

# Design and Simulation Methodology to Improve the Performance of Airspace Tube Networks

Banavar Sridhar<sup>1</sup>

*NASA Ames Research Center, Moffett Field, CA 94035-1000*

Tanim Islam<sup>2</sup> and Gautam Gupta<sup>3</sup>

*University of California, Santa Cruz, Moffett Field, CA 94035-1000*

The concept of high-traffic corridors and tube networks has been proposed to meet air traffic demand in the future. Several airspace tube network designs are available using different approaches. The utility of any transcontinental air traffic tube network is limited by the hub and spoke nature of air traffic in the US and the existence of over 50% of commercial flights with ranges less than 500 miles. Therefore, this paper describes an improved design methodology that accounts for the nature of the domestic air traffic that utilizes this network, characterizes the utility of a given tube network, and demonstrates possible limits in the efficacy of any tube network with current air traffic. Simulation results show that the number of aircraft flying within the redesigned tube network is comparable to the number flying through the other tube networks; however, since the length of the redesigned tube network is roughly half the length of the next-shortest tube network, the instantaneous occupancies are approximately twice that of the other tube designs.

## I. Introduction

AIR traffic is expected to grow by a factor of two or more within the next thirty years.<sup>1</sup> This would significantly increase airspace congestion in already congested airspaces such as the northeastern part of the United States. The routing of aircraft through specialized lanes of air traffic has been proposed as part of the overall strategy to address this anticipated increase in air traffic. The goal of this routing strategy is to design a tube network that maximizes flow of aircraft while minimizing excess distance travelled over the great circle distance between origins and destinations<sup>2,3</sup>. Several methods have been proposed to design tube networks, and an analysis of five designs for airspace tube structures was reported<sup>4</sup>. However, the utility of any transcontinental air traffic tube network is limited by the hub and spoke nature of air traffic in the US and the existence of over 50% of commercial flights with ranges less than 500 miles. Therefore, this paper describes an improved design methodology that accounts for the nature of the domestic air traffic that utilizes this network, characterizes the utility of a given tube network, and demonstrates possible limits in the efficacy of any tube network with current air traffic.

In this paper, an origin-destination tube network is designed for aircraft departing and arriving at airports within the continental United States. The approach attempts to isolate the population of aircraft into those that are best suited for utilization within a transcontinental tube network. For instance, air traffic characterized by hub and spoke patterns with spoke lengths an order of magnitude shorter than the dimensions of the national air space would be ill suited to any tube network that spans the national air space; likewise, one must ensure that the criteria for utilization are not made too restrictive as to yield very low tube occupancies. The utility of this and other tube networks are measured by examining one day's aircraft traffic using the Future ATM (Air Traffic Management) Concepts Evaluation Tool (FACET), an air traffic simulation, control and optimization research tool.<sup>5</sup> As there are many more airports than the number of airports in the tube network, two tube utilization strategies, the locations at which a tube enters, exits, and flies on a tube network, are defined and assessed.

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<sup>1</sup> Senior Scientist for Air Transportation Systems, Aviation Systems Division, Fellow.

<sup>2</sup> Software Engineer, U.C. Santa Cruz, MS 210-8.

<sup>3</sup> Research Scientist, U.C. Santa Cruz, MS 210-8.

This paper is organized in the following manner to address some of the tube network design issues. The introductory section describes the nature of air traffic in the continental United States, summarizes previously proposed tube designs<sup>4</sup> and their limitations, and demonstrates that the structure of air traffic must be considered when designing a tube network. Section II describes the design of an origin-destination based tube network that addresses the deficiencies of previous tube network designs. Section III describes the mechanics of implementing this tube network design with simulated air traffic: a description of the two strategies by which aircraft may enter and exit a tube; a metric to evaluate the goodness of a given tube network utilizing flight plan; and the details of implementing an air traffic control simulation with a tube network in FACET. The results section, Section IV, describes the following: consideration of domestic air traffic that is best suited for utilizing a tube network; a comparison of utilization metrics between different tube utilization strategies and different populations of aircraft; metrics that demonstrate the relative utility of the new tube design to those tube networks described here;<sup>4</sup> and demonstrated deficiencies of this tube network due to the nature of domestic air traffic. Conclusions and directions for further research are described in Section V.

### A. Nature of Air Traffic

The structure of domestic air traffic is analyzed to best determine those aircraft that may utilize a tube network. Fig. 1 depicts the distribution of airports by total domestic (arrivals and departures) traffic. The highest density of airport traffic by origin and destination are located along the northeast corridor, the Chicago area, the Los Angeles area and San Francisco areas, and several geographically separated hubs in the southeast and mountain states.

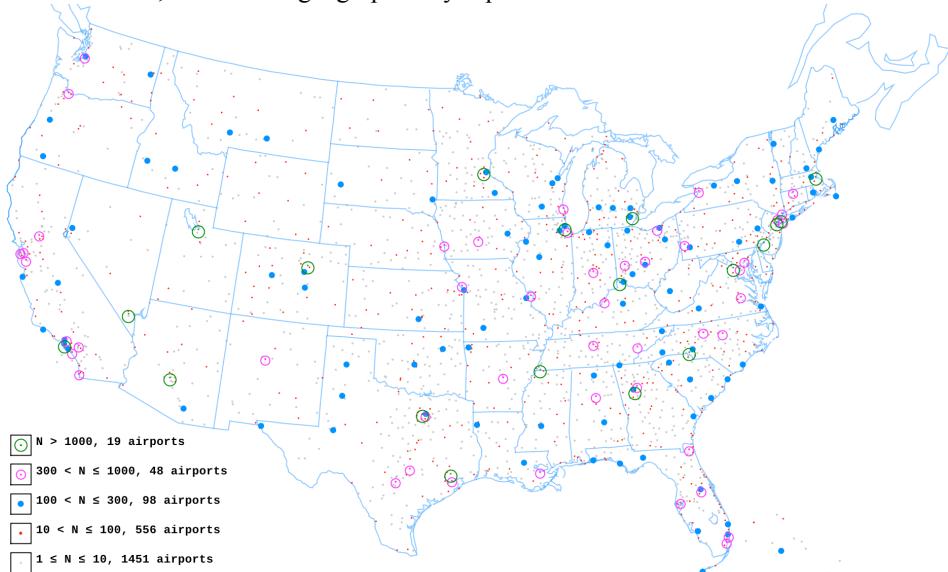


Fig. 1: Distribution of airports by total domestic operations, using air traffic for UTC 0-24 hrs on August 24, 2005.

Table 1 shows the distribution of domestic air traffic by origin-destination distance. The proportion of air traffic, whose origin and destination are separated by 250 nautical miles or less, is approximately 40% of all domestic flights for that day.

Table 1: Number of domestic aircraft by distance traveled.

Population	Count of aircraft
$d \leq 250$ nmi	18,869
$250 < d \leq 500$ nmi	13,579
$500 < d \leq 1000$ nmi	11,936
$d > 1000$ nmi	4817

Fig. 2 depicts domestic flights whose origin-destination distance is less than 250 nmi, and Fig. 3 depicts domestic flights whose origin-destination distances are between 500 and 1000 nmi.

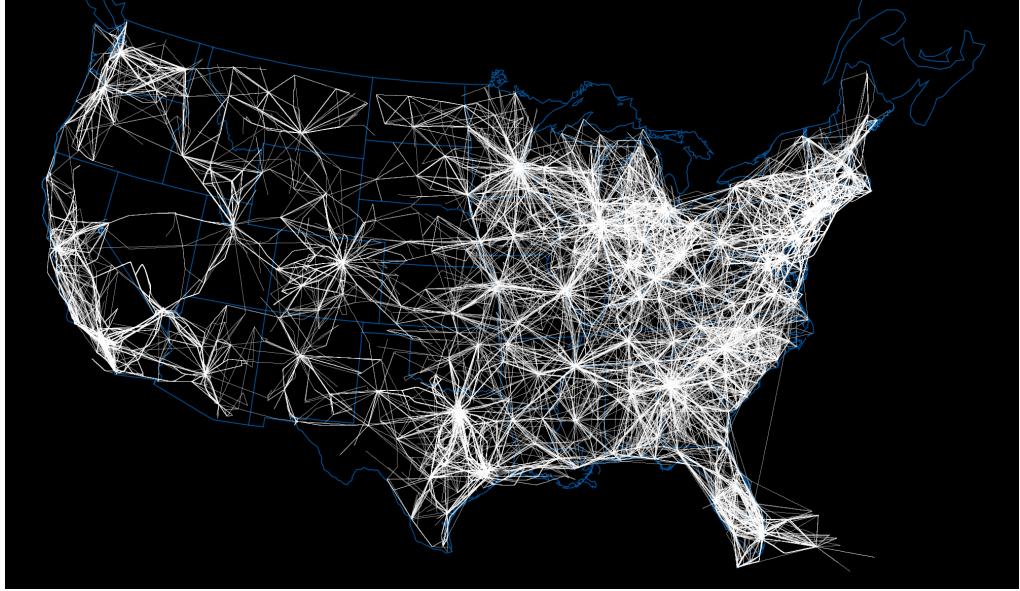


Fig. 2: Domestic flights with origin-destination distance less than 250 nmi.

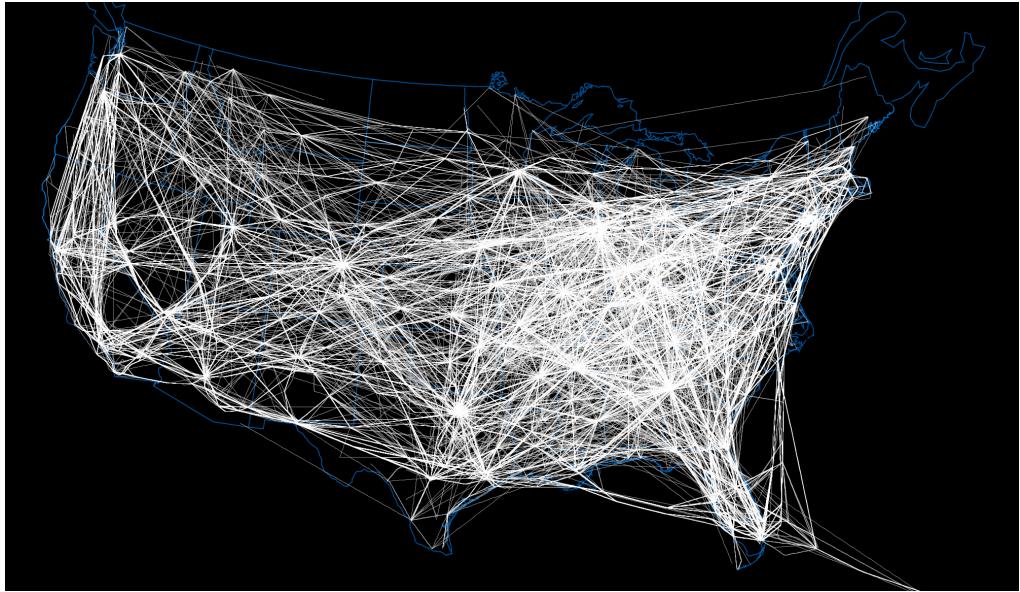


Fig. 3: Domestic flights with origin-destination distance between 500 and 1000 nmi.

Air traffic whose travel distance is less than 250 nmi (Fig. 2) has the appearance of spokes with short arms (smaller than 250 nmi) connecting major hub airports; most air traffic with this structure cannot be incorporated within a tube network unless the route is already aligned with the tube network. Air traffic with origin-destination longer than 500 nmi (Fig. 3) has relatively few hub features and consists largely of transcontinental traffic. Fig. 2 and Fig. 3, and Table 1, make it evident that air traffic in the United States has a special structure that should be taken into consideration in the design of airspace tube networks to improve their location and utility.

## B. Review of Previous Tube Designs

Previous research<sup>4</sup> assessed the relative utility of five representative tube network designs and strategies: (T1) airways and jet-routes as tubes, as shown in Fig. 4, (T2) origin-destination network formed from a Delaunay triangulation of selected high-traffic airports, as shown in Fig. 5, (T3) an origin-destination network designed from

the highest traffic density flows between airport pairs, as shown in Fig. 6, (T4) a Hough transform-based great-circle tube network,<sup>6</sup> as shown in Fig. 7, and (T5) a flow cost optimized origin-destination network between 25 airports,<sup>7</sup> as shown in Fig. 8.

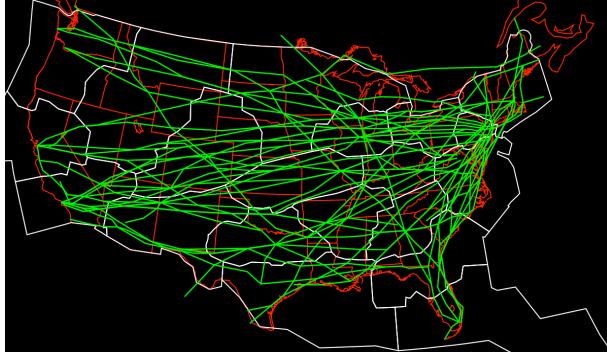


Fig. 4: Top 50 jet routes (T1) network.

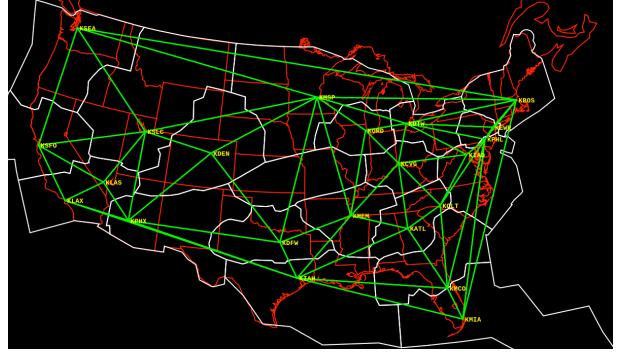


Fig. 5: Delaunay triangulated network (T2).

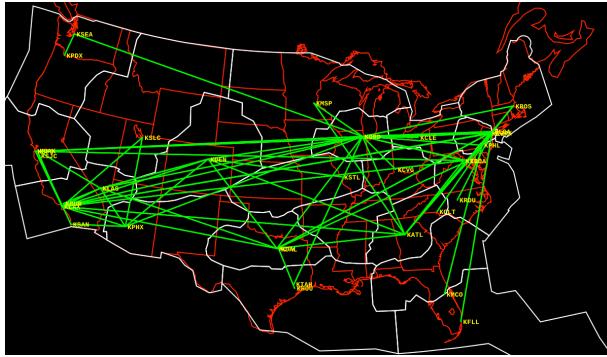


Fig. 6: Traffic density profile based, origin-destination tube design (T3).

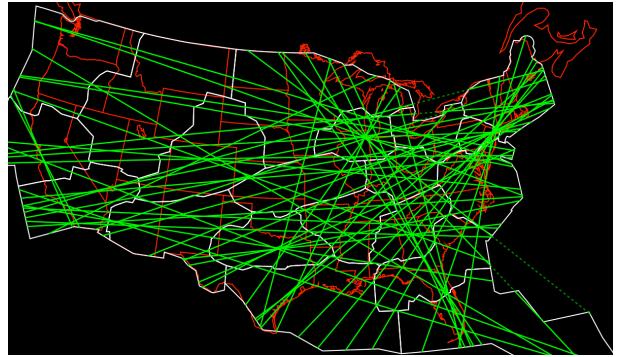


Fig. 7: Hough Transform-based great circle network (T4).

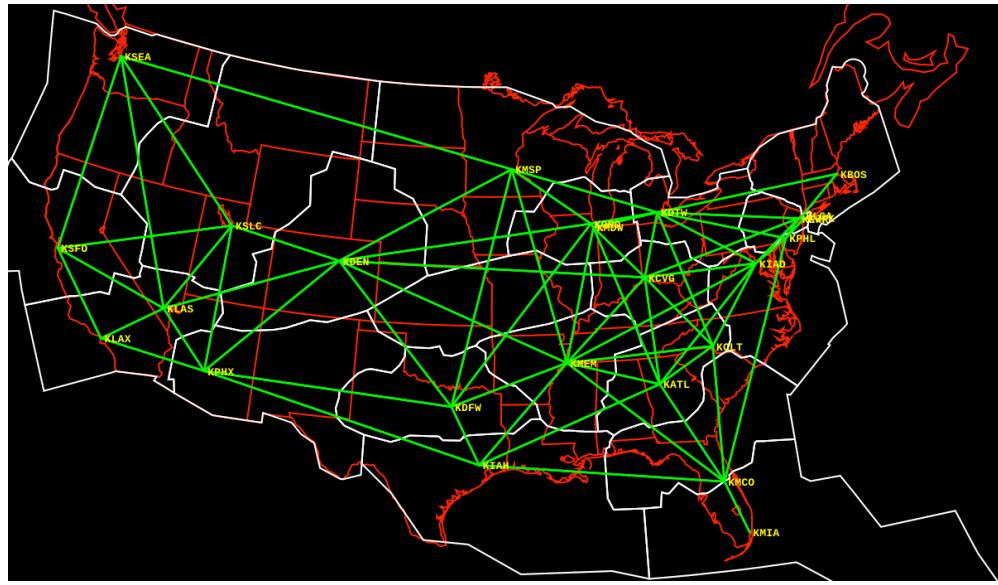


Fig. 8: Network Flow Cost Optimized tube network (T5).

The total length of the tube networks ranged from approximately 200,000 nautical miles for the T4 network to approximately 29,000 nautical miles for the T2 network. The lengths of different tube networks are shown in Table 2.

Table 2: Lengths of Various Tube Networks.

<b>Network</b>	<b>Total length in units of 1000 nmi</b>
T1	159
T2	28.7
T3	47.5
T4	203
T5	28.5

These previous tube network designs are plagued by relatively large tube length or the propinquity of nodes in high-traffic areas within the national air space, such as the separation of nodes in the Chicago area or the northeast corridor by less than 50 nautical miles (see, e.g., these references,<sup>6,7</sup> or Fig. 5, Fig. 7 and Fig. 8). A new tube design must address at least these issues.

A demonstration of those populations of aircraft that are most suitable for the utilization of a transcontinental tube network is described here. The T5 origin-destination tube network is chosen, and aircraft may enter and exit the tube network at the nodal airports. A detailed description of the tube utilization strategies that aircraft may use is provided in Section III. Aircraft are flown using their flight plans for one day's worth of travel, August 24, 2005, for UTC 0-24 hrs. Table 3 shows statistics for aircraft by population of origin-destination travel distance. It becomes apparent that relatively few tube-flying aircraft travel less than 250 nmi, while a significant chunk of non-tube aircraft (1/4) have flight plans shorter than 250 nautical miles. This implies that the best occupancies may be found by removing flights whose origin-destination are shorter than 250nmi; removing these flights removes relatively few aircraft that utilize the tube, while removing a significant portion of aircraft that do not.

Table 3: Aircraft statistics For T5 tube network with nodal tube utilization strategies.

<b>Population</b>	<b>All aircraft</b>	<b>Tube aircraft</b>
All flights	49980	39155
Flights $d \geq 250$ nmi	30796	29781
Flights $d \geq 500$ nmi	16994	16984

## II. Tube Network Design

The tube network design presented here is motivated by the need to improve the performance of earlier designs by taking into account the structure and distribution of the air traffic in the United States. The starting point in the design is an evaluation of a set of major airports that lie within the continental United States as possible nodes in a node-link network.<sup>3</sup> They are airports through which approximately 70% of domestic air traffic flies, and whose performance (e.g., coverage in convective weather) plays a primary role in the level of aircraft delays. Twenty-eight of the thirty-four major airports are chosen such that nodal airports lie more than 100 nautical miles from each other. In any cluster in which major airports lie in a cluster smaller than 100 nautical miles in size, the major airport with greatest domestic operations is chosen; therefore, for example, since Ronald Reagan National Airport (DCA) and Washington Dulles International (IAD) lies well within 100 nautical miles, IAD airport is chosen. Table 4 shows the twenty-eight major airports that were used as nodes in this study.

An intermediate tube network is designed using the optimization method described by Gupta et al<sup>7</sup>. The solution was determined using CPLEX,<sup>8</sup> a software program suited for the solution of linear optimization problems with linear constraints and integer inputs and outputs. The intermediate solution using Mixed Integer Programming (MIP) is shown in Fig. 9. Polygons demarcated by dashed lines denote geographical regions nearest each node in the network and depict those origin and destination airports closest to a given nodal origin and destination airport. Tubes are defined as an ordered set of contiguous links connecting different nodes. Furthermore, these networks are symmetric – if  $A \rightarrow B \rightarrow C \rightarrow D$  is a connection from node  $A$  to node  $D$ , then the connection from node  $D$  to node  $A$  is  $D \rightarrow C \rightarrow B \rightarrow A$ .

Table 4: 28 major airports used as possible nodes.

Atlanta (ATL)	Detroit (DTW)	Orlando (MCO)	Pittsburgh (PIT)
Boston (BOS)	Newark (EWR)	Memphis (MEM)	San Diego (SAN)
Cleveland (CLE)	Ft. Lauderdale (FLL)	Minneapolis-St. Paul (MSP)	Seattle (KSEA)
Charlotte (CLT)	Dulles International (IAD)	O'Hare International (ORD)	San Francisco (SFO)
Cincinnati (CVG)	Houston (IAH)	Portland (PDX)	Salt Lake City (SLC)
Denver (DEN)	Las Vegas (LAS)	Philadelphia (PHL)	St. Louis (STL)
Dallas-Fort Worth (DFW)	Los Angeles (LAX)	Phoenix (PHX)	Tampa (TPA)

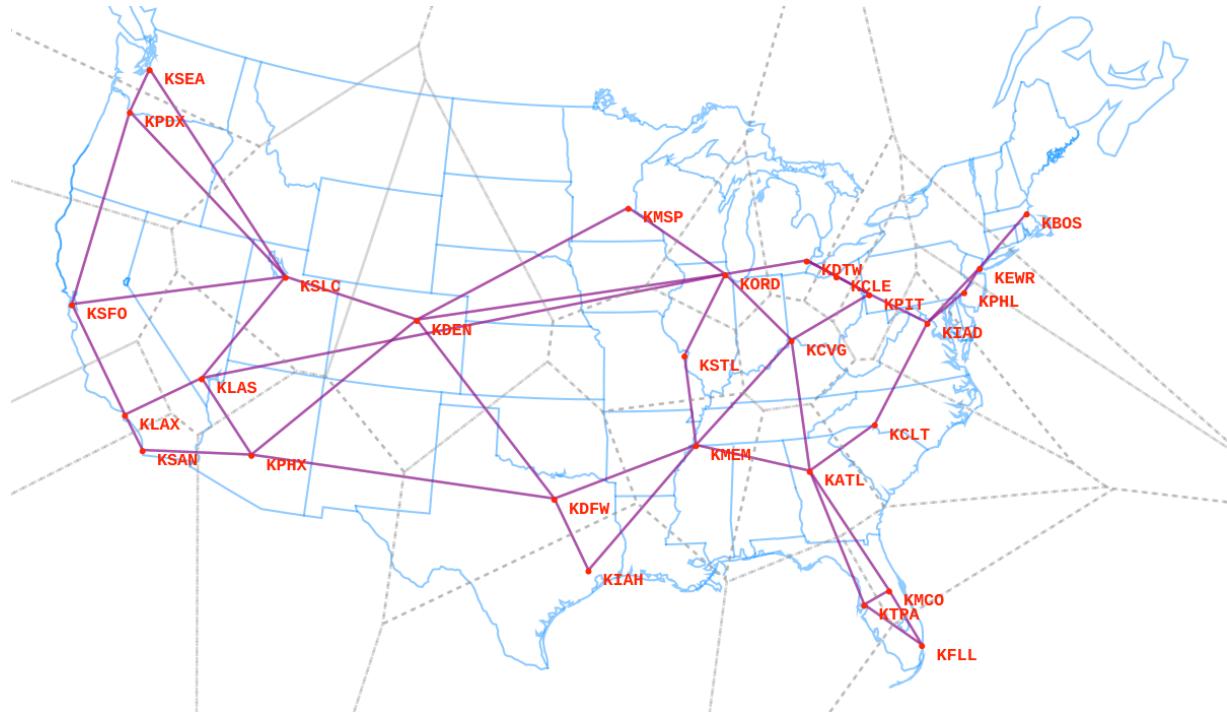


Fig. 9: Intermediate MIP solution of origin-destination tube network determined from high network costs.

Links were added and removed in order to construct a tube network with ten tubes, each containing multiple airports that span a significant portion of the national air space. Each link is taken from sides of those spherical Delaunay triangles formed from the twentyeight major airports within the continental United States. This solution is shown in Fig. 10, and representations of tubes are shown in Table 5. Each tube is denoted by a different line style. The most apparent difference between the intermediate and candidate solution is the removal of St. Louis as a nodal airport. In accordance with the labeling of previous tube networks described in Section I.B and Sheth et al.<sup>4</sup>, this representative tube network will subsequently be referred to as T6.

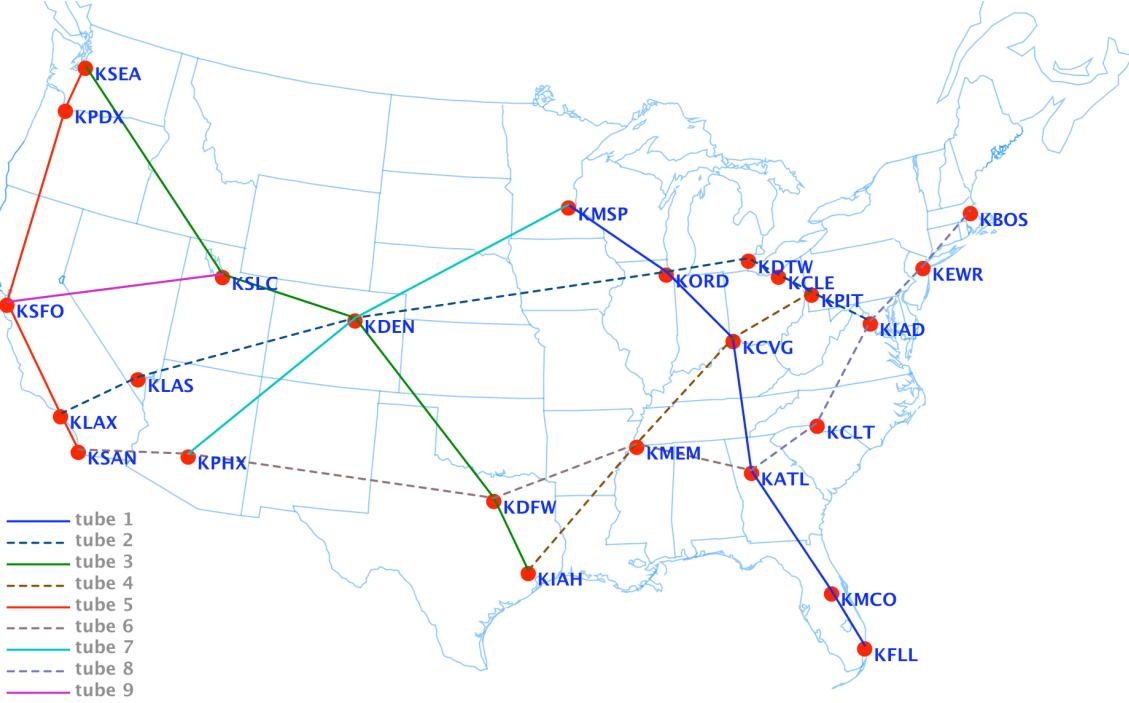


Fig. 10: Candidate tube network solution formed from intermediate high-network cost solution.

Table 5: Representation of Tubes in Candidate Tube Network.

Tube Name	Tube Design
Tube 1	$KMSP \leftrightarrow KORD \leftrightarrow KCVG \leftrightarrow KATL \leftrightarrow KMCO \leftrightarrow KFLL$
Tube 2	$KLAX \leftrightarrow KLAS \leftrightarrow KDEN \leftrightarrow KORD \leftrightarrow KDTW \leftrightarrow KCLE \leftrightarrow KPIT \leftrightarrow KIAD$
Tube 3	$KSEA \leftrightarrow KSLC \leftrightarrow KDEN \leftrightarrow KDFW \leftrightarrow KIAH$
Tube 4	$KIAH \leftrightarrow KMEM \leftrightarrow KCVG \leftrightarrow KPIT$
Tube 5	$KSEA \leftrightarrow KPDX \leftrightarrow KSFO \leftrightarrow KLAX \leftrightarrow KSAN$
Tube 6	$KSAN \leftrightarrow KPHX \leftrightarrow KDFW \leftrightarrow KMEM \leftrightarrow KATL$
Tube 7	$KPHX \leftrightarrow KDEN \leftrightarrow KMSP$
Tube 8	$KATL \leftrightarrow KCLT \leftrightarrow KIAD \leftrightarrow KEWR \leftrightarrow KBOS$
Tube 9	$KSFO \leftrightarrow KSLC$

This tube network design has a total length of approximately 11,400 nautical miles, significantly shorter than those tube networks described in Section 2 and shown in Table 2.

### III. Simulation of Air Traffic With Tube Network

This section describes the mechanisms by which aircraft are simulated to fly on a tube network. The first subsection describes the two tube strategies, described in previous research,<sup>3-5</sup> by which aircraft enter and exit a tube network. The second subsection describes one metric, the relative excess distance travelled, as a measure of how well an aircraft can utilize a tube network. Small values of this metric indicate that the selected aircraft is a good candidate for utilizing a tube network. Real-world implementations of a tube network may place upper bounds on the metric in order for aircraft to fly on a tube network. It is shown that the relative proportions of bad flight plans with good values of this metric, in the five representative tube networks described in Section II are small. The third

subsection describes the implementation of the airspace simulation in FACET, used to assess the utility of the candidate tube network and the other representative tube networks.

### A. Tube Utilization Strategies

Because there are many more airports than the number of airports selected as nodes in the tube network, a strategy is required to lead aircraft from non-node airports into the tube and away from the tube to non-node airport destinations. Two types of tube utilization strategies are considered – in which aircraft enter and exit the tube only at nodal airports (nodal strategy)<sup>6</sup>, and in which aircraft enter and exit the tube at right angles (direct strategy)<sup>7</sup>. In reality, aircraft will enter and exit a tube at some shallower angle, such as 30 degrees, for a direct strategy; right angle entrances and exits are used in an initial evaluation that may later be improved. In the descriptions of tube utilization strategy,  $N_O$  is the nodal origin airport,  $N_D$  is the nodal destination airport,  $O$  is the origin airport, and  $D$  is the destination airport. Diagrams of nodal and direct strategy depict a tube in which  $N_O$  connects to  $N_D$  through an intermediate nodal airport,  $N_I$ , which is denoted as  $N_O \leftrightarrow N_I \leftrightarrow N_D$ .

In the nodal strategy, aircraft fly from  $O$  to the nodal airport  $N_O$  closest to  $O$ , and fly from the nodal airport  $N_D$  closest to  $D$ . If  $O$  and  $D$  lie within the same cluster – if  $N_O = N_D$  – then aircraft may not utilize the tube network.

In the direct strategy, aircraft fly from  $O$  to  $D$  usually by entering and exiting the tube  $N_O \leftrightarrow N_I \leftrightarrow N_D$  at right angles. However, if the origin  $O$  lies “behind” a nodal origin  $N_O$  (i.e., if it is not possible for the aircraft to fly from  $O$  and enter the tube at right angles to the tube), then the aircraft will fly from  $O$  to  $N_O$  as with the nodal strategy. Likewise, if the destination  $D$  lies “ahead” of the nodal destination  $N_D$ , then the aircraft will fly from  $N_D$  to  $D$  as with the nodal strategy. Fig. 11 illustrates the difference between the direct strategy and the nodal strategy. If  $N_O = O$  and  $N_D = D$ , the default and nodal strategies are identical.

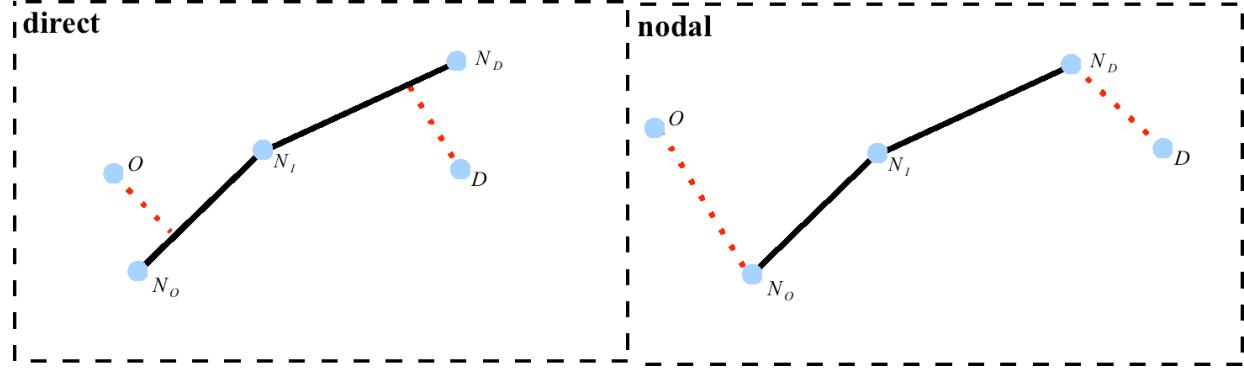


Fig. 11: Comparison of direct and nodal strategies for aircraft tube utilization.

### B. Goodness Metrics For Flights

Any tube-utilizing aircraft may spend some distance outside the tube network and some distance within the tube network. A good candidate for a tube network is an aircraft flight plan that has a relatively large component within the tube, a relatively small component entering and exiting the tube, and a total flight length that is not significantly longer than the great circle distance between the aircraft’s origin and destination airports. The measure used in this report to describe “goodness” of an aircraft flight plan is the relative excess distance  $\varepsilon$ , defined below,

$$\varepsilon = (\alpha + \delta - \sigma) / \sigma \quad (1)$$

$\sigma$  is the great circle distance between the origin and destination,  $\alpha$  is the distance travelled on the tube, and  $\delta$  is the distance travelled on entering and exiting the tube. Flight plans that are good candidates for any tube design have  $\varepsilon \ll 1$ ; however, bad flight plans ( $\alpha \ll \sigma$  and  $\delta \ll \sigma$ ) may also have  $\varepsilon \ll 1$  – these are aircraft that fly at right angles, and a short distance inside, to a given tube. Other goodness metrics for tube utilization, such as  $\delta/\sigma$ ,<sup>6</sup> have similar properties as  $\varepsilon$  in the limit of small  $\varepsilon$ .

However, it is shown that the proportion of bad flights with small  $\varepsilon$  is relatively small. Fig. 12 and Fig. 13 and depict the distribution of tube utilizing flights for the T1 and T5 networks as a function of relative distance outside the tube,  $\delta/\sigma$ , on the horizontal axis, and relative distance within the tube,  $\alpha/\sigma$ , on the vertical axis. These aircraft fly on the tube for August 24, 2005, for UTC 0-24 hrs. For the T1 network, good flight plans (points in green), in which  $\delta/\sigma < 1/2$  and  $\varepsilon < 1/2$ , comprise roughly 87.8% of tube utilizing flight plans; for the T5 network, good flight plans comprise roughly 95.2% of tube utilizing flight plans. These results suggest that one may safely use  $\varepsilon$  as a measure of flight goodness.

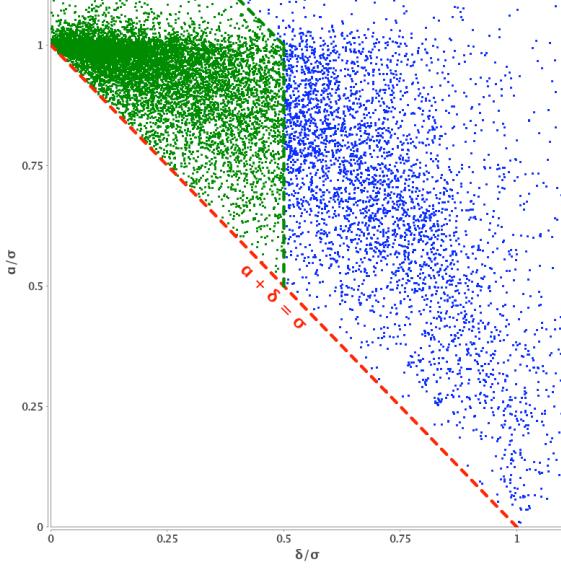


Fig. 12: Distribution of tube-utilizing aircraft in a space of  $\alpha/\sigma$  and  $\delta/\sigma$ , for the T1 tube network.

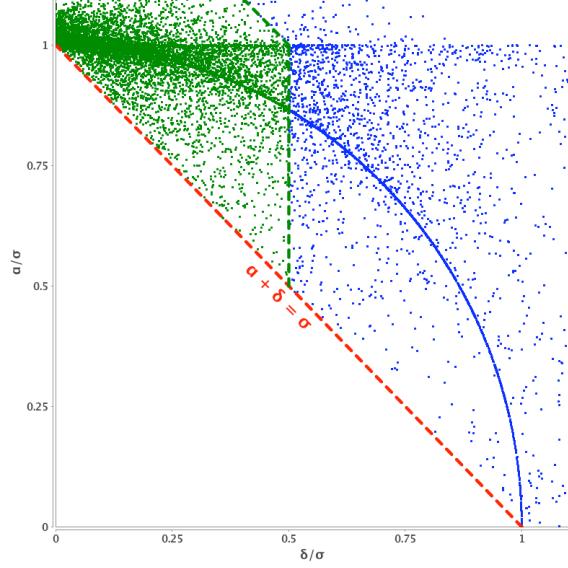


Fig. 13: Distribution of tube-utilizing aircraft in a space of  $\alpha/\sigma$  and  $\delta/\sigma$ , for the T5 tube network.

### C. Implementation of Tube Network Utilization in FACET

The performances of tube networks are evaluated using air traffic simulated to fly their original flight plans for August 24, 2005. Air traffic for this date is noted for the absence of significant levels of convective weather, winds, or other externalities that lead to significant deviations of aircraft from their flight plans; August 24, 2005, provides a relatively clean data source for air traffic research. Only domestic air traffic, airplanes for which origin and destination lie within the continental US, are used to characterize the behavior of the national air flow and to determine the efficacy of a given tube network design. The analysis can be easily modified to include international traffic.

## IV. Results

The first subsection compares the properties of four network designs and utilization strategies using domestic flights: 1) all flights utilizing a nodal strategy, 2) all flights with origin-destination distances greater than 250 nautical miles utilizing a nodal strategy, 3) all flights utilizing a direct strategy, and 4) all flights with origin-destination distance larger than 250 nautical miles utilizing a direct strategy. The four situations with the new redesigned tube network will be identified as strategy 1, strategy 2, strategy 3 and strategy 4 respectively. The superiority of strategy 4 over the others is clearly demonstrated by the results.

The second subsection explores in more detail the efficacy of the tube network design using a domestic aircraft population that has the best occupancies of these networks – domestic aircraft whose origin-destination distance is larger than 250 nautical miles. The third subsection details the distribution of relative excesses for direct tube utilization strategies, ordered by origin airport and destination airport, for aircraft whose origin-destination distance lies longer than 250 nautical miles (strategy 4). These diagrams demonstrate incremental changes to the existing network design to improve its utility: the addition or removal of airport nodes in the network, or the addition and removal of links in order to capture domestic air traffic; and features of air traffic that lead to the limits on the utility of any limited-length transcontinental air tube network. The final results demonstrate instantaneous occupancies of

the best possible strategy (strategy 4), as compared to instantaneous occupancies of other networks, and demonstrate the superiority of the candidate tube network over other types of tube designs.

### A. Utilization Metrics

The four strategies are implemented in FACET, as described in Section III.C, using traffic data for August 24, 2005. No restriction is made on relative excess distance,  $\varepsilon$ , for aircraft that may utilize the tube network. The following utilization metrics, flight counts, distributions of relative excess distance travelled,  $\varepsilon$ , and relative and absolute cumulative distributions of  $\varepsilon$  are collected for these four strategies. Table 6 shows the flight counts associated with these strategies.

**Table 6:** Total Utilization Statistics For Four Strategies For UTC 0-24 hrs, August 24, 2005.

Strategy	Count of aircraft flying	Count of aircraft utilizing the tube
1. All flights, nodal	50,260	39,565
2. Flights $d \geq 250$ nmi, nodal	31,009	30,056
3. All flights, direct	49,870	49,870
4. Flights $d \geq 250$ nmi, direct	30,715	30,715

Those flights that do not utilize the tube network in the nodal case are aircraft whose origin and destination lie within the same cluster, hence the total number of aircraft that can utilize the tube using the direct strategy can become significantly higher than those with the nodal strategy.

Figs. 14 - 17 summarize the distribution of relative excess distance travelled,  $\varepsilon$ , for the four strategies. The best strategy, with relatively large proportions of aircraft that have small  $\varepsilon$  and relatively few aircraft with  $\varepsilon \geq 1/2$ , occurs if one removes aircraft whose origin-destination distance is shorter than 250 nautical miles, with remaining aircraft utilizing the tube network by entering and exiting at right angles (Strategy 4).

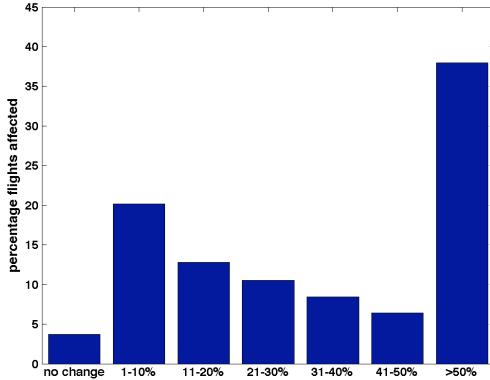


Fig. 14: Distribution of  $\varepsilon$  for all domestic aircraft using nodal strategy (Strategy 1).

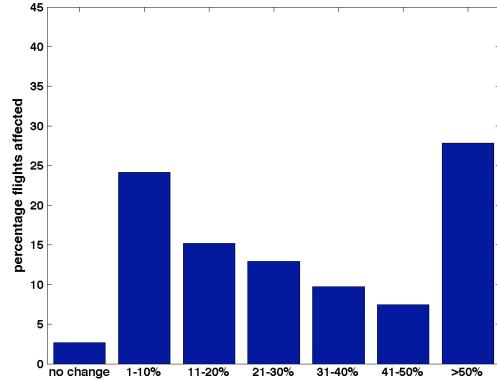


Fig. 15: Distribution of  $\varepsilon$  for all domestic aircraft with origin-destination distances  $d \geq 250$  nautical miles, using nodal strategy (Strategy 2).

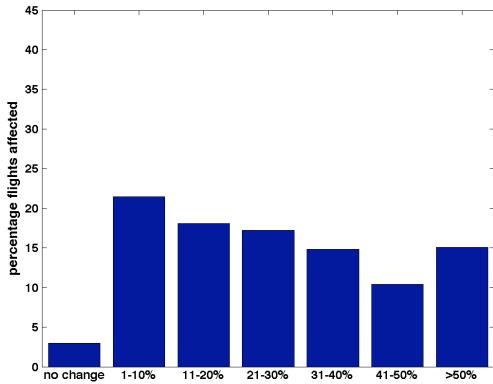


Fig. 16: Distribution of  $\epsilon$  for all domestic aircraft using direct strategy (Strategy 3).

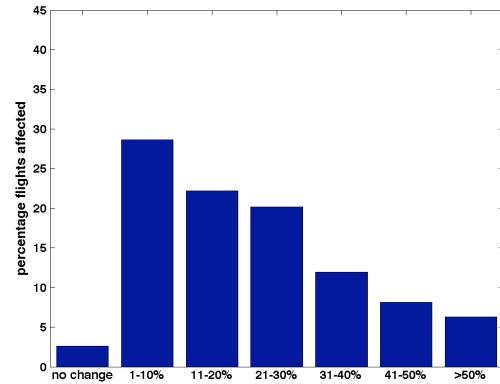


Fig. 17: Distribution of  $\epsilon$  for all domestic aircraft with origin-destination distances  $d \geq 250$  nautical miles, using direct strategy (Strategy 4).

A plot of the cumulative number of flights with  $\epsilon$  below some cutoff threshold is shown in Fig. 18, and plot of the cumulative proportion of all flights that utilize the tube network with  $\epsilon$  below some cutoff threshold is shown in Fig. 19. The relative superiority of Strategy 4 becomes apparent in Fig. 19, resulting in approximately 90% of all flights with relative excess distances shorter than 40%, exceeding the utilization performance of the T4 network (see Fig. 7).

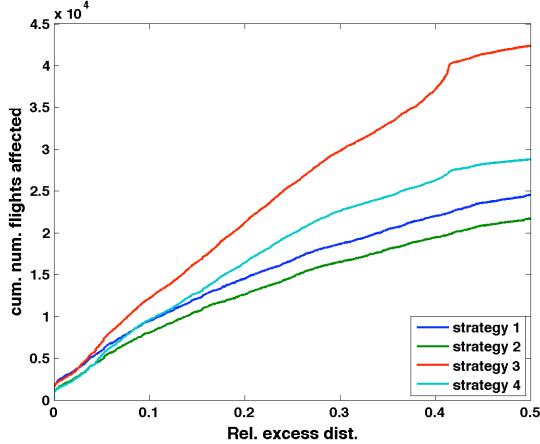


Fig. 18: Cumulative number of flights with relative excess distance below  $\epsilon$ , as a function of  $\epsilon$ .

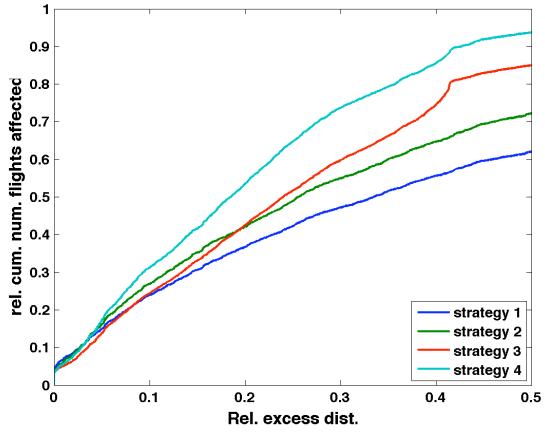


Fig. 19: Relative cumulative number of flights with relative excess distance below  $\epsilon$ , as a function of  $\epsilon$ .

## B. Distribution of Flight Deviations by Origin and Destination

Diagrams of the distribution of relative excess  $\epsilon$  can elucidate relatively small changes to improve the utility of the candidate network, and demonstrate restrictions on tube network utility with current air traffic. The following figures illustrate the geographical distribution of relative excess distance  $\epsilon$  of domestic airports, in which the amount of domestic arrival or departure traffic determines the color of the dot at the airport. The color of the dot goes from blue to red as the airport traffic goes from zero to one hundred and above. To reduce clutter, for airports with traffic varying from zero to thirty, the size of the dot is made proportional to the amount of traffic.

Fig. 20 and Fig. 21 show the distribution of relative aircraft distance excess for  $\epsilon \geq 0.5$  by origin airport (departures) and destination airport (arrivals), respectively; 1933 out of 30,715 aircraft have  $\epsilon \geq 0.5$ . Apparent here is the fact that a significant number of air traffic lies at the borders of the clusters, at the nodes, or along the tubes – hence, they cannot be captured by the tube network. This feature appears to be universal to any transcontinental tube network placed, with a relatively small total tube network length, that is designed to capture and route current air traffic.



Fig. 20: Geographical distribution of  $\epsilon$  by aircraft departure locations for  $\epsilon \geq 0.5$ .



Fig. 21: Geographical distribution of  $\epsilon$  by aircraft arrival locations for  $\epsilon \geq 0.5$ .

Fig. 22 and Fig. 23 show the geographical distribution of relative aircraft distance excess  $\epsilon \leq 0.2$  by origin airport (departures) and destination airport (arrivals), respectively. Approximately 60% of the traffic has  $\epsilon \leq 0.2$ . The main domestic traffic flows are also apparent within these figures, absent those roughly latitudinal flows that travel through the St. Louis area.



Fig. 22: Geographical distribution of  $\epsilon$  by aircraft departure locations for  $\epsilon \leq 0.2$ .



Fig. 23: Geographical distribution of  $\epsilon$  by aircraft arrival locations for  $\epsilon \leq 0.2$ .

### C. Results And Comparisons With Earlier Designs

This new tube network design and strategy, requiring that only flights whose great-circle origin-destination distance is longer than 250 nautical miles should enter and exit the tube network at right angles (strategy 4), is shown to compare favorably with the previous five tube networks. The previous tube networks were simulated with the same traffic allowed to enter the network as strategy 4. Instantaneous occupancies for the new network are compared to the old networks.

Fig. 24 summarizes relative cumulative utilization properties of the five old networks (T1-T5) using domestic aircraft whose origin-destination distance is longer than 250 nautical miles, and for strategy 4 (denoted as candidate network), using simulated tube-utilizing air traffic for 0-24 hrs UTC, August 24, 2005, as a function of cutoff  $\epsilon$ . On the horizontal axis is the cutoff  $\epsilon$ , and on the vertical axis is the relative number of tube utilizing aircraft of aircraft with  $\epsilon$  smaller than the cutoff. The inset legend shows the total length of each tube network in units of one thousand nautical miles. The worst performance in cumulative  $\epsilon$  is the traffic density profile (T3) tube network; the great circle tube network (T4) performed the best, due to its very large ( $2.0 \times 10^5$  nautical miles) total length. One also observes a utilization of approximately 60% of possible flights for  $\epsilon \leq 0.1$ , but only for the great circle network. Furthermore, the new network's (T6) relative utilization compares relatively unfavorably with other, much longer tube networks.

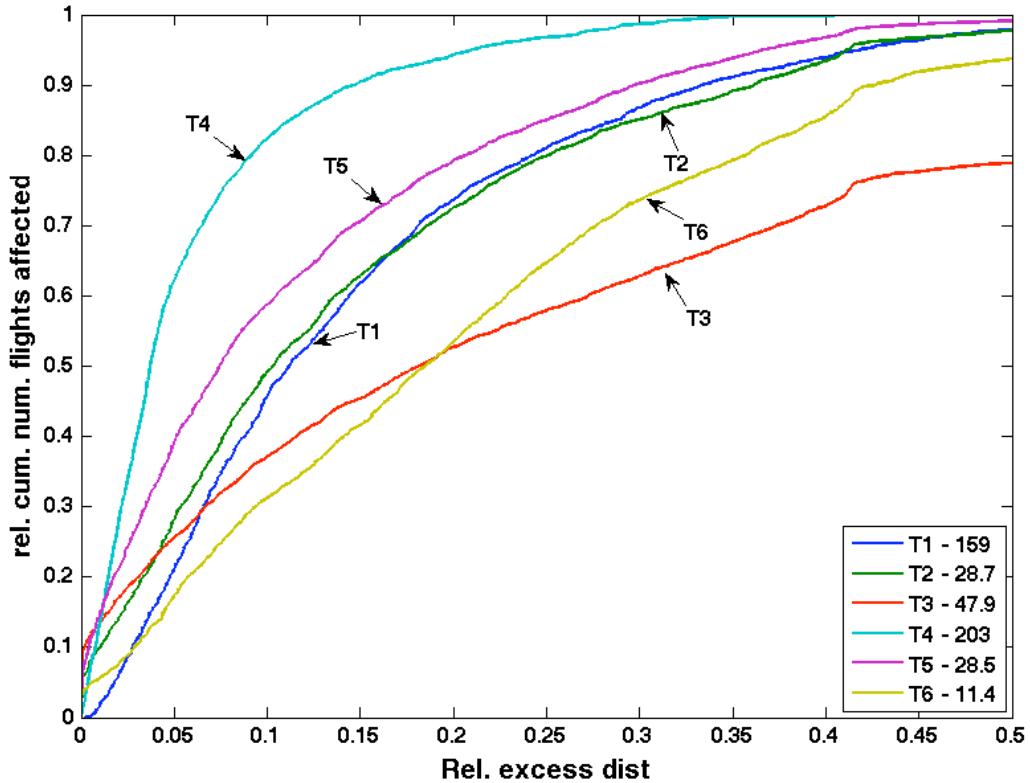


Fig. 24: Relative excess distance metrics  $\epsilon$  for the six tube network designs.

However, the instantaneous occupancy, defined as the number of aircraft flying within the tube divided by the total length of the tube, for strategy 4 compares quite favorably to the other tube networks. The number of aircraft flying within the new tube is comparable to the number flying through the other tube networks; however, since the length of the tube network is roughly half the length of the next-shortest tube network (see Table 2, T5 network), the instantaneous occupancies are approximately twice that of the other tube designs. This feature is seen, for example, where only applicable domestic aircraft with  $\epsilon \leq 0.1$  utilize a network (Fig. 25), and where no restrictions are placed on relative excess distance traveled (Fig. 26). Finally, an examination of Figs. 20-23 makes it apparent that the following slight changes to the tube network can improve its performance:

- Remove Portland as a nodal airport due to lack of traffic and redundancy regarding north-south flows in the western United States.
- Remove Cleveland as a nodal airport due to redundancy with respect to flows between the upper midwest and the northeast corridor.

Include St. Louis as a node, and link connecting Denver and Cincinnati through St. Louis, to capture latitudinal flows through the central United States.

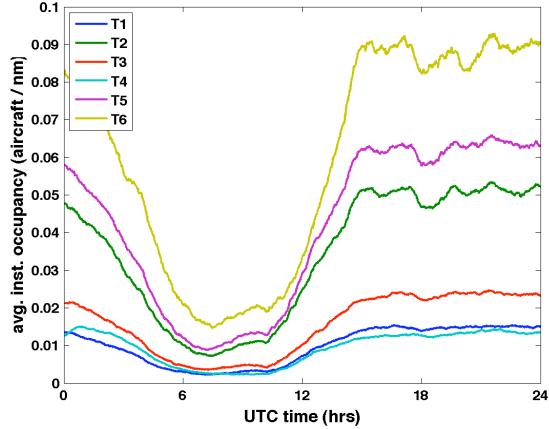


Fig. 25: Relative Instantaneous occupancies for the five tube networks and the candidate tube network. Only aircraft with  $\varepsilon \leq 0.1$  may utilize the tube network.

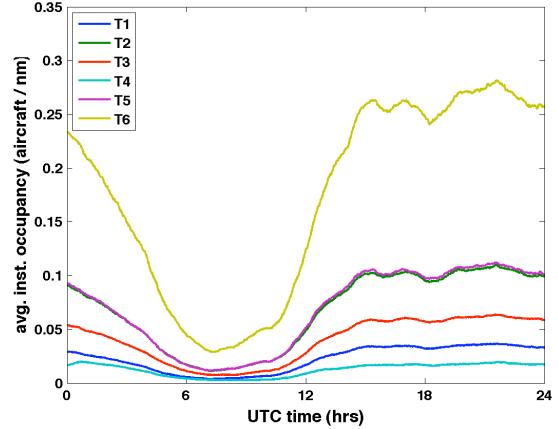


Fig. 26: Relative instantaneouoccupancies for the five tube networks and the new tube network. No restrictions are made on aircraft that may utilize the tube network.

## V. Conclusions

The main results of this report are synthesized here. First, approximately 40% of domestic traffic (those aircraft with  $d \leq 250$  nautical miles) would not utilize any tube network. Therefore, a minimum distance criterion should be placed when considering those aircraft that can fly onto a transcontinental tube network. Second, as expected a tube utilization strategy in which aircraft enter and exit a tube network using the smallest feasible extra distance, such as approaching the tube at right angles with a smooth merge, has significantly better total utilization and flight plan characteristics than a tube utilization strategy in which aircraft enter and exit at the nodal airports; this is unsurprising, as exiting and entering at right angles for a given origin-destination pair yields smaller distances outside the tube and smaller distances within a tube than a nodal tube utilization strategy. And third, the strategy by which this origin-destination based tube network has been chosen implicitly chooses among a basis set of links that do not cross each other – hence links that corresponds to the edges of Delaunay triangles among these nodes. The smaller Delaunay set of links, rather than choosing among all  $N(N - 1)$  possible links among  $N$  nodes, may constrain the search space for good tube networks.

One may argue that, at first iteration, without having to consider the interior structure of a tube network or tube utilization strategies, the best tube networks are those with relatively high occupancies and as small a total length of the tube network as possible. An optimal network is one whose tubes lie along the main traffic flows as fully as possible. This tube network performs quite well in these regards: a relatively short length of tube network, relatively high occupancies, and the removal of domestic aircraft whose flight structure is not well suited to tube utilization. However, slight changes to the candidate network (see Section IV.C) can improve its performance. One may also include international flights in a systematic way in order to increase the tube network’s utility. Finally, other network designs or algorithms – such as solving for the locations of the nodes and the links in the aggregate, rather than solving for an optimal set of links given a fixed set of nodes; or employing line-detection algorithms to match the main domestic traffic flows – can be explored, and the goodness of these networks can be assessed using the methodologies described in this paper.

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