Air Transportation System Architecture Analysis

Project Final Presentation

Advanced System Architecture

Spring 2006

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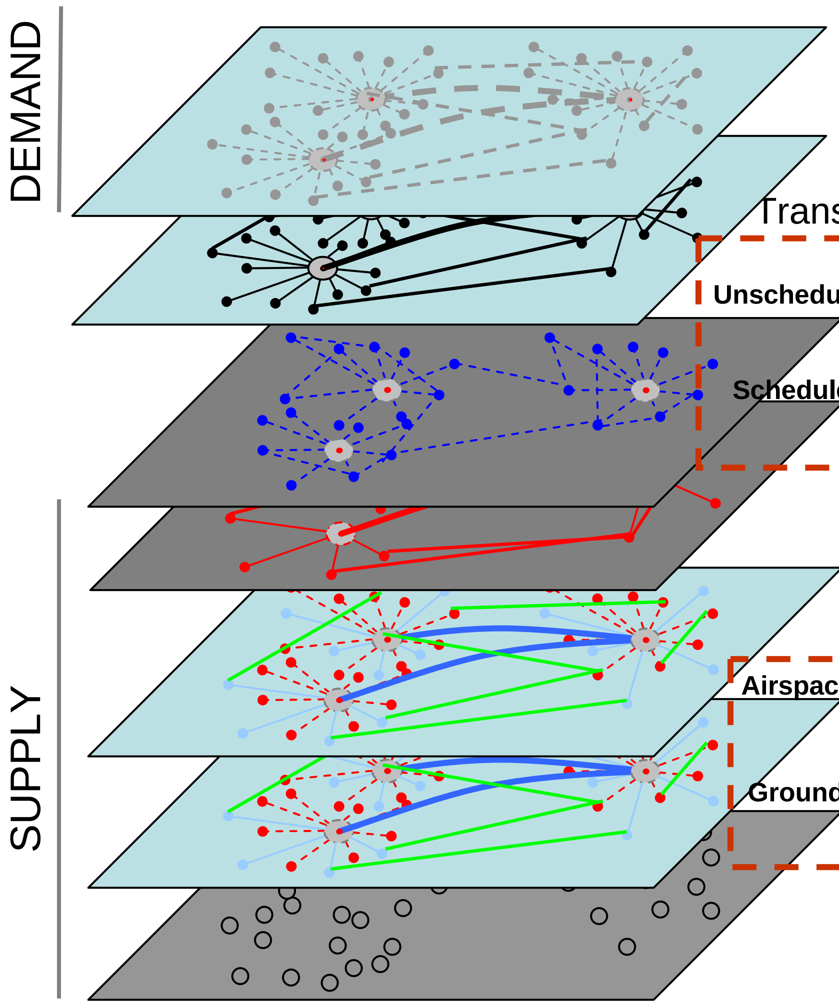
Motivation

- 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*

Transport layer

Unscheduled

Scheduled

Image removed for copyright reasons. Airplane.

Unscheduled

Intra-layer comparison

Image removed for copyright reasons. Airplane.

Scheduled

Cross-layer comparison

Airspace

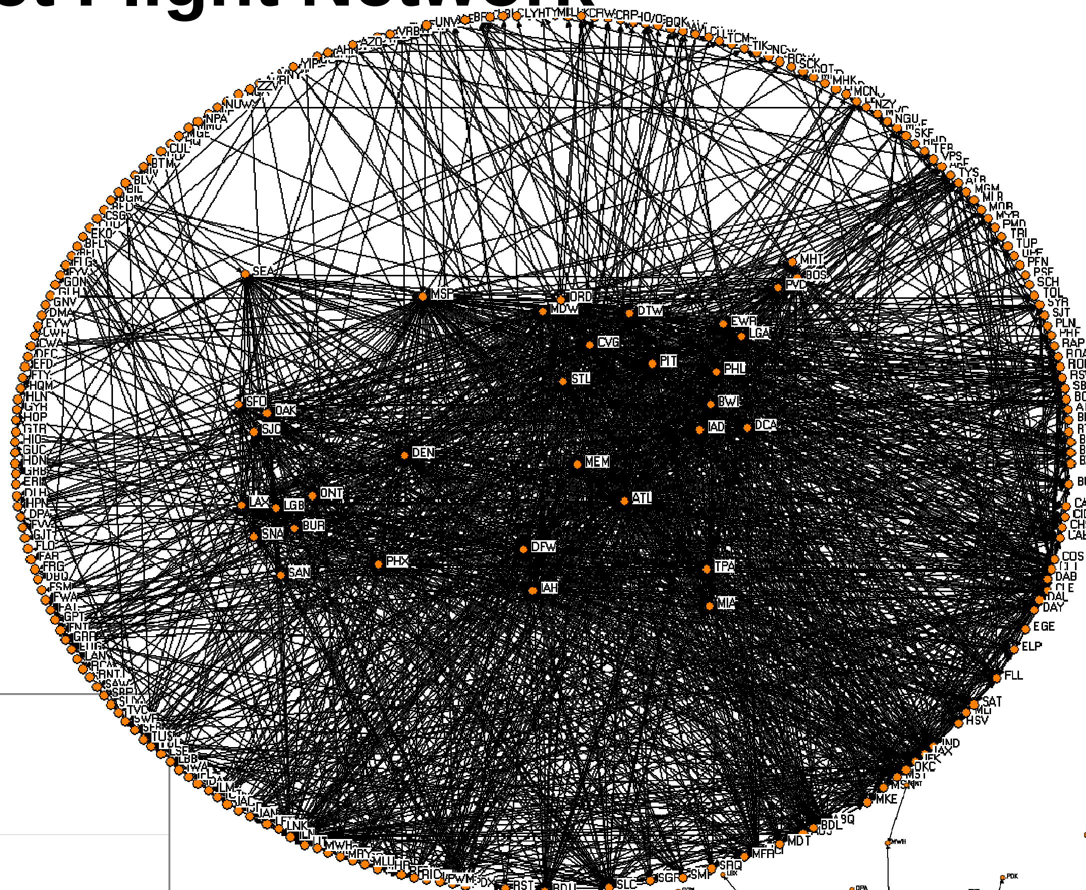
Ground

Infrastructure layer

Image removed for copyright reasons. Chart of jet routes.

Transport Layer Analysis

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



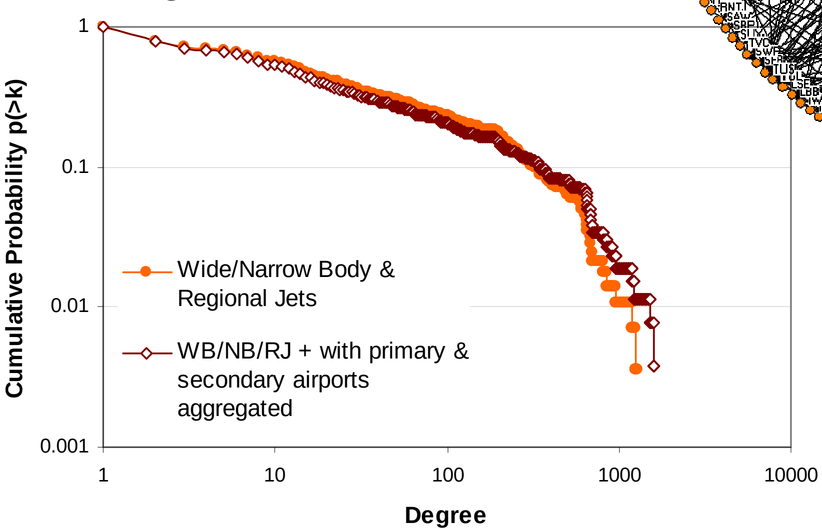
Wide Body Jets

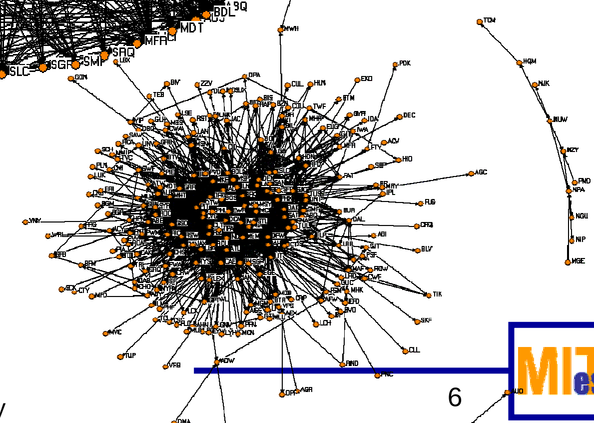
Narrow Body Jets

(Images removed for copyright reasons.)

Regional Jets

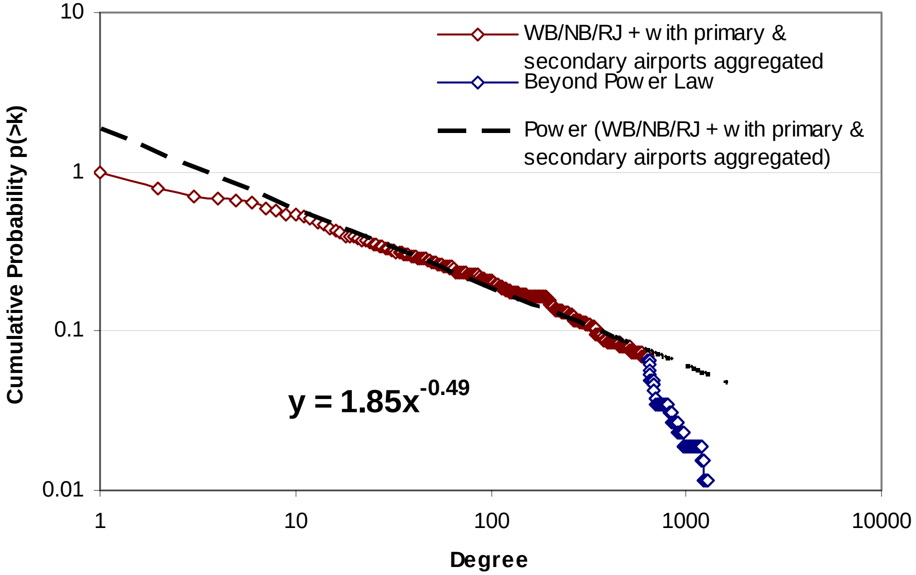
Degree Distribution





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

Degree Distribution Analysis



Coefficient of the degree distribution power law function: **γ = 1.49**

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

Network Characteristics

Network	n	m	Density	Clustering coeff.	r	Centrality vs. connectivity
Scheduled transportation network	249	3389	0.052	0.64	-0.39	13/20 most central also part of the top 20 most connected

Analysis of the Light Jet Route Network

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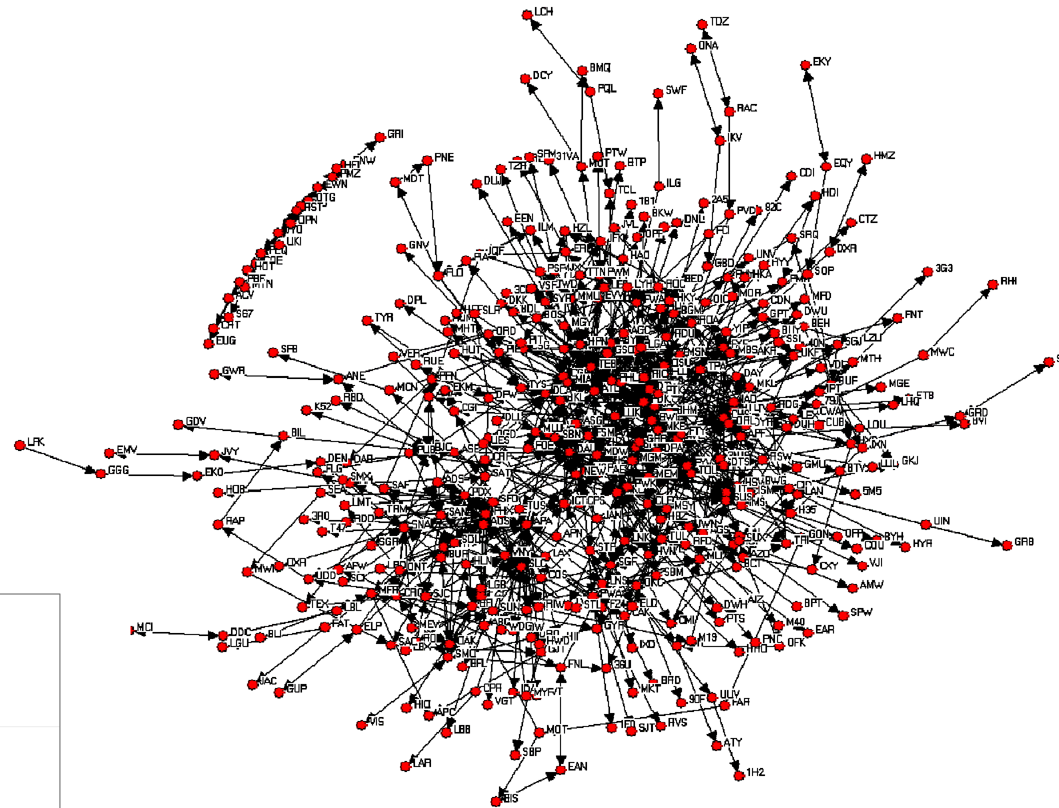
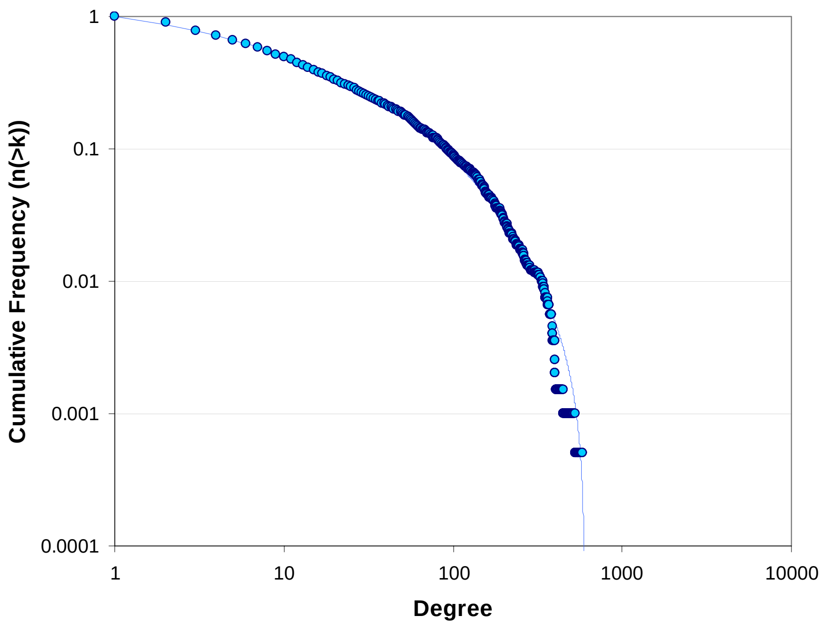
Light Jets

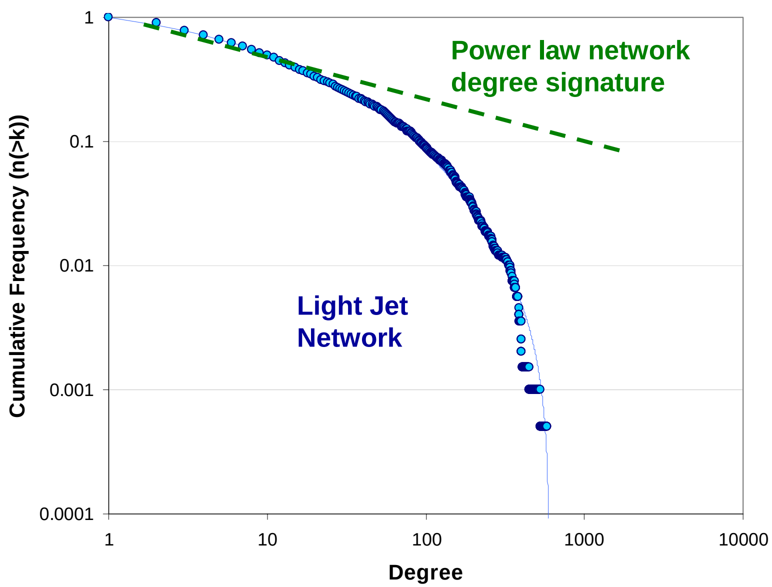


Degree Distribution



Analysis of the Light Jet Route Network

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

Network	n	m	Density	Clustering coefficient	r
Light Jet Network *(Unscheduled)*	900	5384	0.005	0.12	0.0045

Underlying Processes and Attributes Influencing the Sub linear Attachment Dynamics

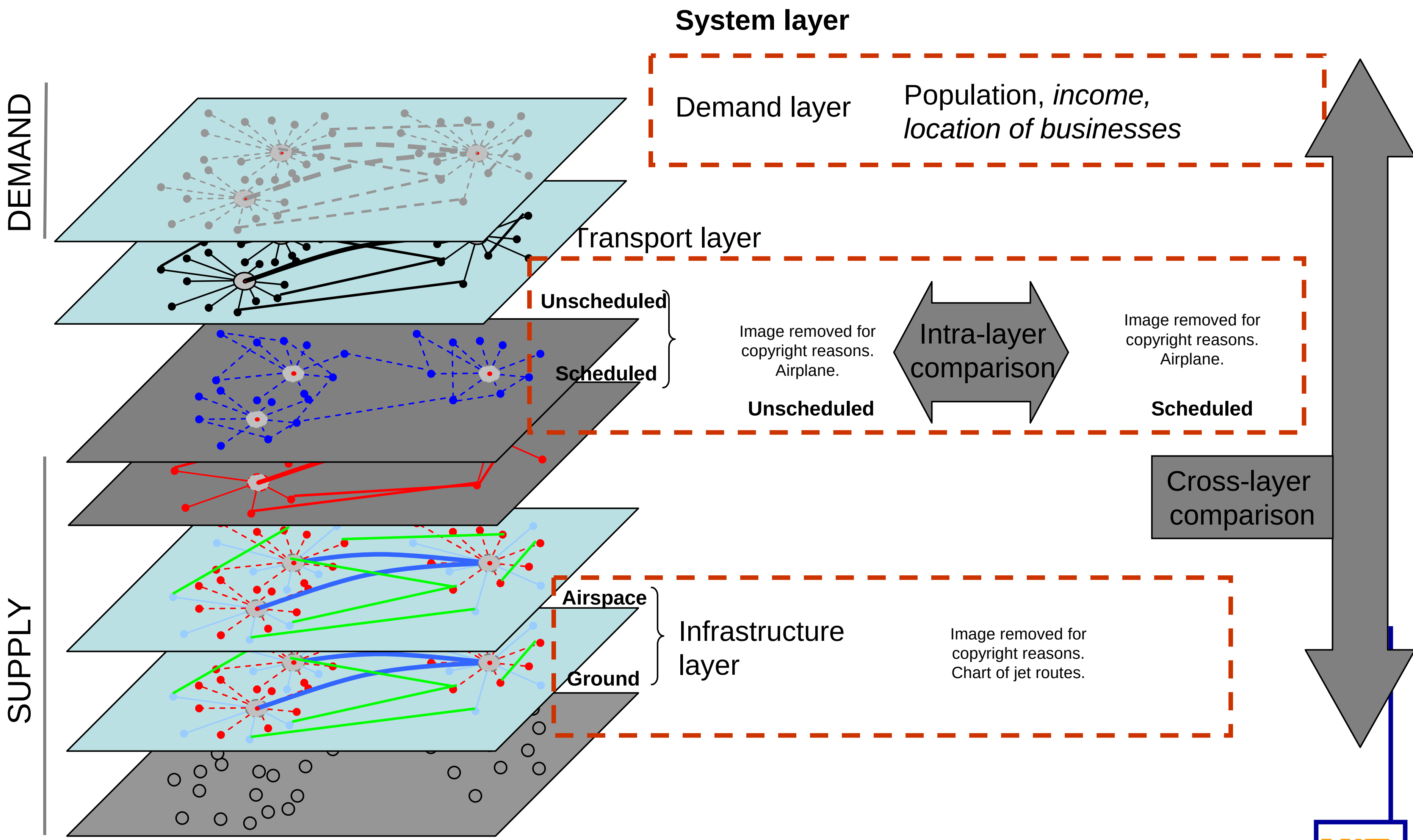
Hypotheses:

- Spatial Constraints
  - Aircraft range (number of airports reachable given aircraft range compatibilities)
- Nodal Capacity
  - Airport capacity
- Underlying demand drivers
  - Population distribution

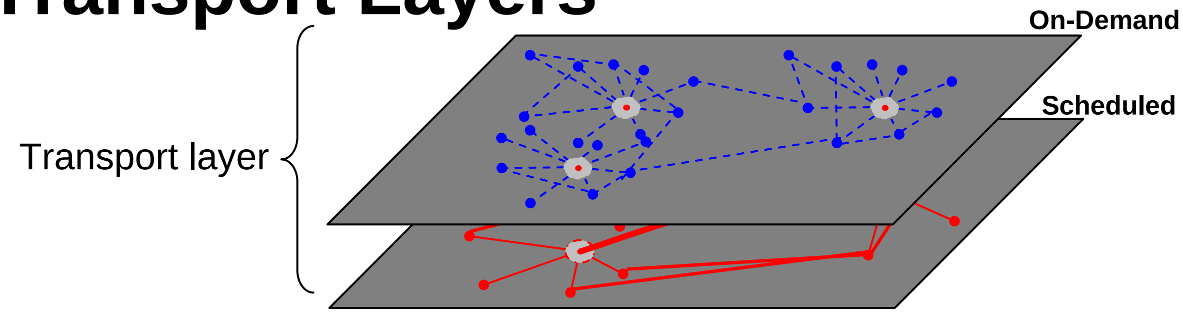
Investigated in Report

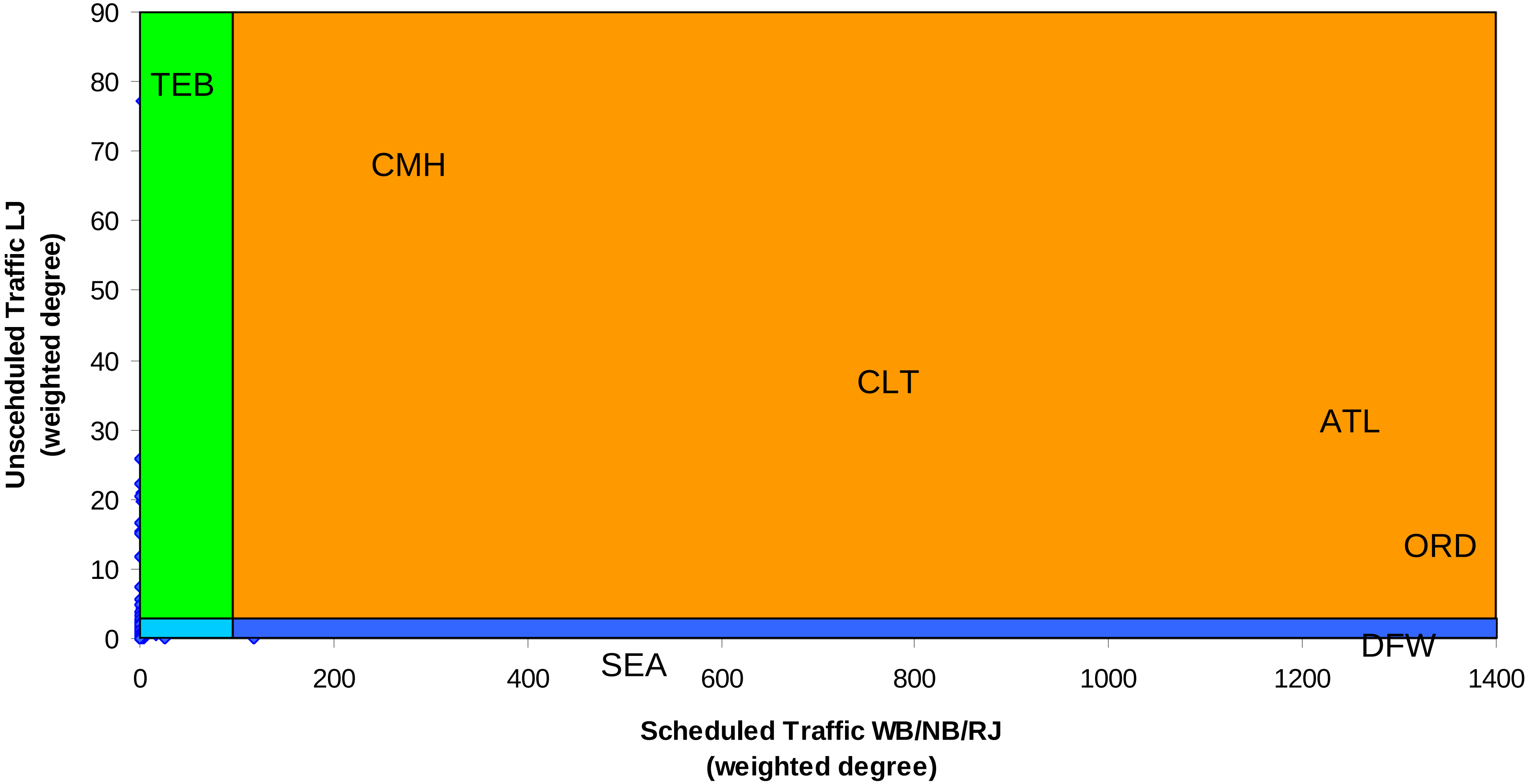
- Modal competition
  - Focusing on the nodes
    - Scheduled transportation with the transition from on-demand traffic to scheduled traffic
  - Focusing on the arcs
    - Economics, passenger mode choice
  - Demand for long range on-demand flights (modal competition)

Overview of the System

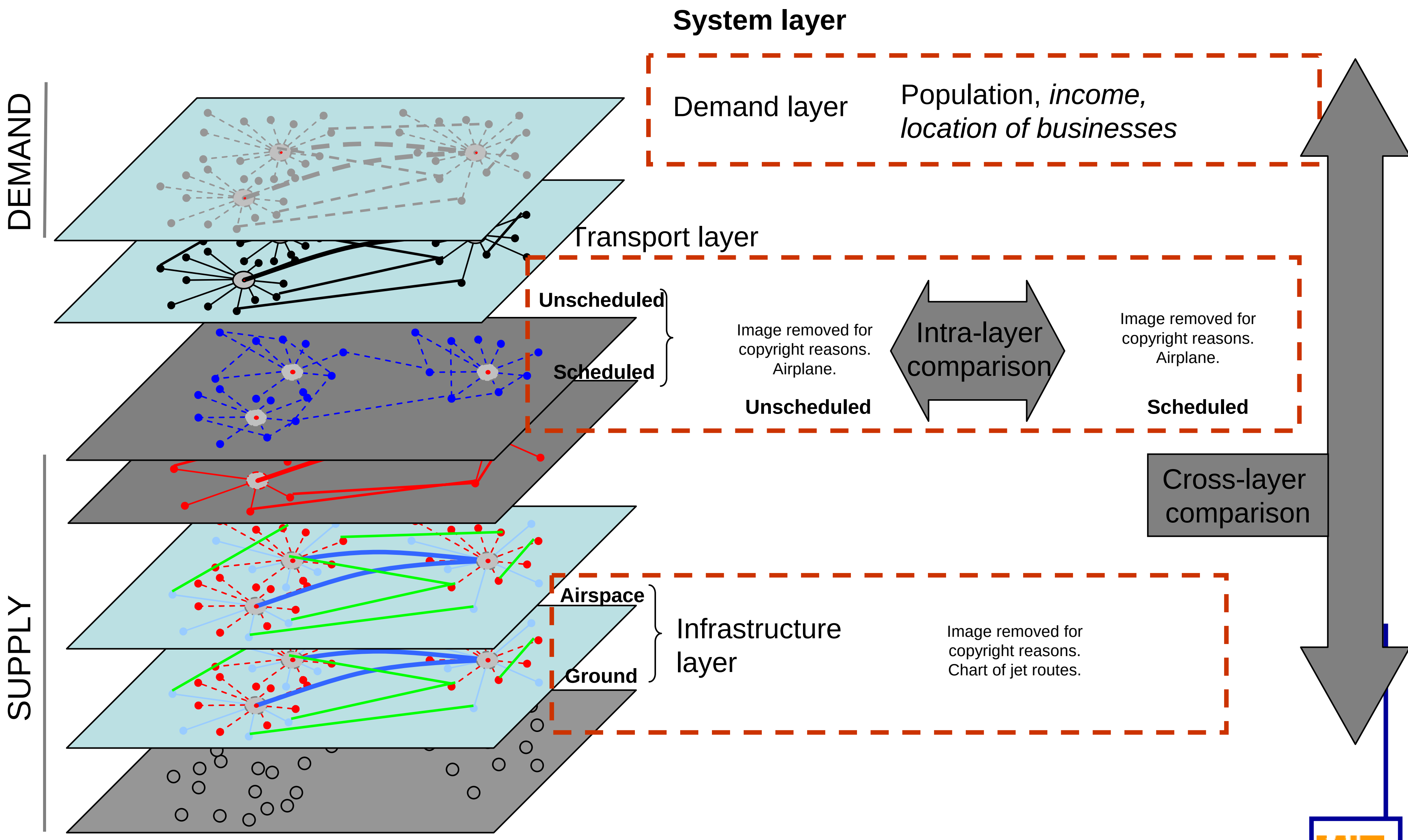


Airport-Level Interactions between Transport Layers





Overview of the System



Analysis of the Demand Layer

- **Single Layer Analysis**

Population/Airport Gravity Model

$$b_i = \sum_{ct \in C_i} p_{ct} \quad s.t. \quad C_i = \left\{ ct \; \middle| \; d_{ct,i} = \min_j d_{ct,j} \right\}$$

Notations:

Pct: population of census track ct

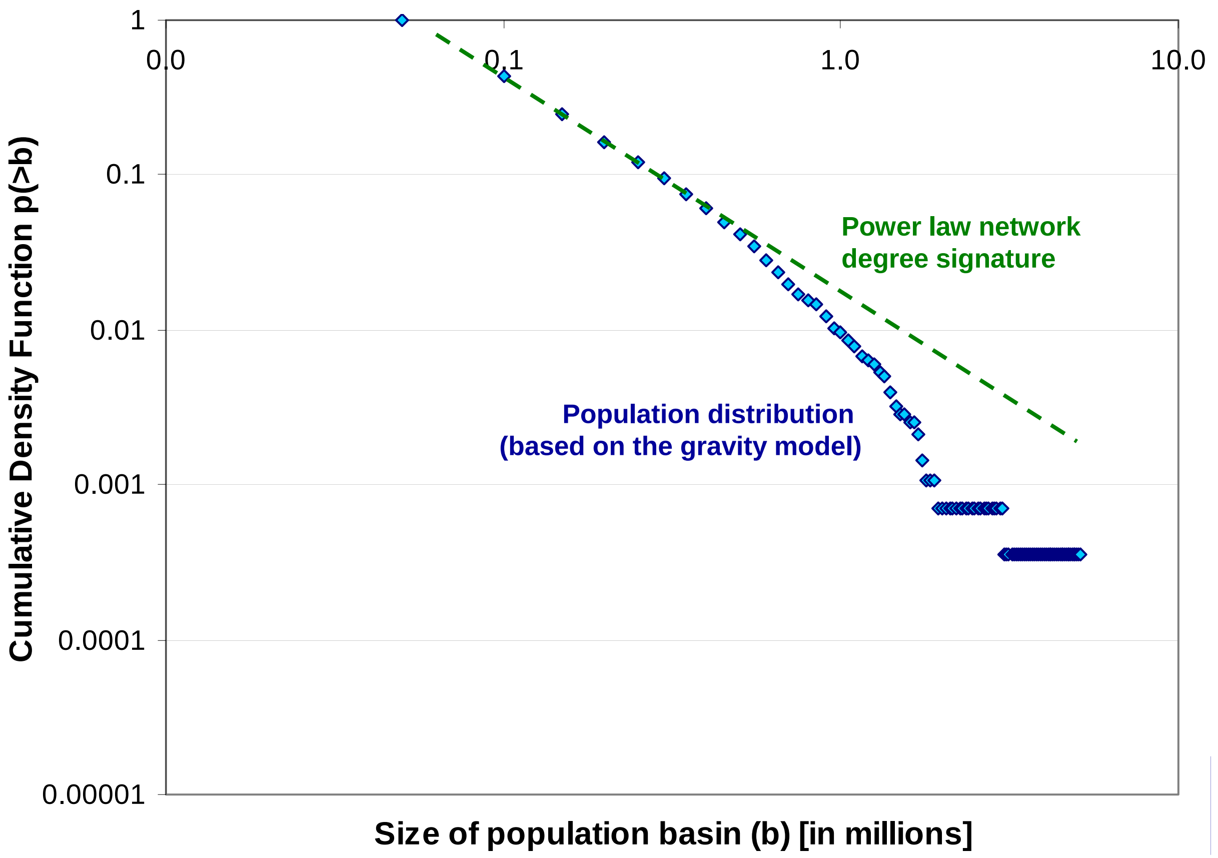
bi: size of population basin around airport i

ct: census track

$d_{i,j}$: Euclidean distance

based on 66,000 Census Track data

Distribution of population around airports does not follow a power law

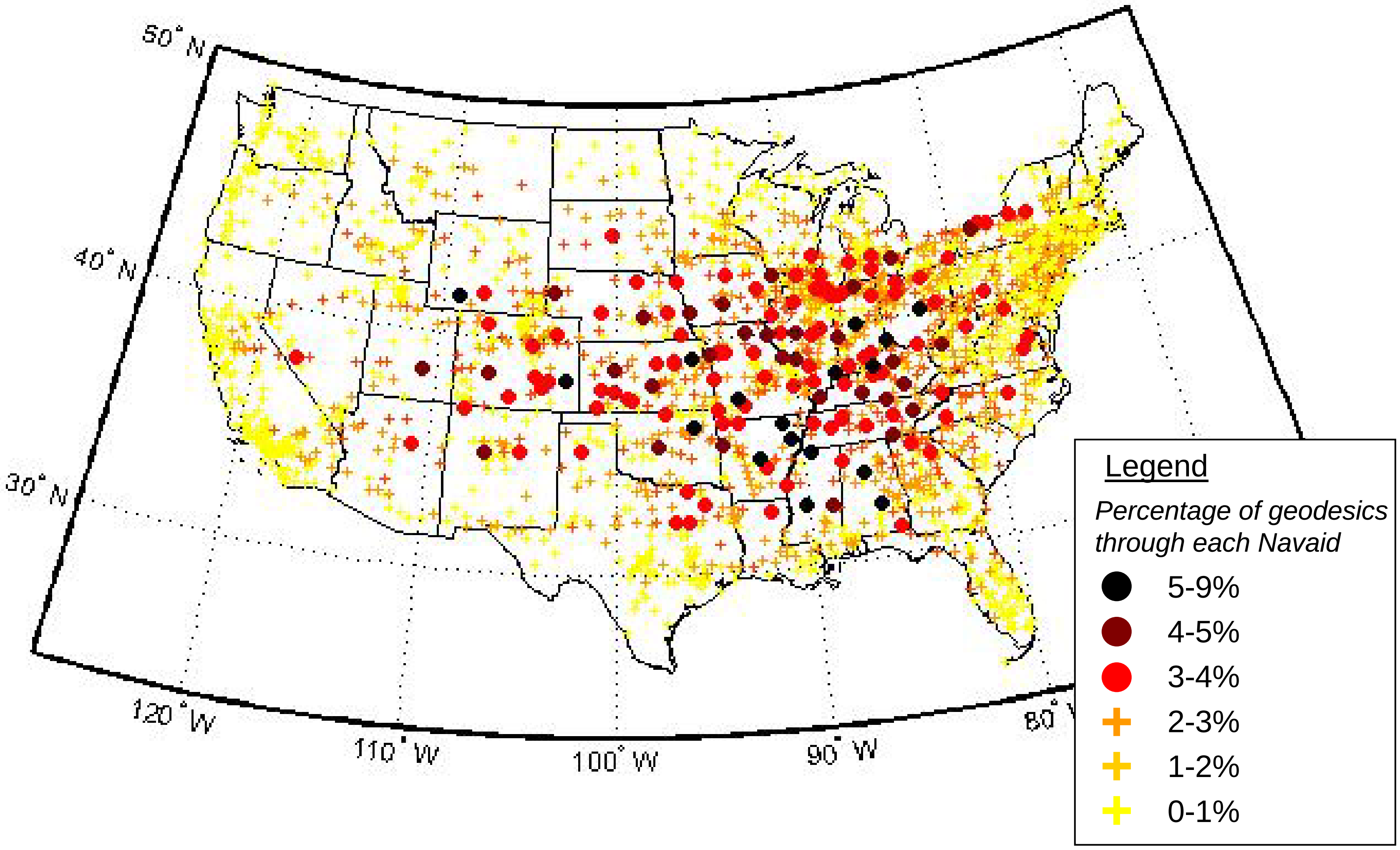


Infrastructure Layer Analysis

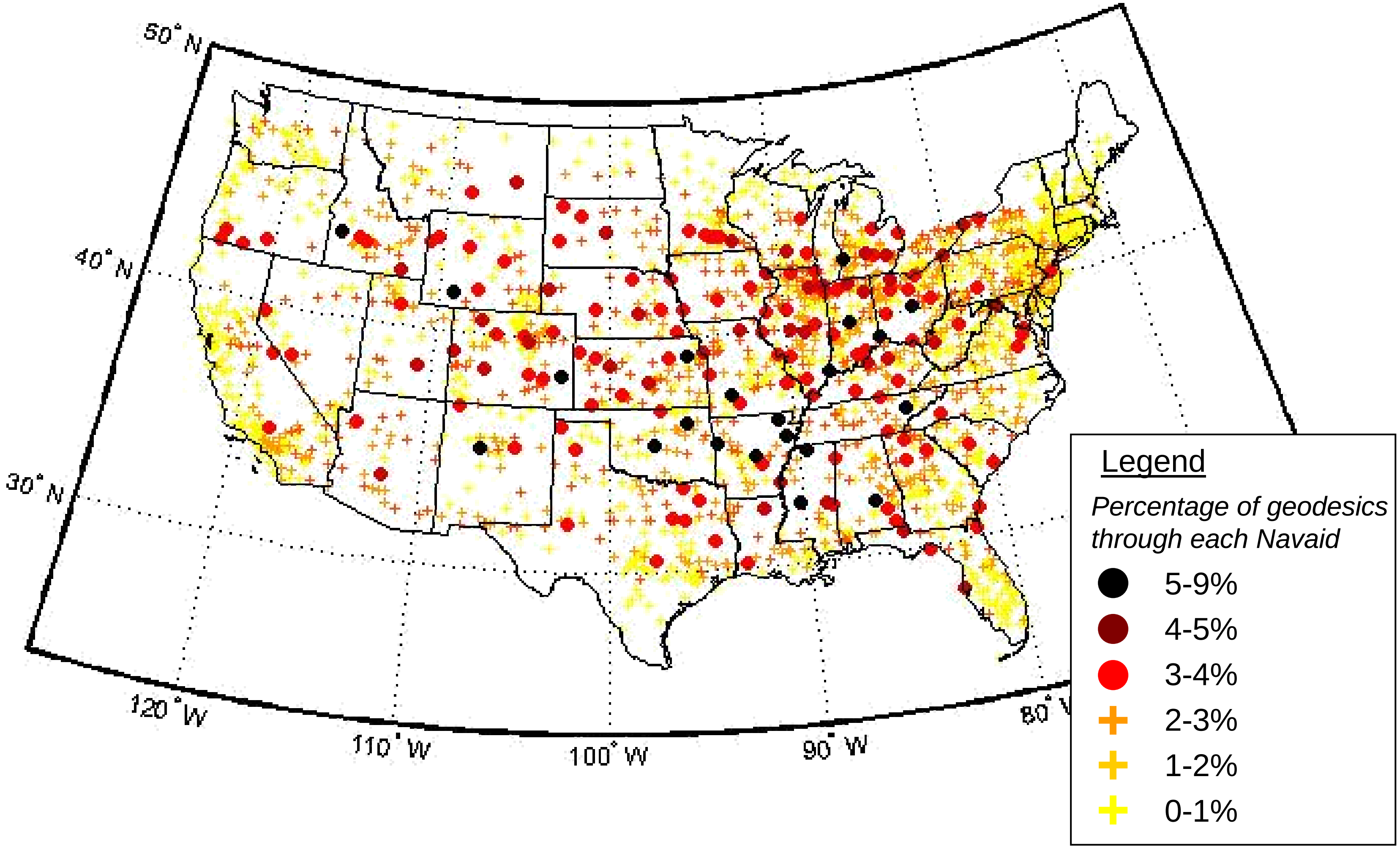
Infrastructure layer analysis

- 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

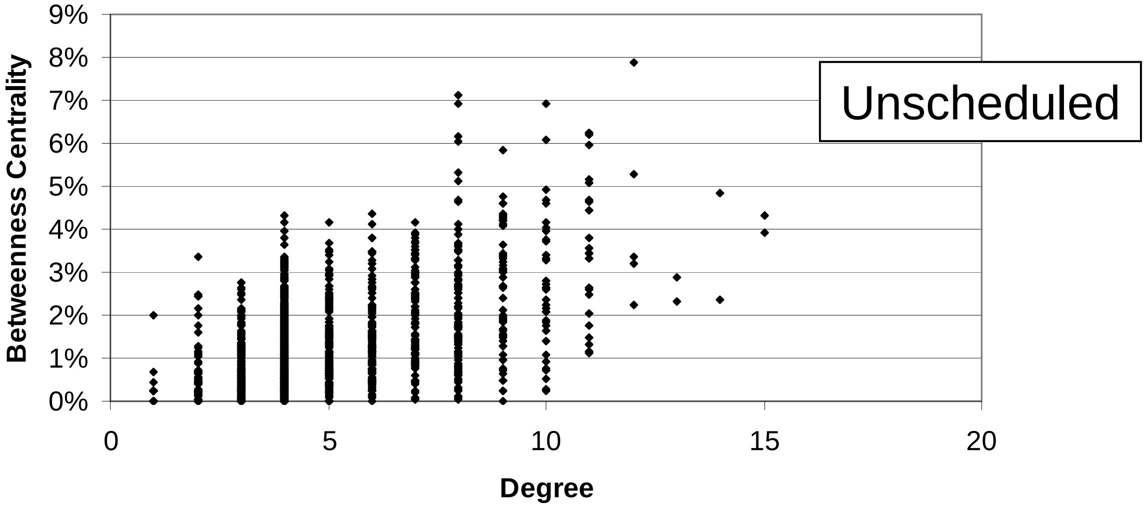
Unweighted Betweenness Centrality - Unscheduled

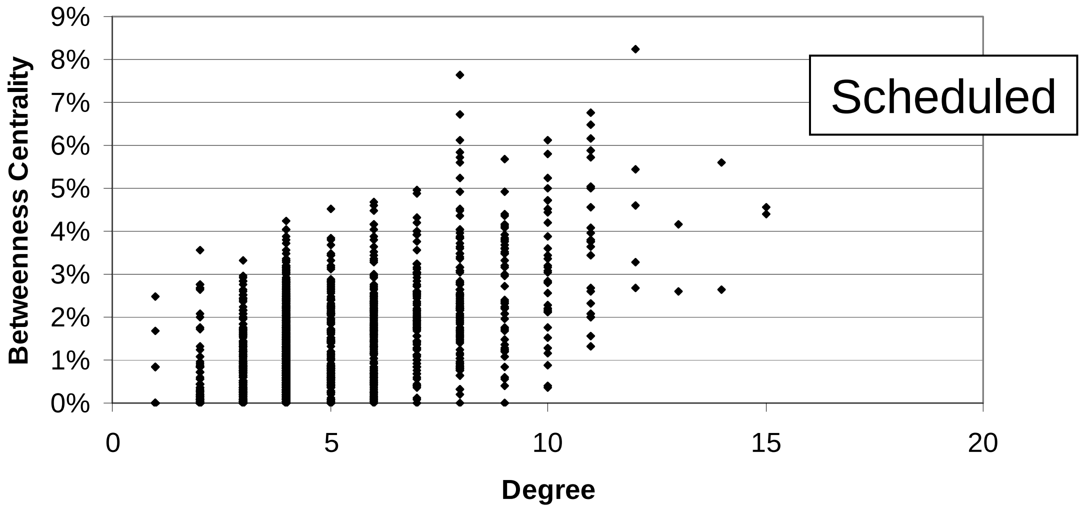


Unweighted Betweenness Centrality - Scheduled



Degree vs. Betweenness for Navaid/Airport Networks





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 & Link Highlighted

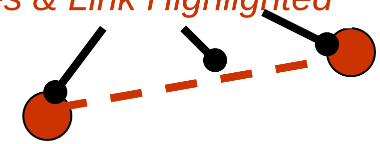


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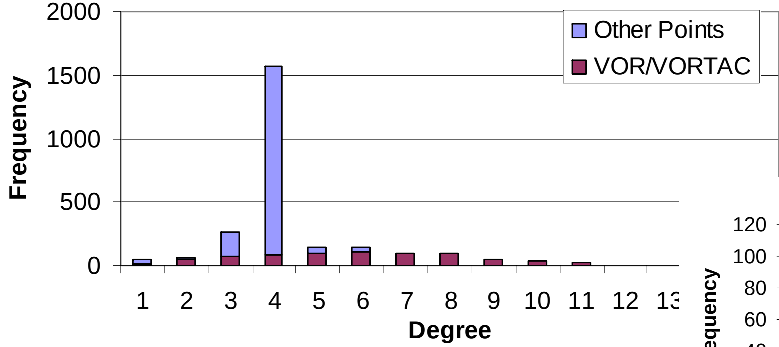
Chart of jet routes.

- 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

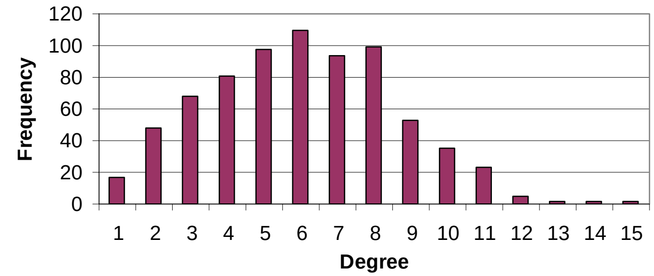
Degree Sequence

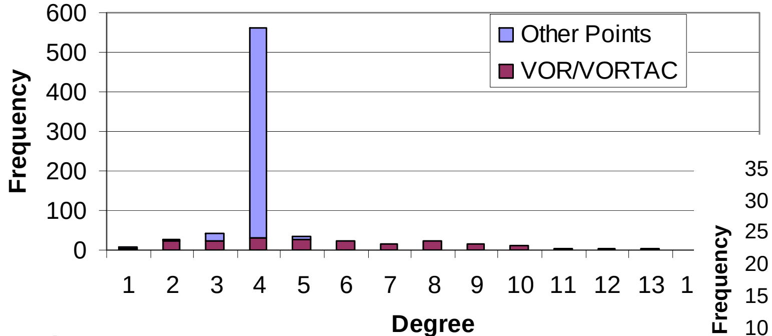


Victor Airways

-All Points (left)

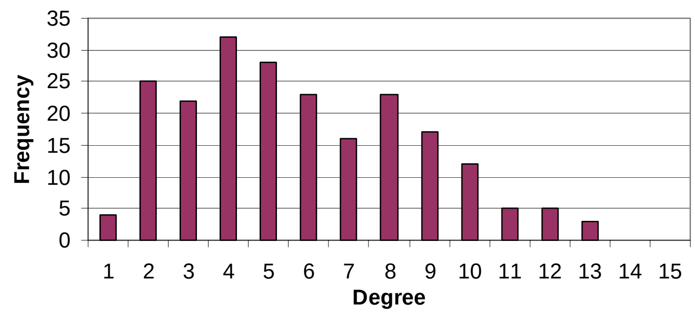
-VOR/VORTAC (below)





Jet Routes

-All Points (left), VOR/VORTAC (right)



NavAid Network	n	m	C (Watts)	r
Jet Routes	1787	4444	0.1928	-0.0166
Victor Airways	2669	7635	0.2761	-0.0728

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

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