BRIEFING - NOVEMBER 2024

Contrail avoidance: aviation's climate opportunity of the decade

A smart solution at low cost

Summary

Contrails, short for condensation trails, are created by aircraft flying through cold and humid areas of the atmosphere. Their warming impact for the climate is estimated to be as bad as that of aviation's CO_2 emissions. However, it is a very concentrated problem - less than 3% of global flights generated 80% of contrail warming in 2019.

Contrail avoidance is a key strategy for contrail mitigation. It consists of small adjustments to flight paths, notably minor climbs or descents, to avoid those cold and humid atmospheric areas where contrails form. Simulations and real life tests have proven that this solution can reduce contrail formation and warming, with limited extra fuel burn.

In this briefing, we analyse the **climate impact and costs of contrail avoidance**. We have made a series of conservative assumptions in our analysis to account for the uncertainties in the exact extent of contrail warming and the potential of mitigating solutions.

We have found that **contrail avoidance strategies targeting only the most warming flights are a no-regret solution**. In a conservative scenario, climate benefits of reducing contrails could be at least 15 times larger than the impact of the CO_2 emissions from extra fuel burn. The contrail benefit over the additional CO_2 goes up to 40 times or larger using values from real life tests. This result proves that the risk of **doing more climate harm than good is nearly non-existent** and can be viewed as a positive return on investment for the climate.

Our analysis concludes that **contrail avoidance is remarkably cost effective**. We have analysed a possible future scenario where half of contrail warming is mitigated by 2040. Using contrail avoidance to abate 1 tonne of CO_2 equivalent could be one third the cost of using solar and wind power generation, and less than 10% the cost of using DACCS.

Translating costs to specific flights, the extra cost of contrail avoidance would be less than 3.90€ per ticket for a Paris - New York flight, or 1.20€ for a Barcelona - Berlin, proving that this solution could have major climate benefits at low cost.

Given the enormous potential of contrail avoidance as a quick, effective climate solution, and acknowledging the barriers that still exist, T&E recommends developing a comprehensive regulatory framework for non-CO_2 emissions that includes:

1. Enhancing data collection and bridging remaining data gaps by monitoring of non-CO_2 emissions of all flights departing the EU under the EU ETS, deploying humidity sensors and satellites
2. Mandating contrail-free skies through adapting European Air Traffic Management for contrail avoidance
3. Eliminating remaining warming and pollution via updated jet fuel standards

1. Contrails warm the planet at least as much as aviation's CO_2

Beyond carbon dioxide, aircraft engines also emit gases such as nitrogen oxides (NOx), sulphur dioxide (SO_2) and water vapour (H_2O), and particulate matter. These emissions impact the chemical and physical properties of the upper atmosphere, affecting the Earth's climate.

Contrails, short for condensation trails, are the largest component of non-CO_2 effects. They form when the water vapour, both emitted by aircraft engines and present in the atmosphere, condenses around particles, in most cases released from the engine exhaust. The majority of contrails dissolve in seconds or minutes. However, contrails which form in cold and humid areas - known as ice supersaturated regions, or ISSRs - may persist in the atmosphere for hours, developing into contrail cirrus. Those persistent contrails have the largest climate impact.

Contrails and contrail cirrus have a cooling effect when they reflect incoming radiation from the sun. At the same time, they also warm the planet when they reflect back outgoing radiation from Earth to space. The net effect is warming.

A landmark study estimated the effective radiative forcing (ERF) - a measure of warming impact - of contrails in the year 2018 to be larger than the ERF from the CO_2 present in the atmosphere from aviation emissions since 1940. Other studies have provided different estimates, but have confirmed that the climate impact of contrails is of similar magnitude to the impact of aviation's CO_2 emissions.

1.1 Mitigating contrails has immediate climate benefits

Contrails are very short-lived, with an impact that only lasts for hours. CO_2, on the other hand, stays in the atmosphere for centuries. Despite their different life spans, the climate impact of both over decades is comparable, due to the outsized impact of contrails during their short life.

The warming effect of contrails mostly disappears when they dissipate. But contrails keep warming the planet because new flights constantly create new contrails. Avoiding contrail formation at scale would lead to a cooling of the atmosphere, as shown by a study of aviation impact on temperatures during the COVID-19 pandemic. This quick climate benefit can play an important role in limiting global warming to 1.5ºC.

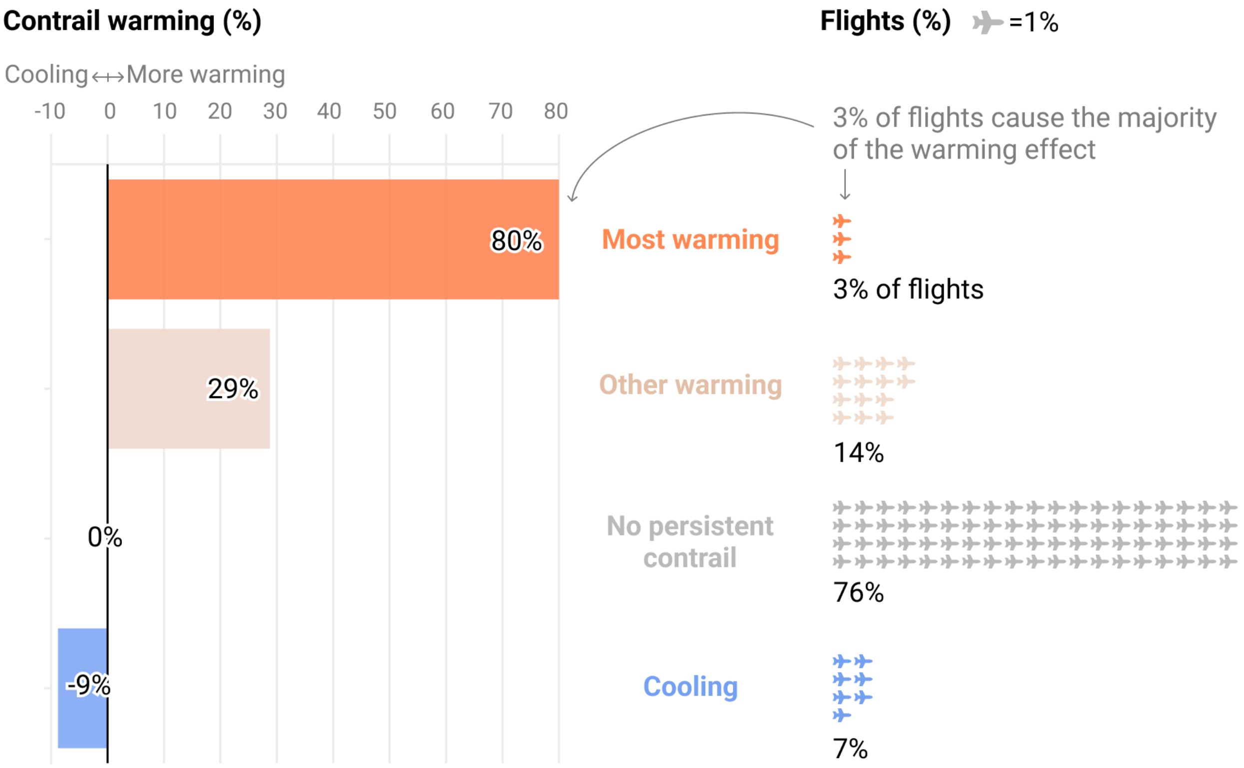
1.2 Contrails are a very concentrated problem

Contrails are a global climate issue, but only form under certain atmospheric conditions. As a result, their impact is unevenly distributed across the global fleet.

A 2024 study by Teoh et al. found that **less than a quarter of flights generated persistent contrails.** Out of those, 7% of flights generated net cooling contrails, while 17% formed net warming contrails. The other 76% of flights did not form any persistent contrails, meaning there was no cooling nor warming effect.

More importantly, less than 3% of worldwide flights generated 80% of contrail ERF in 2019. In Europe, this figure is 5%. Contrail warming is a very localised problem, and effective mitigation actions targeting only the most warming contrails would only impact a small minority of flights.

3% of flights cause 80% of global contrail warming



Source: Teoh et al. (2024). Note: Contrail warming has different distributions depending on the region. In Europe, 5% of flights cause 80% of contrail warming in the region.

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The climate impact of contrails has distinct geographical patterns as well, with flights at higher latitudes more likely to form warming contrails. As a result, North America, Europe and the North Atlantic region accounted for more than half of contrail warming effects in 2019.

The time of day also influences the climate effects of contrails. Those formed by evening and night flights have the largest warming contribution, while early morning flights are more likely to form cooling contrails. As for season, the most warming contrails tend to occur in winter.

2. Promising solutions to fight contrails are being currently tested

The science behind contrail warming has progressed enormously over the past years and decades. On top of better understanding their climate impact, research and tests are proving the existence of really promising mitigation solutions which can be deployed in the near future.

2.1 Contrail avoidance: minor deviations to avoid contrail formation

Ice supersaturated regions (ISSRs), the cold and humid areas of the atmosphere where persistent contrails are more likely to form, can extend for several hundreds of kilometres, but are usually less than 1 km thick.

A key strategy to mitigate contrail formation is navigational contrail avoidance. It consists of making small adjustments to flight trajectories, notably minor climbs or descents, to avoid ISSRs. The principle is similar to avoiding storms or turbulent areas of the atmosphere.

Forecasting the location of ISSRs is essential for contrail avoidance. If a reliable forecast is available sufficiently in advance of the flight departure, operators can create a flight plan to avoid ISSRs. This approach is known as pre-tactical avoidance. On the other hand, if the ISSR forecast is not available sufficiently in advance, contrail avoidance manoeuvers must be decided during the flight, known as tactical avoidance. Depending on who initiates the deviation, contrail avoidance may be led by the aircraft operator or the air traffic controller.

Reliable ISSRs predictions by weather services and collaborative decision making processes are pivotal aspects of successful contrail avoidance. Both are subject to ongoing research that must continue over the next years to reduce uncertainties and scale up this climate solution.

2.2 Contrail avoidance in practice

The feasibility and benefits of contrail avoidance are the subject of simulations and flight tests, which have proven that this solution has the potential to significantly reduce contrail formation.

Flight tests in 2023 by American Airlines and Google managed to mitigate 54% of contrail formation with small deviations that caused an estimated 2% extra fuel burn on deviated flights.

Various research organisations have performed flight simulations to evaluate the potential of contrail avoidance. A 2020 study by Teoh et al. estimated that 60% of contrail ERF over Japan could be mitigated at an extra fuel burn of 0.01%.

A 2024 study by Martin Frías et al. found that contrail warming could be reduced by 72% with a fleet-wide extra fuel burn of 0.11%. The study also analysed more targeted strategies, aimed at mitigating only the most warming contrails, or performing low cost manoeuvers. In both cases, 66% of contrail warming was reduced with extra fuel burn of 0.05% and 0.02%, respectively, proving the efficiency of these strategies.

2.3 Extra fuel burn from contrail avoidance is limited

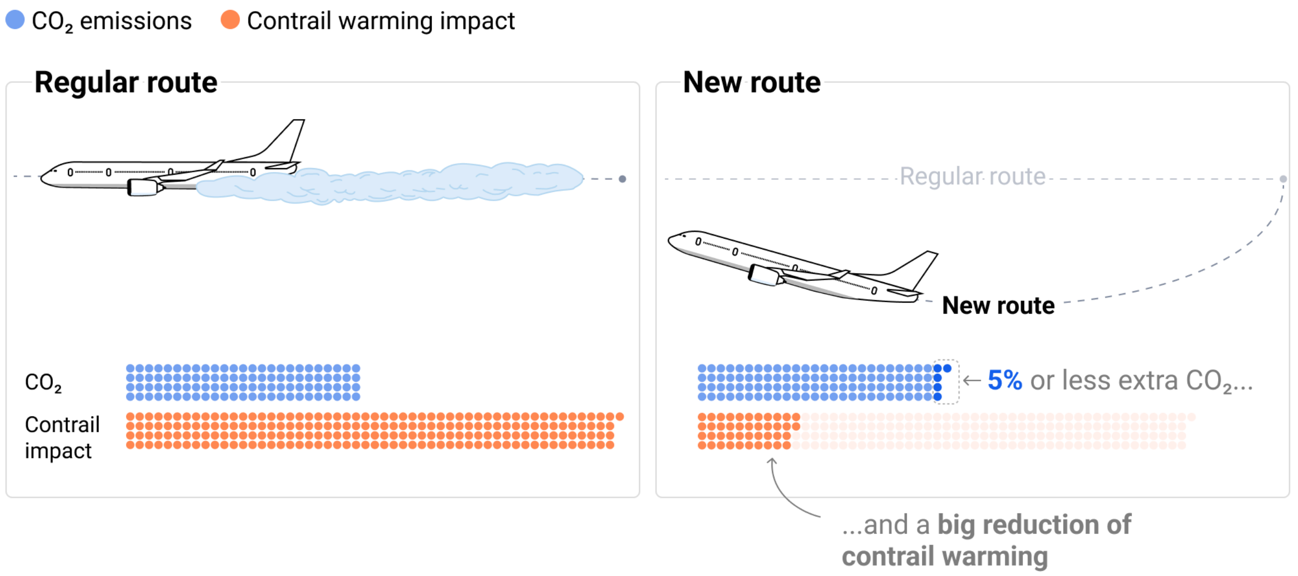
Aircraft usually fly at altitudes that maximise efficiency. Flying above or below this altitude to perform contrail avoidance manoeuvres can increase fuel burn, but fuel burn impact would be limited, especially if smart contrail avoidance strategies are applied.

Contrail avoidance would only impact a small number of flights generating warming contrails. A targeted approach, such as tackling the small percentage of flights generating 80% of contrail warming, would minimise the number of adjusted flights while maximising climate benefits.

Those flights that need to be adjusted would not be deviated for their entire trajectory, but only some sections. The extra fuel burn for those deviated sections is typically less than 5% of the fuel burnt on a flight.

This results in an estimated fleet-wide extra fuel burn between 0.01% and 0.3%, as discussed in section 2.2. The extra fuel burn at scale could be larger than those estimations, due to airspace constraints. An efficient air traffic management is an essential enabler for contrail avoidance, and large scale trials are key to understanding the challenges to scaling it up.

Net climate benefits of rerouting the most warming flights can be huge



Source: Teoh et al. (2024), Frías et al. (2024), T&E. Note: Simulation of the net climate impact of contrail avoidance for a flight within the 5% of European flights that generate 80% of contrail warming. Assumptions: GWP100 used to compare the climate impact of CO2 and contrails. Contrail warming reduced by 80%. The 5% extra fuel burn is a conservative estimate - extra fuel burn in flight tests and simulations is 2% or lower.

2.3.1 Fuel tankering creates an extra fuel burn similar to contrail avoidance

Flight plans are optimised to minimise costs, not fuel or climate impact. Although fuel is a big cost driver, airlines often perform practices to reduce costs, such as minimising airspace charges, which can result in routes that burn extra fuel and release additional CO_2 emissions.

Fuel tankering is also a commonly used practice. It consists of carrying extra fuel on a flight to minimise refuelling at the destination airport, whenever fuel is significantly more expensive than at the origin airport. This minimises costs, but lowers flight efficiency, due to heavier planes.

Eurocontrol estimated that 900 kt of CO_2 emissions in Europe were caused by fuel tankering in the year 2018. This is an increase of European aviation emissions of approximately 0.5%, a similar figure to the estimated extra fuel burn of contrail avoidance at scale.

Extra CO_2 emissions are often cited as a blocking element for contrail avoidance. However, examples such as tankering show that the industry engages in practices that create extra fuel burn to minimise costs. The potential climate benefits outlined in the next section showcase how limited extra fuel burn still makes contrail avoidance a no-regret solution.

2.4 Targeted avoidance is a no-regret solution with net climate benefits

We have analysed the net climate impact of a contrail avoidance strategy targeting the 5% of European flights that generate 80% of contrail warming. We have compared the climate penalty from extra CO_2 emissions with the benefits from contrail reduction for a range of scenarios.

Our analysis assumes that not all manoeuvres will mitigate contrail formation. We define success rate as the ratio of flight adjustments that reduce contrail formation. Unsuccessful flight adjustments are assumed to not reduce or increase contrail warming.

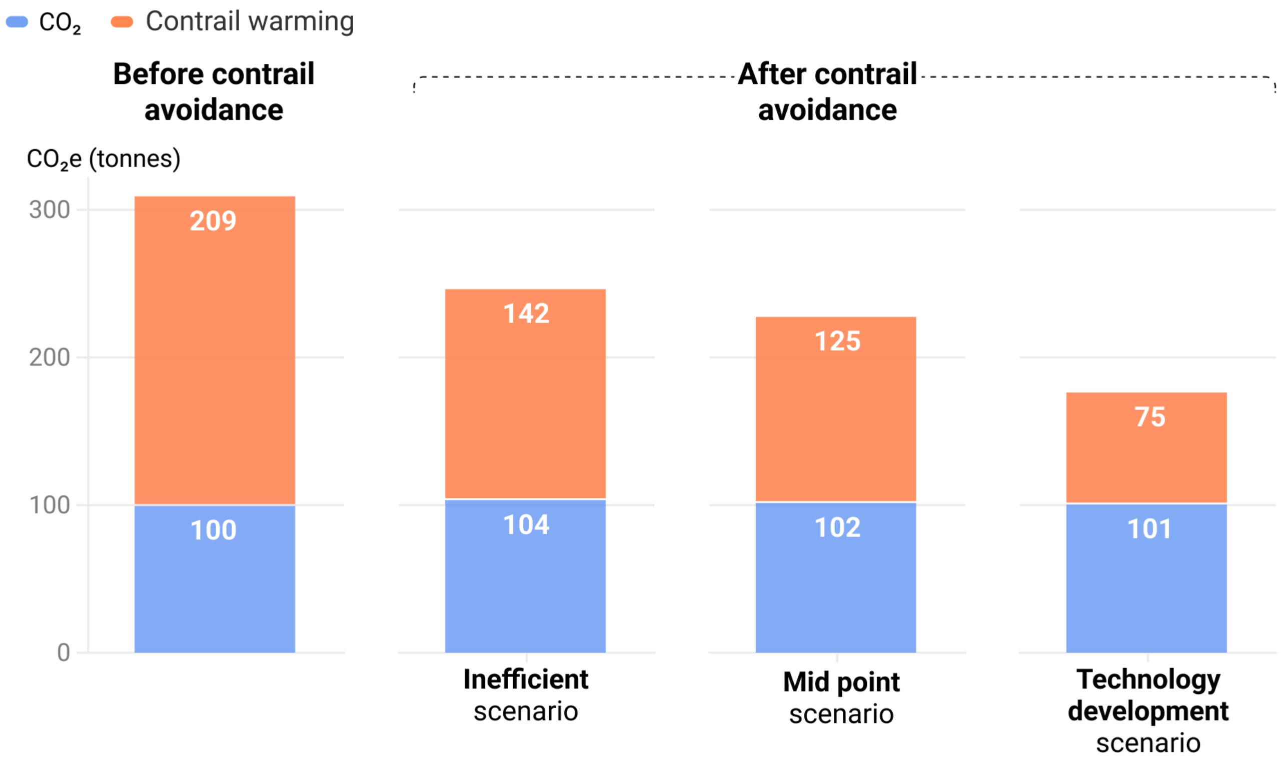
Although technology development will increase success rates, the future values are still unknown. To account for this uncertainty we have analysed success rates between 10% and 100%. Likewise, we have assessed extra CO_2 emission rates per flight between 0.5% and 5%.

To compare the impact of contrails and CO_2, we have selected GWP100 as a climate metric.

In an inefficient scenario, the climate benefits from reduced contrail warming are more than **15 times larger than the climate penalty from the extra fuel burn**. This case assumes 4% extra CO_2 emissions, above the upper bound of tests and simulations, and a 40% success rate.

The climate benefits would be 40 times larger than the climate penalty for deviations where 2% more CO_2 is emitted, and with a 50% success rate. These values are similar to what has been already achieved in American Airlines and Google trials.

Rerouting the most warming flights is a no-regret solution



Source: Transport & Environment (2024), based on data by Teoh et al. (2024). Assume 80% contrail reduction with a 5% fuel burn penalty. Baseline flight emits 100 tonnes of CO2, and is within 5% of European flights generating 80% of contrail warming. Scenario assumptions: Inefficient: 40% successful manoeuvres, 4% extra fuel burn, Mid point: 50% successful manoeuvres, 2% extra fuel burn, Technology development: 80% successful manoeuvres, 1% extra fuel burn.

Overall, all the contrail avoidance scenarios in our analysis have net climate benefits, ranging from 2.35 to more than 300 times the climate penalty from the extra CO_2.

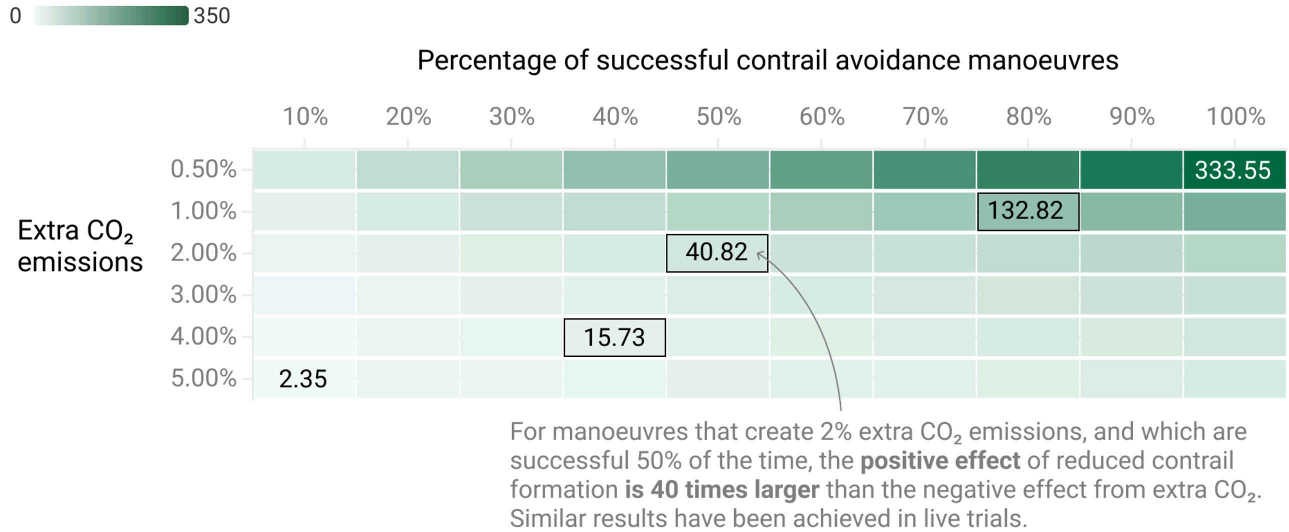
Similarly, scientific research has also found significant benefits from targeted contrail avoidance. Simulations from Martín Frías et al. estimate climate benefits well over 100 times larger than the extra CO_2 emissions. Cornec et al. (2024) have introduced the concept of contrail severity index, highlighting the large net benefits of targeting highly severe contrails.

These results show that the risk of causing more climate harm than good is almost non-existent when targeting the flights that generate the most warming contrails.

This risk can be further reduced by applying safeguards, such as only performing deviations which are expected to generate a climate benefit 100 times larger than the climate penalty from extra fuel burn. In our analysis of the 5% of European flights generating 80% of contrail warming, any deviation generating less than 1.5% extra fuel burn would comply with this safeguard.

Avoiding most warming contrails is a no regrets solution

Rerouting has net climate benefits even in a conservative scenario



Source: T&E, Google (2023), Teoh et al. (2024), Frías et al. (2024). Note: values shown in the cells are the ratio between the net climate benefits from contrail avoidance manoeuvres over the climate impact of extra CO2 emissions. Values above 0 indicate net climate benefits. GWP100 used as climate metric.

2.4.1 Targeted contrail avoidance is beneficial for climate, regardless of metric choice

The use of a climate metric - GWP, GTP, ATR - and time horizon - 20, 50, 100 years - translates the impact of contrails into tonnes of CO_2 equivalent, enabling an easier comparison with CO_2.

Despite recent progress, the choice of climate metric and time horizon for contrails is still subject to scientific and political debate. This is often cited as a source of uncertainty to understand the benefits of contrail avoidance.

However, a 2024 study by Borella et al. found that avoiding the most warming contrails has net climate benefits, and this conclusion is mostly independent of the choice of metric. The study concludes that the lack of consensus on the most suitable CO_2 equivalence metric is not an obstacle to implementing contrail avoidance policies.

3. Contrail avoidance is cheaper than many climate solutions

We have analysed a future scenario where half of contrail warming is mitigated by 2040.

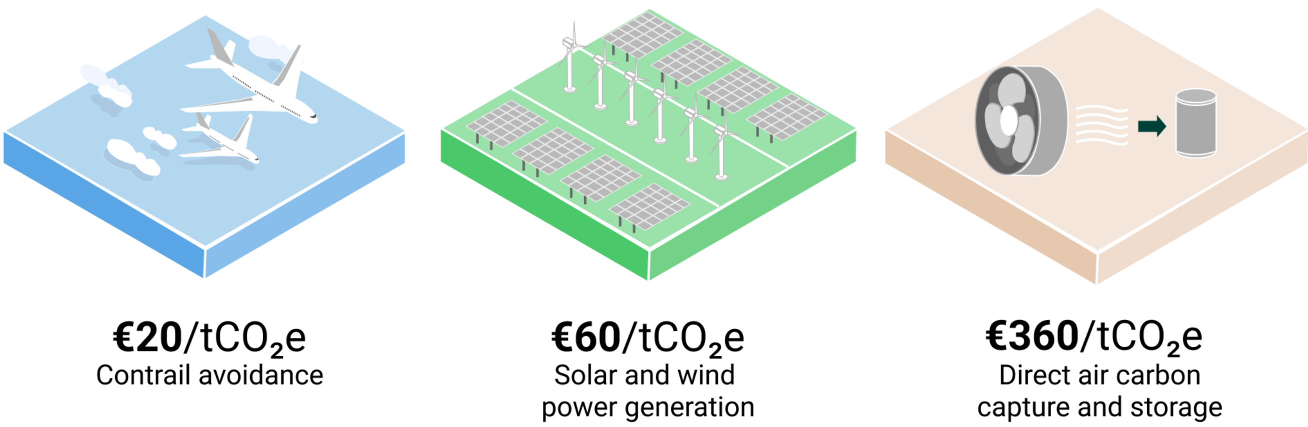
We have found that contrail avoidance costs by 2040 could be less than 20€/tCO_2e - € per tonne of CO_2 equivalent abated, using the GWP100 metric. Compared to other sources, this is an upper bound estimation. Roland Berger has placed 2040 abatement costs between 2 and 6 €/tCO_2e, while Google estimates that they can be in the range of 5-25 €/tCO_2e already today.

The cost of contrail avoidance is driven by operational costs, notably fuel burn, and capital expenditure in infrastructure or equipment, such as satellites and ground cameras for observations, and humidity sensors fitted on aircraft.

Assessing costs in €/tCO_2e abated allows us to compare contrail avoidance with other climate solutions per unit of climate benefit. Solar and wind power generation have estimated costs of 60 €/tCO_2e abated. Direct air carbon capture and storage (DACCS) is estimated to cost 360 €/tCO_2 abated once the technology matures, with current prices in a range of 600-1000 €/tCO_2.

Contrail avoidance is one of the cheapest climate solutions out there

More than 15 times cheaper than direct air carbon capture and storage



Source: Roland Berger (2024), Sievert et al. (2024), Thunder Said Energy (2023), T&E. Note: Indicative costs per tonne of CO_2 equivalent abated for different technologies. We have assumed parity between euro (€) and US dollar ($) for these calculations

3.1 Increase in flight ticket prices would be 1% or lower

We have used our cost model to evaluate the cost increase on 12 representative intra-European and transatlantic routes in the year 2040.

The estimated average cost increase for an intra-European flight would be less than €1.60 per passenger. In the specific case of a Barcelona - Berlin flight, the increase would be €1.20.

For transatlantic flights, the cost increase would be smaller than €4.30 per passenger, with a Paris - New York route seeing an increase of €3.90.

These cost increases are averaged out over all passengers. Economy class passengers will likely see a smaller increase in flights with premium classes.

Contrail avoidance has the potential to make a significant dent to aviation's climate footprint with an extremely low economic impact on industry and passengers.

Contrail avoidance is cheaper than a coffee at the airport

Average cost of contrail avoidance

Source: Roland Berger (2024), Teoh et al. (2024), T&E. Note: indicative costs per passenger for average flights for the routes Paris - New York and Barcelona - Berlin. Extra cost of contrail avoidance flights is averaged out on all flights, including those that are not deviated. Contrail impact data for each route from Teoh et al. (2024)

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4. Decisive action must be taken to seize this climate opportunity

Contrails have a significant warming impact on climate, similar to that of aviation's CO_2 emissions. Some aspects of contrail science are still subject to research, but our level of knowledge is sufficient to highlight how contrail avoidance can be a no regrets, cost effective mitigation for this climate problem.

The uncertainty of trade-offs between contrail warming reduction and potential CO_2 increase from contrail avoidance manoeuvres is often cited as a barrier to action. We have analysed a contrail avoidance strategy targeting the flights that create the most warming contrails for a wide range of scenarios. We have found that, even in the least favourable cases, the benefits largely outweigh the negative effects, resulting in net climate benefits. This conclusion remains true regardless of the climate metric used to compare CO_2 and contrail warming.

These results, backed by scientific research, show that, for smart contrail avoidance strategies that target the small percentage of flights creating most of the contrail warming, the risk of doing more climate harm than good is nearly non-existent.

Contrail avoidance is extremely cost effective, with estimated ticket price increases of less than 1%. This results in an extra €4.30 for transatlantic flights, and €1.60 for intra European flights.

Although proven on a flight by flight level and at simulations, challenges for its large scale deployment remain. On the one hand, the accuracy of predictions needs to increase. On the other, the airspace needs to be improved to accommodate contrail avoidance. A thriving ecosystem of researchers, innovators and industry players is making significant progress on those two aspects. Continuous support to this ecosystem and to other involved actors will be paramount to successfully deploying contrail avoidance at scale.

Finally, and more importantly, the lack of incentives for the aviation industry to reduce contrails has been a key barrier for action. An adequate policy framework will be essential to solve this, and to get the most of this climate opportunity.

4.1 Policy recommendations

Based on the findings of this briefing, Transport & Environment recommends the combination of the below policies to enable the mitigation of aviation contrail-warming. Incorporating these measures into the EU's broader emission reduction policy framework is also vital for addressing the sector's full environmental impact and achieving our climate goals.

The following list focuses on EU internal policy action, but we want to emphasise the importance of international collaboration in this field, for example the need for regional cooperation between EU, the US, UK and Canada on large scale contrail avoidance trials over the North-Atlantic.

1. Developing a regulatory framework for non-CO_2 emissions

Addressing aviation non-CO_2 emissions starts by including non-CO_2 emissions in climate objectives, this involves the EU's 2040 climate target as well as national energy and climate plans (NECPs). Without including it in the remit of policy makers' climate responsibility, the problem will have no chance of being mitigated.

Integrating non-CO_2 emissions into existing EU policies - such as the EU ETS, Single European Sky, and Refuel Aviation - would then create a coherent regulatory framework, enhancing air traffic management and fuel standards. This comprehensive approach would also help drive innovation in aviation technology, improve public health by reducing pollutants around airports, and empower consumers to make informed choices through emissions labelling. By tackling non-CO_2 emissions, the EU can advance its leadership in sustainable aviation and strengthen the competitiveness of its industry in a global shift towards net zero aviation.

1.1 Enhancing data collection and bridging remaining data gaps

1.1.1 Full scope monitoring of non-CO_2 emissions under the EU ETS

The EU was a global first-mover in requiring aviation non-CO_2 emission data collection through a Monitoring, Reporting and Verification (MRV) scheme from 1 January 2025 onwards. Although the geographical scope of the MRV was regretfully reduced to EU-only for 2025 and 2026, it remains a key tool for better understanding and measuring aviation's non-CO_2 emissions.

The collected data will play an important role in shaping future EU regulations, as early as 2027, and can help improve scientific models, enhance forecasting, and optimize flight planning to reduce contrails.Therefore, **the automatic expansion of the scheme to full scope,** as intended in the EU ETS is pivotal. We recommend that other countries, like the UK, US and Canada follow this path and develop their own non-CO_2 monitoring scheme for aviation.

1.1.2 Bridging the data gap through technology developments

One of the key remaining data gaps for contrail avoidance is the accurate weather forecasting and related to that, the identification of ice-supersaturated regions (ISSRs). Thus, the development and use of technologies such as **humidity sensors** on aircraft **or satellites** for observation should be incentivised. These would enable real-time monitoring of atmospheric conditions and improvement of forecast models, helping airlines and air traffic controllers and avoid areas prone to contrail formation.

As contrail avoidance science advances and humidity sensors become more accurate, **installing these sensors on new aircraft and retrofitting existing fleets may become gradually mandated under the EU ETS.**

1.1.3 Encouraging early adopters with financial incentives

To accelerate the shift toward contrail avoidance technology, the EU should prioritise funding through the Innovation Fund targeting early adopters and satellite-based monitoring systems. Prioritising **research, development, and demonstration (RD&D)** projects on contrail avoidance—such as large-scale trials that leverage satellite technology—will enhance the sector's ability to measure, predict, and avoid contrail formation effectively.

Additionally, the EU should **incentivize airlines and manufacturers that integrate these technologies early on**, providing temporary financial support for initiatives like humidity sensor installations and retrofits. Prioritising funding for early adopters within the Innovation Fund will accelerate the adoption of contrail avoidance measures, ultimately paving the way for their establishment as standard practices in the aviation industry.

1.1.4 Increasing transparency through the Flight Emission Label scheme

Transparency and consumer choice contribute greatly to promoting sustainable aviation practices, but only if passengers are provided with the necessary information to make informed decisions. Therefore, in its **Flight emission label framework** the EU **should include information on non-CO_2 climate impacts**, such as contrails. By providing passengers with clearer information on the environmental impact of their flights, this voluntary approach would incentivize airlines to adopt contrail avoidance measures and invest in non-CO_2 mitigation technologies early on.

2. Mandating contrail-free skies

2.1 Adapting European Air Traffic Management for contrail avoidance

Although airlines carry out navigational contrail avoidance, they cannot do so without the support of Air Navigation Service Providers (ANSPs). Whether the strategy is led by airlines or ANSPs, the latter plays a key role in approving flight plans in advance (pre-tactical) and authorising rerouting during flights (tactical) to avoid contrails.

Thus, the **EU shall develop the regulatory framework to incorporate contrail avoidance in Air Traffic Management (ATM)**. This involves adapting flight planning and Air Traffic Control protocols to consider environmental impacts, alongside safety and efficiency. Furthermore **non-CO_2 targets shall be part** of both **the EU-wide level and the ANSP-level environmental KPIs** set for each reference period.

It is also important to **establish clear guidelines for air traffic controllers and airlines through EASA on when and how to implement rerouting** to avoid contrail formation, factoring in meteorological data, traffic congestion, and airspace restrictions.

The EU can also explore a more flexible use of European airspace by enabling more dynamic allocation of flight paths to support contrail avoidance. Any increased airspace flexibility must focus on contrail mitigation and not lead to air traffic increase.

2.2 Enhanced cooperation among national meteorological services and Eurocontrol

To improve the forecasting of ISSRs, the EU can leverage the capabilities of the Copernicus programme and strengthen collaboration between national meteorological services and their cooperation with Eurocontrol.Data sharing and joint research initiatives would enhance forecasting accuracy and contribute to standardized, EU-wide ISSR forecasting protocols for contrail-optimised flight planning.

3. Eliminating remaining warming and pollution through updated jet fuel standards

While not covered in detail by this report, another way to reduce contrail warming is through the use of low-aromatic, low-sulfur aviation fuels. These fuel types produce fewer soot particles, which reduces the likelihood of contrail formation. Although low-aromatic, low-sulfur SAFs will play a significant role in reducing both CO_2 and non-CO_2 emissions, temporary short- to mid-term solutions are needed while their production scales up to meet demand. **Therefore, the EU should establish jet fuel standards mandating the use of these cleaner fuels.**

EASA's pilot project on the feasibility of a European body for jet fuel standards offers an ideal opportunity to re-evaluate the outdated fuel regulations, which have remained largely unchanged since the 1970s. This initiative could propose new standards for lower aromatic and sulfur content in fuels, maximising both climate and health benefits.

Further information

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Annex

I. Choice of baseline for contrail climate impact

There is consensus on the fact that contrails have a significant warming impact on climate. However, their exact extent is still subject to research.

A landmark study from Lee et al. (2021) estimated that the mean contrail radiative forcing (RF) in 2018 was 111.4 (33, 189) mW/m2 (milliwatts per square metre). Another study by R. Teoh et al. (2024) estimated a mean RF of 62.1 (34.8, 74.8) mW/m2 in 2019.

We have used the contrail impact estimate from Teoh et al. as the baseline scenario for the analysis. This estimate is lower than the estimate by Lee et al., and within its uncertainty range.

II. Choice of metric and time horizon

As described in section 2.4.1, the choice of climate metric and time horizon to compare the climate impact of contrails and CO_2 is still subject to scientific and political debate.

In our analysis, we have selected GWP as a climate metric. GWP is the most widely used metric in climate policy, and it will be used in the MRV for non-CO_2 effects under the EU ETS.

As for the time horizon, we have used 100 years. This means we are integrating the effects of contrails and CO2 over a 100-year period.

The reason for this selection is that a time horizon of 100 years gives more weight to the impact of CO_2 over contrails, compared to shorter time horizons like 20 years. This is due to the fact that the warming effect of contrails lasts for a very short time, while CO_2 stays in the atmosphere for decades or centuries.

This choice does not imply a preference for longer time horizons. We welcome the fact that the EU ETS considers time horizons of 20, 50 and 100 years for the non-CO_2 MRV.

The chart shows the multipliers for Lee et al. and Teoh et al. for GWP20, GWP50 and GWP100. These multipliers are a way of expressing the climate impact of contrails in terms of CO_2 equivalent in relation to CO_2. The higher the multiplier, the larger the impact of contrails compared to CO_2.

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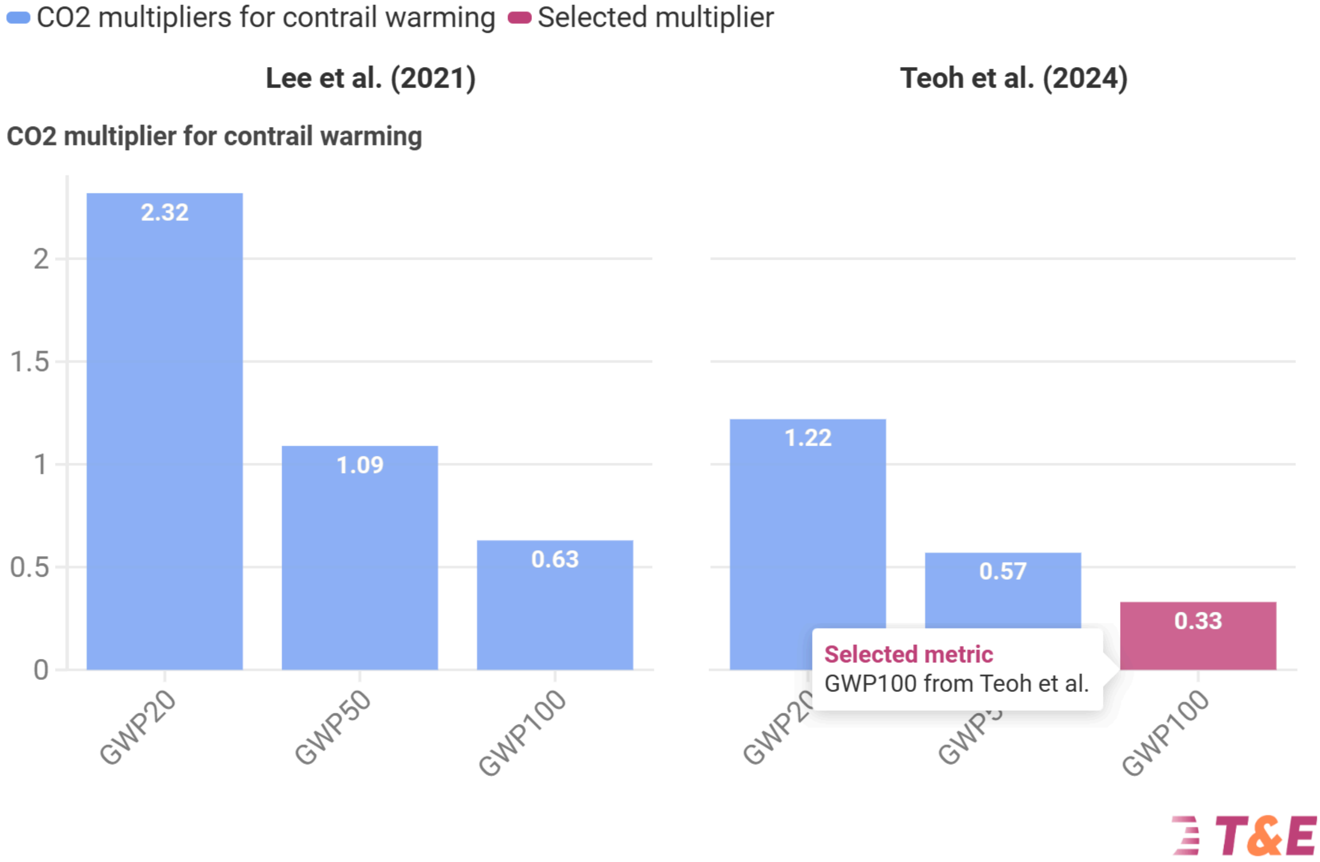
Time horizons and CO2 multipliers from main scientific sources



The selected combination of baseline scenario and time horizon provides the lowest estimate for the climate impact of contrails compared to CO_2. This choice follows the principle of using conservative assumptions whenever possible.

The use of a shorter time horizon would make the climate impact of contrails more prominent compared to CO_2. This would create an even stronger case to mitigate contrail formation.

III. Assumptions of climate benefits of contrail avoidance

To assess the climate benefits of contrail avoidance in section 2.4, we have assumed that each successful deviation reduces contrail warming by 80%. This assumption takes into account that contrail avoidance manoeuvres may not be able to fully mitigate contrail formation in all cases. This may be the case if, for example, the necessary deviations are too large. This assumption is aligned with the results from Martín Frías et al. (2024).

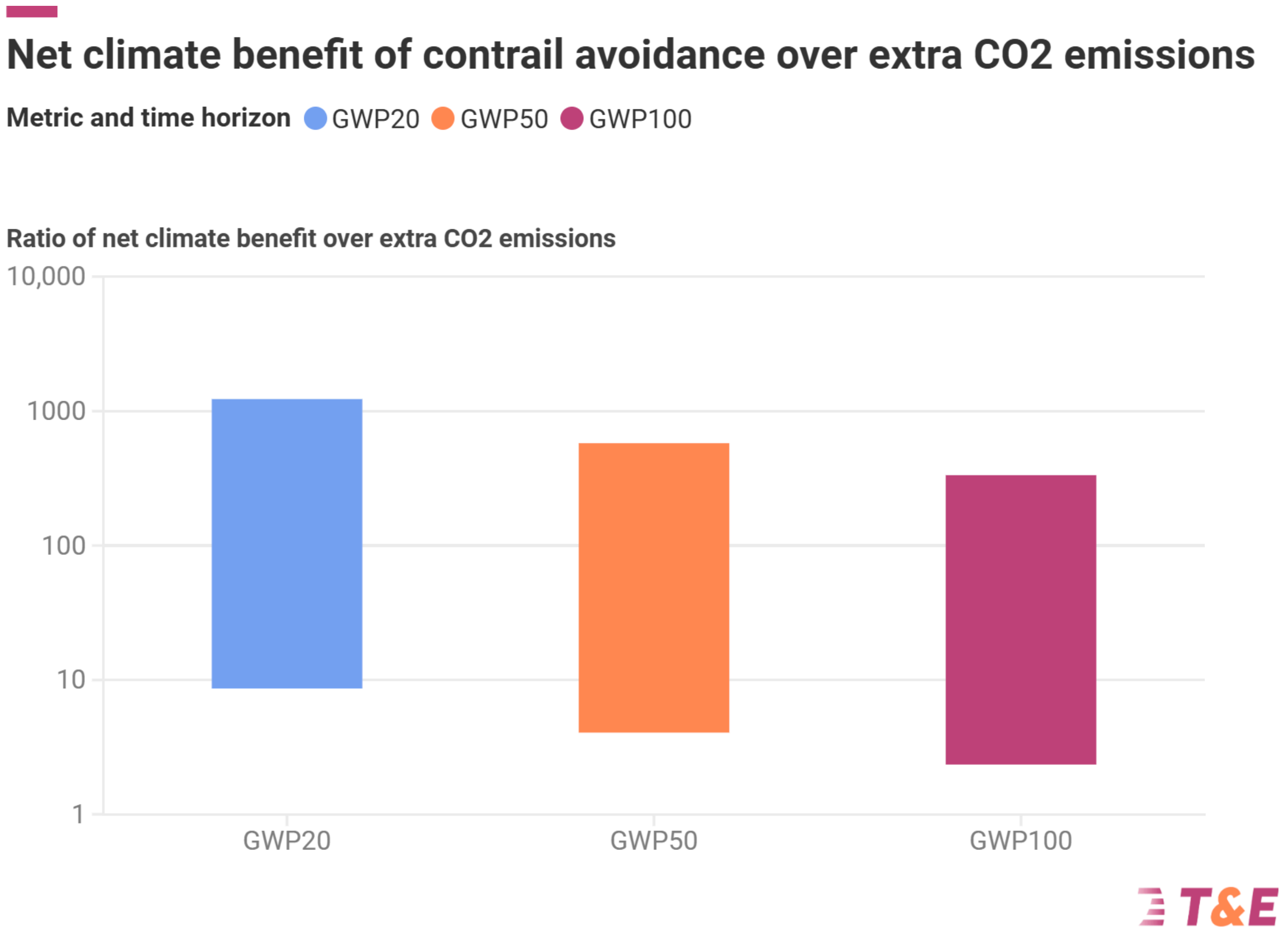
The analysis has been performed using 2019 data from Teoh et al. for European flights, i.e. flights to, from and within Europe. We have assessed the net climate impact of contrail avoidance for the 5% of European flights that were responsible for 80% of contrail warming. The flight is assumed to emit 100 tonnes of CO_2.

IV. Influence of time horizon on climate benefits

We have analysed the influence of time horizon on the climate benefits of contrail avoidance presented in section 2.4. Using GWP100, we find that rerouting the most warming delivers net climate benefits even in very pessimistic cases. The ratio of net climate benefits over the extra CO_2 emissions ranges from 2.35 to 333. This can be perceived as a “climate return on investment”: for every extra tonne of CO_2 emitted by contrail avoidance manoeuvres, we reduce between 2.35 and 333 tonnes of CO_2.

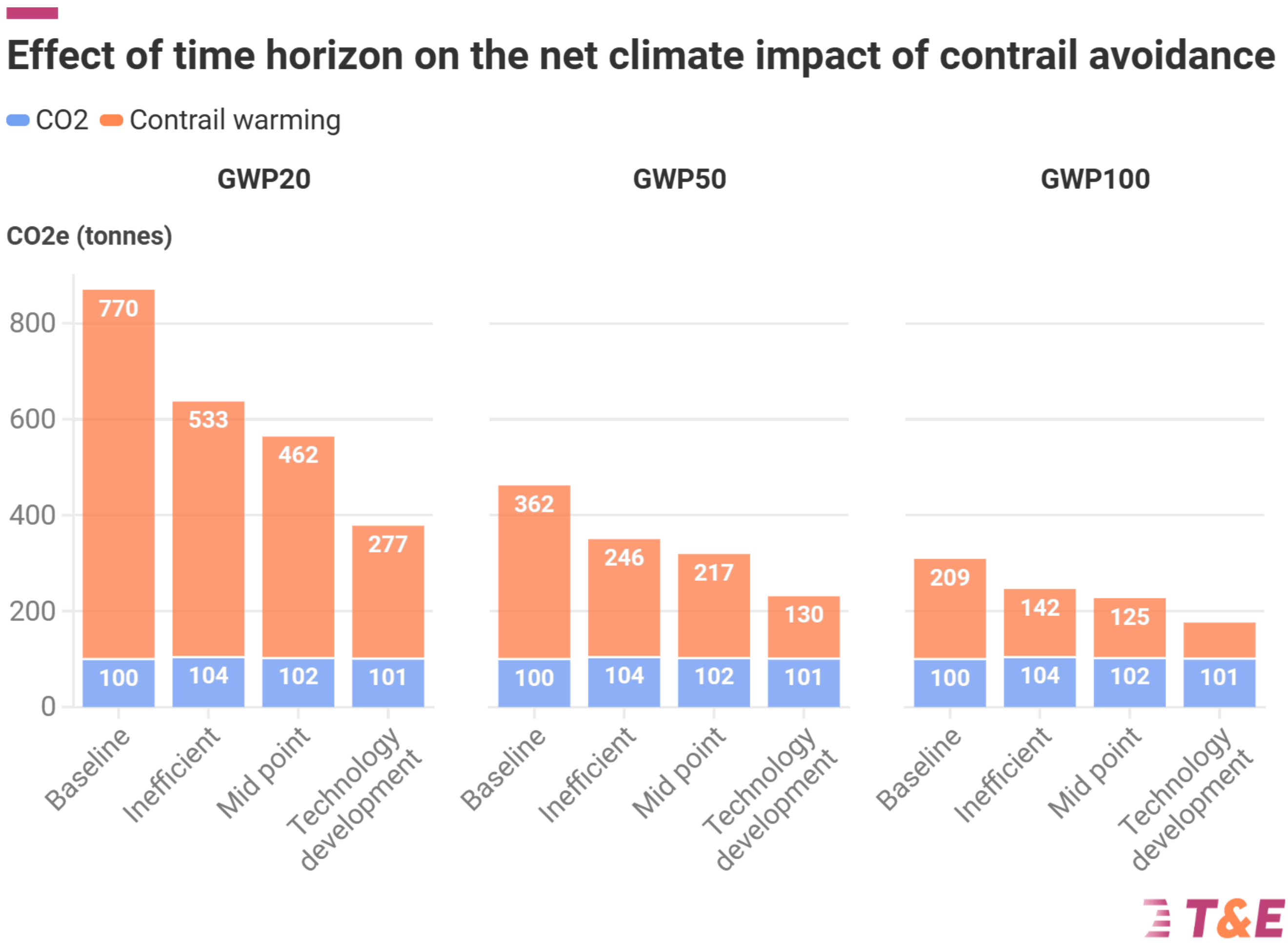
These climate benefits are even larger when using GWP20 and GWP50. This is expected, since shorter time horizons give more weight to the climate impact of contrails compared to CO_2.

For GWP50, for every tonne of extra CO_2 emitted, we can mitigate between 4.06 and 577 tonnes of CO_2. For GWP20, this range is between 8.64 and 1228 tonnes of CO_2. When assessing the net climate benefits with these shorter time horizons, the risk of doing more harm than good is even more reduced.



Section 2.4 presented three different scenarios from the sensitivity analysis, tagged as inefficient, mid point and technology development.

Simulating these scenarios with GWP20 and GWP50, we see a much higher warming impact of contrails in the baseline scenario with no contrail avoidance. We also find a larger net climate benefit, as we have assumed the same percentage of contrail warming reduction.



V. Cost model assumptions

We have assessed the costs of contrail avoidance by 2040, based on our own analysis and on Roland Berger's cost model developed for the Understanding Contrail Management report.

We have started from a scenario in which only the small percentage of flights generating 80% of warming is tackled. Then, we have assumed that 80% of manoeuvres are successful. Finally, we have assumed that, for each successful manoeuvre, 80% of contrail warming will be mitigated. This results in a total contrail warming reduction of 51.2%.

Operational expenditure (opex)

The main component of operational expenditure for contrail avoidance is expected to be the extra fuel consumption. Other costs, associated with extra staff at aircraft operators or air traffic control, are expected to be much smaller and are more difficult to estimate at this point. For that reason, they have not been included, in line with Roland Berger's model.

We have assumed an extra fuel burn at fleet level of 0.5%. This extra fuel burn is 10 to 25 times larger than estimated by Martín Frías et al. for simulations of contrail avoidance strategies targeting the most warming flights.

For fuel costs, we have used a blend of 66% fossil jet fuel with carbon pricing, 24% of bio-based SAF, and 10% of synthetic SAF, in line with the ReFuelEU blend mandate for 2040.

The resulting price of the fuel blend is approximately €2000/tonne.

Capital expenditure (capex)

We have used Roland Berger's model for the capital expenditure, which is driven by aircraft humidity sensors and observation systems.

Roland Berger's model assumes that all commercial aircraft will be fitted by 2040 with a humidity sensor with a service life of 10 years. This can be considered a conservative assumption, as equipping the entire commercial aircraft fleet with humidity sensors may not be necessary for a reliable ISSR forecast and sensing.

Their model also assumes the deployment of a fleet of low Earth orbit satellites dedicated to contrail observation. This constellation of satellites could have other uses that could partly pay for their deployment, so the actual cost would be smaller than estimated.

VI. Influence of time horizon on cost

The use of different time horizons has an impact on the estimated costs of contrail avoidance. Shorter time horizons lower the costs per tonne of CO_2 equivalent.

Using GWP50, costs go below €12/CO_2 abated. The use of GWP20 reduces the costs even further, below €6/CO_2 abated.