

## **Project**

# **Air Transportation System Architecture Analysis**

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## 1. Introduction

The air transportation system is at a critical point in its history with growing demand for enhanced mobility, intense competition between carriers at both the national and international level, new aircraft types expected to enter service in the upcoming years (e.g. Very Light Jets, Unmanned Aerial Vehicles), the lack of capacity at key points in the system, the growing concerns towards sustainability and environmental performance, etc.

The air transportation system is a woven set of networks, which we will call system *layers*. A full system description includes many different layers, capturing demand for service by people and goods, routes flown by aircraft, and the infrastructure utilized by aircraft. These layers will be structured and explained in the following section, and three layers are used for more detailed analysis. The resulting overall topology of the networks has great implications on the ability of the system to respond to disturbances (e.g. environment related such as weather, voluntary attacks such as terrorist attacks, etc.), adapt to changes (e.g. introduction of new type of aircraft or business models, etc.) that ultimately influence its overall performance.

This project is aimed at broadening the understanding of the structure, properties, dynamics of the air transportation network and anticipating the implications of changes - key trends in the system- and policies on the performance of the system. It is anticipated that the network analysis of the air transportation system will provide insight into its current architecture and to potential future architectures.

## 2. Overview of the U.S. air transportation system

### 2.1 General description of the air transportation system

#### 1.1.1. Description

The Air Transportation System is an interconnected system of infrastructure and service providers that is aimed at providing transportation by air to people and freight. Figure 1 represents the stakeholders in the air transportation system: The major actors are the air transportation providers (e.g. airlines, regional carrier operators, fractional ownership operators, etc.) who represent the interface between the foundations of the system (the National Airspace System) and the passengers and freight that are transported. The National Airspace System is the critical subpart of this overall system that is defined as the interconnected system of airports, airways, air traffic facilities and navigational aids. These elements of the NAS are operated and supported by airport employees, air traffic controllers, technicians, airspace specialists, and others. Airports, air traffic facilities and equipment, and navigational aids are static physical components of the NAS.

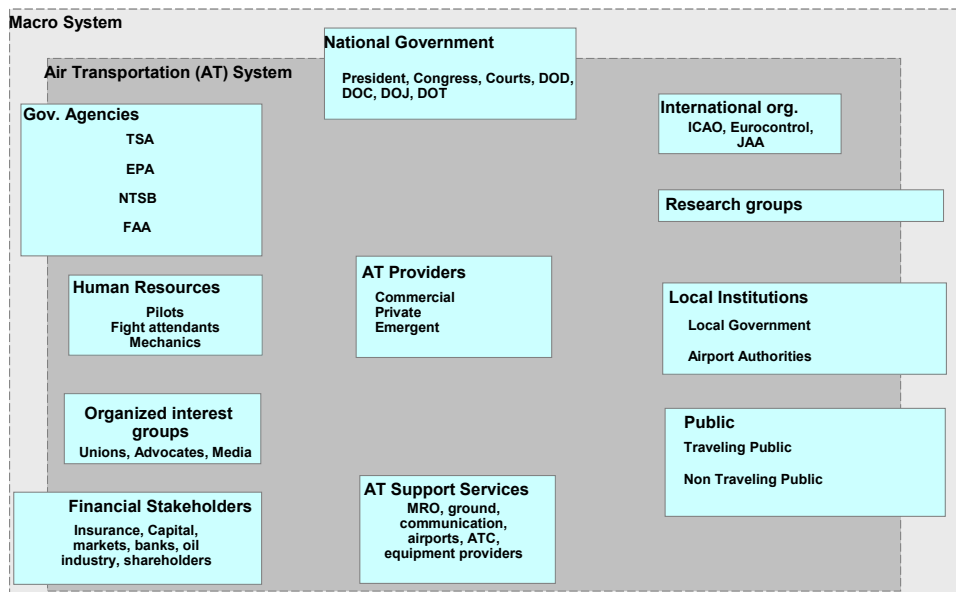


Figure 1. Stakeholders of the air transportation system

Other stakeholders that are part of the system include government agencies that are in charge of the regulatory framework that governs the functioning of the system and the international harmonization of the operations. Financial institutions are also integral part of the system and play a critical role both from an infrastructure but also from an air transportation provider perspective.

The architecture of the system is a result of competition and cooperation between service providers, the state of infrastructure formed both by private entities and government design, and policies created by regulators. Complexities in aligning stakeholder needs typically lead to slow change dynamics in the system due to often unpredictable or uncontrollable actions and dynamics.

#### 1.1.2. Network description of the air transportation system

The air transportation system is a woven set of networks. Figure 2 illustrates the “composite” nature of networks in the air transportation system. The system has been decomposed in several *layers*; from the infrastructure layer to the demand layer. The infrastructure layer is composed of the foundational elements of the National Airspace System. First the ground layer is composed of airports and navigational aids. There are more than 19,000 airports in the United States. However, the Federal Aviation Administration (FAA) considers only 3,364 existing airports to be significant to the capacity of the NAS. These, airports are divided into two major categories: commercial service airports (public airports receiving scheduled passenger service and having 2,500 or more passenger enplanements) and general aviation airports. Airports are also divided into large-hub, medium-hub, small-hub, and non-hub airports, based on their annual enplanements. Even though there is a large number of airports in the United States, traffic is concentrated at the largest airports. The 31 large-hub airports handled 69.2 percent of passenger enplanements in 2001, the 36 medium-hub airports handled 19.8 percent, and the small hubs another 7.6 percent.

The other sub layer in the infrastructure layer is the airspace (airway network). The airspace in the United States is managed by the FAA to provide for its orderly and safe use. The airspace is divided into different classifications and classes; controlled (Classes A

through E airspace) and uncontrolled (Class G airspace). For this layer, the network is represented by nodes that are navigational aids (navaid) such as very high frequency omni directional range (VOR), instrument landing system (ILS), non directional beacon (NDB), etc. The arcs in this network are represented by routes (Victor routes for the class of airspace below 18,000 ft and Jet routes for airspace above 18,000 ft).

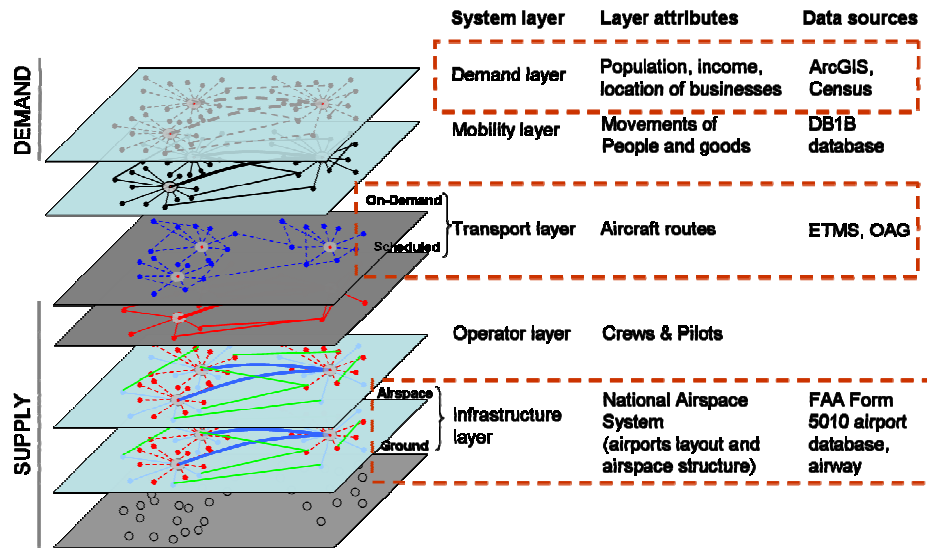


Figure 2. Network layers in the air transportation system

The network of transport layer is defined as the set of origin destination routes between airports (nodes). This layer is comprised of the scheduled transportation layer (flights flown by airlines, regional carriers, etc.) and the unscheduled transportation layer (flights flown by business jet operators, etc.).

The mobility layer is the “reflection” of the demand layer onto the transport layer. The demand layer is defined as the set of true airport to airport paths that passengers and cargo would go through regardless of constraints of supply (transport layer).

## 2.2 History and evolution of the system

### 2.2.1 System historical background, evolution, and architectural changes

The current configuration of the air transportation system is the result of several interacting dynamics and a gradual evolution of technology and government intervention.

A brief history is given in this section to better appreciate the complex nature and many trends that have shaped the system architecture.

Technology has been a driving force since the advent of powered flight. The airplane itself was the result of advances in the science of aerodynamics, propulsion, structures, and materials, brought together successfully by the Wright brothers in 1903. Continued technological advancement resulted in more sophisticated aircraft, and enabled routine airline service starting in the 1930s. The jet age, beginning with the Boeing 707 in 1954 allowed aircraft to fly higher, faster, and further, and continued to expand the extent of the air transportation system. General aviation also began in the 1950s with the surplus of aircraft from World War II, enabling routine recreational flight. Technological advances have also shaped the air traffic control system. The use of radar in the 1950s allowed for positive separation provided by Air Traffic Control in instrument flying conditions. Additional technological advancement has made both air traffic control and operation of the airplane more efficient and safe.

Market forces also drove the historical evolution of the system. The early air transportation system of the 1910s and 1920s was operated by the Postmaster General and almost exclusively carried mail on transcontinental routes. Passenger travel became routine in the 1930s, but was still plagued by safety problems and expensive. Both safety and price were regulated in air travel until deregulation in 1978, when airlines were allowed to set their own prices on routes. Market efficiency drove most major airlines to adopt a hub and spoke system, where demand from smaller markets is aggregated through an airport. The entry of low cost carriers, such as Southwest airlines, typically brought more select point-to-point operation and a large upsurge in demand through lower prices. The entry of regional jets in the 1980s also allowed carriers to increase frequency of traffic on routes while carrying fewer passengers per aircraft.

Multiple airlines competing through multiple economic cycles have resulted today in an industry that, on the whole, loses money in the long term, but very effectively enables economic growth of the country. Extensive regulations still govern the design and operation



of aircraft. In some cases, economic regulations are used to constrain access to key infrastructure, such as over-utilized airports.

### 2.2.2 Current challenges facing the air transportation system

Historical events changed the dynamics and the topology of the air transportation networks and jointly, the performance of the system. Future events and trends are likely to also drive the evolution of the system. The emergence of new vehicle classes, such as Very Light Jets (VLJs) are likely to result in large scale on-demand networks. Additional aircraft types, such as Unmanned Aerial Vehicles will also be operated in different ways and further strain the capacity of the system. Current plans on future system architecture forecast highest-case traffic growth three times 2004 levels by 2025<sup>1</sup>. Such a large increase presents several challenges in how to create a future architecture capable of meeting demand. These trends serve as a strong motivation to analyze air transportation system's architecture from a variety of perspectives.

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<sup>1</sup> Joint Planning and Development Office. "Next Generation Air Transportation System Integrated Plan." December 12, 2004. [http://www.jpdo.aero/site\\_content/NGATS\\_v1\\_1204.pdf](http://www.jpdo.aero/site_content/NGATS_v1_1204.pdf). Retrieved 5/02/2006.

### 3. Network analysis and system architecture

#### 3.1 Literature review

A literature review on “network analysis” related to the air transportation system was conducted. The following list presents the most relevant papers:

- [GMT\_05] Guimera R., Mossa S., Turschi A., Nunes Amaral L., 2004, The worldwide air transportation network: Anomalous centrality, community structure and cities’ global roles , Proceedings to the National Academy of Sciences, PNAS vol. 102 no. 22 7794-7799, 2005.
- [BBP\_04] Barrat A., Barthelemy M., Pastor-Satorras R., Vespignani A., 2004, The architecture of complex weighted networks, Proceedings to the National Academy of Sciences, PNAS vol. 101 no. 11 3747-3752.
- [ASB\_04] Amaral L. A. N., Scala A., Barthelemy M., Stanley H. E., Classes of small-world networks, Proceedings to the National Academy of Sciences, PNAS.
- [KIN\_03] Kincaid R., 2003, Scale free graphs for general aviation flight schedules, NASA/CR-2003-212648.
- [ALE\_04] Alexandrov N., Transportation Network Topologies, NASA Langley, NASA/TM-2004-213259, 2004.

Guimera et al. [GMT\_05] performed an analysis of the global scheduled air transportation network using OAG data. It was found that the degree distribution of the global scheduled air transportation network followed a power law. In addition, the analysis of between-ness centrality and the comparison to node connectivity showed that there are discrepancies between both metrics for some airports. For example, airports such as Anchorage AK, were found to be central to the network but not as connected as other airports –major hubs-. This work focused on the analysis of the topology of the network regardless of the frequency, available seats, passengers flows on the arcs of the network. An arc was considered as an arc in the network whether it was flown by once per week of 50 times per day. The analysis of weighted network was not performed by Barrat et al. [BBP\_04] who chose available seats as the weighting factor on the arcs. Amaral et al.

[ASB\_04] paper presents the air transportation system as an instance of the class of small-world networks. The work presented in this paper is very similar to the work of Guimera et al. These papers focused only on the scheduled commercial segment of the transportation system. However, flights performed by operators from other segments of the industry (e.g. general aviation, business aviation, etc.) are also elements of other networks (refer to section on network description in the air transportation system). Kincaid [KIN\_03] touches briefly on the general aviation network but without performing a deep network analysis. “Transportation Network Topologies” from Alexandrov [ALE\_04] constitute a summary of a meeting at NASA Langley in 2003 on research in network topologies. The notion of scale free network is touched on through the presentation of work done under the NASA Small Aircraft Transportation System (SATS) program. However, this work is presented at a conceptual level without deep analysis of network topology and evolution.

### 3.2 *Infrastructure Layer*

#### 3.2.1 *Single Layer Analysis Methodology*

Data on navigational networks were obtained from the FAA Digital Aeronautical Chart Supplement (DACS), which is a digital representation of FAA-defined waypoints and airways for both low altitude (victor airways) and high altitude (jet route) navigation<sup>2</sup>. Initial network representations of the jet route and victor airway networks were constructed based on data included in the file. For the network representation, a *node* was defined as an FAA-named waypoint where different airways connect, begin, or end. An *edge* was defined corresponding to a unique path defined between and identified by the FAA. This distinction is shown in Figure 3, with the Oakland VOR as an example node, with Jet Route 84 (J84) connected to it.

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<sup>2</sup> Federal Aviation Administration, National Aviation Charting Office. Digital Aeronautical Chart Supplement. CD-ROM. February 16, 2006.

(Image removed for copyright reasons.)

Several simplifying assumptions were made to arrive at a useful network representation. The first assumption involved removal of several nodes that did not convey additional information. There are several types of navigational aids (navaids) defined by the FAA, but each fall into one of two categories. The first category is a VOR or VORTAC (the TAC denotes the addition of military navigation capability), which is a ground-based station that transmits a radio signal indicating the magnetic direction to station. Airways, like highways in the sky, are defined based on their bearings from a VOR, therefore an airway segment can only change direction at a VOR. These were not removed from the network representation.

The second category of points includes reporting, intersection points, or turning points. These identifiers are generally used as a location along a route to reference, much like a mile marker on a highway, but do not necessarily correspond to a physical structure on the ground. They are also placed on air routes when changing between air traffic control sectors but not actually changing the route number. A large number of these points have degree two and are on the same airway. In that case, the points were removed. Otherwise, the degree distribution is heavily skewed by degree 2 nodes. When a node had a degree greater than two, it indicates a reporting point that is also an intersection or merge point along airways. These nodes were preserved.

Simplifying assumptions were also made in defining network edges. First, the FAA defines a limited number of air routes as one way, but this information is not captured in the digital file. All routes were assumed to be bidirectional. Second, as with some highways or roads, one actual path may share several identifiers. In this case, duplicate route naming was ignored, and each edge is a unique path between nodes. Third and finally, traffic is also distributed by altitude, but unique paths by altitude were ignored.

### 3.2.2 Network Analysis Results

The degree sequences for jet routes and victor airways are shown in Figure 4, and selected network metrics are shown in Table 1. The degree sequences are similar between the two networks, especially in the constraints of low and high connectivity, while the exact distribution in the middle varies. Including all points, there is a very high number of degree four points, which are generally located at the intersection of two air routes. Removing those points and focusing only on the physical infrastructure of VORs, one can observe a maximum connectivity of approximately 15 links, and large proportion of nodes with intermediate levels of connectivity, skewed toward lower connectivity for jet routes.

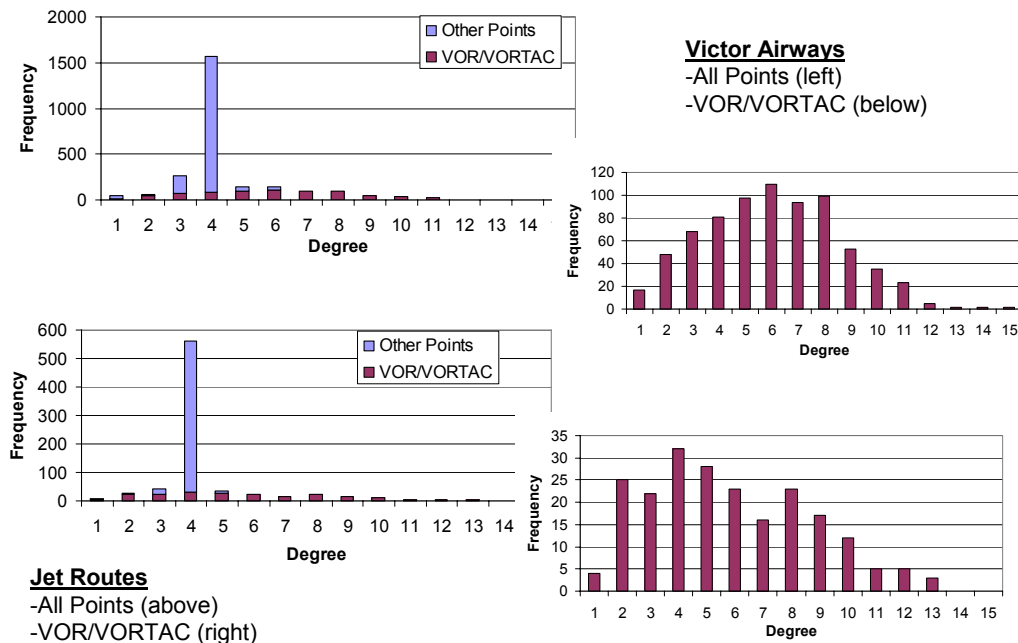


Figure 4: Degree Sequences of Jet Routes and Victor Airways

The jet route degree sequence is skewed toward a greater proportion of nodes at lower degree. This trend is due to having less nodes and fewer jet routes than victor airways. The metrics computed for each navigational network, shown in Table 1, reinforce this reasoning. The victor airway network shows much higher clustering than jet routes, and a more negative degree correlation coefficient and slightly higher mean degree. The negative correlation coefficients are also consistent with a network where large nodes are connected to smaller nodes, thus moving traffic through nav aids with more connections to “end-points” in the structure.

**Table 1: Selected Metrics for Airway Networks**

<b>Navaid Network</b>	<b>n</b>	<b>m</b>	<b>z</b>	<b>C (Watts)</b>	<b>r</b>
Jet Routes	1787	4444	2.49	0.1928	-0.0166
Victor Airways	2669	7635	2.86	0.2761	-0.0728

### 3.3 *Transport layer*

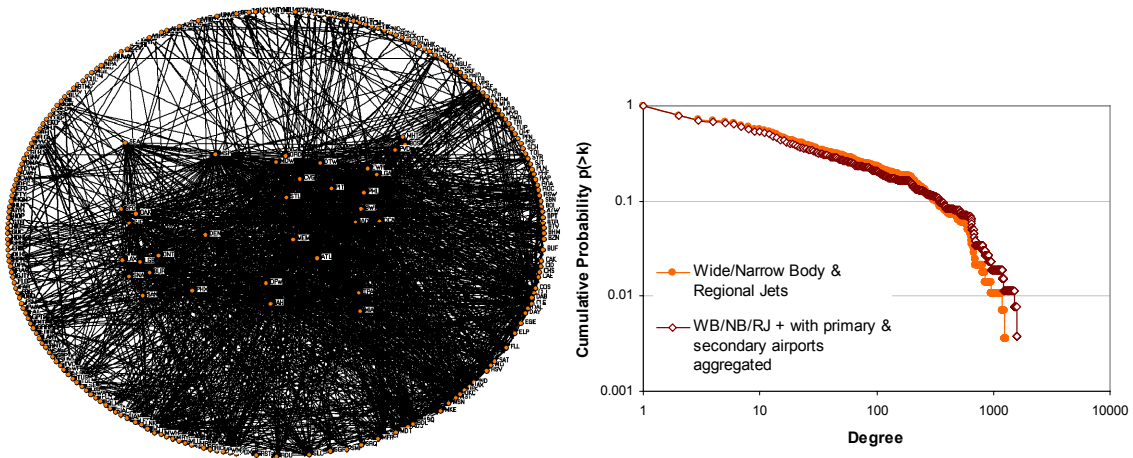
#### 3.3.1 Methodology

In order to construct the networks of scheduled and unscheduled traffic, data of actual flights from aircraft situational display to industry (ASDI) feed compiled from the Federal Aviation Administration’s (FAA) Enhanced Traffic Management System (ETMS) was used. For each flight, this database provided the aircraft type, the airports of departure and arrival, aircraft position (latitude, longitude and altitude) and speed information, in addition to several other flight plan related piece of information that were not of primary interest for this study (user class, engine type, etc.). For the analysis that is presented in the following sections, flights from 31 days of traffic were extracted and used to construct the network matrices. In addition to the detailed ETMS flight database, an aircraft library of 1115 aircraft types, including 133 types of wide body, narrow body, and regional jets in addition to 8 types of light jet aircraft, identified as existing light jets on the basis of maximum take-off weight, were used. A library of 24,912 landing facilities worldwide was also used for the identification of the origin and destination airports reported in the ETMS flight data which also provided latitudes and longitudes for each landing facility. Other

information such as runway characteristics (i.e. length, pavement type) and available instrument approaches at the airports was based on the FAA Form 5010 airport database. The flights extracted from ETMS data were compiled in origin/destination airports matrix (adjacency matrix) therefore providing information on the structure of the network but also on the frequency on the edges.

### 3.3.2 Results, interpretation and discussion

#### Scheduled transportation network



**Figure 5. Wide body/Narrow body/Regional jet network and degree distribution**

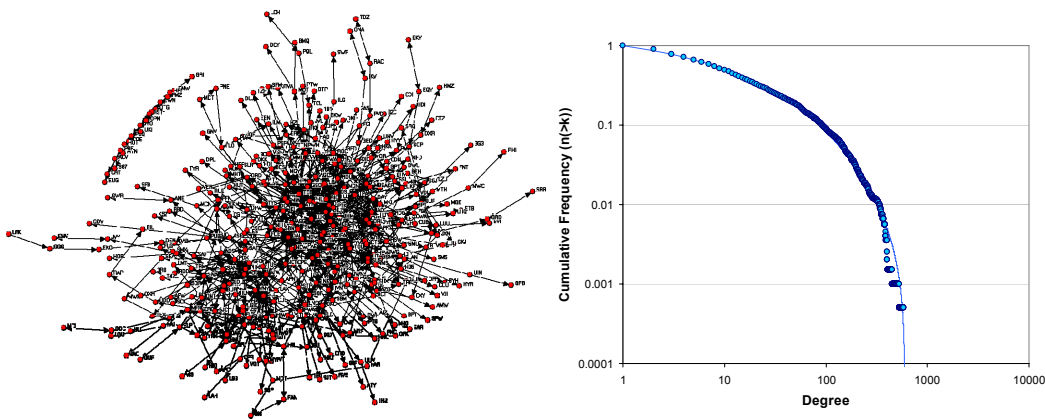
Figure 5 illustrates the topology of the scheduled U.S. air transport network. For visualization purposes, the representation is a modified circle network representation in which the most highly connected nodes were located to their approximate geographical location in the center of the circle. On the right hand side, the weighted degree distribution of this network was computed and it was found that the distribution followed a power law (with  $g = 1.49$ ). However, this power law fit is only valid for a subset of the degree sequence beyond which an exponential cut-off was identified. This exponential cut-off was hypothesized to be the result of nodal capacity constraints, connectivity limitations between core and secondary airports, spatial constraints. The first assumption was found to be the factor explaining this cut-off. Other network characteristics are presented in the following table.

**Table 2: Network descriptive metrics of the scheduled air transport network**

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

This network was found to have a negative correlation coefficient value. The explanation for this observation is related to hub and spoke structure of the scheduled air transportation system, where airlines consolidated demand by connecting small airports (nodes) to large connecting -in terms of passenger flow- airports also called hubs. This network structure is directly related to economic efficiencies enabling airlines to serve a large number of Origin Destination (OD) markets with a limited number of flights (compared to the number of flights required to serve those same markets non-stop).

Unscheduled transportation network



**Figure 6. Light Jet network and degree distribution**

Figure 6 illustrates the topology of the proxy of the unscheduled U.S. air transport network. The representation is a using spring/mass node location from UCINET, and presents the highly connected nodes (e.g. TEB, DAL, CMH, IAD, etc.) in the center of the graph and the loosely connected nodes at the periphery of the network. The degree



distribution of the network of routes flown by light jets was computed and is plotted above. It was found that unlike the scheduled transportation layer of the air transportation system that do exhibit a power law distribution, the network of routes flown by existing light jets does not follow a power law. The degree distribution was best fitted by the following function which combines a power law and an exponential.

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

with  $\gamma = 0.57$ ,  $\mu = 0.16$  and  $a = 0.13$ , where  $\gamma$  and  $\mu$  are respectively the preferential attachment correction exponent and the amplitude. The analysis has also been done on weighted networks (weighted by flight frequencies on the arcs). The degree distribution was then fitted to the following function:

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

with  $\gamma^* = 0.72$ ,  $\mu^* = 0.60$  and  $a^* = 0.011$

This particular network structure (described by the equations above) was identified as the result of network that grow with sub-linear preferential attachment mechanisms. Power law degree sequences are generated by preferential attachment linking (where the probability of connection is proportional to the degree of a node normalized by the sum of all degrees). In the case of sub linear preferential attachment, the probability of connection is modified by an exponent between 0 and 1. This observation has implications in terms of the future growth of the network where highly connected nodes will not grow as fast as they would under a preferential attachment mechanisms.

Other network characteristics are presented in the following table.

**Table 3: Network descriptive metrics of the unscheduled air transport network**

Network	n	m	Density	Clustering coefficient	r
Light Jet Network ( <i>Unscheduled</i> )	900	5384	0.005	0.12	0.0045

Unlike the scheduled transportation network, the value of the correlation coefficient for this network was found to be close to 0. This difference with the scheduled transportation

network was explained by the fact that the economics are totally different. Unscheduled operators do not generally aggregate traffic and connect passengers from one flight leg to another. The flights are mostly point to point flights connecting a wide variety of airports.

### 3.4 Cross-Layer Analysis through Airports

The “sub layers” of the transport layer are not independent of each other since they interact through other layers of the system such as the infrastructure layer. In fact, most airports host a mix of scheduled commercial traffic, unscheduled commercial and non commercial traffic. Understanding the interactions between each transport layer is crucial especially when we anticipate growth in traffic on both layers (continuous growth of scheduled traffic and stimulation of unscheduled traffic with the emergence of new classes of aircraft). In order to assess the level of interaction between the layers that were studied separately in the previous sections of this report, traffic for scheduled and unscheduled transportation was computed for each airport and is plotted on the following figure.

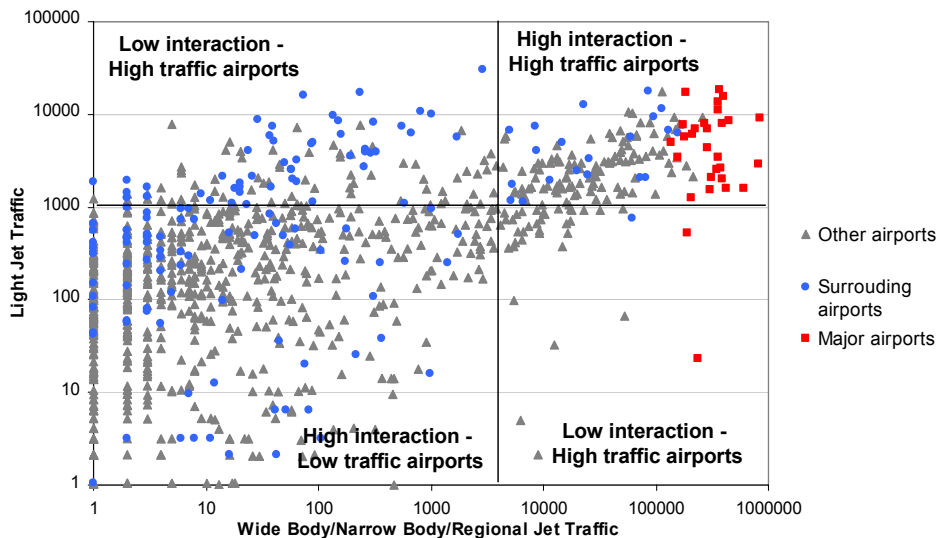


Figure 7. Nodal (airport) interactions between scheduled and unscheduled traffic

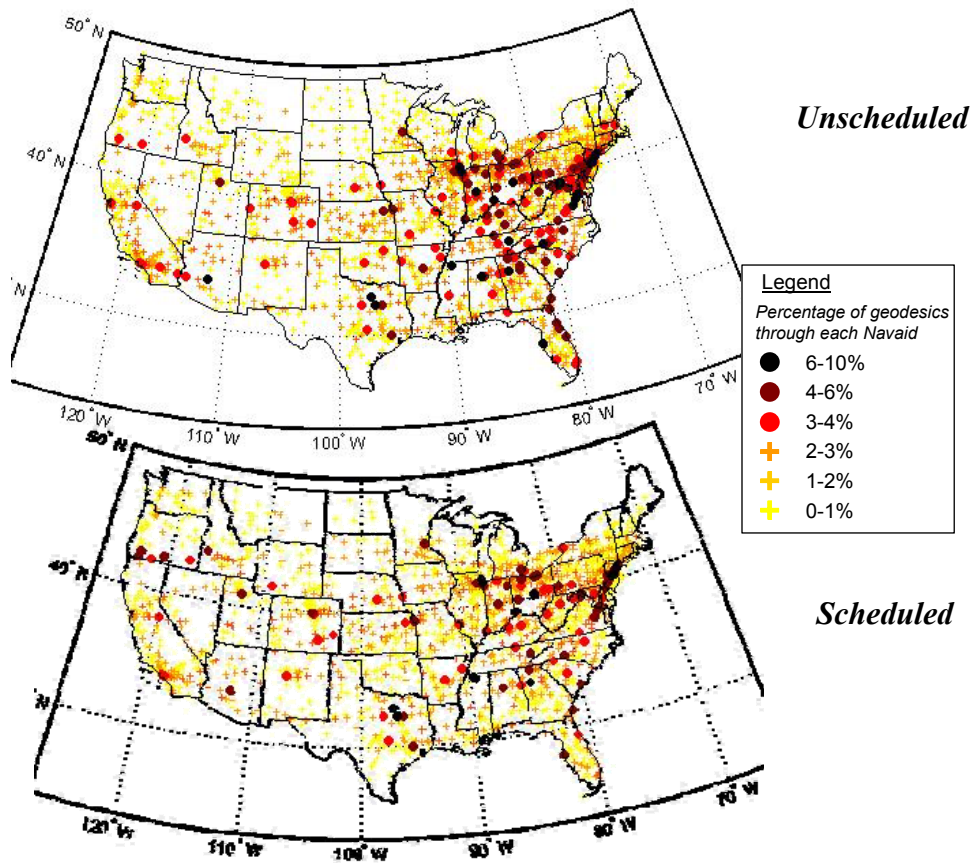
As shown on Figure 7, the set of airport can be divided into four categories; the high interaction-high traffic airports, low interaction airports with high traffic (whether it is scheduled or unscheduled) and high interaction airports with low traffic. It was found that

most major airports (in terms of scheduled traffic) in the U.S. are also airports that handle large volumes of light jet traffic. This finding has implications in terms of the ability of those airports to accommodate the growth on both layers.

### *3.5 Cross-Layer Analysis through Navigational Infrastructure*

Navigation along the victor airway network was examined as a proxy for determining possible locations of airspace congestion, and for comparing the utilization of navigational infrastructure differences between scheduled and unscheduled networks. The key measure for utilization of nav aids used was the betweenness centrality of each nav aid, defined as the proportion of shortest paths through each nav aid divided by the total number of paths in the network. For both the scheduled and unscheduled airport pairings, a shortest-path search was performed from the nearest nav aid at each starting and ending airport. The path used to compute centrality was not weighted by the frequency of flights on the link. Therefore the analysis is an approximation of airspace utilization and from uniform origin-destination distribution of flights.

Flights do not always follow the shortest navigational path, but the shortest does require the least fuel to navigate and is therefore ideal. Aircraft may fly different between airports due to weather or prevailing winds. Routes may also differ on arrival to the airport depending upon the runway configuration used, and navigational paths used for approach, which were not included in the analysis. Aircraft also utilize different altitudes during the flight, which alleviates congestion in any single airspace location. Several of these varying factors make the betweenness centrality results informative, but not strongly conclusive.



**Figure 8: Betweenness Centrality of Nav aids**

The betweenness centrality results for each network are shown in Figure 8. The pattern of navigational utilization is very similar between each network, with a high concentration of top-percentage nodes located in the Northeast, and eastern part of the U.S. There are some central navigational points in common also in the center of the U.S. and on each coast. The Nodes shown by crosses tend to be located near peripheral routes and away from major population centers, representing the end points of flights further away from central infrastructure. The unscheduled network tends to utilize more navigational aides than unscheduled traffic, which is expected due to the broader geographical distribution of unscheduled flights.

**The summary of number of airport nodes, shortest paths, and maximum connectivity and betweenness for each traffic layer is shown in**

Table 4.

**Table 4: Summary of Shortest Path Characteristics**

Network	Number of Nodes	Number of Paths	Maximum Degree	Maximum Betweenness
Unscheduled	900	3389	106	10.8%
Scheduled	239	5348	121	10.3%

### 3.6 Demand layer

In order to understand the origin of the limitations of the scale free characteristic of the scheduled and unscheduled transportation network, a study of the population distribution around airports in the U.S., was performed. Airports are the interface between the distribution of the underlying drivers (e.g. population, business locations) and the network of OD routes flown various types of aircraft (e.g. wide body, narrow body, regional jets, business jets). Using US Census tract data and based on a simple gravity model, population was distributed to public airports that featured at least on runway longer than 3000 ft and can therefore accommodate light jet and very light jet traffic.

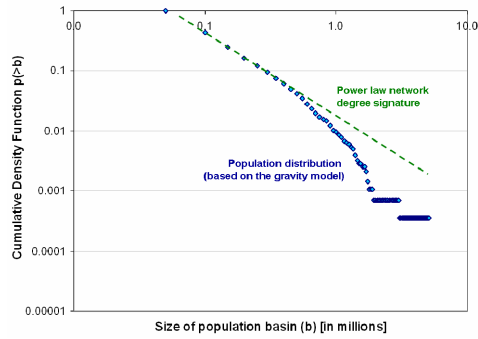
$$b_i = \sum_{ct \in C_i} p_{ct} \quad s.t. \quad C_i = \left\{ ct \mid d_{ct,i} = \min_j d_{ct,j} \right\}$$

Once the population of 65,433 census tracts was distributed to individual airports, an histogram was built with regard to the size of the population basin. Large number of airport are surrounded by very small population basins (e.g. Pembina municipal airport North Dakota, Thomas county airport –Thedford- Nebraska, Boyne mountain airport - Boyne Falls- Michigan) whereas a small number of airports have large population basins (e.g. New York La Guardia, J.F. Kennedy, Newark and Teterboro, Chicago Midway, Washington National, etc.)

#### 3.6.1 Results

It was found that the distribution of population basin sizes by airports initially followed a power law with  $g = -2.15$ . Beyond population basin sizes close to 700,000 the power law fit is no more valid. As slow exponential cut-off is observed. This observation leads to the conclusion that even if the provision of service to every airport according to its

population basin was feasible, we would still not find a perfect power law fit to the degree distribution.



**Figure 9. Airport rank vs. population basin size around the airport**

## 4. Conclusion

### 4.1 *Summary of findings*

The analysis of the networks that compose the transport layer clearly showed that the scheduled transportation network and the unscheduled transportation network had very different topologies. This was identified through the degree (both un-weighted and weighted) distributions, the node correlation coefficients, clustering coefficients. The main differences were explained through the economics, market dynamics and demand characteristics governing those segments of the air transportation industry. It was also found that the system was not scale free (i.e. power law function do not characterize the entire degree sequence). The system has a scale that is defined by the capacity of elements in the system, mostly nodes (airports), airspace and the economics driving the system. These key points in the system that limit the scale of the system are also the locations where sub layers are interacting. The infrastructure analysis also showed the presence of interactions at the airspace level (mix of traffic though the same nav aids). These findings have several implications in terms of the ability of the system to accommodate future growth.

### 4.2 *Implications of results from the network analysis to system architecture and potential architectural improvements*

The strong constraints of the system influenced the current structure of the system but it is believed that these constraints will have a significant impact on the evolution of the system. As passenger traffic and volume of operation is expected to increase significantly in the future the networks will have to evolve in order to meet this demand. There is therefore the need to think about other paradigms in terms of network structure and system architecture. Several changes would be required:

- Increasing the size of aircraft at capacity constrained airports. One of the most constraining element in the system are major airports.
- Increased use of available airports at the regional level (e.g. multi-airport systems).

- Use of smaller aircraft to serve OD markets with thin demand (e.g. air taxi). These models could stimulate demand at small airports that currently have not air service.
- Implementation of communication, navigation, surveillance technology in order to increase the en-route and terminal area capacity.

These changes and long term trends will clearly influence the structure of the air transportation network. It is therefore expected that similar analyzes as the one presented here will be required in the future to characterize the future structure of the networks –and compare it the current structure in order to evaluate the impacts of these changes.



## 5. Feedback on learning objectives

Network architecture is extremely important in the air transportation system, and previous research and tools provided a rich set of data to analyze. Both by the large amount of data and interesting areas of investigation, it proved to be an excellent system to investigate for the course project.

### 5.1 *Lessons learned*

Compared to existing literature in air transportation networks, several new insights were provided in the current network analysis. Therefore, there were several lessons learned beyond the existing knowledge base in the domain. Foremost, previous work performed, as documented in the literature review, lacked domain expertise to inform the results. Due to the highly regulated and complex nature of the air transportation system, domain expertise is essential to create realistic network models, and to interpret the relationship of analysis results with respect to the performance of the system. It is also essential to utilize domain expertise in describing processes resulting in the observed network structure.

Previous work focused almost exclusively on scheduled air transportation, and did not investigate unscheduled operations, or demand and infrastructure characteristics. The multiple perspectives afforded by looking at a different type of operation are more informative in describing the state of the system as a whole. The authors learned a great deal about the characteristics of population demand and utilization of airport and navigational infrastructure by potential future combinations of scheduled and unscheduled operations.

### 5.2 *Valuable aspects of system architecture*

The analysis performed in this report investigated the existing nature of the network to determine potential future evolutionary trends. By that scope, the authors utilized several descriptive analysis techniques, investigating nodal degree patterns, and

connectivity metrics to describe general network structure. The lectures in class on implementing these analysis metrics both for toy systems and through relevant literature were very useful in applying to this project. Insight gained from the course on modeling networks through different attachment dynamics, rewiring, etc. was not as valuable to our investigation, but may play a role in future extension of the work.

Most of the current analysis tools were also not well suited for the large dataset of traffic and infrastructure. UCINET offers a lot of functionality for network analysis, but could only be used for a few limited operations with our dataset. For example, UCINET was used to compute metrics for and visualize the infrastructure layer, with approximately 2700 nodes. However, custom programming had to be performed for path search and data extraction that took a significant effort. Similarly, due to the large datasets of traffic routing and census, most of the data analysis tools were self-written.

Several points have been made in the conclusion section regarding the applicability of power laws and scale constraints to the air transportation system. That discussion is informative on the fact that some metrics are more useful than others, and most have to be put in context of the domain of the system.