Evaluating Tradeoffs between Environmental Impact and Operational Costs for Enroute Air Traffic

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The rapid growth of air traffic has drawn attention to aircraft-induced environmental impact. Aviation operations affect the environment mainly through the release of emissions and by the formation of contrails. Recent research has shown that altering aircraft cruise altitudes can reduce aviation environmental impact by reducing Absolute Global Temperature Change Potential, a climate assessment metric that adapts a linear system for modeling the global temperature response to aviation emissions and contrails. However, these methods will increase fuel consumption that leads to higher operational costs imposed on airlines resulting in reluctance to adopt a new routing strategy. This paper evaluates the tradeoff between environmental impact reduction and the corresponding added operational costs for enroute air traffic. The concept of social cost of carbon and the carbon auction price from California's recent cap-and-trade system were used to provide estimates and a methodology to evaluate environmental costs for carbon dioxide emissions and contrail formations. Depending on the specific environmental policy, the strategy is considered favorable when the reduction in environmental costs exceeds the increase in operational costs. The results show how the net environmental benefit varies with different decision-making time horizons, different carbon and fuel costs, and different days. The study provides guidance towards the development of the environmental reduction strategies.

I. Introduction

Aircraft-induced environmental impact has drawn attention in recent years.[1] A recent study estimates that aviation is responsible for 13% of transportation-related fossil fuel consumption and 2% of all anthropogenic carbon dioxide emissions.[2] Domestic air traffic is expected to grow at an annual rate of 3.5% over the next 20 years, and the global air traffic is expected to grow more rapidly at an annual rate of 4.8% from 2011 to 2030.[3] To address the aviation environment impacts with the forecast in air traffic growth, various methods have been proposed.

The three largest environmental impacts for enroute air traffic include direct emissions of greenhouse gases such as carbon dioxide (CO_2), emissions of nitrogen oxides (NO_x), and persistent contrails. CO_2 and NO_x emissions are related to fuel burn therefore minimizing fuel consumption results in minimal emission solutions. Various procedures have been proposed in the past to reduce the persistent contrail formation, including promising approaches based on changing aircraft flight altitudes. Mannstein[4] proposed a strategy to reduce the climate impact of contrails significantly by only small changes in individual flight altitude. Williams[5,6] proposed strategies for contrail reduction by identifying fixed and varying maximum altitude

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restriction policies. However, these restrictions generally imply more fuel burn, thus more emissions, and add congestion to the already crowded airspace at lower altitudes. Sridhar,[7] Chen,[8] and Wei[9] proposed contrail reduction strategies by altering an aircraft's cruising altitude in a fuel-efficient way, but these strategies did not address the environmental impact from aircraft emissions. Recently, the Absolute Global Temperature Potential was introduced in Ref. 10 and 11 to study the combined effect of CO_2 emissions and contrail formation on the reduction strategies, and effect of NO_x was added in Ref. 12. However, none of the above evaluates both the reduction in environmental cost and the increase in operational costs for the reduction strategies. The idea of placing a financial cost to the impact aircraft operations have on the environment has been used by Virgin America airlines. Virgin America offers passengers the option to pay for carbon-offset based on the length of their flight.[13] A methodology can be developed to evaluate a policy that seeks to minimize the environmental impact due to aircraft operations while considering the cost to the airline for invoking such a policy.

The objective of this paper is to evaluate the tradeoff between environmental impact reduction and the corresponding operational costs for enroute air traffic. First, a linear climate model was used to convert climate effects of CO_2 emissions and aircraft contrails to changes in Absolute Global Temperature Potential,[14] a metric that measures the mean surface temperature change due to aircraft emissions and persistent contrail formations. NO_x is not considered since its effect on the reduction strategy is minor.[12] Next, the concept of social cost of carbon[15] and the carbon auction price from California's 2013 cap-and-trade system[16] were used to provide an estimate of the environmental cost of CO_2, which was used to estimate the cost of contrails. Even though the estimate of the cost is highly uncertain,[17] a suggested value was used and sensitivity analysis was conducted. The environmental impact reduction strategy uses a previously developed fuel-efficient contrail reduction strategy[8] to minimize the combined impacts of emissions and contrails. The strategy minimizes the environmental impact by altering the aircraft's cruising altitude while computing the additional fuel burn and emissions. Some policies may consider this strategy to be favorable when the reduction in the combined environmental cost exceeds the increase in operational cost with a certain trade-off factor. This paper evaluates how the net environmental benefit varies with different decision-making time-horizons, carbon and fuel costs, and atmospheric conditions. Introducing the cost models provides a method to tradeoff environmental cost and operational cost that will result in maximal net environmental benefit.

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

II. Models and Methods

II.A. 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 (RF) for CO_2 emissions is comprised of a steady-state component and three exponentially decaying components.[18] 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 and the temperature response and energy balance to RF can be modeled using either a first order linear model[19] or a second order linear model.[20]

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 occur at different regions of the earth and add non-uniform sources of RF 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.[21] 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. 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. 22.

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 time 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.[14] AGTP provides a way to express the combined environmental cost of emissions and contrails as a function of the fuel cost. Only CO_2 emissions are considered in this paper, as the effect of NO_x emissions are relatively small compared with CO_2.[12] Assume that the RF due to contrails is independent of the location of the contrails, the near surface temperature change ΔT, in Kelvin (K), for the decision-making time horizon of H years, can be approximated as

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

where $\Delta T_{CO_2}(H)$ is the contribution to AGTP from CO_2 emissions for the time horizon of H years and is a linear function of additional CO_2 emissions, and $\Delta T_{Con}(H)$ is the contribution to AGTP from contrails for the time horizon of H years and is a linear function of contrail length. The units of ΔT_{CO_2} and ΔT_{Con} are also in Kelvin. 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.[10] Using the coefficients described in Ref. 12, Eq.(1) can be rewritten as

$$\Delta T(H) = \alpha(H) E_{CO_2} + \beta(H) L_{Con}, \tag{2}$$

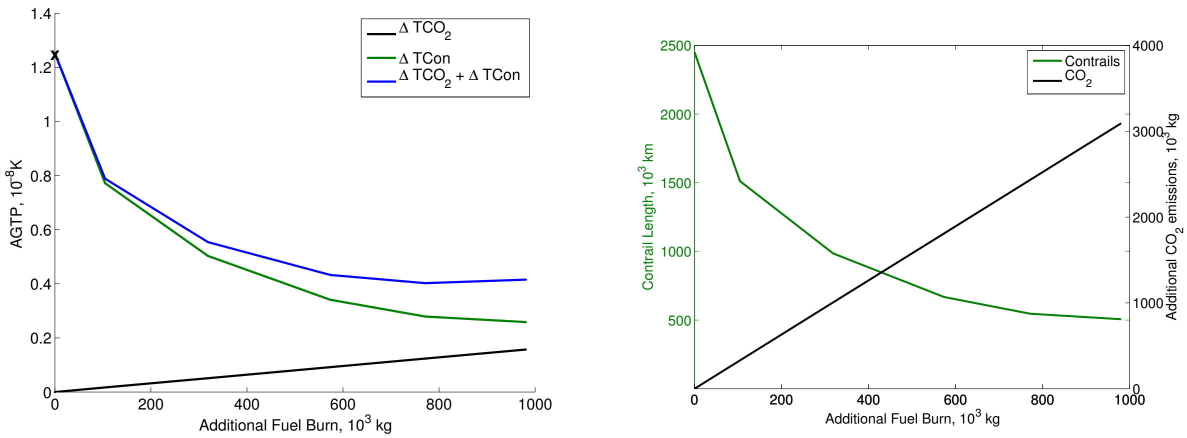
where $\alpha(H)$ is the coefficient of AGTP due to CO_2 for the time horizon of H in K/kg, $\beta(H)$ is the coefficient of AGTP due to contrails for the time horizon of H in K/km, E_{CO_2} is the amount of CO_2 emissions in kg, and L_{Con} is the contrail length in km. A list of $\alpha(H)$ and $\beta(H)$, derived from Ref. 12, is shown in Table 1. Notice that the AGTP coefficient for contrails is much larger at shorter time horizons and smaller at longer time horizons, as contrails have more short-term environmental impact; the AGTP coefficient for CO_2 does not change much with different time horizons.

Table 1. AGTP coefficients for CO_2 and contrails for three different time horizons

Time Horizon	H = 25 years	H = 50 years	H = 100 years
$\alpha(H)$, K/kg	6.71×10^{-16}	5.78×10^{-16}	5.07×10^{-16}
$\beta(H)$, K/km	2.99×10^{-14}	6.98×10^{-15}	5.10×10^{-15}

II.B. Environmental Impact Reduction

Previous research[3] shows that the aviation environmental effect can be reduced efficiently by only changing the flight cruise altitude. This paper modifies the contrail reduction strategy described in Ref. 8 and uses the approach to reduce AGTP rather than contrails. The strategy divides the U.S. National Airspace System into twenty regions horizontally based on the twenty continental U.S. Air Traffic Control Centers (Centers), and ten levels vertically, from 26,000 feet to 44,000 feet at increments of 2,000 feet. At each hour, the strategy looks at all aircraft cruising in a Center at the same flight level, alters their cruise altitude by -4,000, -2000, +2000, or +4,000 feet, and selects the optimal cruise altitude that provides the minimal ΔT. The strategy also computes the additional fuel burn needed for such a move, and uses a fuel-efficient index, the ratio of the ΔT reduction and the additional fuel burn, to determine the temperature to fuel changes ratio. For example, if (a) moving all the aircraft at a Center up 2,000 feet will burn 1,000 kg more fuel for the climb and the remainder of the flight in the Center, and reduce ΔT by 2×10^{-10} K, or if (b) moving the aircraft down 2,000 will reduce ΔT by 3×10^{-10} K but will burn 10,000 kg additional fuel for the descent and the remainder of the flight in the Center, the strategy to minimize the climate impact will choose (b) to move aircraft 2,000 feet lower to achieve a greater reduction in ΔT. However, if the strategy looks at the fuel-efficiency index and only moves aircraft when the fuel-efficient index is greater than 10^{-10} K/ 1000 kg, the strategy will choose (a) to move aircraft 2,000 feet higher, even though the ΔT reduction is 10^{-10} K less, and the additional fuel burn is 10 times less. Using the different thresholds on the fuel-efficient index allows the strategy to tradeoff fuel burn with ΔT. Note that the strategy is applied to each Center at each



(a) AGTP (b) CO_2 emissions and contrails

Figure 1. AGTP (H=100), CO_2 emissions, and contrail length versus additional fuel burn after the environmental reduction strategy for all flights on April 19, 2010.

hour independently. Also 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.

Figure 1 presents the results from a 24-hour simulation based on historical data on April 19, 2010. The environmental impact reduction strategy, which allows the aircraft cruise altitudes to change in the range of -4,000 to +4,000 feet, was applied to the historical data, and the trade-off between AGTP due to CO_2 emissions, AGTP due to contrails, and total AGTP and additional fuel consumption for the decision-making time horizon of 100 years were summarized in Fig. 1a. The corresponding reduction in contrail length and additional CO_2 emissions are shown in Fig, 1b. In Fig. 1a, the contribution to AGTP from CO_2 emissions, the black line, increases linearly with additional fuel burn. The AGTP due to contrails, the green line, decreases faster at the beginning, and slower with more additional fuel burn. This is because the strategy selected the altitude changes with higher fuel-efficiency index first, resulting in more AGTP reduction with less additional fuel burn at the beginning (left end of the curve); the changes with lower fuel-efficiency index were then selected that slowed down the AGTP reduction rate (right end of the curve). The cumulative AGTP, the blue line, 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.

II.C. Cost Model

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.[15] These values were 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.[16] California cites its program as an example for the rest of the world to follow, and plans to use it and other emissions-reduction measures to cut 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 attempts 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 the environmental benefit resulting from the environmental impact reduction strategy. Using the social cost of carbon dioxide as an estimate of environmental cost of CO_2 due to warming, the additional contribution to environmental cost from CO_2 emissions, $\Delta Cost_{CO_2}$, can be formulated as

$$\Delta Cost_{CO_2} = SCC \cdot \frac{\Delta E_{CO_2}}{1000}, \tag{3}$$

where SCC is the social cost of carbon in dollar per metric ton, and ΔE_{CO_2} is the changes in CO_2 emissions in kg. In order to quantify the environmental cost of contrails, the environmental cost of temperature changes, specifically one Kelvin of AGTP, was defined using the SCC and the AGTP coefficient of CO_2 for time horizon H years,

$$ECK = \frac{SCC}{1000 \cdot \alpha(H)}, \tag{4}$$

where ECK is the equivalent environmental cost of temperature change in dollars per Kelvin and $\alpha(H)$ is the AGTP coefficient of CO_2 for the time horizon of H years listed in Table 1. Using the ECK to relate the environmental cost from contrails, $\Delta Cost^H_{Con}$, to $\Delta Cost_{CO_2}$ assuming that the same ΔT_{CO_2} and ΔT_{Con} have the same environmental cost for the time horizon of H years, $\Delta Cost^H_{Con}$ can be formulated as

$$\Delta Cost^H_{Con} = ECK \cdot \Delta T_{Con}(H) = \frac{SCC}{1000} \cdot \frac{\beta(H)}{\alpha(H)} \cdot \Delta L_{Con}, \tag{5}$$

where ΔL_{Con} is the change in contrail length, and $\beta(H)$ is the AGTP coefficient of contrails for the time horizon of H years listed in Table 1. In general, ΔL_{Con} is negative as the strategy is reducing the contrail length and $\Delta Cost_{CO_2}$ is positive due to the additional fuel burn. The superscript H in $\Delta Cost^H_{Con}$ indicates the environment cost due to contrails depends on the decision-making time horizon. The combined environmental cost changes, $\Delta Cost^H_{Env}$, from both CO_2 and contrails for time horizon of H years can be written as

$$\Delta Cost^H_{Env} = \Delta Cost_{CO_2} + \Delta Cost^H_{Con}, \tag{6}$$

All $\Delta Cost^H_{Env}$, $\Delta Cost_{CO_2}$, and $\Delta Cost^H_{Con}$ are in US dollars. Note that $\Delta Cost^H_{Env}$ is always negative after the environmental impact reduction strategy. The net environmental benefit index, NBI^H_{Env}, is defined as

$$NBI^H_{Env} = -\Delta Cost^H_{Env} - \Delta Cost_{Opr}, \tag{7}$$

where $\Delta Cost_{Opr}$ is the additional operational cost of applying the environmental impact reduction strategy. Only the cost of additional fuel burn is considered as additional operational cost in this paper. Note that since $\Delta Cost^H_{Env}$ is always negative after the environmental impact reduction strategy, the first term in Eq.(7), $-\Delta Cost^H_{Env}$, indicates the environmental cost savings.

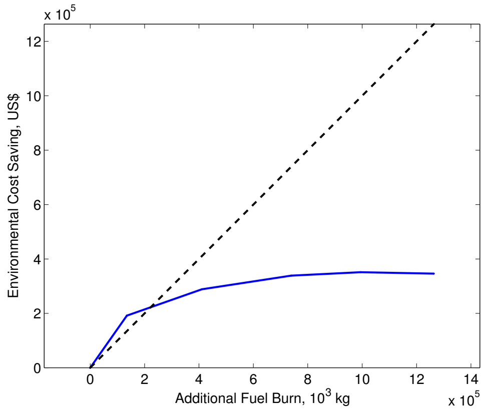
For the same example in the previous subsections, using a social cost of CO_2 of \$21 per metric ton suggested by the United States Government[15] as an estimate of the environmental cost of CO_2, the fuel cost of \$4 per gallon, and the fuel density of 0.82 kilogram per liter, the AGTP and additional fuel burn in Fig. 1a were converted into the environmental cost reduction, $-\Delta Cost^H_{Env}$, and additional operational cost, $\Delta Cost^H_{Opr}$, are shown in Fig. 2a. The blue curve shows the environmental cost reduction versus the additional operational cost after the environmental reduction strategy. The black dash line is a straight line with a slope of one. When the blue curve is above the black line, it suggests that the reduction strategy provided a positive net benefit. The net benefit versus the additional operational cost is shown in Fig. 2b. At the apex of the curve, marked as 'x,' that the strategy could provide a positive $NBI^{H=100}_{Env}$ of around $\$57,000$, or equivalent to around $2,700$ tons of CO_2, after applying the reduction strategy at the point that the strategy will burn an additional 1.05×10^5 kg fuel for all aircraft. When the blue curve falls below the black line in Fig. 2a and Fig. 2b, it suggests 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 fuel-efficiency index described in Section II.B that will result in the most net environmental benefit.

III. Analysis

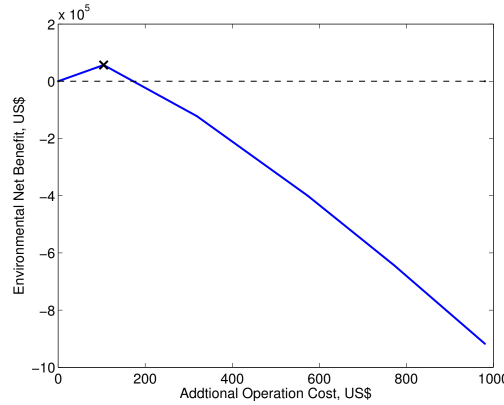
The cost models introduced in the previous section can be used to evaluate the environmental impact reduction strategy with different parameters, including the decision-making time-horizon of environmental impact and the cost estimate of CO_2, and the fuel cost. The variation due to different days are also shown in this section. The social cost of carbon was used as an estimate of the environmental cost of CO_2. The social cost of temperature changes, defined in Eq.(4), was used to relate the environmental cost of contrails to CO_2.

III.A. Varying Decision-Making Time-Horizon

Since CO_2 emissions and aircraft contrails have different life times, a parameter of decision-making time-horizon H needs to be defined to compute the Absolute Global Temperature Potential and evaluate the



(a) Environmental cost saving



(b) Net environmental benefit

Figure 2. Environmental cost saving and net benefit for all flights on April 19, 2010.

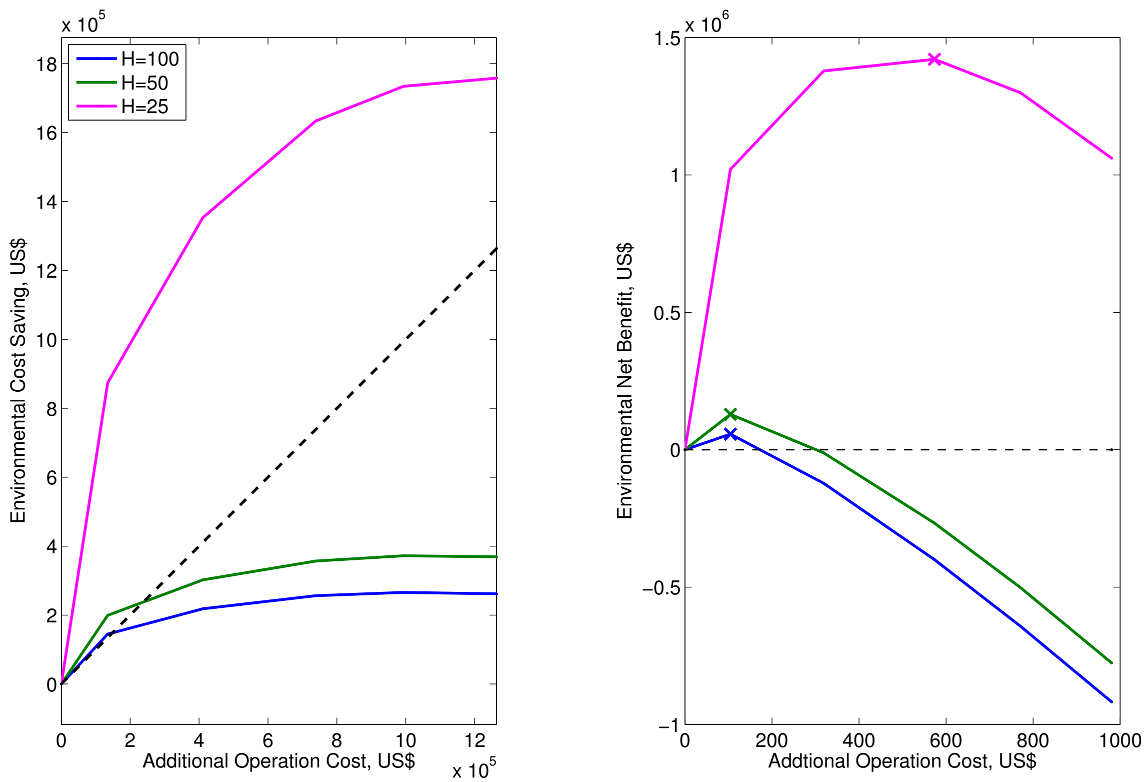
environmental impact. Three different time horizons, 25, 50, and 100 years were considered. Figure 3a shows the environmental cost saving versus the additional operational cost with different time horizons. The social cost of CO_2 at \$21 per metric ton was used as an estimate of the environmental cost of CO_2, the social cost of temperature changes at time horizon 100 years was used to estimate the environmental cost of contrails, and the fuel cost of \$4 per gallon was used in this analysis. The blue line in the figure is the same as in Fig. 2a for $H = 100$, and the green and magenta lines are for $H = 50$ and $H = 25$ respectively. As shown in the figure, the magenta line is much higher than the blue and green lines, and also above the black dashed-line all the time. This indicates that shorter time horizon would result in more short-term environmental cost savings for the same operational cost. This is because aircraft contrails have shorter life time than CO_2 so the benefit from contrail reductions is more obvious in a shorter time-horizon. For longer time-horizons, the impact of contrails decays and the relative impact from CO_2 becomes larger. The net environmental benefit for different time-horizons after applying the environmental impact reduction strategy described in Sec. II.B can be seen in Fig. 3b. Same as in Fig. 2a, at $H = 100$ (blue line), the strategy could result in an net environmental benefit of around \$57,000, or around 2,700 tons of CO_2 equivalent for all aircraft in the U.S. on April 19, 2010, indicated at the blue 'x' in Fig. 3b. For a shorter time-horizon such as $H = 50$ (green line), the strategy could result in net environmental benefit of around \$129,000, or around 6,100 tons of CO_2 equivalent, indicated at the green 'x'. For $H = 25$ (magenta line), the strategy could result in net environmental benefit of around \$1,421,000, or around 67,700 tons of CO_2 equivalent, indicated at the magenta 'x.' It is worth mentioning that the environmental cost saving and net benefit are time-horizon-dependent, meaning a net gain in benefit in a 25-year time horizon might turn into net loss in benefit at 50- or 100- year time horizons because the benefit from reducing contrails decays with the length of the time-horizon.

Figure 4 shows how the maximum net benefit decays with time. The upper right magenta 'x' in the figure is the same as the magenta 'x' in Fig. 3b, showing an net environmental benefit of \$1,421,000 at $H = 25$. The benefit decays to $-\$267,000$ at $H = 50$ and -\$400,000 at $H = 100$, as the magenta line suggested. If the decision-making time horizon for the reduction strategy is $H = 50$, the net benefit decays from \$129,000 at $H = 50$ to \$6,100 at $H = 100$ (green line), which happens to be the net benefit for the strategy with decision time horizon of $H = 100$. This is because the strategy for decision time horizon $H = 50$ and $H = 100$ are the same in this case. The strategy may behave differently with different time horizons and the net environmental benefit may also vary.

III.B. Varying Estimate of the Cost of Carbon Dixocide

Even though an approximate social cost of CO_2 is suggested,[15] the estimate of the cost is highly uncertain.[17] In addition to the suggested price at \$21 per ton of CO_2, a sensitivity analysis was conducted using prices of \$5 and \$64 suggested in Ref. 15. 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 CO_2.[16]

Figure 5a is the same as Fig. 3b and is placed here for easier comparison. Figures 5b, 5c, and 5d show



(a) Environmental cost saving

(b) Net environmental benefit

Figure 3. Environmental cost saving index and factor with different time horizons for all flights on April 19, 2010.

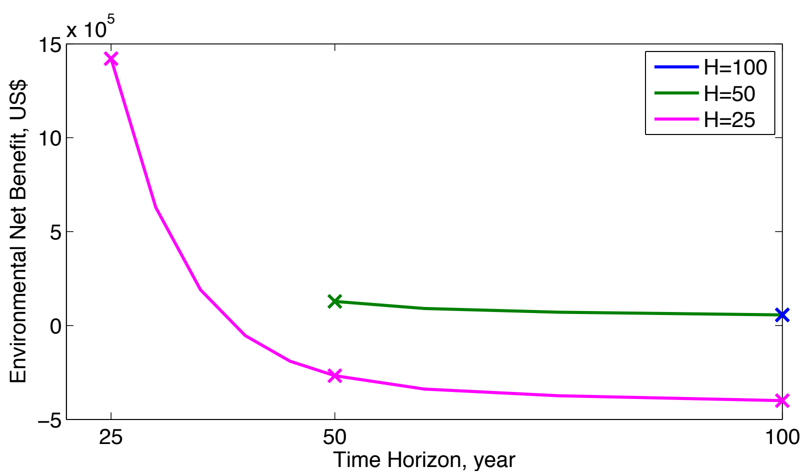
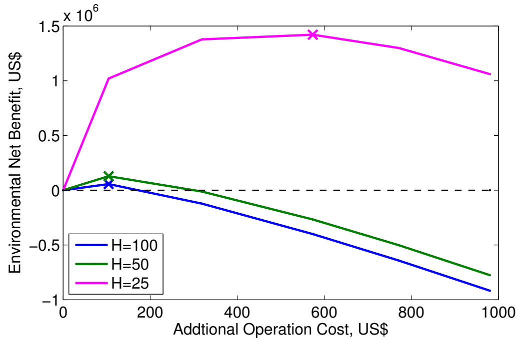
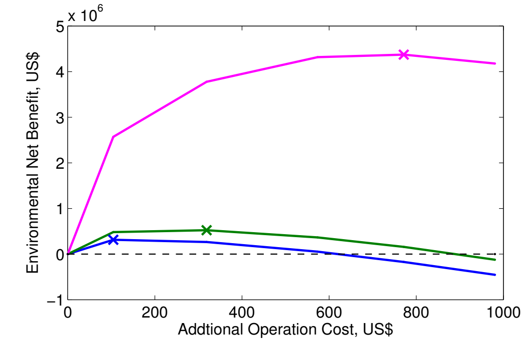


Figure 4. Maximum net benefit with different target time horizon for all flights on April 19, 2010.

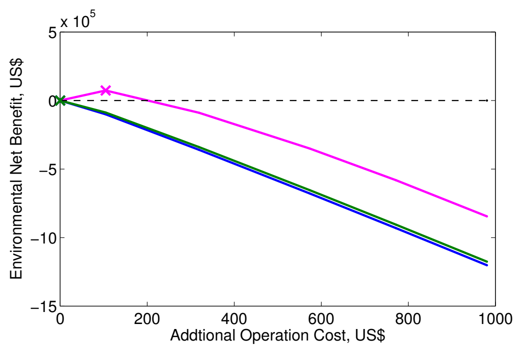
the net environmental benefit curves after reduction strategy for three different time horizons with different estimates of CO_2 cost with the fuel cost of \$4 per gallon. Note that the scales on y-axis in these figures are different in order to shows the variations of the three curves in each individual plot. The maximum net benefit from the strategy is marked as 'x.' If the 'x' is located at the origin, it means there is no feasible solution to reduce environmental impact given the time horizon and the estimate of CO_2 cost. With higher estimate of CO_2 cost of \$65, shown in Fig. 5b, the strategy results in more net benefit compared to that in Fig. 5a. On the other hand, when the estimated cost of CO_2 is small, the environmental benefit was offset by the relatively high operational cost. When the cost is \$5, the strategy can only achieve net benefit at the 25-year time horizon, shown in Fig. 5c. Even with the estimate cost of CO_2 at \$13.62, the current California auction price, the strategy cannot find a feasible solution for the net environmental benefit for time horizons of 50- and 100-years; the strategy can only achieve net benefit in a 25-year time horizon. In order to achieve more net benefit with a given set of time horizons and estimates of CO_2 costs, the efficiency of the environmental impact reduction strategy needs to be improved. Note that the strategy used in this paper is very conservative. It alters the cruise altitudes for all the aircraft within a Center to certain specified altitudes. The strategy can be improved by using a finer spatial resolution[9] and a resulting increase in net environmental benefit. Increasing the carbon cost or reducing the fuel cost will help the strategy to achieve more net environmental benefit. The net benefit with different estimated costs of CO_2 and fuel costs are shown in Table 2. For the environmental impact reduction strategy used in this paper, the net benefit will turn positive at a CO_2 price of \$20 per ton with the fuel cost of \$4 per gallon for $H = 100$, about 47% more than the current California auction price.



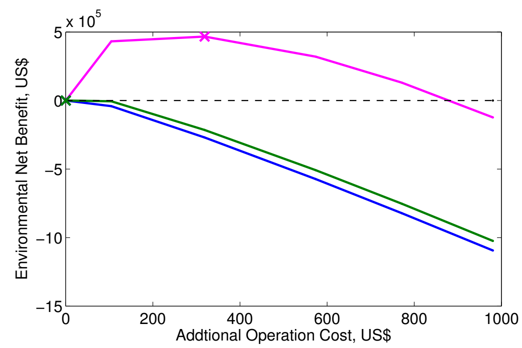
(a) Estimate cost of CO_2=\$21 per ton, fuel cost \$4 per gallon



(b) Estimate cost of CO_2=\$65 per ton, fuel cost \$4 per gallon



(c) Estimate cost of CO_2=\$5 per ton, fuel cost \$4 per gallon



(d) Estimate cost of CO_2=\$13.62 per ton, fuel cost \$4 per gallon

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

III.C. Variation on Different Days

The same simulation and analysis were applied to the entire month of April, 2010 based on the historical air traffic and atmospheric data with the estimated environmental cost of CO_2 at \$21 and the fuel cost at \$4. The daily net environmental benefit for the month with time horizon 25, 50, and 100 years are shown in Fig. 6. The daily net environmental benefits vary on different days mainly because of different atmospheric

Table 2. Net environmental benefit after impact reduction strategy for all flights on April 19,2010

Estimate of CO_2 cost	Fuel Cost	H = 25 years	H = 50 years	H = 100 years
$5 per ton	$4 per gallon	$140,000	$0	$0
$13.62 per ton	$4 per gallon	$750,000	$36,000	$0
$21 per ton	$4 per gallon	$1,421,000	$129,000	$57,000
$65 per ton	$4 per gallon	$6,103,000	$826,000	$483,000
$21 per ton	$3 per gallon	$1,606,000	$162,000	$91,000
$21 per ton	$4 per gallon	$1,421,000	$129,000	$57,000
$21 per ton	$5 per gallon	$1,276,000	$95,000	$23,000
$21 per ton	$6 per gallon	$1,173,000	$61,000	$0

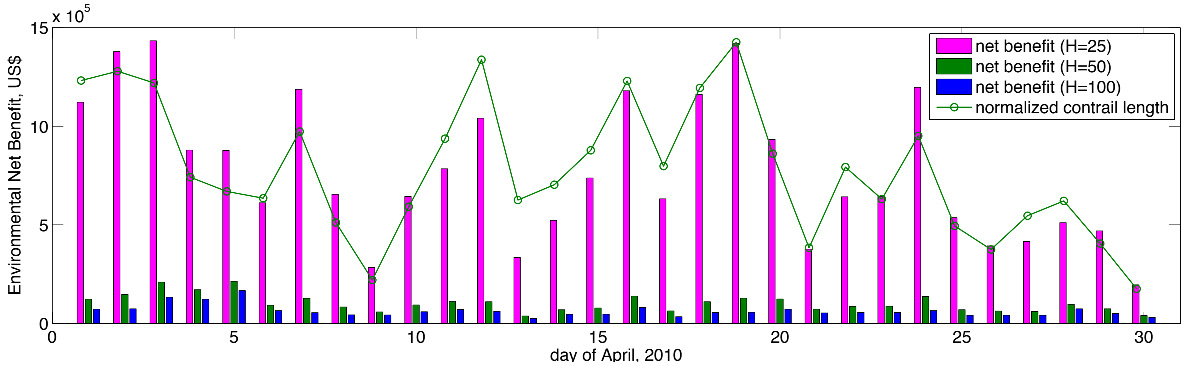


Figure 6. Daily maximum net benefit with different decision-making time horizon and contrails for all flights in April, 2010.

conditions. The net benefit with decision-making time horizon of 25 years (magenta bar) are much higher than the net benefit with time horizon of 50 years (green bars) and 100 years (blue bars). The average daily net benefit for the month is $773,000 for $H = 25$, $102,000 for $H = 50$, and $63,000 for $H = 100$. The results show that the environmental impact reduction can achieve net benefit (environmental cost reduction is greater than the operational cost) for all time horizons on all 30 days in April, 2010. The daily total aircraft contrail length is also shown in the figure (green line). The daily contrail length is normalized so that it has the same magnitude as the environmental net cost at $H = 25$ (magenta bars). It is clear that the daily net benefit for $H = 25$ is highly correlated with the daily total contrail length; the correlation coefficient is 0.92. It is not surprising as the net benefit of the reduction strategy mainly comes from the reduction in contrail length, and in general more aircraft contrails can be reduced on days with more contrail formations. The correlations are not as high for $H = 50$ and $H = 100$. The results show that the environmental impact reduction strategy can reduce environmental cost effectively so that it outweighs the additional operational cost on days with different atmospheric conditions.

IV. Conclusions

This paper provides a method to evaluate the tradeoffs between environmental impact and the corresponding operational costs for enroute air traffic. A linear climate model and the concept of social carbon cost and Absolute Global Temperature Change Potential were used to provide an estimate of the aviation environmental costs. An environmental impact reduction strategy was introduced to reduce environmental costs by changing aircraft's cruise altitude while computing additional operational costs. Depending on the specific environmental policy, the strategy is considered favorable when the reduction in environmental costs exceeds the increase in operational costs. It is shown that the reduction strategy can achieve more environmental benefit with shorter decision-making time horizons. 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 benefits in 25-, 50-, and 100-year time horizons. However, at the recent California carbon auction price of $13.62 per metric ton, the strategy can only achieve net benefit at the 25- and 50- year time horizons. The auction price needs to be about 47% more than the current price in order to see net benefit in 100-year time-horizon. Increasing the efficiency of the strategy or reducing the operational cost would also gain more net benefit. The results also show that the reduction strategy can achieve net environmental benefit on days with different atmospheric conditions, and the daily net benefit for the 25-year time horizon is highly correlated with the daily aircraft contrail formations. This tradeoff study provides guidance to environmental policy that will result in the most net environmental benefit.

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