Contrail avoidance roadmap

Final Report

Aviation Safety • Efficiency
Capacity • Environment

Contrail avoidance roadmap

Final Report

Version 4.0

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Executive summary

Increasingly, air traffic management (ATM) and network management (NM) are expected to play a key role in implementing contrail avoidance at scale. Based on this observation, this report clarifies the bottlenecks for air traffic management to get involved and the actions that need to be implemented to achieve large scale avoidance. This report shows that significant adaptations to systems, ways of working, including key performance indicators, and trainings are needed to render contrail avoidance feasible, not only at ATM level but also at airline and NM level, in particular for coordination tasks.

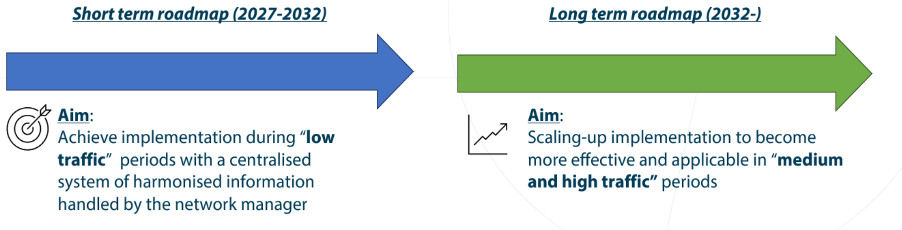
The aim of this report is to provide Transport & Environment (T&E) with insights on **operational contrail mitigation challenges** and **opportunities** for operational contrail avoidance in the form of a **Roadmap**. The report is based on a literature study, a thorough analysis of contrail avoidance trials, interviews with operational experts and leveraging To70's expertise. With this analysis we identify three main challenges, shown in the table hereby, subdivided across the different flight phases further detailed in the report. To tackle these challenges, the roadmap provides stakeholder-aligned and cost-informed actions to scale-up contrail avoidance by 2032 and onwards.

Main Challenges	
1	Integration of contrail avoidance in Air Traffic Management.
2	Integration of contrail avoidance in airline operations.
3	Improving coordination between these two stakeholders to strengthen their collaboration.

The analysis finds that **in the short term large scale avoidance during low traffic periods is achievable**, through ATM involvement and NM leadership. Yet, this remains dependent on the development of large-scale tools supporting decision-making for air traffic controllers. ATM will need to be involved in both pre-tactical and tactical approaches to ensure that capacity and efficiency constraints are included within the trade-offs for efficient contrail mitigation. To get ATM and NM actively involved, systems integration is necessary, procedures to enable the use of these systems must be developed, and training must be provided. Reassessing Air Traffic Controllers KPIs is key to locking new systems in place.

Trials are the best way to start such integration, and should focus on multiple approaches to contrail mitigation to test different setups and responsibilities. The cost per single stakeholder trial is limited as systems are available, in the range of **0.5 to 7 M€ (0.5-1M€ for airline-led trials, 4-7M for ANSP-led trials) per trial.** Multi-faceted approaches across different actors or airspaces and airlines will require more significant resources, in the range of **10-15M€**[1]**.** These trials assume the use (OPEX), at no costs, of available contrail avoidance systems already developed by stakeholders such as Contrails.org, Google, Thales or FlightKeys but assume a software development cost (CAPEX) to be born through public funds or end-consumers (ANSPs or airlines).

In the long term, contrail avoidance needs to scale up both in terms of traffic density but also geographical span (outside of Europe). The NM is expected to play a central role in coordinating contrail avoidance across airspace blocks (short-term) and alignment with other aviation authorities (long-term roadmap). This report leads to a contrail avoidance roadmap, subdivided into short term / long term goals, as shown in the figure below.



[1] The ranges indicated in this paragraph are indications that must be cautiously considered – see appendix 4

0 Introduction

0.1 Background

Aviation's carbon impact, widely recognised across the aviation sector, is responsible for 2 to 3% of global carbon emissions and around 4% in Europe[2]. Based on this observation, efforts have been engaged across the industry to reduce the carbon intensity of air travel: new aircraft technologies, airspace modernisation, alternative fuels and propulsion methods, just to name a few.

Aviation non-CO2 effects, generated by gases and particles such as nitrogen oxides, sulphur oxides, water vapour, and soot, have long been disregarded although the intergovernmental Panel on Climate Change (IPCC) already warned on the aviation non-CO2 effects in the late 1990s[3]. Among non-CO_2 emissions, one of the most significant and visible contributors is contrails, short for condensation trails. At cruise altitude, and under specific atmospheric conditions with high humidity, aircraft exhaust can form persistent warming contrail cirrus (thereafter, contrails). These clouds can have a warming or cooling effect, but on balance their net impact is warming: they trap heat and contribute to the greenhouse effect. Overall, they have the potential to double the overall climate impact of aviation[4]. Yet, their formation is highly uneven: only about 3% of flights, commonly referred to as "big hits" were responsible for roughly 80% of global warming contrails in 2019[5].

In contrast to emerging propulsion technologies that require major changes to aircraft systems, or sustainable aviation fuels that remain expensive at scale, contrails can be mitigated through operational changes. Those changes, such as adjustments in flight paths (deviations), altitude and timing, if implemented at key phases of flight (pre-tactical or tactical), could substantially reduce aviation's overall climate impact. Recent research shows most contrail warming flights, 75%, occur between January and March and October to December, with 40% during late evenings and nights[6]. Therefore, operational changes to avoid contrail warming would only affect a small percentage of flights, and mainly flights in the winter months and during the evening or night when airspace is generally less congested.

While there are different strategies, all stakeholders agree that (large-scale) trials are a key step in the roadmap to reducing aviation induced non-CO_2 emissions. Several trials have been run, led by airlines, Air Navigation Service Providers (ANSPs) and technology providers/researchers. If run well, these trials can support mitigation in three ways:

- Understanding and reducing **operational** uncertainties and risks;
- Understanding and reducing **scientific** uncertainties;
- Providing insight into standardizing and scaling-up operational mitigation strategies.

0.2 Report aim

This report provides Transport & Environment (T&E) with insights on operational contrail mitigation challenges and opportunities through a comprehensive analysis of a selection of current and past trials as well as a forward looking roadmap for operational contrail mitigation. It does this by defining and examining the Air Traffic Management (ATM) related operational challenges and opportunities that arise during current contrail mitigation trials. With these findings in hand, and based on operational experience, we develop a comprehensive roadmap for contrail avoidance from an ATM perspective. This roadmap ambitions to prepare the European Union ecosystem for contrail avoidance at scale within a decade, including large scale operational trials and guidelines for setting up a supportive regulatory and policy framework that enables the roll out of these operations.

0.3 Reading guide

[2] Reducing emissions from aviation - Climate Action - European Commission
[3] Aviation and the Global Atmosphere
[4] EASA
[5] ACP - Global aviation contrail climate effects from 2019 to 2021
[6] 202601_REPORT_how_to_scale_up_contrail_avoidance

The report is structured into four chapters:

- *First*, we set the scene on the overall functioning of ATM by presenting the operational context and the critical decision-making.
- *Second*, we provide an overview of the latest insight on operational contrail avoidance. This overview includes an operational reporting literature review, as well as a summary of past operational contrail avoidance trials with a particular focus on those carried out by ATM stakeholders MUAC, NATS, LFV (Swedish ANSP) but also Thales and within D-KULT. In this chapter, we analyse the trial methodologies, tools used, results and gaps to provide a detailed overview of their achievements.
- *Third*, we explore the operational challenges identified through the literature review and several interviews conducted with operational experts who led the trials.
- *Fourth*, we present a roadmap that combines the learnings of the earlier chapters with our expertise on airspace and contrail avoidance. It offers both a short term perspective with associated actions as well as a long term perspective. This will provide insight into preparing the European aviation ecosystem for large-scale contrail mitigation strategies.

0.4 Methodology

Our methodology relies on a combination of desk research and operational expertise from To70 experts, which is collected and analysed to explore the operational challenges and roadmap for mitigation. This analysis is supplemented by the results of interviews during which experts are asked to share insight into the trials that they have participated in as well as feedback on the roadmaps to achieve large-scale contrail avoidance. The table below further details our methodology.

Table 1 Methodology

Type of information	Methodology	Description of data	Source
Expert input	To70 expertise	ATM expertise, Non-CO2 expertise	Project references and To70 experts in ATM
	Interviews	Reflection on trials and roadmap: Experts are asked to share their insights from their respective trials well as to outline potential actions and pathways for future roadmaps.	6 interviews conducted: Thales, TUI, NATS, MUAC, Contrails.org / Imperial College, LFV (Swedish Air Navigation Service Provider (ANSP)). Several conversations with experts from Google, FlightKeys.
Literature	Desktop research	Identified challenges and opportunities for contrail avoidance	Sector reports and reports on the results of trials, see Appendix A
		Trials performed: best practices and lessons learned	

1 Operational ATM context

This section of the report provides insight into the functioning of ATM, including ANSPs, Air Traffic Controllers (ATC) as well as airline dispatchers and pilots. It describes the key principles of ATM, roles of each stakeholder involved and critical decision making points in flight planning, highlighted in literature, by the interviewees and based on To70's ATM and aviation expertise.

1.1 Flight phases

Airspace operations, including the interplay between stakeholders on flight planning and airspace management can best be assessed in light of the four different stages of flight operations. Each phase has a different timeline, and within each phase each aviation stakeholder has a different role. The phases are described below.

Table 2 Description of flight phases

Phase	Timeline	Description
Strategic	Up to 3 days before the flight	During the strategic phase, the strategy teams of airlines, Network Manager and ANSPs focus on main routes that will be flown and how to manage airspace safety and congestion. They also focus on the software, data and processes to be used in the next phases.
Pre-tactical	3 days before the flight up to 3 hours before flight	In the pre-tactical phase, airlines submit their final flight plan with updates based on the latest changes (meteorological data, fleet change etc). Network managers at Eurocontrol, together with ANSPs ensure the flight plan fits into the expected capacity and approve it. If it does not, the airline is provided with a different take-off time. More information on this process is provided in sections 1.3 to 1.6
Tactical	Less than 3 hours before the flight and during the flight	During the tactical phase, airlines and ATC ensure that the flight plan remains up to date with all unexpected situations (airspace unforeseen closure, turbulences, capacity issues etc). Flight plans can be changed up to flight activation (engine start). After flight activation, changes need to be made tactically and require additional collaboration between pilot, dispatcher and ATC. Tactical deviations can take place due to unforeseen weather, unforeseen congestion or shorter routes available to airlines provided by ATC. In very special cases, when significant delays or cancellations occur, there is a possibility for an airborne change also called an "ATC Change Message".
Post operational	After the flight	After the flight, airlines and ANSPs collect the data from the flight to improve their operations and flight planning and airspace planning and capacity. They can also use this to do their reporting for environmental, safety or other compliance.

The definitions in the table above differ slightly from the standard Eurocontrol definitions[7] in order to better reflect the operational realities of contrail avoidance. For example, Eurocontrol defines the pre-tactical phase as beginning six days before departure and the tactical phase as starting on the day of operations, regardless of departure time (morning / evening). In the context of contrail avoidance, more precise time windows are required because weather forecast accuracy improves significantly closer to departure. The three-hour threshold was therefore selected as it corresponds to the latest point at which flight plan modifications can typically be requested.

1.2 Flight levels

In aviation, altitude is measured by a pressure altimeter within the aircraft. The pressure at a certain altitude is compared to the pressure either at ground level or to a standardised pressure level. The latter is used during the cruise phase of a flight. A flight level (FL) is an aircraft's altitude as determined by the pressure altimeter using the International Standard Atmosphere. The altimeter setting used is the ISA sea level pressure of 1013 hPa or 29.92 inHg. It is expressed in hundreds of feet. By using a standard pressure setting, every aircraft has the same altimeter setting, and vertical separation can be maintained

[7] Network operations | EUROCONTROL

during the flight. The most used flight levels for cruise are comprised between FL 300 and FL 450 (between 30.000 feet and 45.000 feet).

In the same direction, aircraft fly two FLs apart:

- Eastwards flights fly on odd FL (FL 350 – 370 etc)
- Westwards flights fly on even FL (FL 340 – 360 etc)

Therefore, unless specified, when this report indicates a flight level change, it means the flight has deviated by 2,000 ft up or down.

1.3 Air traffic Management

ATM, is an umbrella term that refers to the dynamic and integrated management of air traffic and airspace including air traffic services, airspace management and Air Traffic Flow and Capacity Management (ATFCM). The figure below shows the structure of air traffic management. A description of these stakeholders is proposed thereafter.

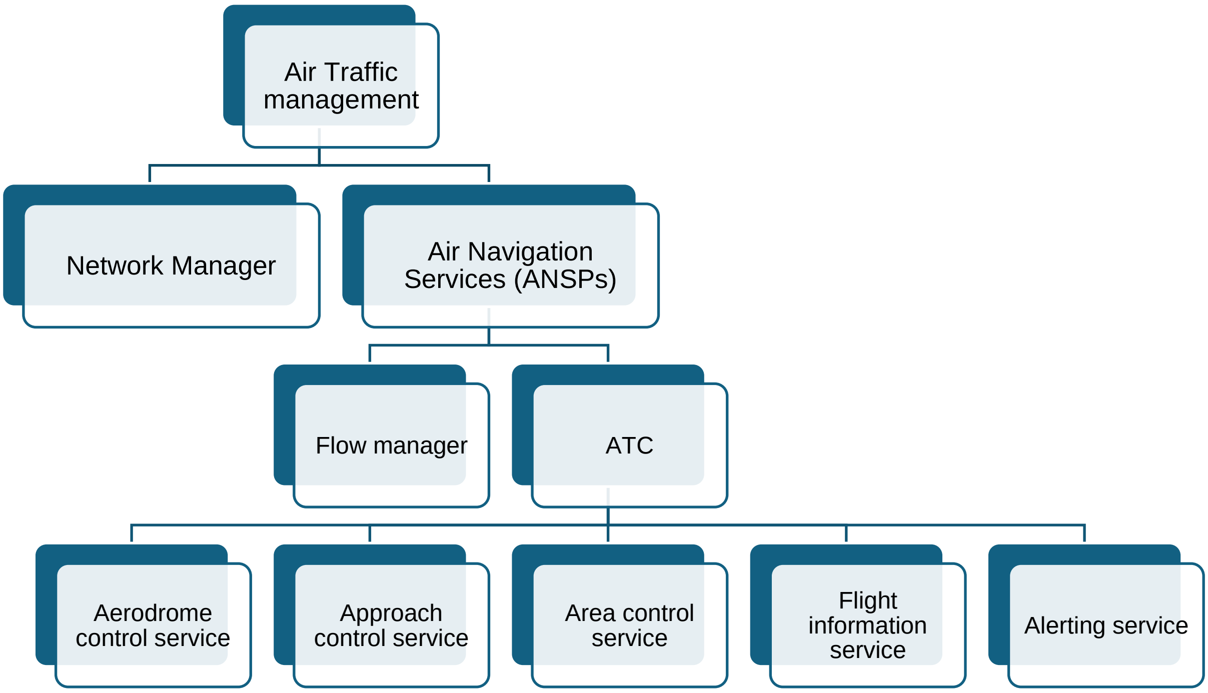


Figure 1 Structure of Air traffic Management (source: To70)

The Network manager (NM) provides a coordinating role between national or regional ANSPs, especially in Europe where the airspace is segmented. The NM manages ATM network functions (airspace design, flow management) as well as scarce resources (transponder code allocations, radio frequencies) and cost division. The NM's general objectives are to support the execution of the network functions and to contribute to the continuous improvement of network operations and the overall performance of the network. Eurocontrol is the only network manager in Europe. In other continents, national ANSP organisations or an aviation authority such as the FAA takes the role of network manager to coordinate between different air traffic control locations and to ensure coordination of airspace.

An **Air Navigation Service Provider (ANSP)** is responsible for managing aircraft in flight and on the manoeuvring area of airports, and is the legitimate holder of that responsibility. The ANSP also plays a key role in determining strategic route availability such as flight paths, permitted flight levels and flight times. Examples of ANSPs are the Direction des Services de la Navigation Aérienne (DSNA) in France or the Maastricht Upper Airspace Control Center (MUAC) in The Netherlands. Within the ANSP, we highlight two main functions:

1. A **Flow Manager (FM)** is a working position usually established within ANSPs to ensure the necessary interface between local ATCs, Aircraft operators and Airports and a central management unit such as the NM on matters concerning the provision of the air traffic flow and capacity management service. This is, for instance, the Amsterdam Area Control Center (Amsterdam ACC).
2. **ATC** is the main service provided by air traffic controllers and is divided into:

    - **Aerodrome control service**. This is focused on aircraft on the ground (the manoeuvring area of the aerodrome) or in the vicinity of the aerodrome.
    - **Approach control service**. This service links the aerodrome control and the area control and is focused on the climb, descent and approach phases of the flight.
    - **Area control service**. This service is focused on the cruising part of the flight.
    - **Flight Information Service (FIS).** This service is performed in uncontrolled airspace. Uncontrolled airspace is that part of airspace where ATC does not provide separation services, clearances, or direct oversight. Pilots are responsible for their own safety using Visual Flight Rules (VFR) to avoid other aircraft, relying on communication and pilot judgment rather than ATC instructions.
    - **Alerting Service**. This service is provided in order to inform the Search and Rescue (SAR) facilities of aircraft in distress.

1.4 Flight planning by airlines

Airline decision making on flight routing is done by dispatchers and pilots collaboratively. First, the dispatch team develops the flight plans for all flights, and coordinates these flight plans with both the NM as well as the airline pilots. As soon as the engines turn on, the pilots take over the decision making on the flight plan, and potential deviations from the latter, though they communicate closely with their dispatchers. Pilots are end-responsible for the safety of their aircraft, including the provision of sufficient fuel and avoidance of adverse weather, but also arrival within the allocated time and communication in the air with air traffic control, hence they need to be in control of the routing.

All airlines use flight planning software to develop their flight plans before these are sent to the NM and pilots. Examples of flight planning software providers include Lido, Flightkeys and Jeppesen. For the same route, day over day, the flight characteristics (flight level, speed, travel time etc) varies very marginally from one flight to the other. Therefore, automatic flight planning software can execute such repetitive tasks for dispatchers and most flight plans are generated automatically. In some unique cases such as flights over critical areas (war, natural disasters, etc.) and for long haul flights, dispatchers will review the flight plan before sending it out.

Some flight planning software developers, including Flightkeys, have recently integrated an option to identify and mitigate for contrail warming-prone flights. This software allows dispatchers to factor in a maximum fuel penalty or delay trade off with contrail avoidance, and provides alternative contrail avoiding routes to the dispatcher. Their contrail identification software is supported by Contrails.org and Google and based on the Pycontrails library and weather ensemble data. Currently, FlightKeys tooling follows Contrails.org API's within their system, and hence also makes use of European Center for Medium-Range Weather Forecasts (ECMWF).

1.5 Flight planning by ANSPs

Airspace is divided into different airspace blocks, with horizontal and vertical dimensions. All airspace blocks are controlled by at least one air traffic controller, though blocks can be combined to form a larger block when there are fewer flights. All airspace blocks have a defined maximum capacity that ensures an air traffic controller responsible for that block of airspace is able to handle the traffic safely and efficiently.

Flight planning coordination between the network manager and airlines ensures the smooth, safe and efficient management of (upper) airspace, considering the capacity (supply) and the requests for overfly (demand). A flight plan requested by an airline goes through a number of steps before being approved by the NM.

Airline dispatchers send each flight plan to the Network Manager Operations Centre (NMOC). Flight plans may be submitted up to a maximum of 120 hours, or five days, in advance of the Estimated Off Block Time (EOBT) of that flight plan, but no later than 3 hours before the EOBT. The flight plan goes through the IFPS (Integrated Initial Flight plan Processing System), which checks if the flight plan is made in accordance with altitude, speed, and avoidance of Military airspace, etc. If it is not approved, the dispatcher must develop a new flight plan. If it is approved, it is checked by the NM and local flow management positions to ensure the flight plan fits within the broader airspace and airport capacity. If not, the NM adapts the flight plan by providing a Calculated Take Off Time (CTOT) or, in limited cases, proposes a new route to the airline.

When an individual flight plan (FPL) has been filed but it is decided within 4 hours of EOBT to use an alternative routing between the same aerodromes of departure and destination a modification message may be sent. By sending an Acknowledgment Message (ACK) to the filer of the flight plan, IFPS indicates the successful processing of a submitted message against the environmental data held by the NM at the time of processing that message. Once the flight plan has been approved by the NM, the aircraft can commence the execution of the flight. From that point onwards (2-3 hours ahead of EOBT), deviations to the flight plan are handled by ATCOs, alike other operational adjustments such as airspace closures and weather deviations. Table 3 below summarizes the role of each of the above stakeholders in pre-tactical and tactical flight planning.

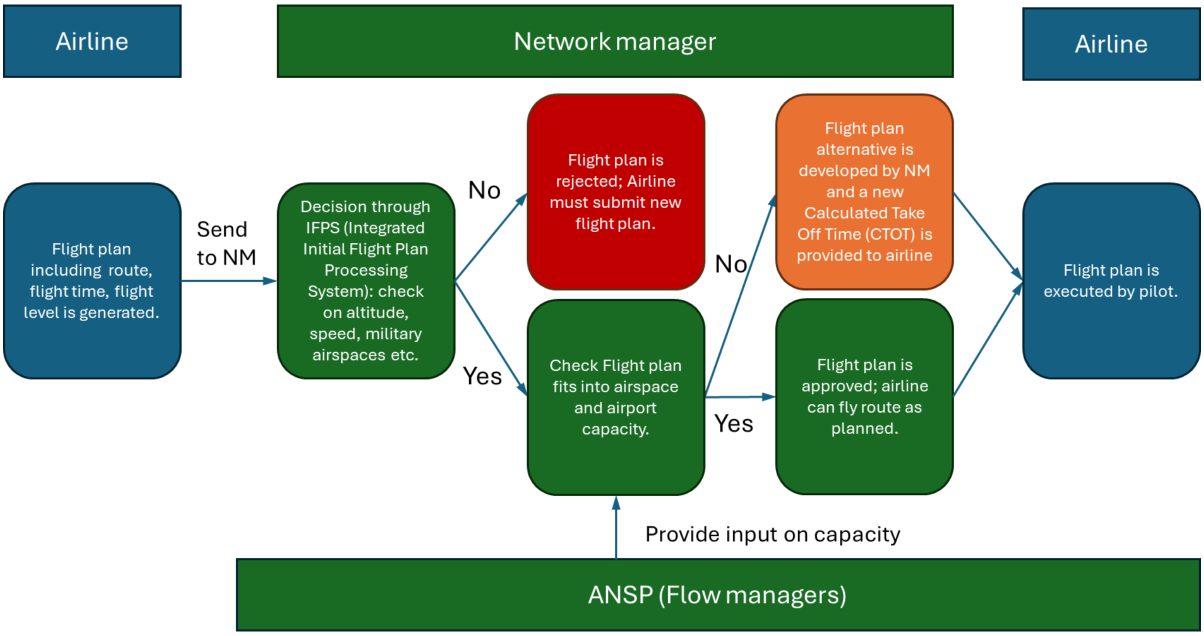
1.6 Flight coordination by Network Management

For every flight in or over Europe, airlines must submit a flight plan to the NMOC during the strategic phase. NMOC uses the airspace and aeronautical data available to check the flight plan. Then, it plans and coordinates network activities through a Collaborative Decision Making (CDM) process. The NMOC reviews procedures and suggests measures to identify major imbalances in the network's capacity demands. When these are identified, the NMOC coordinates and executes strategic air traffic flow and capacity management (ATFCM) planning to optimise all available capacity. Next, in the pre-tactical phase, the NMOC studies the demand for the day of operation, compares it with the predicted available capacity and makes any necessary adjustments to the plan developed. By doing so, NMOC optimises efficiency and balances demand and capacity by organising resources more effectively and by implementing a wide range of appropriate ATFCM measures. Then, during the tactical phase on the day of operations, the NMOC makes the necessary modifications to deliver real-time optimisations to the network.

As the NM has all the essential information of the European network, it plays the central role in balancing the capacity with all the demands in the European Network. As such, the NM is potentially well suited to integrate contrail avoidance strategies that also take into account all flight plans, overall demand and overall capacity. The table below summarises the role of each stakeholder in the flight planning phase.

Table 3 Description of ATM and airlines stakeholders' role per flight phase

Entity	Role	Role in pre-tactical flight planning	Role in tactical flight planning
ANSP	Flow manager	Creates the best balance between capacity and demand from airlines for an individual ANSP / Center. Coordinate with NM.	Monitor possible changes in demand for ATC sectors of the unit of the FMP. Take action (if possible) to mitigate a demand-capacity imbalance in sectors of the unit.
	Air traffic management	Providing airspace and airport capacity data to the NM to enable decision making on the flight plans submitted by airlines.	Communicate with the cockpit crew. Give permission for the reroute. Coordinate with ATCs downstream.
Airlines	Dispatcher	Create a flight plan taking into account weather, fuel, crew, etc. Brief the cockpit crew.	Support pilot with any in-flight alternative routing if needed.
	Pilots	Briefing and communication with dispatcher on flight plan and potential adaptations. Checking weather forecast.	Constant communication with ATC to get clearance and potential rerouting (shorter route, avoiding turbulence etc). Communication with dispatchers if needed.
NM		Supervises the flight planning phase and ensures a coordination role among all ANSPs	Minimal role : information dissemination role to ANSPs on airspace limitations.



1.7 Balancing Safety, Capacity and Environment

The ATM system, and within it all stakeholders including NM, ANSPs and individual ATC, has to work within the framework of safety and, within this, balance different priorities. The framework of ATM is set by a defined minimum acceptable level of safety that is never infringed upon. This includes overall safety such as minimal incidents but also practical boundaries such as minimum separation between aircraft.

Within this framework, the **first priority** is always to deliver the required airspace capacity, based on the demands from airlines. If the required capacity cannot be achieved, safety standards are never reduced. This means that the capacity is reduced. The **second priority** of an ANSP is efficiency, focussing on efficiency across all airspace by NM but also at individual flight level by ANSPs to achieve the minimum time possible within an airspace block, again whilst always maintaining safety. The **final priority** of the ATM system is environment, where the defined minimum noise and emissions requirements are included. Contrail mitigation would fit within this category.

In some cases, for example around airports with strict noise/environmental constraints, the priorities of ATM may change and environment may be considered more important than capacity or efficiency. An ANSP is continuously searching for the optimum balance between the following three elements: capacity, efficiency, and sustainability; **always safe, with sufficient capacity to deal with the traffic demand, efficiently managed and as environmentally sustainable as possible.**

2 Literature review and past trials

This section provides an overview of the literature review and interviews that were conducted. It is split into two sections: (1) the assessment of operational reports from the literature and (2), a detailed analysis of a selection of trials conducted by MUAC, NATS, Thales and within D-KULT by assessing the main research goals and methods of each trial as well as the resources needed. We also look at the outcomes of the trials and how this may inform future ones. Beyond, for completeness, appendix B details an exhaustive summary of documented trials including a breakdown of the different approaches to contrail avoidance applied within each of them.

2.1 Operational insight from the literature

The literature highlights the central role of coordination between ANSPs and airlines in achieving large-scale contrail avoidance. In particular, successful contrail avoidance must address three pillars:

Harmonised developments for procedures and operations between airlines and ANSPs

Contrail avoidance requires ANSP – airline collaboration to be successfully implemented. Using shared tools and relying on common sources of information is critical to achieve large scale implementation, **However, an ATM-led implementation pathway is considered key for scalability.** Based on the literature review and expert's input, ATM, in particular the NM, is uniquely positioned to manage traffic flows across congested regions, coordinate altitude and trajectory changes, and finally, harmonize mitigation strategies across multiple airlines.

Yet, the ATM role in leading contrail avoidance mitigation needs to be carefully designed to ensure its main goal, delivering capacity with minimum safety standards, can be met. Coordination must begin in the flight planning phase when the flight plan is submitted to the NM. Pre-tactical adjustments are particularly relevant for short and medium haul flights where the shorter distance flown makes the weather forecast more reliable the day before departure. In this case, contrail avoidance is more predictable and has higher potential for climate impact reduction. For long-haul flights, tactical adjustment may be necessary, as weather forecasts may evolve along the way, even though recent research shows relatively stable ISSR forecasts up to 48 hours before the flight[8]. This reinforces the need to have inter-operable tools between airlines and ANSPs to enable smooth decision-making.

Supporting scientific certainty by using and challenging weather forecasts

Determining the most operationally sound mitigation strategy to achieve ISSR avoidance at scale remains challenging. In practice, fully avoiding ISSRs is not always necessary since partial avoidance can already reduce contrail radiative forcing significantly (depending on the ISSR properties, e.g. humidity levels). Moreover, accurately predicting ISSRs can still be improved since their characteristics can vary depending on the meteorological data source. Usually, they span horizontally on dozens of kilometres. As a consequence, vertical deviation has more potential, especially as one or two flight level changes is usually sufficient to avoid contrails. Furthermore, lower descending deviation usually has more potential to avoid ISSR due to environmental properties which are less likely to form ISSR. Yet, this needs to be further evaluated during small and large-scale trials. Upcoming trials must work towards exploring operational mitigating solutions, based on improving scientific understanding. Both operations and science must work alongside one another and aim for a centralised source of data to constantly improve contrail prediction models and eventually, the overall climate impact of mitigating measures.

Contrail avoidance must preserve safety standards, capacity requirements and economic viability

Contrail avoidance introduces important operational trade-offs and system-wide coordination challenges that must be carefully managed. Altitude adjustments, particularly flying lower than the optimal cruise level, creates structural impacts within airspace management. The lower an aircraft operates, the more it interferes with climbing and descending traffic flows. This increases airspace complexity and adds workload on air traffic controllers, especially in busy sectors (e.g. MUAC, NATS). At lower altitudes, air density is higher, which increases drag and, therefore, fuel burn. As a result, airlines generally prefer

[8] Impact of forecast stability on navigational contrail avoidance - IOPscience

higher cruise levels for economic and performance reasons. More broadly, contrail avoidance often involves operational compromises. Based on the literature, airlines may face increased fuel consumption, longer flight times, and potential disruptions to scheduling and connectivity, including slot management constraints. These trade-offs are particularly pronounced on long-haul flights, where routes span multiple weather systems and may encounter several contrail-forming regions along the way. Because forecasts can evolve over such long durations, tactical (in-flight) avoidance measures become especially important for long-haul operations, allowing adjustments based on updated meteorological information.

2.2 Overview of current operational contrail mitigation approaches

Based on the desktop research and expert interviews, we assess that contrail mitigation through operational changes can be enabled in multiple ways. While most trials and research focus on pre-tactical **airline/dispatcher led contrail avoidance and tactical ATM lead approaches** in the pre-tactical phase, hybrid alternatives are relevant to further evaluate the decision-making processes between these two stakeholders. An overview of the different approaches is provided below.

Stakeholder approach	Pre-tactical	Tactical	
Airline led *Pilot or dispatcher*	Dispatcher includes contrail mitigation in flight plan. Either automated through flight planning or manual *Dispatcher in lead, Pilot informed*	Pilot receives real time information on contrail mitigation on-route. Pilot requests alternative route or flight level to ATC. *Pilot in lead, dispatcher informed*	No trials
Hybrid *Collaborative*	Dispatcher includes contrail mitigation in flight plan. Network manager includes contrail mitigation in IFPS. If in either case contrail mitigation is possible the flight plan is adapted. *Dispatcher and Network manager in lead.*	Both pilot and ATC are informed based on real time information on contrail mitigation. Both can request a route or flight level change to achieve contrail mitigation or decide to reject measure due to safety, capacity or economic constraints. *Pilot and ATC in lead, both must consent before change*	
ATM led *ATC, NM or flow manager*	Network manager includes contrail avoidance in IFPS, sending back adapted flight plans to achieve contrail mitigation. Dispatcher then confirms flight plan, and flight is flown as per normal. *Network Manager in lead, dispatcher informed*	ANSP flow manager "closes" airspace/ flight levels to mitigate contrails depending on overall airspace congestion and safety. They notify ATC to reroute aircraft flying through these areas. Final decision to reroute is on ATC depending on their capacity. Pilot must be informed "why", this remains an open discussion. *Flow manager and ATC in lead*	Up to 10 trials

Figure 3 Overview of current contrail mitigation strategies (source: To70)

The most trialled approach to operational contrail mitigation is through **a pre-tactical airline led approach**. If an airline files a contrail avoidance route, and this is accepted by the NM, this is expected to have a limited impact on air traffic management as long as the flight path stays relatively smooth and does not jump multiple flight levels over the duration of the flight. However, in such an approach, challenges may arise both in achieving the contrail mitigation or in efficient operations. First, in the tactical phase, both pilots and ATCs who are not informed on the contrail avoiding flight plan may request or initiate a deviation to achieve a more cost effective or efficient route, nullifying the contrail avoidance. Therefore ATC and pilots should be informed. Based on past trials, ATC has put in requests to all airlines to inform them of any upcoming trials. Second, avoiding warming contrail area may free up airspace that another airline takes either in their flight planning phase or during the flight by requesting a deviation from ATC. This reinforces the need for a hybrid approach where both ATM and airspace users are equally involved in the trial, potentially with the support of a coordinator (e.g. network manager).

The second most trialled approach to operational contrail mitigation is through a **Tactical ATM led approach**. If a flow manager is able to identify what flight levels contain contrail inducing areas, they can request air traffic controllers to redirect flights away from these areas. In trials and live simulations this is mainly achieved by informing ATC of the trial execution, and then providing them with information on their screens displaying the flights that should be deviated. It is then up to the discretion of the ATC to initiate a flight level or route change for the aircraft to avoid the contrail and only if they deem it fits within the safety and capacity constraints. The pilot may reject this at their own discretion, for example due to limited fuel or other operational constraints (e.g. time). Within such an approach, the flow manager must be aware of capacity and safety constraints created by asking all ATC to avoid certain flight levels. Moreover, rerouted traffic could enter a different airspace block that is not under the oversight of the flow manager that initiated the contrail mitigation, potentially creating a capacity overload in the adjacent block of airspace. Therefore, tactical trials should always take into account surrounding airspace.

2.3 Summary of all contrail avoidance trials

A summary of the operational achievements and gaps of the assessed trials is provided below. This, alongside the outcomes of the stakeholder interviews informs the operational challenges described in chapter 5.

Table 4 Summary of trials

	What have trials indicated	Remaining gaps that may be solved through trials
Scientific aspects	**The dimensions of ISSR are usually overestimated** in the simulation compared to the observation data. ISSRs may span on dozens of kilometres, even hundreds. However, they are relatively thin therefore vertical deviations of 1 or 2 flight levels is usually sufficient to avoid the creation of persistent contrails in the region.	**Estimation of the ISSR overevaluation:** better prediction of ISSR formation is necessary.
Operational aspects	**In general, pre-tactical avoidance** makes contrail avoidance seamless. **Good understanding of contrail impact on operations:** reduced capacity due to flight level closures, extra coordination (for tactical deviations). **Trials work on a small scale** (both geographical and number of flights). By closing 2 FLs in a congested airspace, around 20% capacity reduction can be expected, during low and medium traffic periods. **Automation** of contrail prediction tools, deviation propositions and seamless **integration** in ATC tools is key to large scale implementation	**Large scale deployment of contrail avoidance measures** **Evolution of the capacity reduction** once ISSR prediction tools are integrated in ATC techniques **Additional specifications on capacity limits** (e.g. constraints during medium traffic periods) is necessary.

The full overview of trials can be found in Appendix B.

2.4 Analysis of the D-Kult, MUAC and NATS trials

Five trials shown in appendix B involve ATM stakeholders to a significant degree. These are the MUAC trials with DLR (2021), MUAC trials with Google (2024-2025), D-KULT – 100 flights trial (2023), CICONIA trial with contribution from NATS (2024 – ongoing) and Concerto – Borealis trial (2024). Therefore these trials are analysed in more detail based on the main research goal of the trial, the trial methods, the resources involved and the main outcomes of the trial (successes & uncertainties).

Table 5 MUAC trial with DLR (2021/2022)

MUAC trial with DLR (2021)			
Main research goal	Trial methods	Resources involved	Main outcomes
The trial aimed to understand the operational impact of avoiding contrails through tactical adjustments in upper-airspace operations, specifically for flow managers and ATC. The trial also aimed to bridge the gap between science and engineering, turning scientific assessment and findings into operational change, and to access	Based on relative humidity weather forecast from Deutsch Wetterdienst (DWD), the trial examined the possibility for airlines to engage in tactical re-routing by adjusting their flight plan. The trial included assessment of pertinent controller actions and real-time feedback processes.	Air traffic controllers, scientists (DLR), meteorological data (DWD), Satavia atmospheric modelling software for contrails observation.	The trials took place during deep night (00.00 to 06.00 local time) and led to around 200 flights re-routed over a 1 year trial period. Tactical re-routing works in uncongested airspaces, yet it leads to a reduction in airspace capacity due to lack of adequate staffing and the extra communication

how the precision of meteorological tools fit into a real operational environment.	Based on the weather forecast, the trial team would manually identify the flights that would be contrail prone and suggest tactical rerouting.		necessary between the flow manager, the supervisor and the Air Traffic Controller (ATCO). ISSR regions were over evaluated leading to unnecessary deviations. Therefore, where weather forecasts converge, a looser approach to ISSR formation might not lead to a significant climate penalty. Better understanding of operational impact in MUAC setting, as operational procedures were established for contrail prevention within MUAC. Yet, it is not clear to what extent the outcomes can be extrapolated to other airspace contexts and at large-scale.

Table 6 MUAC trial (2024/2025) in collaboration with Google

MUAC trial with Google (2024)			
Main research goal	Trial methods	Resources involved	Main outcomes
The trial aims to explores tactical avoidance possibilities through alternative trajectory generation by establishing and testing a tactical contrail avoidance framework that can be scaled to medium / large scale avoidance. In addition, MUAC used Google prediction and analysis tool to evaluate the actual contrail behaviour compared to its expected pattern though satellite observation.	Using Google prediction models for ISSRs, ATC at MUAC had access to a tool showing ISSRs and what flight levels at what time could be avoided to avoid the ISSRs. This tool requires manual activation into ATC as it may require extra capacity. Yet, it still needs significant improvement to include support ATC in balancing environmental benefits to capacity. The flow manager and trial manager together decided day by day whether to enable the trial. As of December 2025, this tool can also be automatically activated, taking into account daily capacity. Within the trial thus far, around 500 tactical deviations were shared to the operational team during the both day and night. Approximately 5 flights per day were selected for contrail avoidance during the trial. The execution of the trial was communicated via NOTAM and direct communication with pilots of relevant aircraft.	The Google prediction model, developed with their own resources was used. At MUAC, the contrail team manually selected the flights that were contrail prone and tactically re-routed them together with ATC.	The official results of this trial are not yet publicised as the trial was just completed. Already, MUAC informed that automating the ISSR identification tool is key. When they did run deviations, contrail avoidance via small vertical deviation was seen to be operationally feasible. The trial team found reduced formation of persistent contrails on avoidance days compared with the reference days. However, the trial team also found that when two flight levels are blocked, this reduces the MUAC capacity by 20% during medium traffic situations (off-peak day time). However, during high traffic (peak daytime), it becomes very difficult to engage in tactical deviations, mainly due to the high altitude / low altitude split.

Table 7 NATS involvement in CICONIA

CICONIA trials with involvement of NATS (ongoing):			
Main research goal	Trial methods	Resources involved	Main outcomes
The goal of the Ciconia project includes multiple research projects on ATC and airline related contrail avoidance and other non-CO_2 effects. A significant part of the project focussed on assessing overall impact of contrail avoidance on ATC. The aim is to *"support the demonstration of a contrail prediction capability in a robust manner and relying on a large set of data"*. The stakeholders also aim to understand how contrail mitigation impacts air traffic management in terms of workload, staffing and effect on other surrounding airspaces. The role of NATS is to evaluate the rerouting impact on ATC workload, especially on North Atlantic routes.	The trials are conducted by *"using different sets of operational data and models to predict contrails and validate their predictions with observation"*. They start with shadow (simulated) trials to assess how often a change of trajectory would be necessary and to understand the implications for airlines. The role of NATS is to include the role of ATC, to support with the communication with controllers (both domestic and oceanic) and prepare for live trials. Live trials will be conducted by Air France, Swiss and easyJet. The trials explore airspace reservation strategies to enable contrail mitigation, and the role ATC can/should play. For now, all trials are still in shadow mode.	The airlines included are Swiss Air, EasyJet and Air France. Swiss only conducted shadow mode trials. EasyJet ran a live trial and Air France live trials are currently ongoing until April. NATS is the main ATC stakeholder, and focussed on trainings and impact assessment for ATC. ISSR prediction is done with different tools and sets of data to validate all different kinds of approaches.	Initial results from shadow trials indicate that avoiding an ISSR region can be achieved through vertical deviation by only one or two flight level changes. Moreover, contrail avoidance can be implemented in high ISSR-prone areas (North Atlantic) though the trial scope remains small scale. The trials reveal that very little extra fuel burn and flight time is observed, more results will be shared once the Ciconia project is completed in June 2026. *The trial is still ongoing and live trials are expected.*

Table 8 D-KULT, including 100 Flights trial

D-KULT project, including 100 flights trial (2024-2025)			
Main research goal	Trial methods	Resources involved	Main outcomes
D-KULT led the 100 flight trial between March and October 2024 where 108 flights operated by Lufthansa, Lufthansa cargo, Tui, DHL and Condor were planned to avoid contrails. The trial was led by airlines, while the German ANSP facilitated. The trial aims to *"provide evidence of the feasibility of eco-efficient flight trajectories"*, mostly in German airspace and with the German ANSP. Communication with other ANSPs was not included, but results showed that other ANSPs, such as MUAC did request to be informed of such trials in the future. *"Flights should be*	The method used in the trial was an all-encompassing, airline led approach to contrail avoidance, from improved weather forecast to flight planning optimised routes that optimise costs. The live trials (100 flight trial) were the final step in the project. Each airline worked with their flight planner and the available contrail data to develop contrail avoiding flight plans. These were flown in coordination with the German ANSP. Finally, a post-flight analysis is conducted to assess the success and impact on all stakeholders.	In the trial, FPO Cloud was used for route optimisation ISSR predicting tool: DWD Airlines involved: Lufthansa, Lufthansa cargo, Condor, TUIfly, DHL	Agreement on methods to obtain PPC (Potential Persistent Contrails) areas. Higher workload. However, depending on the area and time of the day, the workload for ATC can vary. Airspace capacity reduction is reported. Limited collaboration with Airspace, only in some parts of the trial. Low accuracy of ISSR forecast, ISSR is often shorter than expected. Limited scalability of the project (108 flights) Poor communication between airline and ATCO: an email had to be sent from the airline to the ATCO, However, the lack of

planned in such a way, that their trajectories are optimized with regard to reduced climate impact in a suitable defined climate metric." according to D-KULT website.			communication between the supervisor and the ATCO led to some flights being re-routed away from the contrail avoidance route.

Table 9 BOREALIS Airspace trials, zooming in on LFV

CONCERTO project BOREALIS Airspace (2024-ongoing)			
Main research goal	Trial methods	Resources involved	Main outcomes
Pre-tactical evaluation of contrail avoidance potential in the BOREALIS Airspace, comprising 9 large ANSPs. The first aim was to understand how large-scale contrail-avoidance can work in an airspace with large airspace blocs representing a mix of medium and high traffic complexity. The second aim was to better understand the role of ANSPs in pre-tactical deviations and how collaboration can best be achieved. The work was facilitated by Thales, the industrial partner in the project.	The trial with LFV focuses on shadow trials, no live deviations have been conducted. 4-5 hours before STD, the trial team analysed the flights that could be rerouted. All flights within the Borealis airspace were analysed to identify those with higher contrail warming. For flights potentially forming high-impact contrails, an alternative flight plan is sent to the dispatcher, who is free to accept it or not, and network manager to assess the impact on capacity.	Airline involved: Icelandair was the only airline properly involved in the trial but all airlines flying through the BOREALIS airspace have been considered in the shadow trial. Software provider: Thales Weather service provider: DWD Academia: DLR, TU Delft	Contrail avoidance in a quieter airspace is possible and has little impact on capacity when done during off-peak time. Pre-tactical avoidance makes the work of ANSP easier to handle as: - Potential extra workforce requirements can be anticipated. - Capacity is never exceeded. - The Supervision / flow manager can be involved more easily.

3 Operational challenges

Based on the existing literature and the input gathered during the interviews, three overarching operational challenges have been identified at **ATM level, Airline level and airspace coordination level.** The figure below shows how the challenges are broken down per flight planning phases. It is noted that not all challenges are technical and some may be related to **human and / or financial factors.** It is therefore critical to raise awareness among all aviation stakeholders, incorporating contrail avoidance into air traffic controller training, and investing in new integrated solutions ensuring a smooth transition without compromising safety and jeopardising profitability.

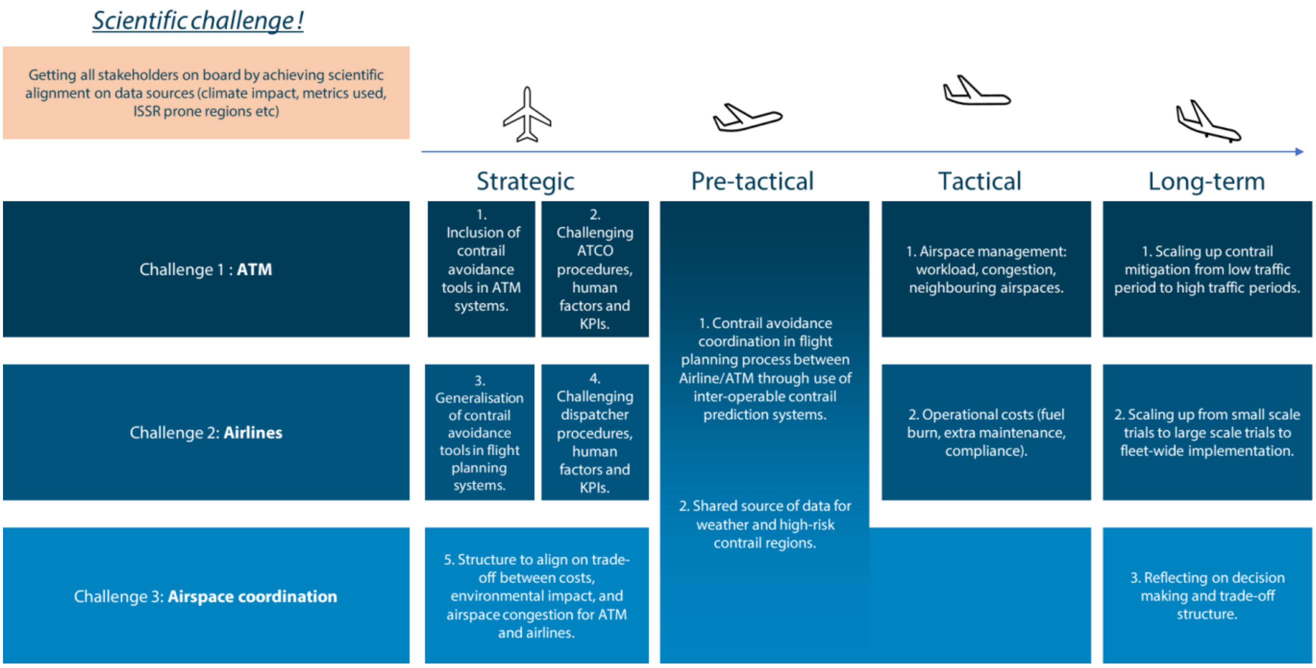


Figure 4 Phasing of challenges (source: To70)

3.1 Scientific challenge

The scientific challenges related to large-scale contrails implementation have been addressed throughout the study, during the desktop research and the interviews.

The existing literature and the expert interviews acknowledge that science and operations are closely intertwined and acting on both and in parallel must be encouraged. One of the most highlighted challenges, identified as a key bottleneck to large scale contrail avoidance, is the uncertainty associated with contrail prediction models. This is being continuously addressed by researchers through validation studies using satellite imagery, ground-observation cameras and in situ measurement campaigns to benchmark and improve models further. Despite the uncertainties in contrail prediction models, interviewees indicated that alignment on contrail management is necessary across all stakeholders.

This alignment is firstly required on input data sources used, provided by different meteorological services. This is needed for accurate ISSR detection and forecasting. Secondly, it is also important to have a wider agreement on used climate metrics. Metrics such as Global Warming Potential (GWP), Global Temperature change Potential (GTP) or Average Temperature Response (ATR), evaluated over 20, 50 and 100 years, may lead to different conclusions on the effectiveness of contrail avoidance, although climate benefits are largely independent[9] from the metric and time horizon chosen for the most warming

[9] ACP - The importance of an informed choice of CO2-equivalence metrics for contrail avoidance

contrails. Moreover, further research is necessary to increase the scientific certainty on the net climate benefits (extra fuel burn balanced against overall climate impact).

The current state-of-the-art contrail research is focused not only on improving contrail prediction models, but also on integrating developments in aircraft performance into the models, which ultimately contribute to decreasing non-CO2 emissions. With the increasing use of Sustainable Aviation Fuels, reducing soot particle emissions, and the use of lean burn engines, models have to be continuously adapted to incorporate the effects of these technologies on contrail formation and properties.

It is noted that the scientific challenges are discussed in more detail in a separate report commissioned by T&E.

3.2 Challenges in the Strategic phase

ATM-related challenges include both systems integration of contrail-avoidance tools for ATC and ensuring these systems can be used within current ATC procedures, ways of working and KPIs.

First, fully integrated ATC systems for contrail avoidance do not exist, contrary to dispatcher tools. Without contrail avoidance functionalities, flow managers will not see what areas to avoid and ATCOs will not be able to select flights to deviate. More importantly, they will lack support in balancing capacity and overall climate impact. Some preliminary trial and “artisanal” tools (as one interviewee described it) have been developed at a relatively low-cost to support ATCOs during trials. These tools support ATM in identifying ISSRs without interfering with current systems and interfaces but they remain unequipped to address large scale contrail avoidance. A critical part within this challenge are the safety considerations that make it difficult to change any part or system currently used in operational traffic management without extensive testing, back-up systems and assurances it does not reduce safety.

Second, sufficient attention must be drawn to the training support needed to enable smooth integration into everyday operations, corresponding human factor aspects and KPIs to evaluate them. ATC staff have been trained in the past years to focus on delivering capacity and efficiency with safety and environmental standards. Preparing air traffic control for contrail avoidance will require increased awareness to enable more regular deviations and support the requests from pilots.

Airlines-related challenges include the integration of contrail avoidance tools into flight planning and the associated procedures, human factors and KPIs to apply these tools. While some flight planning software already enable contrail avoidance tooling (e.g. Flightkeys), others (e.g. Jeppesen and LIDO) cannot integrate contrail avoidance without significant manual efforts. Even with these tools, there are still challenges related to the weather data inputs and timing of forecasts. The second challenge for airlines in the strategic phase is the procedural and human factor integration of contrail mitigation into flight planning, alike the ATM challenge. This technology can only be beneficial if dispatchers use the functionalities. When considering alternative flight plans to avoid contrail prone areas, flight planning tools and/or dispatchers require guidance on trade-offs and decisions regarding additional fuel burn and fuel costs, regulatory compliance, non-CO2 benefits, time of arrival and restricted areas for weather, military or other purposes. **Without clear alignment, procedures, trainings and dispatcher KPI’s on trade-offs the tooling may be complete but it cannot be applied**.

The Airspace coordination-related challenge in the strategic phase is to develop a structure that **includes clear responsibilities for all stakeholders**: the period for which they are responsible, the expected climate impact, the efficiency of the flight and the airspace capacity. These decisions may be different per airline, and per ANSP, and therefore must be harmonised. While airlines wish to fly the most cost-efficient route, ANSPs need to balance capacity versus airline demand across all sectors and times of day. Therefore, airlines focus on cost trade-offs when integrating contrail mitigation, while ATM stakeholders focus on capacity trade-offs. These drivers will lead to different solutions; a structure balancing and harmonising both trade-offs is critical.

Moreover, the challenge is to ensure these trade-off decisions are all made based on harmonised data. Airlines and ANSPs currently apply a range of different data sources (e.g. weather forecasts, aircraft performance data, flight information) and non-CO2/contrail models to take action on contrail management. Harmonisation on data sources, ideally through a unified data base is key. Yet, intellectual properties and business secrecy might be a bottleneck, preventing data sharing. Working on common training among airline dispatchers and pilots on one side, and ANSPs, network manager on the other side is critical to harmonise the framework for decision making.

At the same time, contrail mitigation strategies do not necessarily require high model fidelity for all operations. Instead, it is more important to focus on periods with highest climate-impact flights (prioritising night-time operations as well as winter periods for instance). Such a framework should take into account this prioritisation and ideally take into account the specificities of each airline, such as route flown, historical weather pattern but also, fuel consumption per aircraft type and the declared capacity of major ANSPs, ultimately achieving coverage of all 37 European ANSPs.

3.3 Challenges in the Pre-tactical phase

In the pre-tactical phase, the sub-challenges identified apply across all challenges as the core issue is coordination, efficient data exchange and timely communication between all stakeholders in a limited time frame. The first challenge is ensuring the structures set in the strategic phase on decision making are followed. To enable this, a coordinator role is critical, potentially for the NM. Especially in the pre-tactical phase, the NM already has a strong role in coordinating flight plans to ensure sufficient capacity in all airspaces, which would put them in the right position to coordinate such actions.

The second challenge is the continuous information sharing up to around ~30 minutes before the flight which is essential to bring adaptations to the flight. While the tactical phase begins on the day of operation (see definition in section 1.1), flight plans can be adapted up to around 30 minutes ahead of departure. While this may generate extra workload for supervisors ahead of the flight, it brings an opportunity to adapt the flight plan based on the latest weather forecast, provided this can be met in a safe and operationally efficient manner.

For last minute flight plans adaptations, a major challenge is the efficient use of the unified data base containing, among others, ISSR prediction models and weather forecasts. **Streamlining data exchange and communication in the pre-tactical phase is absolutely essential to minimize tactical deviations**. Interviewees and existing literature highlight that tactical adjustments to flight plans make contrail avoidance significantly more operationally challenging.

3.4 Challenges in the Tactical Phase

The ATM-related challenge in the tactical phase is the potential significant reduction of capacity in airspace and disturbance in the functioning of an airspace block when executing tactical re-routing. This is because it generates extra work for ATCO that is not integrated into their routine and therefore reduces the capacity of the airspace block under their responsibility. This may particularly be the case in the early stages of contrail avoidance, where contrail avoidance does not have tailored procedures in place, and some airlines do avoid contrails while some do not. The challenge is to ensure that contrail avoidance by some airlines do not lead to major inefficiency for the airline that aims to avoid the contrail or for any other airlines. Additionally, if contrail deviations free up airspace prone to contrail formation, ATC must ensure that this airspace is not provided to other airlines (as this would likely nullify the contrail avoidance effort[10]), provided ATM / NM is leading contrail avoidance actions, not airlines. A major challenge is to ensure ANSP/NM support that enables meaningful climate impact and avoids penalizing early adopters of contrail avoidance.

The Airline-related challenge in the tactical phase is mainly understanding and reducing the extra costs that may be generated due to contrail avoidance, both in fuel costs and workload. This includes the potential extra fuel and corresponding ETS charges, but also the additional maintenance on engines, penalties for delays and employee time. For now, airlines are not compensated for these extra costs or incentivised to engage in tactical deviations. Though often cited as the main cost issue, the additional fuel burn cost may be marginal cost compared to the cost of other operational adjustments (waiting time before landing, avoiding turbulences etc). Therefore the challenge is not only to reduce these costs but also better understanding them to propose solutions that (partially) cover these costs.

Beyond financial concerns, airlines also face operational concerns. If an aircraft can tactically deviate to avoid a contrail, usually at a lower FL, pilots may not agree to this as it could cost unanticipated fuel and lead to safety concerns. In addition,

[10] Scientific consensus still needs to be strengthened to evaluate the cumulative impact of one flight flying through an ISSR, and generating contrails, compared to multiple flights.

in some cases, contrail-avoidance may generate additional fuel burn risks for long-haul flights where the fuel uplift matches specific flight time, flight levels and efficiency. When a long haul flight pre-tactically avoids contrails, this is not an issue as the fuel uplift is adapted accordingly. This is not the case in tactical avoidance.

The Airspace coordination-related challenge in the tactical phase as similar to those in the pre-tactical phase. The major challenges are applying the same procedures, agreement on leadership and ensuring the same data is used based on the harmonised database. This is critical to ensure seamless coordination and smooth decision-making.

3.5 Post operational

The ATM-related challenge post operations is to support learning opportunities and share best practices across ANSPs on how to best balance contrail avoidance and capacity reduction. This is critical in the scaling-across to multiple ANSPs and scaling-up from trials, to small scale and eventually to large scale implementation of contrail measures, whether they are taken by airlines, by ANSPs or coordinated by the NM. Research projects such as CICONIA, CONCERTO and CONTRA are ongoing, to investigate mathematical models that can predict the impact on capacity of deviations. The challenge is ensuring the lessons-learned will provide the necessary tools and structure for larger scale adoption. This includes the harmonised automation of tools and procedures across ANSPs in Europe and the NM. It also includes training and adaptation of KPIs which would ensure that the airspace is managed in the safest, most operationally efficient and most environmentally-friendly way.

The post operational airline-related challenge is similar to ATM: ensuring lessons learned from operational and scientific research are fed into a clear approach within each airline team and across different airlines. The difficulty in this challenge will lie in scaling-up an agreed upon contrail avoidance procedures to network-wide operations across airlines and ANSPs throughout the year. For now, TUI Fly Germany is the only airline to have performed a fleet-wide trial over at least one month. Achieving large-scale avoidance requires understanding the extra resources and costs of avoiding contrails.

In the first phase, dispatchers are likely to have extra workload to validate the “contrails mitigating” flight plan that will be generated automatically by software such as FlightKeys. Yet, on the long-term, this verification step is likely to be seamless on their workload as software integration progresses. Data analysts and environment managers are likely to be mobilised in that first phase to ensure the knowledge is disseminated across the company. Training costs are also to be expected. Unless covered otherwise, the airline will have to cover costs related to extra flight time including additional aircraft and engine maintenance, fuel burn and regulatory compliance. In the long-term, these costs would most likely be incorporated into the business model of airlines and transferred over to the passengers.

The post operational coordination related challenge is to sufficiently reflect on data sharing and decision making structures. The challenge is ensuring all research and trials feed into the reflection and that important stakeholders, such as ANSPs, NMs and airlines, as well as their cross-company industry bodies take ownership of the reflection and ensure it is included in future operations. Deprived from this integration, the trials, tests and learnings achieved will not get a place in the day to day operation.

4 Contrail Avoidance Roadmap

4.1 Introduction

This roadmap sets a collaborative, ambitious and clear (SMART[11]) path for all stakeholders to take action on contrail avoidance. It provides a set of actions to be taken by stakeholders within a specific timeframe that, together, will lead to the overall goal of large-scale contrail avoidance during medium and high traffic periods. It takes into account future developments around airspace and aviation regulation and provides resources together with costs indications associated with each action. The roadmap is split into two parts. **The short term roadmap** aims for a centralised system with harmonized information to achieve contrail avoidance during low traffic periods across Europe by 2032. **The long term roadmap** aims for a scaling up of this implementation to become both more effective and to be applied in medium and high traffic periods beyond 2032.

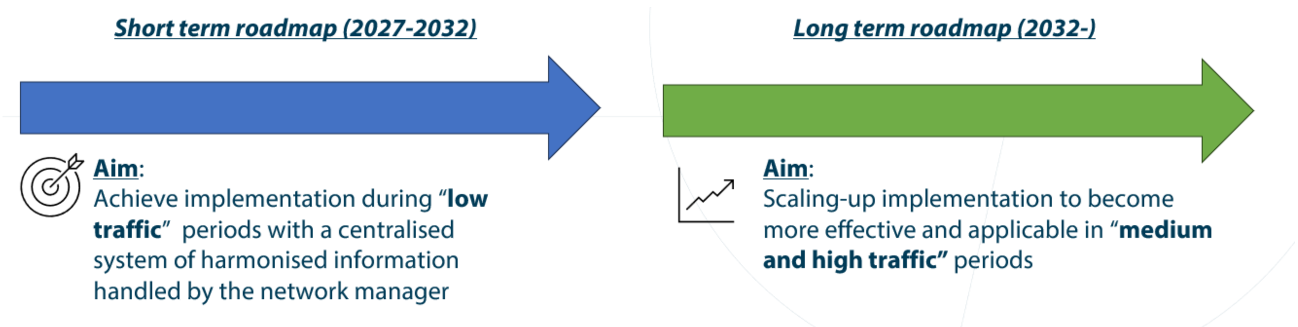


Figure 5 Contrail avoidance roadmap (source: To70)

The actions within the roadmap were determined based on the information extracted from literature and from the interviews with experts. To assess if the actions were complete and clear, several steps were taken. First, the actions we compared to the challenges identified in chapter 5, to assess if they covered all of the challenges. Next, a workshop was held together with T&E, airspace and contrail experts to provide further detail and structure to the actions. At this stage, the action to set up trials (action 1) was split in a single stakeholder and combined stakeholder action, and the importance of harmonised data sources was included, amongst other improvements.

4.2 Short term roadmap

The short term roadmap consists of 5 actions, as shown in the figure below. These are to be executed between 2026 and 2032 to achieve the aim of implementing contrail avoidance across all flights in low traffic periods through a centralised system that uses harmonized information. The actions are plotted on a timeline (figure 6) that also includes critical policy related milestones including the availability of European or national public funds for non-CO2 trials, the revision of EU-ETS to incentivise non-CO2 mitigation, the inclusion of Climate KPIs in SES II+ RP5 and the next NM appointment for the 2030-2039 period in the EU, which will take place in 2029. More detail on the roadmap actions and critical sub steps can be found in Appendix C.

[11] SMART is a technique used to define clear objectives. It stands for **S**pecific, **M**easurable, **A**chievable, **R**ealistic and **T**ime-bound

1 Trials 1a - Single stakeholder trials, 1b Combined trials

Trial different approaches to contrail mitigation and aim to get many stakeholders familiar with contrail avoidance concepts.

Set up a new approach with the NM is leading trials and gathers all relevant information (capacity, fuel costs, climate impacts etc) in a single database.

Led By: Trial Coordinator

2 Contrail Avoidance tools in airline Operations

All flight planning systems to include contrail avoidance.

Clarity on decision making processes (including acceptable trade off) for dispatch and pilots including training.

Led By: Airlines

3 Contrail prediction software in ATC Operations

Both incumbents and new entrants to develop tools supporting contrail mitigation.

Clarity on decision making processes for NM and flow managers including training.

Training for ATCOs

Led By: ANSPs

4 ATC capacity and KPI assessment

Define acceptable circumstances for contrail avoidance in different capacity constraints, primarily during low traffic periods.

Led By: Network Manager

5 Pan-European contrail avoidance procedures

Through a working group: set procedures, systems and a harmonized data sharing platform.

Led By: Legislator

Figure 6 Short-term roadmap actions (source: To70)

Each of the actions shaping the short-term roadmap is addressing at least one of the challenges identified in the previous section. The table below outlines the challenge – action matching.

Table 10 Challenges - actions overview

Challenges	Action 1 - trials	Action 2 – Contrail avoidance tools in airline ops	Action 3 – contrail avoidance tools in ATC ops	Action 4 – ATC capacity and KPI assessment	Action 5 – Pan-European contrail avoidance procedures
Challenge 1 – ATM	Phase: strategic, pre-tactical, tactical, post-operational	/	Phase: Strategic, pre-tactical	Phase: Tactical, post-operational	Phase: Post-operational
Challenge 2 – Airlines	Phase: strategic, pre-tactical, tactical, post-operational	Phase: Strategic, pre-tactical	/	/	Phase: Tactical, post-operational
Challenge 3 - Coordination	Phase: strategic, pre-tactical, tactical, post-operational	/	/	/	Phase: strategic, pre-tactical, tactical, post-operational

The table above reveals that actions 1 and 5 are overarching and bring partial solutions to multiple flight phases across all challenges. Action 2 focuses on addressing airline challenges in the flight planning phase (strategic and pre-tactical). Actions 3 and 4 focus on the role of ATC across all flight phases (strategic to post-operational). These are critical in scaling-up the role of the network manager.

The figure below summarises the phasing of each action on the short-term roadmap.

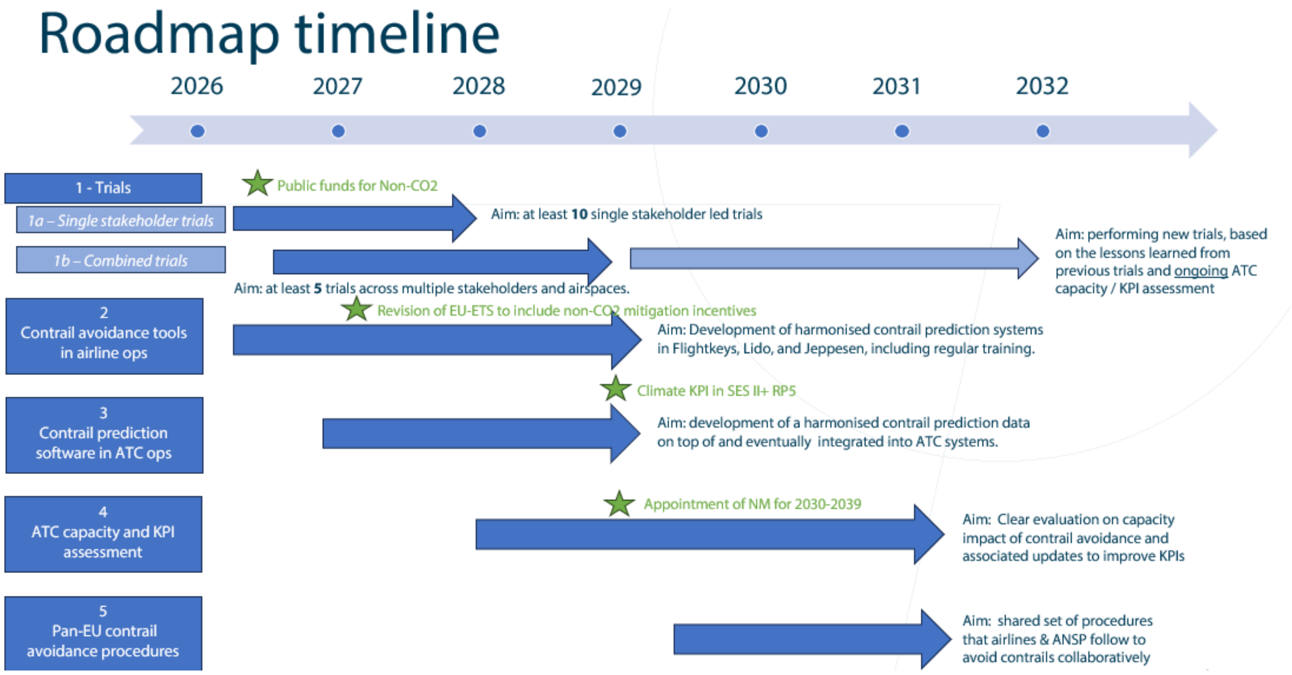


Figure 7 Timeline for short term contrail avoidance (source: To70)

4.3 Short term roadmap Stakeholder roles

Within contrail avoidance, 7 stakeholders have been identified that play a concrete role within the roadmap. For each action, one stakeholder is **accountable**, who must lead the execution of the action. Several stakeholders are **responsible** and must participate to enable the action to succeed. The rest of the stakeholders must be either **consulted or informed**. Most critically, trial coordinators must start trials and hold the responsibility to gather all relevant stakeholders. Such coordinators can be research organisations such as Contrails.org, leading expert groups, but also software and systems developers such as Thales or even airlines or ANSPs themselves, such as MUAC. Actions two and three depend heavily on airlines working together with their respective flight planning systems, and ANSPs with their systems providers or external systems developers such as Google. NMs must take the responsibility to ensure contrail avoidance is accurately assessed in light of its impact on capacity, and to aim for standardized procedures and harmonized data between all stakeholders. NMs may also lead trials. Legislators or regulatory body should eventually align procedures across the sector and, if possible, create incentives for airlines and ANSPs.

The majority of the costs usually lie with the **responsible stakeholders** that need to develop solutions together so that the **accountable stakeholder** can implement it. However, in reality, the cost is either passed on to the end consumer (accountable actor) or covered through public funds. Specifically for actions 2 and 3, most of the costs are born by software providers who need to develop the contrail avoidance tools. Yet, airlines or ANSPs need to pay for its use, be it though a subscription fee or a one-off payment.

Table 11 Stakeholder matrix

	1 Trials *1a – Single stakeholder trials* *1b – Combined trials*	2 Contrail avoidance tools in airline ops	3 Contrail prediction software in ATC ops	4 ATC capacity and KPI assessment	5 Pan-European contrail avoidance procedures
Weather service provider	R	R	R	R	C
Airline	R	A	C	C	C
Systems/software providers	R	R	R	C	C
Legislator (EC and MS)	R	I	I	I	A
ANSP (national)	R	C	A	R	C
Network manager (EUROCONTROL)	R	C	R	A	R
Trial Coordinator	A	C	C	C	C

Responsible | Consulted | Accountable | Informed

4.4 Short term roadmap cost assessment

Having defined what actions need to be taken, by when and by whom, the final step is to understand the implications of the roadmap. This section shows a high-level cost evaluation.

The cost assessment for the roadmap actions is based on previous work on contrails within the sector, interviewee input and best estimates of systems development and resources costs. All assessments serve only as a forward looking indication and may vary from the eventual cost. As the execution of trials (both single stakeholder and combined trials) is a critical first step, the cost assessment for this action has been further broken down in appendix D.

The table below describes the costs:

Table 12 Cost type description

Type of cost	Description
OPEX	**Yearly operational cost per organisation**. If multiple organisations need to be involved per actor group (multiple airlines or ANSPs), the cost presented in this section must be multiplied by the number of organisations.
CAPEX	**One-off cost for the sector**. The costs presented in the table below consider the efforts needed for the sector as a whole (e.g. software development for airlines and ANSPs, efforts needed by weather service providers).
Full Time Equivalent (FTE)	FTEs per organisation involved in each actor group.

Table 13 Cost assessment - short-term roadmap

Action	Cost type (per actor)	Weather service provider	Airline	Systems / software providers	Legislator (EC + MS)	ANSP (national)	Network manager (Eurocontrol)	Total
1a Single stakeholder trials - airlines	CAPEX (M€)	0.5-1 M euros, including FTEs (see appendix D for detailed breakdown), based on past trials intelligence (duration, number of flights). Limited CAPEX increase as size of trials grow. Substantial OPEX increase as the size of trials grow.						
	OPEX (M€)							
	FTE							
1a Single stakeholder trials - ANSP	CAPEX (M€)	4 - 7 M euros, including FTEs (see appendix D for detailed breakdown). Both CAPEX & OPEX growth as the number of trials grow.						
	OPEX (M€)							
	FTE							
1b – Combined trials	CAPEX (M€)	10 - 15 M euros, including FTEs and trial coordinators (see appendix D for detailed breakdown). CAPEX and OPEX already consider larger trials than current ones.						
	OPEX (M€)							
	FTE							
2 - **Contrail avoidance tools in airline ops**	CAPEX (M€)	1-2		2-10*				**3-11**
	OPEX (M€)		1-3***					**1-3**
	FTE	1-3	2-3	2-3				**5-9**
3 - **Contrail avoidance tools in** ATC **ops**	CAPEX (M€)	1-2		74 - 90*		****		
	OPEX (M€)							**75-92**
	FTE	1-3		3-5		1-2	1	**6-11**
4 - **ATC capacity & KPI assessment**	CAPEX (M€)							**0**
	OPEX (M€)					1-2	3-5	**4-7**
	FTE					2-3	3-6	**5-9**
5 - **Pan-European contrail avoidance procedures**	CAPEX (M€)							**0**
	OPEX (M€)						2-5	**2-5**
	FTE				5-10**	2-3	5-10**	**7-13**
Total (excl. action 1) per organisation	***CAPEX (M€)***	***2-4***	***0***	***76-100****	***0***	***See *******	***0***	***78-104***
	OPEX	***Non applicable as costs are shown per organisation (see table 12)***						
	FTE	***2-6***	***2-3***	***5-8***	***5-10*****	***4-6***	***9-17****	***22-40***
Expected involved organisations (currently)		***2:*** *DWD, Météo France*	***Uncertain***	***Airlines (3):*** *Lido, Jeppesen, Flightkeys* ***ATC (3):*** *Thales, Indra, requentis*	***N/A***	***37***	***1***	***/***

*: the cost is born by the software provider and eventually passed on to the airline, the ATC, unless the software provider receives public fund. Airline: Airline: the cost is passed on to airlines through a subscription cost, assuming economies of scale are achieved and limited tailoring per airline is necessary. ANSP: Conservative estimation, assuming little replicability among 37 ANSPs (e.g. a new system would need to be developed for each ANSP). Currently, each ANSP has its own, non-replicable, ATC system. Software developed during trials may reduce overall cost of action 3).

**: the extra FTE are either born by the legislator or the NM, depending on the leading organisation developing pan-European procedures. It is therefore only considered once in the totals.

***: the extra OPEX cost for an airline engaging in contrail avoidance may require further analysis. **The indication provided may cover software subscription costs, training and extra fuel costs**. Yet, the latter depends on multiple factors, such as the baseline definition to evaluate extra fuel costs. For instance, operational disruptions such as thunderstorms avoidance generates extra fuel costs. Assumptions may be taken to average out, per route, the fuel costs for operational disruptions. Assumptions must be carefully considered. Beyond, the size of the airline fleet, the cost model of the airline also impacts the extra fuel cost weight on the airline. This disclaimer is particularly important considering the increasing volatility of fuel prices.

****: The software development costs (74-90 M€) are eventually passed on to the ANSPs through a subscription (OPEX) or simply purchased (CAPEX). Currently, ANSPs usually purchase their tools from software providers directly. In the future, the NM may centralise contrail avoidance software and pass them on to individual ANSPs through subscription.

The assessment of trials shows that single stakeholder trials can be run with relatively limited costs. The main bottlenecks are developing and scaling up the software usage to reach adoption in daily operations. This requires resources for software developers (mostly CAPEX – software development / improvement) and for the end user (mostly OPEX - both training personnel and potential extra costs (e.g. fuels)) when developing or applying these systems. For combined trials, the costs increase due to potential software development for the network manager, additional communication channels and coordination of procedures and data. Yet, as it was explained before, contrail avoidance tools already exist.

Companies such as FlightKeys, Google and Thales have primarily developed flight planning systems for airlines and, to a lower extent, ATM systems integrating contrail avoidance capabilities. This paves the way for other companies to follow-suit. Some of these tools are provided free of charge, such as FlightKeys and Google or have been developed using public funds, such as Thales. They are therefore able to provide these systems free of charge to the end consumer as long as they are used in a trial/test set up, lowering the operational costs of trials significantly. Future integration at scale may however be different, although Google has mentioned this functionality to be considered research activity only and therefore free of charge.

Despite the development of tools costs being potentially covered through public funds, the cost assessment above shows the indicative budget needed to develop such tools, based on interviews and the existing literature. These costs can be either covered through public funds, out-of-profit investments or eventually passed on to the end consumer (airline or ANSP).

As noted previously, software development for airlines is already relatively mature, as some providers offer contrail-avoidance capabilities already. As a result, a portion of the original development costs has already been incurred and is therefore excluded from this assessment. However, scaling contrail-avoidance functionality across all flight-planning software providers and embedding it into daily operations will still require additional investment. This includes software upgrades (CAPEX), training for dispatchers, sustainability teams, and pilots, as well as potential increased fuel consumption (OPEX). Capturing a wide range of potential fuel-cost impacts is particularly important due to the high volatility of jet fuel prices. Overall, the cost of scaling airline flight-planning software to support contrail avoidance is expected to be significant, but still lower than the costs associated with developing equivalent functionality for ATM.

For ATM, the integration of contrail-avoidance functions is still at a very early stage. While some ATC tools can already display ISSR characteristics, such as their location and extent (see Table 6 – trial methodology), they do not yet provide operational support for balancing rerouting decisions with airspace capacity constraints. Scaling up contrail-avoidance capabilities will therefore require significant software improvements (CAPEX) as well as substantial training for controllers during both trial phases, when new functions must be assessed against safety requirements, and their subsequent integration into daily operations (OPEX). Moreover, each of Europe's 37 air navigation service providers (ANSPs) operates with distinct capacity constraints and procedures, meaning that contrail tools will require tailored development for each provider. For these reasons, the global cost is expected to be high and to exceed the cost of scaling airline flight-planning software.

Overall, actions 2 and 3 of the roadmap have a potential (very) high cost due to the development / scale up needed to achieve integration into daily airlines and ATM operations. Specifically for the latter, integrating contrail avoidance tools into a complex and safety-oriented ANSP system will require careful consideration by software developers. Actions 4 and 5 are expected to have a very low (or inexistent) investment cost (CAPEX) but would require workforce to evaluate the learning from the trials (OPEX) and eventually develop guidelines to structure large-scale contrail avoidance during low-traffic periods.

4.5 Long-term roadmap

The long term roadmap outlines a set of high-level actions expected to start from 2032 onwards, provided all actions within the short term roadmap are successfully implemented. The long-term actions aim to scale contrail mitigation implementation to become more effective and applicable in medium and eventually high traffic periods.

The four actions developed are based on both literature review, stakeholder input from interviews, and workshops with contributions from T&E. The actions proposed are more strategic, focusing on large-scale deployment, governance and alignment within international organisations. For the successful deployment of the long-term roadmap actions, a number of pre-requisites need to be in place. In the implementation of large-scale contrail mitigation strategies, it is necessary to have tools which support decision-making and alleviate the workload of all stakeholders. Additionally, contrail mitigation strategies need to remain operationally feasible and economically viable (particularly for Airlines, but also ANSPs) as the implementation scale increases to more traffic dense areas and expansion of geographical scope. Lastly, a large-scale implementation of contrail mitigation requires robust systems for monitoring and verification of contrail warming impacts.

The high-level actions within the long-term contrail mitigation roadmap implemented from 2032 onwards are presented below.

Action	Led By
1 More effective Contrail avoidance Centralized procedures followed by both ATC, NM and airlines will ensure a form of standardisation. Upon this, procedures and KPIs can be iteratively improved to increase efficiency of contrail mitigation. More effective procedures are rolled out EU wide.	EU Network Manager
2 Contrail avoidance in medium / highly congested airspace As processes become standardised and improved, there will be more opportunity to also aim for contrail avoidance in medium and highly congested airspace. In some cases, significant contrail avoidance may need to be achieved by direct increase of ATC capacity (both ATCOs and supervisors) for specific times of day, in the form of a more pro-active approach to contrail avoidance. Extension of contrail avoidance to more congested airspace can be stimulated through new performance-based KPIs and or legislation.	ANSPs
3 Extension of Contrail avoidance to non-EU airspace Based on EU ways of working, best practices can be shared. First with North American stakeholders to enable north Atlantic contrail avoidance and later extending to Asia and other regions. Engagement with international bodies such as ICAO, IATA and CANSO is critical. Sharing systems IP and data would support broader implementation.	International Organisations
4 Contrail management team within the EU NM The NM can play a critical coordinating role. To solidify this, a dedicated team at the EU NM on contrails would ensure that this coordination is improved and strengthened.	Legislator

Figure 8 Long-term roadmap actions (source: To70)

The actions presented above would eventually lead to large scale implementation of contrail avoidance during medium and high traffic periods for both intra-EU and inter-continental flights to/from Europe. Yet, working towards this aim requires deepening contrail leadership at NM level, including extra contrail-dedicated manpower, but also coordination and alignment with international organisations to align procedures and inform of the actions taken in the EU. European leadership must be an example other aviation authorities can rely on.

Along this high-level coordination tasks, continuous improvement of contrail avoidance procedures and processes at operational level is necessary. KPIs must constantly be assessed, lessons learned must be shared among ANSPs and airlines, based on operational developments but also scientific evolutions. The NM (and scientific community) are at the core of the continuous processes and procedures improvement in the long-term roadmap. Appendix C further details each action.

APPENDIX A – Reports and sources

1. ANCEN reports
2. ICAO report *Operational Opportunities to reduce climate effects of contrails and other Non-CO_2 emissions*
3. Roland Berger report *A solvable problem*,
4. RMI report *Understanding Contrail management: Opportunities, challenges and insights*,
5. ATI UK report *Non-CO_2 technologies report*
6. **Presentations from conferences:** Copenhagen Contrails conference, IATA-RAeS contrails workshop, EUROCONTROL/CANSO Sustainable Skies conference

APPENDIX B – Contrail trials

This table contains the most relevant trials that have taken place or ongoing.

Table 14 Contrail avoidance trials list

Trial name	Main stakeholders	Lead	Focus-phase	Description	Funding	Year	Link
TUI	TUI fly	Airline	Pre-tactical & Tactical	Live trial to understand the impact of contrail mitigation options on dispatchers.	Seld-funded	2025	Link
MUAC trial 1	MUAC, DLR	ANSP	Tactical	First nighttime operational trial with MUAC and DLR to mitigate contrails.	MUAC & DLR	2021, 2022	Link Link
MUAC trial 2	MUAC, Google	ANSP	Tactical	Large-scale contrail mitigation using Google's prediction and analysis.	MUAC & Google	2024, 2025	Link Link
D-Kult 100 flights	DFS, Tui, DWD, DLR, Lufthansa, Condor, PACE, DHL, Jeppesen, Flightkeys	Airline	Pre-tactical	D-KULT aims to provide evidence of the feasibility of eco-efficient flight trajectories, considering non-CO_2 emissions in European (German) airspace. Flights should be planned in such a way, that their trajectories are optimized with regard to reduced climate impact in a suitable defined climate metric.	LuFo (German research fund)	2022, 2025	Link Link 2 Link 3
CICONIA trials	NATS, EasyJet, AFKLM, Swiss, Flightkeys, MUAC	Airline	Pre-tactical & Tactical	First simulations, to understand network effect, then trials in shadow mode with ATC members. Also hosted ATC workshops to inform them and hear their perspective. Live trials planned for low traffic scenarios.	EU SESAR	2025, 2026	Link
NATS JetZero trial	NATS, undisclosed	ANSP	Tactical	Live trials over both Shanwick Oceanic and Scottish domestic.	JetZero	Proposal phase	Link
Etihad 1	SATAVIA, Etihad, MUAC	Airline	Not disclosed	Trials using SATAVIA's atmospheric modelling for contrail avoidance.	Self funded	2021	Link
CONCERTO	Thales, BOREALIS Alliance, DWD, EUROCONTROL, PPS, TU Delft, DLR, IcelandAir	ANSP	Pre-tactical & tactical	Thales developed a method to assess all flights in certain areas of Borealis airspace.	EU SESAR	2023	Link
Thales trial 1	Thales, DGAC, Amelia	Airline (systems)	Pre-tactical	Trials in which all amelia flights were analysed, big hits identified, and shared with dispatchers at Amelia. This system was gradually automated and improved.	CORAC, DGAC	2024, 2025	Link Link
American airlines trial 1	American airlines, Contrails.org, Google, Flightkeys	Airline	Pre-tactical	American airlines tested contrail avoidance through dispatcher led rerouting. 70 test flights over six months were done based on google AI predictions to avoid contrails. Satellite imagery assessments found that the predictions reduced contrails by 54% compared to when pilots didn't use predictions. Flights that avoided contrails burned 2% more fuel, which would translate to 0.3% more fuel when scaled across an airline's fleet.	Self-funded	2025	Link

Delta trial 1	Delta, MIT, Google	Airline	Tactical	Delta completed more than 40 test flights. Past trials and simulations by MIT and Delta showed that 70% to 90% of all contrails could be avoided through flight and altitude adjustments.	Self-funded	2022	Link
WIMCOT trial	AFKLM, MeteoFrance, PACE	Airline	Unclear	MeteoFrance provided predictions of contrail-prone areas (ISSRs) and Air France undertook operational trails avoiding those regions. The number of flights were limited and a diversion was not always possible due to airspace constraints.	Self-funded	2023	Link Link
SATAVIA x KLM trial	KLM, SATAVIA	Airline	Pre-tactical	Manually, SATAVIA shared contrail optimized flight plans with KLM dispatchers. Aim was to achieve at least 100 contrail avoidance flights. The need to automate systems and unclear data were the key learnings.	Self-Funded	2023	No link
SATAVIA Decisionx	SATAVIA, Icelandair, Kenya Airways, Condor, SunExpress	Systems	Pre-tactical	SATAVIA deployed its DECISIONX platform to optimise 65 flights across 12 operators for contrail management.	European Space Agency	2021, 2022	Link Link
PRE-TRIALS	GE Research, Southwest Airlines, RTX, Boeing, Northrop Grumman	Airline	Unclear	Predictive Real-time Emissions Technologies Reducing Aircraft Induced Lines in the Sky (PRE-TRAILS) program invests in systems to predict aviation contrails capable of informing pilots and ground controllers in real-time. The program focuses on aircraft, environmental data and sensor development, predictive models; and observer data resources to develop an integrated aviation contrail predictive system. ARPA-E has committed $10 million across 5 projects.	ARPA-E	2024	Link
A4Climate trials	DLR, FlightKeys, TUI	Airline	Pre-tactical	The A4Climate project focusses on several aspects of contrail formation and mitigation including research on ice particle formation but also live trials. The trials are executed by Tui in collaboration with Flightkeys and DLR on 400 flights with a random selection to enable comparison of contrail avoidance success and pricing.	EU Horizon	2026	Link
CONTRA	University of Linkoping, LFV, Avtech	Academia	Unclear	Scientific-led project aiming to predict avoidance regions prone to contrail formation. Evaluation of capacity reduction, extra fuel burn, costs of delay due to contrail avoidance measures.	Self-funded	2025-2028	Link

APPENDIX C- Roadmap actions (short and long term)

ACTION	1 Trials *1a – Single stakeholder trials* *1b – Combined trials*	2 Contrail avoidance tools in airline ops	3 Contrail prediction software in ATC ops	4 ATC capacity and KPI assessment	5 Pan-European contrail avoidance procedures
DESCRIPTION	Start single stakeholder trials in a single airspace with new entrants (1a) and start combined trials with ANSPs, NM and airlines strategically within low density airspace and with willing ANSPs (1b). Scale up to cover multiple airspaces. Include NM to coordinate decision making. Across trials, test different ways of working for ATC, NM and airlines based on same input data (weather, routes flown, contrail formation etc).	Incorporation of contrail avoidance tools as developed in trials in standard operations of airlines. Thereby, for leading airlines contrail avoidance becomes the norm for a subset of their fleet. Dispatchers and pilots are trained to take appropriate decisions based on the tools. This includes a clear decision-making process for extra fuel burn, EU ETS costs vs climate impact.	Develop contrail prediction software for ATC systems. First on top of, then integrated, potentially integrating it into updates already taking place to modernize ATM. Software providers will need to improve contrail prediction tools based on improved weather data, and contrail models. Once included in processes and systems, ATC and NM are trained to make appropriate decisions.	Evaluation of the capacity by ANSPs and NMs in single and combined airspace where contrail avoidance is integrated in ATC systems and processes. Thorough re-assessment of contrail avoidance impact on ATC capacity and workload and newly developed KPI's will provide a basis for the role of ATC in contrail avoidance.	To ensure actions 2 and 3 (i.e. both Airline and ATC led actions) complement each other, it is important to develop European-wide procedures with a clear role for all stakeholders. These are based on traffic density in each airspace and tools available per ATC and airline. These procedures are assessed to understand the operational impacts.
SUB STEPS	1. Funding for trials (EU funds, philanthropy or airlines). 2. Collaboration to include at least 1 ATC, the NM and 1 airline. 3. Start simple (one actor) trials with new entrants, and broader trials covering different types of airspaces, different approaches and different processes for leading ANSPs. 4. Set up centralized contrail trial database with public access.	1. Airlines and flight-planning org. incorporate contrail avoidance in software and processes. 2. Airlines develop clear decision-making processes on contrail avoidance for dispatchers and pilots including training. 3. Contrail avoidance software is regularly updated to reflect latest models and EU MRV.	1. Both incumbents (Thales, Indra) and new entrants (Estuaire, Google) develop contrail prediction software. 2. New software is included "on top of" (i.e. separate system) in ATC operational environment. 3. Trialling the software, gradually include into ATC processes and training, where possible within planned updates. 4. Include processes in ATC and NM training.	1. Assess capacity impacts of contrail avoidance per airspace, focussing on ratio of positive contrail reduction impact vs negative operational impact. 2. Based on findings, set guidelines on acceptable circumstances for (ATC/NM led) contrail avoidance, such as allowable capacity reduction per FL closure and other metrics. 3. Develop NM/ATC FM KPI's that ensure execution of guidelines.	1. Collect learnings from trials and "in-ops" contrail avoidance. 2. Set up working group that prepares **procedures for ATC** on contrail avoidance. 3. Institutionalize such procedures through guidance or policy to be followed by NM, all ATCs and airlines avoiding contrails. 4. Within procedures, harmonize data sources.
	Responsible Stakeholder *Coordinator*	Responsible Stakeholder *Airlines*	Responsible Stakeholder *ANSPs*	Responsible Stakeholder *Network Manager*	Responsible Stakeholder *Legislator*

Figure 9 Short term roadmap – detailed (source: To70)

EU guidelines for set procedures and associated KPI's are in place

ACTION	1 More effective contrail avoidance	2 Contrail avoidance for medium / highly congested airspace	3 Extension to non-EU airspace	4 Contrail management team within EU NM
DESCRIPTION	Through a centralized procedure, followed by all stakeholders, contrail avoidance is standardised for airspace within the capacity constraints. EU wide processes and guidelines enabled by KPI's per stakeholder ensure avoidance becomes more effective. Through iterative improvement in comms, models, and decisions the most warming contrails can be avoided.	As contrail avoidance processes align, NM and ATC can enable avoidance in medium and high congested airspace by coordinating more closely with individual ANSPs. This would require a pro-active approach to capacity, increasing the number of ATCO's during contrail prone days to ensure capacity can be scaled up in line with contrail avoidance.	Based on ways of working in EU and best practices, engage with leading ANSPs (e.g. NavCanada) to align on contrail avoidance systems and procedures.	Dedicated Contrail management team in Network Management organisation.
SUB STEPS	1. The NM and all National ANSPs follow Eu contrail guidance. 2. The NM and leading ANSPs trial efficiency improvements, new comms methods, better data, etc. within their procedures. 3. Proven methods to improve effectivity are centrally agreed upon by operational working group and implemented across EU.	1. NM identifies medium/high congested airspace with significant contrail avoidance opportunities. 2. NM, together with national ANSPs coordinates increased capacity to enable contrail avoidance. This could be funded through national or EU measures or incentives. 3. KPI's are further developed to reward pro-active capacity extensions that support contrail avoidance.	1. Engage with ICAO, CANSO, other international bodies. 2. Provide clear proposals for way of working, starting with North Atlantic corridor. 3. Support other ANSPs and NMs by sharing systems and procedures.	1. Assess the functionality of NM in contrail avoidance. 2. If logical and operationally feasible, set up dedicated NM contrail team to manage contrail avoidance vs congestion.

Figure 10 Long-term roadmap – detailed (source: To70)

APPENDIX D – Trial cost breakdown

Single stakeholder trial - Airline

Trial led by an Airline, using a system for 1 year across a predefined # of flights.					Input used for calculations but excluded from the overall cost assessment	
	Low CAPEX	High CAPEX	comments	Low OPEX	High OPEX	Comments
System provider cost						
Development of airline flight planning system*	€ 1.650.000,00	€ 2.200.000,00	Software development costs passed on as OPEX to the airlines	N/A	N/A	N/A
Airline cost						
Yearly subscription for flight planning systems (assuming 50 - 100 airlines purchase the flight planning software)	N/A	N/A	N/A	€ 19.250,00	€ 38.500,00	If the cost is passed on to the airline through a subscription cost, assuming economies of scale are achieved and limited tailoring per airline is necessary
Personnel costs dispatch & pilots	N/A	N/A	NA	€ 100.000,00	€ 150.000,00	Training + system integration level
Extra fuel and other costs	N/A	N/A	N/A	€ -	€ 200.000,00	May vary on contrail avoidance (potentially no extra fuel burn)
Data costs	N/A	N/A	N/A	€ 50.000,00	€ 100.000,00	Mainly weather data and computing
Project management costs	N/A	N/A	N/A	€ 125.000,00	€ 200.000,00	1 experinced PM FTE**
Across all stakeholders						
Coordination costs	€ 50.000,00	€ 100.000,00	Set up / IF application	€ 125.000,00	€ 200.000,00	1 experienced PM FTE**
Total						
Total	**€ 50.000,00**	**€ 100.000,00**		**€ 419.250,00**	**€ 888.500,00**	
Total CAPEX & OPEX (low)	**€ 469.250,00**					
Total CAPEX & OPEX (high)	**€ 988.500,00**					

***:** The costs indicated simply cover the software development. It specifically excludes costs related to improving the scientific model used (e.g. overall climate impact, cost impact for airlines). This cost is eventually passed on through an OPEX to the airlines. Only the OPEX is shown in the cost assessment.

****:** the average yearly cost per FTE is estimated to be between 125 k and 200 k€.

Figure 11 Single stakeholder trial cost: airline (source: To70)

Single stakeholder trial - ANSP

Trial led by an ANSP, using a system for 1 year across a predefined # moments with low demand.						
	Low CAPEX	High CAPEX	comments	Low OPEX	High OPEX	Comments
System provider costs						
ANSP contrail prediction software*	€ 2.000.000,00	€ 2.500.000,00	One time cost	N/A	N/A	N/A
Project management system provider	€ 500.000,00	€ 1.000.000,00	One time cost needed for the software development	N/A	N/A	N/A
Digital engineering / systems integration	€ 500.000,00	€ 1.000.000,00		N/A	N/A	N/A
Simulation design	€ 250.000,00	€ 500.000,00		N/A	N/A	N/A
Training and coordination with ANSP	N/A	N/A	N/A	€ 250.000,00	€ 500.000,00	
Dissemination and exploitation	N/A	N/A	N/A	€ 300.000,00	€ 700.000,00	
ANSP costs						
Personnel costs FM and ATC	N/A	N/A	Training	€ 250.000,00	€ 400.000,00	1 extra flow manager, 1 extra ATC FTE**
Data costs	€ 50.000,00	€ 100.000,00	N/A	N/A	N/A	Mainly weather data and computing
Across all stakeholders						
Coordination costs	€ 50.000,00	€ 100.000,00	Set up / IF application	€ 125.000,00	€ 200.000,00	1 experienced PM FTE**
Total						
Total	**€ 3.350.000,00**	**€ 5.200.000,00**		**€ 925.000,00**	**€ 1.800.000,00**	
Total CAPEX & OPEX (low)	**€ 4.275.000,00**					
Total CAPEX & OPEX (high)	**€ 7.000.000,00**					

*: The costs indicated simply cover the software development. It specifically excludes costs related to improving the scientific model used (e.g. overall climate impact, cost impact for airlines). This cost must be multiplied by the number of ANSPs purchasing the software.

**: the average yearly cost per FTE is estimated to be between 125 k and 200 k€.

Figure 12 Single stakeholder trial cost: ANSP (source: To70)

Combined trial - ANSP/ Airline / NM

Trail where all stakeholders take a role, data is harmonized and systems and procedures are aligned. Includes more contrail avoidance deviations than single stakeholder trials.						Input used for calculations but excluded from the overall cost assessment
	Low CAPEX	High CAPEX	comments	Low OPEX	High OPEX	Comments
System provider costs						
ANSP contrail total system cost, project management system provider, digitan engineering system integration, simulation design*	€ 2.000.000,00	€ 2.500.000,00	One time cost per ANSP	N/A	N/A	N/A
One time costs for ANSP system development	€ 1.250.000,00	€ 2.500.000,00	One time cost for ANSP software development	N/A	N/A	N/A
Airline flight planning system**	€ 1.650.000,00	€ 2.200.000,00	Software development costs passed on as OPEX to the airlines	N/A	N/A	Varies per airline and type of FP system
NM coordination system	€ 5.000.000,00	€ 7.000.000,00	One time cost	N/A	N/A	N/A
Personnel costs (ANSP, flight planning system, NM system)	N/A	N/A	N/A	€ 375.000,00	€ 600.000,00	2-3 FTEs**
ANSP costs						
Personnel costs FM and ATC	N/A	N/A	Training	€ 250.000,00	€ 400.000,00	1 extra flow manager, 1 extra ATC FTE**
Project management costs	N/A	N/A	N/A	€ 125.000,00	€ 200.000,00	1 experinced PM FTE**
Airline costs						
Yearly subscription for flight planning systems (assuming 50 - 100 airlines purchase the flight planning software)	N/A	N/A		€ 19.250,00	€ 38.500,00	If the cost is passed on to the airline through a subscription cost, assuming economies of scale are achieved and limited tailoring per airline is necessary
Personnel costs dispatch & pilots	N/A	N/A	Training	€ 100.000,00	€ 150.000,00	Varies based on system integration level
Extra fuel and other costs	N/A	N/A	N/A	€ -	€ 200.000,00	Varies based on # of flights (potentially no extra fuel burn)
Project management costs	N/A	N/A	N/A	€ 125.000,00	€ 200.000,00	1 experinced PM FTE**
Network manager						
Personnel costs NM	N/A	N/A	Training	€ 250.000,00	€ 400.000,00	2 FTE extra at NM**
Project management costs	N/A	N/A	N/A	€ 250.000,00	€ 400.000,00	2 experienced PM FTE**
Across all stakeholders						
Coordination costs	€ 100.000,00	€ 200.000,00	Set up / IF application	€ 250.000,00	€ 400.000,00	2 experienced PM FTE**
Total						
Total	**€ 8.350.000,00**	**€ 12.200.000,00**		**€ 1.744.250,00**	**€ 2.988.500,00**	
Total CAPEX & OPEX (low)	**€ 10.094.250,00**					
Total CAPEX & OPEX (high)	**€ 15.188.500,00**					

*: The costs indicated simply cover the software development. It specifically excludes costs related to improving the scientific model used (e.g. overall climate impact, cost impact for airlines). This cost must be multiplied by the number of ANSPs purchasing the software.

*: The costs indicated simply cover the software development. It specifically excludes costs related to improving the scientific model used (e.g. overall climate impact, cost impact for airlines). This cost is eventually passed on through an OPEX to the airlines.

**: the average yearly cost per FTE is estimated to be between 125 k and 200 k€.

Figure 13 Combined trial cost : ANSP / Airline / NM (source: To70)