Energy Efficient Trajectory Designs for Minimizing Climate Impact of Aircraft on Various Timescales

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Future air traffic management systems are developed to enhance safety and efficiency of air traffic operations while accommodating the demand. The impact of aircraft emissions and contrails on the environment adds an additional dimension to aircraft trajectory optimization. This paper describes an optimization module capable of minimizing the climate impact of aircraft emissions and contrails and analyzes the energy efficiency of the trajectory designs and their relationships with the environmental objective. The methodology is used to evaluate the energy efficiency of three designs that each minimizes the total climate impact of aircraft CO_2 emissions and contrails at the end of 25, 50, and 100 years, respectively. Alternatively these designs can be evaluated with respect to how a hypothetical tax on contrail production would influence a stakeholder's willingness to redefine their respective "optimal" cruise trajectory. The baseline wind-optimal routes and the three designs of climate-optimal trajectories are applied to simulated traffic between 12 city-pairs in the United States. Contrail reduction using both route and altitude changes to aircraft trajectories are more energy efficient than contrail reduction using either route or altitude changes only. Initial results show that climate-optimal trajectories involving lateral changes, which minimize total climate impact at the end of 50 or 100 years, result in smaller amount of contrail formation but have larger temperature reduction per unit fuel burn than that of 25 years. Similar results are obtained for the climate-optimal designs for aircraft trajectories involving altitude changes. The contrail cost that can potentially redefine a stakeholder's objective to these climate-optimal goals is about 3.7 \$/nmi for aircraft trajectories involving altitude changes for a contrail radiative forcing of 30mW/m^2 under current scenario.

I. Introduction

The design of aircraft trajectories during operations has to satisfy requirements of safety, capacity and efficiency. In addition, the value associated with these requirements varies between the providers of airspace and airport resources, who are the Federal Aviation Administration (FAA) and other government organizations in the US, and the users of these resources, represented by airlines and general aviation. Interest in reducing climate

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impact of aircraft emissions and condensation trails, or contrails, has increased in recent years. Aviation is responsible for 2% of all anthropogenic CO_2 emissions[1] in which a large portion takes place at altitudes where the emissions remain there longer than if emitted at the surface. Another source of aircraft induced climate impact comes from persistent contrails. They are visible trails of water vapor made by the exhaust of aircraft engines[2]. The latest estimates indicate that contrails caused by aircraft may be causing more climate warming today than all the residual CO_2 emitted by aircraft[3]. The climate impact of CO_2 emissions and contrails can be estimated by measuring the perturbation to the balance between incoming solar radiation and outgoing infrared radiation at the top of the troposphere defined as "radiative forcing" (RF). The resultant RF associated with CO_2 emissions or contrails is positive and has an approximately linear relationship with global mean surface temperature change. CO_2 has a long-term effect on temperature change while contrails have a short-term effect since their lifetimes are very different. Aircraft trajectories that are designed for mitigating the impact of CO_2 emissions and contrails on climate change require an integration of aircraft emissions, contrail, and climate response models and a common metric for assessing their climate effects within the same time horizon. The trajectory optimization approach should also be potentially practical for a national-level airspace simulation and optimization.

New operational strategies in air traffic management such as adjusting cruise altitude[4-5], rerouting aircraft horizontal path[6] or a combination of both[6-7] have been proposed for mitigating the impact of persistent contrails on climate change. These straregies are developed without combining the climate effect of aircraft emissions and contrails. Commonly used climate metrics[8] such as Global Warming Potential (GWP) and Absolute Global Temperature Potential (AGTP) are aimed at providing a common scale to compare different impacts of greenhouse gases. Several authors[9-10] have used linear climate models and metrics to assess the impact of aviation on climate. A recent study[11] modeled the climate response to aviation emissions and contrails as outputs from a series of linear dynamic systems and assesed the effect in terms of AGTP. The model is integrated with a national-level air traffic simulation and optimization capability for studing the environmental impact with a trade-off between producing CO_2 emissions and contrails. The integrated system assumes the climate impacts are independent of the location of aircraft emissions and contrail formation.

This study improves upon previous work by developing contrail mitigation strategies for various timescales. This technique develops optimal aircraft trajectories in winds that minimize aviation-induced climate impact due to CO_2 emissions and contrails for short, medium and long-term effects on global temperature change. The model that assesses the climate impact of CO_2 emissions and contrails which can be computed as changes to AGTP are incorporated into the objective functions of the optimization procedures to develop the climate-optimal trajectories. This optimization framework integrates aircraft fuel burn and emission, contrail formation,, and a simplified climate response model with a national-level airspace simulation. This framework can simulate current and future air traffic scenarios to evaluate the energy efficiency of different designs of aircraft trajectories for three climate goals using a common climate metric. The aircraft trajectories are varied from their wind-optimal path to AGTP minimal trajectories that are optimized for 25, 50, and 100 years time horizons, respectively. This paper analyzes the energy efficiency of optimal stategies minimizing AGTP and their relationships with the environmental objectives while providing an assessment of the value of climate impact reducing strategies from each stakeholder's perspective.

Section II provides the models for assessing the potential climate impact of CO_2 emissions and contrails in terms of AGTP. Section III describes various designs for climate-optimal trajectories and compares their energy effeciency for aircraft flying between 12 city-pairs in the United States. Section IV evaluates the climate-optimal trajectories based on the value assigned by the users and other stakeholders of aviation. Conclusions and future work are described in Section V.

II. Emissions and Climate Impact

This section models the climate response to aircraft CO_2 emission and contrails as outputs from a series of linear dynamic systems. The climate response model for aircraft CO_2 emissions and contrails are based on earlier studies[8,9,11]. The key components of the simulation to compute aircraft emissions, contrails and climate impact are described in the next subsections.

A. Emissions

The air traffic is simulated using Future Air Traffic Management Concepts Evaluation Tool[12] (FACET), a national level air traffic system simulation and optimization tool. FACET uses the fuel consumption model provided by Eurocontrol's Base of Aircraft Data[13] (BADA). The air traffic data provides aircraft information including aircraft type, mass, altitude and speed to compute the fuel burn. The emission models are based on a prototype version of the FAA's Aviation Environmental Design Tool (AEDT). Six emissions are computed which are CO_2,

H_2O, SO_2, CO, HC and NO_x. Emissions of CO_2, H_2O and SO_2 are modeled based on fuel consumption[14]. Emissions of CO, HC and NO_x are modeled through the use of the Boeing Fuel Flow Method[15] (BFFM2). These emissions are dependent on aircraft engine type, altitude, speed, fuel burn and the coefficients in the International Civil Aviation Organization (ICAO) emission data bank. Standard atmospheric conditions for temperature and pressure are used to compare data from different experimental measurements.

B. Contrail Models

Contrails are clouds of ice particles that form when a mixture of warm engine exhaust gases and cold ambient air interact with each other under favorable atmospheric conditions. Contrails form in the regions of airspace that have ambient relative humidity with respect to water (RHw) greater than a critical value[16], r_{contr}. Contrails can persist when the ambient air is supersaturated with respect to ice, i.e., the environmental relative humidity with respect to ice (RHi) is greater than 100 percent[2]. In this study, the regions of airspace that have RHw greater than r_{contr} and RHi greater than 100% are considered favorable to persistent contrail formation. The contrail model used in this paper represents the simplest models for persistent linear contrail formation. However, the modular nature of the simulation allows for contrail models in the paper to be replaced by other more computationally intensive models, such as Contrail Cirrus Prediction Tool[17] and make further enhancements to accommodate updates in the literature on modeling errors and other uncertainties associated with the atmospheric measurements.

C. Radiative Forcing (RF)

RF due to different emissions affects the climate by changing the Earth's global average near-surface air temperature. The impact of CO_2 on climate is better understood than the impact of all other greenhouse gases and contrails. The carbon cycle models describe the changes to the CO_2 concentration due to the transport and absorption of CO_2 by the land mass and various ocean layers. The RF for CO_2 emissions is made of a steady-state component and three exponentially decaying components[18]. The concentration dynamics of other non-CO_2 greenhouse gases can be described by first order linear systems.

Contrails occur at different regions of the earth and add non-uniform sources of energy to the atmosphere. The net RF for contrails includes the effect of trapping outgoing longwave radiation from the Earth and that of reflecting incoming shortwave radiation from the sun; it is measured in terms of unit of power (W) per unit area of contrails (m^2). The large uncertainties in the optical thickness and coverage associated with contrail cirrus results in large uncertainties in RF associated with contrails. Typical values for RF range from 10 mW/m^2 to 80 mW/m^2 for the year 2005[19].

The challenge in quantifying the impacts of emissions and contrails is that the lifetime associated with emissions and contrails varies widely from several hundred years to a few hours. The impact of certain gases depends on the amount and location of the emission, and the decision-making horizon, H in years, when the impact is estimated. These variations make it necessary to develop a common yardstick to measure the impact of various gases. The following section describes climate metrics have been developed to assess the impact of the aviation emissions[8].

D. Absolute Global Temperature Change Potential

AGTP[20] is a climate assessment metric that adapts a linear system for modeling the global temperature response to aviation emissions and contrails. The definition of AGTP is a convolution integral from t_0=0 to t=H, and has the following representation,

$$AGTP(H) = \int_0^H R(H - \zeta)\Delta F(\zeta)\,d\zeta \,, \tag{1}$$

where $R(H - \zeta)$ is the impulse response function for the surface temperature change at time H due to a radiative forcing $\Delta F(\zeta)$ applied at ζ. Note that temperature change $\Delta T(t,t_0)$ on the Earth surface is equivalent to the AGTP(H) when a simplified climate model is chosen. Two versions of AGTP are available in the literature. The pulse AGTP measures the change in the global temperature at a particular time, t, in the future due to an instantaneous disruption at t_0. The sustained AGTP measures the global temperature change at time t due to disruptions constantly applied for a period between t and t_0.

The pulse AGTP is employed in this study for translating aviation induced CO_2 emission and persistent contrails into total effect on global warming. The formulations for AGTP due to CO_2 emission and contrails are provided in an earlier paper[11]. Figure 1 summarizes the steps involved in the generation of AGTP.
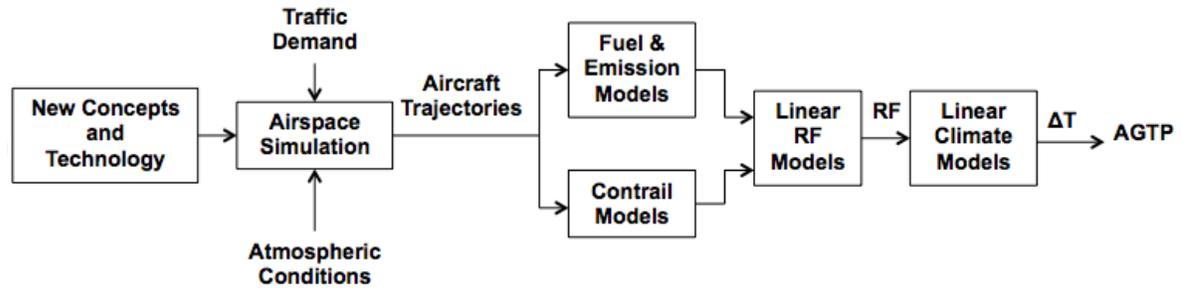
Figure 1. Computation of AGTP from emissions and contrails.

The analysis presented in this paper concentrates on the two major impacts of aviation on climate, CO_2 emissions and contrails. However, the impact of other emissions can be included in the analysis in a similar manner. AGTP provides a way to express the combined environmental cost of CO_2 emissions and contrails as a function of the fuel cost. Assuming, initially, that the RF due to contrails is independent of the location of the contrails, the near surface temperature change ΔT in Fig.1 can be approximated as

$$\Delta T = \Delta TCO_2 + \Delta TCon,$$

where ΔTCO_2 is the contribution to AGTP from CO_2 emissions and is equal to α times additional CO_2 emissions in kg, $\Delta TCon$ is the contribution to AGTP from contrails and is equal to β times contrail formation in km. The values of α and β depend on the linear models for RF, the specific forcing because of CO_2, energy forcing because of contrails, energy balance model and the duration of the climate effect horizon.[11] The units for ΔT, α and β are degrees K, K/kg and K/km.

III.   Climate-Optimal Trajectory Designs

This section describes the generation of climate-optimal trajectories for aircraft flying between 12 major city-pairs during April 12, 2010, in the continental US. The airport codes and their full names for the 12 city-pairs are listed in the Appendix. The atmospheric conditions on this day are highly favorable to persistent contrail formation.
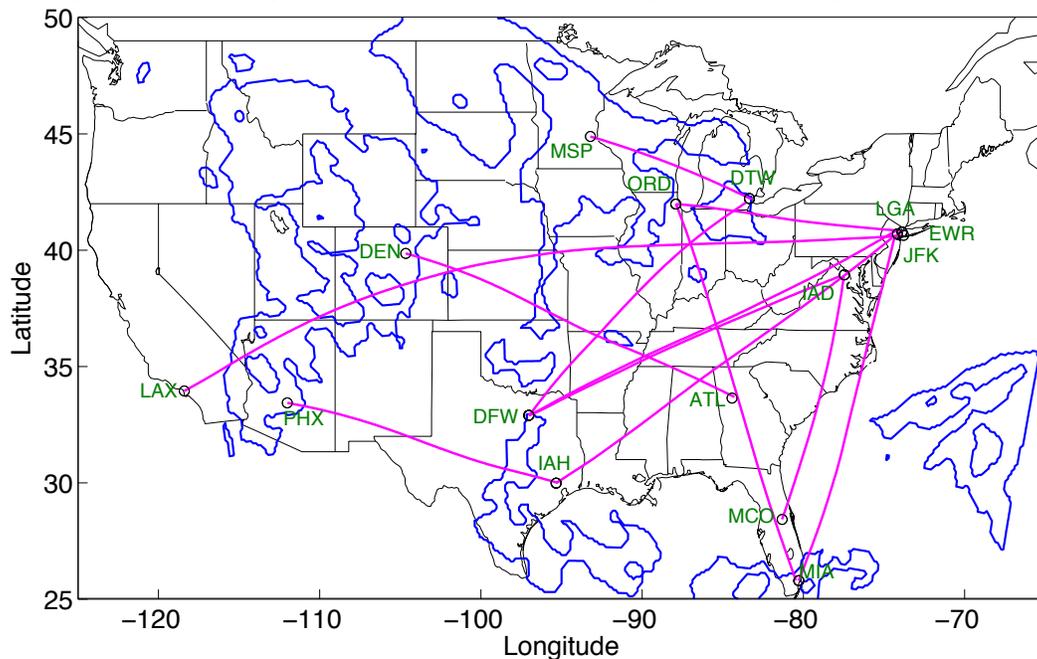

Figure 2. The wind-optimal trajectories for the eastbound flights for 12 city pairs on 35,000 feet at 6 a.m. EDT on April 12, 2010.

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Figure 2 shows the wind-optimal trajectories for the eastbound flights at 35,000 feet during 6 a.m. EDT on April 12, 2010. The 12 city-pairs are listed in the Appendix. The blue polygons depict the potential contrail formation areas at this altitude. The figure indicates that a flight going from Los Angeles (LAX) to New York (JFK) may go through regions of potential contrail formation while a flight from Houston (IAH) to New York (JFK) does not. The contrail formation and computation of aircraft trajectories use forecast of wind, humidity and temperature provided by Rapid Update Cycle (RUC).[21] RUC is an operational weather prediction system developed by the National Oceanic & Atmospheric Administration (NOAA) for users needing frequently updated short-range weather forecasts (e.g. the US aviation community) every hour. The horizontal resolution in RUC is 13-km. RUC data has 37 vertical isobaric pressure levels ranging between 100-1000mb in 25mb increments.

Subsection IIIA presents the contrail reducing strategies and the trade-off between contrail formation time and fuel consumption. Subsection IIIB determines the set of climate-optimal trajectories according to each selected climate-optimal goals and compares their energy efficiency. Section IIIC provides the estimations of contrail cost for the affected stakeholders of aviation given different climate goals.

A. Contrails reducing strategies for 12 City Pairs

The previously described 12 city-pairs were used by the Federal Aviation Administration to assess the impact of implementation of Reduced Vertical Separation Minima (RVSM) on aircraft-related fuel burn and emissions.[22] East-bound aircraft fly odd thousands of feet while westbound traffic fly even thousands of feet. The scenario consists of 287 flights. The baseline trajectory for each aircraft uses the altitude provided by the Enhanced Traffic Management System[23] and a wind-optimal route. The cruising true airspeed was based on the BADA data. The aircraft flight level and speed varies from 26,000 to 41,000 feet and from 434 to 463 knots respectively.

The optimal lateral contrail reducing (LCR) trajectories were generated by applying a penalty[6] for aircraft trajectories going through contrails using the filed altitude and the cruising true airspeed from BADA data. The fuel consumption for each aircraft trajectory is calculated using BADA formulas given the aircraft type with medium weight. The additional fuel consumption of each optimal trajectory is obtained by comparing its fuel burned to that of its wind-optimal trajectory for each altitude. The optimal aircraft trajectory can be determined by selecting the lateral contrail reducing trajectory on the optimal altitude that minimizes contrail formation time for a given additional fuel consumption. The trade-off between fuel consumption and contrail reduction is achieved by generating a group of 21 optimal aircraft trajectories at the filed flight level by increasing the penalty value, C_r, from 0 to 2 with increments equal to 0.1. The optimal aircraft trajectories are generated for each flight using hourly updated weather data from RUC.

A total of 50 bins are defined such that the aircraft trajectories can be categorized based on their additional fuel consumption. The first bin contains the wind-optimal trajectory, which is the baseline for fuel use comparison and corresponds to trajectories that require zero % of additional fuel consumption. The second bin contains aircraft trajectories that consume less than 1% additional fuel, the third bin contains those consuming less than 2 %, and etc. The 50th bin has trajectories that burn more than 49% of fuel. In each bin, the optimal trajectory that has least amount of persistent contrails formation time is selected to represent the bin.

The variation between fuel consumption and contrail formation time for LCR trajectories is shown by the solid curve in Fig. 3. The contrail formation time for the baseline wind optimal trajectories computed at altitudes provided by ETMS is 5885 minutes as indicated by the cross in Fig. 3. The LCR strategy reduces the baseline contrail formation time from 5885 minutes to 2995 minutes for an extra fuel consumption of 90,000 kg over the consumption for wind-optimal routes. The points labeled as blue triangle, green square and magenta circle in Fig. 3 will be explained in the subsequent sections.

More reduction in contrails can be achieved by searching for avoidance trajectories by changing both routes and altitudes. The three-dimensional reduction strategy is computationally intensive and a simplification is used in the paper. As the choice of the cruise altitude varies over a small range, the best three-dimensional contrail reducing (3DR) aircraft trajectories are computed by repeatedly solving the lateral contrail avoidance problems for a small number of altitudes. Four alternative flight levels are considered in addition to the filed altitude and a group of 21 optimal aircraft trajectories are generated for each altitude. The aircraft trajectories are categorized similar to those of LCR strategy.

The dotted curve in Fig. 3 shows trade-off between fuel consumption and contrail formation time for the 3DR strategy. For the current scenario, initially 3DR reduces both contrail formation time and fuel consumption. The contrail formation time is reduced to 2510 minutes while fuel usage is reduced by 21,000 kg. This may not happen in other scenarios and suggests that the aircraft may not be flying at their optimal cruise altitudes in the baseline scenario. Subsequent reductions to the contrail formation time are accompanied by increased fuel usage. The

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contrail formation time can be reduced to 584 minutes by using 131,000 kg of fuel. The 3DR strategy performs better than the LCR strategy as it reduces more contrail minutes for the same extra fuel usage.
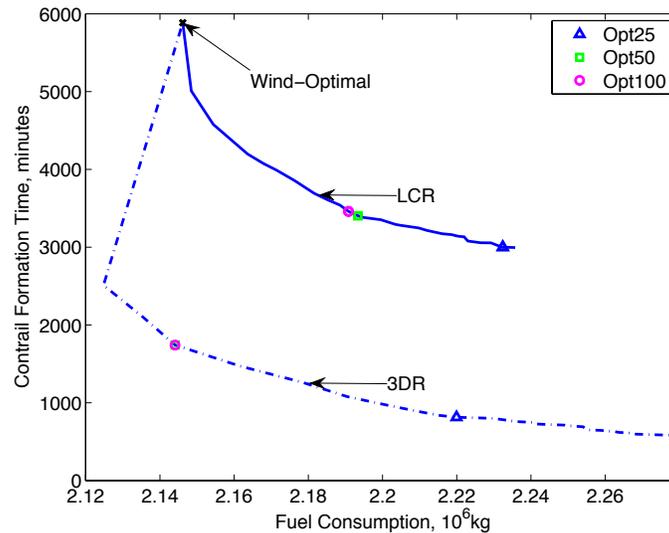

Figure 3. Trade-off between contrail reduction and additional fuel burn for 12 city pairs.

The tradeoff analysis can be adopted for selecting the group of aircraft trajectories that minimizes contrail formation after determining the allowed additional fuel consumption. Next subsection determines the additional fuel burn required for several climate-optimal goals and their energy efficiencies.

B. Climate-Optimal Trajectories for 12 City Pairs

The fuel consumption and contrail formation times of each group of aircraft trajectories can be converted into their equivalent AGTP values. Figure 4a shows AGTP, for H=25, 50, and 100 years in blue, green, and magenta, respectively, and a RF value of 30mW/m^2 for contrails, as a function of the amount of fuel used by LCR and 3DR strategies. As earlier, the solid lines and the dashed lines represent the LCR and 3DR strategies respectively. Fig. 4b shows an expanded view of Fig. 4a for a region of fuel values between 2.12×10^6 and 2.24×10^6 kg. The cumulative AGTP curve decreases initially with reduction in contribution from contrails and is eventually offset by the increase in contribution from CO_2 emissions. The curves show that even if the cost of fuel is not taken into consideration, under certain conditions, reducing contrails beyond a certain level may neither be economical nor good environmental policy.

The climate-optimal goals that minimize the total AGTP due to aircraft CO_2 emission and contrails for three time horizons are compared to the baseline wind-optimal route. The three goals, Opt25, Opt50, Opt100, each minimizes the climate impact at the end of 25, 50 and 100 years, respectively. The lowest value of AGTP and the corresponding fuel consumption is indicated by the 'triangle', 'square', and 'circle' in Fig.4, for horizons of 25, 50 and 100 years respectively. They are also referred to as points A25, B50 and C100. These points, identify the minimum climate impact in terms of AGTP at the end of 25, 50, and 100 years and the fuel consumption of the associated group of climate-optimal trajectories for the each climate goal. The corresponding contrail formation time resulting from Opt25, Opt50, and Opt100 is also indicated by the 'triangle', 'square', and 'circle' in Fig. 3. The wind-optimal strategy always consumes the least amount of fuel. The additional fuel spent for reducing contrails is the largest for Opt25 and the smallest for Opt100.

Figure 5 shows the potential climate impact for the wind-optimal trajectories and the climate-optimal trajectories resulting from LCR strategy. The climate impact of wind-optimal trajectories at the end of 25, 50 and 100 years is denoted by W25, W50, and W100, respectively. The temperature change at the end of 50 and 100 years resulting from Opt25 goal is denoted by A50 and A100. Similarly the intermediate values at the end of 25 and 50 years for Opt100 are indicated by C25 and C50 respectively. Similar definitions are used for Opt50.
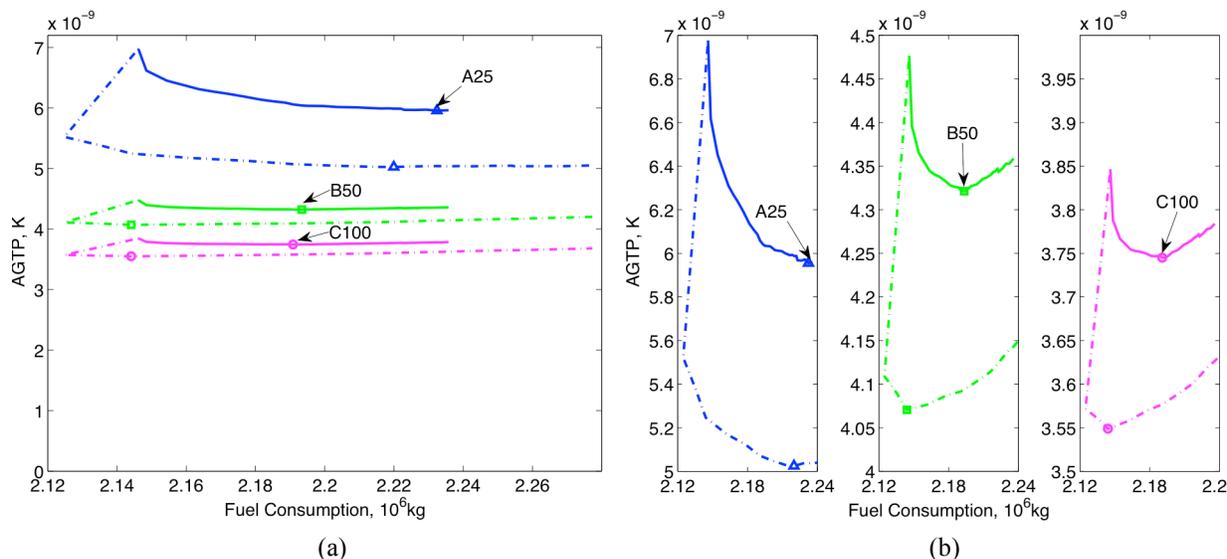
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Figure 4. Trade-off between AGTP and additional fuel burn for 12 city pairs
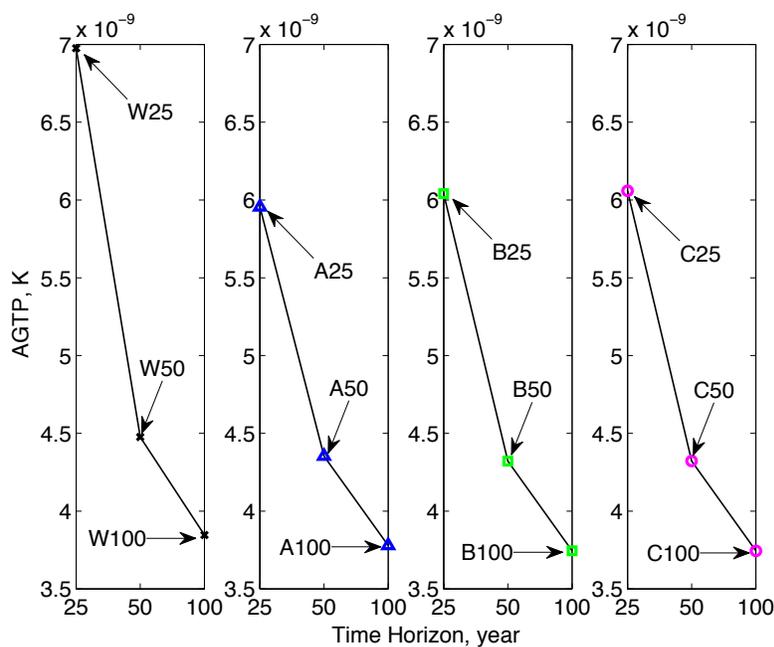

Figure 5. The climate impact associated with various climate goals.

The climate impact of wind-optimal trajectories is larger than that resulting from the climate-optimal goals for all time horizons due to their contrail production. The reduction in AGTP value due to any of the three climate goals is about 15% at the end of 25 years for LCR strategy. The reduction becomes smaller for longer time horizons since the short-term climate advantage resulting from contrails reduction is overtaken by long-term climate impact of CO_2 due to additional fuel consumption. The magnitude of temperature change due to contrails and CO_2 emission and its reduction is significantly larger when a shorter time horizon is considered. Similar trends are obtained for the climate-optimal trajectories for the three goals when 3DR strategy is adopted. The AGTP reduction compared to wind-optimal trajectories is about 28% at the end of 25 years for 3DR strategy.

The climate impacts resulting from the three climate-optimal goals are similar. Their AGTP values are close for the same time horizon although the AGTP value at A25, B50, and C100 is the lowest for the time horizon of 25, 50,

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and 100 years, respectively. These results suggest that the difference in contrail reduction between the climate-optimal goals is balanced by the difference in fuel burn in terms of AGTP at the end of the 25, 50, 100 years.

Figure 6 measures the energy efficiency of the climate-optimal goals for LCR strategy. The energy efficiency is measured by the amount of temperature reduction in Kelvin for a kg of additional fuel over the baseline wind-optimal route. The energy efficiency is indicated by the 'triangle', 'square', and 'circle', for the three groups of climate-optimal trajectories resulting from Opt25, Opt50 and Opt100 respectively. In general, energy efficiency is higher when contrail RF difference is larger and the time horizon is shorter. The climate impact of contrails is larger under these two conditions. However, the set of climate-optimal trajectories for Opt25, which reduces the most contrail formation, is the least energy efficient for all values of contrail RF and over all time horizons. The set of climate-optimal trajectories for Opt100 that reduces the least contrail formation is the most energy efficient among the three goals in all cases and the performance of that for Opt50 is close to Opt100. The 3DR strategy has a similar trend and is more efficient since the AGTP reduction is higher for the same fuel burn. Note that the energy efficiency for the 3DR strategy is not defined for the current scenario since contrail reductions are accompanied by decreased fuel usage when wind-optimal trajectories on the filed cruise altitude is chosen as baseline. Furthermore, the energy efficiency can be measured by the minutes of contrail reduction for a kg of additional fuel over the wind-optimal route based on Fig.3. The efficiency of the LCR strategy increases from 0.033 minutes/kg for Opt25 to 0.052 minutes/kg and 0.054 minutes/kg for Opt50 and Opt100, respectively. Therefore, the groups of climate-optimal trajectories selected for Opt100 and Opt50 are more efficient than that of Opt25. These results suggest that efficiency of contrail reduction decreases, as more contrail reduction is demanded in the case for the climate goal of Opt25.
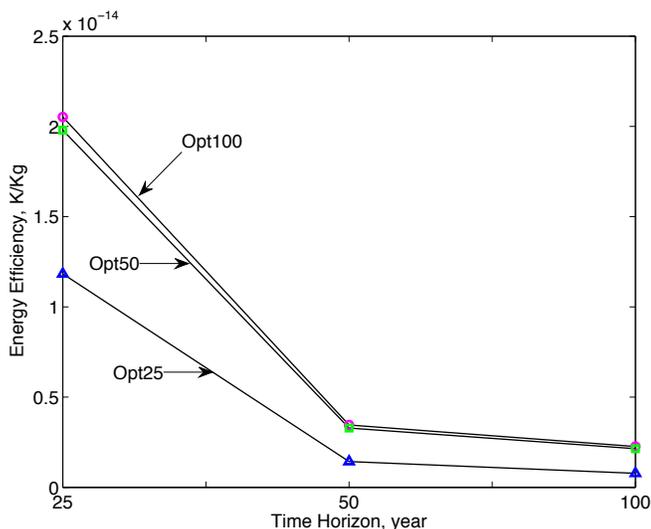

Figure 6. The energy efficiency associate to various climate-optimal trajectories.

The results suggest that the climate goal of Opt50 or Opt100 should be chosen although it does not provide the smallest AGTP values at the end of 25 years when energy efficiency is considered. This implies that a long-term environmental objective is preferred when the additional fuel cost and energy efficiency are concerned. In addition, these climate-optimal trajectories should be adapted sooner the better if an environmental objective is expected to be accomplished at a particular time in future. These results provide inputs to the formulation of aviation policy and operations with an environmental objective. The next section evaluates these climate-optimal strategies with respect to how a hypothetical tax on contrail production would influence a stakeholder's willingness to redefine their respective "optimal" cruise trajectory.

IV. Tradeoff Analysis Framework

The minimum climate impact trajectories described in the previous section may result in higher operating costs or reduced capacity in the system. An alternative way of evaluating the impact of aviation on climate is based on the value the users and other stakeholders of aviation associate with reducing the different types of emissions and contrails. A systematic approach to the development of multiple competing environmental tradeoffs is developed in a recent study[24]. The value to the stakeholders can be expressed as

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$$\text{Value} = J(F_1, F_2, ..., F_n) = \sum_1^n J(F_i(j)) \tag{2}$$

where n is the number of flights and $J(F_i(j))$ is the cost associated with flight i along route j. $J(F_i(j))$, can be expressed as

$$J(F_i(j)) = \lambda_{DOC} \cdot t(i,j) + \lambda_{fuel} \cdot fuel(i,j) + \lambda_{CO_2} \cdot CO_2(i,j) + \lambda_{NO_x} \cdot NO_x(i,j) + \lambda_{con} \cdot con(i,j) \tag{3}$$

where $t(i,j)$ is the flying time associated with flight i along route j, $fuel(i,j)$ is the fuel burn, $CO_2(i,j)$ is the CO_2 emission, $NO_x(i,j)$ is the NO_x emission, and $con(i,j)$ is the contrail length associated with flight i along route j, respectively. The tradeoff analysis framework uses sets of λ values for emissions and contrails. The selection of the λ values depends on the stakeholders. The λ_{DOC} is the average hourly operating cost excluding fuel for an aircraft, λ_{fuel} is the price of Jet-A fuel; λ_{CO2}, and λ_{NOx} are social costs of CO_2 and NO_x emissions. The value to the stakeholder is maximized by minimizing the total operating cost $\sum_1^n J(F_i(j))$ with respect to flights and routes. An analysis was conducted for cruise flights by varying a social cost on contrails "λ_{con}" while holding the other values in the set at their reference values. The tradeoff analysis framework was explored for cruise flights in reference 24 and the value of λ_{con} for which airlines would modify their trajectory to reduce contrails was established for fixed values of λ_{CO2}, λ_{fuel} and other costs. The reference values used in the study are $_{DOC}$=1163 \$/hr, λ_{fuel}=2.49 \$/gal, λ_{CO2}=0.04 \$/kg, λ_{NOx}=4.05 \$/kg.

The climate-optimal trajectories presented in the previous section are re-examined based on the operating costs of stakeholders. The total operating cost for each group of aircraft trajectories in Sec. IIIA is calculated based on their travel time, fuel burn, emissions, and induced contrail length using the valuation in Eq. (3). Figure 7 shows the tradeoff between the total operating cost and fuel burn for three values of the social cost of contrails, λ_{con}, when the 3DR strategy is adopted. The total operating cost increases linearly with fuel burn when the contrail cost is zero since the fuel burn is proportional to travel time and emissions. It is minimized for the smallest amount of fuel burn. In general, operating costs increase with contrail cost and the corresponding minimum operating value occurs at a larger fuel burn for more contrail reduction.
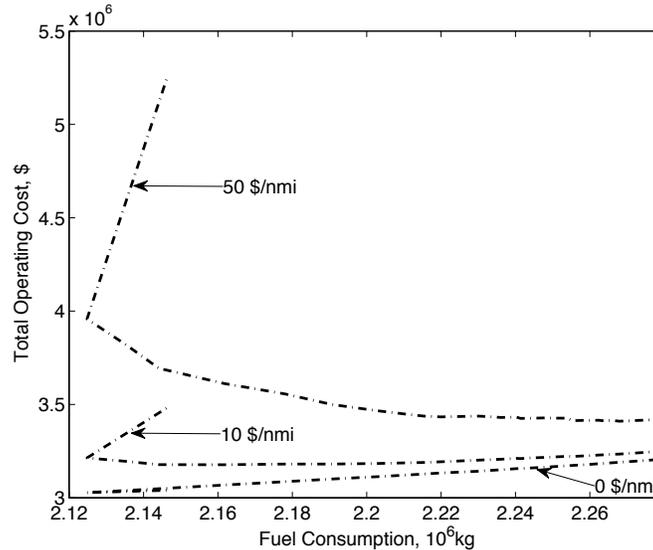

Figure 7. Tradeoff in terms of total operating cost.

Figure 8 shows the minimized total operating cost as a function of the contrail cost for the LCR and 3DR strategies and compares them with the operating cost associated with the Opt25, 3DR climate-optimal trajectories. The minimized operating cost for LCR and 3DR are plotted in black solid and dotted lines, respectively. The blue dotted line shows the total operating costs for the climate-optimal goal, Opt25, for 3DR. It increases linearly with

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contrail cost since the amount of contrail formation is a constant. The Opt25 for 3DR has a higher cost than the minimum operating value of both LCR and 3DR when contrail cost is smaller than about 3 $/nmi. In this case, stakeholders may not choose the set of climate-optimal trajectories since its operating costs are larger than the minimized operating cost for LCR and 3DR. The climate-optimal trajectories of Opt25, 3DR has a smaller operating value than the minimum for LCR and becomes closer to that of 3DR when contrail cost is larger than 3 $/nmi.
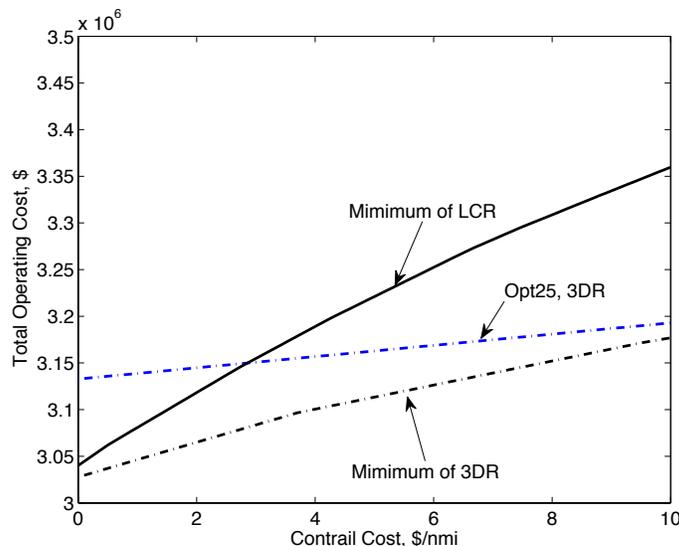

Figure 8. Total operating cost for various contrail reduction startegies.

Figure 9 shows the additional operating costs for LCR as solid curves and as dotted curves for 3DR when compared to their respective minimum operating values for a range of contrail costs. The results of the two groups of climate-optimal trajectories, each developed for Opt50, and Opt100 are plotted in green and magenta for a contrail RF of 30 mW/m^{2}. Note that the group of climate-optimal trajectories resulting from Opt50 is the same as the group resulting from Opt100 for 3DR strategy. They are concave upward curves. Each has a non-zero additional operating cost for a given contrail cost since the baseline is the minimum operating value of LCR or 3DR strategies. The additional operating costs of the climate-optimal goals are between 0.7% and 2.2% when compared to the wind-optimal operation for a zero contrail cost. As the social cost of contrails is increased, the additional operating cost of each goal decreased. The minimum of each curve identifies the contrail cost for which the operating cost of associated climate goal is same as the optimal value of LCR or 3DR strategies. In some cases, the additional operating costs are zero for a small range of contrail cost since there are limited group of trajectories for selection. This happens when the group of the aircraft trajectories resulting from the climate-optimal goal is the same as the group of trajectories that produces the minimum operating value for the chosen range of contrail cost.

Table 1 summarizes the reduction in the contrails, reduction in AGTP and increase in cost for different minimum AGTP trajectories over baseline with wind-optimal operations.

The 3DR strategy has a set of smaller contrail costs than that of LCR since the 3DR strategy is more efficient for reducing contrails. The sets of climate-optimal trajectories for the goals of Opt50 and Opt100 are more energy efficient. The contrail cost that can potentially redefine a stakeholder's objective to these climate-optimal goals is about 3.7 $/nmi for 3DR for a contrail RF of 30 mW/m^{2}. Note that the contrail cost decreases as the strategy becomes more efficient. Current contrail cost can be considered as an upper bound since it decreases as the number of potential aircraft trajectories for each climate-goal increases.

The results will be extended in the future by considering the climate goals at more time horizons for the air traffic in the entire NAS. It is expected that the additional cost to the stakeholders for contrail reduction will be less than the 12 city-pairs since flights with city-pairs less than 500 miles constitute almost 50% of the total number of flights in the NAS[25].
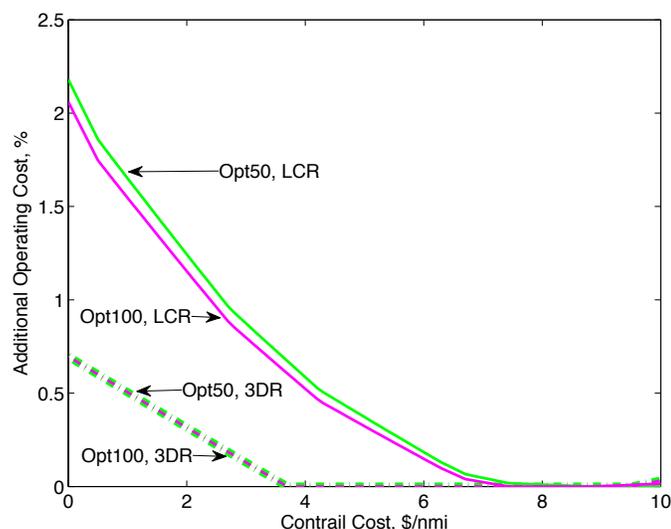
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Figure 9. Additional operating cost for various contrail reduction startegies.

Table 1. Comparison between climate reducing and wind-optimal operations

Climate reduction trajectory	Method of contrail reduction	Contrail reduction (%)	AGTP reduction (%)	Extra operating cost (%)
opt25	LCR	49	14.6	4.0
opt25	3DR	86	28.0	3.5
opt50	LCR	42	3.5	2.2
opt50	3DR	70	9.1	0.7
opt100	LCR	41	2.6	2.1
opt100	3DR	70	7.7	0.7

V. Conclusion

An optimization module capable of minimizing the climate impact of aircraft emissions and contrails is developed in this study. The optimization capability integrates an airspace simulation with aircraft fuel burn and emissions models, contrail formation models, simplified climate response models, and a common climate metric to generate alternate aircraft trajectories for aircraft traveling between city-pairs. The integrated system is applied to analyze the energy efficiency of the trajectory designs and their relationships with the environmental objective. In addition to the baseline wind-optimal trajectories, three climate-optimal designs that each minimizes the total climate impact of aircraft CO_2 emission and contrails at the end of 25, 50, and 100 years, respectively, are applied to a simulated traffic between 12 city-pairs. Initial results show that climate-optimal trajectories, which minimize total climate impact at the end of 50 or 100 years, reduce a relatively smaller amount of contrail formation but have higher energy efficiency than trajectories minimizing climate impact at the end of 25 years. Similar results are obtained for the climate-optimal designs for aircraft trajectories involving altitude changes. The minimum climate impact trajectories described in the previous section may result in higher operating costs or reduced capacity in the system. The value of climate reducing trajectories varies with the cost users and other stakeholders of aviation associate with reducing the different types of emissions and contrails. The hypothetical contrail cost at which a stakeholder may redefine his objective from minimizing the operating cost to these climate-optimal goals is about 3.7 $/nmi for aircraft trajectories involving altitude changes for a contrail RF of 30 mW/m^{2} under current scenario. The optimization results from this research can be used as inputs to analyzing different climate impact policies from the perspective of different stakeholders in global climate modeling tools like the FAA's Aviation environmental Portfolio Management Tool for Impacts[26].

Appendix
Table A1. The 12 airport pairs

	Airport Pairs	
1	Atlanta Hartsfield-Jackson (ATL)	Denver (DEN)
2	Dallas-Fort Worth (DFW)	Detroit Metropolitan (DTW)
3	Dallas-Fort Worth (DFW)	Washington Dulles (IAD)
4	Dallas-Fort Worth (DFW)	New York LaGuardia (LGA)
5	Detroit Metropolitan (DTW)	Minneapolis St. Paul (MSP)
6	Newark Liberty (EWR)	Houston George Bush (IAH)
7	Newark Liberty (EWR)	Miami (MIA)
8	Washington Dulles (IAD)	Orlando International (MCO)
9	Houston George Bush (IAH)	Phoenix Sky Harbor (PHX)
10	John F. Kennedy (JFK)	Los Angeles (LAX)
11	Chicago O'Hare (ORD)	New York LaGuardia (LGA)
12	Chicago O'Hare (ORD)	Miami (MIA)

References

[1] Brasseur, G. P. and Gupta, M., "Impact of Aviation on Climate: Research Priorities," Bull. Amer. Meteor. Soc., Vol. 91, 461–463, April 2010.

[2] Duda, D.P., Minnis, P., Costulis, P.K., and Palikonda, R., "CONUS Contrail Frequency Estimated from RUC and Flight Track Data," *European Conference on Aviation, Atmosphere, and Climate*, Friedrichshafen at Lake Constance, Germany, June-July 2003.

[3] Boucher O., "Atmospheric science: Seeing through contrails," Nature Climate Change, 1, 24-25, 2011.

[4] Klima, K., "Assessment of a Global Contrail Modeling Method and Operational Strategies for Contrail Mitigation," M.S. Thesis, MIT, 2005.

[5] Sridhar, B., Chen, N. Y., and Ng, H. K., "Fuel Efficient Strategies for Reducing Contrail Formations in United State National Air Space," 29th Digital Avionics Systems Conference, Salt Lake City, UT, October 2010.

[6] Sridhar, B., Ng, H. K., Chen, N. Y., "Aircraft Trajectory Optimization and Contrail Avoidance in the Presence of Winds," AIAA Aviation Technology, Integration, and Operation Conference, September 2010, Fort Worth, TX.

[7] Campbell, S. E., Neogi, N. A., and Bragg, M. B., "An Optimal Strategy for Persistent Contrail Avoidance," AIAA 2008-6515, AIAA Guidance, Navigation, and Control Conference, Honolulu, Hawaii, 2008.

[8] Fuglestvedt, J. S., Shine, K. P., Berntsen, T., Cook, J., Lee, D. S., Stenke, A., Skeie, R. B., Veldes, G. J. M., ad Waitz, I. A., "Transport impacts on Atmosphere and Climate: Metrics," *Atmosphere Environment,* Vol. 44, No. 37, 2010, pp. 4648-4677, doi:10.1016/j.atmosenv.2009.04.044.

[9] Khodayari, A., Wuebbles D. J., Olsen, S., Fuglestvedt, J.S., Berntsen, T., Lund, M. T., Waitz, I., Wolfe, P., and Forster, P., "Intercomparision and evaluation of the capabilities of simple climate models to project the effects of aviation on climate," *WCRP Conference*, October 2011.

[10] Aviation environmental Portfolio Management Tool, Partnership for AiR Transportation Noise & Emissions reduction, http://web.mit.edu/aroastro/partner/apmt.

[11] Sridhar, B., Ng, H. K., and Chen, N. Y., "Integration of Linear Dynamic Emission and Climate Models with Air Traffic Simulations," AIAA Guidance, Navigation and Control Conference, Minneapolis, MN, 2012.

[12] Bilimoria, K., Sridhar B., Chatterji, G., Sheth, K., and Grabbe, S. "FACET: future ATM concepts evaluation tool," *Air Traffic Control Quarterly*, Vol. 9, No. 1, 2001.

[13] "User Manual for the Base of Aircraft Data (BADA), Revision 3.6," Eurocontrol Experimental Center (EEC) Note No. 10/04, Project ACE-C-E2, Sept. 2004.

[14] Hadaller, O. J. and Momently, A. M., "The Characteristics of Future Fuels," Project Report D6-54940, Boeing publication, 1989.

[15] Baughcum, S., Tritz, T., Henderson, S., and Pickett, D., "Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis," Project Report NASA CR 4700, April 1996.

[16] Ponater, M., Marquart, S., and Sausen, R., "Contrails in a Comprehensive Global Climate Model: Parameterization and Radiative Forcing Results," *Journal of Geophysical Research*, Vol.107, Issue D13, 2002, pp. ACL 2-1.

[17] Schumann, U. A contrail cirrus prediction model, Geoscientic Model Development, 5, 543-580, 2012

[18] Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R., 2007a. Changes in atmospheric constituents and in radiative forcing. In: Solomon, S., et al. (Eds.), Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

[19] Burkhardt, U., and Kärcher, B. "Global radiative forcing from contrail cirrus," Nature Clim. Change Vol. 1, 2011, pp. 54-58, DOI: 10.1038/NCLIMATE1068.

American Institute of Aeronautics and Astronautics

[20]Shine, K. P., Fuglestvedt, J. S., Hailemariam, K., Stuber, N., 2005b. "Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases," *Climatic Change* 68, 281–302.

[21]Rapid Update Cycle (RUC), http://ruc.noaa.gov/RUC.faq.html.

[22]"Benefit Analysis and Report for Domestic Reduced Vertical Separation Minimum (DRVSM)," CDM/DRVSM Work Group Report, FAA Air Traffic Organization System Operations Services, Sept. 2005.

[23]Volpe National Transportation Systems Center/US DOT., "Enhanced Traffic Management System (ETMS), Functional Description, Version 7.6," Report Number VNTSC-DTS56-TMS-002. August 2003.

[24]M. Gregory O'Neill, Jean-Marie Dumont, R. John Hansman, "Use of Hyperspace Trade Analyses to Evaluate Environmental and Performance Tradeoffs for Cruise and Approach Operations," AIAA 2012-5507, AIAA Aviation Technology, Integration, and Operation Conference, September 2012, Indianapolis, Indianapolis, Indiana.

[25]Sridhar, B., Chen, N. Y., and Ng, H. K., "Energy Efficient Contrail Mitigation Strategies for Reducing the Environmental Impact of Aviation," Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013), Chicago, IL, June 2013.

[26]http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/apmt/

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