Scalability and Evolutionary Dynamics of Air Transportation Networks in the United States

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With the growing demand for air transportation and the limited ability to increase capacity at key points in the air transportation system, there are concerns that, in the future, the system will not scale to meet demand. This situation will result in the generation and the propagation of delays throughout the system, impacting passengers' quality of travel and more broadly the economy. There is therefore the need to investigate the mechanisms by which the air transportation system scaled to meet demand in the past and will do so in the future. In order to investigate limits to scale of current air transportation networks, theories of scale free and scalable networks were used. It was found that the U.S. air transportation network is not scalable at the airport level due to capacity constraints. However, the results of a case study analysis of multi-airport systems that led to the aggregation of these multiple airports into single nodes and the analysis of this network showed that the air transportation network was scalable at the regional level. In order to understand how the network evolves, an analysis of the scaling dynamics that influence the structure of the network was conducted. Initially the air transportation network scales according to airport level mechanisms –through the addition of capacity and the improvement of efficiency- but as infrastructure constraints are reached; higher level scaling mechanisms such as the emergence of secondary airports and the construction of new high capacity airports are triggered. These findings suggest that, given current and future limitations on the ability to add capacity at certain airports, regional level scaling mechanisms will be key to accommodating future needs for air transportation.

I.   Introduction

WITH the growing demand for air transportation and the limited ability to increase capacity at key points in the air transportation system there are concerns that, in the future, the system will not scale to meet demand. Historically, air traffic has grown significantly. As shown in Figure 1, revenue passenger kilometers have increased by a factor of 3.3 from 393 billion in 1978 to 1.304 billion in 2005 [1]. Assuming a similar rate of growth to the rate of growth that prevailed between 1985 and 2005, passenger traffic would approach 1.9 billion RPKs by 2025. Several forecasts also indicate significant growth of traffic in the next decades [2][3][4][5]. However, infrastructure capacity constraints at airports create congestion that result in aircraft and passenger delays that propagate throughout the system. Figure 2 shows the evolution of delays in the United States from 1990 to 2007. In the 1990s, passenger and aircraft traffic increased and reach a peak in 2000.
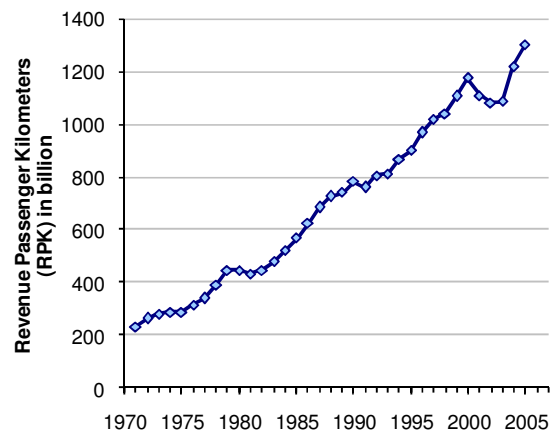

Figure 1: Evolution of passenger traffic (RPKs) in the U.S. Air Transportation System.

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1

Concurrently, delays increased to a reach a peak in 2000. While there was a generalized stress over the system due to traffic loads, a localized capacity crisis at La Guardia airport created record high delays. As a result of the slowdown of the economy and Sept. 11 events, passenger and aircraft traffic decreased in 2001 which relieved pressure on the system thus decreasing delays. Starting in 2003 with a localized capacity crisis at Chicago O'Hare airport and with later a general increase in number of operations, delays increased again to reach a record high of 22.1 million minutes of delays in 2006. Projections of delays for 2007 indicate that a new record is likely to be set. The generation of delays and their propagation throughout the system negatively impact air transportation quality of service, passenger's quality of travel and more broadly the economy.
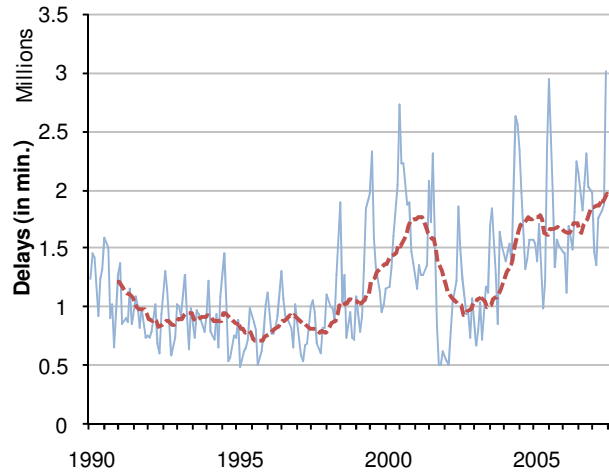
Given the growing demand for air transportation in the future and inherent key capacity constraints, there are concerns that, in the future, the system will not scale to meet demand. This motivates the need to investigate the mechanisms by which the air transportation system scaled to meet demand in the past and will do so in the future.

Figure 2: Evolution of delays in the U.S. Air Transportation System.

II. Methodology & Data Used for the Network Analysis

Because the air transportation system is fundamentally a network system (composed of thousands of interconnected subsystems and parts) it can be described and represented using network abstractions and tools from network theory. In addition, recent theories of scale free and scalable networks were used as a starting point for the analysis [6][7][8][9][10][11].

The network of interest for this research is the flight/aircraft flow network for which the nodes are airports and the arcs are non-stop origin-destination routes. In order to analyze the structure of the current U.S. air transport network, a cross sectional analysis was performed using actual aircraft traffic data from the Federal Aviation Administration's (FAA) Enhanced Traffic Management System (ETMS) [12]. For each flight, this database provided the aircraft type, the airports of departure and arrival, the aircraft position (latitude, longitude and altitude) and speed information.

For the extraction of the network structural information, data of 365 days of traffic was analyzed (from October 1st 2004 to September 30th 2005). In addition to the detailed ETMS flight database, a library of civil airplanes corresponding to 869 ETMS aircraft codes was used. The ETMS airport database was crossed with the FAA Form 5010 airport database [13] that provided additional airport information such as runway characteristics (i.e. length, pavement type). In the following analysis 12,007 public and private airports -of any runway length- where used for the extraction of flights from the ETMS flight database. An extensive data quality assurance process was used to filter data with missing information fields such as aircraft type and clearly flawed trajectory data. In addition, international flights and military and helicopter operations were filtered out. The retained data accounted for 70% of the total number of flights from the original data. The data was also filtered into categories of aircraft (in order to understand the differences in terms of network structure between various modes of operations). These categories included; wide body jets (e.g. Boeing 767, Airbus 300), narrow body jets (e.g. Boeing 737s, Airbus 318/319/320/321), regional jets (e.g. Bombardier CRJ200, Embraer E145), business jets (e.g. Cessna CJ1, Hawker 400), turboprops (e.g. Q400, ATR42) and piston aircraft (e.g. Cessna 172, Pipers). From this detailed flight data, network adjacency matrices were constructed for each of the aircraft types.

Figure 3 shows the graphical representation of the networks that were extracted from the ETMS traffic data and plotted according to the frequency of flights on each route (ranging from 1 to 1000 flights per year). As it can be observed in Figure 3, layers are not homogenous in terms of both frequency and structure. The wide body jet network is primarily composed of sparse long haul cross country flights with fairly high frequency. The narrow body jet network is denser with relatively shorter range (mid range) flights with some routes with very high frequency (i.e. over 900 flights per months or 30 flights per day). The network of flights flown by regional jets is

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sparse with high frequency routes mainly centered to and from hubs such as Chicago O'Hare (ORD), Atlanta (ATL), Denver (DEN), etc. which is consistent with the dominant use of the regional jets as feeders to hub operations.
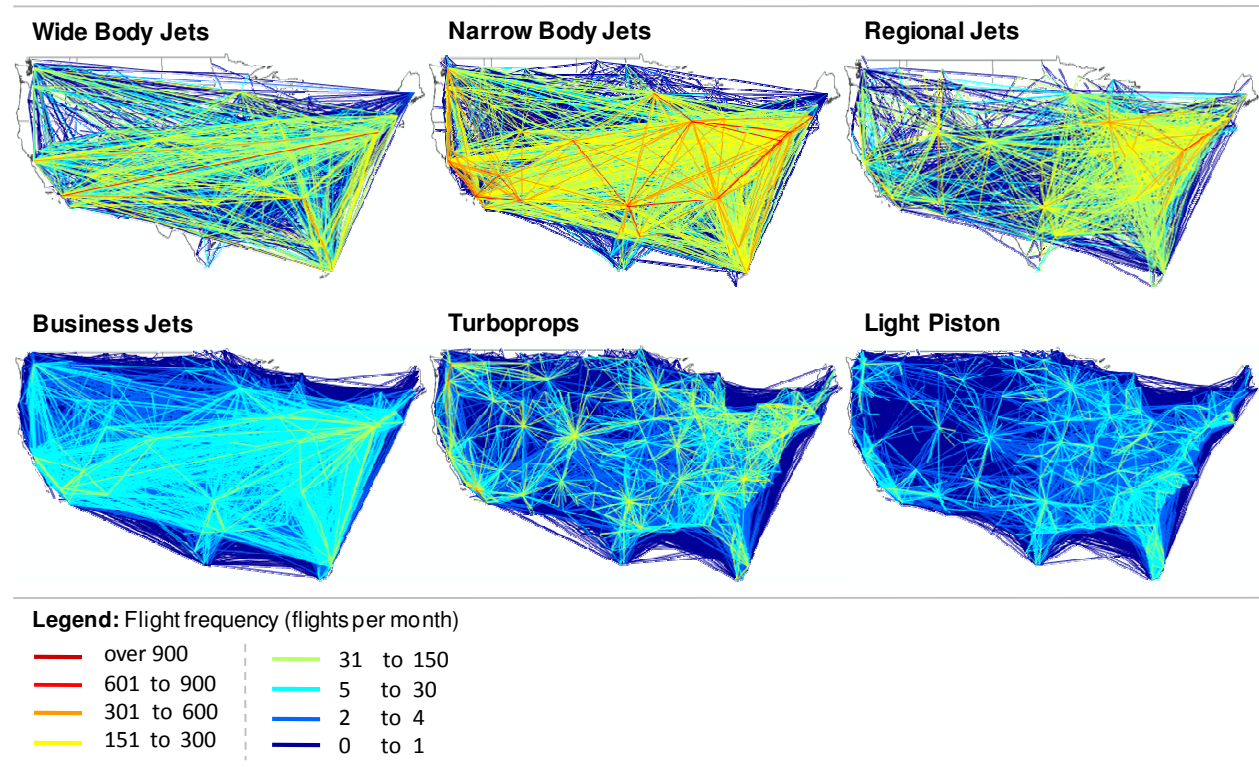

Legend: Flight frequency (flights per month)

—	over 900	—	31 to 150
—	601 to 900	—	5 to 30
—	301 to 600	—	2 to 4
—	151 to 300	—	0 to 1

Figure 3: Air transportation networks (decomposed into layers by aircraft type).

While the wide body, narrow body and regional jet networks are relatively sparse, the network of flights flown by business jets, turboprops and light piston aircraft are denser. The business jet network is dense with low frequency routes. However, there are a few popular (i.e. medium frequency) routes between key metropolitan regions such as New York, Chicago, Dallas, Atlanta, Miami, Denver, Los Angeles, etc. The turboprop network exhibits both a dense set of low frequency routes and a localized set of routes that are centered on key airports. This latter part of the network is formed by feeder flights in and out of connecting hub airports. Finally, the piston aircraft network which is the network that spans across the largest number of airports is composed mainly of low frequency routes. This is consistent with the type of use and unscheduled operations performed by light piston aircraft.

III. Analysis of the U.S. Air Transportation Network at the Airport Level

As shown in Figure 3 the U.S. air transportation network is a woven set of networks or layers (networks composed of airports -nodes- and origin destination routes - arcs-). These layers can be recombined to form the overall U.S. air transportation network as presented in Figure 4.

This overall network is composed of a large set of low frequency routes and a more limited set of very high frequency routes. From Figure 4, it can be observed that despite the large number of nodes present in this network aircraft
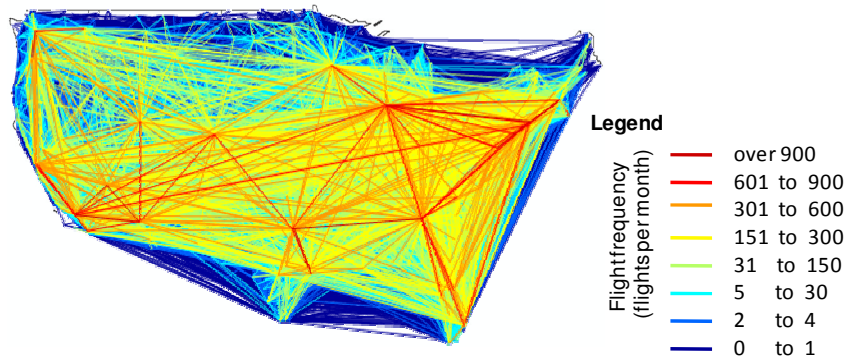

Figure 4: Air transportation network with airport nodes.

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traffic is concentrated at a few key airports. In fact, 30 airports handle almost 80 % of the overall traffic.

One of the key metrics that characterizes the structure of a network is the degree distribution. The degree of a node is the number of incoming and outgoing arcs to and from this node (i.e. number of routes connecting one airport to other airports in the network). The degree distribution of the U.S. air transportation network (with airport nodes) presented in Figure 4 was computed and plotted (Figure 6). As shown in Figure 6, a large number of nodes (i.e. airports) exhibit low number of destinations (i.e. node degree) while there are very few airports that have large number of destinations.

While the degree of a node captures information regarding the number of destinations to and from an airport, it does not capture any information regarding the frequency of flights on the arcs and ultimately the number of flights at each airport. The degree of a node can be weighted by the number of flights on incoming and outgoing arcs which is referred to as a flight weighted degree. The flight weighted degree distribution of this network was computed and is presented in Figure 5.

It was found that there were large number of nodes that have very low flight weighted degree (i.e. flights per year) as shown on the left side of the distribution (Figure 5) and very few nodes that have large number of flights.

From network theory, scale free and scalable networks are characterized by a negative power law distribution. A power law distribution should be represented as a linear relationship (strait line) on a log-log plot. Figure 7 shows the transformation of the plot in Figure 5 into a log-log plot. As shown in Figure 7, it was found that the flight weighted degree distribution did not follow a power law distribution across the full range of weighted degree (annual airport operations) which would have been indicative of a scale free and scalable network. A power law distribution was identified for flight weighted degree lower than 250,000 flights per year at which point nodes do not fit the power law[‡].

The identification of a non power part in the distribution (ranging from 250,000 and 970,000) flights suggests that there are limits to scale in this network and that capacitated nodes (capacity
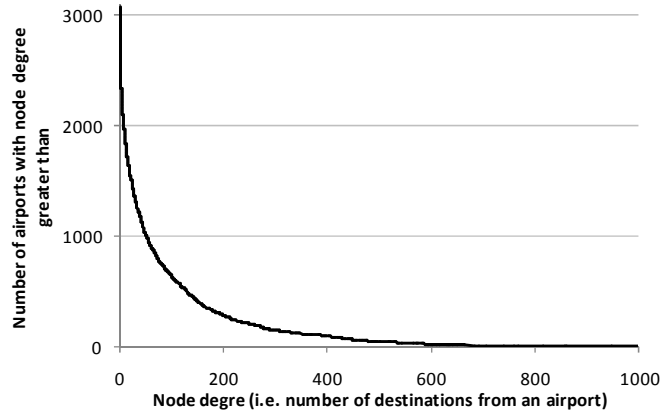

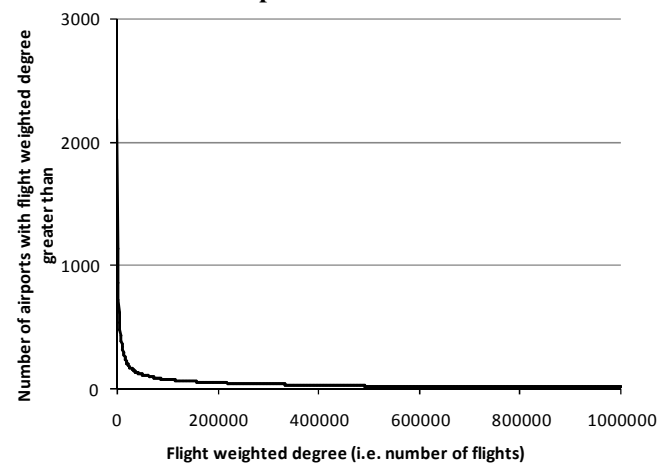**Figure** 6: **Degree distribution of the U.S. air transportation network.**

Figure 5: Flight weighted degree distribution of the U.S. air transportation network.
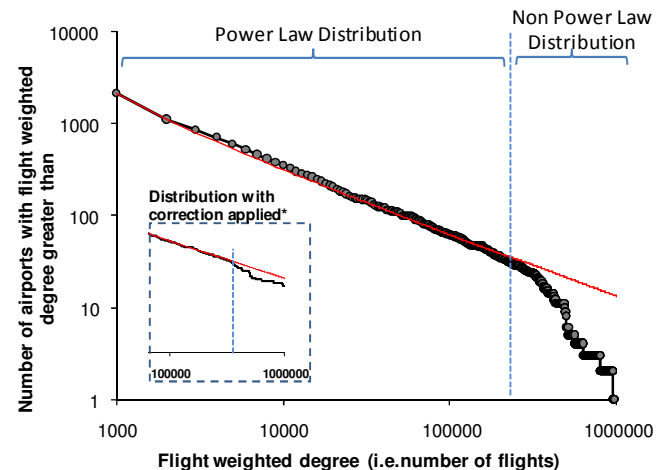

Figure 7: Flight weighted degree distribution of the network (log-log plot).

[‡] Due to the fact that the distribution of degrees has a finite upper limit (i.e. 970,000 flights) and way the power law is constructed, the deviation from the power law fit (i.e. strait line) is slightly greater than it would be for a distribution of non-finite flight weighted range. In order to verify the validity of the observation of a non-power law part in the distribution, a test was developed. This iterative test applies a correction equal to the integral of the power law function from the finite upper limit of flight weighted degree to infinity. The correction function is displayed in the insert of Figure 7 and shows that this part of the distribution is indeed not a power law.

4

constrained airports) are present in this part of the distribution.

There are 29 airports nodes in the non power law part of the distribution (Figure 8). It is clear that some of these nodes are constrained by capacity. In fact, all 4 airports that are slot restricted in the United States (i.e. Chicago O'Hare ORD, New York La Guardia LGA, John F. Kennedy JFK and Washington National DCA) are present in the non power law part of the distribution. In addition, many airports among the 29 airports (i.e. Newark EWR, Philadelphia PHL, Boston Logan BOS and San Francisco SFO) exhibit high levels of delays that are indicative of congestion and capacity constraints.

Airport code	Flight weighted degree (i.e. annual number of operations)	Airport code	Flight weighted degree (i.e. annual number of operations)
ORD	964360	BOS	381064
ATL	949708	MIA	366561
DFW	795974	IAD	361754
LAX	629735	SEA	354658
DEN	556178	MEM	343970
CVG	512830	SLC	339080
MSP	498523	SFO	331498
DTW	498053	PIT	324287
IAH	494410	JFK	311827
LAS	490290	MCO	292520
PHX	484252	MDW	280940
PHL	430218	STL	274770
EWR	420197	BWI	266166
CLT	417485	DCA	264784
LGA	386589		

Figure 8: Set of 29 airports present in the non power law part of the distribution in Figure 7.

IV. Analysis of the U.S. Air Transportation Network at the Regional Level

Because of the trend of emergence of secondary airports in the vicinity of primary airports, leading to the development multi-airport systems, additional insight can be gained by examining the system at the regional level [14]. The 29 airports identified in the non power law part of the distribution formed the basis for a case study analysis of regional airport systems. A regional airport system was defined as all airports within 50 miles of one of the identified airports (Figure 9).

For the purpose of this analysis, a primary airport was defined as an airport serving between 20% and 100% of the passenger traffic in the region and secondary airports were defined as serving between 1% and 20% of the traffic. Other airports serving less than 1% of the traffic in the region were not considered for further detailed analysis.
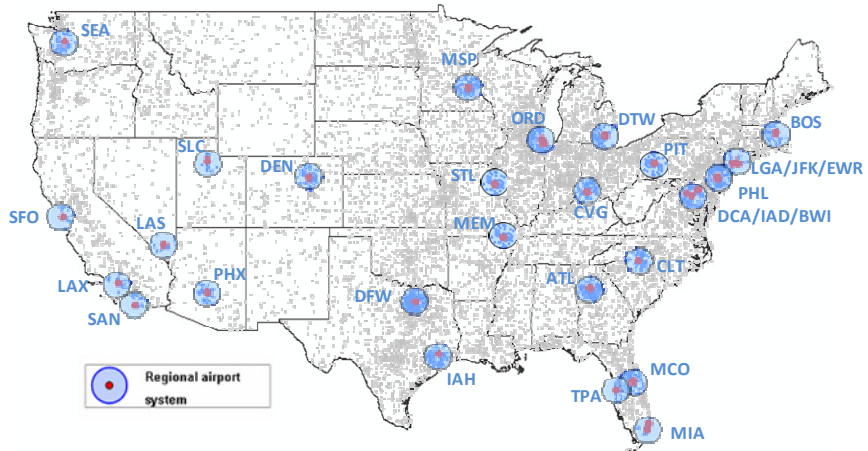

Figure 9: Regional airport systems in the United States.

Figure 10 provides an illustration of two cases of regional airports systems in which multiple airports serving more than 1% of the passenger traffic were found.
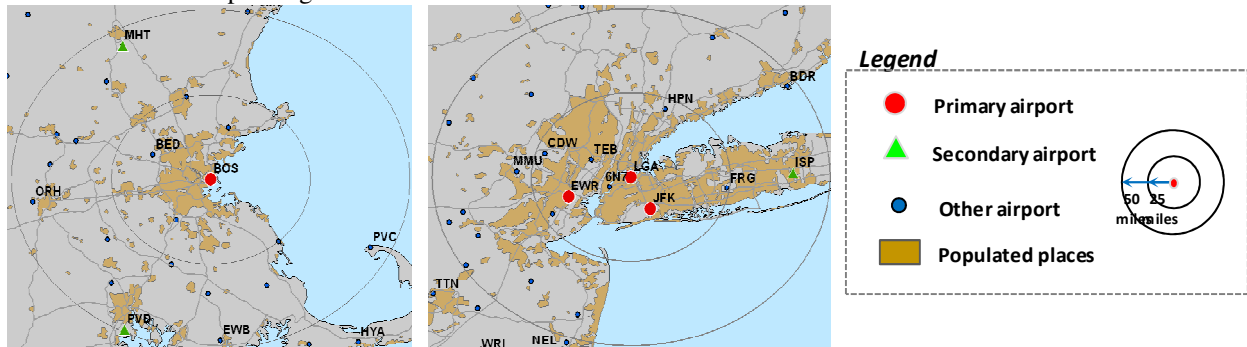

Figure 10: Illustration of multi-airport systems in the United States.

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As illustrated in Figure 10, with the Boston region, which is centered around Boston Logan (BOS) airport, this regional airport system features two other significant airports; Manchester (MHT) airport in New Hampshire and Providence (PVD) airport in Rhode Island. While Boston Logan is considered a primary airport, Manchester and Providence airports are considered to be secondary airports.

While Boston is an example of a single primary airport system, there are more complex multi-airport systems with multiple primary airports and

Figure 11: Primary and secondary airports in the United States (within the regional airport systems around the top 29 airports).

secondary airports such as the New York region. The New York airport system (Figure 10) has three primary airports; New York La Guardia (LGA), John F. Kennedy (JFK) and Newark (ERW). In addition, the region also has a secondary airport located on Long Island; Islip Mc Arthur airport (ISP).

As shown in Figure 11, a total of 16 primary and 16 secondary airports were found in the 11 multi-airport systems in the United States. The remaining 15 airports of the top 29 airports are single primary airport systems as shown on Figure 11.

From a network perspective, the emergence of a new primary and secondary airport implies new connections to the rest of the network of airports. For example, the emergence of Providence airport part of the Boston regional airport system has lead to the creation of origin-destination (OD) pairs such as PVD-ORD (a secondary to primary airport market) and PVD-MDW (a secondary to secondary airport market). These routes are parallel to the primary to primary airport route; BOS-ORD.

Figure 12 shows the structure of the networks of flights from primary to primary airports, and the networks of flights from primary to secondary and secondary to secondary airports. Using Form 41 traffic data for the month of March 1990 and 2003, capturing respectively a total of 18,000 and 15,000 distinct OD pairs, the number of OD pairs for each category was computed for both periods [15].
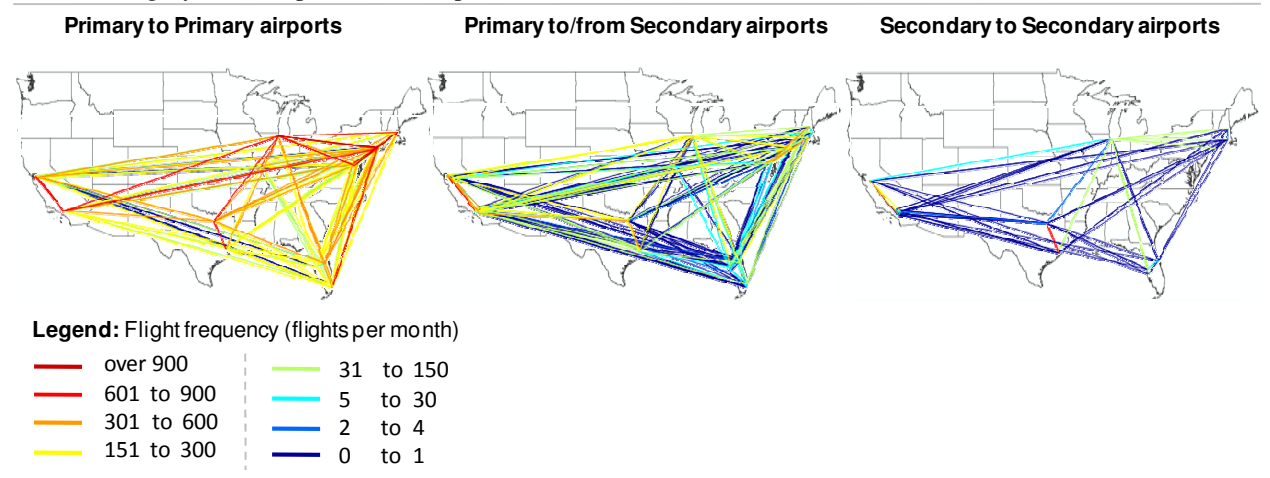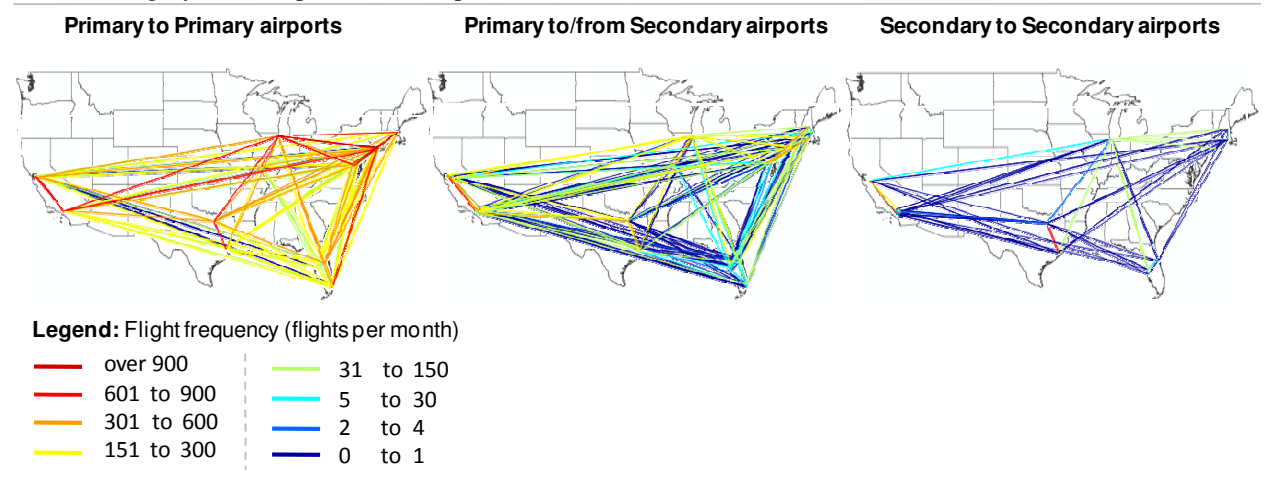

Figure 12: Parallel network in the U.S. Air Transportation Network.

It was found that semi-parallel networks (i.e. primary to secondary airport network) grew by 13 % in terms of number of routes served, from 439 to 193 connections between 1990 and 2003. The largest growth was observed in the parallel network category (i.e. secondary to secondary airport network) where a 49% growth occurred between 1990 and 2003. This phenomenon is mainly due to the emergence and growth of secondary airports in the 1990s

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(e.g. Providence, Manchester, etc). The introduction of new OD pairs between secondary to secondary airports is the result of the strategy of carriers like Southwest that operate largely at secondary airports and connect them together with point to point flights.

Because the primary and secondary airports that were identified in each of the regional airport system serve the demand for air transportation within the same region, these airports can be aggregated into one multi-airport system node. A new network composed of the 11 multi-airport nodes and the 2159 single airport nodes was constructed. Figure 14 shows the graphical network representation of the U.S air transportation network with multi-airport systems aggregated into single nodes. Similarly to the single airport node network (Figure 7), the flight weighted
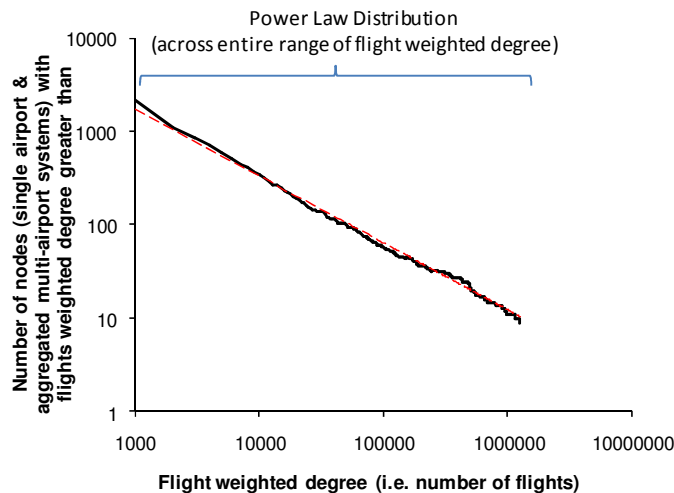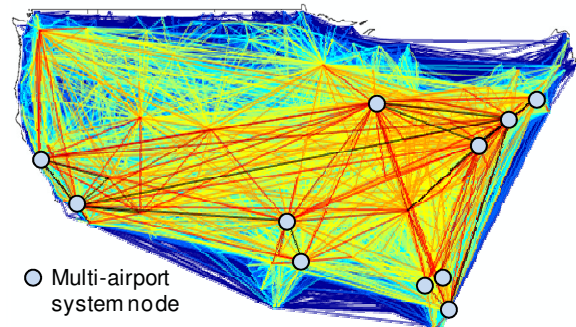

○ Multi-airport system node

Legend: Flight frequency (flights per month)

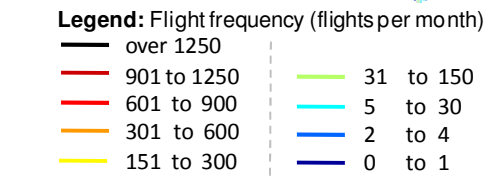|			
■	over 1250		
■	901 to 1250	■	31 to 150
■	601 to 900	■	5 to 30
■	301 to 600	■	2 to 4
■	151 to 300	■	0 to 1

Figure 14: Air transportation network with multi-airport systems aggregated into single.

degree distribution of this new network was examined.

As shown in Figure 13, with the analysis of the U.S. air transportation network at the regional level, the air transportation network is found to follow a power law distribution across the entire range of flight weighted degrees. This finding suggests that the mechanisms by which new airports emerged in a region are key to the ability of the system to scale and to meet demand.

Figure 13: Flight weighted degree distribution of the network with aggregated multi-airport.

V.   Historical Evolution of Nodes in the U.S. Air Transportation Network

The presence of a power law distribution implies that there exists an underlying growth mechanism based on preferential attachment [6][9][10]. This preferential attachment dynamic implies that a node grows proportionally to its size in the network (in an unconstrained case). From an air transportation system perspective, the preferential attachment mechanism implies that new flights added to the network are added to airports proportionally to the size of these airports in the network. Airports that already have significant number of flights are more likely to attract flights than airports with no traffic. This is consistent with network planning behaviors that are generally observed in the air transportation industry where airlines have incentives to add flights to an airport that they are already serving rather than another closely located non-utilized airport.
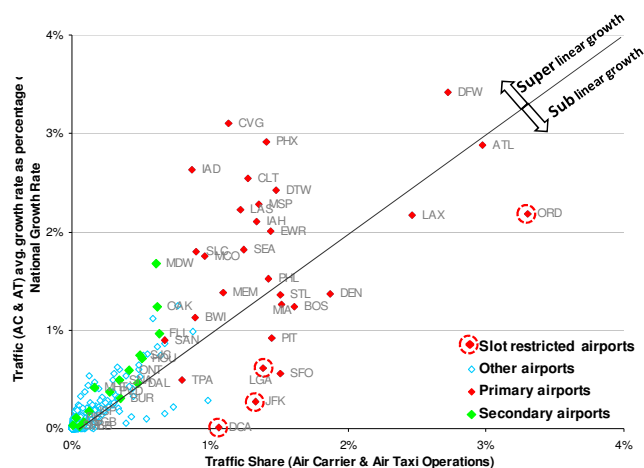

Figure 15: Average rate of growth of airport traffic vs. traffic share in the network (from 1976 to 2005).

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Using historical data from the FAA Terminal Area Forecast database that covers the time period from 1976 to 2005, an analysis of the historical growth rate of airports was performed [5]. It was found that the average growth rate versus weight of the node in the network deviates from the linear relation for individual airports (Figure 15). The alignment of nodes along the linear relationship would have been indicative of preferential attachment growth.

The observed deviation is not surprising and was expected due to capacity constraints that limit the growth of certain airports (e.g. Washington National DCA, John F. Kennedy JFK, New York La Guardia LGA, and Chicago O'Hare ORD). In fact, 4 out of the 29 airports are constrained by capacity through the use of slot restrictions. Other airports such as Newark (EWR), Atlanta (ATL), Boston (BOS), and San Francisco (SFO) exhibit delays that are signs of demand/capacity inadequacy. Airports above the linear growth line (i.e. exhibiting super linear growth) such as Cincinnati (CVG), Washington Dulles (IAD), Dallas Fort Worth (DFW) are airports that grew significantly because they became hubs in the time horizon of the analysis.
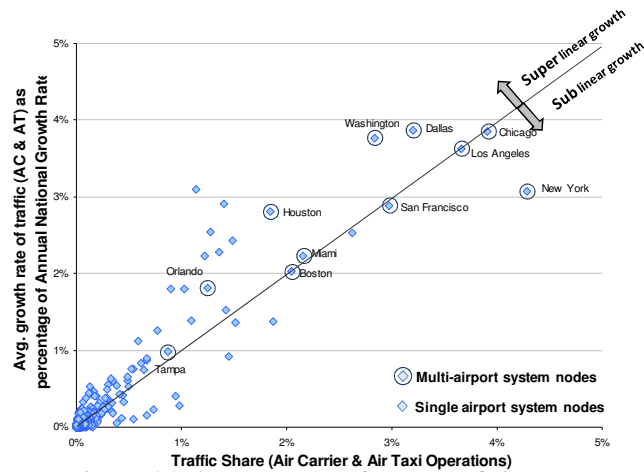
The analysis was also extended to the average growth rate of regional airport systems (Figure 16). It was found that for multi-airport system nodes, the deviations from the linear relationship are significantly reduced which implies that preferential attachment dynamics govern the nodes of the network at the regional level. There are however some deviations from the linear relationship that can be explained by differences in regional economic growth (i.e. South West vs. North East) for the higher than linear growth rates (i.e. super linear growth). In addition, it is believed that the lower growth rate of New York multi-airport system node is due in part to regional level constraints such as airspace capacity limits.

Figure 16: Average rate of growth of single and multi-airport system nodes vs. traffic share in the network (from 1976 to 2005).

VI. Scaling Dynamics in the U.S. Air Transportation System

A detailed analysis of the 15 single airport systems and 11 multi-airport systems (covering 48 airports in the United States) that was conducted, led to the identification of key scaling dynamics by which the air transportation system scales to meet demand. The summary of the results of this analysis is presented in Figure 17.
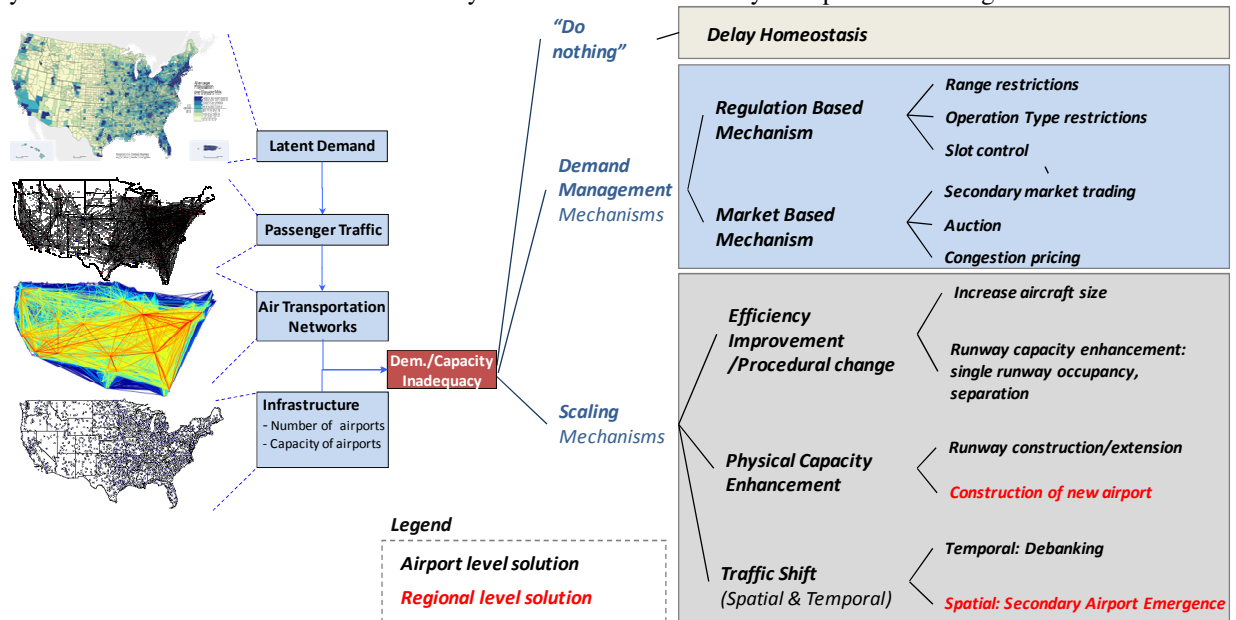

Figure 17: Set of solutions to address capacity inadequacy problem.

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It can be seen in Figure 17 that latent demand for air transportation materializes into passenger traffic in the presence of supply of air transportation services (i.e. air transportation networks). This supply of air transportation services is supported by an underlying infrastructure formed by the national airport system. From a system performance stand point, limited capacity at airports and high demand leads to a demand/capacity inadequacy problem. This problem manifests itself in general with the generation of delays and their propagation throughout the network. As delays increase and negative impacts on quality of travel arise pressure to solve the problem grows.

Several solutions are available to address this problem. As presented in Figure 17, the "do nothing" option assumes a self regulating mechanism (i.e. delay homeostasis) based on a level of delays that airlines and passengers are willing to bear. Another set of solutions is to implement demand management schemes whether they are regulatory based mechanism or market based mechanisms. However none of these solutions increase the capacity of the system. Rather, they attempt to address the problem by limiting demand and growth of traffic.

A set of solutions that allow the system to scale and meet demand are scaling dynamics. As shown in Figure 17, there are three classes of fundamental scaling dynamics;

- **Traffic shift mechanisms** that can involve both temporal and spatial shifts,

    The temporal utilization of an airport throughout a day is highly variable due to temporal demand patterns (i.e. early mornings and late afternoons are high peak demand periods leaving middle of the day and nights low demand and periods of activity), but is also due to airline scheduling behaviors. Airlines operate connecting hub airports with succession of banks of arrivals and departures roughly every hour. While it is difficult to smooth passenger demand uniformly across the day and night because of passenger traveling constraints and preferences, over the last 5 years airlines have been active at debanking the operations at connecting hub airports by smoothing the operations (i.e. implementation of rolling hub concept).

    While the previous mechanisms focused on temporal shift of traffic, traffic can also be shifted spatially with regional based scaling mechanisms (i.e. scaling "out" to existing nodes) involving the emergence of secondary airports. Over the last three decades, several key secondary airports have emerged in the United States serving demand for air transportation within a region. While passengers that live in secondary basins of population within a metropolitan region (e.g. Manchester in New Hampshire, Providence in Rhode Island) used to travel to the single primary airport serving a region, with the emergence of new airports serving the region they can fly directly from a closer and less congested airport. Figure 18 shows the evolutionary paths by which a regional airport system can evolve.

- **Efficiency improvements and procedural changes**,

    Another set of scaling dynamics involve local efficiency improvements. From a network

Figure 18: Transition and evolutionary paths of regional airport systems.

perspective, efficiency can be improved at the nodes (i.e. airports) with mechanisms such as runway efficiency improvements, reduction of separation of aircraft on approach, better utilization of multi-runway operation through greater optimization of sequencing, etc. In addition, efficiency can be improved at the arc level (i.e. flight/route level) by increasing the average size of aircraft (i.e. scaling "up" arcs). From a transportation system performance perspective the true metric of efficiency is the number of passengers carried by unit of capacity. Therefore, utilizing larger aircraft increases the passenger throughput while using the same airport resources. However, the increased competition in the airline industry in the post deregulation era, and the race for higher flight frequency, has driven the decrease in average aircraft size. In fact, in the last 16 years, the average size of aircraft in the United States -for domestic operations- has decreased from 130 to 88 seats. One of the key phenomena underlying this trend was the entry and use of 50 to 90 seat Regional Jets (RJs) in the 1990s. The use of these aircraft is substantial at major airports such as Chicago
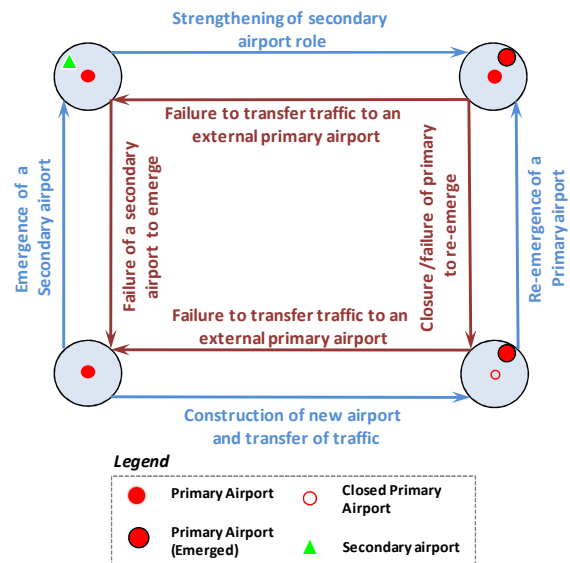
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O'Hare (ORD) and La Guardia (LGA) for which the traffic share of regional jets was 43% and 32% respectively in 2005.

- **Physical capacity enhancement mechanisms**.

    Finally, the system can scale by the addition of physical capacity. As shown in Figure 17, both airport (i.e. local) and regional airport system based mechanisms can lead to an increase in physical capacity of infrastructure serving a region. The airport level based mechanism involves the construction of new runway if this is feasible. The incremental gain in capacity resulting from the construction of a new runway can be highly variable. For example, the new 14/32 runway at Boston Logan airport that entered into service in 2006 after a 30 year planning process is only generating a capacity benefit of approximately 3% due to low annual utilization because of its use in certain rare wind conditions. On the other hand, new runways such as the new runway at Atlanta Hartsfield airport will lead to a 33% capacity increase.

    Another physical capacity enhancement mechanism (i.e. scaling "out" to new nodes) involves the construction of new large capacity airports in the region. This regional level based mechanism has been observed in the United States in the 1970s with the construction of airports such as Washington Dulles (IAD), Dallas Fort Worth (DFW) and more recently with Denver international (DEN) in the 1990s.

Due to strong environmental constraints, it is increasingly hard to build new large capacity airports and even runways at key airports. In addition, the gains in capacity due to efficiency improvements such as runway utilization optimization and remaining debanking opportunities are limited and can only provide marginal capacity improvements on the order of a few percentage points. Given the existence of a dense network of under-utilized airports in the United States, the scaling mechanism involving the emergence of secondary airports, using existing under-utilized infrastructure is seen as a key mechanism for scaling the air transportation network and system and meeting future demand.

VII. Conclusions

From the analysis of the air transportation network structure and the detailed analysis of regional airport systems, it was found that the U.S. air transportation network is not scalable at the airport level due to capacity constraints. However, the analysis of the U.S. air transportation network for which multiple airports serving a region were aggregated into one multi-airport system node based the analysis of case studies of regional airports systems showed that the network is scale free and scalable. In order to understand how the network evolves, an analysis of the scaling mechanisms and the factors that influence the structure of the network was performed. Initially the air transportation network scales according to airport level mechanisms –through the addition of capacity and the improvement in efficiency-. In the absence of constraints the air transportation network scales according to the preferential attachment scaling mechanisms. However, as infrastructure constraints are reached; higher level scaling mechanisms such as the emergence of secondary airports and the construction of new high capacity airports are triggered.

Given the fact that there is a limited capability for adding capacity at major airports, these findings suggest that regional level scaling mechanisms will be key to accommodating future needs for air transportation. The attractiveness of existing underutilized airports will increase leading to the growth of existing secondary airports and the emergence of new secondary airports.

Acknowledgments

Biographies

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