Energy Efficient Contrail Mitigation Strategies for Reducing the Environmental Impact of Aviation

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Abstract— **The main goal of Air Traffic Management (ATM) is to enable safe operation of air traffic while accommodating the demand and doing it efficiently with minimum disruption to schedules. The impact of aircraft emissions on the environment adds an additional dimension to the planning of aircraft operations. This paper describes a new simulation capability to analyze the relationship between air traffic operations and their impact on the environment. This is the first simulation to integrate all air traffic in the US based on flight plans, aircraft trajectory calculations based on predicted wind data, contrail calculations based on predicted temperature and humidity data, a common metric to combine the effects of different types of emissions, and algorithms to generate alternate trajectories for aircraft traveling between city-pairs. The integrated simulation is used to evaluate the energy efficiency of contrail reduction strategies. The aircraft trajectories are varied from their baseline flight plans to reduce contrails in three different ways: changes to altitude, optimal changes to planned route, and three-dimensional change of trajectory. The method is applied to three different scenarios: (a) a single flight between a city-pair, (b) all flights between 12 city-pairs, and (c) all flights in the US airspace. Results for the 12 city-pairs show that contrail reduction involving horizontal route change only is not fuel efficient, the three-dimensional trajectory change produces the best results at a computational cost, and changes to the altitude only produces good results as well as the ability to add airspace capacity constraints. For the scenario of all flights in the US airspace, initial results based on one month data show that contrail reduction strategies involving altitude changes applied to medium and long-range flights on days with high-contrail activity provide the maximum environmental benefit for a small reduction in energy efficiency.**

Keywords-energy efficiency; environmental impact; air traffic simulation; contrail reduction strategies

I. INTRODUCTION

There is increased awareness of aviation-induced environmental impact affecting climate change [1]. Estimates show that aviation is responsible for 13% of transportation-related fossil fuel consumption and 2% of all anthropogenic CO_2 emissions [2]. Although emission contributions from aviation are small, a large portion of the emissions takes place at altitudes where the emissions remain longer in the atmosphere than if emitted at the surface. After a small decline over the last few years, air traffic has increased since 2011, and the Federal Aviation Administration (FAA) expects domestic air traffic to grow at an annual rate of 3.5% over the next 20 years [3]. Global air traffic is expected to grow more rapidly than domestic air traffic at an annual rate of 4.8% from 2011 to 2030 [4]. The desire to accommodate growing air traffic needs while limiting the impact of aviation on the environment has led to research in green aviation with the goals of better scientific understanding, utilization of alternative fuels, introduction of new aircraft technology, and rapid operational changes.

Aviation operations affect the climate in several ways. The climate impact of aviation is expressed in terms of "radiative forcing" (RF). RF is a perturbation to the balance between incoming solar radiation and outgoing infrared radiation at the top of the troposphere. The amount of outgoing infrared radiation depends on the concentration of atmospheric greenhouse gases (GHG). RF associated with each type of emission has an approximately linear relationship with global mean surface temperature change. CO_2, water vapor, and other gases are unavoidable by-products of the combustion of fossil fuel; of these CO_2 and water vapor are GHG resulting in a positive RF. Because of its abundance and long lifetime, CO_2 has a long-term effect on climate change; the non-CO_2 emissions have a short-term effect on climate change. The important non-CO_2 impacts associated with aviation are water vapor, oxides of nitrogen (NO_X), condensation trails (contrails) and cirrus clouds due to air traffic. Contrails are clouds that are visible trails of water vapor made by the exhaust of aircraft engines [5]. 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 [6].

The complexity and uncertainty in understanding the various components of the climate equation requires models, analysis, optimization, and validation at several levels. This paper describes a climate impact simulation capability by integrating a national-level air traffic

system simulation and optimization capability with aircraft fuel and emission models similar to models in Aviation Environmental Design Tool (AEDT) [7]. In addition, the simulation includes contrail models that use forecast weather data and climate metrics based on advances in climate science research. The simulation can provide both CO_2 and non-CO_2 emissions resulting from different current and future operational scenarios. The capability is intended to evaluate new aircraft technologies and alternative operational concepts to mitigate the impact of air traffic on the environment. The modular nature of the simulation allows for the introduction of more detailed emission and climate models, as needed, to evaluate mature concepts. The integrated capability is used to examine the energy efficiency of three different contrail reduction strategies. The aircraft trajectories are varied from their baseline flight plans in three different ways: (a) changes to altitude, (b) optimal changes to route, and (c) changes to both altitude and route. The methodology is applied to all aircraft flying in the US airspace. Initial results show that contrail reduction strategies involving altitude changes applied to medium and long-range flights on days with high-contrail activity are promising and provide the maximum environmental benefit for a small increase in fuel consumption.

The main contributions of this paper are (a) the integration of aircraft emission models, contrail models, simplified climate response models and metrics with a national-level airspace simulation that can simulate current and future air traffic scenarios and (b) the use of the simulation capability to evaluate the energy efficiency of three different contrail reduction strategies. The development in this paper uses real traffic data and air traffic simulations providing details about air traffic operations, such as delays, sector congestion and wind optimal routes, while using simplified climate models. Simple emission and climate models, based on the input/output relations of linear systems, capture the fundamental emission to climate impact behavior by careful selection of key variables and their dynamics.

The rest of the paper is organized as follows: Section II provides background about research activities in the US and Europe to get a better understanding of the environmental impact of aviation. Section III describes the airspace simulation, fuel and emission models, contrail models, and linear climate response models and metrics. Section IV reviews contrail reduction methods, describes three contrail reducing strategies and applies the methodology to a traffic scenario consisting of flights between twelve city-pairs in the United States. Section V extends the application of the method to all US air traffic during a month. Conclusions and future work are described in Section VI.

II. Background

This section briefly reviews international efforts to get a better understanding of the environmental impact of aviation. National Aeronautics and Space Administration (NASA) and FAA are supporting research to reduce uncertainties in modeling atmospheric physics and chemistry and weather forecasting [8]. A comprehensive update on the role of key uncertainties in estimating the impact of aviation on climate change is provided in a recent paper [9]. FAA is developing AEDT with fuel and emission models for environmental concept and policy analysis [7]. NASA is conducting research on vehicle concepts and enabling technologies that will reduce the impact of aviation on the environment under the Environmentally Responsible Aviation (ERA) Program [10]. Similar research is conducted in Europe under the Clean Sky and Single European Sky ATM Research (SESAR) [11] projects.

Modeling and simulation to understand the impact of aviation on climate covers airspace from small regions to the entire world and intervals of time varying from seconds to several hundred years. The modeling of aircraft emissions and their interaction with each other to change the concentration levels of different gasses in the atmosphere and the resulting impact of the RF on the equilibrium of the Earth's atmosphere is complex and requires the use of coupled atmosphere-ocean general circulation models together with three-dimensional models of carbon cycle and chemistry of other non-CO_2 greenhouse gases. These models are computationally intensive and may neither be feasible nor necessary for studies emphasizing aviation operations in the presence of uncertainties in climate modeling and that require thousands of scenarios to evaluate new procedures and technology. It is appropriate to use a hierarchy of models with different levels of accuracy subject to computational limitations and driven by the questions to be answered by the modeling process. Using pre-calculated atmospheric data with aircraft emission data generated by climate-chemistry models, AirClim [12], a climate evaluation tool, reduces the computational time in predicting the evolution of gas concentrations, RF, and temperature changes. Such models can be integrated with detailed airspace simulations.

III. Integrated Simulation Capability

The key components of the simulation are described in the next subsections.

A. *Air Traffic Simulation*

The air traffic is simulated using Future Air Traffic Management Concepts Evaluation Tool (FACET) [13], a national level air traffic system simulation and optimization tool. FACET has the ability to simulate current traffic scenarios using predictions of weather and atmospheric conditions and has been used to evaluate air traffic concepts using future traffic and technology scenarios.

B. Fuel and Emission Models

FACET uses the fuel consumption model provided by Eurocontrol's Base of Aircraft Data (BADA) [14]. The air traffic model 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 AEDT and were verified in collaboration with Volpe Transportation System Center by comparing emissions produced by a number of aircraft trajectories by the simulation and AEDT.

Six emissions are computed including 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 [15]. Emissions of CO, HC and NO_x are modeled through the use of the Boeing Fuel Flow Method 2 (BFFM2) [16]. The emissions are determined by aircraft engine type, altitude, speed, fuel burn and the coefficients in the International Civil Aviation Organization (ICAO) emission data bank. Standard conditions for temperature and pressure are used to compare data from different experimental measurements.

C. 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, r_{contr} [17]. Contrails can persist when the ambient air is supersaturated with ice, i.e., the environmental relative humidity with respect to ice (RHi) is greater than 100% [5]. 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. The size of linear contrails can be verified using satellite imagery [5]. Linear contrails may spread to become contrail cirrus with considerable cloud cover (several kilometers in width) and depth depending on the wind and temperature conditions. The model can be extended to account for dynamical processes of advection, gravity, and diffusion and to distinguish between contrails formed during day and night with different RF values [18]. Using satellite imagery and numerical models, the size of the contrail cirrus is estimated to be 10 times larger than the linear contrails in some studies [19]. Both numerical models and satellite observations have difficulty distinguishing between natural cirrus and contrail cirrus. The large uncertainties in the optical thickness and coverage associated with contrail cirrus results in large uncertainties in RF associated with contrails. [20]. 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 [21] and make further enhancements to accommodate updates in the literature on modeling errors and other uncertainties associated with the atmospheric measurements.

D. Linear Climate Models and Metrics

The climate response to aviation emission and contrails can be modeled as outputs from a series of linear dynamic systems. The linear systems are generated against a background of concentration of various greenhouse gases resulting from past emissions from all sources. Linear emission models provide the incremental changes to the greenhouse gas concentrations resulting from the emission due to some or all aircraft operation.

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 [22]. The concentration dynamics of other non-CO_2 greenhouse gases can be described by first order linear systems.

Radiative Forcing due to different emissions affects the climate by changing the Earth's global average near-surface air temperature. The temperature response/energy balance to RF can be modeled using either a first order linear model [23] or a second order linear model [24-25].

Contrails occur at different regions of the earth and add non-uniform sources of energy to the atmosphere. The latest estimates indicate that contrails caused by aircraft may be causing more climate warming today than all the residual CO2 emitted by aircraft [6]. 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 (m2). Typical values for RF range from 10 mW/m2 to 80 mW/m2 for the year 2005 [20]. Contrail RF is also represented in terms of unit distance flown by the aircraft (W/km). Energy Forcing (EF) is the net energy flux induced to the atmosphere by a unit length of contrail over its lifetime. Estimates of EF given the RF forcing due to contrails are described in [26]. The EF is expressed as joules/km of contrails. The results presented in this paper uses Contrail RF measured in mW/m2 and can be easily converted to EF units.

The lifetime associated with different emissions and contrails varies from a few hours to several hundred years. 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. Several climate metrics have been developed to assess the impact of the aviation emissions. Using linear climate response models, the Absolute Global Temperature Potential (AGTP) measures the mean surface temperature change because of different aircraft emissions and persistent contrail formations [27]. Figure 1 summarizes the steps involved in the generation of AGTP.
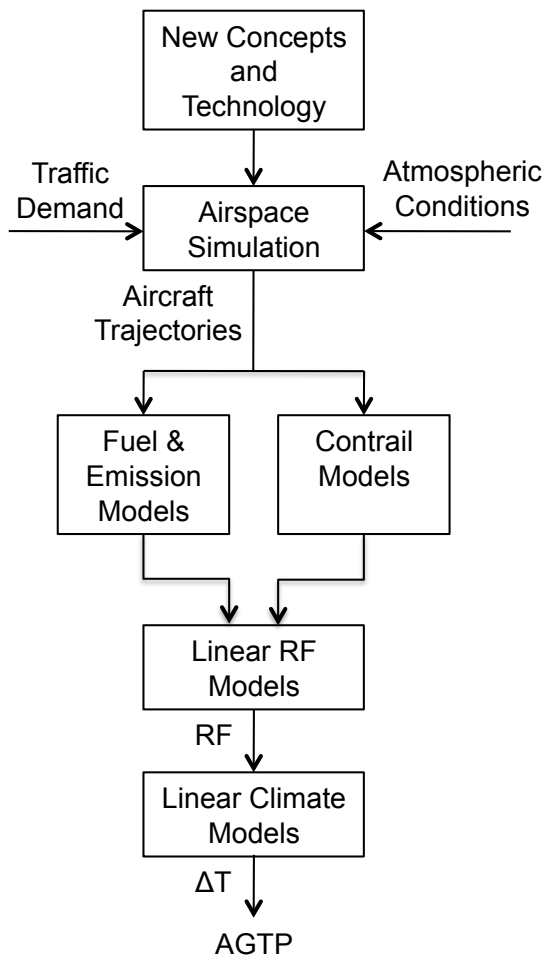
New Concepts and Technology

Traffic Demand → Airspace Simulation ← Atmospheric Conditions

Aircraft Trajectories

Fuel & Emission Models | Contrail Models

Linear RF Models

RF

Linear Climate Models

ΔT

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 [28]. The units for ΔT, α and β are degrees K, K/kg and K/km.

IV.   CONTRAIL REDUCTION STRATEGIES

Several strategies have been proposed to reduce the formation of contrails. Mannestein [29] proposed a strategy to reduce the contrail formation by only small changes to individual flight altitude. Fichter [30] showed that reducing cruise altitude could reduce the global mean annual contrail coverage. Williams [31-32] proposed strategies for contrail reduction by restricting aircraft cruise altitudes. These restrictions generally imply more fuel burn, thus more emissions, and add congestion to the already crowded airspace at lower altitudes.

Three strategies to reduce the amount of contrail formation are described next. The contrail formation and computation of aircraft trajectories use forecast of wind, humidity and temperature provided by Rapid Update Cycle (RUC) [33] . 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). The horizontal resolution in RUC is 13-km. RUC data has 37 vertical isobaric pressure levels ranging between 100-1000mb in 25mb increments. The RUC produces short-range forecasts every hour. A trade-off between energy efficiency, measured as excess use over baseline fuel consumption, and climate impact, measured as the change to the AGTP between the baseline and the contrail avoidance trajectories is generated for each concept.

Consider a flight going from airport A to airport B as shown in Figure 2. The planned or baseline route is shown in the bottom figure and the vertical profile is shown in the top part of the figure. The contrail susceptible airspace is shown as blue areas. The vertical extent of the contrails is shown in the top figure. The nominal aircraft trajectory passes through the predicted contrail region. The one-dimensional contrail reduction concept (CRC1) varies only the altitude of the aircraft, dotted lines in the top figure, to reduce the amount of contrails. No changes are made to the horizontal route of the aircraft. The two-dimensional contrail reduction concept (CRC2) maintains the baseline speed and altitude while varying the route of the aircraft by lateral maneuvers, dotted lines in the bottom figure, to reduce the amount of contrails. The three-dimensional contrail reduction concept (CRC3) varies both the altitude and

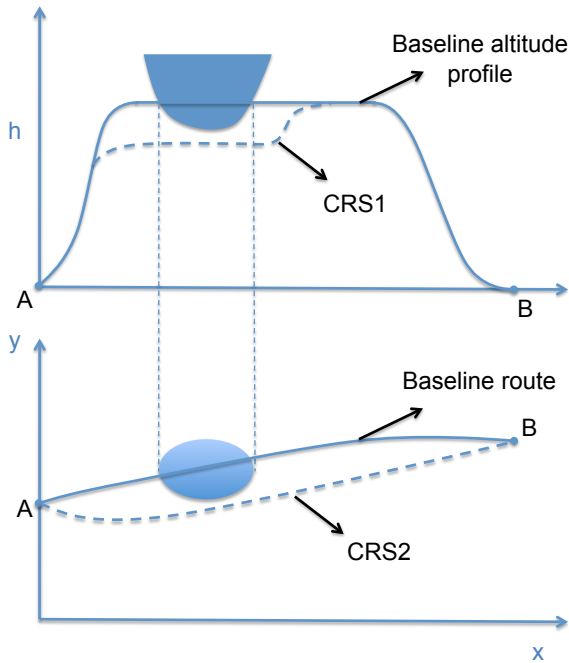the route of the aircraft to reduce the amount of contrails.

Figure 2. One and two-dimensional contrail reduction concepts.

The design of aircraft trajectories to reduce contrails involving several thousand aircraft requires a trade-off between optimality and computational requirement. The computational complexity is reduced in the CRC1 concept due to one dimension. Several algorithms based on optimal control and linear programming have been proposed to solve the two-dimensional and three-dimensional problems involving CRC2 and CRC3 strategies. A practical solution is provided by solving the three-dimensional problem as a series of two-dimensional problems with varying altitude. The algorithmic details of the contrail reducing trajectories used in this paper are described in [34,35].

A. Twelve City-pair Scenario

This section applies the contrail reducing strategies to aircraft flying between 12 major city-pairs (involves 15 airports) during a day, April 12, 2010, in the continental US. The same 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 [36]. The scenario consists of 287 flights. The baseline trajectory for each aircraft uses the speed and altitude provided by the Enhanced Traffic Management System [37] and a wind-optimal route. The aircraft flight level and air speed varies from 26,000 to 41,000 feet and from 434 to 463 knots respectively. Figure 3 shows the wind-optimal trajectories for the eastbound flights at 35,000 feet at 6 a.m. EDT on April 12. Blue polygons depict the areas favorable to persistent contrails formation. The figure indicates that a flight going from Los Angeles (LAX) to New York (JFK) may go through regions of contrail activity while a flight from Houston (IAH) to New York (JFK) may not be affected by contrail activity.

The CRC1 concept varies the baseline altitude of the aircraft up or down by 4,000 feet. Each variation in the
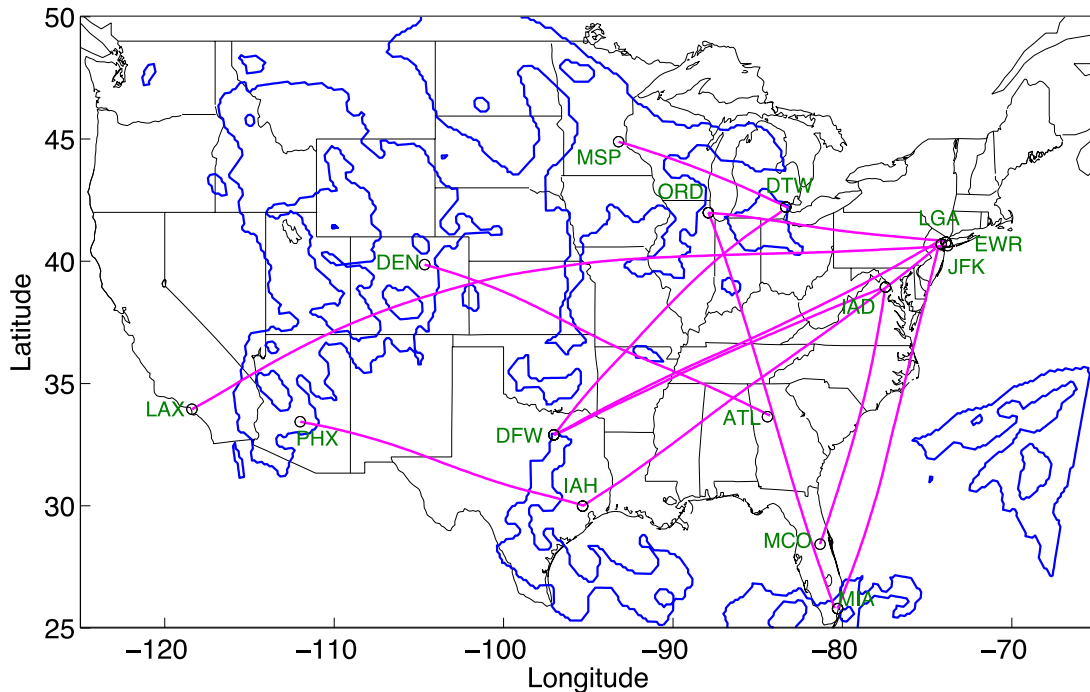

Figure 3. The wind-optimal trajectories for the eastbound flights for 12 city pairs at 35,000 feet at 6 a.m. EDT on April 12, 2010.

altitude results in fuel consumption different from the baseline. The selection of the altitude in CRC1 is limited to one change per Center as the aircraft traverses through different Centers in the airspace. The altitude changes are also limited not to exceed the airspace capacity of the sectors and maximum cruise altitude for each aircraft. Considering the relative environmental impact of emissions and contrails, the aircraft altitudes are modified only if the contrail reduction benefits exceed the environmental impact of additional emissions. The strategy uses a user-defined trade-off factor λ to determine whether the strategy should apply to an aircraft. It can be interpreted as the equivalent emissions in kg that the user is willing to trade-off for travel through areas of contrail formation in minutes. In general, higher value of λ would result in more contrail reduction and extra CO_2 emissions [35]. The data from individual aircraft can be converted into actual amount of fuel consumed by various flights and then can be aggregated to produce a simplified total fuel consumption versus total minutes through the contrail regions for all the flights between the 12 city-pairs.

Fig. 4 shows the variation between fuel consumption and contrail formation time for the CRC1 concept. The symbol X in Fig. 4 denotes the amount of fuel consumption (in million kg) and contrail formation time (in minutes) associated with the baseline operation. The CRC1 concept reduces the contrail formation time from 5,885 minutes to 2,572 minutes, indicated by C in Fig. 4, for an extra fuel consumption of 20,000 kg over the consumption for wind-optimal routes. This corresponds to the maximum amount of contrail reduction achievable by the CRC1 concept without any restriction on fuel usage. The slope of the contrail formation with fuel consumption trade-off curve measures the reduction in contrail time for unit fuel usage and can be used as a measure of the efficiency of the contrail reduction concept. The average slope between X and C is 0.166 minutes/kg.
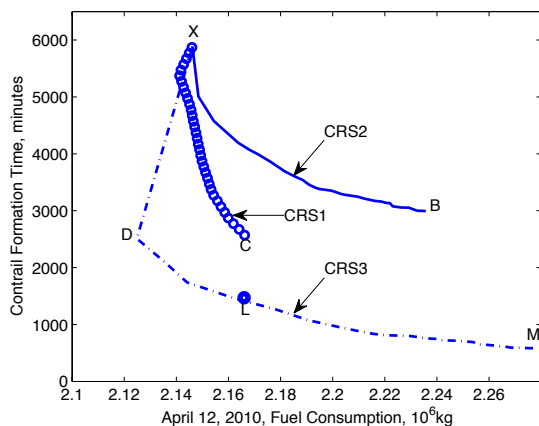

Figure 4. Comparison between three contrail reducing concepts for 12 city pairs on April 12, 2010.

The optimal lateral contrail reducing trajectories in CRC2 are generated by applying a penalty for aircraft trajectories going through contrails using the filed aircraft speed and altitude. 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 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.

The variation between fuel consumption and contrail formation time for the CRC2 concept is shown by the curve XB in Fig. 4. The CRC2 concept reduces the contrail formation time from 5885 minutes to 2995 minutes (B in Fig. 4) for an extra fuel consumption of 90,000 kg over the consumption for wind-optimal routes. The average slope between X and B is 0.032 minutes/kg. Comparing the average slopes shows that the CRC2 concept is less energy efficient than the CRC1 concept.

The cruise altitude of most commercial aircraft varies between 29,000 feet to 41,000 feet. Eastbound aircraft fly odd thousands of feet while westbound traffic fly even thousands of feet. The flight levels are separated by 2000 feet between two levels of flight in the same direction. As the choice of the cruise altitude varies over a small range, the optimal contrail reducing aircraft trajectories in CRC3 are computed by repeatedly solving the CRC2 problem. Five flight levels are considered for each direction of air traffic for each city pair. The cruising true airspeed is based on the BADA data. The fuel consumption for each aircraft trajectory is calculated using BADA formulas given the aircraft type with nominal weight. In each group, the additional fuel consumption of each optimal trajectory is obtained by comparing its fuel burned to that of its wind-optimal trajectory. The persistent contrails formation time associated with each trajectory is also recorded.

Curve XDLM in Fig. 4 shows trade-off between fuel consumption and contrail formation time for the CRC3 concept. For the current scenario, as indicated by D, initially the CRC3 concept 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 contrail formation time can be reduced to 1470 minutes, indicated by L, and 584 minutes, indicated by M, by using 20,000 kg and 131,000 kg of fuel respectively. The CRC3 concept performs better than the CRC2 concept as it reduces the contrail minutes by an additional 1102 minutes for the same extra fuel usage of 20,000 kg. However, the efficiency of the CRC3 concept reduces between points L and M as the

average slope reduces from 0.22 minutes/kg to 0.04 minutes/kg, respectively.

As discussed earlier in the paper, the fuel consumption and contrail formation times can be converted into their equivalent AGTP values. Figure 5 shows AGTP, for H=25 years and a RF value of $30mW/m^2$ for contrails, as a function of the amount of fuel used for the three different contrail reduction strategies. The figure shows the AGTP due to CO_2, contrails and the total contribution from both sources. The contribution to AGTP from CO_2 emissions increases linearly with fuel consumption and the contribution due to contrails is nonlinear. 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.
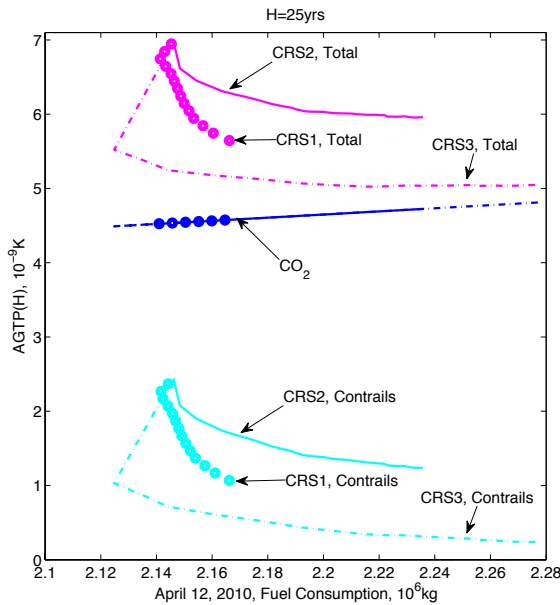

Figure 5. AGTP trade-off curves on April 12, 2010.

A second measure of the efficiency of contrail reduction strategies can be defined in terms of the average slope, E, of the variation of AGTP with respect to fuel consumption. The measure E includes the effectiveness of the concept in reducing the major contributors to the climate impact of aviation. The AGTP curves confirm that the CRC3 concept is more energy efficient than the other two strategies as measured by the reduction in AGTP for extra amount of fuel consumption. The CRC1 concept produces contrail reduction close to CRC3 concept. It is computationally efficient, can handle additional airspace constraints, and the next section extends the CRC1 concept to all aircraft flying in the continental US airspace.

V. US AIRSPACE ANALYSIS

This analysis uses traffic simulated using all the aircraft flying in the US National Airspace System (NAS) on April 12, 2010. The flights can be classified based on the distance between the arrival and departure airports. They are Short (< 500 miles), Medium (500-1000 miles), Long (1000-1500 miles), and Transcontinental flights (>1500 miles). Table 1 summarizes the contrail activity associated with different flight classes.

TABLE I. CONTRAIL ACTIVITY

Class	Number of Flights	Contrail Minutes	Total Distance (1000 miles)
Short	13,212	12,796	3,672
Medium	8,096	52,504	5,814
Long	2,864	36,021	3,378
Transcontinental	1,953	67,420	3,378
Total	26,125	168,741	16,242

Table 1 indicates that although short flights account for approximately half the total number of flights, they contribute only 7.6% of the total contrail activity. This can be explained by comparing the cruise altitudes of short flights with the altitudes of the contrail formation airspace. Figure 6 shows a box and whisker plot of the distribution of the altitudes of the different classes of aircraft flying in the NAS, in blue color, and the altitude distribution of the contrails favorable regions in dotted green color.
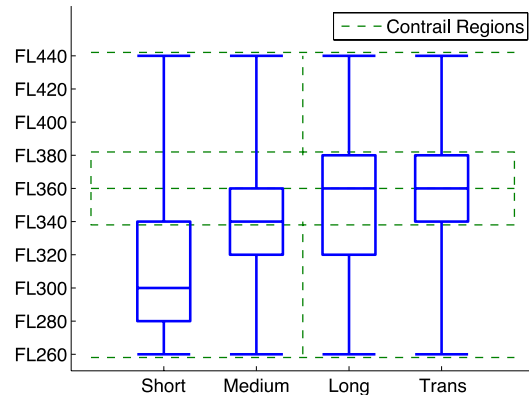

Figure 6. Distribution of aircraft and contrail favorable regions altitudes.

Figure 7 summarizes the trade-off between the contrail reduction time and fuel consumption using the CRC1 concept. The fuel consumption corresponding to all aircraft in the baseline flying wind-optimal trajectories is 43,215 Mg ($1Mg = 10^6$ kg), indicated by
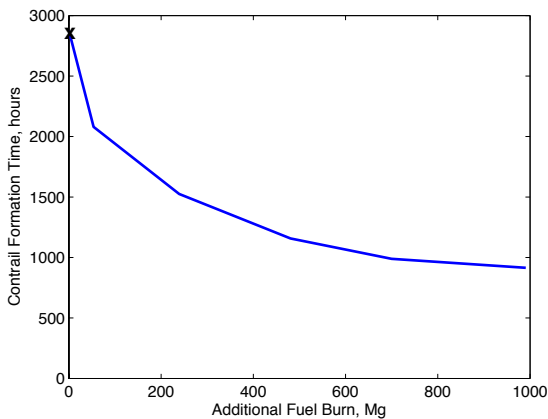
Figure 7. Variation of contrail time with additional fuel consumption for aircraft flying in the NAS.

X. The wind-optimal routes travel through contrail formation region for 2,875 hours. The CRC1 concept is applied while maintaining the baseline routing and enforcing the airspace capacity and aircraft maximum cruise speed constraint. As the trade-off factor λ is varied from 0 to it's maximum value, the contrail formation time reduces by 1,960 hours, while increasing the fuel consumption by 991 Mg. The contribution to the maximum total contrail reduction is 9.6%, 33.3%, 20.8% and 36.3% for short, medium, long and transcontinental flights respectively. The short flights play a less significant role both in the creation and the reduction of contrails compared to other category of flights.

Figure 8 converts the trade-off curve in Figure 7 to a trade-off curve between changes to the AGTP and fuel consumption. The slope of the curve in Figure 8, reduction in AGTP per unit fuel consumption (K/Mg), ex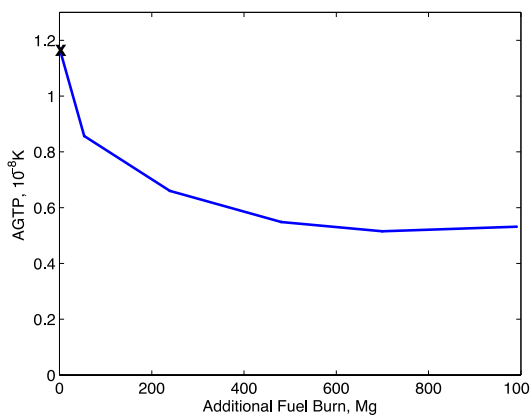presses the energy efficiency associated with the contrail reduction method. The efficiency of the method is significant in the beginning and is small, or may even be negative, after an additional fuel usage of 550 Mg. Around this extra fuel consumption, environmental benefit due to reduction in contrail formation is beginning to be outweighed by the increase in CO_2 emissions. The variation of AGTP with excess fuel provides a metric to examine whether the benefits of further reduction in aviation climate impact is outweighed by additional fuel costs.

The performance of the contrail reduction concept is affected by the daily variation in the atmospheric conditions. This variation was studied by repeating the analysis for the entire month of April 2010. The baseline fuel consumption and the amount of contrails produced vary with each day depending on the traffic and the atmospheric conditions. The amount of contrail formation varies from 3,000 hours to 300 hours and the baseline fuel usage varies from 48,000 Mg to 38,000 Mg. The days during the month can be divided into high contrail, medium contrail and low contrail days depending on the amount of contrail formation. Figure 9 shows a plot of the reduction in the amount of contrails versus the amount of extra fuel used to achieve the reduction. The trade-off curves for the high contrail days are indicated by pink marks, the medium contrail days by green marks, and the low contrail days by blue marks. The curves indicate that the amount of contrail reduction achieved for the same amount of fuel spent over the baseline is generally highest on high contrail days, followed by medium contrails days. The contrail reduction method is not as effective on low contrail days. The trade-off curves between AGTP and excess fuel consumed is shown in Figure 10. The AGTP curves confirm the earlier observation that the reduction in aviation climate impact, measured as decrease in AGTP from the baseline per additional fuel usage is more effective on days with more contrails. Also the rate of AGTP reduction reduces as more fuel is used.

Figure 8. Variation of AGTP with additional fuel consumption for aircraft flying in the NAS.
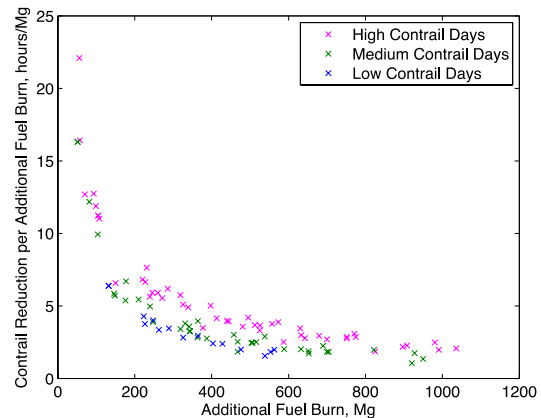

Figure 9. Reduction in contrail formation per additional fuel usage during April 2010.
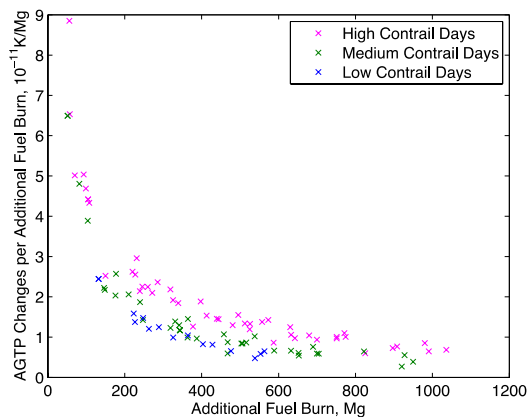
Figure 10. Reduction in AGTP per additional fuel usage during April 2010.

Based on the simulation results described earlier, the following observations can be made about the characteristics of the contrail reduction concept as applied to NAS-wide traffic. It is not energy efficient to apply CRC1 to short flights. The most energy efficient contrail reduction is achieved by changing the flight altitudes of aircraft with ranges greater than 500 miles on medium and high contrail days.

VI. CONCLUDING REMARKS

This paper presented an airtraffic simulation with simplified climate response models to evaluate the energy efficiency of three contrail reduction strategies based on a 25 years decision horizon and a constant radiative forcing for contrails. The method was applied to the simulation of air traffic data for a month in the continental US. Initial results demonstrate that a contrail reduction policy involving altitude changes to aircraft flying distances greater than 500 miles applied on days with high contrail activity is more energy efficient than applying altitude changes to avoid contrails to all aircraft on all days. These results need to be evaluated further with a range of values covering uncertainties in contrail formation and RF associated with contrails. The analysis can be repeated using more detailed models of contrails formation and with spatially and temporally varying RF for contrails [38]. The results can be expanded to include other non-CO_2 emissions [39]. The optimization results from this research can be used as inputs to global climate modeling tools like the FAA's Aviation environmental Portfolio Management Tool for Impacts [40].

ACKNOWLEDGEMENTS

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