Creating En Route (Cruise) Trajectories That Have Minimal Impact on the Environment

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Current Operations Sub-Optimal

• Except in a sub-set of instances...
  – certain regions of the Pacific

• Flight plans are sub-optimal from both the economic and the environmental perspective
  – Aircraft are constrained to fly fixed (or partially fixed) routes
  – Fuel cost and over-flight fees considered but emissions not explicitly considered
  – Combinatorial problem (from ANSP perspective) that is intractable given existing resources
Proposed Operations Not Tenable

• Trajectory-Based Operations (TBO) proposed as the way forward
  – Operators would negotiate 4D-trajectory with ANSPs and then “stick to the agreed trajectory” except in extenuating circumstances when they would have to “renegotiate” their trajectories

• However, this “Big giant head” approach to trajectory-based operations is not tenable...
Proposed Operations– Why not?

• Uncertain operating environment
  – Imperfect weather and trajectory prediction (poor understanding of dynamics of operating environment) means that the local optimal solution might often not be the same as the global optimal solution
  – changing airspeed to maintain planned groundspeed can put aircraft in a position where it is unable to meet its ultimate RTA
Proposed Operations—Why not?

• If we ignore uncertainties...
  – Really large MILP problem due to large number of aircraft combinations and long duration of aircraft trajectories (each aircraft is considered multiple times)

• If we consider uncertainties....
  – Huge stochastic programming problem due to large number of aircraft combinations, long duration of aircraft trajectories, and very large number of possible events and recourse actions (similar to the “curse of dimensionality” experiences with real options)

• Limits on communication bandwidth
Pragmatic Approach

• Break the TBO problem into “functional” steps
  – Determine the number of aircraft that can (at a point in the future) traverse each sub-volume of airspace considering traffic and weather uncertainties
  – Determine the “optimal” route for each aircraft subject to volume constraints in each sub-volume
  – Resolve potential conflicts in a fuel and emissions optimal manner when “certain” that conflicts will arise
Air Traffic Flow Management in the Presence of Uncertainties

Principal Investigators: John-Paul Clarke
Funded by: NASA Ames Research Center
Determining Airspace Capacity

• Step 1: Develop set of airspace blockage scenarios for given volume of airspace that are “consistent” with probabilistic convective weather forecast
• Step 2: Derive “probabilistic capacity” at future times using Monte Carlo simulation of efficient (fuel-optimal) conflict resolution algorithm in scenarios from Step 1.
• Step 3: Determine number of aircraft to send towards volume of airspace using two-stage stochastic program and probabilistic capacities from Step 2.
Capacity – Step 1

**Flowchart Description:**
- **Input:** Forecast Probabilities
- **Pre-processing:**
  - Re-sampling
  - Probability Matrices
- **Simulation Loop:**
  - Random Matrix Generator
  - Smoothing
  - Mapping
  - Intermediate Blockage
- **Output:**
  - Blockage Map Sequence

**Steps:**
1. **Input**
   - Forecast Probabilities
2. **Pre-processing**
   - Re-sampling
   - Probability Matrices
3. **Simulation Loop**
   - Random Matrix Generator
   - Smoothing
   - Mapping
   - Intermediate Blockage
4. **Output**
   - Blockage Map Sequence
Capacity – Step 2
Capacity – Step 2 (cont’d)

- 10 samples per arrival rate level
- 100 samples per arrival rate level
Capacity – Step 3

• Input data including bounds on decision variables

  – $M$: set of flights, $m$ as the index
  – $S$: set of time periods; $s, t, u$ as the index
  – $b_m$: scheduled departure period of flight $m$
  – $\Delta k_m$: regular flying period of flight $m$ to the sector
  – $\Delta s_m$: maximum number of periods flight $m$ can be ground-delayed
  – $\Delta t^*_m$: maximum number of periods flight $m$ can be scheduled to arrive early
  – $\Delta t^+_m$: maximum number of periods flight $m$ can be scheduled to arrive late
  – $\Delta h_m$: maximum number of periods flight $m$ can be air-held
Capacity – Step 3 (cont’d)

- **Costs and capacity**
  - $g_m^s$: ground-delay cost for flight $m$ if it is sent at time $s$
  - $c_m^{t-s-\Delta k_m}$: speed-change cost for flight $m$ if it is sent at time $s$ and arrived the sector at time $t$
  - $a_m^{u-t}$: air-hold cost for flight $m$ if it arrives the sector at time $t$ and enters the sector at time $u$
  - $d_m^t$: diversion cost for flight $m$ which diverts at time $t$
  - $C^u$: sector capacity at time $u$

- **Variables**
  - $x_m^{st}$: 1 if flight $m$ is sent at time $s$ and arrives the sector at time $t$; 0 otherwise
  - $p_m^{tu}$: 1 if flight $m$ arrives the sector at time $t$ and enters the sector at time $u$; 0 otherwise
  - $q_m^t$: 1 if flight $m$ arrives the sector and diverts at time $t$; 0 otherwise
min \ \sum_{m \in M} \left\{ \sum_{s=b_m}^{b_m+\Delta s_m} \sum_{t=s+\Delta k_m+\Delta t^+}^{s+\Delta k_m+\Delta t^+} \left[ \left( g_m^s + c_m^{t-s-\Delta k_m} \right) \cdot x_{st}^m \right] + \sum_{t=b_m+\Delta k_m-\Delta t^+}^{t+b_m+\Delta k_m} \left[ E\left[ d_t^m \cdot Q_t^m (\xi) \right] + \sum_{u=t}^{t+b_m+\Delta k_m} \left( a_u^{u-t} \cdot E\left[ P_u^{tu} (\xi) \right] \right) \right] \right\} \\

s.t. \ \sum_{m \in M} \sum_{t} p_{m}^{tu}(\xi) \leq C^u \\

q_t^m (\xi) + \sum_{u=t}^{t+b_m} p_{m}^{tu}(\xi) = \sum_{s} x_{s}^m \\

\sum_{s=b_m}^{b_m+\Delta s_m} \sum_{t=s+\Delta k_m-\Delta t^+}^{s+\Delta k_m+\Delta t^+} x_{st}^m = 1 \\

x_{st}^m \quad \text{binary} \\
p_{m}^{tu}(\xi), q_t^m (\xi) \quad \text{binary}
## Computational Study (Number of Period Considered = 11)

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<thead>
<tr>
<th>flights depart in</th>
<th># of flight</th>
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<tr>
<td>period 1-2</td>
<td>27</td>
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<tr>
<td>period 1-3</td>
<td>28</td>
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<tr>
<td>period 1-4</td>
<td>31</td>
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<td>period 1-6</td>
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<tr>
<td></td>
<td>44</td>
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<tr>
<td>period 1-7</td>
<td>48</td>
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<table>
<thead>
<tr>
<th></th>
<th>Solve to Optimality</th>
<th>Rolling Horizon Method</th>
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<tbody>
<tr>
<td></td>
<td>objective value</td>
<td>Time (sec)</td>
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<tr>
<td>period 1-2</td>
<td>2,644.95</td>
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<tr>
<td>period 1-3</td>
<td>2,647.95</td>
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<td>period 1-4</td>
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<td>422.59</td>
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<td>period 1-6</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>period 1-7</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Optimal Routing

Aircraft Operations for Minimum Environmental Impact

Stephen Altus, PhD
Jeppesen, A Boeing Company
San Jose, CA

Geoffrey C. Bower
Stanford University, Department of Aeronautics & Astronautics
Stanford, CA
Optimal Routing

Flight Planning Objective Functions

One way to include the atmospheric impact is to rely on an intelligent emission taxing scheme

Minimize: \[ \text{Cost} = C_{\text{fuel}} + C_{\text{time}} + C_{\text{overflight}} + C_{\text{spill}} + C_{\text{emissions tax}} \]

If no official scheme exists, operators can define their own weighting based on cultural values and operational goals

Alternatively, we could do multi-objective optimization for cost and environment – a current aircraft design research topic
Optimal Routing

Flight planning for min $\text{NO}_x$: system allowed to vary route, altitudes

- SJC-IAD
- 150-seat aircraft, 30,000lb payload
- Mach 0.78, NWS RUC winds & temperatures

Minimum-$\text{NO}_x$ route: Fuel 25,746lb; $\text{NO}_x$ 337lb

FL330 to OCS

FL350

FL350 to BFF

FL370

Minimum-fuel route: Fuel 25,663lb; $\text{NO}_x$ 389lb
**Optimal Routing**

**Minimum Cost vs. minimum NO\(_x\) varying speed, altitudes, route**

- SJC-IAD, optimal routes matched in this case
- 150-seat aircraft, 30,000lb payload
- NWS RUC winds & temperatures

<table>
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<tr>
<th>Scenario</th>
<th>Min Cost CI = 50</th>
<th>Min NO(_x)</th>
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<tbody>
<tr>
<td>Altitudes</td>
<td>FL350 for 1393nm, then FL370</td>
<td>FL310 for 206nm, then FL330</td>
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<tr>
<td>Speeds</td>
<td>Mach .778 - .783</td>
<td>Mach .760</td>
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<tr>
<td>Fuel</td>
<td>24,576 lb</td>
<td>25,193 lb</td>
</tr>
<tr>
<td>NO(_x) (Cruise only)</td>
<td>416 lb</td>
<td>394 lb</td>
</tr>
<tr>
<td>Advantage</td>
<td>2.4% less fuel 1% less time</td>
<td>5.3% less NO(_x)</td>
</tr>
</tbody>
</table>
Fuel Optimal Conflict Resolution

Partnership for AiR Transportation Noise and Emission Reduction
An FAA/NASA/TC-sponsored Center of Excellence

NEXTGEN EN ROUTE TRAFFIC OPTIMIZATION TO REDUCE FUEL BURN AND EMISSIONS
(Project 5)

Lead Investigators: Prof. John-Paul Clarke, Prof. Karen Feigh
Georgia Tech Project Manager: Atri Dutta
FAA Project Manager: László Windhoffer

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Problem Description

• Given
  – N aircraft
  – Initial location
  – Initial heading
  – Intended exit location
  – Time to reach exit point

• Allow
  – Speed, heading, and altitude changes

• Required
  – Conflict resolution
  – Min fuel burn
**Conflict Resolution Strategy**

- **Heading changes**
  - Two required for providing a lateral separation
  - Third required to turn back to intended exit point

- **Altitude change**
  - One per aircraft during flight through center
Other Constraints

• Time constraints
  – Total time taken over the altered trajectory of each path must be within pre-specified value

• Speed constraints
  – Speed over a particular linear segment is constant and within pre-described limits

• Geometry constraints
  – Projected length of the path is distance between the initial and final points on path
  – Linearized constraint to include in MILP framework
Cost Function

• Fuel Expenditure
  – Convex function of speed
  – Can be approximated by piecewise linear functions to incorporate within the MILP framework

• Minimize total fuel expended during the flight of the aircraft in their altered routes
Case Study: Cleveland ARTCC

- 24hr Period - Sunday, May 1, 2005
  - FL36 (Westbound) – Nominal day in NAS
Case Study: Results

• Lower Bound on Fuel Savings: 1.4%
• If aircraft fly at suboptimal speeds (0% or 15% below optimal): 3.37% and 6.13%
• Flights > 350NM, (24% of all flights): 2.1%.
Summary

- Current en route operations sub-optimal
- Centralized, deterministic, trajectory-based operations untenable
- Pragmatic approach where operations divided into functional steps shows great promise