

Reducing Persistent Contrail Formation through Optimization of Flight Trajectories within Operational Constraints

MSc Thesis

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Thesis report

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Preface

With this thesis, my time as a student will come to an end. A transformative period in my life, which has learned me so much through its many experiences.

First of all, I would like to thank my supervisors Junzi Sun and Esther Roosenbrand for guiding me through the process of my graduation thesis. Although it was a process with ups and downs, you always stayed positive and constructive to help me bring this project to the finish line. I also want to thank Jacco Hoekstra for his valuable insights during the milestone meetings.

Then I would like to thank my family and friends for supporting me, but also for all the good times we spent together that have made my student years as amazing as they were. I look forward to spending even more time together in the future. I want to give a special shout out to the VSV 'Leonardo da vinci'. This study association and the people I met through it have enriched my life in infinitely many ways.

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Part I

Literature Review & Research Definition (week 6)

General Introduction (week 6)

Aviation significantly impacts the climate through CO₂ emissions and non-CO₂ effects, which can be twice as large as the first [1]. The sector has made numerous efforts to decrease this impact [2], further encouraged by the International Civil Aviation Organization's (ICAO) goal to achieve carbon neutrality by 2050 [3]. These efforts range from optimizing the aircraft design stage [4] to fuel production [5]. Research has proven that persistent contrail forming can also significantly contribute to the non-CO₂ climate impact of flights [6]. As persistent contrails only form in specific circumstances, the effect can be minimized by optimizing routes to prevent these persistent contrails from forming. This research aims to develop an optimization framework that studies the possibility to reduce the climate impact of flights at a network level, while respecting the bounds of the standard airline flight plans.

This research is carried out to contribute to the search for solutions to minimize the climate impact of aviation. Its aim is to not only show that trajectory optimization can decrease persistent contrail formation, but also that these trajectories are realistic options for airlines to fly. Right now, there is a gap between the open source research in optimized trajectories and the closed source optimizers used by airlines, which also include airline specific operational constraints. The novel aspect of this research is that it tries to address this gap. It shows a method to translate these optimized trajectories in unrestricted airspace into flight trajectories that could be used by airlines.

Literature Review (week 6)

To carry out this research, some background knowledge needs to be established on the climate impact of aviation and on route optimization. It should also be determined which topics have already been researched and where the research is still lacking such that this thesis can contribute to scientific advancements. This chapter aims to outline the existing research on the topic.

Firstly, the way aviation impacts the climate is outlined in Section 2.1. The role persistent contrails specifically play in this is explained in Section 2.2. Lastly, the research on route optimization is described in Section 2.2.3.

2.1. Climate impact aviation

At the moment, aviation accounts for 3-5% of global warming. Aviation causes climate impact through both CO₂ and non-CO₂ emissions. The non-CO₂ emissions account for about 2/3 of the total climate effects caused by aviation. [1] This section outlines the different types of emissions before describing a method of comparing them in terms of climate impact.

2.1.1. Types of climate impact caused by aviation

Climate impact of aviation can be categorized in two parts. Firstly, there are emissions at altitude and secondly, there is local air pollution. As this research focusses on optimizing the flight trajectory at cruise altitude, the local air pollution caused during takeoff and landing are not considered.

Emissions at altitude are CO₂ and non-CO₂ emissions. Non-CO₂ emissions consist of NO_x, SO_x, water vapour (H₂O) and soot aerosols and cause contrail and cirrus cloud formation [7]. The climate effect of each type of emissions is explained below.

Carbon dioxide (CO₂)

CO₂ is a greenhouse gas with an atmospheric lifetime of up to 200 years. This means that it mixes well in the atmosphere over a longer time frame and thus ends up in the lower atmosphere too, regardless of where the CO₂ is emitted. It has a net warming effect on the atmosphere as it prevents outgoing radiation from the earth's surface leaving the atmosphere [8]. Radiative forcing taking place right now is the result of CO₂ emitted over the past 100 years, thus this will only increase as CO₂ emissions from aviation have risen in the past 50 years [9].

Nitrogen oxides (NO_x)

When nitrogen oxides are emitted, this triggers different chemical reactions in the atmosphere. In the presence of light, NO_x produces ozone (O₃). As the light intensity is higher at the altitude aircraft fly than at the earth's surface, more ozone is formed from aircraft emissions than from comparable pollutants emitted around sea level. This ozone produced will increase radiative forcing. It must be noted, however, that ozone will in return react with other chemicals resulting in the depletion of methane (CH₄) in the atmosphere, reducing the radiative forcing [8]. Next to this, sulphur and water vapour from aircraft emissions will deplete ozone again. However, due to the complexity of all these chemical reactions and variability in concentrations, it is difficult to determine the net warming effect caused by nitrogen oxides present in aircraft plumes [7].

Sulphate and soot aerosols

Due to the presence of sulphur traces in aircraft fuel, aircraft emissions include aerosols of sulphur compounds. As these reflect incoming solar radiation, these reduce net radiative forcing. On the other hand, aircraft emissions also contain soot, small carbon particles that will trap outgoing infra-red radiation in the atmosphere, and thus have a net positive radiative forcing effect [8]. As the effects of the two are opposite and relatively small compared to other emissions, they can generally be excluded from climate impact calculations [7].

Water vapour (H₂O)

For subsonic aircraft, most emissions are released in the troposphere. Water vapour is precipitated here in 1 to 2 weeks and does not have a warming effect. However, when emitted in the lower stratosphere it might build up to larger concentrations and increase the warming effect, as it is a greenhouse gas. However, this effect is assumed to be relatively small [7].

Contrail formation

Although water vapour itself does not contribute largely to the warming effect, it can do so indirectly in the form of contrails. Contrails are formed due to particles in the aircraft emissions if the ambient atmospheric conditions allow this. This is when the ambient atmosphere is sufficiently humid and cold. Line-shaped clouds will form, which are called contrails. When the clouds retain this linear shape, they may be called persistent contrails, otherwise they are referred to as contrail cirrus. Together they are known as aircraft-induced clouds (AIC) [10]. If these contrails persist for a longer time, they can contribute to a net warming effect as they trap outgoing radiation from the earth's surface. The net effect of this is still uncertain and highly dependent on the optical properties of the contrail and the place and time they form [7]. However, it has been proven that an increase in cirrus cloud cover increases radiative forcing and thus net warming of the earth [11]. Therefore, this effect should not be ignored.

2.1.2. Quantifying the climate impact of aviation

Quantifying the climate impact of a single flight is a complex process. As mentioned in Section 2.1.1, the exact impact of each substance present in aircraft emissions is not known yet. However, ongoing research aims to estimate the climate impact of all the emission components such as is done by Lee et al. [1]. To be able to get a total impact to compare different flights and flight trajectories, one metric of climate impact should be determined.

Global Warming Potential is a metric that is often used to quantify climate impact. It is equal to the radiative forcing of one kilogram of emitted gas relative to one kilogram of reference gas. The reference gas used is in practice always CO₂. However, it does not take into account short-lived gasses such as nitrogen oxides and it is unsuitable for the impact of contrails [8].

Another, more suitable, measure is radiative forcing (RF). RF is defined as "the change in the energy balance of the lower atmosphere by a climate change mechanism" [8][p.7] and is measured in W/m². It can be used to find the impact over a certain time scale. The RF of a doubling of CO₂ is determined as 3.7 W/m² [12] [p.357]. The RF of the other notable gasses and substances within aircraft emissions can also be found in literature [1]. The RF of contrails can be determined using a simple cloud radiative-transfer model such as this one by Corti and Peter [13].

However, it should be noted that for most emitted substances, the climate impact tends to reduce when there is a reduced fuel burn. An important exception to this is contrail formation caused by aviation, as this depends more on the atmospheric conditions. [1]

2.2. Persistent contrail formation

Contrails form due to the hot exhaust gases from aircraft engines. These gases are for a large part CO₂ and water vapour, with smaller amounts of NO_x, sulphates and soot aerosols and traces of other pollutants. If the ambient air is cold enough, the particles in the water vapour from the exhaust can condense onto condensation nuclei in the ambient air, but even more so on particles released in combustion, such as soot or small volatile particles, and form ice crystals in the air, as explained by Schumann [6].

This study further notes, that if the air is dry, with relative humidity below saturation over an ice surface, the ice particles in the contrail will evaporate and the contrail can disappear within seconds to minutes. Contrails will persist for longer than this only if two conditions are satisfied. Below they are explained.

2.2.1. Ice Super-Saturated Regions

The relative humidity above ice (r_{hi}) of the ambient air in which the contrail is formed should be greater than 1 Pa/Pa as defined by Sonntag [14]. Such an environment is called an Ice Super-Saturated Region (ISSR). The r_{hi} can be calculated using Equation 2.1, where p_{H_2O} represents the water vapour partial pressure in Pascal (Pa). This is calculated using Equation 2.2, where p_a is the ambient air pressure in Pa and x_v is the mole fraction of water vapour in moist air. Lastly, the saturation pressure with respect to ice e_i is calculated using Equation 2.3 where T is the temperature of the ambient air.

$$r_{hi} = \frac{p_{H_2O}}{e_i} \quad (2.1) \quad p_{H_2O} = p_a \cdot x_v \cdot 1e-6 \quad (2.2)$$

$$\ln e_i(T) = -6024.5282 T^{-1} + 24.7219 + 1.0613868 \times 10^{-2} T - 1.3198825 \times 10^{-5} T^2 - 0.49382577 \ln T \quad (2.3)$$

2.2.2. Schmidt-Appleman Criterion

The Schmidt-Appleman Criterion (SAC) states that contrails are only formed if the combined conditions for humidity, ambient pressure and the water and heat content of the exhaust are of a specific kind. Firstly, for the ice crystals to form properly and persist, the ambient air needs to be at -40 °Celsius (233.15 Kelvin (K)) or colder. This typically only happens at high altitudes or at lower altitudes around the polar region [15]. Next, G represents the ratio between changes in water vapour pressure and temperature during mixing of the exhaust plume with the ambient air [15]. To determine if the SAC criterion is satisfied, the slope of the mixing line G in Pa/K should be calculated using Equation 2.4. p_a is the ambient pressure in Pa, c_p is the specific heat capacity (1.0035e3 J/kg/K) and ϵ is M_{H_2O}/M_{air} (equal to 0.622). The other variables all depend on the fuel combustion characteristics. The efficiency η of the aircraft engines, the water vapour emissions index EI [kg/kg] and the specific heat content for the fuel Q in J/kg [15]. The propulsion efficiency η can be determined using Equation 2.5, which is the ratio between work rate and chemical energy. This means F is the thrust of the engine in Newton, V is the true airspeed of the aircraft in m/s, m_f is the fuel flow rate in kg/s and Q again the specific combustion heat in J/kg [6].

$$G \approx p_a \cdot c_p \frac{EI(H_2O)}{\epsilon \cdot (1 - \eta) \cdot Q} \quad (2.4)$$

$$\eta = \frac{FV}{m_f Q} \quad (2.5)$$

Figure 2.1 shows the Schmidt-Appleman Diagram. It dictates the conditions in which contrails will never form, possibly form, or always form. If the temperature is below the line of 0% relative humidity, contrails will always form. If the temperature exceeds the line of 100% relative humidity, contrails will never form. In the situation that the ambient temperature is in between those two lines, the formation is possible depending on the relative humidity. If it falls on the right side of the corresponding relative humidity line, it will always form, if not, it will never form [6].

2.2.3. Contrail coverage

When persistent contrails have formed, these can be observed as line shapes in the atmosphere. However, it has been found that these contrails may spread due to non-uniform winds and humidity fluctuations in the surrounding atmosphere. As contrails can be spread out due to wind shear, it can be difficult to distinguish aircraft contrails from naturally occurring cirrus clouds after some time. Determining the total size of the aircraft-induced cloudiness is further complicated by a limited understanding on whether and how particle emissions affect natural liquid phase and ice phase clouds [10]. This is exacerbated by the fact that the wind may push some of the ice crystals outside the ISSR, which leads to disappearance of the contrail cirrus. To illustrate the size of the problem, contrail cirrus has been found to have a width up to 100 km due to wind shear [10].

2.3. Route optimization

Route optimization is a very broad concept and can mean different things to different stakeholders. In general, it is done by airlines to minimize their operational cost. This means that the objective is to minimize

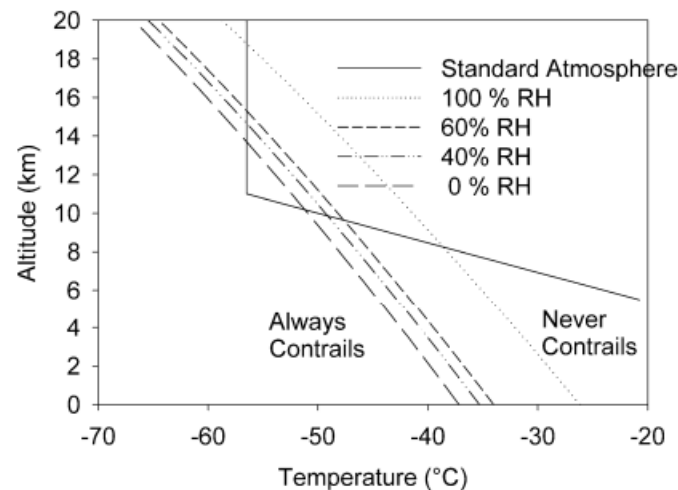


Figure 2.1: Schmidt-Appleman Diagram

the total of fuel costs, overflight fees and flying time costs [16]. This can cause the most optimal flight trajectory for an airline to differ from the Great Circle Distance, which is the shortest possible distance for the flight to go from origin to destination [17]. This chapter will touch upon optimization with respect to the weather and new innovations in the operational efficiency of aircraft. Lastly, Section 2.3.3 will describe OpenAP.top. This is a flight trajectory optimizer tool.

2.3.1. Optimization with respect to wind and weather

One reason that using the Great Circle Distance is not always the most fuel optimal trajectory is due to the weather and winds present. Flying a longer distance with a significant amount of tail wind can actually reduce the time of a flight and subsequently its fuel consumption [Pleter2022Aoptimisations].

This knowledge is also used when utilising jet streams as tail wind. Jet streams are narrow bands of strong wind in the atmosphere, typically at higher altitudes around 30,000 feet [18]. If an aircraft were to fly within this jet stream in the direction of the wind, this could significantly cut down on flight time and fuel consumption [19]. Cases have been reported where flights have cut down up to 25% of the flight time using this knowledge [20]. On the other hand, if aircraft fly with headwind this can result in longer flight distances and in return higher fuel consumption [21].

2.3.2. Innovations for operational efficiency

Next to optimization with respect to weather, there is also research being done in many other causes of operational inefficiencies. These inefficiencies can generally be divided over three areas as is done by Reynolds [22]. These are the departure terminal area, en-route and arrival terminal area. The inefficiencies can then be converted into a metric such as fuel consumption to indicate the potential that is left to optimize. An example of this is the presence of other traffic, which prohibits each flight from taking its most optimized route [Pleter2022Aoptimisations].

2.3.3. Optimization models

To optimize flights, simulation models are used. Many airlines use their in-house simulators, which are closed-source and inaccessible to researchers. However, an open source optimizer called OpenAP.top was created by Sun [23]. It depends on aircraft performance models, emissions models and operational constraints. By incorporating meteorological conditions and fuel cost index objectives, the optimizer can simulate optimal flight trajectories for different scenarios. The model also includes climate objectives and can thus be used to simulate climate optimal flight trajectories.

Research Questions (week 6)

This chapter outlines the research question that this research will aim to answer. It has been broken up into sub questions to be able to efficiently answer the question when the final results are obtained. This chapter also provides a hypothesis for each of the sub questions. Chapter 4 explains how this research will attempt to answer these questions.

The main research question as well as the sub-questions are described below. For each sub-question a hypothesis is constructed, which is written in *Italics*.

3.1. Main research question

How much can flight trajectories be optimized to minimize climate impact, considering fuel burn and persistent contrail formation, while adhering to the bounds of the standard airline flight plan?

3.2. Sub-questions

1. How can a flight trajectory be optimized for both fuel burn and persistent contrail formation? *Using literature, a balance can be found to obtain an objective function optimizing for a minimal fuel use and minimal persistent contrail formation.*
 - What is the confidence level of the estimation in both fuel burn and the persistent contrail formation?
 - How should the climate impact of extra fuel burn be compared to the impact of a persistent contrail forming?
2. What fitting algorithm is suitable to fit a continuous optimized route to discrete coordinates? *Airlines use many different flight points and thus there is a dense distribution of discrete coordinates. This means a simple algorithm can be used.*
 - How detailed may the fitted route be, seeing that a pilot should be able to follow it?
 - How much may the climate impact of the fitted routed differ from the initial optimized continuous route?
3. Can a reduction in climate impact be achieved by optimizing standard flight trajectories from different airlines? *The hypothesis is that this is possible. This is due to the fact that airlines at this point only optimize for cost-effectiveness, thus minimal fuel burn and overflight fees. Even though this also means the fuel used is minimized, the climate impact of persistent contrails is not included at all at this point.*
 - Is the reduction significant enough to justify the additional workload of optimizing for persistent contrail formation?
 - How does the reduction vary between different airlines?

Project Plan (week 6)

The first version of the project plan was presented at the research proposal review. In this plan, the first version of the methodology was set up, as well as a description of the expected results. Next to this, the planning and timeline was described for the rest of the project.

The following section from the research proposal are presented here. Firstly, the methodology is described in Section 4.1. Subsequently, the expected results are outlined in Section 4.2. Lastly, the project planning is shown in Section 4.3

4.1. Methodology

The objective is to propose a model that can generate new flight routes that minimize persistent contrail formation and obtain results on possible minimization of climate impact on these trajectories. However, these trajectories should be within bounds of the traditional flight routes. There are operational limits imposed by the Network Manager [24], but airlines themselves may also impose operational limits due to country specific sanctions for example [25]. The reasons can therefore differ between airlines and therefore different airlines may have different routes.

4.1.1. Data gathering

To start, this is the methodology for one city pair, for one airline, for a period of 3 months taken throughout the year. The route must be optimized separately for each airline. This way, the operational bounds associated with each airline can be respected.

Plan of action

1. Determine period over which the data should be used. A period of three months, spread over the year would manage to include both summer periods (many flights, on average few contrails) and winter periods (less flight, on average many contrails).
2. Get the flight data for three months, listing the flights, origin and destination, their actual routes, the airline and Estimated TakeOff Time (ETOT).
3. Get GFS (Global Forecast System) weather data for the same period.

4.1.2. Possible flight points

To determine possible flight points (coordinates that are used to plan a route, these can be waypoints, but as there is no open data on those, it is not exclusive to waypoints), all flights of this airline around Europe should be evaluated, to determine which flight points they have used before. As soon as a flight point is used at least 5 (amount up for discussion) times over the three months, this can be considered a flight point the airline has accepted for use.

Plan of action

1. Filter "All flights" for a single airline
2. Extract all flight point coordinates
3. Group coordinates together that are relatively close to each other

4. Count number of times a location (coordinate) is used in separate flights.
5. List all locations that are used at least 5 times. This is a comprehensive list of possible usable waypoints for this airline.

4.1.3. Determine most optimal flight route for city pair

Use Open AP.top with weather data of actual dates to get most optimal flight route in terms of CO₂ and persistent contrail for the flights in the selected time period.

Plan of action

1. From literature find method to determine climate impact persistent contrail formation (see Section 2.2)
2. Program method to determine persistent contrail formation
3. Call weather data to obtain ambient air temperature and pressure.
4. Determine weighting between fuel burn and persistent contrail formation in objective function
5. Implement method to include persistent contrail formation in objective function in OpenAP.top
6. Determine if optimal flight route should be found for each separate flight, over average weather three months, average optimized route of all separate flights, etc.
7. Get optimal flight route for city pair for each flight

4.1.4. Determine fitted optimal flight route for city pair for specific airline

Use least squares or some other sort of fitting algorithm to fit the continuous route to the available flight points and get the fitted optimal route.

Plan of Action

1. Research different fitting algorithms
2. Determine KPI for these algorithms such as: computational cost, deviation from original path, smoothness (no sharp turns) etc.
3. Choose algorithm best suited for the application
4. Program method to fit output to list of flight points
5. Obtain fitted route
6. Implement method to quantify deviation from actual optimized route

4.1.5. Determine change in climate impact of optimal route for all flights of that airline over the selected time period

Use OpenAP simulator to get the impact of that fitted optimal route over the time period in terms of fuel burn and amount of persistent contrails formed.

Plan of Action

1. Implement the method to determine persistent contrail formation in OpenAP as well
2. Use OpenAP to determine fuel burn and persistent contrail formation of workable optimal route
3. Iterate for all flights over the selected time period
4. Sum the climate impact (fuel burn + amount of persistent contrails formed) of all flights

4.1.6. Determine climate impact of actual flown flights over selected time period

There are two options here:

1. First extract all flight paths, take the "average" flight path and determine climate impact of that for the weather conditions of all the days using OpenAP.top
2. Find the climate impact for each flight at that flight time. This might be too computationally heavy, but that is to be determined.

The latter would be possible for one city pair, if the optimization is run for the whole of Europe this would start to introduce too much computational cost. However, as the results for single city pairs are significant too, the latter can be chosen.

Choosing the latter:

Plan of Action

1. Redefine flight trajectories in coordinates to feed to OpenAP
2. Feed flight trajectories to OpenAP to simulate climate impact (fuel burn + persistent contrail formation)
3. Sum climate impact of all flights over selected time period

4.1.7. Determine the reduction in climate impact

This is just subtracting the climate impact of the optimized routes from the original climate impact.

Plan of Action

1. Subtract climate impact of the optimized routes from original routes
2. Give answer in percentage reduction fuel burn and percentage reduction in persistent contrail formation
3. Obtain amount of fuel used in old vs new case
4. Draw conclusion on decreased climate impact (CO_2 and non- CO_2 of fuel burn) cost of fuel.
5. Touch upon the estimated impact of the decreased amount of persistent contrails formed. This can not easily be calculated into a number for climate impact reduction, but some soft conclusions might be drawn.

4.1.8. Do the same for different airlines

The process from Section 4.1.2 until Section 4.1.7 can now be repeated for all airlines operating that city pair.

Plan of Action

1. Find out airlines that operate the same city pair at least n times per week
2. Repeat aforementioned steps for different airlines
3. Compare differences between airlines: fuel burn, amount of persistent contrails formed, differences in routes, possibly even overflight costs

4.1.9. Do the same for other city pairs

The process from Section 4.1.2 until Section 4.1.8 can be repeated for other city pairs.

Plan of Action

1. Find city pairs that are operated often by different airlines
2. Repeat aforementioned steps for different city pairs

4.1.10. Conflict analysis

The implication of the new routes could be investigated, determining if there are now more conflicts on ATM level. This might be out of the scope. Therefore, no further method is determined for this now.

4.1.11. Verification and validation

To prove that the model was built correctly and that its results can be trusted, verification and validation of the model should be done. This section explains the proposed procedure for both points.

Verification

Verification is checking if the model actually does what it is intended to do [26]. This will already happen during its creation, however there should be some additional tests done when the model is finished. A variety of unit tests can be performed to check separate parts of the model. Some possible unit tests are listed below:

- Manual check if continuous routes are fitted to the nearest waypoints
- Input perfect conditions for persistent contrail formation and check the output
- Input conditions which make persistent contrail impossible and check the output

- Input inhibiting conditions that test for each of the three criteria for persistent contrail formation
- Test if a fitted route is only made up of available waypoints

Next to these unit tests, it is also important that the model is reproducible. To check this, the model can be run several times using the same inputs, checking if the outputs are the same as well. This should be checked for different inputs such as the flight coordinates, weather conditions and available waypoints.

Validation

After verification, validation can also take place. Here it is checked if the model gives satisfactory accurate results for its application. Ideally, the model should be checked against another, previously validated model to compare the results. An option to validate the results on persistent contrail formation is for example to compare with satellite data as is done by Roosenbrand, Sun and Hoekstra [27]. However, this is very labour intensive and requires a lot of unavailable data and is thus out of the scope of this research.

Another method of validation is more suited for this research, which is a sensitivity analysis. In such an analysis is tested how sensitive the model outcome is to the changing of the parameters of the model itself and not its inputs. To perform such an analysis for this model several things can be done, as listed below.

- Changes to coefficients in objective function to prioritize the minimization of fuel burn
- Changes to coefficients in objective function to prioritize the minimization of persistent contrail formation
- Changes to parameters in the fitting algorithm
- Changes to parameters determining if a waypoint is usable

4.2. Expected Results

This section describes the expected outcome from the thesis. This includes the model that will be developed, the results that can be obtained from it and the expected conclusions. Next to this, the possible impact from this thesis and its significance in research will be analysed.

4.2.1. Expected model

The model that will be created, will be an addition to the existing OpenAP model. This model can already estimate the fuel use of flights on specified trajectories. Its addition OpenAP.top uses this program to optimize flight trajectories to minimize fuel burn. At the end of this thesis, there should be the possibility to also estimate if a persistent contrail is formed for a certain trajectory at a certain point in time using the model. Next to this, OpenAP.top should be adjusted such that it can optimize for the balance of fuel burn and persistent contrail formation.

4.2.2. Expected model results

The results will be obtained by feeding data to the model. The exact scenarios that will be tested, are to be determined. However, it is expected that at least 3 scenario's of 3 different airlines on a city pair (so at least 3 different city pairs) will be evaluated.

The outcomes per scenario:

1. An optimized route per airline
2. The difference in fuel burn and contrail formation from the original route to the optimized route for each airlines
3. Notable differences between the different airlines: fuel burn/contrail formation/routing/flight level

4.2.3. Expected conclusions

These results from Section 4.2.2 can then be used to draw conclusions. The general conclusion expected will be that this model and the underlying principles can be used to optimize flight routes with respect to climate impact. To be able to draw such a conclusion, some sub-conclusions should be verified first.

It should be determined if the model can indeed optimize the flown trajectories, reducing the fuel burn and persistent contrail formation. As the climate impact of persistent contrails is difficult to quantify, there

should be a significant decrease in at least one of the measures, while the other stays the same or is reduced as well, to be able to say that the climate impact can be reduced using the optimized trajectories.

Another outcome that should be evaluated, is the fact that the different airlines will have different optimized routes. From this it might be possible to conclude that one airline favours climate impact minimization more than other airlines, which can be a significant piece of knowledge.

4.3. Planning

For this thesis the time frame is as follows. The kick-off meeting took place on 26/02/2024. Following the workload availability as communicated in this kick-off, the Mid-Term Review should take place in February 2025, the Greenlight Review end of May 2025 meaning the thesis should be defended towards the end of June 2025, making for a graduation at minimum 20 working days after the Greenlight Review.

As per the official Brightspace of the Aerospace Engineering Master Thesis, there are four different phases to the thesis. These are highlighted in Figure 4.1. The Literature Review & Research Definition phase will be finished with the completion of this report. Research Phase 1 and 2 will be the phase in which all the research activities as planned in this chapter are carried out. The phases do not differ from each other, except for the fact that in between them there will be a Mid-Term review with a Go, Adjust or No-Go verdict. The Research Dissemination is the final phase before graduation can take place.

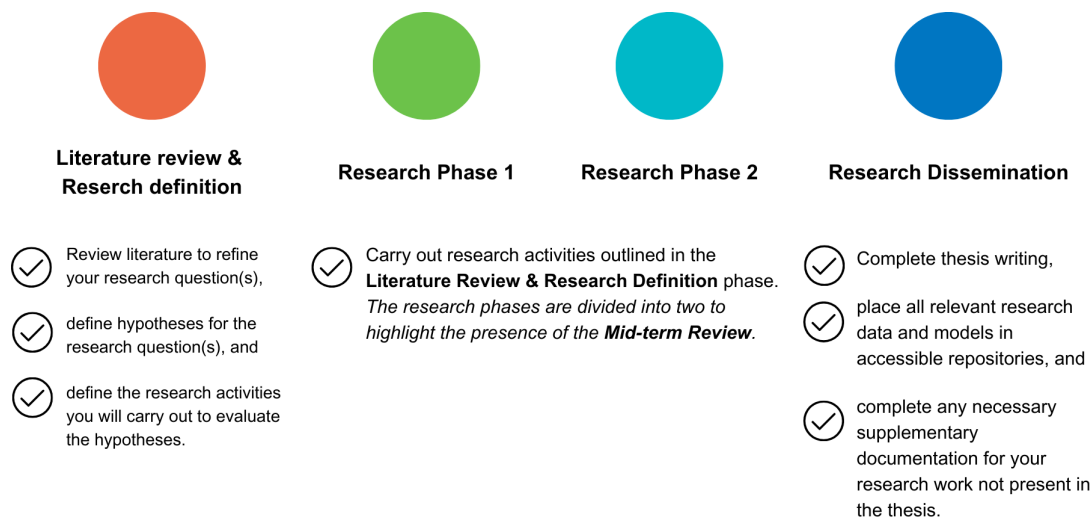


Figure 4.1: Research phases thesis

4.3.1. Research activities

This section is a summary of all the research activities that will be carried out during Research Phase 1 and 2.

1. Collect and prepare data for implementation: ECTRL data and GFS weather data
2. Adjust OpenAP model:
 1. Implement persistent contrail formation determination
 2. Adjust objective function OpenAP.top to balance fuel burn with persistent contrail formation
3. Create model to fit optimized route to available coordinates
4. Determine for which scenarios results should be obtained
5. Obtain and visualize/summarize results for selected scenarios
6. Analyze results

7. Perform Verification and Validation
8. Draw conclusions and recommendations from result analysis
9. Write the thesis

These activities should be performed in the order as they are presented, starting from this research proposal and ending in the thesis defense. However, this is not just a linear order, as results from one activity may mean that earlier activities need to be revised. This relation is visualized in Figure 4.2. An example is when verification and validation proves that there are errors in the model, this model should be revised.

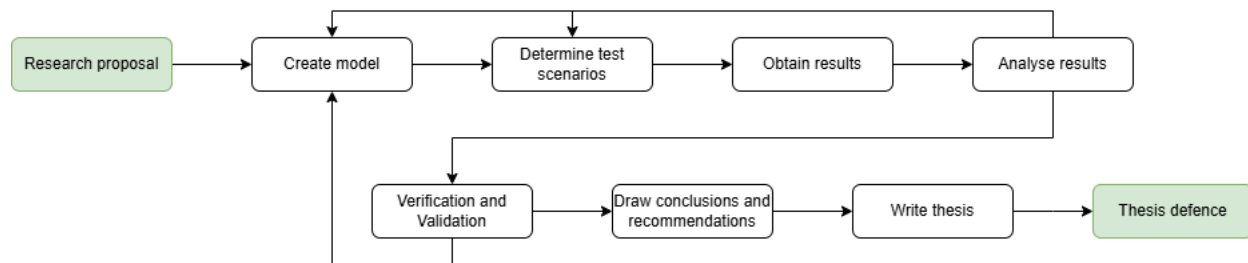


Figure 4.2: Flowchart research activities

4.3.2. Schedule

This section presents a planning of the research activities in line with the proposed deadline of handing in the thesis end of June 2025.

To do so, the research activities planned should be divided over the Research Phase 1 and Phase 2. This will determine which activities should be performed in order to hold the Mid-Term Review and which activities should be performed after this to have a Greenlight Review.

Research Phase 1 will consist of research activities 1 through 5 from Section 4.3.1 and Phase 2 will consist of activities 6 through 9. As explained before, some activities in 1-5 might have to be iterated following from steps 6 or 7, however the idea is that sufficient progress will have been made that this will consist of smaller iterations and can thus be done after the Mid-Term Review. Table 4.1 shows what this planning means in term of dates.

Table 4.1: Planning research activities

What	When	Time to work on it (work weeks)
Hand-in research proposal	6-12-2024	-
Collect and prepare data	20-12-2024	2
Adjust OpenAP model	10-1-2025	3
Create model to fit optimized route to available coordinates	31-1-2025	3
Determine for which scenarios results should be obtained	14-2-2025	2
Obtain and visualize/summarize results for selected scenarios	28-2-2025	2
Mid-Term Review	3-3-2025	-
Analyse results	21-3-2025	3
Perform Verification and Validation	11-4-2025	3
Draw conclusions and recommendations from result analysis	2-5-2025	3
Write the thesis	23-5-2025	3
Prepare Greenlight review	30-5-2025	1

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Part II

Scientific Article (week 15 & week 27)

Reducing Persistent Contrail Formation through Optimization of Flight Trajectories within Operational Constraints

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ABSTRACT

Aviation contributes to global warming not only through its CO₂ emissions, but also through contrail formation. The latter may be combatted by taking this effect into account in flight trajectory optimization. Research already shows some possibilities of doing this, but often lacks integration with the operational limits that airlines need to adhere to. In this paper, an approach is described to first optimize flight trajectories for persistent contrail minimization and then show the feasibility of these trajectories as standard flight plans. This is done by using the open source OpenAP.top trajectory optimizer and atmospheric data. An entire day of European flights in and out of Schiphol are analyzed in determining the potential reduction of climate impact for these flights. It was demonstrated that the amount of persistent contrails can be reduced with optimized trajectories and it was shown that these trajectories can, to a large extent, be approximated by waypoints that are included in standard flight plans.

Keywords: Sustainability, Aviation, Contrails, Optimization

1. Introduction

Aviation significantly impacts the climate through CO₂ emissions and non-CO₂ effects, which can be twice as large as the first [1]. The sector has made numerous efforts to decrease this impact [2], further encouraged by the International Civil Aviation Organization's (ICAO) goal to achieve carbon neutrality by 2050 [3]. These efforts range from optimizing the aircraft design stage [4] to fuel production [5]. Research has proven that persistent contrail formation can also significantly contribute to the non-CO₂ climate impact of flights [6]. As persistent contrails only form in specific circumstances, the effect can be minimized by using optimized routes that prevent these persistent contrails from forming. However, optimized routes are often created without the limitations of standard flight plans, which might make the routes incompatible with real-life operations. This research aims to develop an optimization framework that studies the possibility to reduce the climate impact of flights at a network level, while respecting the bounds of the standard airline flight plans.

The objective of this research is to answer the question: how much can flight trajectories be optimized to minimize climate impact, considering fuel burn and persistent contrail formation, while adhering to the bounds of the standard airline flight plan? This will be done by analyzing flights within Europe flying in and out of Schiphol and comparing them with simulated optimal trajectories with respect to fuel use and persistent contrail formation. Subsequently, a fitting algorithm is created to approximate the trajectory using standard flight plan waypoints.

The structure of this paper is as follows. [Section 2](#) will outline the state of the art on this research topic and the data used for this research. The methodology adopted to analyze the data is explained in [section 3](#). The results are then presented in [section 4](#), which are then discussed in [section 5](#). [Section 6](#) then presents the final conclusions of this research.

2. Background

Before the methodology of this research is described in [section 3](#), this section will present the literature review that was conducted to determine the research gap that can be addressed with this research. In addition to this, some background is explained about the data sources used in this research.

2.1. Climate impact aviation

At the moment, aviation accounts for 3-5% of global warming. Aviation causes climate impact through both CO₂ and non-CO₂ emissions. The non-CO₂ emissions account for about 2/3 of the total climate effects caused by aviation. [1] Climate impact of aviation can be categorized in two parts. Firstly, there are emissions at altitude and secondly, there is local air pollution. As this research focusses on optimizing the flight trajectory at cruise altitude, the local air pollution caused during takeoff and landing are not considered.

Emissions at altitude are CO₂ and non-CO₂ emissions. Non-CO₂ emissions consist of NO_x, SO_x, water vapour (H₂O) and soot aerosols and cause contrail and cirrus cloud formation [7]

Quantifying the climate impact of a single flight is a complex process. Ongoing research aims to estimate the climate impact of all the emission components such as is done by Lee et al. [1]. To be able to get a total impact to compare different flights and flight trajectories, one metric of climate impact should be determined.

Global Warming Potential is a metric that is often used to quantify climate impact. It is equal to the radiative forcing of one kilogram of emitted gas relative to one kilogram of reference gas. The reference gas used is in practice always CO₂. However, it does not take into account short-lived gasses such as nitrogen oxides and it is unsuitable for the impact of contrails [8].

Another, more suitable, metric is radiative forcing (RF). RF is defined as "the change in the energy balance of the lower atmosphere by a climate change mechanism" [8][p.7] and is measured in W/m². It can be used to find the impact over a certain time scale. The RF of a doubling of CO₂ is determined as 3.7 W/m² [9][p.357]. The RF of the other notable gasses and substances within aircraft emissions can also be found in literature [1]. The RF of contrails can be determined using a simple cloud radiative-transfer model such as this one by Corti and Peter [10].

However, it should be noted that for most emitted substances, the climate impact tends to reduce when there is a reduced fuel burn. An important exception to this is contrail formation caused by aviation, as this depends more on the atmospheric conditions. [1]

2.2. Contrail formation

Contrails form due to the hot exhaust gases from aircraft engines. These gases are for a large part CO₂ and water vapour, with smaller amounts of NO_x sulphates and soot aerosols and traces of other pollutants. If the ambient air is cold enough, the particles in the water vapour from the exhaust can condense onto condensation nuclei in the ambient air, but even more so on particles released in combustion, such as soot or small volatile particles, and form ice crystals in the air, as explained by Schumann [6].

This study further notes, that if the air is dry, with relative humidity below saturation over an ice surface, the ice particles in the contrail will evaporate and the contrail can disappear within seconds to minutes. Contrails will persist for longer than this only if two conditions are satisfied. Below they are explained.

2.3. Ice Super-Saturated Regions

The relative humidity above ice (rhi) of the ambient air in which the contrail is formed should be greater than 1 Pa/Pa as defined by Sonntag [11]. Such an environment is called an Ice Super-Saturated Region (ISSR). The rhi can be calculated using [Equation 1](#), where p_{H_2O} represents the water vapour partial pressure in Pascal (Pa). This is calculated using [Equation 2](#), where p_a is the ambient air pressure in Pa and x_v is the mole fraction of water vapour in moist air. Lastly, the saturation pressure with respect to ice e_i is calculated using [Equation 3](#) where T is the temperature of the ambient air.

$$rhi = \frac{p_{H_2O}}{e_i} \quad (1)$$

$$p_{H_2O} = p_a \cdot x_v \cdot 1 \times 10^{-6} \quad (2)$$

$$\ln e_i(T) = -6024.5282 T^{-1} + 24.7219 + 1.0613868 \times 10^{-2} T - 1.3198825 \times 10^{-5} T^2 - 0.49382577 \ln T \quad (3)$$

2.4. Schmidt-Appleman Criterion

The Schmidt-Appleman Criterion (SAC) states that contrails are only formed if the combined conditions for humidity, ambient pressure and the water and heat content of the exhaust are of a specific kind. Firstly, for the ice crystals to form properly and persist, the ambient air needs to be at -40 °Celsius (233.15 Kelvin (K)) or colder. This typically only happens at high altitudes or at lower altitudes around the polar region [12]. Next, G represents the ratio between changes in water vapour pressure and temperature during mixing of the exhaust plume with the ambient air [12]. To determine if the SAC criterion is satisfied, the slope of the mixing line G in Pa/K should be calculated using Equation 4. p_a is the ambient pressure in Pa, c_p is the specific heat capacity (1.0035e3 J/kg/K) and ϵ is M_{H_2O}/M_{air} (equal to 0.622). The other variables all depend on the fuel combustion characteristics. The efficiency η of the aircraft engines, the water vapour emissions index EI [kg/kg] and the specific heat content for the fuel Q in J/kg [12]. The propulsion efficiency η can be determined using Equation 5, which is the ratio between work rate and chemical energy. This means F is the thrust of the engine in Newton, V is the true airspeed of the aircraft in m/s, m_f is the fuel flow rate in kg/s and Q again the specific combustion heat in J/kg [6].

$$G \approx p_a \cdot c_p \frac{EI(H_2O)}{\epsilon \cdot (1 - \eta) \cdot Q} \quad (4)$$

$$\eta = \frac{FV}{m_f Q} \quad (5)$$

Figure 1 shows the Schmidt-Appleman Diagram. It dictates the conditions in which contrails will never form, possibly form, or always form. If the temperature is below the line of 0% relative humidity, contrails will always form. If the temperature exceeds the line of 100% relative humidity, contrails will never form. In the situation that the ambient temperature is in between those two lines, the formation is possible depending on the relative humidity. If it falls on the right side of the corresponding relative humidity line, it will always form, if not, it will never form [6].

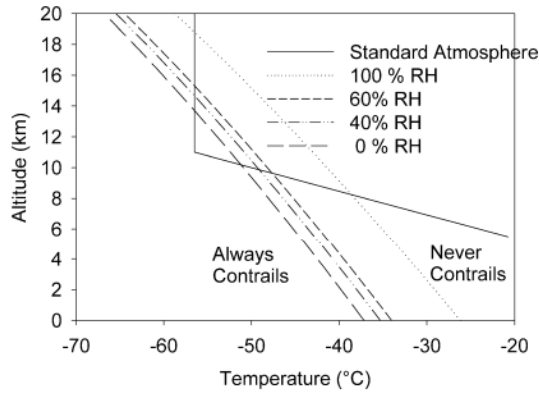


Figure 1: Schmidt-Appleman Diagram

2.5. Contrail coverage

When persistent contrails have formed, these can be observed as line shapes in the atmosphere. However, it has been found that these contrails may spread due to non-uniform winds and humidity fluctuations in the

surrounding atmosphere. As contrails can be spread out due to wind shear, it can be difficult to distinguish aircraft contrails from naturally occurring cirrus clouds after some time. Determining the total size of the aircraft-induced cloudiness is further complicated by a limited understanding on whether and how particle emissions affect natural liquid phase and ice phase clouds [13]. This is exacerbated by the fact that the wind may push some of the ice crystals outside the ISSR, which leads to disappearance of the contrail cirrus. To illustrate the size of the problem, contrail cirrus has been found to have a width up to 100 km due to wind shear [13].

2.6. Route optimization

Route optimization is a very broad concept and can mean different things to different stakeholders. In general, it is done by airlines to minimize their operational cost. This means that the objective is to minimize the total of fuel costs, overflight fees and flying time costs [14]. This can cause the most optimal flight trajectory for an airline to differ from the Great Circle Distance, which is the shortest possible distance for the flight to go from origin to destination [15]. One reason that using the Great Circle Distance is not always the most fuel optimal trajectory is due to the weather and winds present. Flying a longer distance with a significant amount of tail wind can actually reduce the time of a flight and subsequently its fuel consumption [15].

To optimize flights, simulation models are used. Many airlines use their in-house simulators, which are closed-source and inaccessible to researchers. As a consequence, it is difficult to determine if trajectories created by open source trajectory optimizers fall within the operational limitations of an airline. These operational limits may be (temporary) airspace restrictions, but can also be airline specific. This is for example the case if some airlines can not use a certain country’s airspace due to sanctions or safety measures [16]. This research attempts to bridge that gap by testing optimized trajectories as a sequence of waypoints to propose a trajectory that can fulfil the requirements of a flight plan [17]. For the trajectory optimization, the open-source trajectory optimizer OpenAP.top by Sun [18] is used.

2.6.1. Trajectory optimization with OpenAP.top

OpenAP.top is a completely open four-dimensional flight trajectory optimizer. Although it can cover all flight phases, for this study only its cruise optimization will be leveraged. This optimizer is built on the open aircraft model OpenAP [19] and uses the open-source non-linear optimal control solvers CasADi [20] and IPOPT [21] for the optimization.

To generate optimal trajectories, OpenAP.top adopts a non-linear optimal control approach that uses direct collocation methods. It can integrate meteorological conditions while optimizing for conventional fuel and cost index objectives. Its performance and the accompanying uncertainties have been analyzed for several factors such as varying mass, cost index and wind conditions. Where other optimizers might focus on solely the cruise phase [22] or specifically the climb or descent phase [23], this optimizer is unique in the way that it can integrate all flight phases in the optimization. However, more importantly for this research, it is a fully open source trajectory optimizer that can create results within seconds. This time efficiency is important in a time limited research project such as this one.

The time efficiency of this optimizer comes at a cost. It relies on deterministic objective functions with fixed coefficients, which in principle can be random variables. Treating these coefficients as such, would allow the problem to be considered a stochastic optimization. However, this would demand more computationally intensive methods such as the Monte Carlo method to solve the optimization problem.

2.7. Data sources

For this study, two notable data sources are utilized. Namely flight data, as explained in [subsubsection 2.7.1](#) and weather data, as explained in [subsubsection 2.7.2](#).

2.7.1. Aviation Data Repository for Research

For this research, only flights within Europe will be considered. The flight data is retrieved from the Aviation Data Repository for Research (ADRR) [24]. This contains data on both the filed flight plan and the actual flight path flown. The variables used for this research include the call sign, latitude, longitude, altitude and

time. Flight data was downloaded for one single day to keep computation times to a minimum. The chosen day is March 14 2019. This date was chosen to eliminate any influences from the Covid-19 Pandemic [25], but also because it was identified as a date with a larger amount of contrail occurrence, as illustrated in [subsubsection 2.7.2](#). To further reduce the amount of data it was chosen to only consider flights of the top 10 airlines flying in and out of Schiphol within Europe that day. The flights were then reduced to their cruise phase, using the `Traffic` library [26] and resampled to 10-second intervals. This collection of flights is portrayed in [Figure 2](#).

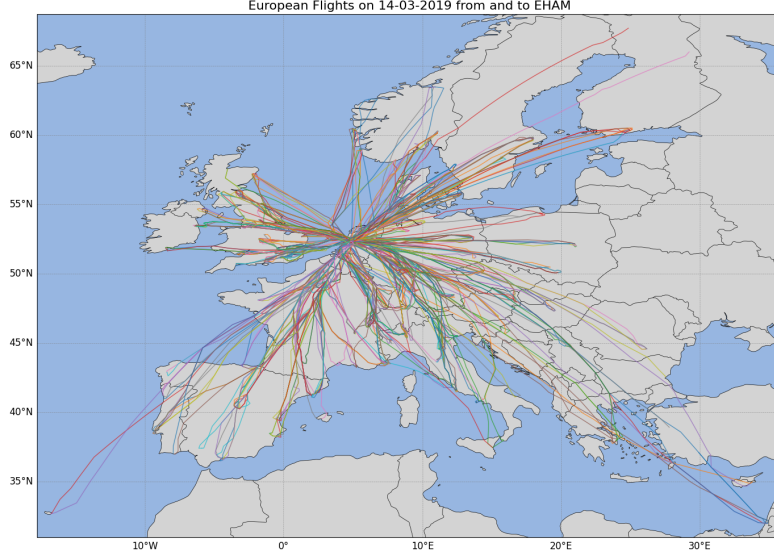


Figure 2: European flights from/to EHAM top 10 airlines 14-03-2019

2.7.2. Atmospheric data

For the purpose of trajectory optimization, weather data is needed on variables such as wind, temperature and humidity. This is obtained from the ECMWF ERA5 dataset which provides hourly atmospheric data on a 31 km grid using 137 levels from the surface of the earth up to a height of 80 km [27]. Obtaining this data can be very time consuming, but this is mitigated using the open-source `fastmeteo` tool [28]. Using the conditions explained in [subsection 2.2](#) a 4D grid can be created which associates a binary cost indicator to each coordinate and timestamp in the grid to determine if persistent contrails will form at that time and place. The trajectory optimizer shall then avoid grid points associated with a cost of 1. However, as this binary mask can create challenges in the optimization, the grid is smoothed to allow for more realistic trajectories. For each altitude a kernel of 3 by 3 pixels is applied using two-dimensional convolution. The binary values will stay intact, while the surrounding pixels are assigned a higher cost. This is done using the SciPy `convolve2d` function [29]. This method of smoothing was obtained from Roosenbrand, Sun, and Hoekstra [30].

As only one day of data is analyzed in this research, it is important to consider a day where the conditions allow for persistent contrail formation to see a significant change using the optimized trajectories. Therefore a period of two weeks was analyzed to determine which day had the highest amount of non-zero grid points, this was identified to be March 14 2019, see [Table 1](#).

The grid cost per location depends on the altitude and the time. However, to show the concentration of where atmospheric conditions allow for persistent contrail formation, [Figure 3](#) and [Figure 4](#) show some examples.

3. Methodology

This sections presents the approach used to determine how much flight trajectories can be optimized for contrails within the limits of standard flight plans. [Subsection 3.1](#) highlights how the optimal trajectories

Table 1: Percentage of persistent contrail conditions per day

Date	Percentage	Date	Percentage
14-03-2019	10.58%	01-03-2019	8.16%
12-03-2019	9.05%	06-03-2019	7.92%
08-03-2019	8.69%	09-03-2019	7.81%
13-03-2019	8.62%	04-03-2019	7.80%
02-03-2019	8.34%	03-03-2019	7.41%
05-03-2019	8.19%	07-03-2019	7.27%
11-03-2019	7.01%	10-03-2019	7.05%

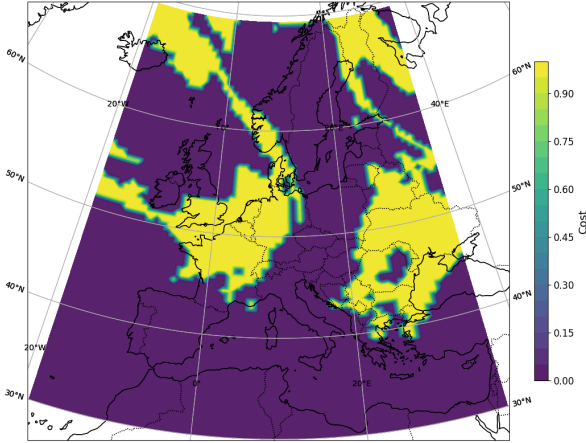


Figure 3: Contrail cost grid FL28 14-03-2019 06:00:00

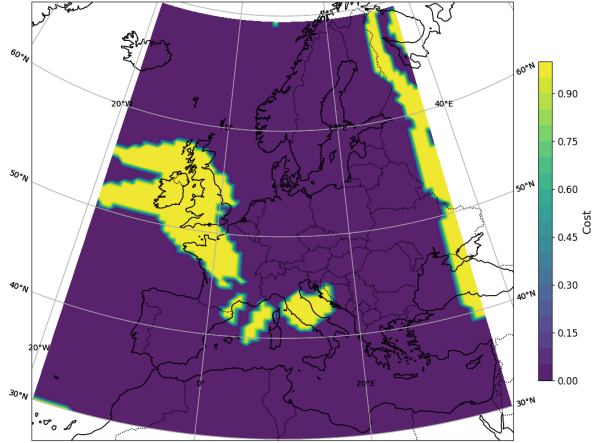


Figure 4: Contrail cost grid FL34 14-03-2019 22:00:00

were simulated. Subsequently, [subsection 3.2](#) will describe how this optimal trajectory is approximated using waypoints to imitate a flight plan. Lastly, the method used to estimate the emissions of different flights is explained in [subsection 3.3](#).

3.1. Trajectory optimization

To determine how much the climate impact of the flights can be decreased in terms of fuel use and persistent contrail formation, the original flight trajectories shall be compared to optimal simulated trajectories. These will be created using OpenAP.top [18], which is an optimizer that accommodates using a grid-based cost function, such as the contrail grid described in [subsubsection 2.7.2](#). As persistent contrails need a lower temperature to form, they are more prevalent at higher altitudes. Therefore only the cruise phase of the flights is considered. The objective function is then defined to balance fuel use and persistent contrail formation, as is done in [Equation 6](#). The fuel use is computed using the `obj_fuel` function from OpenAP.top. The cost index C_i can then be chosen to determine how much the optimized trajectory should favour contrail minimization at the cost of fuel.

$$\text{Cost Function} = C_i \cdot \text{Contrail} + (1 - C_i) \cdot \text{Fuel} \quad (6)$$

To illustrate the effect of this C_i , [Figure 5](#) and [Figure 7](#) show the cruise optimization of a flight from Athens to Amsterdam for different C_i for two different synthetic cost grids. The first uses as cost grid created using a step function as described in [Equation 7](#) and shown in [Figure 6](#), which divides Europe horizontally in an area with high cost and an area with low costs, separated through a gradient. The latter creates a circular cost area, where the cost smoothly decreases as the distance from the centre decreases. This cost grid is

created using Equation 8 and is shown in Figure 8. From figures Figure 5 and Figure 7, the trade-off made between contrails and fuel can be clearly seen with the increasing C_i . For higher C_i , the trajectories show an increasingly larger detour, resulting in higher fuel use, but a minimization in contrail formation.

$$\text{cost}(x, y) = \frac{1}{1 + e^{-s(y-y_0)}} \quad (7)$$

$$\text{cost}(R) = \begin{cases} \frac{1}{2} \left(1 + \cos \left(\pi \cdot \frac{R}{R_{\max}} \right) \right), & \text{if } R \leq R_{\max} \\ 0, & \text{if } R > R_{\max} \end{cases} \quad (8)$$

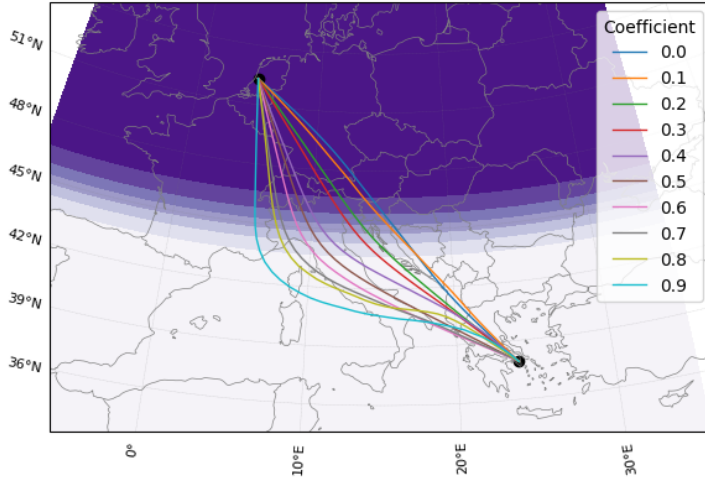


Figure 5: Optimized trajectories from Athens to Amsterdam with varying C_i

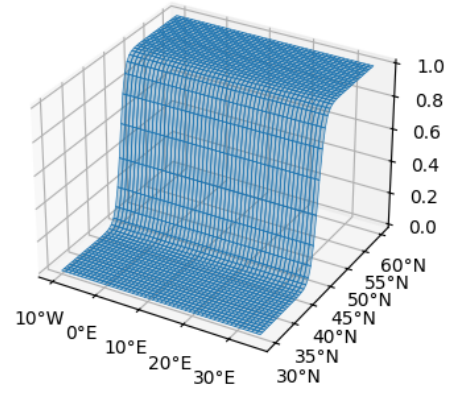


Figure 6: Cost grid of step function

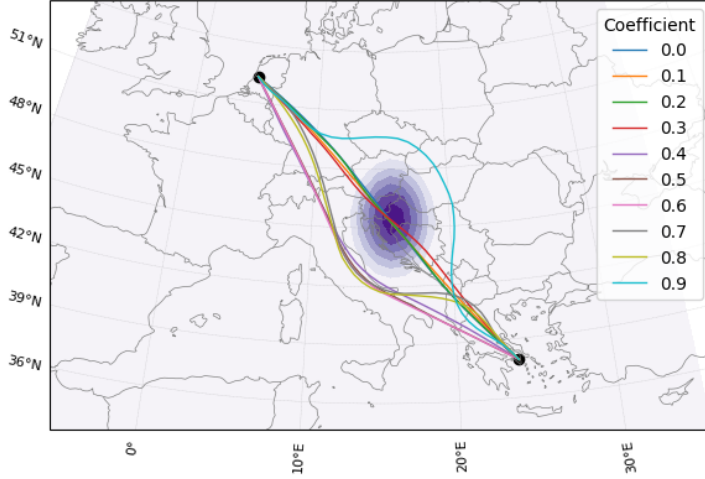


Figure 7: Optimized trajectories from Athens to Amsterdam with varying C_i

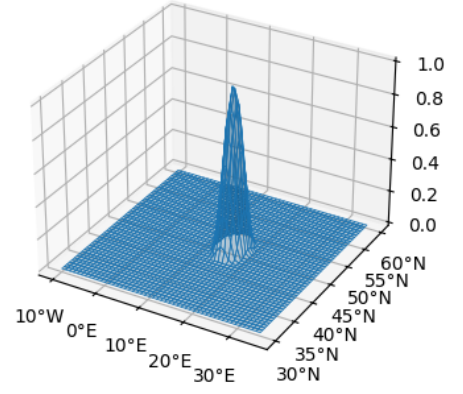


Figure 8: Cost grid of cosine based function

For this research a cost index C_i of 0.8 is chosen to bias the minimization of persistent contrails without removing all limits on fuel use. In addition to this, atmospheric data is used to account for the wind in the optimization. The initial mass is estimated using a definition from Tassanbi [31] created to estimate the takeoff mass in kg for the A320, which can be seen in Equation 9. h_{ft} is the altitude in ft and d_{km} is the

total flight air distance in km. As this function estimates takeoff mass, 2000 kg of is subtracted to simulate the fuel used during climb. To ensure that only significant flights are taken into account in the analysis, only flights with a minimum cruise time of 30 minutes are considered.

$$m_{\text{takeoff}} = 1.8533d_{\text{km}} - 1.99133h_{\text{ft}} + 133497 \quad (9)$$

Before the flights are optimized, the original flights are evaluated for persistent contrail formation. As the objective is to minimize persistent contrails, flights that do not create persistent contrails originally, are not taken into account in the optimization. The threshold is set at a minimum of 20 minutes of contrail formation in the original flight. To carry out the optimization, an initial guess can be provided to minimize the chance of the optimizer not converging within the maximum amount of iterations determined. For this purpose, the original flight is used as the initial guess.

3.2. Fitting algorithm to approximate the trajectory

This research aims to answer not only the question of how much flight trajectories can be optimized to minimize climate impact, but also how this can be done while adhering to the bounds of the standard airline flight plan. This section explains the methodology used to test if the optimized trajectories could be used within operational limits.

3.2.1. Airline-specific waypoints

Different airlines will have different cost functions to determine their standard flight plan for a route. In general, airlines will try to minimize the operational costs, but trade-offs can be made to for example minimize flight time or avoid certain regions for political reasons. An example of such a difference between two airlines can be seen in [Figure 9](#). KLM, as a full-service carrier, will be less concerned with en-route unit rates for air traffic control services and more so with minimizing the total flight time. For Transavia, a low-cost carrier, this is the other way around. As the en-route unit rates for air traffic control services in Switzerland are the second highest out of all European countries [\[32\]](#), both airlines will try to avoid flying through its airspace. However, it can be seen that Transavia favours Slovenian and Croatian airspace for Italian airspace, as these en-route unit rates are both lower, while this does increase the total flight distance [\[32\]](#).

Because of these differences, the collection of possible waypoints for fitting a flight depends on the operator. The official set of waypoints defined in March 2019 is not available, thus all coordinates used in the filed flights from the ADRR dataset are defined as the set of usable waypoints. Then it is determined that for each operator, only the waypoints are available that have been used at least once in any of the flights carried out by that operator in March 2019. An example for different airlines is shown in [Figure 10](#).

3.2.2. Waypoint selection by clustering algorithm

With the optimal trajectory defined and a selection of airline-specific waypoints determined, the trajectory can be approximated as a sequence of waypoints. This shall be called the fitted route. The fitted route is constructed as follows.

The latitude and longitude coordinates of the contrail optimized trajectory are transformed to Cartesian coordinates. Subsequently all waypoints that fall within a range of 20 km from any point on the trajectory are selected. These waypoints are then clustered using a hierarchical density-based clustering clustering called HDBSCAN [\[33\]](#). For each cluster only one waypoint is selected, which is the waypoint with the smallest distance to the optimized trajectory. Out of the outlier waypoints that are not in any cluster, only the waypoints with a maximum distance of 5 km to the trajectory are included. This collection of points is then completed with the origin and destination coordinates of the contrail optimized flight and makes up the fitted route. An example of this for a flight from Amsterdam to Madrid can be seen in [Figure 11](#).

Subsequently, the full trajectory is created by obtaining the flight data from the points in the optimized trajectory closest to the fitted route points. These are then ordered by timestamp before being resampled at 10-second intervals to complete the trajectory.

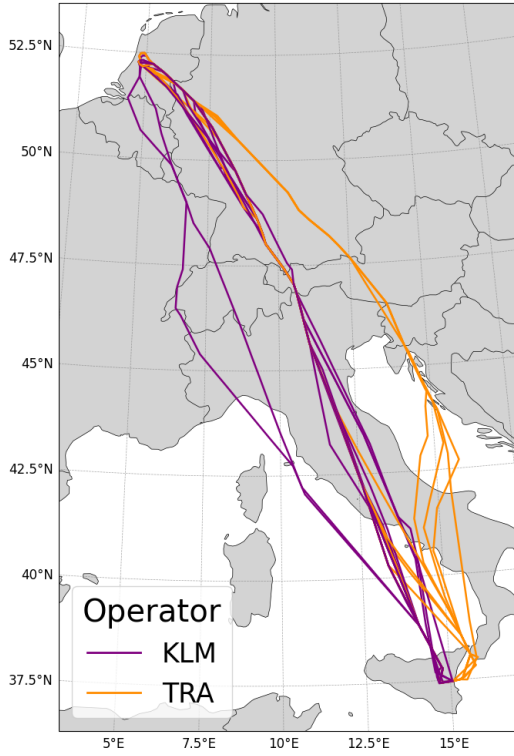


Figure 9: Flights from EHAM (Amsterdam) to LICC (Catania) for KLM and Transavia 03-2019

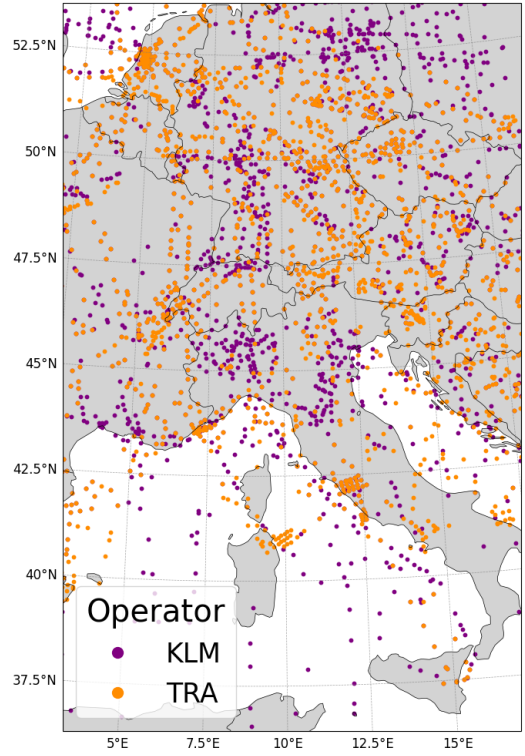


Figure 10: Available waypoints for KLM and Transavia 03-2019

An exception to this method is made when the contrail optimized route fails to converge. In such a case, the cost of the optimized route is higher than that of the original route. The contrail optimized route is then discarded, but a fitted route is still needed. To obtain the fitted route, the fuel optimal route is now considered the optimal route and is used as the base for the fitted route.

3.3. Emissions simulation

In this study, the goal is to present a method that can produce optimized trajectories to minimize climate impact. To that end, several metrics need to be determined. The fuel use of a flight shall be determined using OpenAP [34]. As only flights in Europe are considered, the aircraft characteristics of an A320 will be used in all calculations, as it is a popular narrow body aircraft used in Europe [35]. Equation 9 is used to estimate the takeoff mass. Next to this, the amount of time that persistent contrails are produced per flight shall be found. This is determined by interpolating the flight trajectory along the contrail cost grid.

4. Results

Using the method explained in section 3 a set of 841 European flights flying in or out of Schiphol on March 14 2019 are evaluated. This section will present the results. Different metrics such as fuel use, persistent contrail formation, flight time and distance will be analyzed, as well as the adherence to operational limits for the fitted routes. Subsection 4.1 will explain the different metrics used. Then two flights will be shown in detail in subsection 4.2, before showing the analysis of the total result set in subsection 4.3.

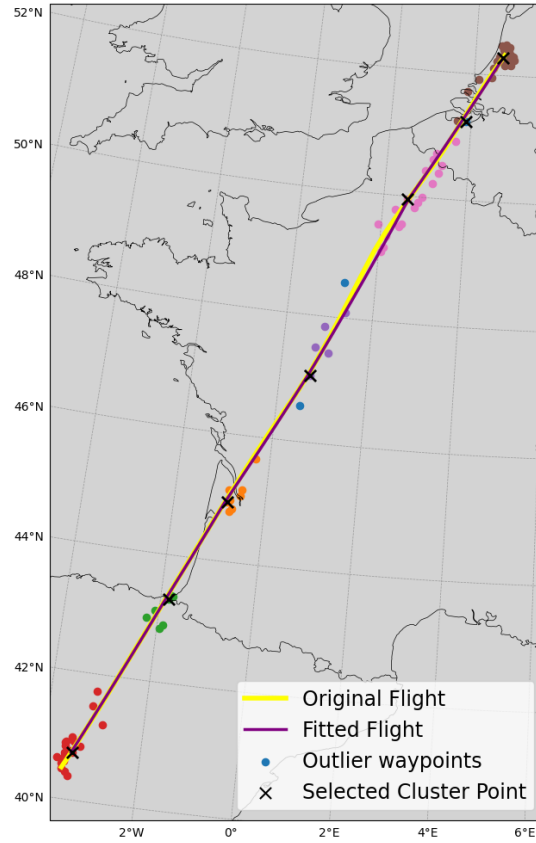


Figure 11: Fitted route and waypoint clusters EHAM-LEMD

4.1. Metrics used for comparison

For each flight, three different trajectories are compared. Namely the original trajectory, the optimized trajectory and the fitted trajectory. They will be compared on the following metrics:

1. Fuel use [kg]
2. Flight distance [nm]
3. Flight time [s]
4. Time persistent contrail formation [s]

Next to this, the deviation of the fitted flight from the optimized flight is considered to determine if the trajectory can fulfil operational constraints.

Out of 841 flights, the computations were done for 257 flights. The other flights could not be analyzed because the cruise phase was shorter than 30 minutes. This was either because part of the flight took place on another day, but mostly because flights were too short for **Traffic's** **phases** function to be able to identify (a long enough) cruise phase. Out of these 257 flights, the analysis is only done for flights that already produced persistent contrails in the original trajectory, as that is what is being minimized. Flights which already did not produce persistent contrails for 20 minutes or longer in the original trajectory were discarded, leaving 75 flights total.

4.2. Highlighting two flights in detail

Figure 12 and Figure 13 show a flight from Amsterdam to Porto. They show the original, optimized and fitted trajectory, and the underlying red lines indicate persistent contrail formation. In Table 2 the different

metrics are shown. It can be seen that even though there is no difference in flight time and only a small difference in flight distance between the optimized and fitted route, there is a difference in fuel use and persistent contrail time. The fuel use of the fitted flight is higher and so is the contrail time. The cause for this can be deduced from Figure 12 and Figure 13 as it can be seen that the trajectory and altitude of the fitted flight deviate from the optimized flight. The maximum deviation in the horizontal plane is only 9.21 km, as can be seen in Table 2, but the 8.3% difference in fuel use between the optimized and the fitted can be attributed more to the difference in altitude. Although the contrail time has a large relative difference between the fitted and optimized flight, an absolute difference of 2 minutes is very small and does not significantly change the climate impact of the flight.

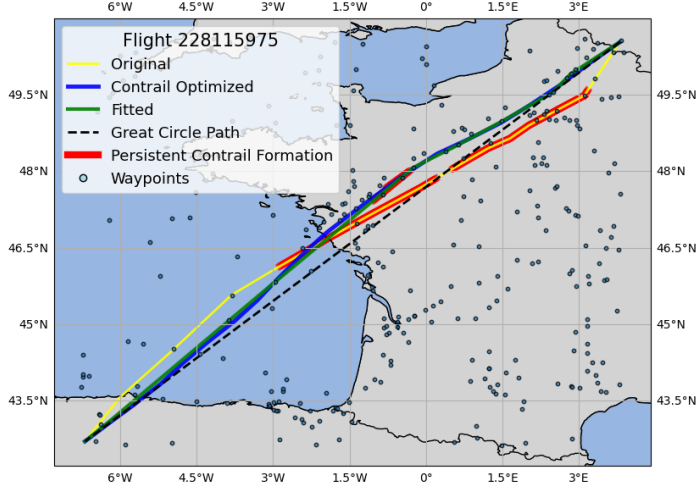


Figure 12: Trajectories flight 228115975

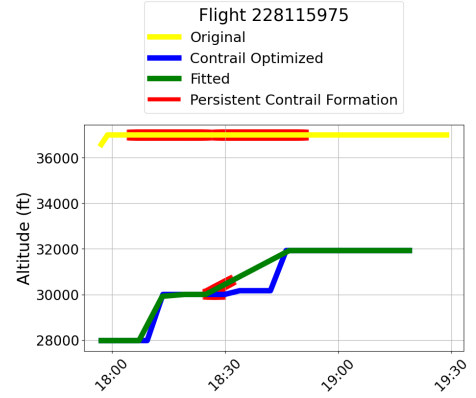


Figure 13: Altitude trajectories flight 228115975

Table 2: Comparison metrics for flight 228115975

Metric	Original vs Contrail Optimal	Original vs Fitted	Contrail Optimal vs Fitted
Flight time	-10 (-10.7%)	-10 (-10.7%)	+0 (+0.0%)
Flight distance	-122 (-16.0%)	-123 (-16.1%)	-1 (-0.1%)
Fuel use	+342 (+10.3%)	+644 (+19.5%)	+302 (+8.3%)
Persistent contrail time	-40 (-92.2%)	-38 (-87.5%)	+2 (+60.0%)
Maximum deviation of fitted flight [km]			9.21 km

The second flight considered takes off in Madrid and lands in Amsterdam. From Table 3 it can be seen that the fitted route deviates more from the optimized route than the previous flight, with a maximum of 16.65 km. As the altitude for both the optimized and fitted route are the same, which is shown in Figure 15, this small deviation results in the difference of 0.6% in fuel use described in Table 3 between the two trajectories. A notable result for this flight is the large increase in fuel use for the optimized, and subsequently the fitted flight, with respect to the original flight, considering the flight distance is shorter. This is caused by the lower altitude of the optimized flight.

Table 3: Comparison metrics for flight 228115502

Metric	Original vs Contrail Optimal	Original vs Fitted	Contrail Optimal vs Fitted
Flight time	+1 (+1.0%)	+1 (+1.0%)	+0 (+0.0%)
Flight distance	-132 (-20.8%)	-195 (-30.7%)	-63 (-12.5%)
Fuel use	+373 (+14.2%)	+391 (+14.9%)	+19 (+0.6%)
Persistent contrail time	-29 (-81.6%)	-29 (-79.7%)	+1 (+10.0%)
Maximum deviation of fitted flight [km]			16.65 km

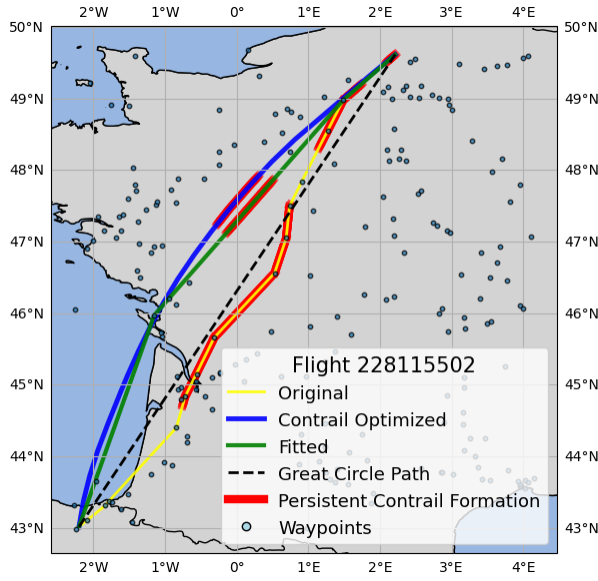


Figure 14: Trajectories flight 228115502

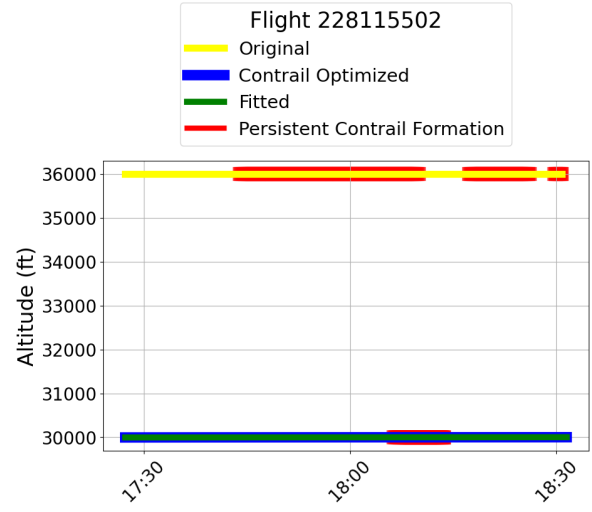


Figure 15: Altitude trajectories flight 228115502

4.3. Results of total data set

The results presented for only two flights in the tables in [subsection 4.2](#) are also computed for the total of 75 flights and can be seen in [Figure 17](#). The complete set of contrail optimized trajectories can be seen in [Figure 16](#), with the contrail grid showing the persistent contrail forming areas at the mean altitude of these trajectories. Out of the 75 flights, there were 13 flights for which the optimization did not converge and the cost of the contrail optimized trajectory was higher than the cost of the original flight. For those flights, the fitted flights are based on the fuel optimal trajectories. In the histogram the three different trajectories - original, contrail optimal, fitted - are compared to each other. The three different histograms are in one plot to ease comparison. This does result in mixing of the colors where there is overlap. To be able to see where there is overlap, the different histograms have different opacity.

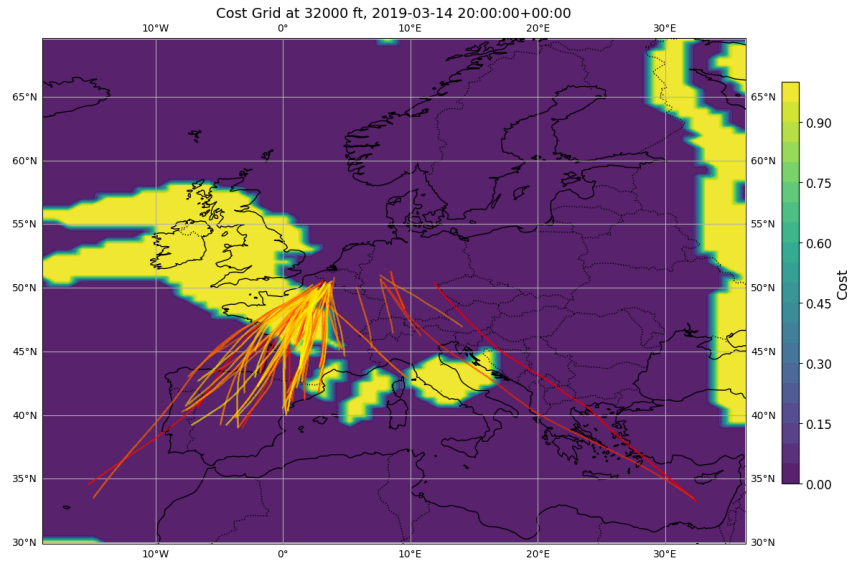


Figure 16: Contrail optimized trajectories and the contrail cost grid at 32000 ft

It should be noted that there is only a small difference in flight time for the optimized and fitted flights. The flight time for the optimized and fitted flights are very similar. Looking at the flight distance, it can be seen that this is more often decreased for the optimized flight compared to the original. This happens even more so for the fitted flights. The contrail optimized and fitted trajectories show a lower contrail time overall, but a higher fuel use in the majority of the cases.

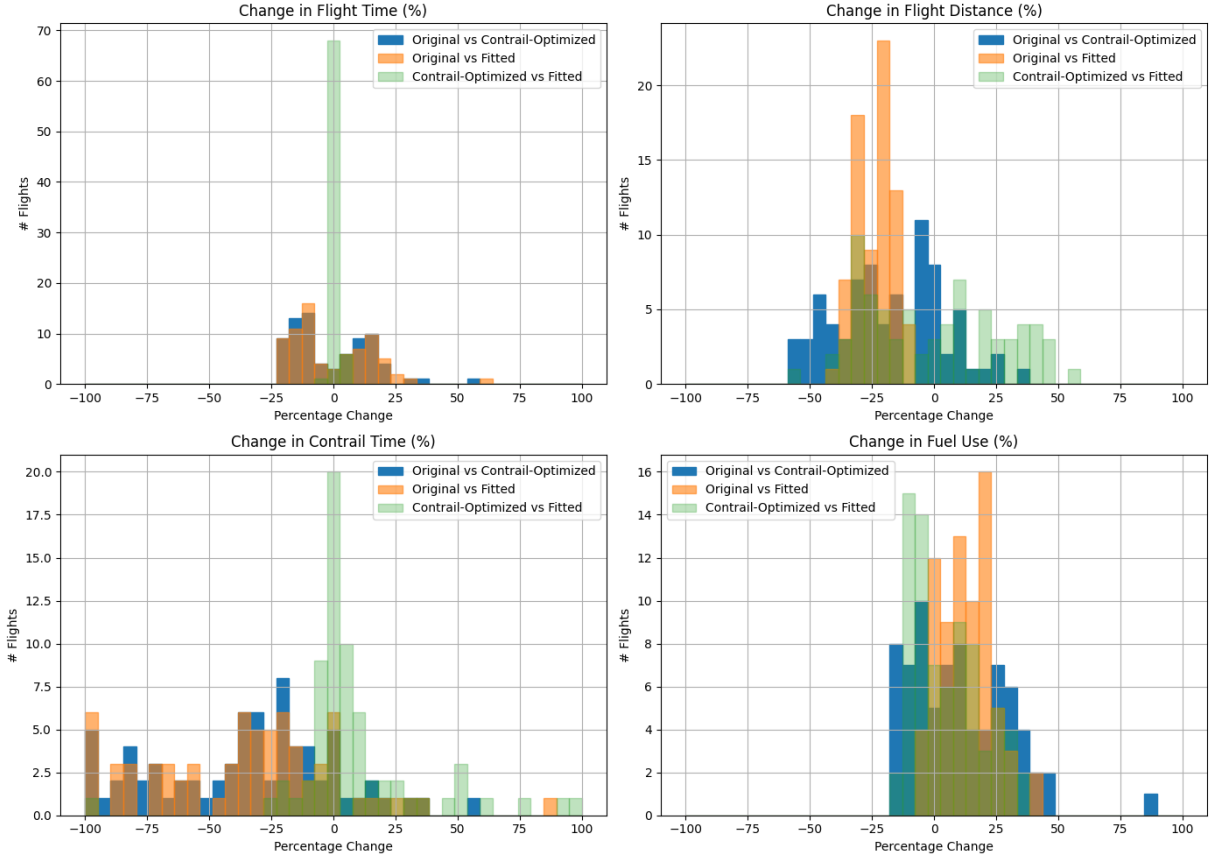


Figure 17: Histograms of change in flight time, flight distance, contrail time and fuel use

Figure 18, Figure 19, Figure 20 and Figure 21 show scatter plots for all 75 flights where the differences in contrail time and fuel use between the different trajectories are shown. In each plot, it has been marked which flights had a successful optimization. The following definitions are used:

- Contrail failed : $\text{cost contrail optimal} > \text{cost original}$
- Fuel failed: $\text{fuel use fuel optimal} > \text{fuel use original}$
- Total failed: both contrail failed and fuel failed

From Figure 19 it can be seen that for the successfully optimized flights, there can be a trade-off where more fuel is used to offset the mitigation of persistent contrails. Figure 19 shows that the contrail optimized trajectories use the same amount or more fuel than the fuel optimized trajectories, which is to be expected. Figure 20 gives a clear view of the flights where the fuel optimization did not converge and no optimal trajectory was found with a lower fuel use than the original flight. Lastly, in Figure 21 it can be seen that the fitted flights stay close to the optimal flights in terms of persistent contrail formation, with a maximum of 21 minutes more persistent contrail formation for one of the flights. On the other hand, the fuel use has larger deviations, both in the negative and positive direction.

Lastly, the quality of the fitting approximation can be determined using the results on the maximum deviation of each fitted trajectory. Figure 22 shows a histogram of the maximum deviation for all flights as a ratio

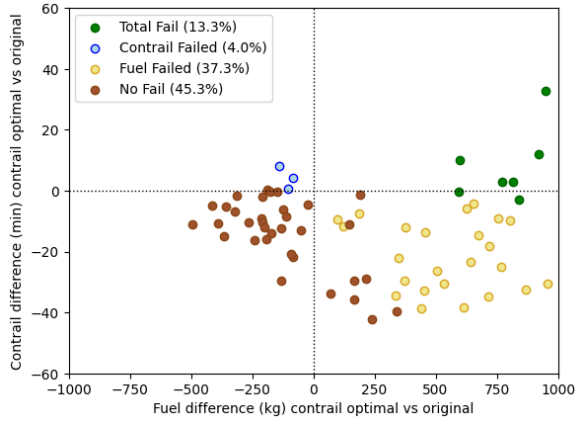


Figure 18: Contrail optimal vs original trajectory

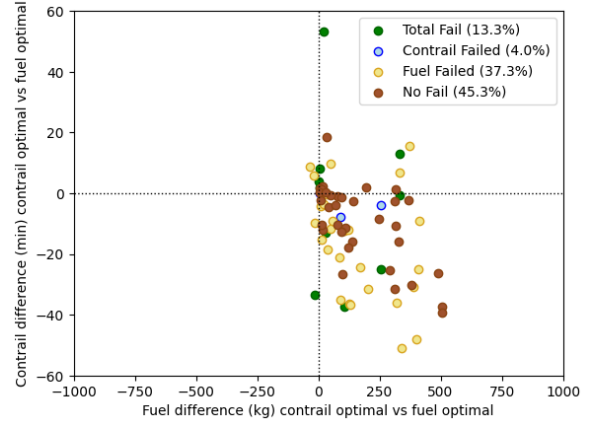


Figure 19: Contrail optimal vs fuel optimal trajectory

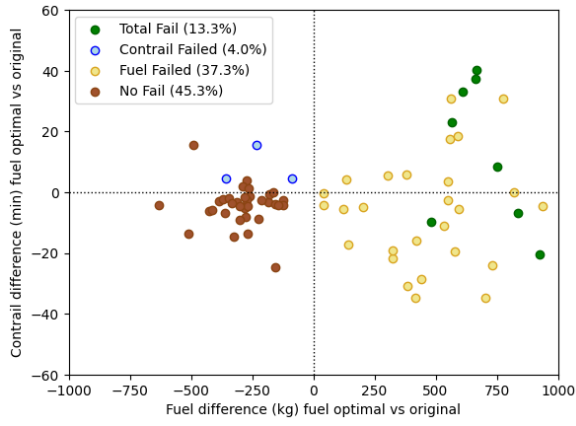


Figure 20: Fuel optimal vs original trajectory

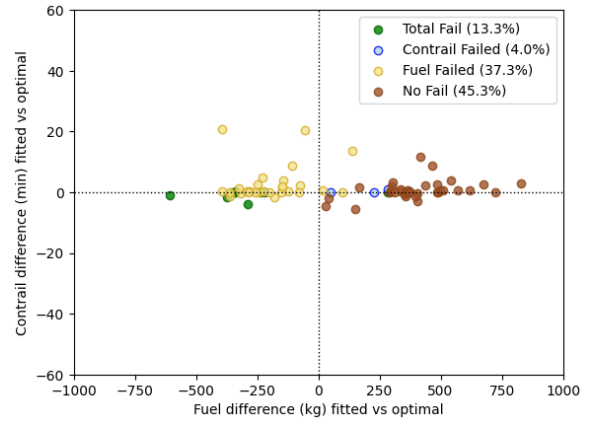


Figure 21: Fitted vs optimal trajectory

of the along track distance of the optimized trajectory. The maximum deviation is 4%. In [Figure 23](#) the absolute deviations are shown. While the majority of flights has a maximum deviation lower than 10 km, there are some outliers that have a maximum deviation of over 40 km, which can be seen from the box plot in [Figure 23](#).

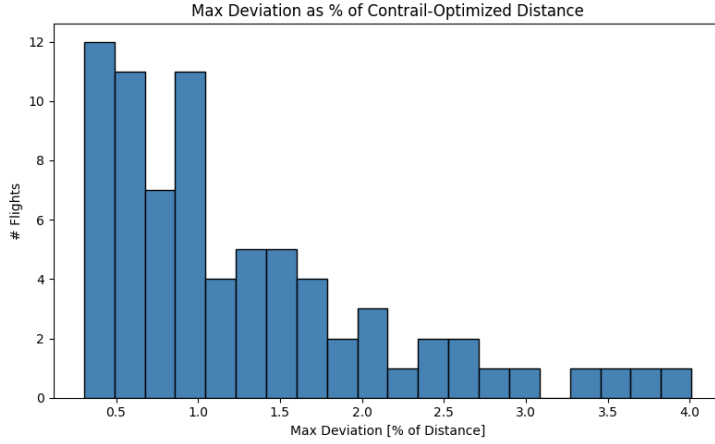


Figure 22: Histogram of maximum deviations of fitted flight trajectories

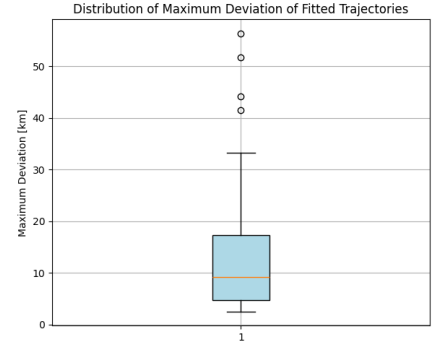


Figure 23: Box plot of maximum deviations of fitted flight trajectories

5. Discussion

The hypothesis was that the optimized flight trajectories should decrease persistent contrail formation along with keeping the fuel use to a minimum. The cost function Equation 6 ensures that this happens when optimizing the trajectories. However, from Figure 18 it can be determined that this is not the case for a small part of the flights. Close to a 100 % of the flights are expected to be in the lower half of the plot, as the cost index C_i of 0.8 heavily biases the reduction of persistent contrails. For 13.3% of the flights, both the contrail and fuel optimization failed, which is significant. In Figure 18 many flights have reduced contrail formation compared to the original flight. However, it is clear from the concentration of fuel failed flights in the bottom right of this figure, that, if the fuel optimization does not converge, this also influences the contrail optimized flights as 20% of the cost is based on the fuel use.

Subsequently, the quality of the fitting algorithm can be discussed. From Figure 23 it can be deduced that a large part of the flights has relatively small horizontal deviations. However, there is also a substantial amount of flights that do show a larger deviation, impacting the fuel usage and persistent contrail formation as can be seen in Figure 17. There is no metric for the deviations fitted flights show in altitude from the optimized trajectories, but as can be seen in Figure 13, this can also cause a change in fuel use or persistent contrail formation.

5.1. Issues trajectory optimization

First and foremost, it should be said that the optimization is not always working as intended. From Figure 18 it can be seen that over half of the flights either failed in fuel or contrail optimization. There are several possibilities for the cause of these sub-optimal results. Firstly, a maximum of 8000 iterations is set for each optimization. For a small number of flights it was tested to set this to a higher number, which did not immediately result in more favourable results, so the maximum amount of iterations is not likely to be the culprit of this discrepancy. Next to this, the amount of nodes in the optimization was also varied, without seeing a change in the results. Therefore, it must be considered that there is another reason for the sub-optimal trajectories. To this end, the optimization was done again using a C_i of 0.8 for the 75 flights with a different scenario, which can be seen in Figure 24. The wind is not considered in this optimization and a circular cost grid is placed in the South-East of France. Visually, it can be identified that the contrail optimal trajectories minimize the distance flown through the high cost areas. From this, it raises the question if the sub-optimal flights in the optimization for 14-03-2019 may be caused due to the optimizer struggling with the wind grid or the location and amount of ISSR areas. For a comprehensive analysis to be made, this issue should be investigated in future work.

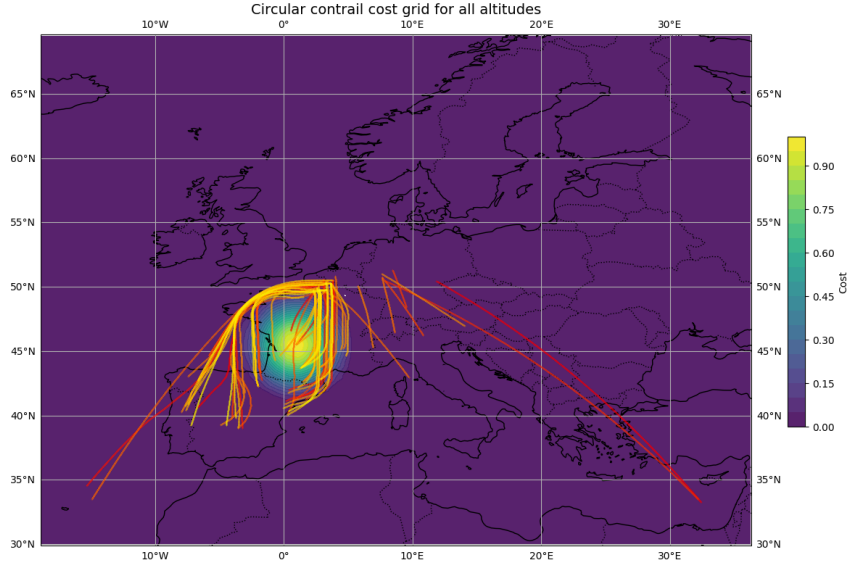


Figure 24: Contrail optimized trajectories and a circular contrail cost grid for all altitudes

5.2. Issues emission simulation or contrail evaluation

The fuel use of the flights is determined using OpenAP. As this is a simulation tool, it can be expected that the fuel use is not exactly calculated, although it should be an accurate approximation. However, uncertainties will carry over to the calculation of all the flights, so relative differences are less prone to errors. However, it is important to verify whether the evaluation was performed correctly. Otherwise, the trajectory optimization might actually be valid, but an error in the fuel analysis or contrail analysis could lead us to incorrectly conclude that the optimization did not converge. The flights for which the fuel optimization failed were analysed and it was found that the optimal trajectory proposed was indeed suboptimal, thus the fuel evaluation was not the culprit. An example of this can be seen in [Figure 25](#). The fuel optimal flight uses 29.2% more fuel than the original flight, although it has a more direct trajectory. This added fuel use is because the fuel optimal flight is at a lower altitude, which also causes the total flight time to be longer, even at a higher speed, as can be seen in [Figure 26](#). This shows, that the optimized trajectory itself is the problem and not the evaluation of the fuel use that is done afterwards.

5.3. Influence chosen C_i

For this analysis a cost index C_i of 0.8 was chosen, heavily biasing the minimization of persistent contrails with respect to the minimization of fuel use. The net climate effect of contrails is still uncertain and highly dependent on the optical properties of the contrail and the place and time they form [\[7\]](#), as contrails can also have a cooling effect on the earth. Therefore it might be more beneficial for the climate to bias the trajectories more towards minimizing fuel use.

5.4. Influence cluster size

As explained in [subsection 4.3](#), some fitted flights show a large deviation from the optimized trajectory. This can either be due to sub-optimal clusters or a lack of available waypoints in certain regions. It must be noted that the minimum cluster size used was 5. A smaller cluster size was not used as the current fitting algorithm forced one point to be included from each cluster. Smaller clusters might result in an overly specified flight path, resulting in a type of zigzagging effect. However, in some cases it may also help reduce the maximum deviation for the fitted trajectories.

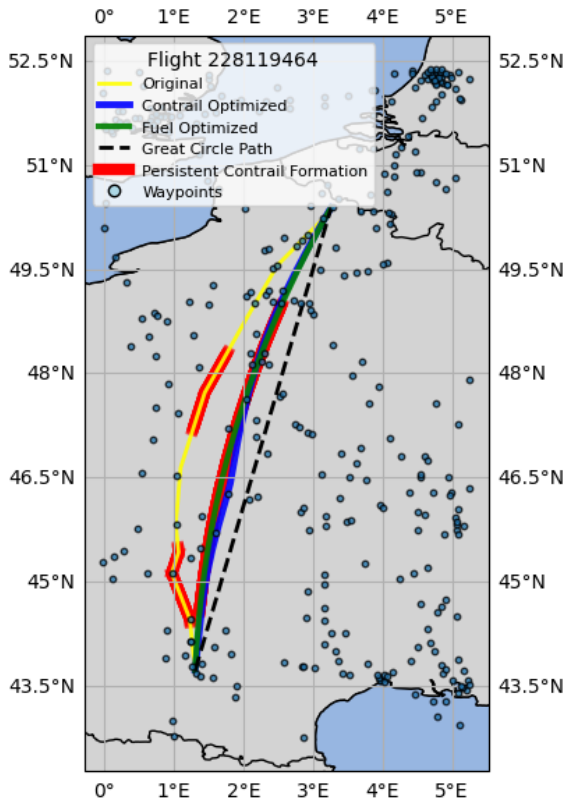


Figure 25: Trajectories flight 228119464

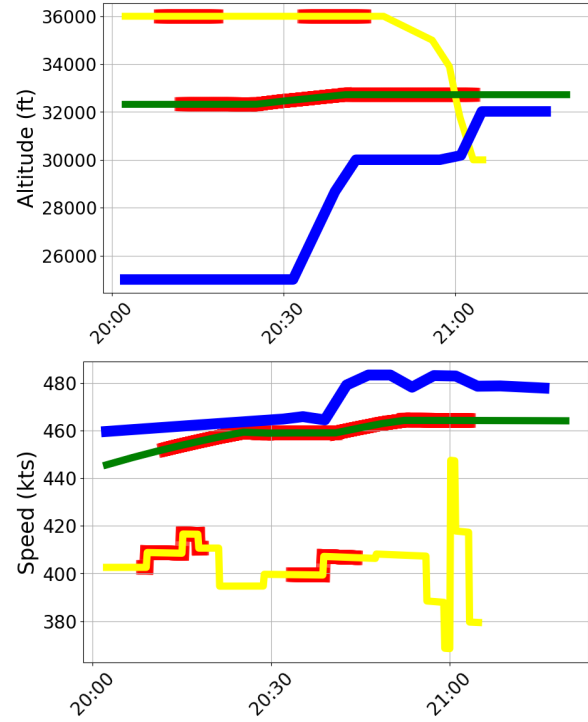


Figure 26: Altitude and speed trajectories flight 228119464

5.5. Influence of altitude retrofitting

In Figure 13 it can be seen that the altitude profile of the fitted flight does not match the altitude of the optimized flight. This is due to the fact that the fitted flight is initially only defined by a small number of waypoints. Flight data is then extracted for the nearest points of the optimized trajectory, including altitude data. If there is a change in altitude, this will be filled by the resampling for the fitted flight, resulting in a linear altitude increase. However, in the optimized trajectories this is more often a steep increase over a short period of time. This difference might result in the fitted flight flying through persistent contrail formation zones for a longer time.

5.6. Cruise only analysis

In this analysis, only the cruise phase is considered. This makes sense from the contrail minimization perspective, considering these form mostly at higher altitudes. However, if the topic is approached for climate impact as a whole, the climb and descent procedures can contribute significantly, especially regarding local air quality. Another issue with this cruise only approach, is the fact that shorter flights, such as many flights within Europe, do not have a long dedicated cruise phase. The time and distance between Top of Climb and Top of Descent may be relatively short preventing the simulation from creating a trajectory. However, these flights can also contribute to persistent contrail formation, but they are currently not considered.

5.7. Single day analysis

Due to the scope of the project, flights are now only analyzed for one day and flying in and out of Amsterdam. However, as persistent contrail formation highly depends on the temperature, it would be more interesting to see if there are large differences between the summer and winter months. In addition to this, it has been found that a large part of persistent contrails are created in relatively small geographical areas [36], making

a case for exploring concentrations of flights in other areas in Europe as well.

5.8. Assumption A320 and MTOW

It must be noted that for this analysis the assumption for all flights was made to use aircraft characteristics for an A320 at the approximated Maximum Takeoff Weight by Equation 9. This does not have a great impact when showing the potential for reduction, however for absolute values of reduction this has its limitations. Only airlines know the actual takeoff weight, which can result in different optimized trajectories.

5.9. Unknown operational limits airlines

It was assumed for this analysis that airlines allow for flight plans that use waypoints they have used in the month of June 2019. However, this is a simplification and many other factors may apply when determining airline-specific waypoints. In addition to this, flight plans that airlines file are not just created as a sequence of waypoints, but must also detail the flight levels at which to fly, as well as departure and approach procedures. None of these are specifically included in the flight plans created in this research.

6. Conclusion

The objective of this research was to determine how much flight trajectories can be optimized to minimize climate impact, considering fuel burn and persistent contrail formation, while adhering to the bounds of the standard airline flight plan. Due to inconsistent results, this research cannot give a conclusive answer.

One day of European flights in and out of Schiphol Airport were evaluated and a contrail optimal trajectory was determined for each flight using the OpenAP.top trajectory optimizer and contrail cost grids created with ECMWF ERA5 data. Each optimized trajectory was then approximated by a sequence of waypoints resulting in a fitted route. By only using waypoints utilized more often by the airline operating the flight, it is expected that the fitted trajectory could indeed be utilized in real life operations.

Due to an unknown issue in the trajectory optimization, it cannot be concluded that most original flight trajectories can further be optimized to reduce fuel use and persistent contrail formation. Most flights do show a reduction in persistent contrail formation, but in many cases this is offset by a large increase in fuel use due to fuel optimization failing.

It can be determined that trajectories optimized without any spacial limitations, except for a minimum flight level, can be approximated using discrete waypoints. For many trajectories, this results in a fitted route which does not deviate more than 15 km from the optimized route.

Future studies may solve the issues encountered with the trajectory optimization to effectively answer the questions posed. If this issue is solved, the study might contribute to less aviation induced climate effects as persistent contrail formation might be reduced.

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