REPORT

Contrails

A solvable problem?

Roland Berger

Management summary

Aviation is facing significant pressure to reduce its climate impact. In addition to the well understood challenge of decarbonization, another key contributor to aviation's climate impact are contrails: clouds formed by the interactions of engine exhaust and cool, moist air. In total, the impact of contrails could be approximately as significant as that of aviation's CO_2 itself – or potentially even greater, depending on how it is measured.

While there are still significant uncertainties as to the exact climate impact of contrails, there are a range of potential mechanisms to reduce their impact.

- **Engine efficiency:** Continued improvements in specific fuel consumption may reduce soot and water emissions, thus limiting contrail formation. However, this does come at a cost and without the ability to eliminate contrails altogether.
- **Novel fuels:** Adjusting the fuel used by aircraft to low aromatic fuels or SAFs can also reduce contrail impacts. This will take several years to ramp up to scale and also cannot eliminate contrails. Hydrogen and electric aircraft present possibilities for significant reduction but face significant technological, development, certification, and commercial challenges to implementation.
- **Trajectory optimization:** Rerouting aircraft to avoid the ice-supersaturated regions (ISSRs) where contrails form. This can be achieved through altitude adjustments or optimizing routes, which have been shown to significantly reduce contrail formation with minimal fuel penalties. Indeed, this approach may offer the most promising medium-term solution.

With this in mind, this study highlights **trajectory optimization case studies** from SATAVIA and FLIGHTKEYS. Both companies are providing frontrunning solutions and already trialing practical applications of contrail avoidance. SATAVIA uses advanced weather modeling to help airlines reroute flights, while FLIGHTKEYS integrates contrail forecasts into flight planning. Both show that contrail management can be achieved with limited operational costs.

This report first reviews the latest understanding of the challenges posed by contrails as a driver of climate forcing (Chapter 1), before summarizing the key potential solutions (Chapter 2). We then hand over to SATAVIA and FLIGHTKEYS to explain their potential solutions as well as recent results from their trials (Chapter 3). After reviewing recent Roland Berger analyses on the potential system costs for contrail management (Chapter 4), we conclude with our thoughts on key next steps for the aviation sector (Chapter 5).

Contents

1 Contrail management: Assessing the challenges and opportunities

The aviation industry faces multiple challenges as part of its effort to help urgently reduce global greenhouse gas emissions and limit global warming to 1.5°C. Aviation is responsible for approximately 2.5 % of annual global CO_2 emissions, but it receives significant public attention given its highly visible, public-facing nature. The industry must now reduce CO_2 emissions through radical innovation in aircraft technology and flight operations, supported by the transition to sustainable aviation fuels (SAFs) and other means of propulsion such as hydrogen and battery electric aircraft.

Alongside CO_2, the industry faces the equally daunting challenge of addressing the non-CO_2 effects of flying, whose climate impacts are becoming increasingly understood. Of these, contrails and contrail cirrus currently appear to have the highest net warming significance. Contrails are small clouds formed by the hot exhaust from aircraft engines interacting with cold, moist air, which may have cooling or warming effects depending on the time of day they are produced. During the day, contrails can help to reflect incoming solar radiation, leading to a cooling effect, while also containing outbound thermal radiation, leading to a warming effect. At night, contrails only contain outbound thermal radiation, causing a net warming effect over the course of 24 hours.

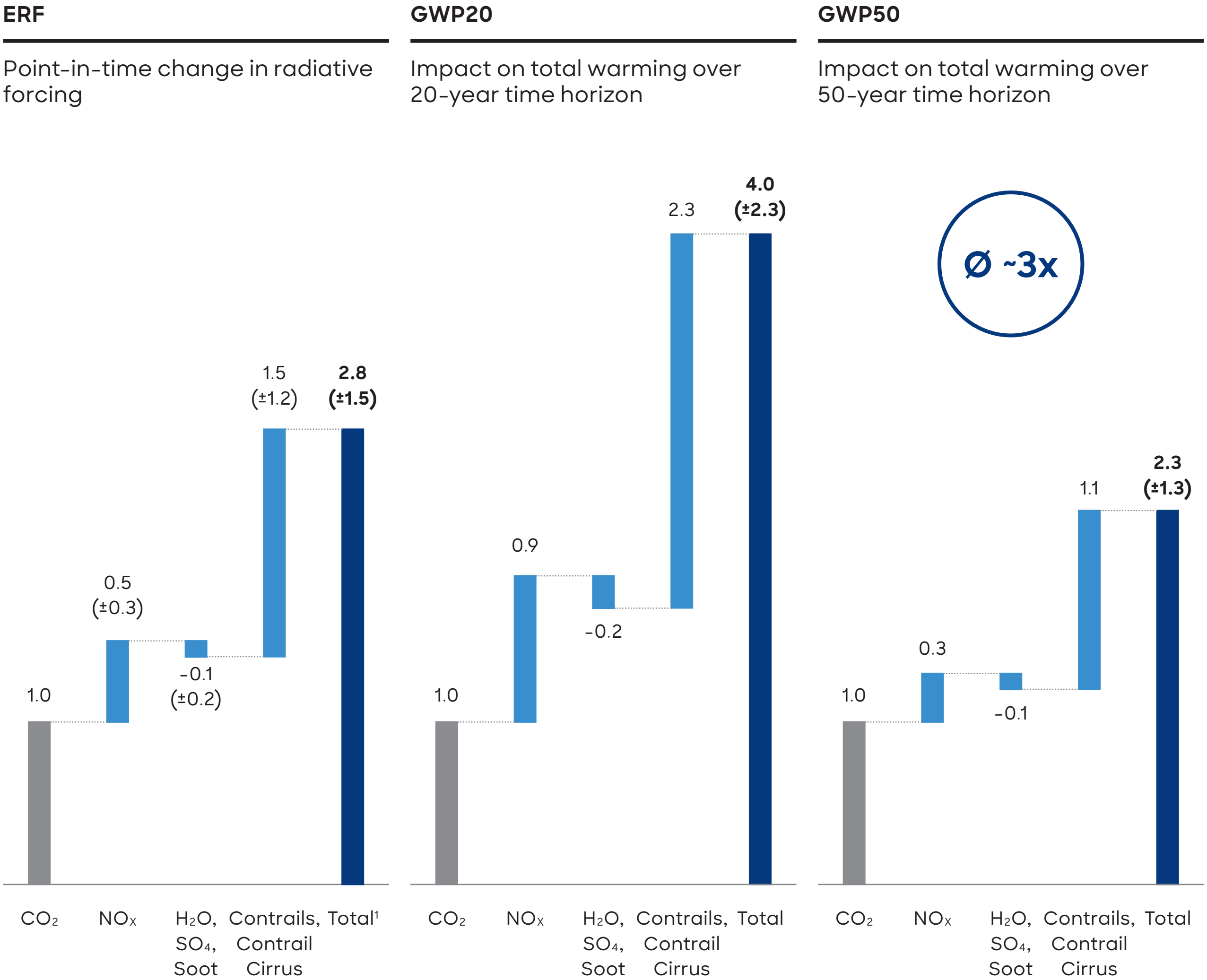
The exact climate impact of contrails remains uncertain. Accurately measuring their radiative forcing (RF) or effective radiative forcing (ERF) impact is challenging, with the latter taking into account feedback between contrails and the surrounding atmosphere. However, based on a GWP50 (global warming potential over 50 years) median estimate averaged over all flights, contrails may cause a warming effect comparable to an additional 130 % of aviation's annual CO_2 emissions.[1] Even the lower-bound estimate of an additional 18 % of annual aviation CO_2 is significant, meriting efforts to gain improved understanding. Measured on a GWP20 basis (global warming potential over 20 years), the relative climate impact of contrails is significantly more pronounced. ▶ A

1 D. S. Lee et al., Atmospheric Environment. 244, 117834 (2021) and Myhre, G. et al., AR5 (2013)

> **"The climate impact of contrails, even on the lower-bound estimate of ~18 % of the impact of CO_2, merits further attention."**
>
> **Robert Thomson, Partner**

A Climate impact of different emissions and effects

Radiative forcing[1] contributions due to aviation, 2018 – Indexed to impact of CO_2



1 Radiative forcing measures the balance of energy moving into vs. out of the Earth's atmosphere (i.e., the instantaneous impact on global warming)

Source: D.S. Lee et al., 2021, Roland Berger

Regardless of the time horizon, the climate impact of contrails deserves attention. This is particularly true for airlines serving North American and European markets, as these are prone to higher levels of warming due to regional operating factors and seasonality.[2]

This report provides an overview of the status quo for contrail management and highlights how navigational avoidance solutions are already being put into practice by commercial providers – a potential way for aviation to substantially reduce its climate impact in the medium term.

2 Teoh, R., Engberg, Z., Schumann, U., Voigt, C., Shapiro, M., Rohs, S., and Stettler, M., Global aviation contrail climate effects from 2019 to 2021, EGUsphere [preprint], 2023, https://doi.org/10.5194/egusphere-2023-1859

2

Contrail management solutions

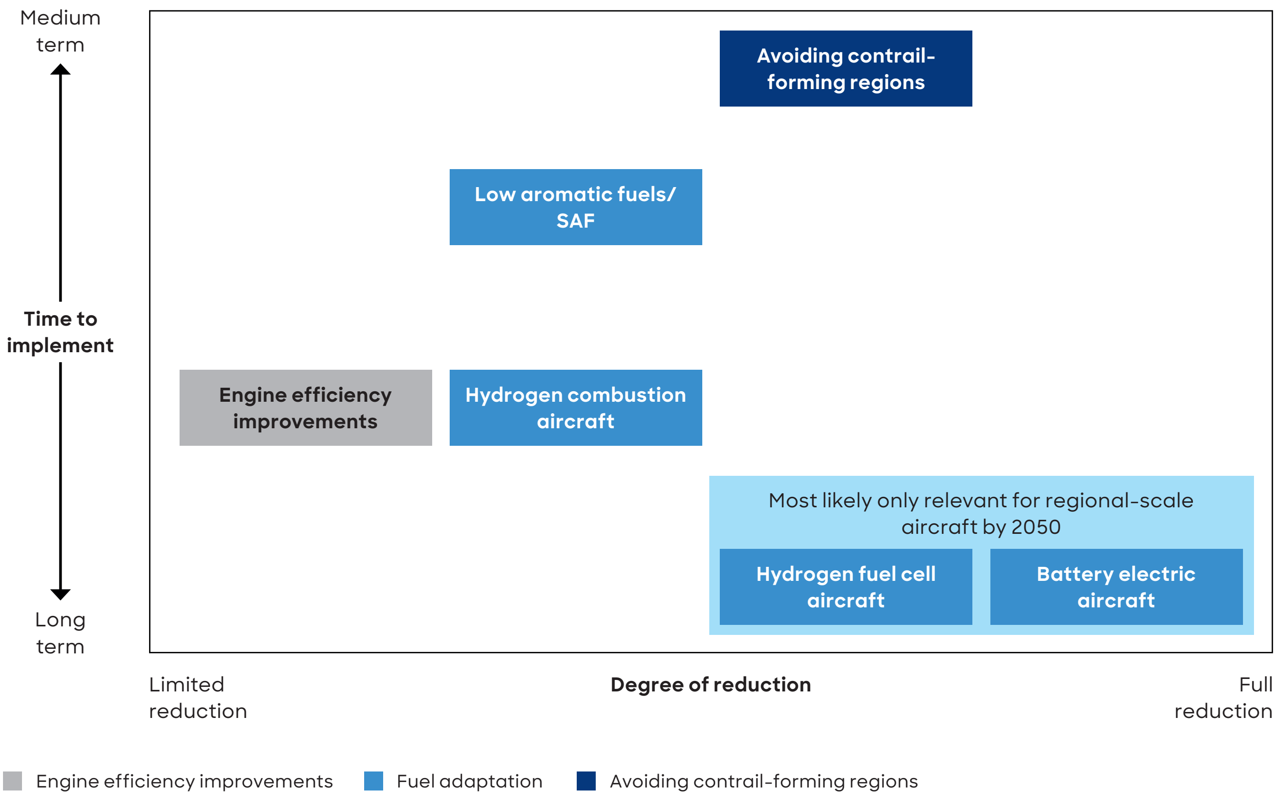
There are a raft of solutions to potentially reduce the impact of contrails or even fully avoid their formation. If implemented correctly, these would significantly lower aviation's climate footprint.

The solutions can be split into three main groups, with each having a different implementation timeframe and effect on contrail formation:

- Engine efficiency improvements
- Fuel adaptation (including novel propulsion technologies)
- Avoiding contrail-forming regions

The focus of this report is on the potential for avoiding contrail-forming regions. This solution appears to be the only option that promises significant, if not complete, reductions in contrail formation in the medium term, given that widespread adoption of alternative propulsion and SAFs is unlikely before 2040. However, we also briefly cover the other two groups, as all three solutions have complementary benefits, particularly in regard to aviation's other emissions – CO_2, NO_x, and particulates. In the long term, and indeed to address aviation's total impact and move towards zero aviation climate impact, it may be necessary for the whole suite of solutions to be implemented. ▶ B

B Potential solutions to reduce aviation's climate impact



Source: Roland Berger

2.1/ Engine efficiency improvements

How exactly improvements to aircraft engines will impact contrail formation is unclear. Reducing fuel burn should lower both the number of soot particles (which serve as nucleation points for ice crystals, supporting contrail formation) and amount of water emitted, with both partially reducing contrail formation. However, increasing engine efficiency may increase the number and size of regions in which contrails can form, due largely to lower exhaust temperatures.

Future engine types are expected to continue the trend toward cleaner combustion. In addition, jet engines increasingly use lean burn combustion approaches, reducing soot formation. This means the number of nucleation points in the exhaust should drop, increasing the size of ice particles formed and thus reducing their lifetime and radiative forcing impact. The exact engine dynamics, including exhaust temperature, will determine the atmospheric conditions under which contrails will form.

At best, improvements to conventional aircraft engine technology represent only a partial solution to contrails and will take at least 10-20 years to implement at scale due to the need to develop and certify new aircraft and renew the fleet.

2.2/ Fuel adaptation

Adopting novel fuels, in addition to reducing carbon emissions (whether gross or net), could also reduce the impact of contrail formation. Both hydrogen and electric aircraft have considerable benefits in terms of reducing carbon emissions, as well as NO_X, particulates, and contrails. Drop-in fuels (e.g., SAF), with lower aromatic content, can also be expected to reduce contrail formation. ▶ C

Drop-in fuels (kerosene equivalents)

Fuel soot content can be reduced either by the adoption of low aromatic fuels, or by increased SAF uptake. This should decrease the number of nucleation points in the exhaust plume, in turn reducing the number of ice particles and increasing their diameter. It is hoped that increasing ice particle diameters will reduce the time ice particles remain in the atmosphere (due to increased particle mass), potentially reducing the lifetime of contrails and their aggregate climate impact. It must be noted that, at this point, the use of SAF is not expected to eliminate the formation of contrails, but partially reduce them. Initial experimental validation of the impact of SAF on contrail RF has been promising,[3] however further work must be done to confirm the impact that could be achieved at scale.[4]

Adjusting to SAF will require engine modifications as fuel lubrication properties and sealant requirements change. Some engine and airframe manufacturers are already producing 100% SAF-compatible engines, with Boeing, Embraer, and Airbus targeting 100% SAF-compatible aircraft entering service by 2030. However, with new SAF facilities requiring trillions of dollars in investment, it is unlikely that SAF will completely replace conventional kerosene even by 2050. In the medium term, SAF is expected to continue to cost more than standard aviation fuel. During 2024, for example, SAF cost 2.5 to 3.5 times more than conventional jet fuel. SAF costs under the EU and UK mandates are indeed even higher.[5]

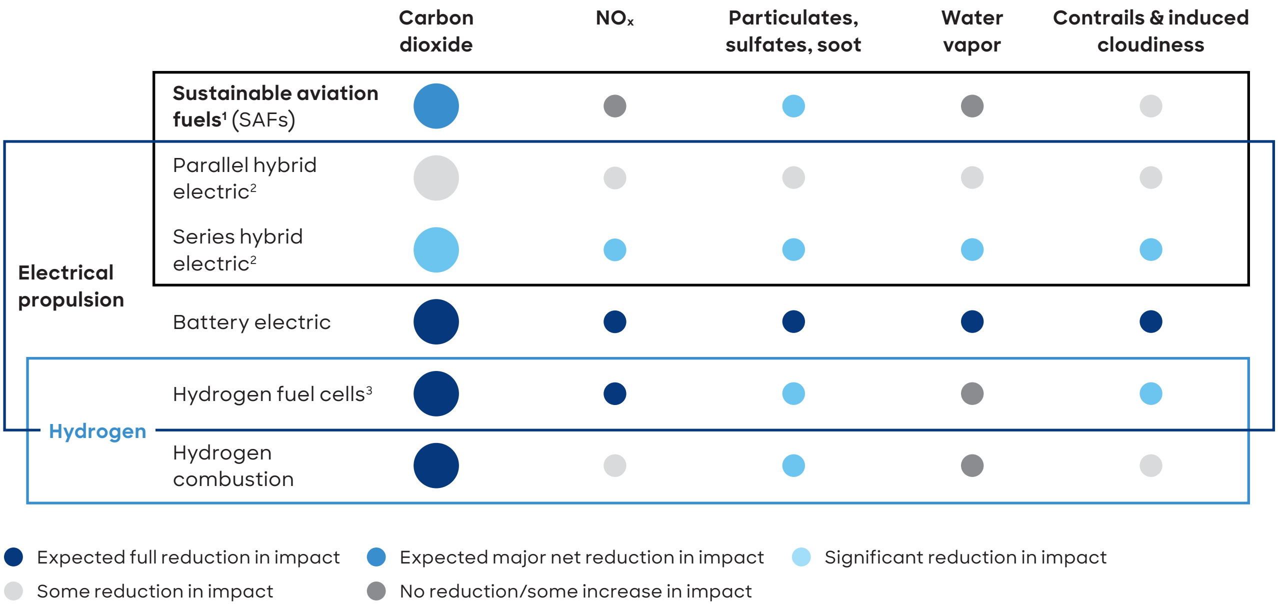
3 Voigt, C., Kleine, J., Sauer, D. et al., Cleaner burning aviation fuels can reduce contrail cloudiness, Communications Earth Environ 2, 114 (2021), https://www.nature.com/articles/s43247-021-00174-y

4 Further validation work is already underway with both Boeing (https://www.nasa.gov/centers-and-facilities/armstrong/nasa-partners-explore-sustainable-fuels-effects-on-aircraft-contrails/) and Airbus (https://www.dlr.de/en/latest/news/2023/01/emissions-and-contrail-study-with-100-percent-sustainable-aviation-fuel) in partnership with academic institutions like NASA and the DLR

5 Based on comparison of IATA's jet fuel price monitor and Argus Media's SAF fob ARA index

C Emissions impact of different propulsion architectures

Landscape of "revolutionary" sustainable aviation solutions



1 100% fuel drop-in, including 100% SAF-compatible engines 2 Hybrid solutions also compatible with SAFs, which would reduce net carbon impact 3 True zero possible only if operated appropriately to minimize contrails

Source: Secondary research, Roland Berger

Hydrogen and battery electric aircraft

The impact on contrail formation of transitioning from aviation fuels to hydrogen is currently unclear, given the interplay between lower soot and increased water content. Modeling suggests that both hydrogen combustion and fuel cells will produce more contrails but these will persist for shorter amounts of time,[6] resulting in reductions in total climate impact. Hydrogen fuel cell aircraft are also expected to significantly reduce contrail formation as the exhaust plume changes to water. A short-term solution is unlikely, though, given the lengthy timelines expected for the development, certification, ramp-up, and production of new aircraft; Airbus, for example, is targeting a 2035 entry-into-service for its ZEROe aircraft. Hydrogen-powered widebody long-range aircraft are unlikely to be widely available by 2050 due to the challenges posed by energy density and technology. Given that widebody long-range aviation currently represents around 50% of global revenue passenger kilometers, without major changes to the global network, hydrogen propulsion (as its potential is understood today) will be unable to significantly impact global aviation's environmental footprint before 2050.

Battery electric aircraft have no tailpipe emissions, so avoid contrail formation entirely. But challenges around battery energy densities make their use beyond short-haul, sub-regional flights unlikely. Short of a revolution in battery chemistries to increase energy densities by 3-5x, successful introduction of hybrid electric solutions, or a complete redesign of the aviation network, this limits the ability of electric aircraft to resolve the contrail problem. As a result, without significant technological developments, the use of novel fuels is likely to only lower, not completely avoid, the climate impact of contrails. Other mechanisms will be required to fully mitigate their impact.

6 Rap et al., The climate impact of contrails from hydrogen combustion and fuel cell aircraft, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-5520, https://ui.adsabs.harvard.edu/abs/2023EGUGA..25.5520R/abstract

2.3/ Avoidance of contrail-forming regions

Persistent contrails only form in ice-supersaturated regions (ISSRs), characterized by high humidity and low ambient temperature. Outside these regions, any ice particles that cluster in the exhaust plume rapidly sublime as they mix into the surrounding atmosphere. By avoiding ISSRs, aviation could drastically reduce the warming effects from contrail formation.

Avoidance methods

Aircraft can avoid contrail-forming regions by cruising at altitudes with higher temperatures or lower specific humidity, making it a feasible solution across the entire fleet. There are challenges, though: Increasing cruise altitudes would require significant airframe redesigns to accommodate longer wings or adopting blended-wing body aircraft; meanwhile, at reduced altitudes, higher temperatures may prevent contrail formation, but aircraft may have to burn significantly more fuel or extend flight times.

Avoidance of ISSRs can also be achieved in a targeted way by local rerouting to avoid specific regions. Models used in several studies[7] suggest this approach can substantially decrease contrail length, with only limited increases in fuel burn. Reducing contrail length by approximately 50 %, for instance, would only require a 0.8 % increase in fuel burn; an 80 % reduction in contrail length would see a 2.3 % increase in fuel burn. These models are now being tested. Google, American Airlines, and Breakthrough Energy, for example, have conducted flight trials demonstrating an approximate 54 % reduction in contrail formation, with a 2 % increase in fuel burn across 35 pairs of flights.[8] The potential to reduce contrails varies significantly depending on the degree of flexibility in rerouting as well as local atmospheric variability. Vertical and horizontal deviations around ISSRs can reduce contrail formation by around 80 % for an approximate 2 % fuel burn increase. However, in purely horizontal rerouting, the reduction in contrail formation falls to approximately 20 %, for the same increase in fuel burn.[9] This makes it important to reroute flights both vertically and horizontally to maximize the overall impact of avoidance solutions. ▶ D

However, the precise fuel burn increase can be further limited by updating the trajectories only of those flights that are expected to enter ISSRs in the first place. Indeed, most flights don't enter ISSRs – only 14 % of flights are estimated to enter ISSRs – and only this subset would even need to be rerouted, if they can be precisely identified. As an illustration of this effect, this more fine-tuned approach was also estimated in the Google and American Airlines test, which found that fuel burn increase at the fleet level could be limited to 0.3 % to achieve the aforementioned 54 % reduction in contrails.

Contrail prediction

Currently, ISSR prediction is typically made using computational modeling of humidity, pressure, and temperature. These predictions are iteratively improved via observational validation from geostationary satellites, using detection of persistent contrails and observation of natural cirrus as a proxy for ISSRs. The results are then fed back into the numerous prediction models available. As they leverage different datasets, parameters, and assumptions, the models don't all fully overlap, but by combining them, there is potential to significantly increase the accuracy of the predictions.

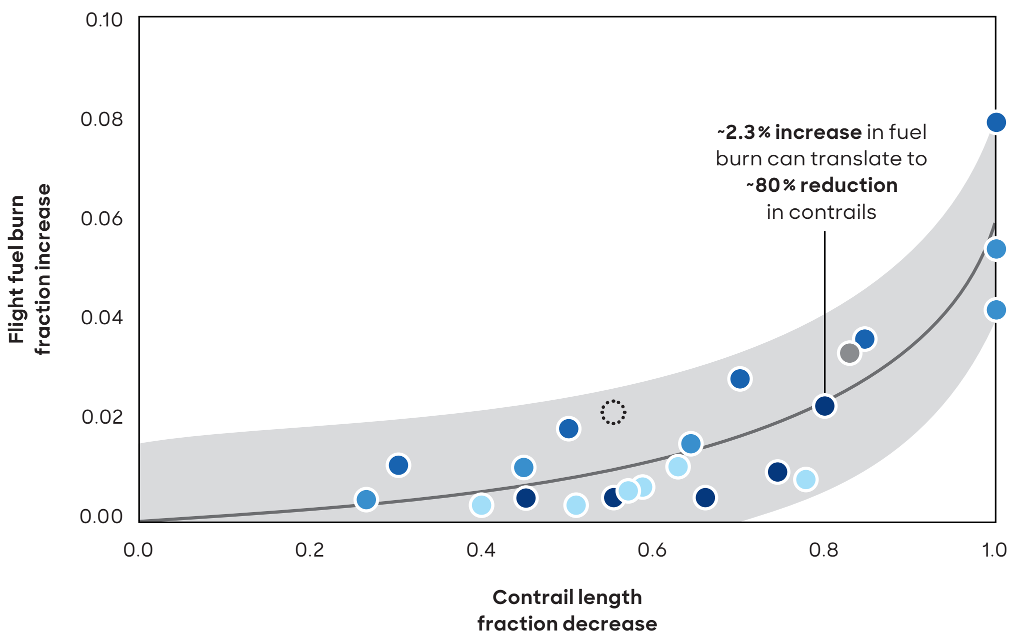
7 Dray, L., Schäfer, A.W., Grobler, C. et al., Cost and emissions pathways towards net-zero climate impacts in aviation, https://doi.org/10.1038/s41558-022-01485-4, which assesses 5 recent papers

8 https://blog.google/technology/ai/ai-airlines-contrails-climate-change/

https://news.aa.com/news/news-details/2023/American-Airlines-participates-in-first-of-its-kind-research-on-contrail-avoidance-CORP-OTH-08/default.aspx

9 Sridhar et al., Aircraft Trajectory Optimization and Contrails Avoidance in the Presence of Winds, https://doi.org/10.2514/1.53378

D Fuel burn cost of ISSR avoidance when deviation occurs[1]



1 Only applies to flights that require deviations; at fleet level, this is significantly lower

Source: Dray et al., Google, Roland Berger

As forecasting models evolve and increase in accuracy, strategic contrail management will become increasingly simple to integrate into an airline's holistic flight-planning activities. However, there will still be a need for tactical avoidance (descent/ascent) in response to direct or sensor observations of contrails to avoid further formation.

Air traffic controllers (ATCs) will see an increase in workload as a result of ISSR avoidance, as the number of requests for adjustments grows. However, there are already established procedures for adjusting routing or altitude to avoid areas of turbulence and other natural hazards, and similar methods could be applied here. Should ISSR avoidance become widespread, there are potential challenges with implementation in congested airspace areas. These will either increase fuel burn or reduce the impact on emissions reduction.

While there are implementation challenges, particularly around predicting ISSRs and increased ATC workloads, ISSR avoidance appears to be a highly promising short- to medium-term solution to the significant climate impact of contrails.

As such, we invited two providers of ISSR avoidance solutions, SATAVIA and FLIGHTKEYS, to present an overview of their solutions, as well as their ongoing work to validate and implement them.

3 Provider case studies

3.1/ SATAVIA: Optimizing flight plans for contrail prevention

SATAVIA is a UK-based startup delivering atmospheric intelligence to airlines to reduce the climate impact of flying by mitigating the warming effect of contrails. It does this by providing airlines with weather forecasts based on advanced numerical weather prediction (NWP) modeling, helping them to reroute aircraft that might otherwise fly through ISSRs, where persistent contrails are likely to form. The company has cooperated on operational contrail management research with several airlines as well as the UK Space Agency (UKSA) and European Space Agency (ESA). ▶ E

Once SATAVIA's platform has forecast the regions where persistent warming contrails are likely to form, it then calculates climate impact converted to CO_2e using a GWP100 climate metric. Applying per-flight calculations in this way, an entire airline schedule can be analyzed to target flights for navigational avoidance based on expected contrail climate impact. Information is then provided on regions where warming contrails will form, which flight dispatch teams use to optimize and refile flight plans. Final briefing packs can also be taken on-board the flight deck to support tactical deviations as required.

E Weather prediction modeling for reduced climate impact
SATAVIA's DECISIONX numerical weather prediction and climate impact models

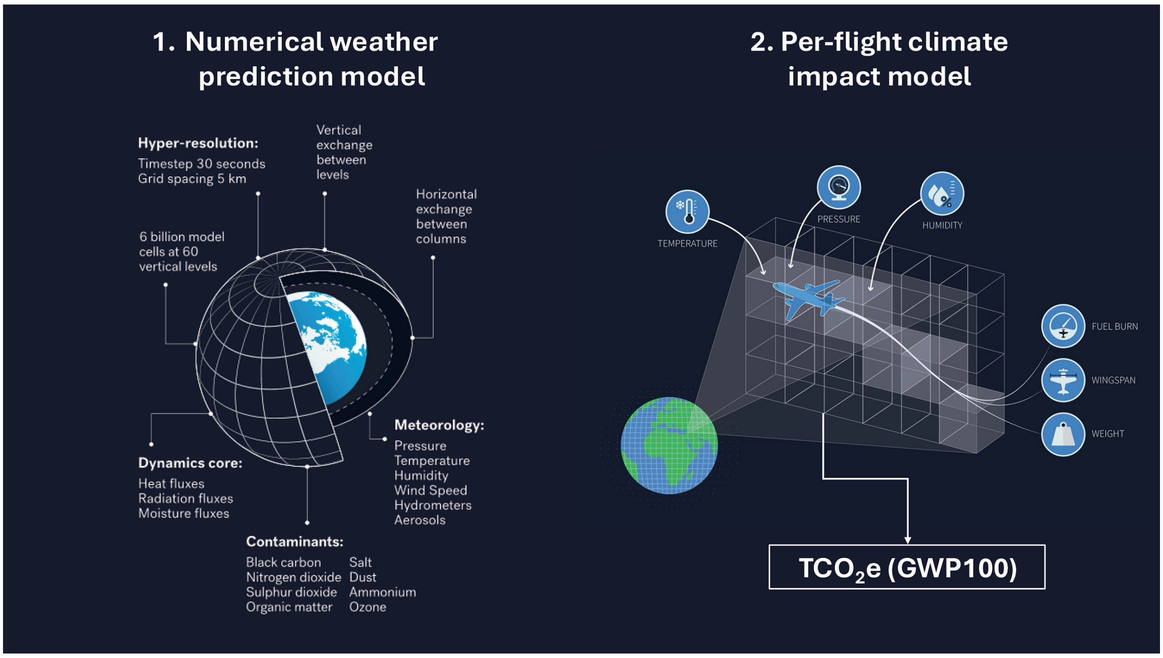


Photo: SATAVIA Ltd

The model is configured for the prediction of relative humidity and other key parameters at cruise altitudes, with enhanced vertical resolution alongside explicit physics-based cloud microphysics. These NWP enhancements are necessary, as off-the-shelf weather models show strong dry bias at cruise altitude, increasing the probability of false negative predictions of contrail-forming conditions and potentially allowing flight into seemingly dry atmosphere that may, in reality, be supersaturated.

After each modified flight, the climate impact of the trajectory that the aircraft flew is analyzed using ADS-B or GPS tracking data and compared to the original flight plan. The mitigated climate impact could then be converted into tradable units expected to be issued with Gold Standard, a major carbon program.[10] Future tradable units could be retired against net zero goals or traded on global markets, providing near-term incentives for airlines to undertake contrail management.

10 https://www.goldstandard.org/news/gold-standard-approves-aircraft-contrails-methodology-concept

Flight test results

Trials with the UK Space Agency and European Space Agency, as well as a proof-of-concept engagement with 11 airlines, saw SATAVIA undertake more than 60 real-world contrail management flights in 2023 and 2024. The results indicated several potential advantages of the technology:

- Significant CO_2e saving per optimized flight (approximately 40 tons average)
- Minimal average impact on flight time (-0.3 minutes average)
- Minimal fuel burn penalty (approximately 100 kg per modified flight)

Managing uncertainty with scientific rigor

These results highlight the potential for navigational contrail avoidance to generate significant climate benefits at very limited operational cost: average CO_2e savings are typically several orders of magnitude larger than associated fuel burn penalties. As contrail management is only necessary for a small minority of flights, associated operational costs are also limited in scale.

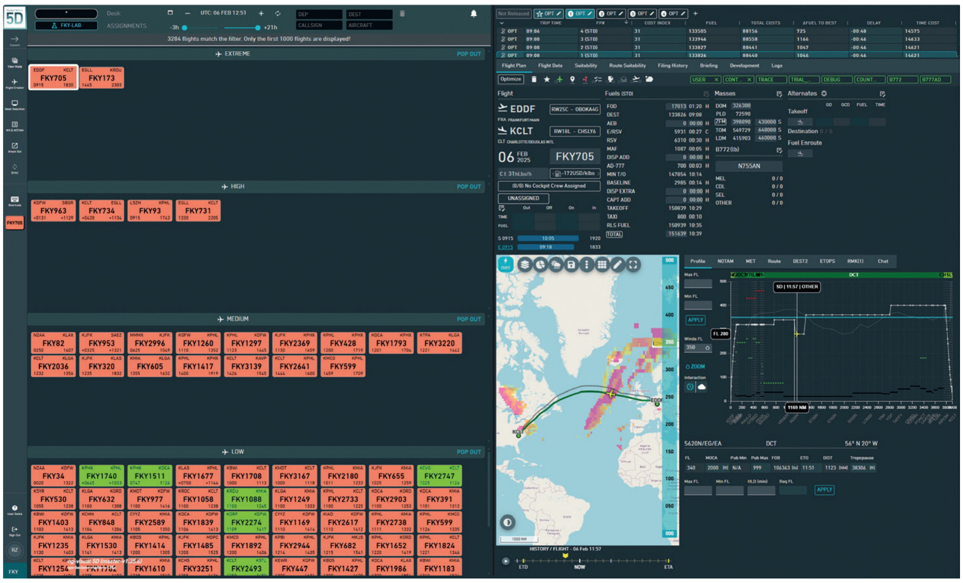
When applied to contrail management, the model correctly identifies ISSRs where persistent contrail formation is likely up to 50% of the time. When implemented using a linear interpolation approach, the NWP model allows for up to 90% certainty of placing aircraft into non-ISSR conditions following a prediction of ISSR.

This approach to contrail management via flight trajectory modification takes place within a wider, multi-step framework designed to reduce uncertainties and maximize climate benefit. These steps include utilizing forecasts generated on the day of flight plan optimization to ensure maximum accuracy; only modifying flights above a certain threshold of expected climate benefit; and only modifying flights where required navigational diversions don't involve an unacceptable degree of extra fuel burn

3.2/ FLIGHTKEYS: Optimizing environmental impact and cost-effectiveness

FLIGHTKEYS is a global flight-planning service provider for airline, cargo, and business aviation operators. The company has recently developed FLIGHTKEYS 5D, a flight-planning solution that allows pre-tactical contrail avoidance through vertical and horizontal route deviations around contrail formation regions. ▶ F This is achieved by adding contrail forecast data as an additional weather element, alongside wind and temperature, into a trajectory generator. The system's Loretta flight-deck assistant extends this strategy into the flight execution phase, providing pilots with decision support on tactical contrail avoidance. ▶ G

F FLIGHTKEYS 5D contrail avoidance example



G Loretta contrail detection example

Photos: FLIGHTKEYS

11 https://www.dlr.de/pa/en/desktopdefault.aspx/tabid-8859/15306_read-42749/

12 A. Martin Frias et al., 2024, Environ. Res.: Infrastruct. Sustain. 4 015013, DOI: 10.1088/2634-4505/ad310c

Key results from flight simulation tests

By the end of 2022, FLIGHTKEYS had successfully implemented the CoCiP model[11] into FLIGHTKEYS 5D and performed its first fully automated contrail avoidance simulation, using flight and aircraft performance data from one of its customers. The results indicated that from a total of 5,666 flights, 12% created warming contrails; these could be rerouted at an extra cost of 0.07%, with a 0.11% increase in fuel (Martin Frias, Zopp, & Soler, 2023).

A more comprehensive study[12] simulated more than 49,411 flights to assess contrail avoidance. The results again underscored the feasibility and substantial environmental potential of contrail avoidance, with minimal associated costs and fuel investment risks. ▶ H This study was complemented by another two-week analysis in January of 2024 using the same airline's flight data. ▶ I

Highlighting the potential of contrail avoidance

These two simulations demonstrated that contrail avoidance can be achieved with minimal extra fuel burn and financial cost. They also highlight that, despite the seasonal dependency of contrail formation, avoidance can be successfully implemented in both winter and summer.

H Results simulation, AAL summer season

Statistics	Units	Cost optimal [USD]	Contrail optimal	Delta [%]
Total number of flights	–	49,411	49,411	–
Flights forming net warming contrails	–	5,945 (12.0%)	4,159	-30.4%
Total flight time	Thousands of hours	120.63	120.61	-0.02%
Total fuel burn	Megatons of jet fuel (Mt)	0.3795	0.3800	+0.11%
Total cost	USD m	892.54	893.30	+0.07%
Total EF contrails	Exajoules of radiative forcing (PJ)	0.56	0.18	-68.9%
Total warming (CO_2e in 20 years' time)	Megatons of CO_2 ($MtCO_2$ GWP20)	1.78	1.38	-22.43%

I Results simulation, AAL winter season

Statistics	Units	Cost optimal [USD]	Contrail optimal	Delta [%]
Total number of flights	–	35,428	35,428	–
Flights forming net warming contrails	–	5,675 (16.0%)	4,403	-22.41%
Total flight time	Thousands of hours	89.02	89.03	+0.02%
Total fuel burn	Megatons of jet fuel (Mt)	0.2809	0.2812	+0.12%
Total cost	USD m	543.83	544.37	+0.10%
Total EF contrails	Exajoules of radiative forcing (PJ)	0.31	0.06	-80.34%
Total warming (CO_2e in 20 years' time)	Megatons of CO_2 ($MtCO_2$ GWP20)	1.21	0.95	-21.36%

FLIGHTKEYS is also exploring intervention methods that could reduce the number of required reroutings. The first approach focuses on significant contributors – a small subset of flights, ranging between 2% and 10%, which are responsible for 80% of contrails.[13] The second approach is a cost-based strategy, which selects flights based on their potential for the highest radiative forcing (RF) reduction per cost investment. The findings below underscore the feasibility of efficient contrail management while emphasizing strategies that optimize both environmental impact and cost-effectiveness.

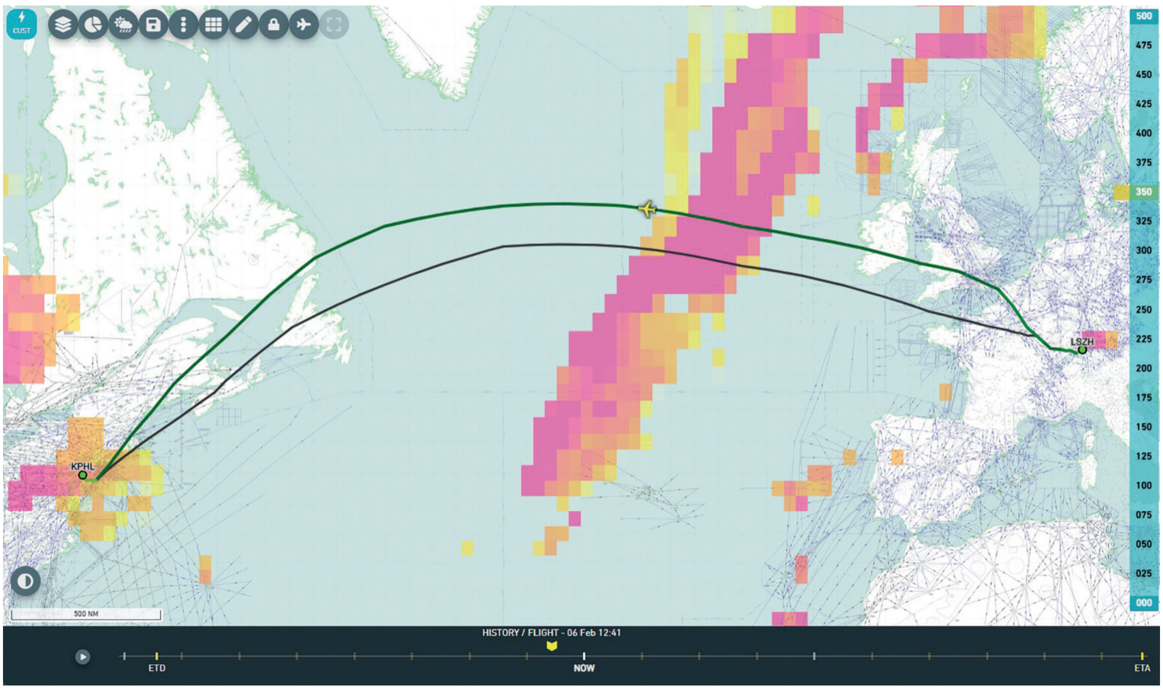
13 Roger Teoh, Ulrich Schumann, Arnab Majumdar, and Marc E. J. Stettler, Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption, Environmental Science & Technology, 2020, 54 (5), 2941–2950, DOI: 10.1021/acs.est.9b05608

Integrating cost-based avoidance

Despite the promising results of the latest simulations, successfully rerouting all flights will be challenging due to rigid restrictions. In the summer simulation, despite 5,945 flights generating warming contrails, only 5,840 could be rerouted. For the winter simulation, 604 flights could not be rerouted around the contrail-sensitive areas. In response, FLIGHTKEYS has modified its strategy, transitioning from hard restriction avoidance to a more adaptable approach: cost-based avoidance.

The core of this solution is a cost-based route optimizer that contains all necessary functions to optimize trajectories within any set of constraints and cost parameters. By adding contrail forecast data to wind and temperature values in a four-dimensional grid, the trajectory generator evaluates a cost function. It converts the contrail RF value into a cost value based on a user-definable cost per ton of CO_2e. This cost forms part of the total cost per flight segment, together with fuel, time, and overflight costs, and drives a cost optimization algorithm. Eventually, airlines will be able to consider contrail avoidance in their cost management and commercial strategies. ▶ J

J GRIB data visualization in FLIGHTKEYS 5D



Photos: FLIGHTKEYS

Tests are also underway to reduce the uncertainty of the numerical prediction models used to forecast ISSR regions. These are exploring the implementation and operational feasibility of other contrail prediction models, from contrail detection through satellite imagery to probabilistic climate models, as well as performing live simulation trials.

In discussing the efficacy of contrail avoidance strategies, it is pertinent to introduce the concept of the "hit rate" – the success rate at which strategies accurately avoid the formation of contrails. Even with an incomplete success in contrail avoidance due to uncertainties in atmospheric conditions and modeling errors, the minimal increases in cost and fuel consumption do not significantly alter the cost-benefit analysis. The decision to reroute is evaluated under probabilities and risks, affirming that the potential benefits of reduced environmental impact remain considerably high.

For example, based on the findings of Martin Frias et al.,[14] even assuming a very conservative hit rate of 0.5 %, there remains a slight reduction in the overall warming effect. This strongly supports the conclusion that the risk of inadvertently increasing net warming by prematurely implementing contrail avoidance strategies is extremely low. The achieved reductions in warming range from negligible at a 0.5 % hit rate to significant (22.0 %) at 100 % efficiency. ▶ K

14 A. Martin Frias et al., 2024, Environ. Res.: Infrastruct. Sustain. 4, 015013, DOI: 10.1088/2634-4505/ad310c

K Warming reduction with different hit rate assumed values

		Avoidance hit rate				
CO_2/CO_2e (Mt CO_2e GWP20)	Cost opt.	0.5 %	10 %	50 %	100 %
CO_2 fuel	2.089	2.089	2.089	2.089	2.089
Contrail warming	0.906	0.903	0.840	0.576	0.245
Total warming	2.9920	2.9917	2.9289	2.2645	2.3340
Achieved reduction	0.0000	0.0003	0.0631	0.3275	0.6580
	0.0 %	0.01 %	2.11 %	10.9 %	22.0 %

4

The potential cost of navigational avoidance

While there are still a range of substantial uncertainties surrounding contrail management, it is important to understand the potential commercial implications, especially the likely cost of implementation. To that end, we quickly cover the likely cost implications of contrail management by navigational avoidance, which we have further detailed in Chapter 8 of Understanding Contrail Management (published by RMI).[15]

There are two main areas of investment needed to gather the necessary information to avoid contrails: retrofitting aircraft with sensors to continuously detect ISSRs (e.g., humidity sensors); and building the observation infrastructure (satellite, in-flight, and/or ground based) to continuously monitor the atmosphere for ISSRs and track the lifecycles of formed contrails.

These are required to gather the information needed to develop flight plans that mitigate contrails, as well as to help further data gathering to continuously improve contrail science. Conservative estimates (based on IATA estimates of sensor shipset cost,[16] and a new satellite constellation and supporting ground-based infrastructure) would require USD 5-8 billion of investment every 10 years, amortized to USD 500-800 million per year, which would equal less than USD 1 per ton of CO_2e reduction.

Additional operational costs would primarily be driven by additional fuel burn, as discussed in Chapter 2.3. Based on a range of impact estimates, given a ~2.3% fuel burn penalty on deviated flights ▶ D, it appears that the operational costs will be between USD 1-5 per ton CO_2e if all warming contrails are mitigated, with the potential to reduce this further with a more targeted approach. While other operational costs may adjust – such as additional personnel or software to enable weather modeling and flight scheduling, additional ATC costs, variations to flight durations, and overflight charges – these appear relatively limited in scale compared to the fuel costs.

15 Joey Cathcart et. al., Understanding Contrail Management: Opportunities, Challenges, and Insights, RMI, 2024, https://rmi.org/insight/understanding-contrail-management-opportunities-challenges-and-insights/

16 Aviation contrails and their climate effect, IATA, April 2024, https://www.iata.org/en/pressroom/2024-releases/2024-04-30-01/

> **"Even with conservative assumptions on the OpEx and CapEx required for contrail management, the total cost seems limited at USD 2-6/tCO_2e."**
>
> **Nikhil Sachdeva, Principal**

5 Conclusion: Realizing the potential of contrail avoidance

Current understanding suggests that contrails represent a significant portion of aviation's climate impact. Many uncertainties remain – and will continue to do so – regarding humidity and temperature data, aircraft performance, atmospheric interactions, modeling, and cloud properties, with knock-on effects on uncertainties surrounding the effectiveness of contrail management solutions. Nevertheless, the case studies presented here suggest that action can still be taken to create a net climate benefit. Indeed, similar uncertainties are already considered and operationalized in turbulence avoidance and the analogous avoidance of turbulent regions.

In parallel to aviation's critical ongoing decarbonization efforts, the ecosystem should thus also explore how to reduce the climate impact of contrails. In the near term, continuation of trials and introduction of schemes like the European Union's Monitoring, Reporting and Verification regulation to accurately measure and track contrails and their climate impact will be vital. In the medium term, navigational avoidance solutions appear to have significant potential to reduce aviation's climate impact at a limited cost.

To unlock the full potential of contrail management, the next steps are clear: enhance prediction models with additional weather and aircraft performance data, assess operational impacts – particularly for air traffic management– and conduct large-scale trials. Then, if the trials succeed and it is proven to be viable at scale, contrail mitigation can be rolled out globally.

AUTHORS

Robert Thomson
Partner
robert.thomson@rolandberger.com

Nikhil Sachdeva
Principal
nikhil.sachdeva@rolandberger.com

Miguel Lopez
Project Manager
miguel.lopez@rolandberger.com

Christopher Stern
Project Manager
christopher.stern@rolandberger.com

Yimian Tang
Consultant
yimian.tang@rolandberger.com

CONTACTS

Adam Durant
CEO, SATAVIA
adam.durant@satavia.com

Alejandra Martin Frias
Head of Contrail Research & Sustainability, FLIGHTKEYS
alejandra@flightkeys.com

Conor Farrington
Chief of Staff, SATAVIA
conor.farrington@satavia.com

Raimund Zopp
Director Innovation & Shareholder, FLIGHTKEYS
raimund@flightkeys.com

With thanks to Adam Durant and Conor Farrington (SATAVIA), and Raimund Zopp and Alejandra Martin Frias (FLIGHTKEYS) for their case studies.

05.2025

ROLANDBERGER.COM

ROLAND BERGER is one of the world's leading strategy consultancies with a wide-ranging service portfolio for all relevant industries and business functions. Founded in 1967, Roland Berger is headquartered in Munich. Renowned for its expertise in transformation, innovation across all industries and performance improvement, the consultancy has set itself the goal of embedding sustainability in all its projects. Roland Berger generated revenues of around 1 billion euros in 2024.

Publisher

Roland Berger GmbH
Sederanger 1
80538 Munich
Germany
+49 89 9230-0

24_2072_REP