequately replicate the complexity of current operations.

While trials to date have demonstrated the contrail avoidance concept to a certain extent, further trials may be necessary. This would more fully test the ability of ANSPs to accommodate the extra dynamism of routinely adding contrail avoidance to millions of flights each year. With NATS handling over 2 million flights travelling over the UK and across the North Atlantic every year, it has the unmatched ability to support contrail avoidance at scale. For instance, with trials focused on North America bound flights travelling through the Shanwick and Scottish airspace areas.

One of the key characteristics of contrails is their greater tendency to form at high latitudes. The northerly position of the UK and Europe means the region's departing flights have a disproportionate contribution to contrail formation. By some estimates, the North Atlantic accounted for 5% of the total flight distance flown in 2019 but 10-11% of the annual contrail warming effects. As a result, UK departing flights offer not only opportunities for large-scale trials but also cover airspace with high potential for contrail formation.

3.4 Trial Validation and Observation

A review of work to date demonstrates that assessing avoidance efficacy falls into two broad categories. Some trials actively look for agreement between forecast meteorological conditions and those encountered on the route as the flight is taken. Here, ISSR-related meteorological conditions represent a proxy for contrails.

A smaller number of trials have attempted to identify the contrails themselves, to both validate the methods and assess the extent to which contrails have been avoided. This work on detecting and tracking contrails is in its infancy. Evidence suggests that pre-existing geostationary satellites that maintain a fixed position over the earth's surface can be used to monitor large areas such as the North Atlantic. These also provide continuous coverage and have the necessary instrumentation to collect data on contrails, clouds, temperature, humidity and wind conditions.

Previous trials have proven the concept of using geostationary satellites to continuously monitor an area for contrail formation. However, no one has undertaken this at a scale consistent with designing a future contrail navigational programme roll-out over an area such as the North Atlantic. There is also no evidence of pre-existing trials that have combined geostationary satellite data with that from other sources, such as Low Earth Orbit (LEO) satellites and ground-based Lidar techniques. Combining these diverse datasets might provide considerable additional insights and improved validation and assurance.

3.5 Ownership of Optimisation Decisions

Whilst all contrail avoidance trials include a flight optimisation step, there is wide variation in where this optimisation decision resides. Early projects have mainly featured one of two models. In some cases, a single airline owns the role of building in contrail optimisation. In other cases, an ANSP makes the decision-making on behalf of single or multiple airlines. Both the 'airline-led' and 'ANSP-led' models have advantages and disadvantages, although arguably, trials have not fully explored these in the small-scale European and US avoidance trials undertaken to date.

The JZTF CIM T&F Group has not found any evidence of greater integration across decision-making. For instance, with optimisation decisions made by an ANSP working closely with a large number of airlines to arrive at closely coordinated integration of contrail avoidance into long-range flight plans. There is also no evidence of multiple ANSPs working together with large numbers of airlines to develop sophisticated solutions. Arguably, such an approach will eventually be necessary if seamless contrail avoidance is to be achieved across multiple jurisdictions – say for flights crossing continental European, UK and North American airspace.

As the scale and complexity of trials grows towards that required in future roll-out, inevitable questions arise around participation. The different decision-making models pose different challenges in terms of recruitment of trial participants. Airline-led trials, particularly at small scale, favour an opt-in approach.

Larger ANSP-led trials possibly favour an opt-out approach if sufficient wide-scale participation is to be achieved, for example the MUAC-Google Contrail Prevention Trial where any flight could be assessed as eligible and included[3].

3.6 Pre-Tactical and Tactical Contrail Avoidance

As described in 3.1, contrail avoidance typically begins with a high-fidelity weather forecast, which planners combine with planning tools. This helps to identify contrail-likely regions on route which form the basis for contrail optimisation of flight plans, alongside other considerations such as fuel use, turbulence etc. To date, the vast majority of contrail avoidance has focused on pre-tactical planning where the contrail avoidance element of the flight plan is fixed before take-off. This contrasts with a tactical or hybrid approach, where planners integrate data becoming available after take-off in real time.

Whilst the majority of trials to date have been purely pre-tactical, some including MUAC, Delta Airlines and American Airlines, have been tactical or included tactical elements. However, these were extremely small-scale and required significant manual intervention. The JZTF CIM T&F Group also understands that organisers specifically selected the most experienced pilots to fly the aircraft involved. There are also some anecdotal accounts that airlines have been reluctant to include tactical changes, citing the need for additional pilot training and workload.

3.7 Application of Artificial Intelligence

Identifying and tracking contrails requires automation, as pure manual intervention is insufficient at anything but the smallest scale trial/roll-out. The use of Artificial Intelligence (AI) represents an obvious solution, particularly for large numbers of flights over wide geographical areas. Not only does AI offer the opportunity to completely automate the process, it may also permit contrail measurement as part of any impact assessment.

Whilst the concept has been proven at small scale, AI use in this application is still relatively immature, and a perceived need exists to build on work to date. Other possible AI applications in this field include:

[3] MUAC – Google Contrail Prevention Trial Supplementary info – AO brief 08/2024
https://flyger.no/images/Supplementary_info_fra_Eurocontrol.pdf

- Using data from satellite imagery, weather data, and flight path information to characterise atmospheric conditions
- Identifying the specific meteorological conditions (ISSRs) that lead to contrail formation
- Optimising minor adjustments to an aircraft's altitude

The JZTF CIM T&F Group has found only limited application of AI in the above, and future trials offer the opportunity for fuller integration to deliver larger projects with greater scale and impact.

4.0 UK CIM Framework Maturity

4.1 Workstream 1 – Aircraft/Engine OEMs

4.1.1 Current Maturity Level

The current maturity level for Aircraft/Engine OEMs stands at Level 2 Reactive, known, project-by-project.

4.1.2 Justification

Efforts in this workstream are restricted to isolated projects that concentrate on specific technical or operational technologies, including the influence of different fuel properties and/or combustor technologies on engine emissions and contrails. Because of considerable uncertainties in the underlying science and impact estimates, the consideration of contrail impact mitigation is not yet a standard element of the design and review process. Recent and ongoing projects in this area include Emission and CLimate Impact of Alternative Fuels 3 (ECLIF3)[4], EcoDemonstrator[5], Particle emissions, Air Quality and Climate Impact related to Fuel Composition and Engine Cycle (PACIFIC)[6], BlueCondor[7], VOL avec Carburants Alternatifs Nouveaux (VOLCAN)[8] and PRE-TRAILS[9].

4.1.3 Roadmap to Achieve Level 3, Level 4 and Level 5

Objectives

Achieving Level 3 signifies the transition to proactive, standardised processes based on validated data from operational trials and/or emissions test campaigns. The primary objectives required for this transition are inclusion in design reviews, which involves incorporating design guidelines and contrail impacts into relevant system gate reviews (the formal 'go/no-go' decision points in the design process); the development of estimation tools to build contrail climate impact estimation into standard preliminary design tools and processes; and tradeoff

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[4] ECLIF3 : World’s first in-flight study of commercial aircraft using 100% sustainable aviation fuel show significant non-CO2 emission reductions | Airbus

[5] EcoDemonstrator: Boeing, NASA, United Airlines To Test SAF Benefits with Air-to-Air Flights - Oct 12, 2023

[6] PACIFIC: A new European project led by Airbus, will advance research on contrail mitigation and non-CO2 impacts | Airbus

[7] BLUECONDOR: https://www.airbus.com/en/newsroom/stories/2023-11-contrail-chasing-blue-condor-makes-airbus-first-full-hydrogen-powered

[8] VOLCAN : Airbus’ most popular aircraft takes to the skies with 100% sustainable aviation fuel | Airbus

[9] PRE-TRAILS : CX-029413: Predictive Real-time Emissions Technologies Reducing Aircraft Induced Lines in the Sky-- PRE-TRAILS (FOA No. DE-FOA-0002784) | Department of Energy

quantification, which involves understanding and quantifying the tradeoffs between contrail climate impact and other design objectives. These objectives will have the greatest impact on new product design, distinct from optimising the existing fleet's operations.

It is important to recognise that the models used for estimating contrail climate impact are still actively being developed, refined, and improved. This evolving landscape is further complicated by the fact that many different metrics can be used to quantify climate impact. Crucially, the choice of a specific metric, or even the time horizon at which that metric is evaluated, could lead to different design decisions. As a result, it will be important to build periodic updating of the contrail models and climate metrics into the preliminary design process. This ensures the project can access the latest modelling capabilities and reflect the most current scientific understanding.

Further objectives identified for achieving Levels 4 and 5 include:

- **Mitigation Awareness** - Increasing awareness of operational contrail mitigation options as either an additional or alternative reduction lever.
- **Sensor Integration** - Considering the integration of improved meteorological sensors onto aircraft

Required Actions

OEMs must undertake the following actions

The process involves continuing to develop and refine models of emissions, such as particulate matter, relevant to contrail formation, properties, and climate impact (Level 3), as well as understanding and modelling typical use cases to determine the spatial and temporal distribution of emissions, resulting in emissions inventories from which contrail climate impact can be assessed (Level 3). It also requires understanding how design choices enable or support operational choices for reduced climate impact and characterising the associated trade-offs against other design drivers (Level 3). Throughout this, progress and findings must be communicated to other stakeholders, for instance, through conferences or workshops (Levels 3 to 5).

At Level 4, emissions models are connected with contrail models and/or climate impact models. This will enable assessment of climate impact from the above-mentioned emissions inventories; as mentioned above, there will be a need to keep up to date with the latest contrail modelling capability and/or metric choices. This stage also involves assessing the relative attractiveness of design-focused contrail mitigation efforts versus operational approaches, considering the trade-offs of each method (Level 4). Scientific literature shows that a large proportion of contrail climate impact is attributable to only a small proportion of aviation activity. This creates a core challenge: making design changes to an aircraft or engine to reduce its propensity to form contrails will provide benefits during only that small part of its operation. However, the design tradeoffs necessary to achieve such a contrail mitigation outcome, potentially affecting other objectives like fuel efficiency, may manifest themselves over the entirety of the product's operation. The nature and extent of tradeoffs will likely be very different for these "design-based" approaches compared to "operational" approaches to contrail mitigation. Manufacturers should therefore maintain an awareness of the characteristics of available options from both categories. Level 4 also includes collaborating with the scientific and weather community to define the required performance characteristics and standards for meteorological sensors.

Finally, Level 5 involves collaborating with suppliers to develop and/or incorporate meteorological sensors for improved contrail forecasts. The deployment of humidity sensors could be contemplated in three waves. The first wave would be retrofitting them to in-service aircraft at a trial scale, followed by a second wave of large-scale retrofitting. The third wave would be incorporating the sensors into new, future aircraft types. The first two steps could be achieved by either OEMs or by Maintenance, Repair, and Overhaul (MRO) organisations, while the third step would likely be completed solely by the OEMs.

ANSPs must execute the following actions

A continuous dialogue with OEMs is necessary to ensure a full understanding of how proposed new operational practices may impact engine or airframe life; this dialogue must also address impacts on emissions, including Carbon Dioxide (CO_2) and Nitrogen Oxide (NO_X) (Level 3). This engagement also serves to ensure OEM awareness of operational options and the design features that might be necessary or advantageous to support or enable selected operational options (Level 3).

Airworthiness Certification Authorities

Airworthiness Certification Authorities are responsible for certifying airborne meteorological sensors for integration onto both new and existing aircraft fleets (Level 5).

Contrail Modelling Community and Tool Providers

This community, which might include academic/scientific model developers, software communities, and/or commercial modelling tool providers, must focus on advisory and integration actions. At Levels 2 & 3, this involves advising on the selection of suitable tools for modelling contrail climate impact. This advice must consider the type of assessment required, such as granular (flight-by-flight) or high-level summary (average route structure). It also includes providing advice on tool implementation and sharing best practice findings through workshops and conferences.

At Level 3, the community must collaborate with OEMs to perform emissions test campaigns and/or to use results of such campaigns to validate and/or test modelling results against the measured data. This collaboration also extends to ensuring that modelling assumptions regarding engine and/or aircraft performance and/or emissions reflect the latest publicly available understanding, and/or to perform validation of such assumptions. Moving to Level 4, the focus shifts to coordinating with meteorological service providers to integrate routine aircraft sensor data into numerical weather prediction tools.

Climate Scientists

Climate Scientists are responsible for recommending frameworks for assessing the overall climate impact, encompassing both CO_2 and non-CO_2 effects; these recommendations should prioritise frameworks that are robust to future changes in understanding (Level 3). They must also implement improvements to climate models to reduce uncertainties regarding the climate impacts of NO_x and particulate matter (Level 3).

Key Stakeholders

The primary stakeholders in this workstream are:

- OEMs
- Airlines
- ANSPs
- Airworthiness certification authorities
- Contrail modelling community and tool providers
- Climate scientists

4.2 Workstream 2 – Airlines Operations

4.2.1 Current Maturity Level

The current maturity level for Airlines Operations stands at Level 1 - Unknown, not practised or not controlled. Initial state with no formal processes or consideration of the issue.

4.2.2 Justification

UK airlines currently lack operational experience with contrail avoidance flights during commercial operation. Two UK airlines have very limited experience with operational contrail mitigation (Virgin Atlantic and easyJet). In addition, some UK carriers, such as easyJet, have performed shadow mode trials, which equate to contrail desktop simulations without modifying existing operations[10].

While some UK airlines, like Jet2 and TUI Airways, use flight planning systems with contrail optimisation capabilities (such as FlightKeys), this functionality is not yet integrated into the systems used by most UK operators. These systems optimise trajectories by allocating costs to the climate impact (CO_2e) of contrails, making it part of the standard cost optimisation algorithm. This integrated capability is essential for filing flight plans almost automatically, and avoids considerable manual effort in the dispatch function (estimated at up to 20 minutes per flight). The integrated contrail optimisation functionality is therefore essential for an industry-wide roll-out of operational contrail mitigation. As of today, there is no incentive for flight planning providers, nor an agreed metric to make the contrail/fuel/time trade, to pursue such a development, but regulation could change this.

Consequently, real-life operational data from UK airlines regarding the time or fuel penalty associated with contrail mitigation is unavailable. Time and fuel penalties are available from various simulations and operational trials with non-UK airlines. The UK sector has not established best practices or standards. Operational limitations, such as those imposed by congested airspace, remain unknown, and no overarching mitigation target exists.

[10] While easyJet conducted a small-scale contrail avoidance trial in early 2023, this was a limited feasibility study with SATAVIA to test the operational model. With very few flights actually modified, the trial represents an initial 'project-by-project' (Level 2) effort and does not yet constitute widespread, standardised operational experience.

4.2.3 Roadmap to Achieve Level 2, Level 3, Level 4 and Level 5

Objectives

Achieving Maturity Level 2 requires multiple UK airlines to acquire real-life operational experience by executing commercial flights that are rerouted (vertically, horizontally, or both) for contrail avoidance. This experience begins with intense stakeholder management and ensuring the readiness of systems and processes. At this stage, systems can have either integrated or separate contrail avoidance functionality for a small number of flights, while processes include defining company rules for fuel or time penalties and informing pilots or ANSPs on the day of operation.

Once these systems and processes are tested and stable, selected flights (no more than a few per day) are strategically re-routed pre-flight to avoid contrails. To verify successful avoidance, scientific post-flight analysis must accompany these actions. Collaboration with research institutions and ANSPs in preparation and validation is essential to enable more data to be gathered at scale. Ideally, this should involve multiple airlines, including non-UK ones, all using consistent approaches and a common data and reporting system. This system is distinct from Monitoring, Reporting, and Verification (MRV), which typically happens post-flight.

Required Actions

Real-life strategic contrail avoidance requires a structured ramp-up to embed new processes into existing operational procedures and ensure proper risk management. As shown in Fig. 1, the ramp-up usually starts with intense stakeholder management in observation only flights, where new systems and processes are tested without changing the standard trajectory. This is a safe way to finetune systems and processes and gain confidence in their effectiveness.

The approach to achieving Maturity Level 2 involves the following stepwise implementation (see Figure 1 below).

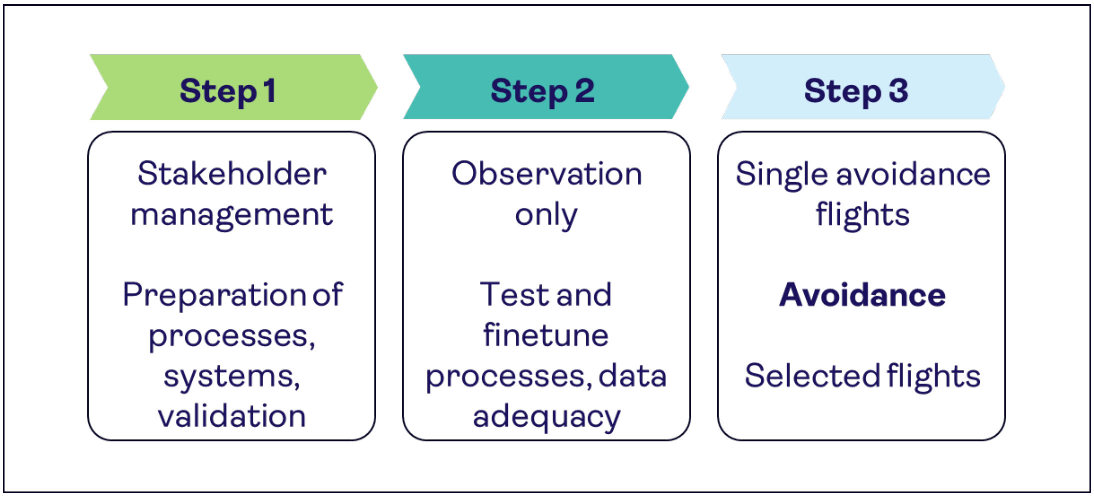

Figure 1. Steps to ramp up airline contrail operations to maturity level 2

Stakeholder Engagement (Step 1)

It all starts with careful stakeholder management to obtain full support for the initiative. This includes securing general approval from the airline board, engaging with flight operations for risk assessment and management of change, preparing the dispatch function for using contrail avoidance functionality, creating awareness within the pilot community, and collaborating with workers' councils or unions regarding trajectory data sharing with research institutions. Crucially, close collaboration with ANSPs is essential from the outset.

Process Development (Step 2a)

Once stakeholders secure engagement, processes are developed and tested using observation flights. These are flights predicted to produce persistent contrails with a warming climate impact, where actual avoidance manoeuvres are not yet initiated. The processes tested include selecting a contrail flight in dispatch, the information provided to pilots and ANSPs, the collection and sharing of flight data, and the reanalysis of the executed flight.

Data Refinement (Step 2b)

This observation phase serves to fine-tune procedures and ensure the adequacy of flight data for research purposes. The validation of observation flights, for example with satellite imagery, gives the operator confidence in the prediction of persistent contrails, which is essential before starting with avoidance.

Avoidance Execution (Step 3)

Following this, the first avoidance flights are executed. This may initially involve only a subset of pilots and dispatchers to further fine-tune operational procedures. Pilots will be asked to fly the filed plan and provide feedback in case that was not possible for operational reasons, such as delays, non-availability of a requested flight level, adverse weather like turbulence, or the offering of tactical shortcuts. As with observation flights, these avoidance flights must also be validated with ground-based cameras or satellite imagery to verify the success of the mitigation action.

Moving on to Levels 3, 4, and 5, the objective is to validate the results obtained from this series of single avoidance flights. More extensive flight trials need to be undertaken to understand the system-wide impact of extending the scope of both the number of flights within the trial as well as the number of airlines participating.

Clearly there are a significant number of interdependencies between the different stakeholders to enable airlines to scale up contrail avoidance flight trials. This wider trial should ensure that participating airlines have access to more automated flight planning tools or possibly weather forecasting tools to allow airlines to routinely undertake avoidance flights without excessive planning activity. Prior to any trials airlines need to work with ANSPs to understand the results of any system-wide modelling exercises to understand the potential impacts of larger scale trials. This modelling is essential to understand potential impacts on overall airline and airspace operations under different traffic conditions to ensure trials do not create delays, create excessive additional fuel burn and hence CO_2 emissions, and to ensure safety procedures can always be adhered to.

The required actions for these higher levels involve stakeholders working with ANSP providers to support airlines in undertaking routine contrail mitigation activity, supporting airlines' efforts to optimise efficiency as well as to perform avoidance flights. It is also essential to ensure that scientific and weather forecasting stakeholders are providing support to regarding appropriate observational data-driven approaches to validate the results of airline avoidance flights. To also ensure that a consistent and verifiable approach is taken to data collection to ensure that data collected by different airlines is comparable and robust. This can also be used in assessing the usefulness of existing monitoring and reporting procedures in contributing to contrail mitigation activity.

Support from government is provided to support airlines in mitigating the cost of contrail avoidance for airlines, for example the EU has a system of allowing funding from Emissions Trading System revenues to be provided to support climate related projects and investments.

Stakeholders must be able to assess the overall impact of contrail avoidance activity at a system level. This will enable an assessment of the overall CO_2 and non-CO_2 impacts related to a much larger number of flights and for participants to establish the case for routine contrail mitigation (or not); a system-wide understanding of the operational impacts of routine contrail mitigation; and an evaluation of the efficacy of existing monitoring and reporting methods for non-CO_2, working with the scientific community to contribute to the development of appropriate methods to express overall contrail-related warming impacts.

Larger trials form the basis of future work to increase participation in contrail mitigation activity and although the scope of this study is the UK, there are clearly multiple global airlines who pass through UK-controlled airspace that would need to be bought into a future whole airspace approach.

Figure 2 presents a potential roadmap for achieving maturity levels 3, 4, and 5.

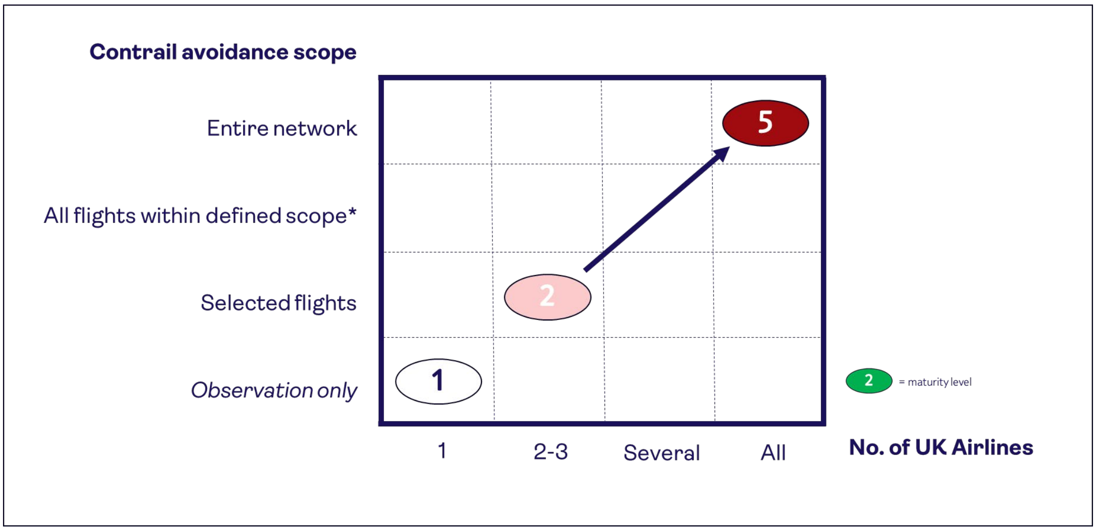

Figure 2. Airline Operations – Maturity roadmap (indicative)

Key Stakeholders

Achieving Maturity Levels 2 to 5 requires the involvement of several key stakeholders:

- Airline Top Management:
  - Airlines are strictly measured on efficiency metrics like Cost per Available Seat Kilometre (CASK).
  - Leadership buy-in is crucial to secure the necessary budget and resource allocation.
  - This commitment reframes the project as a strategic investment rather than a simple operational cost.

- General and Operational Support:
    - The wider workforce must support leadership's commitment.
    - Broad operational buy-in is essential for successful implementation.
- Airline flight operations management:
    - Risk assessment and management of change, amendment of operating manual or Operations Notice to Air Missions (OPS NOTAM)
- Pilot associations, e.g. British Airlines Pilots' Association (BALPA).
    - Data sharing with research institutions and general support
- Airline dispatch department
    - Testing and using of contrail avoidance functionality
    - Information of pilots and ANSPs
- Airline pilot community of the respective airline
    - Awareness, understanding (fuel consumption vs. contrail avoidance) and willingness to support
- Research institutes
    - Validation of executed flights
- Flight planning system providers
    - Provision of contrail or climate optimised trajectories
- Air traffic management (e.g. NATS)
    - Support in flying as filed

4.3 Workstream 3 – Climate Impact

4.3.1 Current Maturity Level

The current maturity level for Climate Impact stands at Level 2 Reactive, known, project-by-project.

4.3.2 Justification

There is consensus that contrails cause a net positive radiative forcing (warming), yet they are assessed to have higher uncertainty than CO_2 emissions and are a topic of increasing research.

The IPCC defines 'climate impacts' as the "consequences of climate change on natural and human systems"[11]. These physical impacts include changes in weather patterns and rainfall, which can in turn affect agriculture, ecosystems, and energy production, ultimately impacting human systems. Such climate impacts result from:

1. Emissions of greenhouse gases (GHG), including carbon dioxide and short-lived climate forcers (SLCF);
2. Change in atmospheric concentrations of GHG: by dispersal and accumulation in the atmosphere;
3. Radiative forcing: a change the energy balance of the Earth, which can happen by trapping heat in the atmosphere, inducing a warming effect, or by reflecting incoming heat from the sun;
4. Climate change: changes in surface air temperature, temperatures throughout the atmosphere, and sea temperatures, which can influence long-term patterns of weather, precipitation, sea-level rise, and other physical indicators of climate change.

Estimates show persistent contrails contribute to a net positive radiative forcing (warming) and have a lifetime of hours. They trap heat (longwave radiation) that would otherwise escape to space, but also reflect sunlight (shortwave radiation). Their net effect is the difference between these two.

Several peer-reviewed studies have quantified contrail radiative forcing using models. A smaller number of peer-reviewed studies have used observations to quantify the contribution of contrails to radiative forcing, an approach that is developing rapidly.

While the climate science community reserves the term 'climate impact' for those impacts that result from radiative forcing and climate change (consistent with the IPCC definition). The term 'climate impact' is frequently used to refer to radiative forcing or climate change indicators. While this usage is not strictly aligned with the definition of the IPCC, it is used to associate the radiative forcing of contrails to climate change in a way that can be understood by a wider audience (i.e. the term radiative forcing is not commonly understood).

Several scientific challenges, which are the subject of intense research, constrain the level of scientific understanding and the estimation of climate impacts resulting from contrails. The causal effect of contrails on climate change indicators, including on surface temperatures

[11] https://www.ipcc.ch/site/assets/uploads/2018/03/wg2TARannexB.pdf

(often referred to as 'efficacy'), involves significant uncertainty. This is due to a relatively poor understanding of the influence of contrails on natural cloud processes, including the availability of humidity affecting the formation and lifetime of cirrus clouds, and the relatively small 'signal' of contrails relative to the 'noise' that is present due to the variability of other clouds. However, there is consensus that the annual global average radiative forcing from contrails is net positive (warming)[12].

While it is possible to compute different climate metrics (e.g., temperature impacts) from contrail radiative forcing models, the algorithms for doing so are not standardised. Groups have conducted contrail management trials, but the consideration of climate impacts has been on a project-by-project basis, without standardising how models or observations are used to estimate or infer contrail abundance, radiative forcing, climate change or climate impacts.

Several trials have been completed with different airlines and ANSPs (see above). Each project used a different contrail impact forecast and different protocols for interpretation and action (e.g., rules/restrictions for deviations, stages within the flight execution at which the forecast is incorporated). This variation in models highlights a wider challenge: the significant scientific uncertainty and the corresponding need to develop more and different approaches to climate impact modelling, particularly for non-CO_2 effects where models are scarce, and to conduct model intercomparison projects to reduce these uncertainties. Each airline or ANSP has different processes and tool-stacks, meaning forecasts must be provided either (i) as standalone and additional tools, which are difficult to operationalise, or (ii) in a format conforming to existing system requirements. These specifications vary, meaning that even within the same project, it may not have been possible to implement a single, universal forecast tool.

In previous trials, particularly those that have been ANSP-led, it has not been possible to obtain aircraft data held by airlines to calculate the fuel consumption and CO_2 emissions from that flight and the delta relative to what was planned. Indeed, establishing what the fuel consumption and CO_2 emissions would have been had an avoidance manoeuvre not occurred is challenging due to the range of other factors that could affect flight fuel consumption and deviations from the flight plan.

[12] https://www.icao.int/sites/default/files/environmental-protection/Documents/ScientificUnderstanding/CAEP14-ISG-ContrailWorkshop.pdf

In trials to date, forecasters have constructed contrail forecasts on top of weather forecasts, e.g., European Centre for Medium-Range Weather Forecasts (ECMWF), Météo-France, Deutscher Wetterdienst (DWD) and sometimes augmented them with real-time satellite observations, e.g., American Airlines (AA) trial with Google and Contrails.org[13]. Differences in the underlying weather forecasts can lead to differences in the contrail forecast.

A small number of real-world trials have shown the potential for statistically significant reductions in contrails (based on models and observations). A range of estimates and metrics can be used to evaluate such trials, which challenges the community on how best to demonstrate effectiveness (though such choices usually affect only the magnitude of results, not whether the action was climate-positive).

To date, there have been no comprehensive studies on the effect of large-scale contrail management on CO_2 and non-CO_2 radiative forcing, either in simulation or real-world trials. However, this work is ongoing.

4.3.3 Roadmap to Achieve Level 3

Objectives

Forecasting and Observation

The Forecasting and Observation objective group forms the foundation, addressing the primary need to observe and predict contrail formation and impacts. It includes the development of tools for both retrospective analysis based on existing data and reliable forward-looking forecasts.

- Retrospective, observation-driven methods to quantify contrail climate impacts using existing remote sensing platforms, which report a set of objective indicators for contrail abundance and radiative forcing (for example, but not limited to contrail length, contrail coverage, contrail radiative forcing).
- Reliable forecasts of contrail formation, persistence, and climate impacts. These must inform on the severity and likelihood of warming predicted to result from flights operating in regions susceptible to contrail formation, and must also allow for consistent implementation across a variety of operational environments.

[13] https://contrails.org/

Standardised Methodologies and Metrics

Following observation and forecasting, this group focuses on establishing agreed-upon methods for measurement. These methodologies are essential for consistently quantifying both the climate impact of contrails and the associated CO_2 and fuel costs of any mitigation actions.

- Standardised approaches to calculate fuel consumption and CO_2 from flights in contrail management situations, and the difference compared to standard operations, for individual flights, carriers, and at the network level.
- Standardised calculation methodologies for computing contrail abundance, radiative forcing, and climate metrics. These must allow the comparison of CO_2 and non-CO_2 climate impacts over different timescales, providing the basis for decision-making and combined considerations of CO_2 and non-CO_2 effects.

Operational Application

This final group details the practical implementation of these tools. Based on the ability to predict (Group 1) and measure (Group 2), these practices outline how to apply the information in an operational environment to manage contrail effects effectively.

- Recommended practices for utilising weather and contrail forecasts in pre-tactical flight planning and tactical flight manoeuvres. The design of such practices must incorporate a hybrid approach, using both pre-tactical and tactical solutions in tandem to optimise the overall solution.

Required Actions

Validation Data and Tools

This group of required actions outlines the foundational resources required to test, verify, and improve the contrail forecasts mentioned previously. It includes both the raw observational data and the open-source software necessary to conduct validation in a consistent and rigorous manner.

- Open-source and large-scale datasets of atmospheric measurements and contrail remote sensing observations, for use in validating contrail forecasts, including but not limited to In Service Aircraft for a Global Observing System (IAGOS), Global Climate

Observing System (GCOS) Reference Upper-Air Network (GRUAN), ground-based cameras, and geo-stationary and low-earth orbiting satellites.

- Open-source software tools to perform such validation and evaluation of contrail forecasts in a standardised and rigorous manner.

Standardised Performance Metrics

This action addresses the need for agreed-upon methodologies to measure the outcome of any interventions. These standardised calculations are essential for evaluating the effectiveness of contrail management and understanding its overall climate impact.

- Standardised calculation methodologies for climate metrics and indicators, for evaluating contrail climate impacts to measure the performance and effectiveness of interventions.

Large-Scale Operational Trials

This final action describes the practical, real-world application and testing of contrail management strategies. These trials are necessary to confirm whether operational changes produce the intended reduction in contrail abundance and radiative forcing under diverse conditions.

- Large-scale contrail trials to evaluate the change in contrail abundance and radiative forcing that may (or may not) result from operational contrail management. These trials must have clearly defined objectives, protocols, and standardised reporting that can be replicated for different trials in different locations and seasons.

Key Stakeholders

- Academia
- Weather forecasting service providers
- Airlines
- ANSPs

4.4 Workstream 4 – Weather Data

4.4.1 Current Maturity Level

The current maturity level for Weather Data stands at Level 2 Reactive, known, project-by-project.

4.4.2 Justification

The current maturity level for Weather Data stands at Level 2 Reactive, known, project-by-project. This applies to both forecasting tools and models, and also to weather observation-based products relevant for improving contrail prediction, such as those generated by satellite products and ground-based cameras.

4.4.3 Roadmap to Achieve Level 3, Level 4 and Level 5

Objectives

Weather data comes into several categories relevant to the contrail observation and prediction problem and requires substantial improvement to get to maturity level 5:

A. Products for forecasting future regions susceptible to the formation of contrails.
B. The underlying weather models that drive the products in (A).
C. Observational data that enables the generation of existing contrail locations.

Required Actions

Improving the three categories above requires the following ongoing activities:

- Activities to improve and extend humidity observations in aircraft, improving category (B), and to understand the impact they have on existing weather models.
- Activities to improve the exploitation of cutting-edge geostationary satellite data (e.g., Meteosat Third Generation) to generate maps of existing contrail locations for the validation and calibration of weather forecast products.
- Activities to understand how to combine other data with geostationary satellite data to produce optimised information on contrail locations.
- Activities to provide continuous improvements to existing contrail prediction capabilities (e.g., pycontrails) through validation with new observations sources and

direct feedback from users in contrail trials. This includes the exploitation of machine learning techniques.

- Activities to determine how non-weather data, such as actual flight tracks, can be combined with observational information.

Several new workstreams are also required, linking back to the data categories above:

- Improving and comprehensively validating contrail prediction products. This covers timescales from 'now' (observations), to the next few hours (nowcasting up to T+6 hours), and up to T+36 hours (forecasting).
- Developing and implementing increased/improved aircraft-based humidity sensor observations and assessing their impact on weather model performance for contrail prediction.
- Generating integrated observational products that take satellite, ground-based camera, and flight information to generate as complete a picture as possible of where contrails were generated at any given time.
- Robustly testing these weather products in a trials environment to test and validate models/predictions and to understand how to build the capabilities described to reach the higher maturity levels.

Weather roadmap steps:

Level 3: Proactive, standardised

- Implementing processes, tools, and algorithms to standardise the provision of ISSR forecasts & climate impact estimation data for contrail mitigation measures.

Level 4: Measured and controlled

- Generating standardised reports using a consistent framework for measuring the effect/impact of contrail mitigation measures with comparison to a baseline (e.g., effect - increased cloudiness, impact - altered radiation balance).

Level 5: Optimising with active feedback

- Improvements in weather forecast models.
- Improvements in contrail process models and climate impact estimations.
- Improvements in validation accuracy.
- Integration into users' decision-making processes.

Key Stakeholders

- Academia and Research Institutes
- Aircraft Manufacturers and Wider Industry
- Met Office
- Air Traffic Management (e.g. NATS)
- Airlines / Pilots

4.5 Workstream 5 – ANSP Operations

4.5.1 Current Maturity Level

The current maturity level for ANSP Operations stands at Level 2 Reactive, known, project-by-project.

4.5.2 Justification

Trials are taking place on a project-by-project basis to validate the effectiveness of contrail mitigation actions and operational impacts (process, tools, workload, etc).

NATS is the UK's leading provider of air traffic control services and has been supporting contrail research for over a decade through demonstration flights, collaborative projects like SESAR's Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment (CICONIA)[14], and ongoing partnerships with academic institutions.

NATS represents ANSPs and the UK in international groups focusing on non-CO_2 such as Aviation Non-CO_2 Expert Network (ANCEN)[15], Civil Air Navigation Services Organisation (CANSO) Contrails Task Force[16], the European Union Aviation Safety Agency's (EASA) Avenir Pillar 3[17] and the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) WG2 Task 7[18]. Through this work and the engagement in multiple non-CO_2 projects, NATS works to support coordination and lessons learned across different trial activities and projects.

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[14] https://www.sesarju.eu/projects/CICONIA
[15] https://www.easa.europa.eu/en/research-projects/ancen-nonco2
[16] https://canso.org/clearing-the-air-on-contrails/
[17] https://www.easa.europa.eu/en/newsroom-and-events/news/easa-and-eurocontrol-reinforce-environmental-transparency-handover-avenir
[18] https://www.icao.int/environmental-protection/caep-working-group-2

Within CICONIA, NATS is supporting airline trials in UK controlled airspace (domestic and oceanic), and developing the future concept for airline-led and ANSP-led navigational contrail avoidance. To date, partner airlines have run multiple shadow mode trials, mainly on transatlantic flights, where they have re-planned filed flight plan trajectories to avoid forecasted contrail sensitive areas and run comparisons of climate effects (non-CO_2 and CO_2) between the altered profile and the original flight plan, as well as assessing other operational implications. Initial results have shown significant potential to reduce the climate impact of highly warming flights with minor increases in fuel burn, and even in cases with greater additional fuel burn, with the change in climate impact always considered beneficial. Live airline-led trials are planned in UK/oceanic airspace during early 2026.

Controller workshops run in the context of CICONIA concluded that the concept of reducing the impact of persistent warming contrails is achievable at scale in terms of air traffic operational feasibility in low traffic environments, but not currently achievable in busier, more complex environments. Safety is always the number one priority. The workshops concluded that small vertical level changes (1,000-2,000 ft) for contrail mitigation are feasible where capacity allows and can be incorporated with relative ease, but larger level changes are potentially less feasible.

The extent to which large-scale navigational contrail mitigation would be able to be practiced from the ATC (Air Traffic Control) perspective is often dependent on the specific situation. Different sector structures, traffic flows, and ISSR instances could all significantly alter how feasible it would be to enact contrail mitigation procedures.

The feasibility of practising large-scale navigational contrail mitigation from an Air Traffic Control (ATC) perspective is often dependent on the specific situation. Different sector structures, traffic flows, and ISSR instances could all significantly alter how feasible it would be to enact contrail mitigation procedures.

Defined levels of contrail mitigation action as a function of air traffic complexity are desirable, and these levels would need to be regularly assessed throughout each day. Another option to minimise implications on controller workload would be to limit avoidance of contrail sensitive areas to aircraft in the cruise phase of flight, but not include avoidance for aircraft which have planned climbs or descents through the contrail sensitive area.

From an ATC perspective, the conclusion based on current evidence is that airline-led contrail mitigation, rather than ANSP-led, would be preferable in the longer term, if only one option was pursued. This is because the airlines have the most detailed information about their particular flights, not all of which is available to ATC, therefore airlines can plan a more optimal overall trajectory and fuel accordingly. The most optimal strategy however, (i.e., minimising workload, fuel burn, and system complexity) would be a hybrid approach, where initially the airline-led approach is actioned as a baseline and the ANSP-led approach refines trajectories in the context of airspace management; this additionally replicates the current workflow of flight planning and execution, reducing the potential overheads in implementing distinctly new systems.

There are not yet any published results on the impacts on the network and potential delays if all flights filed flight plans to mitigate contrail warming. However, partner organisations are conducting validation exercises within the CICONIA project to better understand network effects. Flow Management personnel were also included in the CICONIA ATC workshops. They concluded that if the contrail mitigation requests were all tactical, there would be no impact to Flow Management Position (FMP) directly, although FMP intervention could be requested if sustained high workload was expected as a result of contrail mitigation requests.

MUAC has been the first ANSP to run an ATC-led trial, and NATS is following their progress and supporting them through the CICONIA Validation Work package. MUAC's work includes development of a support tool for ATC to propose deviation advisories to aircraft to avoid forming warming contrails. This makes use of a role specific to the Maastricht operation, which is not, however, directly replicated in the UK operation.

Deutsche Flugsicherung GmbH (DFS) have also run experiments on contrail mitigation and have shared their results in dedicated sessions with NATS. NATS is also planning to work together with NAV Canada with a view to conducting joint oceanic live trial activities.

4.5.3 Roadmap to Achieve Level 3, Level 4 and Level 5

Objectives

Achieving Level 3 requires ANSPs to focus on several key objectives.

- Determine the operational feasibility and limits of ANSP-facilitated contrail mitigation in both low- and high-density traffic environments.
- Define the procedures, controller training, and tool support (e.g., ATC displays, workload prediction) required to move from project-based trials to a standardised (Level 3) capability.

- Understand the network-level impacts on capacity, controller workload, and potential delay through large-scale simulations and live trials.
- Establish the requirements for integrating meteorological forecasts and climate impact assessments into operational decision-making for FMPs, Supervisors, and Air Traffic Controllers (ATCOs).

Required Actions

Achieving the next roadmap level (Level 3) potentially requires considering two development streams - maturing the ability to facilitate contrail mitigation from the ANSP perspective in low density/complexity traffic levels (e.g., particular circumstances including winter night time traffic) and maturing the ability to facilitate contrail mitigation from the ANSP perspective in busier situations where tool support may be required. A key factor will be the availability of spare capacity, which may require active intervention. For domestic airspace, this involves collaboration between NATS FMP and the EUROCONTROL Network Manager.

Large-scale fast-time simulations, human-in-the-loop simulations and trial activities will be important to help understand what is achievable with different traffic levels and in different situations (e.g. size/distribution of contrail sensitive area, complexity of traffic flow in or near contrail sensitive area) and what the impacts on the network as a whole will be, helping to define under what circumstances different levels of contrail mitigation action should be implemented.

Investigation is required to determine what level of contrail mitigation ANSPs can support before controller support tools are needed. Controller support tools may need to be developed in the future to support not only the avoidance of contrail sensitive areas by the most appropriate aircraft, but also to support the most efficient management of contrail impact mitigation action, e.g., ensuring that flights are able to return to their optimum cruise levels following avoidance manoeuvres, or facilitating increased coordination between sectors and or other Air Traffic Service (ATS) units. This is likely to be different between the oceanic operation in the North Atlantic and UK domestic airspace, and will require investigation in both, while ensuring alignment across the operations.

It is also necessary to understand the ‘cut-off’ point when traffic levels may be too busy or complex to accommodate large-scale navigational contrail avoidance without significant impacts on delay.

Based on the improved understanding of impact on capacity, a function to enable contrail workload prediction for Supervisors, flow managers and the network manager will be needed. Note that the network management function is handled at European level by EUROCONTROL and is not limited to UK controlled airspace only.

An ATC display for controllers and supervisors showing the contrail sensitive areas, which could be on a separate support screen, will need to be developed. How such data should be curated and displayed (e.g., climate effect estimates or classifications of severity, discrete vs. continuous grids) will also require examination. ATCOs and Air Traffic Supervisors will require training in contrail mitigation procedures and the use of any new support tools.

Achieving Levels 4 & 5 involves developing an updated metric which includes measurement of the performance and impact of the ATM contribution to contrail impact mitigation, alongside CO_2 emissions; environmental performance targets also include non-CO_2 emissions. Additionally, performance is continuously analysed to understand where improvements can be made and what trade-offs may be necessary between contrail mitigation, CO_2 optimisation and delay minimisation.

Key Stakeholders

- EUROCONTROL Network Manager
- Neighbouring and European ANSPs
- Airlines

While ANSPs are central to coordinating contrail mitigation, their ability to act successfully depends on several critical external factors and stakeholders:

1. Airlines - the ANSP is dependent on airline engagement in practising contrail mitigation.
2. Regulation - Without regulation, it is hard for the ANSP to act to reduce contrail warming as airlines may not want to fly contrail mitigation trajectories. For trial purposes, excluding contrail flights from standard service quality metrics, such as Three Dimensional Insight (3Di), could support full engagement without unintended impacts on existing metrics designed with fuel efficiency in mind.
3. Climate Impact assessment - the ANSP needs to be able to measure and report on the potential for climate benefit from conducting contrail mitigation.
4. Meteorological forecasting of climate sensitive areas - Although the ANSP can support individual flights to fly a filed trajectory to mitigate the contrail impact without any direct

specific weather information, for larger-scale implementation, ANSPs will need regular updates of contrail sensitive areas in a format they can display to FMP, Supervisors and ATCOs.

4.6 Workstream 6 – Regulation

4.6.1 Current Maturity Level

Maturity Level 1 for current regulation in the UK, while noting that i) UK Government is actively supporting a Non-CO_2 Research & Development (R&D) Programme, and ii) jet aircraft flights to the UK from European Economic Area (EEA) airports are currently subject to non-CO_2 MRV requirements, including for contrails, under the European Union (EU) Emissions Trading System (ETS).

4.6.2 Justification

No regulation currently exists in relation to contrails in the UK, and climate targets for the sector (in UK policy and ICAO Resolutions) focus on the mitigation of CO_2 emissions only (although the temperature goals of the Paris Agreement could be interpreted to include all climate impacts, including contrails, providing a supportive rationale for contrail mitigation).

Existing regulations covering safety, environment and performance focus on CO_2 and efficiency. The potential deployment of contrail mitigation measures could impact these: performance metrics linked to efficiency apply to ANSPs, while carbon pricing schemes (like the UK ETS and CORSIA) and SAF mandate costs could both penalise aircraft operators for additional fuel burn.

4.6.3 Roadmap to Achieve Level 3, Level 4 and Level 5

Objectives

- The objective for reaching Maturity Level 3 in the UK is to mandate contrail mitigation as a consideration in flight planning.
- This must be supported by an enabling framework that:
    - Avoids creating disincentives and penalising participants.
    - Provides incentives for ANSPs and airlines to mitigate contrails.
- This process includes:
    - Demonstrating the efficacy of MRV.
    - Gathering information to estimate the climate impact and benefit.

    - Understanding which interventions are the most powerful to prioritise.
- Consideration should be given to whether the contrail mitigation mandate is confined to flight planning only (intent), or is based on the flown trajectory and whether a contrail is produced (result).
- It is important to note that changes in meteorological conditions may result in a contrail even when there was a strong intent to plan for avoidance.
- The objective for reaching Level 5 is to operationalise contrail mitigation in flight planning, supported by an effective MRV with appropriate policy incentives and penalties.

Required Actions

UK Government and MRV

An MRV will require a methodology. While no regulations exist in the UK at present, airlines and other entities operating jet aircraft within the scope of the EU Emissions Trading System are subject to MRV provisions for non-CO_2 including for contrails.

Given the UK Government is working towards linking the UK and EU ETSs, the UK Government should:

- Use trials to demonstrate the efficacy of MRV arrangements;
- Review the suitability of current EU ETS MRV provisions with a view to encouraging standardisation and minimising administrative burdens on operators wherever possible, while noting that its current scope does not extend to transatlantic operations (and flights outside the EEA region generally) where UK trials are likely to be focused;
- Consult on options for a UK MRV;
- Identify existing regulations that could limit the application of contrail mitigation, or create perverse incentives, and propose options that support action while maintaining the effectiveness of their intended primary function (for example, minimising CO_2 emissions), including the potential for temporary exemptions to support trials for some non-safety related regulations, and;
- Explore options for incentives for airlines and ANSPs to engage in contrail mitigation.

Considerations for Trial Exemptions

During trials, flights engaged in contrail mitigation could benefit from potential temporary exemptions from current rules and regulations pertaining to ANSPs and aircraft operators. Examples could include:

- Exemption from airport specific night noise regulations where curfew period infringements are caused solely by virtue of participation in contrail mitigation;
- Exemption of flights participating in contrail mitigation trials from existing ANSP or airline service performance measures, targets and financial incentives.
    - Note: for NATS these are set for a price control period (typically for 5 years) with a two-year lead time. The next UK price control is due to start in 2028 (the timetable will be published by the CAA shortly).
- Capacity targets also require consideration as contrail mitigation could lead to Air Traffic Flow Management (ATFM) delays that penalise ANSPs, and/or have knock-on impacts for the efficiency of the European network. Where performance indicators are impacted as a direct result of contrail mitigation, participating flights could receive a code which is non-attributable to NATS (En Route) plc (NERL)'s financial performance measures.

Examples of Future Policy-Enabled Operational Measures

A key function of future regulation will be to create an enabling policy framework that allows for new operational procedures. While the procedures themselves are operational, they require policy or guidance from DfT/CAA for implementation. The following list provides examples of such policy-enabled operational measures to explore further:

- Applying higher en-route handling charges to aircraft not participating in pre-tactical active contrail mitigation (with the justification that it increases ATC costs associated with en-route tactical interventions).
    - Note, this is a consideration for Maturity Levels 4 and 5 only since the Level 3 mandate on flight planning puts the onus on airlines, and without regulation, NATS can generally only propose avoidance if customers request it.
- Looking beyond Maturity Level 3 to achieve Level 5 goals:
    - Charges for aircraft flying through known and promulgated areas of persistent contrail formation, if there is robust ISSR forecasting.
    - Alternatively, existing carbon markets like the ETS could reward/penalise operators accordingly (for example, the fractional support currently offered to incentivise SAF usage), although a methodology and metric would be required to address fungibility issues.
    - An assessment of potential trade-offs is also required.

Key Stakeholders

To get to Maturity Level 3,

- Department for Transport (DfT) - demonstration of contrail specific regulation, policy and guidance
- Department for Energy Security and Net Zero (DESNZ) - potential exemptions/incentives relating to UK ETS
- ANSPs, Civil Aviation Authority (CAA) - performance oversight of ANSPs, and

To get to Maturity Level 4 & 5,

- Department for Transport (DfT) - implementation of contrail specific regulation, policy and guidance
- Potential international partners or collaboration (i.e. the EU for EU ETS MRV) and EASA.
- ICAO (global oversight).

4.7 Workstream 7 – Fuel Producers & Standards

4.7.1 Current Maturity Level

The current maturity level for Fuel Producers & Standards stands at Level 2 – Reactive, known, project-by-project.

4.7.2 Justification

Efforts in this workstream presently remain restricted to isolated projects that focus on specific technical or operational technologies. Current trials that have been recently reported or are ongoing include [Quante et al., 2025][19] and the project Quantifying Reduction in Thermal Contrails by Optimising SAF (QRITOS)[20] [21]. The impact of contrails is not yet a standard component of the design and review process.

4.7.3 Roadmap to Achieve Level 3, Level 4 and Level 5

Objectives

Achieving Level 3 requires fulfilling of the following objectives:

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[19] https://doi.org/10.1016/j.jatrs.2024.100049

[20] https://gtr.ukri.org/projects?ref=10141068

[21] Rolls-Royce leads UK project to demonstrate smarter use of Sustainable Aviation Fuel | Rolls-Royce

- **Prioritisation Procedures** - Establishing airline and airport procedures to prioritise the use of fuels which can reduce contrail climate impact on those flights which offer the greatest mitigation potential from the use of such fuels.

  Note: Implementing these procedures may be logistically difficult, particularly at large airports that use centralised hydrant systems (underground pipes) to fuel aircraft. However, these procedures may be much more straightforward at smaller airports. At these locations, fuel is often delivered by road-trucks, and planes are refuelled individually by bowsers (refuelling trucks), which allows for greater flexibility.

- **Segregated Supply** - Ensuring the routine availability of segregated storage or delivery for fuels, such as SAF, which can reduce contrail climate impact.

Further objectives identified for achieving **Levels 4 and 5** include:

- **Mitigation Recognition** - Implementing mechanisms to recognise the contrail-mitigation value derived from using fuel, such as SAF, which can reduce contrail climate impact (Level 4).
- **Value Assignment** - Develop mechanisms for "value flow-through" or "value-sharing" to incentivise both the purchase and the optimal use of SAF. This is important because the best opportunity to use a batch of SAF for contrail mitigation may not involve the airline that originally purchased it (Level 4).
- **Blend Ratio Optimisation –** Refining the fuel-loading infrastructure and the decision-making tools to allow for the targeted deployment of *different* SAF blend ratios. This is done to get the maximum contrail mitigation benefit from a limited amount of SAF, by taking factors like specific routes, departure times, aircraft types, and meteorology into account (Level 5).

Required Actions

Aircraft operators and/or airports

These stakeholders must undertake the following actions:

- Access or deploy decision-making tools and procedures to identify flights that offer the most benefit from the use of contrail-reducing fuels (such as SAF).
- Secure segregated deliveries of fuels, such as SAF, which can reduce contrail climate impact, ensuring they are not mixed with the general fuel supply.
- Where necessary, provide segregated storage for fuels that reduce contrail climate impact, such as SAF, to facilitate preferential fuelling for selected flights.

- Develop streamlined procedures for refuelling identified flights with fuels, such as SAF, which can reduce contrail climate impact.

OEMs

OEMs must focus on the following development areas:

- Identify, characterise, and pursue opportunities for improved fuel-efficiency and reduced life-cycle CO_2 emissions offered by the use of contrail-reducing fuels (such as SAF).
- Identify and, where feasible, develop the product characteristics necessary to enable the use of fuels, such as high-percentage SAF blends, which can reduce contrail climate impact.
- Align this work with existing OEMs[22,23,24,25,26,27] goals and compatibility tests for 100% SAF, which is required as part of the journey towards Net Zero CO_2 emissions.

Fuel Standards Bodies, Fuel Producers and OEMs

These groups must continue collaborative efforts toward establishing a new fuel specification that permits compatible aircraft to reach higher levels of contrail mitigation. This process must also account for the wider ecosystem, ensuring that ground-based fuel distribution equipment has compatible seals and that combustion equipment can accommodate different fuel properties like autoignition temperature and timing. This work is already underway, for example, within the ASTM task force on 100% Paraffinic Synthetic Aviation Turbine Fuel, which is working to define such a specification.

Fuel Producers

Fuel Producers must undertake the collaborative action of working with airports and airlines to identify, characterise, and overcome the logistical difficulties related to the segregated delivery, storage, and loading of fuels, such as SAF, which can reduce contrail climate impact. This action is necessary to unlock increased climate mitigation from such fuels.

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22 Our commitment to sustainable aviation fuel | Airbus

23 Boeing will deliver commercial airplanes ready to fly on 100% sustainable fuel

24 Rolls-Royce successfully completes 100% Sustainable Aviation Fuel test programme | Rolls-Royce

25 News | We tested a tried-and-true engine on 100% sustainable aviation fuel. It passed with flying colors. | Pratt & Whitney

26 GE Aerospace and partners achieve new milestone, testing 10 different aircraft engine models with 100% Sustainable Aviation Fuel | GE Aerospace News

27 https://www.safran-group.com/news/how-safran-helping-develop-sustainable-fuels-2023-05-25

Regulators

Regulators must ensure that regulatory frameworks meet the following requirements:

- Ensure that mandates for SAF provide sufficient flexibility to accommodate targeted SAF usage. This includes allowing for fluctuations in SAF usage intensity over large timescales, for example seasonal variations.
- Ensure that monitoring and reporting schemes possess the flexibility to account for flight-specific or flight-segment-specific fuel compositions, recognising that for contrail mitigation it is the properties, rather than provenance, of the fuel that influences the outcome.
- Ensure that charging or penalty schemes consider the actual usage on specific flights (rather than average usage) of fuels, such as SAF, which can reduce contrail climate impact. This must include the resulting contrail climate impact reduction, thereby providing an incentive for increased contrail mitigation.

Key Stakeholders

The key stakeholders involved in this segment are:

- Aircraft operators and/or airports
- OEMs
- Fuel Standards Bodies, Fuel Producers and OEMs
- Fuel Producers
- Regulators

4.8 Assessment of Maturity and Scope

This section provides a summary of the UK's current capability to mitigate the climate impact applying the CIMF defined in Section 2.0.

Based on the Gap Analysis (Section 3) and the workstream findings (Section 4.1-4.7), the assessment shows that current contrail projects largely fall into the first two maturity levels. The UK is currently transitioning from a Level 1 (Unknown, not practised or not controlled) state to a Level 2 (Reactive, known, project-by-project) state.

Table 2 provides a summary of this assessment applied to each workstream. The preceding sections (4.1-4.7) present a more detailed view of the current maturity level for each workstream and synthesise these individual findings into a series of roadmaps. This outlines the cross-cutting actions, dependencies, and performance indicators required to advance the UK's collective capability.

Table 2. Contrail Impact Mitigation Framework - Summary

Maturity	Level 1 ▼	Level 2 ▼	Level 3 ▼	Level 4 ▼	Level 5 ▼
Workstreams	Unknown, not practised or not controlled.	Reactive, known, project-by-project.	Proactive, standardised.	Measured and controlled.	Optimising with active feedback.
1. Aircraft / Engine OEMs	Efforts are restricted to isolated, project-by-project technical studies (e.g., ECLIF3, VOLCAN, PACIFIC, BlueCondor).		Include contrail impacts in system gate reviews; build impact estimation into standard design tools; quantify trade-offs.	Connect emissions data with contrail/climate models; assess trade-offs of design vs. operational mitigation; define standards for meteorological sensors.	Develop and certify new, lightweight airborne meteorological sensors for integration onto aircraft.
2. Airline Operations	No real-life operational experience with contrail avoidance; systems lack integrated contrail optimisation functionality.	Multiple UK airlines gain real-life operational experience by executing (and scientifically analysing) a small number of re-routed commercial flights.	Integrate contrail avoidance functionality into flight planning systems; establish standardised processes across the operation.	Achieve fully integrated contrail avoidance in flight planning; implement quantitative measurement (MRV) of mitigation effectiveness.	Implement an optimised, continuous improvement loop for both pre-flight (strategic) and in-flight (tactical) avoidance.
3. Climate Impact	Climate impact is considered on a project-by-project basis using different, non-standardised models and metrics.		Establish standardised methodologies and metrics for calculating climate impacts (fuel, CO_2, contrails); develop reliable forecasts; use large-scale trials to validate models.		
4. Weather Data	Forecasting tools and observation-based products are developed on a reactive, project-by-project basis.		Standardise the provision of ISSR forecasts and climate impact data; improve and validate contrail prediction products (nowcasting to T+36 hours).	Generate standardised reports measuring mitigation impact against a baseline; test weather products robustly in large-scale trials.	Achieve continuous improvement in forecast models and validation; fully integrate data into users' live decision-making processes.
5. ANSP Operations	Supporting contrail research on a project-by-project basis (e.g., CICONIA) in low-traffic environments; not yet feasible at scale.		This level involves two distinct development streams: - Low-density/complexity traffic: Define standard procedures and controller training. - High-density/complexity traffic: Use large-scale simulations and trials to determine feasibility, and develop advanced procedures, controller training, and ATC support tools (e.g., displays).		
6. Regulation	No UK regulation for contrails exists; current policies (e.g., ETS) focus only on CO_2 and may penalise contrail mitigation.	Use trials to test MRV efficacy;	Mandate contrail mitigation as a consideration in flight planning; implement an enabling framework with incentives and consult on a UK MRV.	Formally establish the UK MRV framework; monitor its performance and measure its impact against national baselines.	
7. Fuel Producers & Standards	Efforts are restricted to isolated, project-by-project trials (e.g., QRITOS) focusing on specific fuel technologies.		Establish procedures to prioritise contrail-reducing fuels (e.g., SAF) for high-impact flights; ensure segregated storage is available; create new fuel standards.		
Governance					
Indicative Features		**• Project-level Management • Quality Control • Configuration Management**	**• Shared Standards • Shared Capabilities • Organisational Improvement WG**	**• Quantitative Measurements • Performance Baselines**	**• Ongoing Performance Management • Causal Analysis and Resolution**
Oversight	**None**	**Project-level**	**Joint Governance Body**		
			Legend	**Achieved maturity**	Scoped improvement

5.0 Discussion – Overview of National Maturity

Many organisations undergo transformation and operational efficiency, and the UK's aviation ecosystem is no different when it comes to Contrail Impact Mitigation. Maturity models have been created to manage the complexity of transformation across diverse organisations with a common overall objective. It seems, therefore, reasonable to assume that such a scheme is applicable to the UK's aviation ecosystem. Although applying this model to a national-level topic may seem ambitious, with some adaptation it provides good insights and clear guidance for decision-making. Such a scheme allows all parts of the aviation ecosystem to see the synchronisation points required to reach a common level of operational transformation maturity that is otherwise obscured through trials and studies.

Looking at the end result, the national maturity is, unsurprisingly, low, because Contrail Impact Mitigation does not yet exist at a systematic, operational scale. However, it is clear that the aviation community and its partners are engaged and actively working to understand the subject.

The academic community has identified the core scientific issues around contrails, particularly their formation in ice-supersaturated regions and their net warming effect on the climate. This has led to the development of models that can estimate their potential impact and, by extension, the potential benefit of mitigation.

However, these models still contain significant scientific uncertainties, including the complex interactions between aerosols and clouds, the precise radiative properties of contrail ice crystals, and the net climate effect of NO_X emissions. Furthermore, while there is consensus that non-CO_2 effects are net warming, there remains a healthy scientific debate regarding the precise magnitude of these impacts and the appropriate metrics for measuring them, which requires value judgements between impacts occurring over different timescales and is therefore beyond a purely scientific question.

In addition to these scientific limitations, academic modelling alone cannot fully assess the impact of contrail mitigation in terms of what is operationally possible. This requires operational partners to assess the impacts on the network and the extent to which contrail mitigation may actually be feasible, for instance, in a busy traffic environment. Operational trials must provide real-world data to evidence this modelling; this is one of their key contributions.

Air traffic control maturity remains low because the UK has not developed or tested trials to create learning. Likewise, such trials are fundamentally dependent on weather data and analysis in the upper atmosphere, a capability that remains in the very early stages of maturity, not only for the UK but globally. This is a critical point: the lack of high-resolution, real-time humidity data in the upper troposphere is a systemic challenge that limits the accuracy of all contrail prediction models. Airlines, themselves, have made progress in their understanding of the complex trade-offs between additional fuel burn (and associated CO_2 emissions), flight time, and contrail formation, but they have yet to evidence these trade-offs with real-world data at scale. Aircraft, Engine and Fuel OEMs have tested their equipment in scientific and localised trials but the timing of the technology, mainly SAF, has not enabled the testing or evidencing of mature operational benefits.

Despite the UK's low maturity, it is not vastly different to the level of expectation for any country. The framework, however, gives us the areas of focus to reach the next step. While some stakeholders can mature faster than others, and progress can be made in all domains even if out of synchronisation, there still needs to be a level of synchronisation across stakeholders to achieve an overall national level of maturity.

The CIMF, by its nature, highlights the need for a level of governance to drive it from Maturity Level 1 though to Maturity Level 4 with different levels of focus. The early levels require synchronisation of trials and learning, leading to a strong governance role and a key decision point at Level 3 to align on the standardised operating model across all organisations. The governance can then begin to move from directing to overseeing, bringing the community of operators, manufacturers, and service providers together for monitoring and reporting on performance. This allows for dynamic adaptation based on performance data at Level 5.

6.0 Recommendations

Based on the consolidated findings, this report proposes the following strategic recommendations to accelerate the UK's national capability in contrail mitigation. They are organised by strategic priority and sequenced to build capability logically from the current reactive state towards a future of proactive, optimised mitigation.

6.1 Recommendation 1: Establish a Permanent Governance Body for CIMF.

Contrail mitigation has been a subject of research for many years across the UK, EU and US. Projects are typically three to four years in duration with no overall coordination between them, instead depending on the willingness and ability of individual airlines, air navigation service providers, manufacturers, and research institutions to fund. Progressing from these isolated projects to a state of operational maturity, requires a PBG. This body would own and drive the national maturity roadmap, with a mandate to coordinate trials, synchronise learning between the different parts of the aviation ecosystem, and provide the strategic direction needed to achieve a standardised, proactive mitigation capability.

No.	Recommendation
Recommendation 6.1.1	Establish a Permanent Governance Body.
Recommendation 6.1.2	Members of the Governance to include, but not limited to: ● CIM Group Members: NATS, Airbus, University of Cambridge, Met Office, BALPA, Boeing, GE, UK-ARC, IAG, AEF, ATI, Imperial College London, Rolls-Royce, TUI. ● National Organisations: UK MOD, CAA, NERC, EPSRC, National Physical Laboratory, Airport representation. ● International Advisory: EASA (ANCEN), NAV CANADA, ICAO (Working Group 2).

Table 3. Recommendations - Permanent Governance Body

6.2 Recommendation 2: Use the CIMF to drive stakeholder synchronisation

Making CIMF an operational realisation requires coordination across many stakeholders. The Permanent Governance Body will use the CIMF to prioritise activities to drive towards their common goal. The group believes that this framework presents a starting position that must be owned, used as guidance and updated as learnings from trials evolve understanding.

No.	Recommendation
Recommendation 6.2.1	Use the CIMF to inform prioritisation.
Recommendation 6.2.2	Update the CIMF with learnings from trials and other activities, nationally or internationally.
Recommendation 6.2.3	Promote the use of the model for engagement in an international context, such as the EU Horizons.
Recommendation 6.2.4	Use the maturity framework to align regulatory measures with national and international capability.

Table 4. Recommendations - Contrail Impact Mitigation Framework

6.3 Recommendation 3: Implement large-scale trials in airspace where the UK provides an ATC service

The proposed large-scale UK controlled airspace trials have the potential for a high impact on contrail impact mitigation due to the geographical characteristics of the North Atlantic air traffic. The trials increase in complexity and impact over a period of time and feed one of the streams of the CIMF.

No.	Recommendation
Recommendation 6.3.1	Implement large-scale trials, starting in NATS' oceanic airspace during a winter period across different times of day, with potential extension to domestic airspace to ensure measurable results.

Recommendation 6.3.2	Use the learnings to inform further national and international trials in accordance with the CIMF.

Table 5. Recommendations - UK Large Scale Trials

6.4 Recommendation 4: Develop the enabling policy and operational procedures for CIM

Consider limiting contrail trials to flights where the predicted fuel burn penalty does not exceed a threshold (for example, 1% of total fuel burn). As one available option, pilots, in coordination with ATC, could reduce speed to reduce or eliminate any fuel burn penalty associated with contrail mitigation. ATC-instructed slowdowns are normal practice, but this must consider the optimised cruising speed of newer aircraft such as the B787 or A350 and the airline Cost Index (CI); it may also require ANSPs to reduce the speed of any following aircraft to maintain separation.

Where airport holding delays exist at congested airports, consider giving aircraft that have been instructed to slow down as part of a contrail mitigation trial (incurring a time penalty) preference when allocating the order of aircraft to commence approach (subject to normal safety and fuel-related operational issues).

**Note: Extending this potential measure to flights inbound to international (transatlantic) destinations would require coordination by multiple ANSPs and local airport approach functions that may vary at different times of the day. This would also depart from NATS First-Come, First-Served principle, although tactical changes can be made for safety, efficiency or regulatory reasons. A further consideration is whether an aircraft practicing contrail mitigation has already potentially benefitted from both linear holding and a lower stack entry level, and/or a slow down for extended arrival management purposes (XMAN - cross border arrival management), providing additional rewards.*

Promote the standardisation of prediction software and mandatory use in the pre-tactical phase of flight planning.

**Note: The alternative, a voluntary approach, risks some airlines not investing in the software potentially resulting in increased costs due to less efficient and more unpredictable tactical interventions. Regarding tactical interventions, note that current rules limit the* *opportunities for ANSPs to initiate such interventions, as opposed to interventions initiated and requested by airlines, so this could require enabling regulation. Operators should avoid filing for a below optimum altitude and then requesting a different cruising level that could still result in a contrail being produced (unless for safety and other operational priorities, or when acting on revised information).*

No.	Recommendation
Recommendation 6.4.1	Explore the use of ATC-coordinated speed reductions to mitigate fuel penalties, considering the impact on optimal cruising speeds (Cost Index) and following aircraft.
Recommendation 6.4.2	Investigate limiting contrail mitigation trials to flights where the predicted fuel burn penalty does not exceed a defined threshold (e.g., 1%).
Recommendation 6.4.3	Assess the feasibility of giving landing preference to aircraft that incurred a time penalty from contrail mitigation, noting the complexities for international coordination and 'First Come First Served' principles.
Recommendation 6.4.4	Promote the standardisation of contrail prediction software and its mandatory use in pre-tactical flight planning to ensure equitable participation and operational predictability. This includes enhanced humidity measurements to improve, initiate and validate the forecasts as well as ongoing improvements to contrail prediction.
Recommendation 6.4.5	Review existing rules that limit ANSP-initiated tactical interventions and develop enabling regulation to support ANSP-led mitigation.
Recommendation 6.4.6	Establish guidance to ensure operators file flight plans that reflect contrail mitigation intent, minimising tactical requests for non-compliant cruising levels.
Recommendation 6.4.7	Use trials to demonstrate the efficacy of MRV elements and identify where policy interventions are most needed.

Table 6. Recommendations - CIM Policy and Operational Procedures

7.0 Conclusion

This report has provided the first consolidated national assessment of the United Kingdom's capability to mitigate the climate impact of aviation contrails. The analysis confirms that the UK's capability is in its early stages, assessed at Level 2 ("Reactive, project-by-project"). This is not a unique UK failing but reflects a global challenge where efforts remain isolated, small-scale, and uncoordinated, as highlighted in the gap analysis.

The findings show that progress to Level 3 ("Proactive, standardised") is currently blocked for all workstreams. This is due to critical, cross-cutting gaps that no single entity can solve alone. These include the lack of standardised tools and climate impact metrics, deficiencies in upper-atmosphere weather data and the absence of an enabling regulatory or policy framework.

The CIMF developed by this group is not only an assessment tool but a collaborative and strategic roadmap. It makes clear that no workstream can mature in isolation; a "whole system" approach is essential. Airlines cannot act without tools from OEMs and procedures from ANSPs, and industry investment is unlikely without clear policy signals from Government.

To break this impasse, the report's strategic recommendations are clear and sequential. The first priority is to establish a permanent, UK-led governance body to own and drive the national roadmap. This body must use the CIMF to synchronise stakeholder efforts, develop the enabling policy and operational procedures for CIM, and, most critically, implement large-scale trials in airspace where the UK provides an ATC service (it should be noted that the North Atlantic area is international airspace partially managed by NATS under agreement).

These trials, particularly leveraging the unique strategic opportunity of the North Atlantic airspace, are the only practical way to validate the science, close the data gaps, and build the operational evidence needed for standardisation. By adopting this structured, collaborative framework, the UK can move from a reactive to a proactive state, effectively addressing aviation's significant non-CO_2 impacts and ensuring efforts are aligned with its net-zero ambitions.

Glossary

3Di	Three Dimensional Insight
AA	American Airlines
AI	Artificial Intelligence
ANCEN	Aviation Non-CO_2 Expert Network
ANSP	Air Navigation Service Providers
ASTM	American Society for Testing and Materials
ATC	Air Traffic Control
ATCOs	Air Traffic Controllers
ATFM	Air Traffic Flow Management
ATS	Air Traffic Service
BALPA	British Airlines Pilots' Association
CAA	Civil Aviation Authority
CAEP	Committee on Aviation Environmental Protection
CANSO	Civil Air Navigation Services Organisation
CASK	Cost per Available Sit Kilometre
CI	Cost Index
CICONIA	Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment
CIM	Contrail Impact Mitigation
CIMF	Contrail Impact Mitigation Framework
CMMI	Capability Maturity Model Integration
CODEX	COronal Diagnostic EXperiment
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DESNZ	Department of Energy Security and Net Zero
DfT	Department for Transport
DFS	Deutsche Flugsicherung GmbH
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DWD	Deutscher Wetterdienst
EASA	European Union Aviation Safety Agency

ECLIF	Emission and CLimate Impact of Alternative Fuels
ECMWF	European Centre for Medium-Range Weather Forecasts
EEA	European Economic Area
ETS	Emissions Trading System
EU	European Union
FMP	Flow Management Position
GCOS	Global Climate Observing System
GHGs	Greenhouse Gases
GRUAN	GCOS Reference Upper-Air Network
IAGOS	In Service Aircraft for a Global Observing System
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
ISSR	Ice Super Saturated Region
JZTF	Jet Zero Task Force
KPIs	Key Performance Indicators
LEO	Low Earth Orbit
MRO	Maintenance, Repair, and Overhaul
MIT	Massachusetts Institute of Technology
MRV	Monitoring, Reporting and Verification
MUAC	Maastricht Upper Area Control
NASA	National Aeronautics and Space Administration
NATS	National Air Traffic Services
NERL	NATS (En Route) plc
OEM	Original Equipment Manufacturer
OPS NOTAM	Operations Notice to Air Missions
PACIFIC	Particle emissions, Air Quality and Climate Impact related to Fuel Composition and Engine Cycle
QRITOS	Quantifying Reduction in Thermal contrails by Optimising SAF
R&D	Research and Development
SAF	Sustainable Aviation Fuel
SLCFs	Short-Lived Climate Forcers
UK	United Kingdom

VOLCAN	VOL avec Carburants Alternatifs Nouveaux
XMAN	Cross Border Arrival Management