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Time of the day-dependent impact of Contrail Avoidance Strategies on Airline Delay Costs

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***Abstract*—Condensation trails play a significant role in anthropogenic climate change and are subject to considerations for establishing a sustainable global air transport system. However, many optimization strategies employed currently utilize simplified models that overlook the influence of time of day on the climate impact of contrails. Additionally, operational costs, including delay costs, are often disregarded in contrail avoidance efforts. In this study, we conduct an optimization analysis for a scenario involving 129 flights, employing various contrail avoidance techniques. We evaluate the costs associated with each technique based on the time of day. Our findings enable us to determine the conditions that encourage or discourage contrail avoidance. Throughout most of the day, delay costs surpass contrail costs. However, during daytime hours, significant reductions (up to $50\,\%$) in contrail costs can be achieved by minimizing the distance traveled through ice-supersaturated regions. During the nighttime, only minor detours (resulting in short delays) should be considered for contrail avoidance, as the fuel savings from avoiding contrails do not outweigh the induced delay costs. Notably, contrails during sunrise and sunset exhibit negative costs and should not be avoided at all. An increased cruising speed by $10\,\%$ reduces the delay costs by approximately $30\,\%$ (which is less than required for flying a detour around ice-supersaturated areas) and requires $1.12\,\%$ more fuel. Furthermore, an increase in cruising speed by $5\,\%$ results in an additional fuel consumption of $0.36\,\%$. These results can be utilized for strategic flight planning, particularly for flights during sunrise and sunset.**

***Keywords*—contrails, delay costs, trajectory optimization**

I. Introduction

A growing environmental awareness grows with each environmental disaster and has now reached every stratum of society and every industry. Air transport is not exempt from this. The contribution of air transport to global warming is a major contributor to anthropogenic climate change [1]. Condensation trails (Contrails) represent a highly volatile, but obviously also avoidable contribution [1]. Contrails are ice crystals condensed around soot particles and other condensation nuclei. The condensed water vapor is either emitted by the aircraft or is already in the atmosphere. In an ice-supersaturated environment, contrails may form into long-living artificial cirrus clouds with increased impact on global warming due to the optical properties of ice crystals with soot cores [2]. However, the shape and location of ice-supersaturated regions are difficult to predict, which is why tactical contrail avoidance is not trivial. But perhaps contrails don't always have to be avoided. In the daytime, can have a solar cooling effect by scattering solar radiation coming from above into the upper hemisphere. However, throughout the whole day, a terrestrial warming effect due to the absorption and re-emission of terrestrial radiation often dominates the cooling effect. Global analysis from 2005 found that $10\,\%$ of the flights' induced condensation trails and therewith contributed to global warming as much as $21\,\%$ of the total aviation CO_2 emissions in the same year [3]. Therefore, lots of studies and optimization strategies focus on avoiding contrail formation by detouring ice-supersaturated regions [4–7]. In those and similar studies, sometimes, lots of delays are generated, and operational impact is not considered/discussed. Specifically, primary and reactionary delay costs are not considered in those optimization scenarios. From this follows: avoiding contrail formation is not necessarily a good optimization function when following a minimum total cost strategy. The situation is aggravated by the fact, that delay costs depend on daytime [8]. This dependency was also not taken into account in previous optimization approaches. Additionally, the impact of contrails depends on the time of the day and year (because solar cooling effect at large solar zenith angles sometimes compensates/exceeds terrestrial heating effect) [9]. Taking into account the time-of-day-dependent influence of contrails on the Earth's radiation budget, the question arises under which conditions contrails should be avoided at the expense of delay costs.

In this paper, we optimize a scenario of 129 flights with different contrail avoidance strategies and calculate time-of-day-dependent contrail costs and delay costs for each strategy. From these results, we can derive circumstances where contrail avoidance is recommended or discouraged.

A. State of the Art

In order to find a global cost minimum between contrail costs and delay costs, methods for optimizing aircraft trajec-

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tories with multi-criteria target functions, for modeling airline delay costs, and for modeling contrail costs are required.

The goal of aircraft trajectory optimization is to maximize the state of the aircraft (such as position, speed, etc.) as a function of time. Ideally, the aircraft is considered as a dynamical system governed by differential equations, or the Equation of Motion (EoM). For example, [10] modeled a vertical trajectory and optimized it in terms of flight time and fuel consumption. To evaluate the effect of wind speed on deterministic optimization, the optimization was evaluated with various constant wind speeds. From takeoff until the final approach, the entire trajectory was optimized by Dalmau et al. [11], whereby the fuel and time savings were calculated using various Cost Index (CI) and aircraft mass values. Occasionally, multiple-phase optimum control is used to model individual flight phases. In this case, numerous approaches to phase separation have been put forth, including the knotting approach [12] and the OC problem divided into a number of switching subsystems [13]. In addition to OC, other formulations have been suggested. Dynamic programming was used to compute a four-dimensional (4D) trajectory in [14], and to speed up the computation, the problem was solved by combining the gradient approach with dynamic programming search. [15, 16] have proposed parametric optimization, in which the trajectory is described by a set of static parameters, and the differential equations are transformed into the corresponding algebraic equations while assuming a common trajectory pattern. Since 2016, a toolchain for simulation-based aircraft trajectory optimization, the TOolchain for Multi-criteria Aircraft Trajectory Optimization (TOMATO) has been developed by [17, 18]. The simulation environment is under continuous development and will be used in this study.

Costs of delays, particularly those that affect passengers, are seldom published in the airline industry. Costs associated with airline delays are frequently a trade secret and a component of the airline business model. The University of Westminster tabulated the expenses associated with delays for various European airlines and released mean numbers for three distinct situations [19]. The scenarios, which are categorized as high, base, and low, reflect various passenger sensitivities. This estimate, which allows for a more thorough analysis of airline delay costs, was designed specifically for 15 aircraft types. Based on the year 2014, [19] provides reference values for the cost of delay to European airlines. The quantity and connectedness of passengers on a particular trip who are sensitive transfer passengers are not taken into account, nor are all cost factors and aircraft types. Several studies approximate delay costs, in order to predict and optimize the aircraft turnaround time [20–26]. These studies frequently linearize or ignore passenger-related expenditures when calculating delay costs. The costs are approximated as parameterized boundary conditions in analytical approaches aiming for the best distribution of airport resources, such as ground handling equipment [27, 28], pushback trucks [29], de-icing slots [30], or aircraft stands [31, 32]. All of these studies do not combine ground and flight operations, therefore they are not required to account for specific financial delay charges associated with individual flights [33].

Effects on delay propagation were studied by Beatty et al. [34] by calculating a network delay multiplier for American Airlines at Dallas/Ft Worth International Airport. Although it would be simple to apply this multiplier to each of these prices, it is unclear how effectively it works in the current environment, especially for flights operated by airlines with significantly different route systems and at various airports.

The radiative forcing of individual contrails was evaluated by Avila and Sherry [35] using a model developed by Schumann et al. [36], under the assumption of a constant optical depth. Using a Monte Carlo code for photon transport in a rough spatial grid and ignoring the impact of flight performance on the optical properties of the contrail, Gounou et al. [37] and Forster et al. [38] examined the radiative effect of single contrails, focusing on the significance of large solar zenith angles at sunset and sunrise. At least, various scattering phenomena are taken into consideration. The Contrail Cirrus Prediction Tool (CoCiP), created by Schumann et al. [36, 39], is an empiric and parametric radiative forcing model that calculates the radiative extinction of single contrails with low dependence on solar zenith angle and particle radius. Rosenow [40, 41] has developed a Monte Carlo approach based on optical properties of single ice particles and considering multiple scattering events thorough investigations with a granular spatial resolution and considering all possible solar zenith angles in order to allow investigations of all day times.

The effectiveness of contrail avoidance strategies has been reviewed and summarized by Gierens et al. [42]. Here, the missing investigations on the impact of delay costs are already emphasized. Furthermore, Soler et al. [5] proposed an application of a multiphase mixed-integer optimal control approach for aircraft trajectory design avoiding contrails without quantifying the induced costs. Avila et al. [6] and Sridhar et al. [7] analyzed contrail avoidance strategies without considering the impact of delay on the airline network.

B. Preliminary Work

In 2018 [33], we already analyzed 129 flights from and to Boston within three hours on 17^{th} of April, 2018, noon. In addition to purely modeling the flights and assessing the contrail costs incurred, we optimized the trajectories with a variable weighting of the contrails in the cost function and compared the delay costs and fuel costs incurred by the detours with the saved contrail costs. Therefore, we used the simulation environment TOMATO [17]. Thereby, we simplified the estimation of contrail costs by $32\,\text{t}$ of CO_2 equivalent emissions per flight hour in the ice-supersaturated region. Subsequently, the CO_2 equivalent emissions are converted into monetary values by using the European Emission Trading System (ETS) and assuming a price of 65 € per ton CO_2 equivalent emission.

In [33], we approximated the delay costs by four cost components: For each pilot and each steward, a linear cost rate per minute delay of 2.34 €/min and 1.02 €/min was used, respectively. The slope of crew salaries was derived from European airlines [19]. Delay costs per passenger were taken from European airline delay cost reference values [19], considering passenger rebooking, compensation and care (hard costs), and subjective factors such as loss of market share due to unpunctuality (soft costs).

However, in recent studies on both topics, we identified a more complex behavior. On the one hand, contrail costs depend on daytime [9]. Considering this dependency may even lead to times of the day (sunrise and sunset) when contrail cool the atmosphere [9]. On the other hand, airline delay costs are functions of daytime. First, reactionary delay as a function of primary delay decrease between morning and evening [8]. Second, airline delay costs peak in the morning hours when feeders to hub airports are critical connections [43].

In this study, we combine all dependencies on daytime and evaluate, how much contrail costs can be saved in contrail avoidance procedures without exceeding the total costs due to increased delay costs.

II. Methodology

A. Approach

For this application, we assume constant contrail formation conditions throughout the day (i.e. we use only one weather data set, see Section II-D). For each hour of the day, we simulate eight scenarios consisting of 129 flights to and from Boston. The scenarios differ by different weighting factors for contrail formation. The higher the weighting for contrail formation, the greater the detours took to achieve a global cost minimum [33]. Furthermore, with the highest contrail weighting $W_{\text{contr.}}$, we simulated two additional scenarios with increased cruising speed by $5\,\%$ and $10\,\%$ in order to reduce both contrail costs and delay costs at the expense of fuel costs and environmental costs.

Therewith, we emphasize that rerouting around ice-supersaturated regions for contrail avoidance without considering the time of the day may not always come to a global minimum cost- and acceptable operational solution.

B. Trajectory Optimization and -assessment with different contrail weighting

The 129 flights are optimized with the TOMATO [17, 44], an iterative simulation-based optimization tool for aircraft trajectory optimization. Besides the usual components of a 4D aircraft performance model, TOMATO can deal with optimization target functions. In the vertical dimension, the target for speed, altitude, and flight path angle may be fixed or computable using the Sophisticated Aircraft Performance Model (SOPHIA) [45, 46]. Typical optimization target functions are minimum fuel, - time, - noise or - emissions, minimum total costs, environmental costs, or direct operating costs. The quantification of the costs is described in [44, 47]. For minimum fuel, maximum specific range, and if not predefined, SOPHIA uses analytical functions for estimating the state variables True air speed v_{TAS}, altitude z, and flight path angle γ for each time step. In an aircraft type-specific proportional plus integral plus derivative controller (PID controller), $v_{\text{TAS,target}}$, z_{target}, and γ_{target} are employed as controlled variables, and the lift coefficient c_L is used as regulative variable [45]. Other and multi-criteria optimization targets are achieved iteratively within the trajectory assessment loop (see the "Comparison" loop in Figure 1). For the quantification of the fuel burn and the engine emissions (required for environmental costs) SOPHIA is enriched by a jet engine combustion model, (described in [47]). The drag polar is taken over from the Open Aircraft Performance model (OpenAP) [48].

In the horizontal direction, an arbitrary number of cost layers may be considered (added, removed, and manipulated during the optimization) by the path-finding algorithm A*. Besides typical cost layers, such as emission costs, the weather impact (e.g. wind), overfly charges or restricted areas, some special features distinguish TOMATO from other aircraft trajectory optimization tools. Most important for this study: contrail costs, identified after the first trajectory assessment support a desired cost weighting. Furthermore, the flexibility of the path-finding algorithm is used to insert various time-specific 3D weather data sets [49] and pre-calculate the approximated aircraft position for each corresponding weather data set [17, 50]. Therewith, 4D weather data can be used in a path-finding procedure (which actually cannot look into the future) and in flight performance calculation.

The iterative coupling of the vertical and horizontal trajectory optimization is described in [44].

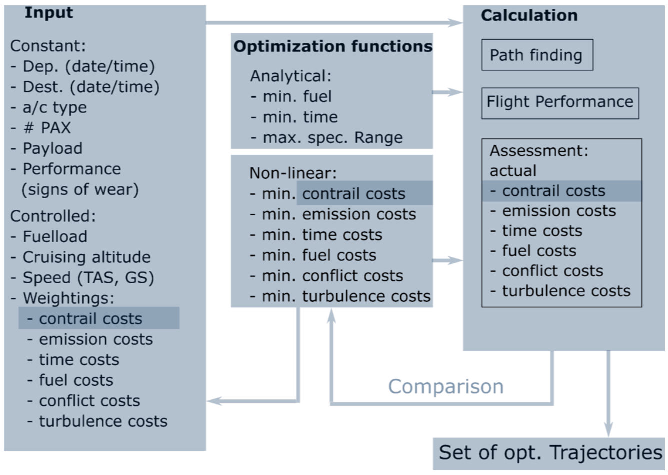

Figure 1: Tomato's simulation-based aircraft trajectory optimization considering condensation trails in a multi-criteria context.

After trajectory calculation, the flight is assessed regarding direct operating and delay costs and environmental costs. To the latter, we assign contrail costs depending on the time of the day and year and latitude and longitude [9]. With the exception of the contrail costs (see SectionSec:Contrailcosts), we would like to refer to references [44, 47] for the determination of the other costs. In the case of multi-criteria optimization without analytically solvable optimization functions, at this stage, TOMATO compares the ratios or total numbers of the assessed costs with the cost weightings. In the subsequent iteration, TOMATO adjusts the weightings (using a Newton iteration) to achieve the desired ratio or numbers of costs. In the current study, the cost layers are not adjusted during the optimization, because we want a specific contrail cost weighting. For each time step, target values of flight performance, the state variables v_{TAS}, z, and γ are calculated analytically for minimum fuel.

In this study, we define eight scenarios distinguished by different weighting factors for contrail formation (i.e. contrail weighting $W_{\mathrm{contr.}}$). Contrail cost weightings vary by $W_{\mathrm{contr.}} = 0$, 6, 12, 16, 24, 40, 36, and 56 t of CO_2 equivalent emissions per flight hour in the ice-supersaturated region. TOMATO converts CO_2 equivalent emissions into monetary values at a price of 65 e per ton CO_2 equivalent emission.

Note, the actual contrail costs assessed by TOMATO at the end of each iteration do not depend on the contrail weighting at the beginning of each iteration. On average, contrails contribute to global warming with 32 t CO_2 equivalent emissions per flight hour in an ice-supersaturated region [33].

C. Contrail costs depending on daytime

In order to compare different contrail avoidance strategies (i.e. different contrail weighting), the impact of contrail on the radiation budget of the Earth-atmosphere system is transferred into costs (as explained in [9]). Contrail radiative forcing mainly depends on the solar zenith angle θ of the sun and on the intensity and flux density of solar and terrestrial radiation, irradiating the contrail. For a specific latitude, the solar intensity is a strong function of θ as well. Hence, θ is the main impact variable for daytime-specific contrail costs (see Equations 1 to 3 for details). Since each time of the day refers to a specific θ, a diurnal variance in contrail costs is to be expected.

The impact of contrails on global warming constitutes the sum of a cooling effect and a warming effect. This creates an imbalance in the Earth-atmosphere radiation balance, which is generally defined as radiative forcing Radiative Forcing (RF) [$\mathrm{W\,m^{-2}}$].

The ice particles in the contrail absorb radiation of every wavelength and from all directions. This causes the contrail to heat up. The ice particles re-emit absorbed radiation according to their new temperature (Stefan-Boltzmann law). The emitted radiation can be re-absorbed by the ice particles [40]. This is generally known as the greenhouse effect.

On the other hand, the ice particles can scatter solar radiation. Since forward scattering dominates due to the shape and size of the ice particles and solar wavelength, only a small effect on the radiation budget is to be expected [40]. At large zenith angles, i.e. during sunrise and sunset, the probability increases that photons coming from above are scattered into the upper hemisphere and thus cool the atmosphere between the Earth's surface and the contrail [9].

There are therefore multiple possibilities for re-directing and extinguishing radiation of a certain wavelength and a certain angle of incidence on the longitudinal axis of the contrail as it passes through the contrail. For a specific time of the day, the optical properties of the contrail are calculated using a Monte Carlo simulation. In this simulation, both the location and the type of radiative extinction are determined with conditional probabilities [40].

The result of the Monte Carlo simulation is initially independent of the intensity of the incident radiation. Only multiplying the results with the actual intensity results in the extinguished power due to the contrail. By integrating all directions of incidence and wavelengths, we calculate the radiative forcing of the contrail per meter and per second. Finally, multiplication with the contrail length and the lifetime gives the contrail radiative forcing. The development of the contrail microphysical properties along its lifetime is approximated assuming a Gaussian Plume model [51].

For investigating the impact of daytime on the optical properties of the contrail, the angle-dependent results are multiplied with day-specific radiative intensities. Solar intensities and terrestrial irradiances are estimated with the radiative transfer software package libRadtran [52]. libRadtran is utilized to calculate this atmospheric radiative transfer depending on wavelength, longitude, latitude, altitude, the presence of clouds, time of day, and season. Both solar and terrestrial radiation is irradiating the contrail from directions in space. The solar zenith angle only defines the single direction of the direct beam, which is the contribution of solar radiation coming directly from the sun without any radiative extinction due to scattering and absorption by the atmosphere. Solar and terrestrial irradiances summarize radiation, already scattered and/or re-emitted by the atmosphere. Irradiances are always coming from a specific solid angle, whereas solar intensity is only coming from a single direction. The contribution of the direct beam dominates the directional distribution of the incident radiation, which is why the contrail radiative forcing mainly depends on θ. Details on the calculations of solar intensity, solar and terrestrial irradiances are provided in [41].

The intensity of the sun is not particularly high during sunrise and sunset, of course. Apparently, these low intensities are sufficient to briefly compensate for the warming terrestrial effects and in some cases even to achieve a cooling radiation balance(see Figure 2). With increasing time and decreasing theta, the solar intensity increases, and the probability that photons coming from above are scattered upwards decreases. For this reason, the absorbing, warming effects dominate the radiation balance at noon (see Figure 2). At night, on the other hand, the solar cooling effects are completely absent, while the terrestrial warming effects depend on the underlying Earth-surface type and remain largely constant [9]. For this study, we assume an urban surface type around Boston.

The contrail life time [51], the microphysical and optical properties of every single contrail have been calculated for a radiation balance (i.e. sum of incoming and outgoing solar intensities and terrestrial irradiances) typically prevailing at midnight in Boston in April [41]. From the investigated behavior of the contrail radiative forcing depending on solar zenith angle θ, we derive θ-specific, location- and season-specific multipliers which can be applied to all contrails in the scenario studied (129 flights to and from Boston). The multiplier is shown in Figure 2. Therewith, the contrail-specific radiative forcing per minute contrail formation is weighted by multipliers depending on the time of the day, represented by the solar zenith angle θ.

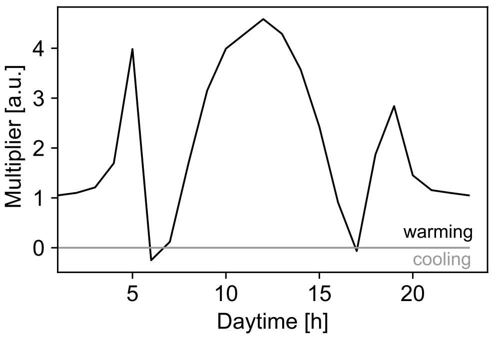

Figure 2: Multiplier of the contrail cost compared to the night value as a function of the time of day. At night, no cooling effect of backscattered solar direct radiation is possible. During sunrise and sunset, the probability of cooling effects is maximum. At noon, the solar direct intensity is maximum (with a dominant warming effect).

D. Input data for Atmosphere and Radiation

The weather data are provided as 3D weather data sets from the Global Forecast System (GFS) [49]. Figure 3 highlights the ice-supersaturated regions at FL 200 in the US on April, 17th 2017, at noon. The irregular distribution of partly highly ice-saturated areas poses a challenge for the simulation environment TOMATO to determine trajectories with different arrival times (i.e. different delays) using different contrail cost weightings.

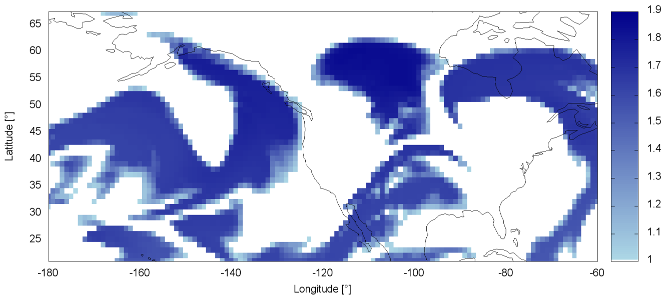

Figure 3: Ice-supersaturated (blue squares) in the investigation area at FL 200 indicating areas with a high probability of contrail formation. The color bar represents the amount of supersaturation. We assume this distribution of relative humidity over ice for the whole day.

A constant weather scenario over the day is chosen because we want to analyze contrails with identical microphysical properties in all scenarios, i.e. at all times of the day. For transferring the θ-specific multiplier to a daytime-specific multiplier, θ is calculated for all day times.

θ [°] is a function of latitude, longitude, and daytime and is calculated from the solar elevation angle ψ [°] [53].

$$\sin\psi = \sin\varphi\sin\delta_s - \cos\varphi\cos\delta_s\cos\left(\frac{2\pi UTC}{t_d} - \lambda\right) \quad (1)$$

$\varphi = 42.357778°$ and $\lambda = -71.059444°$ define longitude and latitude, UTC describes the time adjusted for UTC (GMT-5 for Boston), $t_d = 24$ the number of hours per day and δ_s [°] describes the solar declination angle and is defined as the angle between the equatorial plane of the Earth and the angle of the sun rays as the strike the Earth

$$\delta_s = \Phi_s\cos\left(\frac{2\pi(d-d_r)}{d_y}\right). \quad (2)$$

Here, $\Phi_s = 23.5$ °describes the tilt of the Earth on its axis, $d = 107$ the Julian day on 17th of April 2017, $d_y = 365$ defines the number of days per year and $d_r = 173$ is the Julian day of the summer solstice. Finally, θ is defined by

$$\theta = 90° - \psi. \quad (3)$$

Figure 4 shows the expected symmetric behavior of the position of the sun along the day with maximum values during sunrise and sunset and a minimum value at noon.

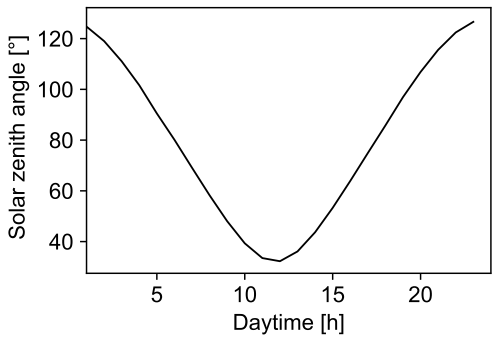

Figure 4: Calcuated solar zenith angle θ in Boston on 17th April, 2017 as function of daytime.

E. Delay costs depending on daytime

Depending on the time of the day, the connectivity of the flight, and the number of sensitive transfer passengers a detour may not only lead to a primary delay but bat also to a reactionary delay, in case of delayed aircraft waiting for delayed passengers and airport turnaround facilities [54]. Usually, primary and reactionary delays are summed up and burdened with airline-specific costs. Hence, the total delay is the sum primary delay $D_{\text{prim.}}$ and reactionary delay $D_{\text{react.}}$:

$$D_{\text{total}} = D_{\text{react.}} + D_{\text{prim.}} \quad (4)$$

According to [19],$D_{\text{react.}}$ linearly depends on daytime:

$$D_{\text{react.}} = a\,D_{\text{prim.}} + b. \quad (5)$$

Here, slope a and intersection with the origin b of Equation 5 are approximated based on the evaluation of European airline data [19]. Usually, due to a decreasing number of connection flights with increasing daytime and due to the delayed recovery at night, reactionary delay decreases with daytime [54].

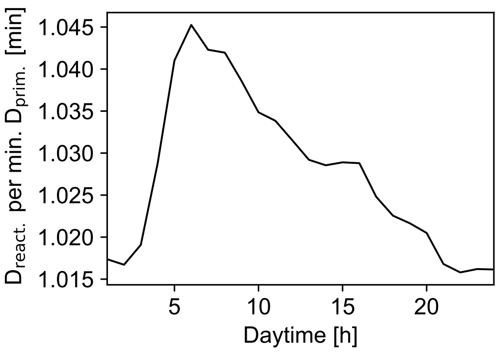

Figure 5: Reactionary delay per minute primary delay as a function of daytime following a European analysis [19].

Since our scenario consists of American flights and considering important differences between European and American airline delay costs, we adapt the total amount of delay costs per delay minute from American studies [43]. Here, the main differences are in costs for passenger compensation (cheaper in America than in Europe due to the EU Passenger Bill of Rights). Furthermore, in America, aircraft take more time taxiing out and America applies stricter Ground Delay Programs to avoid holding patterns. From this follows a higher amount of ground delay in America, compared to Europe, where the amount of en-route delay is greater than the amount of ground delay [43]. In this study, we assume daytime-specific delay costs, elaborated in [43] considering an exchange rate of 1 \$ = 0.92 €. Figure 6 shows a morning peak at 6 a.m. with 1.7 times higher delay costs per minute delay, compared to noon and evening. A cost minimum occurs between 4 and 5 a.m. during the delay recovery time.

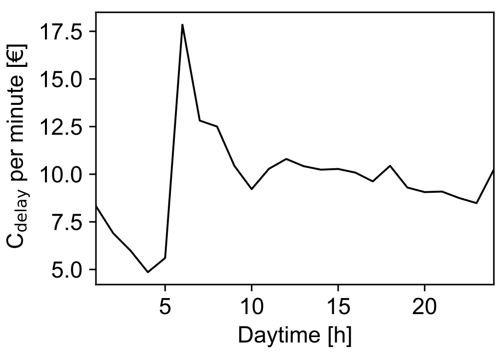

Figure 6: Delay costs per minute delay as a function of daytime.

III. Results

Finally, all 129 trajectories are optimized for each contrail weighting. For $W_{\text{contr.}}$ =0 t CO_2, 42 out of 129 flights formed a contrail. With the highest $W_{\text{contr.}}$ =56 t CO_2, 15 contrails out of 129 flights where formed. Each flight holds an individual potential of avoiding contrails by flying detours. During the cruise, the filed flight level has been taken. Due to airspace capacity constraints, in this study, we did not allow flight level changes. Therefore, most of the flights could only reduce the time, spent in ice-supersaturated regions. The heterogeneous distribution of atmospheric ice supersaturation also meant that both contrail costs and delay minutes did not change continuously between the scenarios (i.e. with increasing contrail weighting), but remained erratic and sometimes constant in several scenarios.

A. Individual trajectory analysis

In individual cases only, the formation of contrails could completely be avoided by increasing the contrail weighting. The most successful example demonstrates a flight from Los Angeles to Boston (Figure 7). Here, contrail formation could be avoided considering $W_{\text{contr.}}$ =40 t CO_2 in the path finding module and a delay of D_{prim} =20 min. Note, to the primary delay, we add in the assessment reactionary delay depending on daytime between 102 and 104 % (see Section II-E). The delay costs range from 213 € at 3 a.m. to 783 € at 5 a.m. The detours induced an additional fuelburn of 0.15 % (from 6.8 t to 6.81 t). For contrail avoidance, the A320 aircraft would have had to fly a detour of 0.47 % (from 2740 km to 2753 km).

An increased cruising speed by 5 % and 10 % yield a delay of D_{prim} =16 min and D_{prim} =12 min. The increased cruising speed by 5 % and 10 % required an additional fuelburn of 0.6 % and 2 % (6.84 t and 6.93 t), respectively.

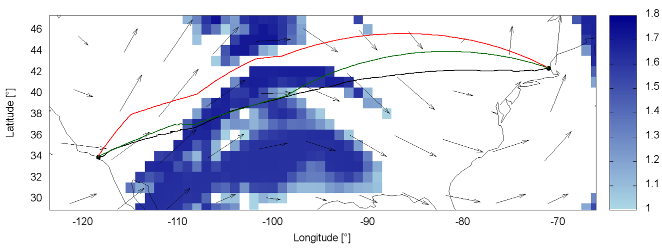

Figure 7: Optimized trajectories from Los Angeles to Boston in an ice-supersaturated atmosphere (blue squares): Black: originally filed, green: multi-critically cost optimized ($W_{\text{contr.}}$ =32 t CO_2 per hour) and red: complete contrail avoidance ($W_{\text{contr.}}$ =40 t CO_2). Black arrows mark wind speed (length) and wind direction.

B. Analysis of 129 flights

For comparability, we analyze the summed contrail costs and delay costs of each scenario, in which there is a clear decrease in contrail costs and an increase in delay costs with increasing contrail weighting. First, we ignore those scenarios with increased cruising speed.

As expected, delay costs are increasing with decreasing contrail costs (Figure 8). During sunrise and sunset (6 a.m. and 5 p.m.), negative contrail costs amplify the effect of the delay costs incurred on the overall balance of costs. In case of negative contrail costs during sunrise and sunset, no detour should be taken, especially because of high delay costs in

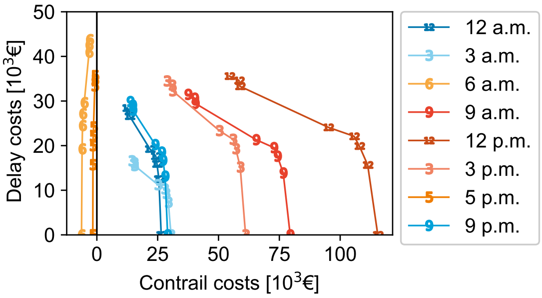

Figure 8: Daytime-depending delay costs as a function of contrail costs for different contrail weightings. Delay costs decrease with increasing contrail costs.

the morning. At noon, contrail costs are approximately twice the delay costs. Hence, flying around the ice-supersaturated areas will always be worthwhile. At night, in the morning, and evening, delay costs are in the range of contrail costs. Those flights need further investigation (as shown in Figure 9).

In Figure 9, the volatile behavior of delay and contrail formation leads to jumps in costs with continuously increasing contrail weighting. Obviously, in this weather scenario, with a contrail weighting of $W_{\text{contr.}}$ =40 t CO_2 per hour, the critical threshold for contrail costs in the overall balance was reached and delays were preferred (at 3 a.m. and 3 p.m.). However, at 9 p.m. and 12 a.m., delay costs already exceed contrail costs at $W_{\text{contr.}}$ =24 t CO_2, due to lower contrail costs (see Figure 2). At 9 a.m., on the other hand, high contrail costs mean that delay costs cannot compensate for contrail costs in any weighting scenario.

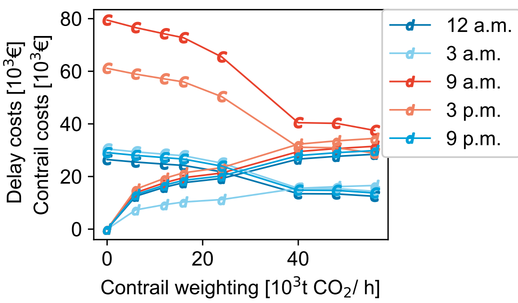

Figure 9: Daytime-depending delay costs (d) and contrail costs (c) as functions of contrail weightings. At 9 p.m. and 12 a.m., delay costs exceed contrail costs at $W_{\text{contr.}}$ =24 t CO_2. At 3 a.m. and 3 p.m., delay costs exceed contrail costs with higher values of $W_{\text{contr.}}$ =40 t CO_2.

Three important time steps can be identified over the whole day (Figure 10). As already mentioned, negative contrail costs during sunrise and sunset should be considered in flight planning. However, a morning peak in delay costs at 7 a.m. (see Figure 12) and positive contrail costs as soon as the position of the sun exceeds $\theta = 80°$ can very quickly reverse the desired effect into a state with both high contrail costs and high delay costs. Interestingly, around 4 p.m., shortly before sunset, a similar trend (i.e. high delay costs) can be seen, which, however, is due to spontaneously increased delay costs in the afternoon peak of air traffic. We can also see in Figure 10 that during the day the influence of the costs depends on the time of day dominates over the possibilities of contrail avoidance. At night it is possible to reverse the relationship between delay costs and contrail costs by detours at a certain time of day. In the daytime, the costs only adjust.

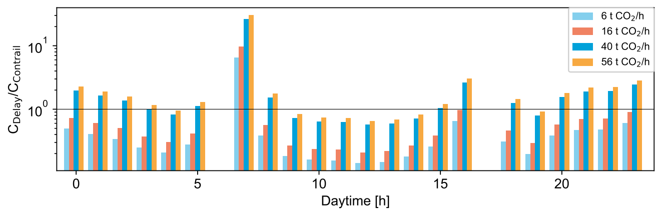

Figure 10: Ratio between delay costs and contrail costs as a function of daytime. Most of the day delay costs will exceed contrail costs, if contrails are weighted with $W_{\text{contr.}} \leq 40$ t CO_2 per hour. Note, in favor of a logarithmic scale, negative contrail costs at 6 a.m. and 5 p.m. are not plotted.

Nevertheless, also at daytime, contrail costs can be remarkably reduced by shortening the distance, flown through ice-supersaturated regions (Figure 11). Especially in the daytime, contrails costs can be reduced by up to 50 %.

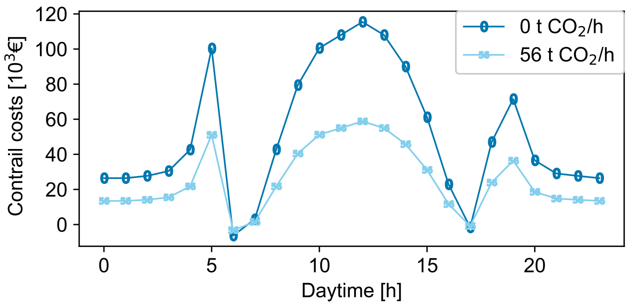

Figure 11: Daytime-depending contrail costs. At noon, contrail costs can be reduced by 50 %, when weighting contrails with $W_{\text{contr.}}$ =56 t CO_2.

A similar effect can be seen in the cost of delays (Figure 12). These too can easily double by flying around ice-supersaturated areas. So we can see that avoiding contrails can neither be achieved by flying around ice-saturated areas nor by a general quantification of delay or contrail costs.

C. Impact of increased cruising speed on delay costs and fuel costs

Now that the delay costs of various detour scenarios have been analyzed, the possibility of compensating for the detour-related delay by increasing the cruising speed by 5 % and 10 % should now be considered. In order to reduce the analysis to the maximum possible savings, only the scenario with the highest contrail costs is evaluated below. Furthermore, we assume, that the contrail microphysical properties remain constant, because the impact of a slightly increased speed on contrail conditions is low, compared to the impact of the atmosphere. However, in the pathfinding module, the increased speed is taken into account when calculating the contrail cost layer.

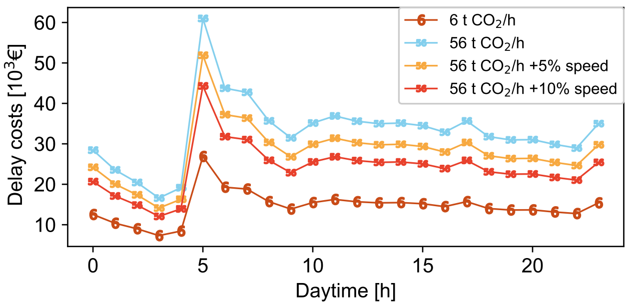

Figure 12: Daytime-depending delay costs. At noon, delay costs can be reduced by 50 % (similar to the contrail costs), when weighting contrails with $W_{\text{contr.}}$ =56 t CO_2.

As expected, an increased speed reduces the delay costs by approximately 30 %, but not in the order of magnitude as when reducing the detour (see Figure 12). Specifically at daytimes with high delay costs, e.g. 6 a.m. to 9 a.m. and 4 p.m. an increased cruising speed might be a valid opportunity for reducing the overall costs.

In this case, however, at least the increased fuel consumption must be taken into account in the overall cost balance. While we added up the fuel consumption for the 129 flights to 786,230 tons, the 5 % scenario resulted in an additional fuel consumption of 2.9 tons (corresponds to 0.36 %) and the 10 % scenario an additional consumption of 8.9 tons (that is 1.12 % more fuel). Note, the fuel consumption does depend on daytime, and only 40 out of 129 flights are affected by contrail formation. Only the speed of these flights was changed. Additionally, the compliance with the aircraft-type-specific flight performance envelope (e.g. the maximum Mach number) might have led to single flights operated by old aircraft types which could not increase the cruising speed by entire 10 %. Specifically, those older aircraft types have the most important impact on the increased fuel burn with increased speed.

The benefit of an increased cruising speed on the ratio of delay costs to contrail costs is well reflected in Figure 13. At three times (3 a.m., 3 p.m., and 6 p.m.) a speed increase is sufficient for the contrail costs to exceed the delay costs.

IV. Conclusion and Outlook

In this study, we analyzed the impact of detours for contrail avoidance on airline delay costs. In preliminary studies, we identified both contrail costs and delay costs depending on the time of the day. Specifically, contrail costs depend on the solar zenith angle. Knowing this makes the effect of saved contrails costs on delay not only depending on daytime but also on the geographical location and the day of the year. In this study, we concentrated on a scenario of flights from and to Boston on April 17th, 2017. We optimized the chosen set of flights with our aircraft trajectory optimization tool TOMATO after

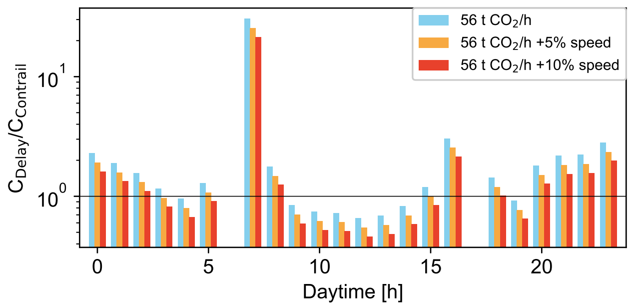

Figure 13: Impact of an increased cruising speed on the ratio of daytime-depending delay costs and contrail costs. At 3 a.m., 3 p.m., and 6 p.m. the increase in cruising speed results in contrail costs exceeding the delay costs.

we improved the time of day dependent contrail costs and delay costs. Additionally, the delay costs have been specified to American Airlines. With TOMATO, we used six different contrail weightings to receive different values of contrail costs and delay costs per flight. We conclude, that at noon, contrail formation should be avoided because of high contrail costs and low delay costs. At night, contrail formation should only be avoided by accepting small detours. Particular caution is required in the mornings and evenings. Because contrails are preferable during sunrise and sunset. However, around an hour before and after sunrise and sunset, the contrail costs are particularly high. In addition, the delay costs are particularly high in Boston in April at this time, since the airport hub is supplied with feeders. From this follows, in the evening, contrail avoidance via detours might be considerable, in the morning, the delay should be avoided.

We are aware that the considerations of this paper are based on a theoretical construct that contrail costs (similar to emission costs in the European Emissions Trading Scheme) have to be borne by airlines. This cost balance, therefore, does not correspond to everyday operations. The conversion of the radiative forcing of contrails into monetary costs therefore only serves the purpose of comparability between delay and contrail impact.

The method used is still based on simplifications, which are to be analyzed promptly. On the one hand, we have limited contrail avoidance to lateral detours. In the next step, vertical trajectory changes are additionally taken into account. We expect this to have less influence on the delay, but we have to accept capacity overruns or take capacity restrictions into account. On the other hand, we used a temporally constant, deterministic weather data set in favor of the comparability of the contrails over the day. In the future, we would like to counter this obvious lack of reality with fuzziness in the input data and additionally evaluate the results stochastically.

References

[1] G. Myhre, D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, "Anthropogenic and natural radiative forcing. in: Climate change 2013: The physical science basis. contribution

of working group i to the fifth assessment report of the intergovernmental panel on climate change," *Cambridge University Press*, 2013.

[2] W. (WMO). Cloud atlas. [Online]. Available: https://cloudatlas.wmo.int/aircraft-condensation-trails.html

[3] D. S. Lee, G. Pitari, V. Grewe, K. Gierens, J. E. Penner, A. Petzold, M. J. Prather, U. Schumann, A. Bais, T. Berntsen, D. Iachetti, L. L. Lim, and R. Sausen, "Transport impacts on atmosphere and climate: Aviation," *Atmospheric Environment*, vol. 44, pp. 4678–4734, 2010.

[4] C. Demouge, M. Mongeau, N. Couellan, and D. Delahaye, "A dynamic subgraph-capacity model for multiple shortest paths and application to co2/contrail-safe aircraft trajectories," *preprint hal-03900872*, 2022.

[5] M. Soler, B. Zou, and M. Hansen, "Flight trajectory design in the presence of contrails: Application of a multiphase mixed-integer optimal control approach," *Transportation Research Part C: Emerging Technologies*, vol. 48, no. 5, pp. 172–194, 2014.

[6] D. Avila, L. Sherry, and T. Thompson, "Reducing global warming by airline contrail avoidance: A case study of annual benefits for the contiguous united states," *Transportation Research Interdisciplinary Perspectives*, vol. 2, p. 100033, 2019. [Online]. Available: https://www.sciencedirect.com

[7] B. Sridhar, H. K. Ng, and N. Y. Chen, "Aircraft trajectory optimization and contrails avoidance in the presence of winds," *Journal of Guidance, Control, and Dynamics*, vol. 34, no. 5, pp. 1577–1584, 2011. [Online]. Available: https://doi.org/10.2514/1.53378

[8] J. Rosenow, P. Michling, M. Schultz, and J. Schönberger, "Evaluation of strategies to reduce the cost impacts of flight delays on total network costs," *Aerospace*, vol. 7, no. 11, 2020. [Online]. Available: https://www.mdpi.com/2226-4310/7/11/165

[9] J. Rosenow and H. Fricke, "When do contrails cool the atmosphere?" in *SESAR Innovation Days (SID 2022)*, 2022, Budapest, Hungary.

[10] S. G. Park and J.-P. Clarke, "Optimal control based vertical trajectory determination for continuous descent arrival procedures," *Journal of Aircraft*, vol. 52, pp. 1469–1480, 2015.

[11] R. Dalmau and X. Prats, "Fuel and time savings by flying continuous cruise climbs estimating the benefit pools for maximum range operations," *Transportation Research Part D: Transport and Environment*, vol. 35, pp. 62–71, 2015.

[12] S. Kamo, J. Rosenow, H. Fricke, and M. Soler, "Fundamental framework to plan 4d robust descent trajectories for uncertainties in weather prediction," *Aerospace*, vol. 9, no. 2, 2022.

[13] M. Soler, A. Olivares, and E. Staffetti, "Multiphase optimal control framework for commercial aircraft four-dimensional flight-planning problems," *Journal of Aircraft*, vol. 52, no. 1, pp. 274–286, 2015.

[14] Y. Miyazawa, N. K. Wickramasinghe, A. Harada, and Y. Miyamoto, *Dynamic Programming Application to Airliner Four Dimensional Optimal Flight Trajectory*, 2013.

[15] A. Valenzuela and D. Rivas, "Optimization of aircraft cruise procedures using discrete trajectory patterns," *Journal of Aircraft*, vol. 51, no. 5, pp. 1632–1640, 2014.

[16] N. Takeichi, "Nominal flight time optimization for arrival time scheduling through estimation/resolution of delay accumulation," *Transportation Research Part C: Emerging Technologies*, vol. 77, pp. 433–443, 2017.

[17] S. Förster, J. Rosenow, M. Lindner, and H. Fricke, "A toolchain for optimizing trajectories under real weather conditions and realistic flight performance," in *Greener Aviation, Brussels*, 2016.

[18] J. Rosenow, D. Strunck, and H. Fricke, "Trajectory optimization in daily operations," in *International Conference on Research in Air Transportation (ICRAT)*, 2018.

[19] A. Cook and G. Tanner, "European airline delay cost reference values," University of Westminster, v4.1, 2015.

[20] C. Wu and R. E. Caves, "Modelling and simulation of aircraft turnaround operations at airports," *Transportation Planning and Technology*, vol. 27, no. 1, pp. 25–46, Feb 2004.

[21] H. Fricke and M. Schultz, "Delay impacts onto turnaround performance," in *8th USA/Europe Air Traffic Management Research and Development Seminar*, Napa, 2009.

[22] J. Kuster, D. Jannach, and G. Friedrich, "Extending the RCPSP for modeling and solving disruption management problems," *Applied Intelligence*, vol. 31, no. 3, pp. 234–253, Dec 2009. [Online]. Available: http://link.springer.com/10.1007/s10489-008-0119-x

[23] B. Oreschko, T. Kunze, M. Schultz, H. Fricke, V. Kumar, and L. Sherry, "Turnaround prediction with stochastic process times and airport specific delay pattern," in *5th International Conference on Research in Airport Transportation*, Berkeley, 2012.

[24] M. Schultz, T. Kunze, B. Oreschko, and H. Fricke, "Microscopic process modelling for efficient aircraft turnaround management," *Air Transport and Operations*, 2013.

[25] J. Evler, E. Asadi, H. Preis, and H. Fricke, "Stochastic control of turnarounds at hub-airports," in *Eighth SESAR Innovation Days*, 2018.

[26] ——, "Integrated operations control at hub-airports with uncertain arrival times," in *International Conference on Research in Air Transportation (ICRAT2020)*, 2020.

[27] G. Andreatta, L. De Giovanni, and M. Monaci, "A Fast Heuristic for Airport Ground-Service Equipment–and–Staff Allocation," *Procedia - Social and Behavioral Sciences*, vol. 108, pp. 26–36, Jan 2014. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1877042813054578

[28] S. Padrón, D. Guimarans, J. J. Ramos, and S. Fitouri-Trabelsi, "A bi-objective approach for scheduling ground-handling vehicles in airports," *Computers & Operations Research*, vol. 71, pp. 34–53, Jul 2016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0305054815002968

[29] J. Y. Du, J. O. Brunner, and R. Kolisch, "Planning towing processes at airports more efficiently," *Transportation Research Part E: Logistics and Transportation Review*, vol. 70, pp. 293–304, 2014. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S136655451400129X

[30] A. Norin, D. Yuan, T. A. Granberg, and P. Värbrand, "Scheduling de-icing vehicles within airport logistics: a heuristic algorithm and performance evaluation," *Journal of the Operational Research Society*, vol. 63, no. 8, pp. 1116–1125, 2012. [Online]. Available: https://www.tandfonline.com/doi/full/10.1057/jors.2011.100

[31] U. Dorndorf, F. Jaehn, and E. Pesch, "Flight gate assignment and recovery strategies with stochastic arrival and departure times," *OR Spectrum*, vol. 39, no. 1, pp. 65–93, 2017. [Online]. Available: http://link.springer.com/10.1007/s00291-016-0443-1

[32] B. Dijk, B. F. Santos, and J. P. Pita, "The recoverable robust stand allocation problem: a GRU airport case study," *OR Spectrum*, vol. 41, no. 3, pp. 615–639, 2019. [Online]. Available: http://link.springer.com/10.1007/s00291-018-0525-3

[33] J. Rosenow and M. Schultz, "Coupling of turnaround and trajectory optimization in an air traffic simulation," in *Winter Simulation Conference*, 2018.

[34] R. Beatty, R. Hsu, and J. Rome, "Preliminary evaluation of flight delay propagation through an airline schedule," *Air Traffic Control Quarterly*, vol. 7, 01 1998.

[35] D. Avila and L. Sherry, "Method for calculating net radiative forcing from contrails from airline operations," in *2017 Integrated Communications Navigation and Surveillance (ICNS) Conference*, ser. DOI: 10.1109/ICNSURV.2017.8011927, 2017.

[36] U. Schumann, B. Mayer, K. Graf, and H. Mannstein, "A parametric radiative forcing model for contrail cirrus," *American Meteorological Society*, vol. 51, pp. 1391–1405, 2012.

[37] A. Gounou and R. J. Hogan, "A sensitivity study of the

effect of horizontal photon transport on the radiative forcing of contrails," *Journal of Atmospheric Sciences*, vol. 64, pp. 1706–1716, 2007.

[38] L. Forster, C. Emde, B. Mayer, and S. Unterstrasser, "Effects of three-dimensional photon transport on the radiative forcing of realistic contrails," *American Meteorological Society*, pp. 2243–2255, 2011.

[39] U. Schumann, "A contrail cirrus prediction tool," in *Intern. Conf. on transport, Atmosphere and Climate, DLR/EUR, Aachen and Maastricht, 22-25 June*, 2009.

[40] J. Rosenow, "Optical properties of condenstation trails," Ph.D. dissertation, Technische Universität Dresden, 2016.

[41] J. Rosenow and H. Fricke, "Individual condensation trails in aircraft trajectory optimization," *Sustainability*, vol. 11, no. 21, 2019. [Online]. Available: https://www.mdpi.com/2071-1050/11/21/6082

[42] K. Gierens, L. Lim, and K. Eleftheratos, "A review of various strategies for contrail avoidance," *The Open Atmospheric Science Journal*, vol. 2, pp. 1–7, 02 2008.

[43] J. Ferguson, A. Q. Kara, K. Hoffman, and L. Sherry, "Estimating domestic us airline cost of delay based on european model," *Transportation Research Part C: Emerging Technologies*, vol. 33, pp. 311–323, 2013.

[44] J. Rosenow, T. Zeh, M. Lindner, S. Förster, and H. Fricke, "Multiple aircraft in a multi-criteria trajectory optimization," in *submitted to Fifteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2023)*, 2023, Savannah, USA.

[45] J. Rosenow, G. Chen, H. Fricke, and Y. Wang, "Factors impacting chinese and european vertical fight efficiency," *Aerospace*, vol. 9, no. 2, 2022. [Online]. Available: https://www.mdpi.com/2226-4310/9/2/76

[46] J. Rosenow, T. Sachwitz, S. Kamo, G. Chen, and H. Fricke, "Aircraft-type-specific impact of speed brakes on lift and drag," *Aerospace*, vol. 9, no. 5, 2022. [Online]. Available: https://www.mdpi.com/2226-4310/9/5/263

[47] J. Rosenow, S. Förster, M. Lindner, and H. Fricke, "Multi-objective trajectory optimization," *International Transportation*, vol. Special Edition 1, 2016.

[48] J. Sun, J. M. Hoekstra, and J. Ellerbroek, "Openap: An open-source aircraft performance model for air transportation studies and simulations," *Aerospace*, vol. 7, no. 8, 2020. [Online]. Available: https://www.mdpi.com/2226-4310/7/8/104

[49] National Oceanic and Atmospheric Administration. (2016) Global data assimilation system (gdas). [Online]. Available: ncei.orders@noaa.gov

[50] M. Lindner, J. Rosenow, and H. Fricke, "Aircraft trajectory optimization with dynamic input variables," *CEAS Aeronautical Journal*, vol. 11, no. 2, pp. 321–331, 2020. [Online]. Available: https://doi.org/10.1007/s13272-019-00430-0

[51] J. Rosenow, M. Kaiser, and H. Fricke, "Modeling contrail life cycles based on highly precise flight profile data of modern aircraft," in *Proceedings of the International Conference on Research in Airport Transportation (ICRAT)*, 2012.

[52] B. Mayer and A. Kylling, "Technical note: The libradtran software package for radiative transfer calculations description and examples of use," *Atmospheric Chemistry and Physics*, vol. 5, pp. 1855–1877, 2005.

[53] G. W. Petty, *A first course in Atmospheric Radiation*. Sundog Publishing, 2006.

[54] J. Rosenow, M. Lindner, and J. Scheiderer, "Advanced flight planning and the benefit of in-flight aircraft trajectory optimization," *Sustainability*, vol. 13, no. 3, 2021. [Online]. Available: https://www.mdpi.com/2071-1050/13/3/1383