Air Transportation System Architecture Analysis

Project Phase II
Advanced System Architecture
Spring 2006

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Motivation

• 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”

• Navigation in current system under most conditions requires use of fixed-location of current infrastructure to facilitate mobility

• 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
- **Mobility layer**: Movements of People and goods

**Layer attributes**
- **Data sources**
  - ArcGIS, Census
  - DB1B database

**Transport layer**
- Aircraft routes
- Data sources: ETMS, OAG

**Operator layer**
- Crews & Pilots

**Infrastructure layer**
- National Airspace System (airports layout and airspace structure)
- FAA Form 5010 airport database, airway

**Ground layer**
- Ground

**Airspace layer**
- Airspace

**Scheduled**
- Scheduled

**On-Demand**
- On-Demand
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

\[ \hat{d} = \sum_{i}^{n_{\text{airports}}} \sum_{j,j>i}^{n_{\text{airports}}} d_{ij} \]

\[ \%_{\text{reduction}} = 1 - \frac{\hat{d}}{d} \]
Transport Layer Analysis
Preliminary Analysis of the Wide-Body/Narrow Body & Regional Jet Flight Network

Wide Body Jets  Narrow Body Jets

Regional Jets

Degree Distribution

Cumulative Probability p(>k)

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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
- Spatial constraints

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</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>
Preliminary Analysis of the Light Jet Route Network

Image removed for copyright reasons.

Light Jets

Degree Distribution

Cumulative Frequency (n(>k))

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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: \( \gamma = 0.57 \)
\[ \mu = 0.16 \]
\[ a = 0.13 \]
Interactions between Transport Layers

- Scheduled Traffic WB/NB/RJ
- Unscheduled Traffic LJ

Transport layer

- On-Demand
- Scheduled

- TEB
- CMH
- CLT
- ATL
- ORD
- SEA
- DFW

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Demand Layer Analysis
Analysis of the Demand Layer

- Single Layer Analysis

Population/Airport Gravity Model

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

*Notations:*

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

*Based on 66,000 Census Track data*

- Non scale free nature of distribution of population around airports
Questions & Comments

Thank you