Modeling, Optimization and Software in Air Traffic Management

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Modeling, optimization and software in Air Traffic Management Workshop
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Animation: A Day in the Life of Air Traffic

Actual FAA Traffic Data
Outline

• System Characteristics
• Models
• Optimization Methods
• Data Mining
• Software
• Summary
Air Traffic Management

• Air traffic management (ATM) is a complex engineering problem involving large number of decision-makers, competing interests and vital to the economy of nations.

• Needs major overhauling in US and Europe and rapid growth in Asia.
  – Technical changes
  – Policy changes

• Goal is to present some of the technical challenges to interest the Control and Decision Sciences Community to become part of the solution.
National Airspace System (NAS)

- NAS refers to the hardware, software and people (runways, radars, networks, FAA, airlines..) involved in managing air traffic in the U.S.

- Centralized command and control structure
- Command Center, Herndon, VA
- 22 Centers
- 830 high and low-altitude sectors
Air Traffic Management (ATM) Functions

- Traffic Flow Management (TFM) ensures safe and efficient flow of traffic
  - Minimize system delay without overloading sectors
Elements of the TFM problem
Airport Operations

Operations at towered airports in the contiguous U.S.
Flight Operations

Flight operations between the top-$n$ airports in the contiguous U.S.

Total Flights = 35,898
Top-25 airports (red) and all other towered airports (white)
Network Structure of ATM

- ATM can be viewed as a network at several different levels
- Major advances in the understanding of the behavior of networks with large number of components
- Structure of the network has a strong influence on the functionality
- Degree of a node
- Scale-free Network
  - Tolerance to random failures
  - Susceptibility to targeted attacks
Scale-free Behavior of Nodes in ATM

ATM Networks

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<tr>
<th>Network</th>
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![Graph showing scale-free behavior](image)
Outline

• System Characteristics
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# Traffic Flow Models

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<th>Detailed</th>
<th>Aggregate</th>
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<td>Deterministic</td>
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- **Detailed models**
  - Useful for developing algorithms affecting individual aircraft
  - Controller/Traffic Manager decision support tools
- **Aggregate models**
  - Useful for understanding the general behavior of the system
  - Effectively address system uncertainties and long term behavior
Eulerian Traffic Flow Model

Departures from Center i
\[ d_i(k) \]

Outflow to Center j
\[ \beta_{ij}x_i(k) \]

Inflow from Center j
\[ \beta_{ji}x_j(k) \]

Arrivals into Center i
\[ \beta_{ii}x_i(k) \]

Region i
\[ x_i(k) \]

\[ x_i(k + 1) = x_i(k) - \sum_{j=1}^{N} \beta_{ij}x_i(k) + \sum_{j=1}^{N} \beta_{ji}x_j(k) + d_i(k) \]

\[ \mathbf{x}(k + 1) = \mathbf{A}(k)\mathbf{x}(k) + \mathbf{B}(k)\mathbf{u}(k) + \mathbf{C}(k)\mathbf{w}(k) \]
A Matrix (May 6, 2003: 6 hour average, 5-11P.M, PST)

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Strategic Traffic Flow Models

- Linear dynamic traffic flow system model with a slowly varying transition matrix and Gaussian departure representation adequately represents traffic behavior at the Center-level.

- Advantages
  - The model order is reduced by several orders of magnitude from 15000 aircraft trajectories to 23 states at any given time
  - Tools and techniques of modern system theory can be applied to this model because of its form.

- Capabilities of this class of models for strategic traffic flow management will be explored in the future.
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• Models
• **Optimization Methods**
• Data Mining
• Software
• Summary
Optimization of TFM Problem

• Two Point Boundary Value Problem (TPBVP) with first order non-linear differential equations and state constraints

• System dynamics: \( x(k+1) = f[x(k), u(k), w(k)] \)
  – Size (~15000 for 4hours) depends on the planning interval

• Control variable: Departure time and route followed by each aircraft

• Cost function: Minimize variation from schedule and many other factors (minimize fuel, equity,..)

• Constraints: Number of aircraft in a given region is below a certain quantity (state constraint)
  – Function of controller workload (~ 800 sectors)
  – Weather
Optimization Methods

- Baseline
- What-if and Heuristic Methods
- Optimization Methods
  - Dynamic Programming
  - Mixed Integer Linear Programming
  - Decomposition Methods: Time, Space, Functionality
  - DP Approximations

![Diagram showing optimization methods and their cost function](Diagram.png)
Baseline

- West Watertown Playbook route diverts traffic around convective weather
- National-level action causes localized congestion in Minneapolis Center
- What is the best combination of local- and national-level Traffic Management Initiative (TMI) to avoid the convective weather while satisfying sector capacity constraints?
Effects of Alternative TMIIs

Nominal

Playbook

MIT

Local Reroute

Local Reroute

Sector Count

File Edit Table

Time ZMI1 ZMI1 T

Cap 18 18
00:00 16 5
00:05 16 7
00:10 16 13
00:15 14 13
00:20 9 16
00:25 11 16
00:30 11 12
00:35 15 10
00:40 13 10
00:45 11 6
00:50 16 7
00:55 13 4
Example:

- Rerouting for weather causes local congestion in ZNY
- What is the optimal combination of EWR and LGA departure controls required to mitigate this local congestion?
Optimization Approach

- Dynamics
- Cost function \( x(k + 1) = f[x(k), u(k), w(k)] \)

\[
J^*(k) = M \text{ in } E \{ g(x(k), u(k), w(k)) + \sum_{k=0}^{N-1} J^*(k+1) \}
\]

- Weather is a major uncertainty
- Approach is a combination of
  – DP framework
  – Functional Approximation
  – Mixed integer linear programming
  – Decomposition methods
  – Simulation
Evaluation of TFM Algorithms

Airline schedules and flight planning -> Real World

Weather Forecast -> TFM Simulation 0-8 hours

TFM Initiative Playbook Reroute Metering

Severe Weather Telecon What-if Optimization

Traffic Prediction

Metrics

Observed traffic flow
Outline

- System Characteristics
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Performance Metrics

1. Traffic Flow Management initiatives in response to surface & enroute weather are the major cause of NAS delays.

2. Extensive database of Traffic, Weather and Delay

3. Develop a method to determine the performance of NAS relative to the weather conditions
Weather Impacted Traffic Index (WITI)

\[ WITI(k) = \sum_{1 \leq j \leq m} \sum_{1 \leq i \leq n} T_{i,j}(k)W_{i,j}(k) \]
Model Features

- Delay modeled as a linear combination from a subset of 16 features

- Features to represent enroute weather and traffic
  - Average WITI: $f_1$
  - Standard deviation: $f_2$
  - Values of six selected histogram bins: $f_3,..f_8$
  - Values of six selected time bins: $f_9,..f_{14}$

- Features to represent surface conditions
  - Number of major airports with wind speed $> 5$ knots: $f_{15}$
  - Number of major airports with visibility $< 6$ miles: $f_{16}$
NAS Delay Estimation

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Weights

$$w = (F^T F)^{-1} F^T d$$

Delay estimate

$$\hat{d}(p) = [f_1(p) f_2(p) \cdots f_r(p)] w$$
Linear Delay Estimation Results

- 85% within error bounds for 39 days of data used for building the model
- 73% within error bounds for 26 days of model validation data
Average Center WITI Distributions: July 2005

**Low Delay Days**

- ZNY
- ZBW
- ZMA
- ZJX
- ZTL
- ZDC
- ZOB
- ZME
- ZID
- ZAU
- ZHU
- ZPY
- ZKC
- ZMP
- ZAB
- ZDV
- ZLC
- ZLA
- ZOA
- ZSE

**Medium Delay Days**

- ZNY
- ZBW
- ZMA
- ZJX
- ZTL
- ZDC
- ZOB
- ZME
- ZID
- ZAU
- ZHU
- ZPY
- ZKC
- ZMP
- ZAB
- ZDV
- ZLC
- ZLA
- ZOA
- ZSE

**High Delay Days**

- ZNY
- ZBW
- ZMA
- ZJX
- ZTL
- ZDC
- ZOB
- ZME
- ZID
- ZAU
- ZHU
- ZPY
- ZKC
- ZMP
- ZAB
- ZDV
- ZLC
- ZLA
- ZOA
- ZSE

UTC Time (hour)
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Software

• NASA ATM Software Tools
  – Center-TRACON Automation System (CTAS)
  – Future ATM Concept Evaluation Tool (FACET)
  – ACES (Airspace Concept Evaluation System)

• FACET
  – Available to universities world-wide and U.S. companies through a Non-Disclosure Agreement

• CARAT#
  – Integration of FACET with MATLAB tools

• Berkeley Eulerian Toolbox
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Summary

• Traffic Flow Management is a key element of Next Generation Air Transportation System

• Large number of aircraft, uncertainty in weather prediction and priorities of different decision-makers poses challenges to the solution of TFM

• Modeling and Optimization methods provide a methodology to increase the value of TFM decisions
Acknowledgements