Design of Aircraft Trajectories based on Trade-offs between Emission Sources

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Impact of Aviation on Climate Change

• Increased urgency to deal with factors affecting climate change

• Climatic changes include
  – Direct emissions: CO₂, Water vapor and other greenhouse gasses (GHG) (best understood)
  – Indirect effects: NOₓ affecting distributions of Ozone and Methane (Ozone and Methane effects have opposite signs)
  – Effects associated with contrails and cirrus cloud formation

• Aviation responsible for 2% of all anthropogenic CO₂ emissions

• Large uncertainty in the understanding of the impact of aviation on climate change

*“Workshop on the Impacts of Aviation on Climate Change,” June 7-9, 2006, Boston, MA.
Research Projects

- NASA/FAA research on understanding the atmospheric physics and chemistry and weather forecasting
- FAA environmental tool development
- Environmentally Responsible Aviation (ERA)
  - Vehicle concepts and enabling technologies that will reduce the impact of aviation on the environment
- Research in Europe
  - Climate compatible Air Transport System (CATS)
- Research limited to Modeling, data analysis and operational concepts
  - Inclusion of environmental factors based on climate science research and ERA technologies in airspace simulations to evaluate alternate concepts and policies
Outline

• Modeling approach
• Persistent contrails formation model
• Aircraft fuel burn model
• Wind optimal contrails avoidance aircraft trajectories
• Tradeoff between persistent contrails mitigation and extra fuel burn
• Concluding remarks
Approach

Flight Schedules

Atmospheric and Air Space Data

Future ATM Concepts Evaluation Tool (FACET)

Visualization and Analysis of Aircraft Operations

Application Programming Interface

Emission Models and Metrics

Optimization Algorithms
  - System level
  - Aircraft level

Contrail Models
Contrails

- Aircraft condensation trails occur when warm engine exhaust gases and cold ambient air interact
  - Contrails form when Relative Humidity with respect to Water (RHW) > Temperature dependent threshold
  - Persist when Relative Humidity with respect to Ice (RHI) > 100%
- Contribution of contrails to global warming may be larger than contribution from CO₂ emissions

http://www.nature.com/nclimate/journal/v1/n1/full/nclimate1078.html
Persistent Contrail Formation Model

RHI > 100% Contours

RHW Contours

RHI Contours

RHI > 100% Contours

Persistence Contrail
Fuel Consumption Model (BADA)

- Eurocontrol’s Base of Aircraft Data (BADA)
- Fuel burn during cruise: 
  \[ f_c = t \times SFC \times Th \]

Fuel burn for a typical jet from Chicago to Newark
Emission Models
(Systems for Assessing Aviation’s Global Emissions)

\[ e(CO_2) = 3155 \times \sigma \]
\[ e(H_2O) = 1237 \times \sigma \]
\[ e(SO_2) = 0.8 \times \sigma \]
\[ e(HC) = EIHC \times \sigma \]
\[ e(CO) = EICO \times \sigma \]
\[ e(NO_x) = EINO_x \times \sigma \]

- Fuel and emission models undergoing additional verification using Aviation Environmental Design Tool (AEDT)
  - Collaboration with Volpe National Transportation Systems Center
Optimal Aircraft Trajectories

• Find the optimal trajectory given the arrival and departure airports, cruise speed and winds subject to environmental constraints
• Optimization performed in the horizontal plane for different cruise altitudes
• Aircraft equations of motion in the horizontal plane are

\[
\begin{align*}
\dot{x} &= V \cos \theta + u(x,y) \\
\dot{y} &= V \sin \theta + v(x,y) \quad \text{subject to} \\
Th &= D \\
L &= W \\
m &= -f
\end{align*}
\]
Optimization Subject to Environmental Constraints

• Optimize horizontal trajectory by determining the heading angle that minimizes the cost function

\[ J = \frac{1}{2} X^T(t_f)MX(t_f) + \int_{t_0}^{t_f} [C_t + C_f f + C_r \cdot r(x,y)] \, dt \]

• Solution reduces to solving

\[ \dot{x} = V \cos \theta + u(x,y) \]
\[ \dot{y} = V \sin \theta + v(x,y) \]
\[ \dot{\theta} = \frac{(V + u(x,y) \cos \theta + v(x,y) \sin \theta)}{(C_t + C_f f + C_r r(x,y))} \left( -C_r \sin \theta \frac{\partial r(x,y)}{\partial x} + C_r \cos \theta \frac{\partial r(x,y)}{\partial y} \right) \]
\[ + \sin^2 \theta \left( \frac{\partial v(x,y)}{\partial x} \right) + \sin \theta \cos \theta \left( \frac{\partial u(x,y)}{\partial x} - \frac{\partial v(x,y)}{\partial y} \right) - \cos^2 \theta \left( \frac{\partial u(x,y)}{\partial y} \right) \]
Contrail Reducing Aircraft Trajectories

Diagram showing trajectories for partial contrail reduction, wind optimal, and complete contrail reduction.
Tradeoff between Contrail Reduction and Extra Fuel Consumption

![Graph showing the tradeoff between contrail reduction and extra fuel consumption for JFK/LAX (2D), LAX/JFK (2D), JFK/LAX (3D), and LAX/JFK (3D). The x-axis represents additional fuel consumption in percentage, and the y-axis represents contrails formation time in minutes.]
Optimal Trajectories for 12 City Pairs

Persistent contrails at 33,000 ft

Wind optimal trajectories
Results for 12 City-pairs

One day’s simulation is just the beginning!
Climate Impact of Emissions

- Air (Oxygen, Nitrogen)
- Fuel (Hydrocarbons, Sulphur)
- Aircraft Engine
  - CO₂
  - NOₓ
  - CH₄
  - O₃
  - H₂O
  - SOₓ
  - HC
  - Soot
- Microphysical Processes
- Clouds
  - Aerosol
  - Contrail
- Change in Radiative Forcing Components
  - Climate Change
    - Temperature
    - Mean Sea Level
Uncertainty Quantification

• Each trade-off curve requires approximately 73,000 simulations

• Some of the uncertainties
  – Daily variation of traffic and atmospheric conditions
  – Aircraft parameters: Thrust, Weights (variation of 15%), Fuel flow
  – Atmospheric parameters: Relative humidity, Winds
  – Quantity, location and lifetime of emission
  – Climate impact (Radiative Forcing) of emission
  – Emission Goals (10/20/50/100 years, Carbon neutral/reduce)
  – How much can we afford?

• Magnitude of uncertainty and importance to decision-making
Daily variations in the trade-off of emissions

Contrails Formation Time

Contrails Formation Time, minutes

Additional Fuel Consumption, %
Variation in Contrail Regions due to Uncertainty in RHW Measurements
Effect of RHW Uncertainty on Emission Tradeoff

May 4, 2007

Contrails Formation Time, minutes

Additional Fuel Consumption, %

- Nominal
- 2D
- 3D

- 10%
- 5%
- 2%
Concluding Remarks

- Presented research on environmentally friendly en route traffic flow concepts incorporating models developed by basic climate research
- Developed an optimal contrail reduction trajectory concept
  - Investigated the tradeoff between persistent contrails formation and additional fuel burn
  - When altitude and route are optimized, a small increase (2%) in total fuel consumption can significantly (30 to 60%) reduce the total travel times through contrail regions
- Developed capability to conduct system level analysis of Traffic Flow Management concepts with environmental impact