Evaluation of Contrail Reduction Strategies Based on Environmental and Operational Costs

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This paper evaluates a set of contrail reduction strategies based on environmental and operational costs. A linear climate model was first used to convert climate effects of carbon dioxide emissions and aircraft contrails to changes in Absolute Global Temperature Potential, a metric that measures the mean surface temperature change due to aircraft emissions and persistent contrail formations. The concept of social cost of carbon and the carbon auction price from recent California's cap-and-trade system were then used to relate the carbon dioxide emissions and contrail formations to an environmental cost index. The strategy for contrail reduction is based on minimizing contrail formations by altering the aircraft's cruising altitude. The strategy uses a user-defined factor to trade off between contrail reduction and additional fuel burn and carbon dioxide emissions. A higher value of tradeoff factor results in more contrail reduction but also more fuel burn and carbon emissions. The strategy is considered favorable when the net environmental cost benefit exceeds the operational cost. The results show how the net environmental benefit varies with different decision-making time-horizon and different carbon cost. The cost models provide a guidance to select the trade-off factor that will result in the most net environmental benefit.

I.   Introduction

Aircraft-induced environmental impact has drawn attention in recent years.[1] The three largest emission impacts include direct emissions of greenhouse gases such as CO_2, emissions of NO_x, and persistent contrails. Contrails are clouds that are visible trails of water vapor made by the exhaust of aircraft engines. Contrails form when a mixture of warm engine exhaust gases and cold ambient air reaches saturation with respect to water, forming liquid drops which quickly freeze. Contrails persist if aircraft are flying in certain atmospheric conditions. Persistent contrails reduce incoming solar radiation and outgoing thermal radiation in a way that accumulates heat.[2] The global mean contrail coverage in 1992 was estimated to double by 2015, and quadruple by 2050 due to predicted increase in air traffic.[3] Studies suggest that the environmental impact from persistent contrails are estimated to range from three to four times,[4] to ten times[5] larger than from aviation-induced emissions. To address minimizing environmental impacts due to contrails, methods to reduce aircraft induced persistent contrails have been proposed.

Various approaches have been proposed in the past to reduce the persistent contrail formation. The approach based on changing aircraft flight altitudes looks promising. Mannstein[6] proposed a strategy to reduce the climate impact of contrails significantly by only small changes in individual flight altitude. Fichter[7]

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showed that the global annual mean contrail coverage could be reduced by downshifting the cruise altitude. Williams[8,9] proposed strategies for contrail reduction by identifying fixed and varying maximum altitude restriction policy. These restrictions generally imply more fuel burn, thus more emissions, and add congestion to the already crowded airspace at lower altitudes. Sridhar,[10] Chen,[11] and Wei[12] proposed contrail reduction strategies by altering an aircraft's cruising altitude in a fuel-efficient way. The strategies were designed without increasing congestion in the airspace. The Absolute Global Temperature Potential were introduced in Ref. 13 and 14 to study the combined effect of CO_2 emissions and contrail formation on the reduction strategies. However, none of the above strategies provide the solutions to minimize the net environmental impact.

The objective of this paper is to evaluate contrail reduction strategies based on environmental and operational cost and provide a solution to maximize the net environmental benefit. A linear climate model was first used to convert effect of the carbon dioxide emissions and aircraft contrails to the changes in Absolute Global Temperature Potential,[15] a metric that measures the mean surface temperature change because of aircraft emissions and persistent contrail formations. The social cost of carbon concept[16] were then used to relate the carbon dioxide emissions and contrail formations to environmental cost. Even though the estimate of the cost is highly uncertain,[17] a suggested value was used and sensitivity analysis was conducted. The carbon auction price from the recent California's cap-and-trade system[18] in 2013 was also used for comparison. A previously developed contrail reduction strategy was used in this paper. The strategy for reducing the persistent contrail formation is to minimize the contrail frequency index by altering the aircraft's cruising altitude. A user-defined factor is used to trade off between contrail reduction and extra fuel burn and carbon dioxide emissions. A higher value of tradeoff factor results in more contrail reduction but also more fuel burn and carbon emissions. The strategy is considered favorable when the net environmental cost benefit exceeds the operational cost with certain trade-off factor. This paper evaluates how the net environmental benefit varies with impact at different decision-making time-horizon and with different carbon cost. Introducing the cost models provides a solution to select the trade-off factor that will result in the most net environmental benefit.

The remainder of the paper is organized as follows. Section II provides descriptions of the contrail model and reduction strategy, definition of linear climate model, and the environmental and cost models. Next, Section III shows the results and analysis of contrail reduction strategies with various parameters. Finally, Section IV presents a summary and conclusions.

II.   Models

II.A.   Contrail Model and Reduction Strategy

This paper follows the contrail models described in Ref. 11. The contrail models use atmospheric temperature and humidity data retrieved from the Rapid Updated Cycle (RUC) data, provided by the National Oceanic and Atmospheric Administration (NOAA). The horizontal resolution in RUC is 13-km with 37 vertical isobaric pressure levels ranging between 100 and 1000 millibar (mb) in 25 mb increments. Since the vertical isobaric pressure levels do not correspond to 2,000 feet increments, linear interpolation was used to convert the RUC data to a vertical range from 26,000 feet to 44,000 feet with increments of 2,000 feet. This range is chosen because it generally is too warm for contrails to form below 26,000 feet and most commercial aircraft fly below 44,000 feet. The 2,000 feet increment is chosen is because in general same direction of flights have a vertical separation range of 2,000 feet due to the standard in Reduced Vertical Separation Minima.[19] These modifications result in dividing the U.S. national airspace into a three dimensional grid with 337 elements along the latitude, 451 elements along the longitude, and 10 altitudes ranging from 26,000 feet to 44,000 feet.

Contrails form when a mixture of warm engine exhaust gases and cold ambient air reaches saturation with respect to water, forming liquid drops which quickly freeze. Contrails form in the regions of airspace that have ambient Relative Humidity with respect to Water (RHw) greater than a critical value r_{contr}.[20] Regions with RHw greater than or equal to 100% are excluded because clouds are already present.[21] Contrails can persist when the environmental Relative Humidity with respect to Ice (RHi) is greater than 100%.[22] In this paper, contrail favorable regions are defined as the regions of airspace that have $r_{contr} \leq RHw < 100\%$ and $RHi \geq 100\%$.

This paper uses the contrail reduction strategies described in Ref. 11. That strategy for reducing the persistent contrail formations is to minimize contrail formations by altering the aircraft's cruising altitude.

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Note that these altitude changes are subject to the cruise altitude limits of each aircraft. An additional constraint is added such that where an aircraft crosses a sector boundary and causes congestion, it will stay at the original cruise altitude. Additional conditions can be added to satisfy other operational procedures.

The strategy uses a user-defined trade-off factor α to determine whether the strategy should apply to an aircraft. It can be interpreted as the equivalent fuel in kg that the user is willing to trade off for a contrail frequency index of 1. In general, higher α would result in more contrail reduction and more fuel. Figure 1 summarizes the trade-off between the contrail time and fuel consumption using different α values when the aircraft altitudes are allowed to alter by 4,000 feet for a 24-hour period on April 19, 2010. The strategy is applied while maintaining the baseline routing and enforcing the airspace capacity and aircraft maximum cruise speed constraint. At the upper-left point, no reduction strategy ($\alpha = 0$) is applied. The lower-right point is the maximal reduction strategy ($\alpha = \infty$). As the value of α increases, the curve moves from upper-left to lower-right, resulting in less contrail time and additional fuel burn. In Ref. 11, user needs to define the α value. In this paper, the optimal α can be determined using the cost models introduced in the later section.
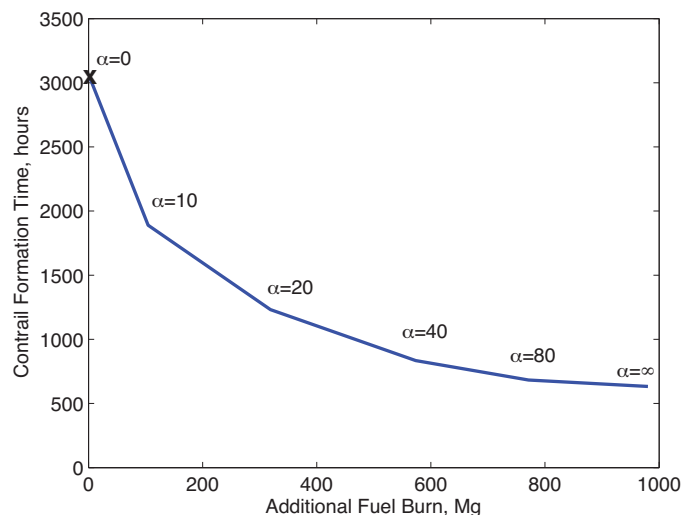

Figure 1. Contrail time versus additional fuel burn with different α values for all flights on April 19, 2010.

II.B.   Linear Climate Models

The climate response to aviation emission and contrails can be modeled as outputs from a series of linear dynamic systems. 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 Radiative Forcing for CO_2 emissions is made of a steady-state component and three exponentially decaying components.[23] 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 Earths global average near-surface air temperature. The temperature response/energy balance to RF can be modeled using either a first order linear model[24] or a second order linear model.[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 CO_2 emitted by aircraft.[26] 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). Typical values for RF range from $0.01\ W/m^2$ to $0.08\ mW/m^2$, or $10\ mW/m^2$ to $80\ mW/m^2$, for the year 2005.[27] 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 Ref. 28. The EF is expressed as joules/km of contrails. The results presented in this paper uses Contrail RF measured in mW/m^2 and can be easily converted to EF

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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.[15] AGTP provides a way to express the combined environmental cost of CO_2 emissions and contrails as a function of the fuel cost. Assume that the RF due to contrails is independent of the location of the contrails, the near surface temperature change ΔT can be approximated as

$$\Delta T = \Delta T_{CO_2} + \Delta T_{Con}, \tag{1}$$

where ΔT_{CO_2} is the contribution to AGTP from CO_2 emissions and is a linear function to additional CO_2 emissions in kg, ΔT_{Con} is the contribution to AGTP from contrails and is a linear function to contrail formation time in hour. The coefficients of the linear functions 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.[13]

The combinations of CO_2 emissions and contrail formation times in Fig. 1 were converted into their equivalent AGTP values and shown in Fig. 2, with decision-making horizon $H = 100$ years and a RF value of 30 mW/m^2 for contrails. The figure shows the AGTP due to CO2, contrails and the total contribution from both sources. The contribution to AGTP from CO2 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 CO2 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.
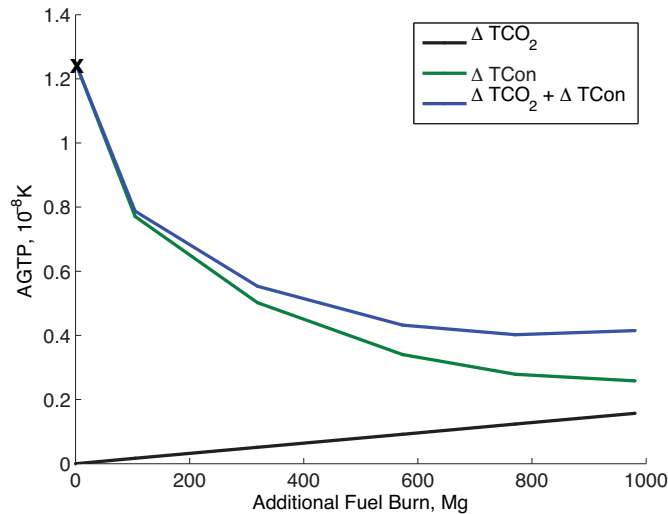

Figure 2. Absolute Global Temperature Potential (AGTP) versus additional fuel burn with different α values for all flights on April 19, 2010.

II.C. Cost Models

The United States Government recently concluded a process to develop a range of values representing the monetized damages associated with an incremental increase in CO_2 emissions, commonly referred to as the social cost of carbon.[16] These values are used in benefit-cost analyses to assess potential federal regulations. In California, the state has a carbon cap-and-trade system which is the largest of its kind in the U.S. and the second-biggest carbon market in the world behind the European Unions.[18] California cites its program as an example for the rest of the world to follow, plans to use it and other emissions-reduction measures to cut

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greenhouse-gas pollution to 1990 levels by 2020. The cap-and-trade system recently sold carbon allowances for \$13.62 per metric ton. This paper attempted to relate AGTP due to CO_2 emissions and aircraft contrails to the environmental cost in dollar amounts in order to perform a quantitative analysis of environmental benefit for the contrail reduction strategy.

Use the social cost of carbon dioxide as an index of environmental cost due to CO_2, the additional contribution to environmental cost from CO_2 emissions, $\Delta Cost_{CO_2}$, can be determined. The combined environmental cost index of CO_2 and aircraft contrails can be written as

$$\Delta Cost_{Env} = \Delta Cost_{CO_2} + \Delta Cost_{Con}, \tag{2}$$

where $\Delta Cost_{Con}$ is the additional contribution to environmental cost from contrails. All $\Delta Cost_{Env}$, $\Delta Cost_{CO_2}$, and $\Delta Cost_{Con}$ are in US dollar. Since both $\Delta Cost_{CO_2}$ and ΔT_{CO_2} are linear function of CO_2 emissions, the ratio of environmental cost index to AGTP can be determined and the same ratio could be applied for computing $\Delta Cost_{Con}$. Use the cost when $\alpha = 0$ (no reduction strategy) as baseline, the environmental cost saving index, CSI_{Env}, can be defined as:

$$CSI_{Env} = \Delta Cost_{Con}|_{\alpha=0} - \Delta Cost_{Env}. \tag{3}$$

The net environmental benefit index, NBI_{Env}, is also defined as

$$NBI_{Env} = CSI_{Env} - \Delta Cost_{Operaion}, \tag{4}$$

where $\Delta Cost_{Operation}$ is additional operational cost of applying contrail reduction strategy with corresponding α value. NBI_{Env} is positive when there is a net positive environmental benefit for applying the contrail reduction strategy. Note that the dollar amounts of CSI_{Env} and NBI_{Env} should be used as an index to evaluate the environmental cost and benefit rather than the actual real life cost and benefit. For the operational cost index, only the fuel cost is considered in this paper but can be added in the future research.

For the same example in the previous subsections, assume that the social cost of CO_2 is \$21 per metric ton as suggested in Ref.16 and the fuel cost is \$4 per gallon, the AGTP and additional fuel burn in Fig. 2 are converted into environmental cost index and additional operational cost index, shown in Fig. 3a. The blue curve shows the environmental cost index versus the additional operational cost index with different α values for the contrail reduction strategy. The black dash line is a straight line with a slope of 1. When the blue curve is above the black line, it suggested that the contrail reduction strategy provided a positive net benefit. In this case, applying the contrail reduction strategy with the trade-off factor $\alpha = 10$ provided more environmental benefit than additional operational cost. It can be clearly seen in Fig. 3b when $\alpha = 10$, it provides a positive NBI_{Env} of \$57,000 in 100-year time-horizon after applying the contrail reduction strategy. When the blue curve fell below the black line in Fig. 3a or the blue bar is negative in Fig. 3b, it suggested that the additional cost for the strategy exceeded the environmental benefit thus the strategy is not recommended. Introducing the cost model provides a solution to select the trade-off factor α that will result in the most net environmental benefit.
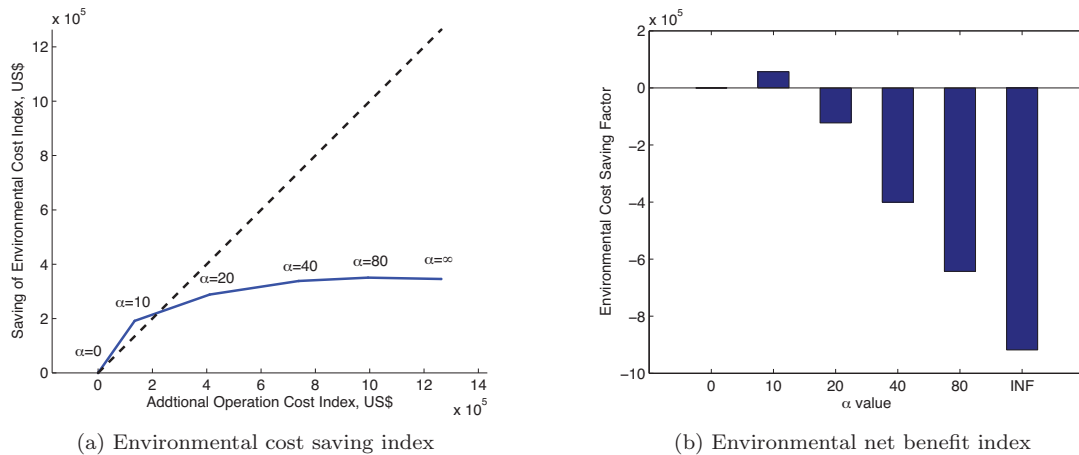

(a) Environmental cost saving index   (b) Environmental net benefit index

Figure 3. **Environmental cost saving index and net benefit index with different α values for all flights on April 19, 2010.**

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III. Analysis

The cost models introduced in the previous section can be used to evaluate the contrail reduction strategy with different parameters, including the decision-making time-horizon of environmental impact and the social cost of CO_2.

III.A. Decision-Making Time-Horizon

Since CO_2 emissions and aircraft contrails have different life time, a parameter of decision-making time-horizon H needs to be defined to compute the Absolute Global Temperature Potential (AGTP) and evaluate the environmental impact. Three different time horizon, 25, 50, and 100 years are considered. Figure 4a shows the environmental cost saving index versus the operational cost with different time horizon using the social cost of CO_2 at \$21 per metric ton and the fuel cost of \$4 per gallon. The blue line is the same as in Fig. 3a with $H = 100$, and the green and magenta lines are with $H = 50$ and $H = 25$ respectively. As indicated in the figure, the magenta line is much higher than the blue and green line, and also above the black dash-line for all α values. It indicates that shorter time horizon would result in more environmental cost saving index with same operational cost index. This is because aircraft contrails have shorter life time than CO_2 so the benefit from contrail reductions are more obvious in short time-horizon. For longer time-horizon, the impact of contrails decay and the relative impact from CO_2 becomes larger. Figure 4b shows the net benefit index for different time-horizon. Similar to the case when $H = 100$ (blue bars), for $H = 50$ (green bars), the contrail reduction strategy would use $\alpha = 10$ to achieve maximum net benefit. For $H = 25$ (magenta bars), the strategy would use $\alpha = 40$ to achieve maximum net benefit index. It is worth mentioning that the cost and benefit indices are time-dependent, meaning a net gain in benefit in 25-year time horizon might turn into net loss in benefit at 50- or 100- time horizon because the benefit from reducing contrails decays at longer time-horizon.
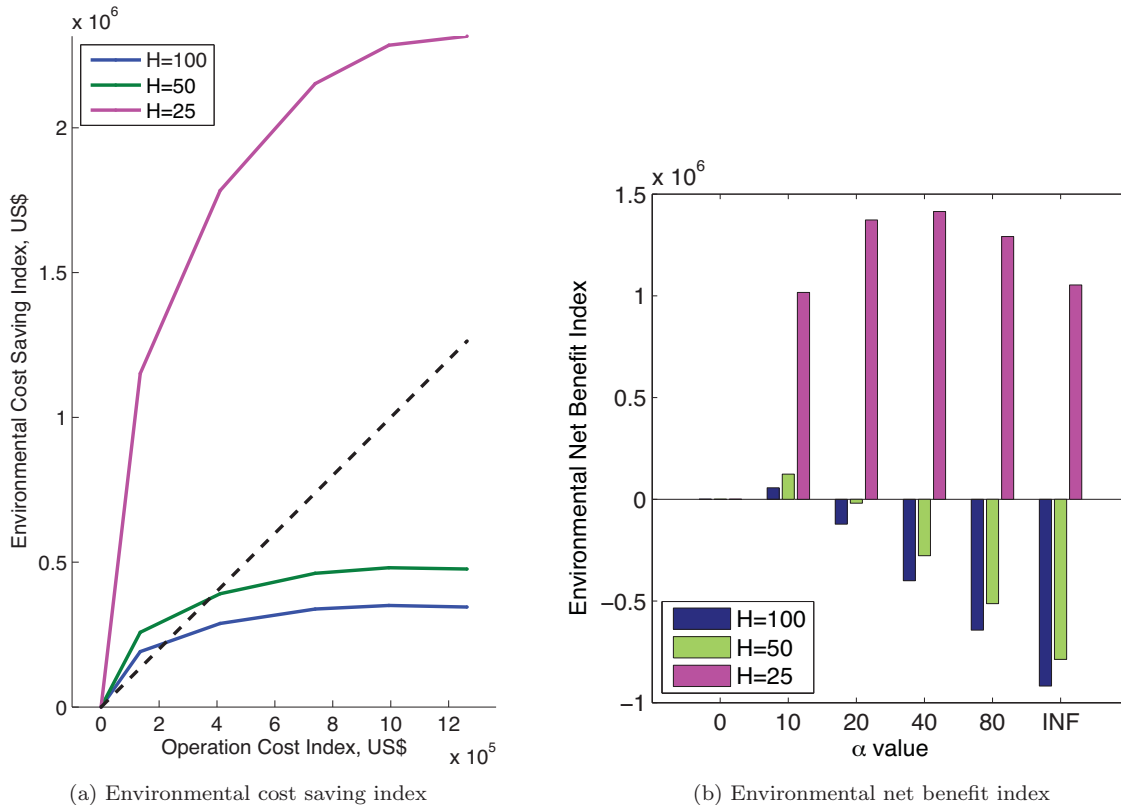

(a) Environmental cost saving index

(b) Environmental net benefit index

Figure 4. **Environmental cost saving index and factor with different time horizon for all flights on April 19, 2010.**

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III.B. Social Cost of Carbon

Even though an approximate social cost of CO_2 is suggested,[16] the estimate of the cost is highly uncertain.[17] In additional to the suggested price at $21 per ton of CO_2, a sensitivity analysis was conducted for the price of $5 and $64 used in Ref. 16. Another good reference of the carbon cost is the auction price under California's cap-and-trade system in 2013, at $13.62 per metric ton of carbon,[18] or $3.71 per metric ton of CO_2.

Figure 5a is the same as Fig. 4b and is placed here for easier comparison. As mentioned in the previous section, the contrail reduction strategy would pick the trade-off factor α that provides maximum environmental net benefit, which is $\alpha = 10$ for $H = 100$, $\alpha = 10$ for $H = 50$, and $\alpha = 40$ for $H = 25$ in this case. With higher social cost of CO_2, $65 in Fig. 5b, the strategy results in more net benefit compared to Fig. 5a. The best trade-off factors are $\alpha = 20$ for $H = 100$, $\alpha = 20$ for $H = 50$, and $\alpha = 80$ for $H = 80$. On the other hand, when the social cost of CO_2 is small, the environmental benefit was offset by the relative high operational cost. When the cost is $5 or the California auction price of $3.71, the net benefit are negative in both 50- and 100- year time horizon, as shown in Fig. 5c and 5d. The strategy only provides net benefit in a 100-year time horizon with $\alpha = 10$. In order to achieve more net benefit, the efficiency of the contrail reduction strategy needs to be improved. Note that the strategy used in this paper is very conservative. It alters the cruise altitude for all the aircraft within a center at certain altitudes. It can be improved by using a finer spatial resolution[12] and therefore results in better net environmental benefit. Another approach is to increase the carbon cost or carbon auction price. For the contrail reduction strategy used here, the net benefit will turn positive at the price at $11 for $H = 50$ and at $15 for $H = 100$, about 3 to 4 times to the current California's auction price.
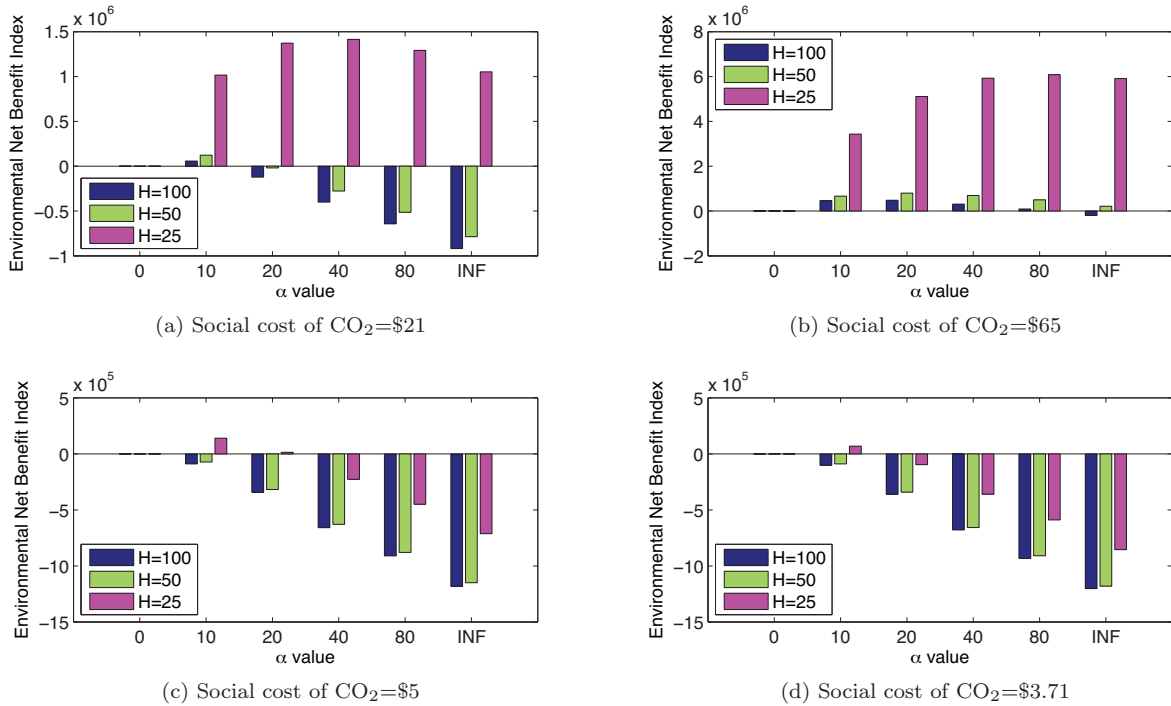

(a) Social cost of CO_2=$21

(b) Social cost of CO_2=$65

(c) Social cost of CO_2=$5

(d) Social cost of CO_2=$3.71

Figure 5. Environmental net benefit index with different social cost of CO_2 for all flights on April 19, 2010.

IV. Conclusions

This paper evaluates a set of contrail reduction strategies based on environmental and operational cost. A linear climate model was first used to convert effect of the carbon dioxide emissions and contrail formation to the changes in Absolute Global Temperature Potential, a metric that measures the mean surface temperature change due to aircraft emissions and persistent contrail formations. The social cost of carbon concept and the most recent California's cap-and-trade system for carbon were then used to relate the carbon dioxide emissions and contrail formations to environmental cost at different time-horizon. The contrail reduction

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strategy then try to maximum the environmental net benefit based on the cost indices. The results show at the current suggested social cost of CO_2 at \$21 per metric ton and higher, the reduction strategy can achieve net benefit in all 25-, 50-, and 100-year time horizon. However, at the recent California's carbon auction price \$13.62 per metric ton, the strategy can only achieve net benefit at the 25-year time horizon. The auction price needs to be 3 to 4 times over the current price in order to see net benefit in 50- and 100-year time-horizon. Another way is to increase the efficiency of the strategy to gain net benefit for longer time horizon. Introducing the cost models provides a solution to select the trade-off factor that will result in the most net environmental benefit.

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