Cross-Polar Aircraft Trajectory Optimization and the Potential Climate Impact

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Research Challenges for NextGen

The two big questions

What is the appropriate human/automation mix?

How decentralized should the roles and responsibilities be?

10 years ago

Today

Fully automated

Hardly automated

Centralized

Decentralized

NextGen 2025?
Air Traffic Operations
Investigate modeling, simulation and optimization techniques to manage air traffic flows subject to airspace and airport capacity constraints while accommodating user preferences with increased traffic demand in the presence of uncertainty.
Current Research Goals

• Develop optimal aircraft trajectories
  – Aircraft Dynamic Models (Point Mass, 3-DOF)
  – Winds, Uncertainties
  – Minimize
    • Fuel burn
    • Climate impact of emissions
      – Global Warming Potential (GWP), Global Temperature Potential (GTP)
    • Persistent contrails
      – Global models for contrail formation using weather forecast
  – Methods based on calculus of variations
  – Accuracy versus computation time

• Model convective weather and other weather hazards and translate their impact on airspace capacity

• Integrate climate models and metrics with US national airspace simulation
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
Annual operations grew from 402 flights in 2000 to 8527 flights in 2009
Current Cross-Polar Flights

- Provide shorter paths between many North American and Asian cities
- Have not fully utilized the potential benefits of flying wind-optimal routes due to limited track flexibility
- Do not consider climate impact
Environmentally Responsible Trajectory

- Find the optimal trajectory given the arrival and departure airports, cruise speed and winds subject to environmental constraints.
- The aircraft equations of motion at a constant altitude above the spherical Earth’s surface are:

\[
\begin{align*}
\dot{\phi} &= \frac{V \cos \psi + u(\phi, \theta, h)}{R \cos \theta} \\
\dot{\theta} &= \frac{V \sin \psi + v(\phi, \theta, h)}{R} \quad \text{subject to}
\end{align*}
\]

\[Th = D\]
\[L = W\]
\[m = -f\]
\[R >> h\]
Optimization Subject to Environmental Constraints

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

$$J(h) = \int_{t_0}^{t_f} [C_t + K(\phi, \theta, h)] dt$$

- Solution reduces to solving

$$K(\phi, \theta, h) = \sum_i C_i \cdot GWP_i(\phi, \theta, h) \cdot EI_i \cdot f(h) + C_r r(\phi, \theta, h)$$

- Time cost

$$\dot{\phi} = \frac{V \cos \psi + u(\phi, \theta, h)}{R \cos \theta}$$

- Emissions cost

$$\dot{\theta} = \frac{V \sin \psi + v(\phi, \theta, h)}{R}$$

- Contrails penalty cost

$$\dot{\psi} = \frac{-[F_{\text{wind}}(\psi, \phi, \theta, u, v) + F_{\text{climate}}(\psi, \phi, \theta, u, v, K(\phi, \theta, h))]}{R \cos \theta (C_t + K(\phi, \theta, h))}$$
Atmospheric Model

- Compute and predict contrails using Global Forecasting System (GFS)

Contrail Favorable Regions at 8 p.m. EDT on Dec. 31, 2009
Fuel and Emission Models

Aviation Environmental Design Tool (AEDT)
Eurocontrol’s Base of Aircraft Data (BADA)
Variation of Emissions with Altitude

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

- Fuel and emission models undergoing additional verification using AEDT (Collaboration with Volpe National Transportation Systems Center)
Cross-Polar Trajectories-Chicago to Hong Kong

Altitude at 32,000 ft
Trajectories for 15 Origin-Destination Pairs

- For 15 Origin-Destination pairs during the days with medium and high contrail formation in 2010
  - Analyze the fuel burn and climate impact
  - Investigate the tradeoff between persistent contrails formation and additional fuel burn, with and without altitude optimization

<table>
<thead>
<tr>
<th>Origin-Destination Pairs</th>
<th>Beijing Capital, Hong Kong, Shanghai Pudong, Seoul Incheon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago O’Hare</td>
<td></td>
</tr>
<tr>
<td>Hartsfield-Jackson Atlanta</td>
<td>Seoul Incheon</td>
</tr>
<tr>
<td>John F. Kennedy</td>
<td>Beijing Capital, Hong Kong, Seoul Incheon</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>Dubai</td>
</tr>
<tr>
<td>Newark Liberty</td>
<td>Hong Kong, Shanghai Pudong, Singapore Changi</td>
</tr>
<tr>
<td>Washington Dulles</td>
<td>Beijing Capital, Narita, Seoul Incheon</td>
</tr>
</tbody>
</table>
Potential Contrails Formation in 2010

Contrails Formation Time

Minutes

Contrails Formation Time

Average: 203 minutes

Medium: August 7

High: December 4

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Fuel Burn and GWP for Cross-Polar Trajectories

<table>
<thead>
<tr>
<th>Date</th>
<th>FP Fuel Burn (ton)</th>
<th>GWP (1000)</th>
<th>Fuel Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/7/10</td>
<td>91.7</td>
<td>442</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>GC 89.1</td>
<td>430</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>WO 84.4</td>
<td>407</td>
<td>8.0</td>
</tr>
<tr>
<td>12/4/10</td>
<td>91.4</td>
<td>441</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>GC 89.3</td>
<td>431</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>WO 87.4</td>
<td>422</td>
<td>4.4</td>
</tr>
</tbody>
</table>

- Climate impact of cross-polar trajectories equivalent to about 400 tons of CO₂ emissions
- WO trajectories reduce average fuel burn (GWP) by 8.0% and 4.4%
- Conducting similar fuel savings analysis for Pacific Project Paper Trial and Data Analysis (Routes through Anchorage Center)
Cross-Polar Trajectories Generation

• For each day (High: December 4, Medium: August 7)
  For each Origin-Destination pair (15 pairs)
    For each possible flight level (6 levels between 300 – 400)
      Compute 1 flight plan trajectory
      Compute 1 great circle trajectory
      Compute 1 wind optimal trajectory
      Compute 20 contrails avoidance trajectories
    Compute fuel burn, emissions, GWP, persistent contrails formation time for each of the 23 trajectories
Trade-off between extra GWP and Contrails

Contrails (minutes)

Additional GWP, %

Contrail Formation, minutes

12/4/2010 (2D)

12/4/2010 (3D)

8/7/2010 (2D)

8/7/2010 (3D)
Aggregate Global Temperature Potential (AGTP)

\[ \dot{x}_1 = A_1 x_1 + B_1 E(t) \]
\[ y_1 = C_1 x_1 \]
\[ \dot{x}_2 = A_2 x_2 + B_2 y_1 \]
\[ y_2 = C_2 x_2 \]
Aggregate Global Temperature Potential (AGTP)

\[ \begin{align*}
\dot{x}_1 &= A_1 x_1 + B_1 E(t) \\
y_1 &= C_1 x_1
\end{align*} \]

\[ \begin{align*}
y_1 &= RF_{CO_2}\]

\[ \begin{align*}
\dot{x}_2 &= A_2 x_2 + B_2 y_1 \\
y_2 &= C_2 x_2
\end{align*} \]

\[ y_2 = \Delta T \]
Aggregate Global Temperature Potential (AGTP)
Influence of emission and contrail parameters

\[ \Delta T \] (Kelvin)

\[ \Delta T \] (Kelvin)

\[ \Delta T \] (Kelvin)

\[ \Delta T \] (Kelvin)

\[ \text{CO}_2 \]

\[ \text{CO}_2 \]

\[ \text{CO}_2 \]

\[ \text{CO}_2 \]
Concluding Remarks

- Developed an algorithm to calculate route optimization trajectories for aircraft while avoiding the regions of airspace that facilitate persistent contrails formation, convective weather or other hazards.

- Presented trajectory optimization results for 15 origin-destination pairs between major international airports in the United States and Asia during the days with medium and high contrail formation in 2010.

- Integrated contrails, emission models and optimized routing strategies to a national level airspace simulation with capability to visualize, evaluate technology and alternate operational concepts and provide inputs for policy-analysis tools to reduce the impact of aviation on the environment.