Modeling and Simulation of the Impact of Air Traffic Operations on the Environment

Banavar Sridhar [1] and Neil Y. Chen[2]
NASA Ames Research Center, Moffett Field, CA 94035-1000

Hok K. Ng [3] and Alex Morando[4]
University of California, Santa Cruz, Moffett Field, CA 94035-1000

Air traffic affects the environment locally, regionally and globally. Recently, there is increased urgency to understand and mitigate the impact of air traffic on climate. Greenhouse gases, nitrogen oxides, and contrails generated by air traffic affect the climate in different and uncertain ways. Understanding the changes requires a hierarchy of models to deal with multiple disciplines, time scales ranging from few minutes to few hundred years and uncertainties in modeling parameters affecting both science and policy. The models described in this paper are useful to evaluate alternate operational decisions at the national level. The modeling approach is built on the simulation and optimization techniques developed for the design of efficient traffic flow management strategies in the presence of uncertainties. The air traffic flow simulation is augmented by models that simulate aircraft fuel flow, emissions and contrails. The integrated capability enables the evaluation of different traffic flow management concepts based on congestion, capacity, efficiency and emissions. The impact of various decisions on climate can be evaluated by converting CO_2 emissions, non-CO_2 emissions and contrails through the use of radiative forcing functions. Alternatively, the optimization results from the simulation can be used as inputs to global climate modeling tools like the FAA's Aviation Environmental Portfolio Management Tool for Impacts.

I. Introduction

THERE is increased awareness of aviation-induced environmental impact affecting climate change.[1] Aviation operations affect the climate in several ways. CO_2, water vapor and other greenhouse gases are unavoidable by-product of the combustion of fossil fuel. Transportation consumed 28% of the energy used in the US during 2008. It is estimated that aviation is responsible for 13% of transportation-related fossil fuel consumption and 2% of all anthropogenic CO_2 emissions. Oxides of nitrogen, commonly referred to as NO_x, created by the high temperatures in the aircraft engines affect the environment indirectly by affecting the distributions of ozone and methane. There is also concern about the impact of 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. Persistent contrails reduce incoming solar radiation and outgoing thermal radiation in a way that accumulates heat. [2] The emission of water vapor from the aircraft is small but may be of concern at higher altitudes

The complexity and uncertainty in the understanding of the various components of the climate equation requires models, analysis, optimization and validation at several levels. This paper develops a Climate Impact Simulation Capability by integrating a national level air traffic system simulation and optimization capability with aircraft fuel and emission models. In addition, contrail models are developed using forecast weather data. The tool can provide both CO_2 and non-CO_2 emissions resulting from different current and future operational concepts and policies to mitigate the impact of air traffic on the environment.

---

[1] Senior Scientist for Air Transportation Systems, Aviation Systems Division, Fellow, AIAA.
[2] Research Aerospace Engineer, Systems Modeling and Optimization Branch, MS 210-10, Member, AIAA.
[3] Senior Software Engineer, University Affiliated Research Center, MS 210-8, Member, AIAA.
[4] Senior Software Engineer, University Affiliated Research Center, MS 210-8.

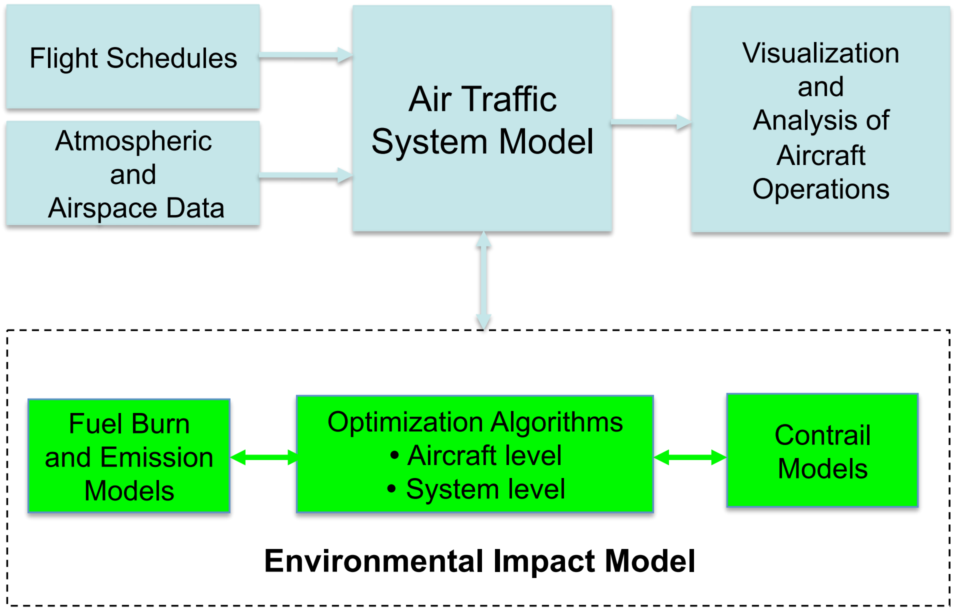


Figure 1. Air traffic system and environmental impact models.

The remainder of the paper is organized as follows. Section II provides the description of the air traffic system simulation and optimization capability and the environmental impact models used in the tool. Section III demonstrates how the tool simulates and displays the various environmental parameters. Example simulation results are described in Section IV. Finally, a summary and conclusions are presented in Section V.

II. Models

The air traffic system and environment impact models are described in this section. The data flow and interaction between the two models are shown in Fig. 1. The air traffic system model uses flight information and atmospheric and airspace data as inputs and simulates air traffic in the National Air Space (NAS). The environmental impact model uses simulated traffic data. Environmental impact metrics are computed and sent to the air traffic system model. The optimization algorithms use the impact metrics to determine solutions that can reduce environmental impact and suggest solutions to the air traffic system model. The outputs are displayed on a graphical user interface (GUI) and stored in data files for visualization and analysis of aircraft operations on environmental impacts. Details of the two models follow.

A. Air Traffic System Model

Air traffic is modeled using the Future Air Traffic Management Concepts Evaluation Tool (FACET). FACET is a flexible simulation environment for exploration, development, and evaluation of advanced Air Traffic Management (ATM) concepts.[3] FACET models en route airspace operations over the contiguous United States and offers ATM researchers a balance of fidelity, flexibility, scalability, and performance. Core features include air traffic simulation, prediction, visualization, and playback of actual traffic data. Four-dimensional aircraft trajectories are modeled using spherical-earth equations. Aircraft are flown along flight plan or great circle routes as they climb, cruise, and descend according to performance models.

FACET software consists of four components: algorithms, databases, applications, and a graphical user interface (GUI). Algorithms use databases and process information needed by applications, where each application supports one or more ATM concepts or research areas. Many applications generate decision support data and display their results on the GUI. Real-time aircraft position and flight plan data are obtained from the FAA Enhanced Traffic Management System (ETMS). Weather data (winds, temperature, convective cells, etc.) are read and displayed from multiple sources, including the National Oceanic and Atmospheric Administration, MIT Lincoln Labs, and the FAA.

Aircraft in FACET are modeled as parametric 3-dimensional trajectories using an inertial reference system. Values of the parameters vary depending on the aircraft. The equations of motion can be defined by the equations,

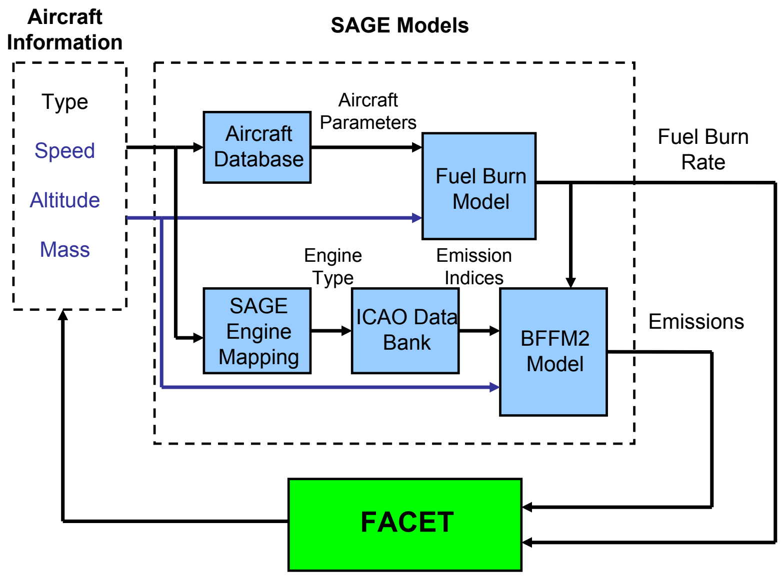


Figure 2. Emission model and interaction with FACET.

$$\begin{aligned}
\dot{x} &= V\cos\varphi\cos\gamma + u(x,y),\\
\dot{y} &= V\sin\varphi\cos\gamma + v(x,y),\\
\dot{E} &= (T-D)V/mg,\\
\dot{h} &= V\sin\gamma,\\
\dot{\gamma} &= (L\cos\phi - mg\cos\gamma)/mV,\\
\dot{\varphi} &= L\sin\phi/mV\cos\gamma,\\
\dot{m} &= -\sigma(h,V,T),
\end{aligned} \tag{1}$$

where x is the downrange position, y is the cross track position, E is the energy height, h is the altitude, γ is the flight path angle, ϕ is the roll angle, φ is the heading angle, m is the aircraft mass, T is the aircraft thrust, D is the drag and V is the airspeed. The fuel flow σ is a function of thrust, altitude and air speed. $u(x, y)$ and $v(x, y)$ are the x- and y-components of the wind. The generation of optimal aircraft trajectories using equation 1 is a new feature in FACET

B. Environmental Impact Model

FACET provides a platform for exploring environmental impacts on current and future ATM system. The environmental impact models, which include fuel burn, emission and contrail models are described in the following sections. The data flow between FACET's air traffic system and environmental models are illustrated in Fig. 2.

1. Fuel Burn Model

This tool uses the fuel consumption model in Eurocontrol's Base of Aircraft Data Revision 3.7 (BADA) [4]. The air traffic model provides aircraft information including aircraft type, mass, altitude and speed to compute the fuel burn. There are five stages, climb, cruise, descent-idle, descent-approach, and descent-landing that are determined by the aircraft altitude and speed. All but cruise and descent-idle stages use the following equation to calculate fuel burn for aircraft,

$$FB = SFC \cdot T \cdot \Delta t, \tag{2}$$

where FB is the fuel burn in kilograms, SFC (kg/min*kN) is the thrust specific fuel consumption, T is the trust in Newtons, and Δt is the elapsed time in minutes. σ in (1) is equal to fuel burn per unit time. For cruise, the fuel burn is

$$FB = SFC \cdot T \cdot C_{fcr} \cdot \Delta t, \tag{3}$$

where C_{fcr} is the cruise fuel flow factor. For descent-idle, the fuel burn is

$$FB = C_{f3}(1 - \frac{h}{C_{f4}}), \tag{4}$$

where C_{f3} and C_{f4} are descent fuel flow coefficients, and h is the altitude in meters. SFC in (2) and (3) are formulated as

$$\begin{aligned} \text{JET}: SFC &= C_{f1}(1 + \frac{V_{TAS}}{C_{f2}}), \\ \text{Turboprop}: SFC &= C_{f1}(1 - \frac{V_{TAS}}{C_{f2}})(V_{TAS}/1000), \end{aligned} \tag{5}$$

where V_{TAS} is the true air speed in meters per second, and C_{f1} and $C_{f2}$are thrust specific fuel consumption coefficients. The thrust in (2) for climb stage is formulated as

$$\begin{aligned} \text{JET}: T_{c\lim b} &= C_{Tc1}(1 - \frac{h}{C_{Tc2}} + C_{Tc3} \cdot h^2), \\ \text{Turboprop}: T_{c\lim b} &= C_{Tc1}(1 - \frac{h}{C_{Tc2}})/V_{TAS} + C_{Tc3}, \end{aligned} \tag{6}$$

where C_{Tc1}, C_{Tc2} and C_{Tc3} are climb thrust coefficients. The descent trust is computed as a ratio of climb thrust in (6), formulated as

$$\begin{aligned} \text{Descent approach}: T_{des\,app} &= C_{Tdes\,app} \cdot T_{c\lim b}, \\ \text{Descent landing}: T_{des\,ld} &= C_{Tdes\,ld} \cdot T_{c\lim b}, \end{aligned} \tag{7}$$

where $C_{Tdes\,app}$ is the approach thrust coefficient and $C_{Tdes\,ld}$ is the landing thrust coefficient. For cruise, thrust is set equal to drag. Drag is computed by

$$D = \frac{C_D \cdot \rho \cdot V_{TAS}^2 \cdot S}{2}, \tag{8}$$

where D is the drag in Newtons, C_D is the drag coefficient, ρ (kg/m^3) is the air density, and S (m^2) is the wing reference area.

Instantaneous and cumulative fuel burn for all aircraft are computed and stored in the air traffic system model and are used in the emission model described in the next section.

2. Emission Model

The emission model is based on the System for assessing Aviation's Global Emissions (SAGE) developed by the Federal Aviation Administration (FAA)[5]. Six emissions are computed including CO_2, H_2O, SOx, CO, HC and NOx. Emissions of CO_2, H_2O and SOx (modeled as SO_2) are modeled based on fuel consumption.[6] The emissions are computed by

$$\begin{aligned} E_{CO_2} &= 3155 \cdot FB, \\ E_{H_2O} &= 1237 \cdot FB, \\ E_{SO_2} &= 0.8 \cdot FB, \end{aligned} \tag{9}$$

where E_{CO_2}, E_{H_2O} and E_{SO_2} are emissions of CO_2, H_2O and SO_2 in grams, and FB is fuel burn in kilograms.

Emissions of CO, HC and NOx are modeled through the use of the Boeing Fuel Flow Method 2 (BFFM2)[7]. The emissions are determined by aircraft engine type, altitude, speed, and 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. In the models, fuel burn is corrected to reference temperature of 0 °C (273.15 K, 32 °F) and pressure (14.696 psi):

$$\begin{aligned} FB_c &= (FB/\delta_{amb})[\theta_{amb}^{3.8}\exp(0.2M^2)], \\ \delta_{amb} &= P_{amb}/14.696, \\ \theta_{amb} &= (T_{amb}+273.15)/273.15, \end{aligned} \tag{10}$$

where FB_c is the corrected fuel flow, P_{amb} is the at-altitude ambient pressure, T_{amb} is the at-altitude ambient temperature, and M is the Mach number. FB_c is used in ICAO emission data bank to determine the reference emission index $REIHC$, $REICO$ and $REINOx$ for HC, CO and NOx. The reference emission indices are converted to emission indices by

$$\begin{aligned} EICO &= REICO(\theta_{amb}^{3.3}/\delta_{amb}^{1.02}), \\ EIHC &= REIHC(\theta_{amb}^{3.3}/\delta_{amb}^{1.02}), \\ EINOx &= REINOx[\exp(H)](\delta_{amb}^{1.02}/\theta_{amb}^{3.3})^{0.5}, \\ H &= -19.0(\omega - 0.0063), \end{aligned} \tag{11}$$

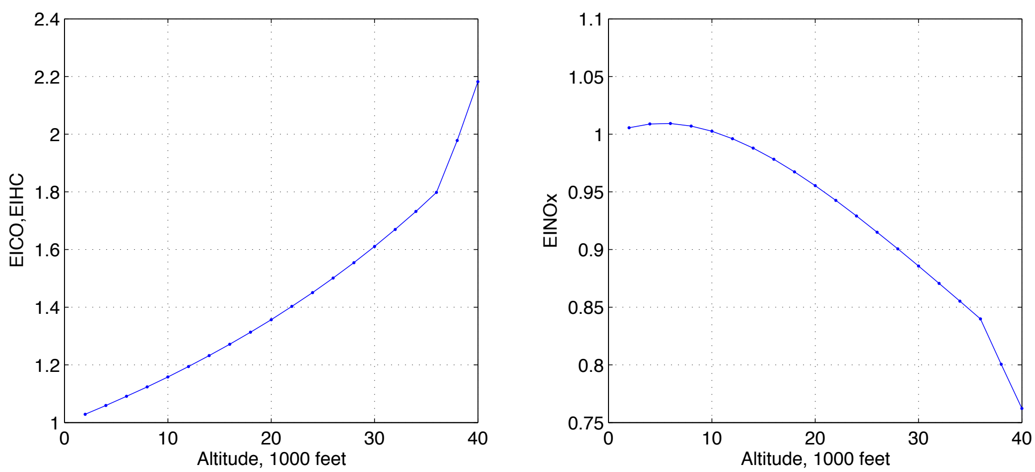


Figure 3. Variation of emission indices with altitude under standard atmosphere.

where *EICO*, *EIHC* and *EINOx* are emission indices of CO, HC and NOx, H is the humidity correction factor, and ω is the specific humidity. Given the reference emission index, while the emission indices for CO and HC increase as a function of altitude, the emission index for NOx decreases with altitude. The variation of emission indices with respect to altitude under international standard atmosphere condition is shown in Fig. 3. The emissions are computed by

$$\begin{aligned} E_{CO} &= EICO \cdot FB, \\ E_{HC} &= EIHC \cdot FB, \\ E_{NOx} &= EINOx \cdot FB, \end{aligned} \tag{12}$$

where E_{CO}, E_{HC} and E_{NOx} are emissions in grams.

3. Contrails Model

Contrails are clouds that 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}.[8] Contrails can persist when the ambient air is supersaturated with respect to ice, i.e., the environmental Relative Humidity with respect to Ice (RHi) is greater than 100%.[9] In this study, the regions of airspace that have RHw greater than r_{contr} and RHi greater than 100% are considered favorable to persistent contrails formation.

The estimated critical relative humidity for contrails formation at a given temperature T (in Celsius) can be calculated as

$$r_{contr} = \frac{G(T - T_{contr}) + e_{sat}^{liq}(T_{contr})}{e_{sat}^{liq}(T)}, \tag{13}$$

where $e_{sat}^{liq}(T)$ is the saturation vapor pressure over water at a given temperature. The estimated threshold temperature (in Celsius) for contrails formation at liquid saturation is

$$\begin{aligned} T_{contr} &= -46.46 + 9.43\ln(G - 0.053) + 0.72\ln^2(G - 0.053), \\ G &= \frac{EI_{H_2O} C_p P}{\varepsilon Q(1-\eta)}, \end{aligned} \tag{14}$$

where EI_{H_2O} is the emission index of water vapor, and it is assumed to be 1.25; $C_p = 1004\,\mathrm{JKg^{-1}K^{-1}}$ is the isobaric heat capacity of air, P (in Pa) is the ambient air pressure, $\varepsilon = 0.6222$ is the ratio of molecular masses of water and dry air, $Q = 43 \times 10^6\,\mathrm{JKg^{-1}}$ is the specific combustion heat, and $\eta = 0.3$ is the average propulsion efficiency of the jet engine. The values of r_{contr} and RHi are computed using measurements from the Rapid Update Cycle (RUC). 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 40-km. RUC data has 37 vertical isobaric pressure levels ranging between 100-1000mb in 25mb increments. The RUC produces short-range forecasts every hour. The value of r_{contr} is computed by Eq (13) and (14) using RUC measurements for RHw and temperatures. RUC does not provide measurements for RHi directly. Instead, RHi is calculated by the following formula:

$$RHi = RHw \cdot \frac{6.0612 e^{18.102 \cdot T/(249.52+T)}}{6.1162 e^{22.577 \cdot T/(273.78+T)}} \tag{15}$$

where T is the temperature in Celsius. Note that the numerator on the right hand side of Eq. (15) is the saturation vapor pressure over water from the model denoted as AERW(50, -80) in Ref. 10 and the denominator is the saturation vapor pressure over ice from the model denoted as AERWi(0, -80) in Ref. 10.

III. Simulations

This section describes how FACET computes the above mentioned fuel burn, emissions, and contrail variables and displays the resulting environmental impact on the GUI. The simulation can be used in playback mode for historical data analysis, or simulation mode for methodology validation.

A. Aggregate Fuel Burn and Emission

FACET computes the fuel burn and emission for all aircraft. The tool provides flexible ways to analyze aggregate fuel burn and emission. For example, aggregate fuel burn and emission can be computed for individual aircraft, for certain type of aircraft, for aircraft of the same airlines, for aircraft flying between a city pair, or all the aircraft flying in a certain Center. This is made possible by the aircraft filter function in FACET. In the function, aircraft can be categorized and displayed based on the following characteristics: aircraft identifiers, type, origin, destination, tail number, flight level, Center, sector, jet route, origin Center, destination Center, flight plan, fix, weight, equipage, length of flight (short/long haul), delay, ascending, descending, controlled, flight congested areas (FCA), special use airspace (SUA), and filed altitude. Each of these identifiers can be used separately or in conjunction with other identifiers. The fuel burn and emission of the filtered aircraft can then be plotted and stored. Figure 4 shows a FACET simulation with plots of cumulative fuel burn and NO_x emission for all Boeing 737-300 aircraft in the simulation.

B. Emission Density

The emission density function in FACET can monitor the location and altitude of emissions produced by aircraft. It calculates the emission density plot on a uniform grid at certain altitude range over the NAS. Parameters that define the grid are:

- Center: USA or Center in which to calculate traffic density
- Grid type: The shape of the grid cells. Either square or hexagon can be selected.
- Bounding box: Increases the grid by the specified number of nautical miles in each direction.
- Grid cell dimensions: East/West and North/South dimension of each grid cell in nm
- Flight level range: Vertical dimensions of each grid cell in 100s of feet
- Data collection: There are several options for data collection at each cell. The software can keep track of either cumulative values or current values in a cell.

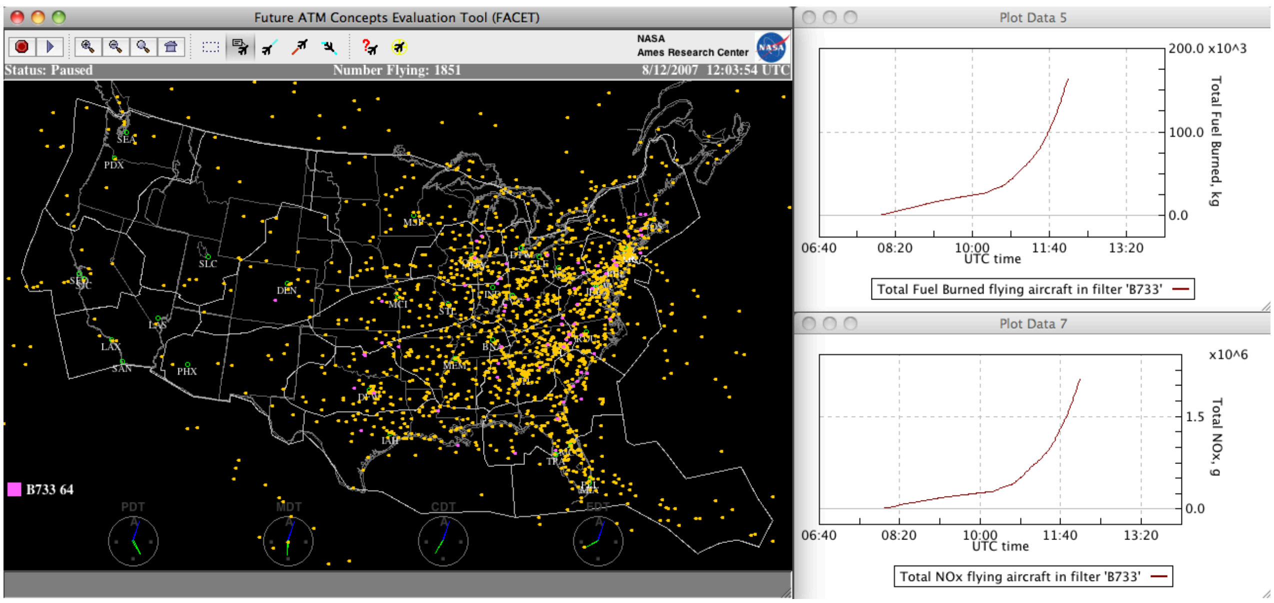
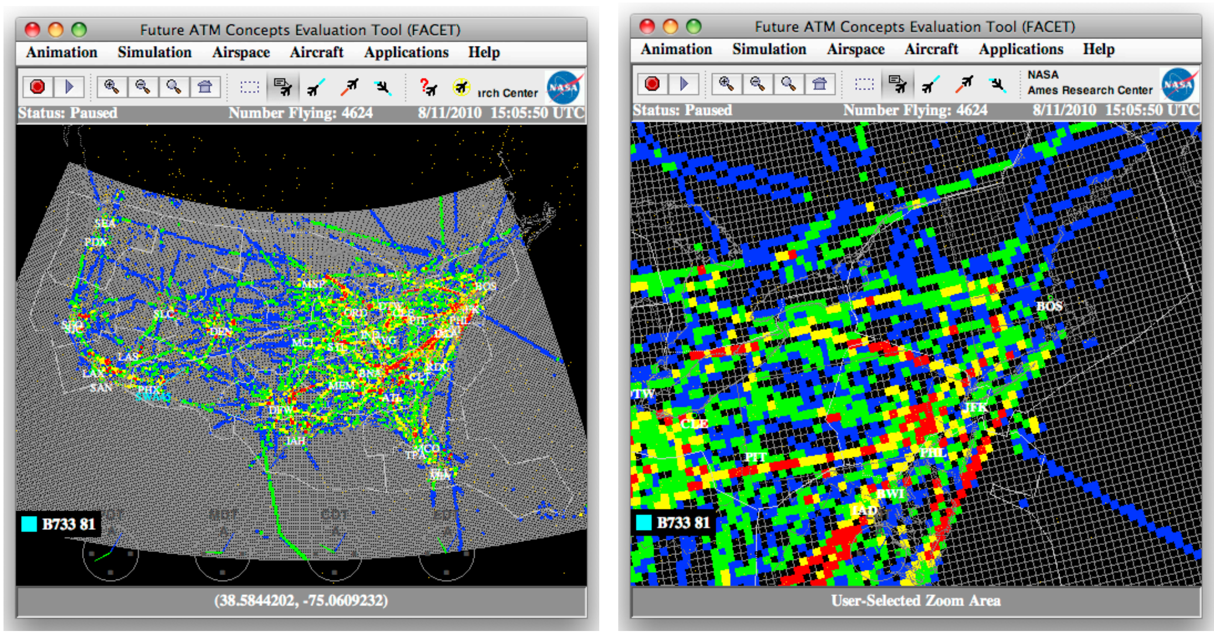


Figure 4. FACET aircraft display with cumulative plots of fuel burn and NOx emission for all Boeing 737 -300 aircraft.

The emissions can then be displayed over the grid and stored. Figure 5(a) shows a FACET simulation with emission density plot of NOx for all Boeing 737-300 aircraft flying between 30,000 feet and 32,000 feet during a two-hour period. Each grid cell is 10 by 10 nautical miles. The colors shows the severity of emissions, where blue is 0-2 kg of NOx in each cell, green is 2-4 kg, yellow is 4-6 kg, and red is 6 kg and above. Figure 5(b) is a zoom-in plot indicating that there are high NOx emissions above Boston and New York areas. This function provides a display of the distribution of the emission locations, flight levels and magnitudes.



(a) (b)

Figure 5. Density of NOx emissions for all B737-300 aircraft flying in the NAS.

C. Contrail

FACET reads and processes atmospheric data and determines regions that are favorable to persistent contrails formation. When aircraft fly through these regions, contrails could form. FACET displays both contrail favorable regions and potential contrail formations. As shown in Fig. 6, red polygons represent the contrail favorable regions at 31,000 ft. The yellow lines indicate the tracks of aircraft flying through the contrail favorable regions and contrails formation since the start of the simulation. The total length of the yellow tracks is used as a measure of contrails. Contrails do not form in some of the red polygons in the Gulf Coast and south of US due to lack of air traffic. Contrail favorable regions are useful information for applying contrail reduction strategies. In order to reduce the contrail formation, decisions need to be made whether to reroute the aircraft around the regions horizontally or vertically, or to fly through it with a minimal intersection. Contrail formations are quantified as the total length of contrail formed. The information is used to determine the severity of contrail and quantify environmental impact. It is also used to determine effectiveness of contrail reduction strategies.

IV. Results

The integrated capability described in the previous sections simulates the impact of aviation on the environment at the national level using realistic traffic and weather data. It can also be used to evaluate concepts based on future traffic growth scenarios, new vehicle designs and technologies. This section provides examples of analysis and concept evaluation using the integrated simulation capability.

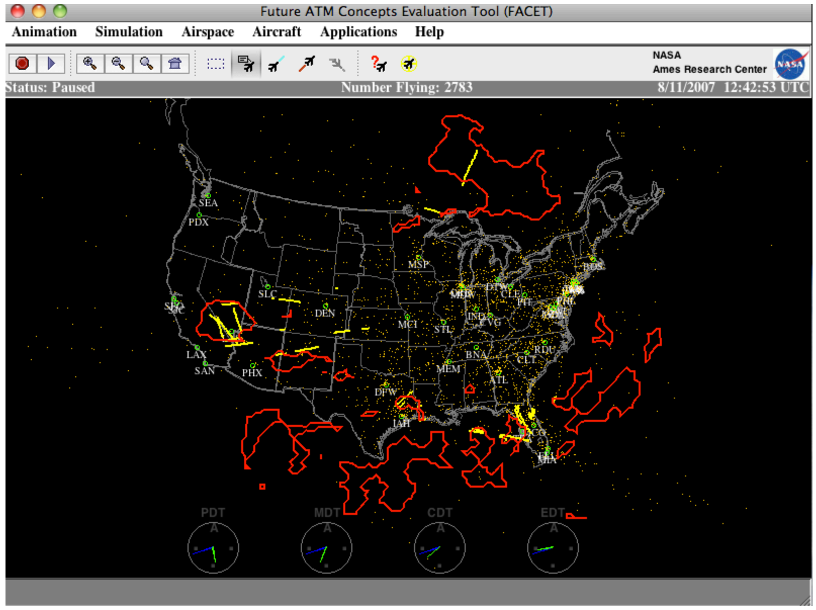


Figure 6. FACET display of contrail favorable regions and contrail formations at 31,000 ft.

A. Historical Data Analysis

FACET can process historical data and obtain valuable information that helps researchers develop methods to reduce the environmental impact of aviation. A year of atmospheric and air traffic data are processed to compute the aggregate contrail length for each hour. The monthly average hourly contrail length over U.S. in 2010 is shown in Fig. 7. The amount of contrails varies by month and by altitude. The results show that contrails are more likely to form in higher altitudes than at lower altitudes. The results also show that the total contrail formations among all altitudes are smaller in summer than in winter.

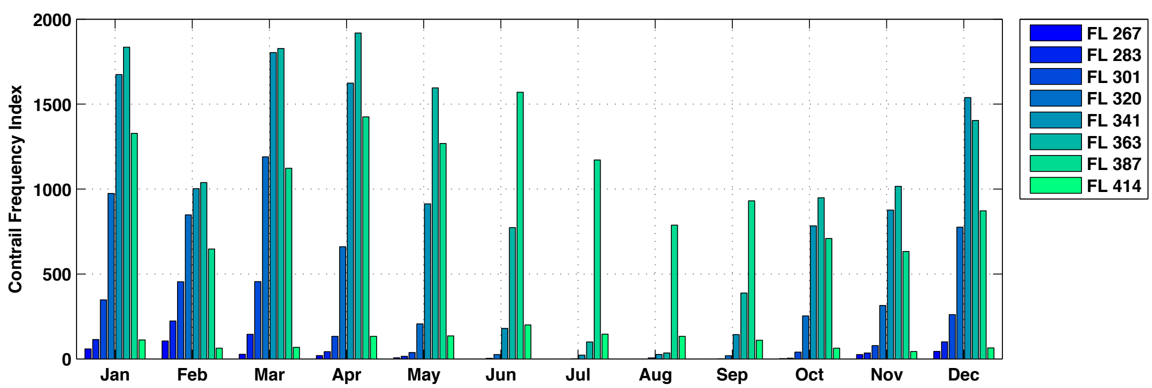


Figure 7. Monthly average hourly contrail frequency during 2010 at different altitudes.

B. Aircraft trajectories with environmental constraints

Wind-optimal trajectories are fuel-efficient trajectories between any two city-pairs. They are also environmentally friendly since most emissions are directly proportional to fuel usage. However, if the trajectory goes through a region where the atmospheric conditions are favorable to persistent contrail formation, contrails create additional impact on the climate. The optimization module in the simulation generates trajectories that reduce travel time through contrail regions by imposing a penalty on travel through potential contrail areas.[11] Three optimal trajectories from Chicago O'Hare airport (ORD) to Newark Liberty airport (EWR) are shown in Fig. 8 for flights with cruising altitude equal to 34,000 feet. The cruising speed is assumed to be 400 nmi/hr (741 km/hr). The green arrows represent the wind directions, obtained from RUC, at 6 a.m. EDT on May 24, 2007. The arrow sizes are plotted in proportion to the wind magnitudes. The areas favorable to persistent contrails formation (RHi > 100%) are indicated by the blue polygons. C_r is a weighting factor used to impose a penalty on a trajectory going through a potential contrail region. The wind-optimal trajectory is generated imposing no penalty, $C_r = 0$, for travel through contrail regions. Two optimal trajectories in additional to the wind-optimal route are also plotted in Fig. 7. The optimal route with $C_r = 0.6$ completely avoids the contrail polygons near the departure airport. The optimal route with $C_r = 0.2$ only partially avoids the polygons but is shorter. Note that both routes travel through the blue polygon surrounding the destination where aircraft start to land. In this case, there is a tradeoff between flying a shorter route with more persistent contrails formation versus flying a longer route with less persistent contrails formation. The performance of optimal trajectories is evaluated by investigating the total travel time and the time spent traveling through regions of persistent contrails formation.

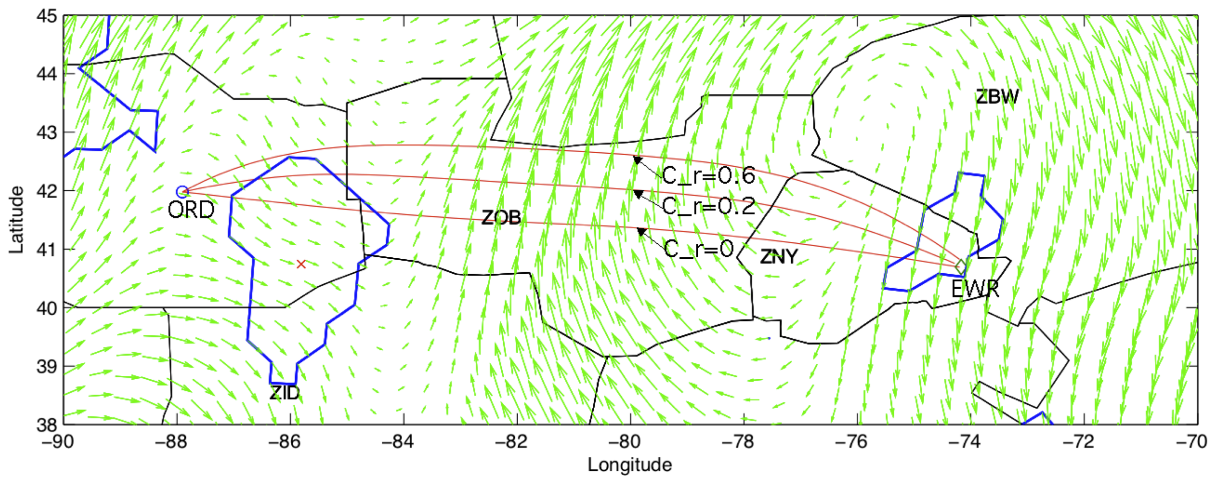


Figure 8. Optimal trajectories at 34,000 feet from ORD to EWR with different penalties on contrail regions.

C. Trade-off between different types of emissions

The next example shows trade-off between two major sources of aviation emissions, CO_2 and contrails. As the amount of CO_2 is directly proportional to the fuel burn, the trade-off is presented in terms of extra fuel burn and reduction in travel time through contrails. The analysis is based on generating the wind-optimal and contrails-avoidance trajectories for 12 origin-destination pairs during a day in 2007. 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.[12] The optimal aircraft trajectories are generated at the beginning of each hour using hourly updated weather data from RUC. Six flight levels are considered for each direction of air traffic for each city pair. A group of 21 optimal aircraft trajectories are calculated for each flight level by varying the penalty on contrail regions. The cruising true airspeed is assumed to be 420 nmi/hr. The fuel consumption for each aircraft trajectory is calculated using BADA formulas by assuming that the aircraft are short to medium range jet airliners with medium 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. In general, flights that can afford additional fuel burn induce fewer contrails since they have more choice of routes. The result based on analyzing 72,576 wind-optimal trajectories is shown in Fig. 9. The y-axis in Fig. 9 represents the total amount of travel time through contrail regions for aircraft flying between the 12 city-pairs. The amount of fuel used by wind optimal trajectories is minimum and the x-axis indicates the percentage extra amount of fuel used over the wind optimal fuel usage. Consider the solid green and blue curves. The green curves in figure show, when altitude and routes (baseline-3D) are optimized, a two percent increase in total fuel consumption reduces the total travel times through contrail regions from 55 minutes to 16 minutes. Allowing further increase does not result in proportionate reduction in contrail travel times. Without altitude optimization (baseline-2D), the reduction in contrail travel times is small with increase in total fuel consumption. This type of analysis can be used to develop optimal fleet allocation and scheduling strategies to minimize the travel time through contrails.

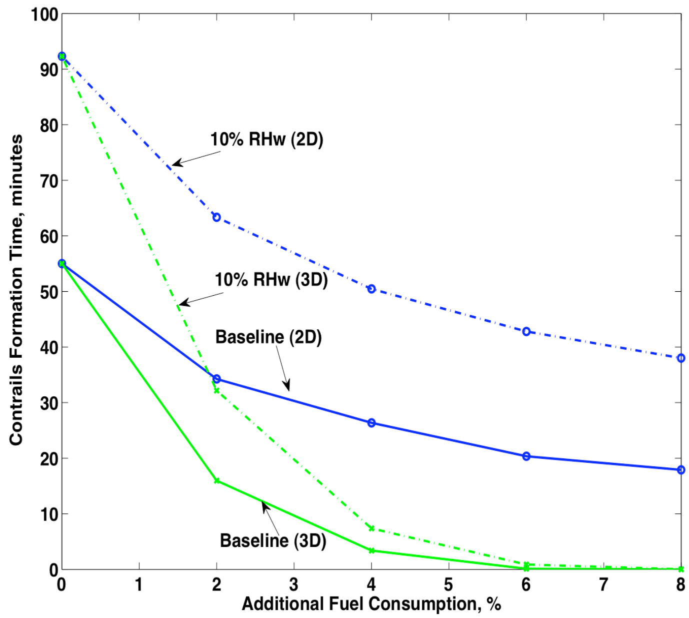


Figure 9. Trade-off curves between fuel consumption and contrail avoidance.

D. Sensitivity Analysis

There are several uncertainties in developing trade-off between persistence contrail times and additional fuel flow. A major source of error is the relative humidity values used to generate the contrail regions. RUC weather models provide the relative humidity values. It has been observed that numerical weather models underestimate humidity in the upper-tropospheric regions.[13] NOAA has been improving the RUC models and the Rapid Refresh (RR) is the next-generation version of the system, planned to replace the current RUC by July-August 2011. Assuming RHw values in RUC models are underestimated, the trade-off curves computations for city-pairs are repeated by increasing the RHw values by 10%. The trade-off curves with 10% additional humidity is shown in (dotted lines) Fig. 9. The amount of time that wind optimal routes go through persistent contrail regions increases to 92 minutes from 55 minutes due to the changes in the contrail formation areas. As in the baseline case, use of altitude optimization results in a significant reduction of travel time through contrail regions from 92 minutes to 32 minutes by using only 2% extra fuel. Similarly, for horizontal maneuvers only, the decrease in travel time through contrail regions is small with extra fuel consumption. Although, the actual trade-off curves are different the trend observed in the baseline is maintained even in the presence of uncertainties in the contrail formation regions due to uncertainties of relative humidity values in weather forecast models.

E. Concept Evaluation

FACET integrated with emissions and contrails modeling capability can be used to evaluate the performance of methodologies proposed for reducing the environmental impact of aviation. A previously developed contrail reduction strategy[14] is used to exemplify the capability. The strategy uses contrail frequency indices, similar to contrail length, to quantify the severity of contrail formation. The strategy for reducing the persistent contrail formations is to minimize contrail frequency index by altering the aircraft's cruising altitude. The strategy uses a cost function that penalizes extra fuel consumed while minimizing the amount of contrail formation. It provides a flexible way to trade off between contrail reduction and fuel consumption. The strategy is illustrated using FACET. The atmospheric data at 8AM EDT on April 23, 2010 was first run to identify the severity of contrail formation at different altitudes. FACET provides alternate cruising altitudes to aircraft causing most contrails. The contrail length was regenerated with the new air traffic operation. The new results were compared with earlier results before the strategy is applied. The results are shown in Fig. 10.

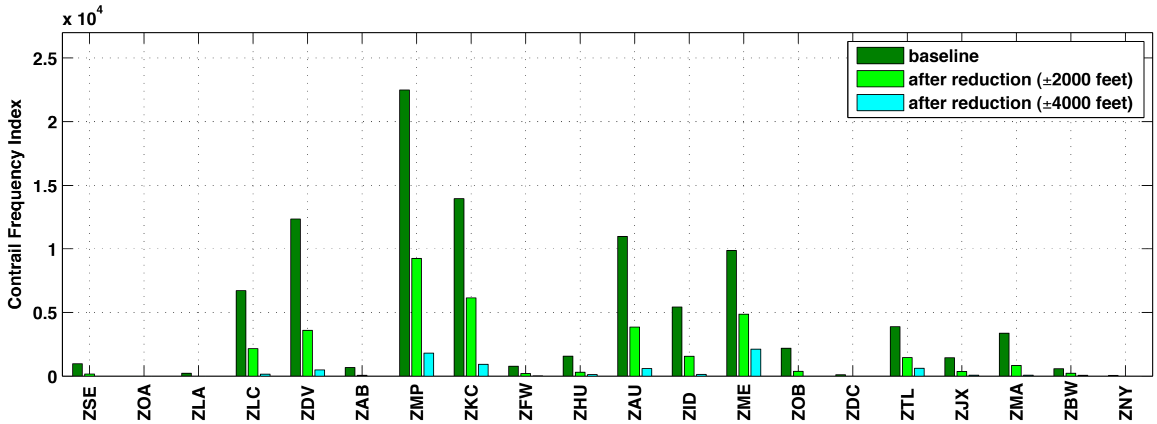


Figure 10. Contrail frequency index before and after contrail reduction at 8AM EDT on April 23, 2010.

V. Conclusions

The ability to make good policy decisions to reduce the impact of aviation on climate change requires modeling capability that covers several disciplines and large variations in time and space. This paper describes a set of models that can be used to simulate various traffic flow management policies and assess their impact on different types of emissions. The simulation approach builds on traffic flow management research to design efficient flows in the presence of uncertain weather information and subject to airport and airspace constraints. Several examples are presented to illustrate the simulation capability. The emissions can be converted into environmental impact through the use of radiative forcing functions. Alternatively, the results can be used in other global climate models.

References

[1]"Aviation and the Global Atmosphere," Tech. rep., Intergovernmental Panel on Climate Change's Working Groups, Cambridge University Press, Cambridge, UK, 1999.

[2]Meerkotter, R., Schumann, U., Doelling, D. R., Minnis, P., Nakajima, T., and Tsushima, Y., "Radiative forcing by contrails," *Annales Geophysicae*, Vol. 17, 1999, pp. 1080–1094.

[3]Bilimoria, K., Sridhar, B., Chatterji, G. B., Sheth, K., and Grabbe, S., "FACET: Future ATM Concepts Evaluation Tool," *Air Traffic Control Quarterly*, Vol. 9, No. 1, 2001, pp. 1–20.

[4]EUROCONTROL Validation Infrastructure Centre of Expertise, France, *User manual for the base of aircraft data (BADA)*, 3rd ed., March 2009.

[5]Federal Aviation Administration, Washington, DC, *SAGE System for assessing Aviation's Global Emissions Technical Manual*, 1st ed., September 2005.

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

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

[8]Ponater, M., Marquart, S., and Sausen, R., "Contrails in a Comprehensive Global Climate Model: Parameterization and Radiative Forcing Results," *Journal of Geophysical Research*, Vol. 107, No. D13, 2002, pp. ACL 2–1.

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

[10]Alduchov, O. A. and Eskridge, R. E., "Improved Magnus Form Approximation of Saturation Vapor Pressure, "*Journal of Applied Meteorology*, Vol. 35, No. 4, April 1996, pp. 601–609.

[11]Sridhar, B., Ng, Hook K., and Chen, Neil Y., "Aircraft Trajectory Optimization and Contrails Avoidance in the Presence of Winds," *10th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, September 2010, Fort Worth, TX.

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

[13]Duda, D. P., Palinode, R. and Minis, P., " Relating Observations of Contrail Persistence to Numerical Weather Analysis Output," Atmos. Chem. Phys., Vol. 9, 1357-1364, 2009.

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