Air Transportation System Architecture Analysis

Project Final Presentation
Advanced System Architecture

Spring 2006

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Presentation by:
Philippe Bonnefoy
Roland Weibel

Instructors: Chris Magee, Joel Moses and Daniel Whitney
Motivation

• Future demand is expected to increase significantly due to the introduction of new classes of aircraft, such as Very Light Jets and Unmanned Aerial Vehicles
• There are several constraints on system evolution driven by infrastructure, economics, safety, and technology
• The air transportation system is facing and will continue to face significant challenges in terms of meeting demand for mobility
• Current multi-agency effort to establish a roadmap for the “Next Generation of Air Transportation System”
• Future (evolved) architecture of the system require understanding of the structure of the current system
• Lack of integrated quantitative analysis of structure of the current system
Objective of the project

• Better understand the architecture of the current system through network analyzes

• Understand
  – the network characteristics of individual system layers
  – Influence of constraints, desired properties (i.e. safety, capacity, etc.) in explanation of network characteristics
  – comparison of network characteristics across different layers, through coupling of infrastructure or comparison of different network characteristics across layers
Overview of the System

System layer

Demand layer
Population, income, location of businesses

Intra-layer comparison

Cross-layer comparison

Image removed for copyright reasons.
Airplane.

Chart of jet routes.
Transport Layer Analysis
Analysis of the Wide-Body/Narrow Body & Regional Jet Flight Network

Wide Body Jets  Narrow Body Jets

Regional Jets

Degree Distribution

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Analysis of the Wide-Body/Narrow Body & Regional Jet Route Network

Degree Distribution Analysis

Coefficient of the degree distribution power law function: \( \gamma = 1.49 \)

Hypotheses for the exponential cut-off:
- Nodal capacity constraints
- Connectivity limitations between core and secondary airports

Network Characteristics

<table>
<thead>
<tr>
<th>Network</th>
<th>( n )</th>
<th>( m )</th>
<th>Density</th>
<th>Clustering coeff.</th>
<th>( r )</th>
<th>Centrality vs. connectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduled transportation network</td>
<td>249</td>
<td>3389</td>
<td>0.052</td>
<td>0.64</td>
<td>-0.39</td>
<td>13/20 most central also part of the top 20 most connected</td>
</tr>
</tbody>
</table>
Analysis of the Light Jet Route Network

Degree Distribution

Cumulative Frequency ($n(>k)$)

Degree

Image removed for copyright reasons.

Light Jets
Degree Distribution Analysis

Degree distribution identified as resulting from sub-linear preferential attachment.

\[
n_k = a k^{-\gamma} \exp \left[ -\mu \left( \frac{k^{1-\gamma} - 2^{1-\gamma}}{1-\gamma} \right) \right]
\]

with:
\[
\gamma = 0.57 \\
\mu = 0.16 \\
a = 0.13
\]

Network Characteristics

<table>
<thead>
<tr>
<th>Network</th>
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<th>Density</th>
<th>Clustering coefficient</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Jet Network</td>
<td>900</td>
<td>5384</td>
<td>0.005</td>
<td>0.12</td>
<td>0.0045</td>
</tr>
<tr>
<td>(Unscheduled)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Underlying Processes and Attributes Influencing the Sub linear Attachment Dynamics

Hypotheses:

• Spatial Constraints
  – Aircraft range (number of airports reachable given aircraft range compatibilities)

• Nodal Capacity
  – Airport capacity

• Underlying demand drivers
  – Population distribution

• Modal competition
  – Focusing on the nodes
    • Scheduled transportation with the transition from on-demand traffic to scheduled traffic
  – Focusing on the arcs
    • Economics, passenger mode choice
  – Demand for long range on-demand flights (modal competition)

Investigated in Report
Overview of the System

System layer

Demand layer
Population, *income*, location of businesses

Transport layer

Supply

Demand

Airspace

Ground

Intra-layer comparison

Cross-layer comparison

Image removed for copyright reasons.
Airplane.

Image removed for copyright reasons.
Airplane.

Scheduled

Unscheduled

Scheduled

Unscheduled

Image removed for copyright reasons.
Chart of jet routes.
Airport-Level Interactions between Transport Layers

Scheduled Traffic WB/NB/RJ
(weighted degree)

Unscheduled Traffic LJ
(weighted degree)

Transport layer

On-Demand

Scheduled

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Scheduled
Unscheduled

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Ground

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Airplane.

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Chart of jet routes.

Image removed for copyright reasons.
Airplane.
Analysis of the Demand Layer

• Single Layer Analysis

Population/Airport Gravity Model

\[ b_i = \sum_{ct \in C_i} p_{ct} \quad \text{s.t.} \quad C_i = \left\{ ct \mid d_{ct,i} = \min_j d_{ct,j} \right\} \]

based on 66,000 Census Track data

Distribution of population around airports does not follow a power law

Notations:

- \( P_{ct} \): population of census track \( ct \)
- \( b_i \): size of population basin around airport \( i \)
- \( ct \): census track
- \( d_{ij} \): Euclidean distance

Cumulative Density Function \( p(>b) \)

Power law network degree signature

Population distribution (based on the gravity model)
Infrastructure Layer Analysis
Infrastructure layer analysis

• Problem
  – Airspace is a shared resource between various type of traffic (e.g. scheduled commercial, unscheduled commercial, general aviation, etc.)
  – What is the level of interaction between types of traffic at key points in the airspace

• Network analysis
  – Betweenness centrality
  – Connectivity

• Methodology
  – Shortest-path search through fully-connected airport network along ground-based Navigational Aids
  – For scheduled & unscheduled traffic data
Unweighted Betweenness Centrality - Unscheduled

Legend
Percentage of geodesics through each Navaid
- 5-9%
- 4-5%
- 3-4%
- 2-3%
- 1-2%
- 0-1%
Unweighted Betweenness Centrality - Scheduled

Legend
Percentage of geodesics through each Navaid
- 5-9%
- 4-5%
- 3-4%
- 2-3%
- 1-2%
- 0-1%
Degree vs. Betweenness for Navaid/Airport Networks

Unscheduled

Scheduled
Conclusions

• Distribution of Scheduled & Unscheduled Nodes
  – **Scheduled**: power law with exponential cut-off
  – **Unscheduled**: product of exponential and power law
  – Air transportation system is **not scale free**

• Several System Attributes That Impose Scale on System
  – Apparent in **degree sequences** investigated
  – Apparent in utilization of **airports** and **navigational aids**
  – Influences such as **capacity**, **economics**, and **policy** are acting to limit nodal connections and edge flows

• Several Implications for future growth of the Air Transportation System
  – Constraints important in future system evolution
  – Analysis forms basis for further understanding of constraints and growth dynamics
Questions & Comments

Thank you
Infrastructure Layer Analysis
Navigation Infrastructure Analysis

- **Nodes**: FAA-Defined Navigational Aids of Different Types
  - VORs, Reporting Points, etc
- **Links**: Air Routes Between Nodes
  - Victor (low alt) & Jet Routes (high alt)

**Network Metrics**
- Clustering Coefficient (Watts method) – Proxy for robustness of network
- Correlation Coefficient

**Architecture Analyses**
- Shortest-Path Navigational vs. Direct Distance between Airports
- Nodal Betweenness/Centrality
### Degree Sequence

**Victor Airways**
- All Points (left)
- VOR/VORTAC (below)

**Jet Routes**
- All Points (left), VOR/VORTAC (right)

<table>
<thead>
<tr>
<th>NavAid Network</th>
<th>n</th>
<th>m</th>
<th>C (Watts)</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Routes</td>
<td>1787</td>
<td>4444</td>
<td>0.1928</td>
<td>-0.0166</td>
</tr>
<tr>
<td>Victor Airways</td>
<td>2669</td>
<td>7635</td>
<td>0.2761</td>
<td>-0.0728</td>
</tr>
</tbody>
</table>
Navigation Architecture Analysis

• End Nodes: Navaids corresponding to published airports

• Geodesic (shortest path by navigational distance) computed between top 1,000 airport pairs
  – Airports ranked based on 2004 FAA traffic data
  – A-Star search algorithm implemented to find shortest distance along network

• Results – Dynamics Along Network
  – Navigational Distance Compared to Shortest Path Distance by Airport Ranking – Maximum “direct-to” efficiency
  – Betweenness centrality to be calculated for navigation nodes as measure of their utilization
  • Number of shortest-paths through nodes as a proportion to total shortest paths
Navigation Distance Results

$$\hat{d} = \sum_{i}^{n_{\text{airports}}} \sum_{j, j > i}^{n_{\text{airports}}} d_{ij} \quad \%_{\text{reduction}} = 1 - \frac{\hat{d}}{d}$$