

HIGH-VOLUME TUBE-SHAPE SECTORS (HTS): A NETWORK OF HIGH CAPACITY RIBBONS CONNECTING CONGESTED CITY PAIRS

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Abstract

We propose a network of High-Volume Tube-Shape Sectors (HTS) which is stretched between congested city pairs as a more efficient system for organizing and managing the aircraft flow, into and out of the large airports. One can think of this network as analogous to the system of interstate highways with passing lanes, breakdown areas, on-ramps and off-ramps, all designed to quickly move as much traffic as possible. This network would maximize the airspace throughput by more efficiently transporting aircraft, into and out of the congested airports. We apply visualization techniques to classify the current air traffic into different layers based on the demand profiles and route structure between origin and destination (OD) pairs. We also model the air traffic as flow of a fluid, where aircraft are the particles of the fluid. Velocity vectors for small volumes of the airspace are calculated as resultant of the velocity vectors for individual aircraft. Accordingly, we construct vector fields of the fluid velocity. Analysis of the routing structure and vector fields' topology assists us to determine the geometry and location of potential HTS.

Introduction

Airspace capacity is limited by ability of the Air Traffic Controllers (ATCs) in dealing with complex traffic situations [1]. In the congested areas of the National Airspace System (NAS) the ATC workload limitation is a critical capacity constraint which generates significant en route delay [2]. The ATCs often enforce Miles in Trail (MIT) restrictions or they may reroute the aircraft or deny access into a sector to avoid high workload situations. Without a new way to reduce the ATC workload, airspace capacity could not be maintained up to a level which satisfies the future growth of the air traffic [3].

ATC workload is directly related to the situational awareness. Structured air traffic reduces the system dynamics and enables the ATC to develop mental abstractions to reduce the cognitive complexity of traffic situation. This complexity reduction results in airspace capacity improvement [4, 5]. Current air traffic pattern in the US contains highly structure routes that are favorable for the controllers. However current airspace sectorization is not often in accordance with these structured routes and ATCs are not able to take full advantage of existing highly structured traffic. For example, an aircraft destined to ORD from LAX could cross up to 15 different sectors while en route. Such a non-centralized system produces significant amount of controller-to-controller and pilot-to-controller coordination workload and this results in system inefficiency.

Recent advances in Air Traffic technology are changing operating conditions of the ATC. Today, with the use of advanced data links, one controller could be able to track an aircraft and communicate with a pilot all the way from origin to destination. Advanced navigation equipments and data links such as Airborne Separation Assurance System (ASAS), Automated Dependent Surveillance Broadcasting (ADS-B) and Cockpit Display of Traffic Information (CDTI) enables pilots for self separation. Hence the ATC functions could become more strategic in nature.

The ATC workload limitations, existence of structured patterns in the NAS and capabilities of advanced data links lead us to a hypothesis that one sector could be stretched between TRACON boundaries of congested airports and one or few controllers control all the aircraft entering these High-Volume Tube-Shape Sector (HTS). Centralizing the command and control in one sector would potentially improve situational awareness of ATCs [6, 7] thus reducing their workload and increasing the system throughput [8].

In this paper we summarize the operational concept of the HTS and explore potential corridors for development of the HTS network. We also present an aircraft flow modeling methodology which assists us to study the topology of the traffic flow.

Current Route Structure

Study of current route structure assists us to determine the potential location and geometry of the HTS. The location of current airports in the US is fixed and construction of new large airports is not proposed in the short future. Also the demand profiles of city pairs are not changing quickly. Hence today's air traffic network consists of fixed nodes and established links with insignificant variation of daily demand. In other words, the Air Traffic Management (ATM) system deals with an established network of nodes and links. In this section we show that a significant portion of total flights in the NAS are operated in a limited number of origin and destination (OD) pairs. We also classify the current air traffic into different layers based on the demand profiles and route structure between origin and destination (OD) pairs.

Congested City Pairs

Figure 1 illustrates the histogram of daily airline operations between different OD pairs. As shown in the figure, there are over 2000 OD pairs with less than 5 daily operations [9]. These OD pairs account for a small portion of total daily operations and are not candidates for the HTS network.

On the other hand, there are OD pairs with more than 60 operations per day. Figure 2 depicts the fact that 33 percent of the total scheduled flights are operated between about 10 percent of the OD pairs. These OD pairs are backbones of the airspace system and increasing the capacity of these routes could significantly improve the total system capacity. The ultimate aim of a HTS network is to facilitate the en route movement between these congested city pairs.

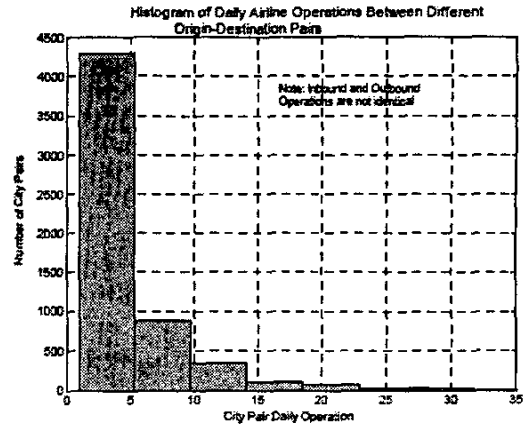


Figure 1. Histogram of Daily Airline Operations between Different Origin-Destination Pairs

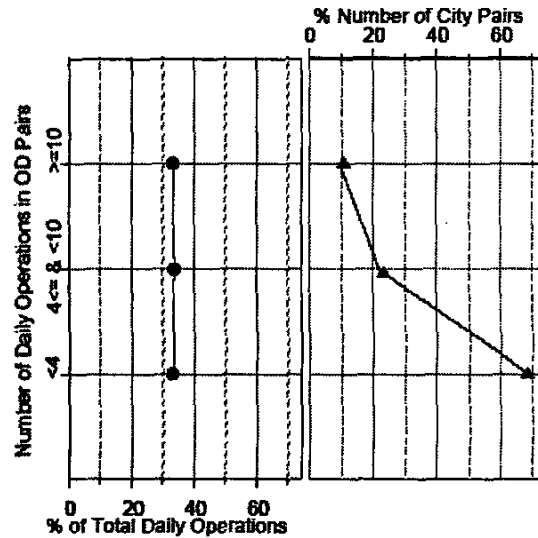


Figure 2. Classification of OD Pairs Based on the Number of Daily Operations

Operational Layers

Figures 3 to 8 classify OD pairs based on their number of daily operations. As it is illustrated in Figure 3, city pairs with at least one daily operation almost cover the entire airspace but many of these routes are not flown frequently. As we filter out layers of the non-congested routes in Figure 6 the backbone of NAS routing structure becomes visible. The NY-Metro, DC-Metro, BOS, ORD, DFW, ATL, DEN, LAX, SFO, SEL, MCO, PHX and SAN airports are the legs of this backbone structure. These routes could be grouped together

and one HTS could serve for few OD pairs with geographically close routes. For example all the flights destined from ATL to BOS, NY-Metro and DC-Metro are passing through very close routes. One HTS may be developed to serve this group of routes. Same analogy can be recognized for ORD to NY-Metro or LAX to ORD routes.

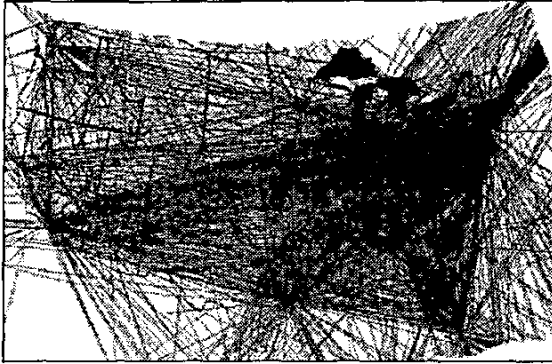


Figure 3. All OD Pairs with at Least One Daily Operation and One Airport in the Inland USA

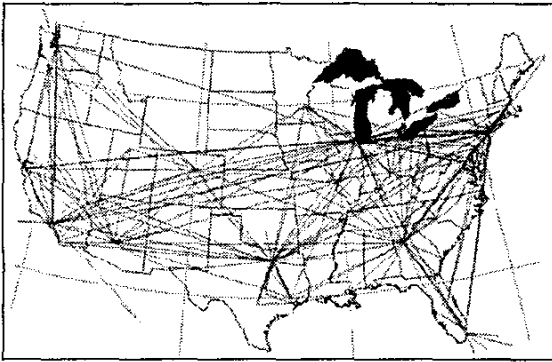


Figure 4. OD Pairs with 10 to 20 Daily Operation and One Airport in the Inland USA

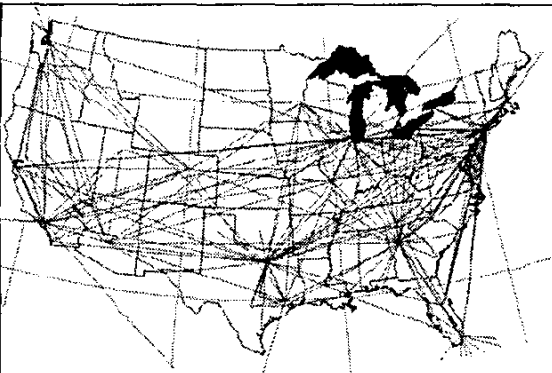


Figure 5. OD Pairs with 20 to 40 Daily Operation and One Airport in the Inland USA

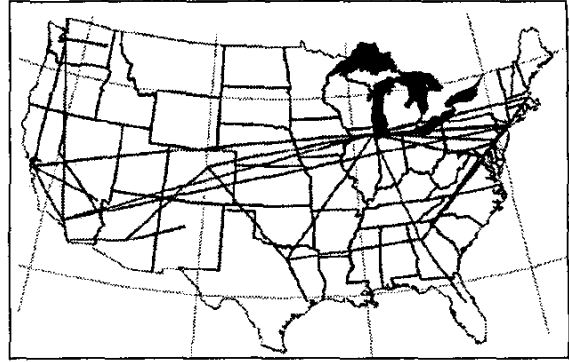


Figure 6. OD Pairs with 40 to 60 Daily Operation and One Airport in the Inland USA

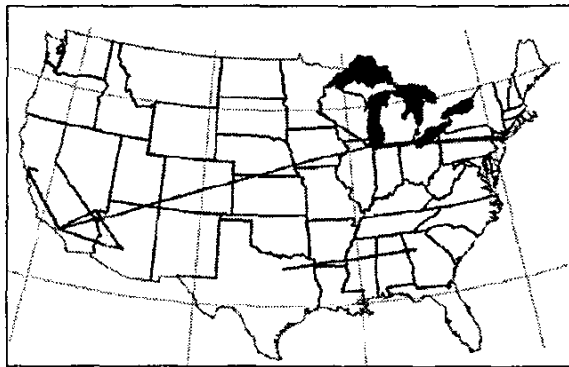


Figure 7. OD Pairs with More Than 60 Daily Operation and One Airport in the Inland USA

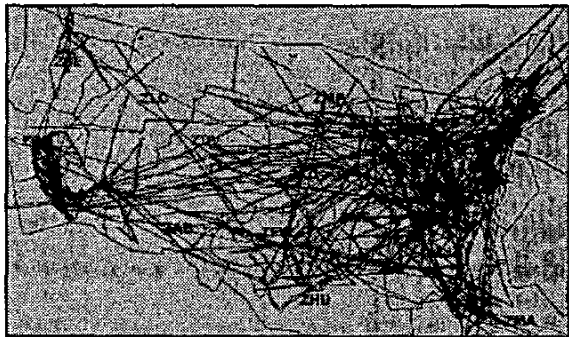


Figure 8. Flight Tracks for One Day of GA Operations

A significant portion of US operations is General Aviation (GA) flights. GAs do not fly similar routes every day and their routing is highly effected by season change and day of the week. As shown in Figure 8, there is no underlying structure in GA route structure. Except for the business jets most of the GA aircraft are not equipped with required avionics for the HTS and they are not capable to fly high enough to participate in HTS network.

Role of HTS in Relieving the Existing ATM Chokepoints

ATM chokepoints are areas in the airspace where there is a potential for many conflicts and the flow pattern is complex. The Federal Aviation Administration (FAA) has identified seven major chokepoints east of the Mississippi river as far north as Boston and as far south as Atlanta [10]. This region consists of the country’s major population areas and busiest airports. Congestion at one chokepoint can propagate to rest of the system and create delays at many airports. Figure 9 illustrates these national chokepoints.

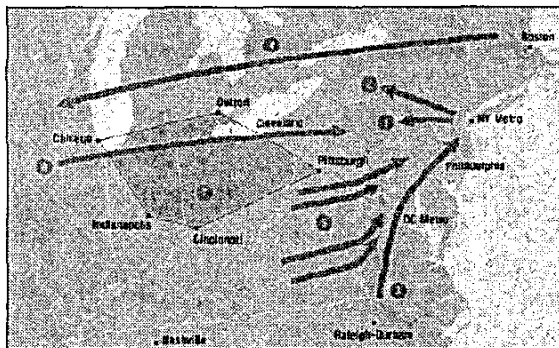


Figure 9. National Choke Points from FAA’s Aviation Capacity Enhancement Plan (ACE Plan) 2001

Currently, the arrival flows into Newark and LaGuardia Airports pass through narrow sectors located in the airspace of the Washington en route Center. These sectors can only accommodate a few aircraft in the holding patterns and the rest of the traffic has to be delayed before arriving to this area. This configuration creates congestion in neighboring sectors. Comparing the Figures 6, 7 and 9 it is apparent that a HTS network between

ORD, NY-Metro, DC-Metro could relief the existing chokepoints.

Potential HTS Corridors

In this section we study a few congested OD pairs that are potentially suitable for development of the HTS network. Figure 10 shows the flight tracks for all the scheduled flights between LAX and ORD for a full day. Wind optimized routes are recognized from east to west and vice versa. Note the significant number of sectors that these tracks are currently crossing. Each direction could have a distinct HTS that is optimized for wind direction and could be dynamic to avoid adverse weather. Figure 11 illustrates all the routes to DFW for airline operations. DFW is another example of a congested airport that could be one leg of a HTS network.

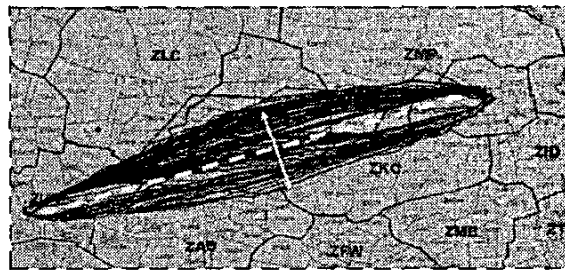


Figure 10. Flight Tracks for One day of Operation between LAX and ORD

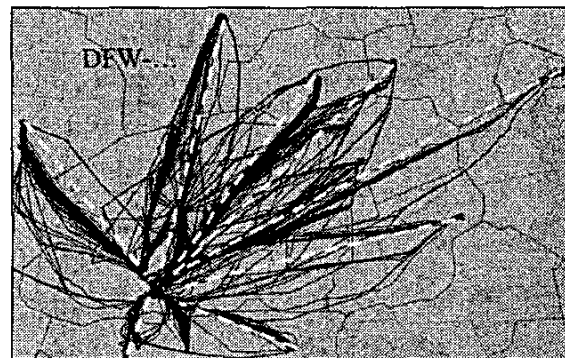


Figure 11. Flight Tracks for all the Flights Destined to DFW

As shown in Figure 12 most of the aircraft between BWI and ATL are flying a direct route. In addition, an alternate route is developed to avoid the adverse weather. In this corridor there may be two HTS which could be used based on the weather conditions in vicinity of each airport.

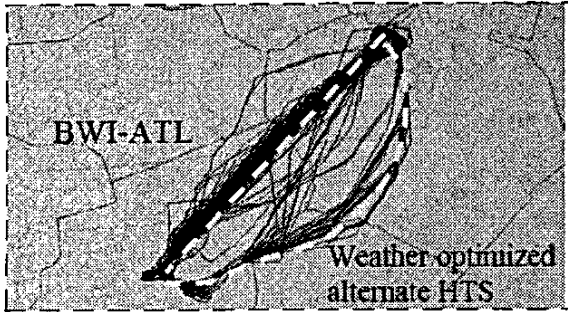


Figure 12. Flight Tracks for One day of Operation between BWI and ATL

HTS Concept

HTS development is proposed as creation of a network of elongated sectors between high volume airports connecting congested city pairs. This system could be viewed similar to the interstate highway system that includes multiple travel lanes, on-off ramps, breakdown lanes, passing lanes and standard -dynamic detours around obstructions such as weather. HTS network could include parallel lanes to increase the tube's capacity, breakdown lanes to accommodate avionics failures and passing lanes to accommodate aircraft with different performance characteristics operating in the same tube.

The HTS is a highly regulated operating environment requiring participating aircraft to be equipped with avionics that permit self-separation and station-keeping. Aircraft participating into the HTS must be equipped with ADS-B, GPS based navigation system and CDTI for more precise aircraft-to-aircraft separation. High degree of situational awareness could permit reduction of lateral separation. Such a network would potentially maximize the airspace throughput by more efficiently transporting aircraft, into and out of the congested airports.

Based on the congestion level and tube size, one controller could manage one tube or tubes

could be segmented and one controller could be assigned to each segment. The HTS is proposed to be an additional operating environment to the Air Traffic Management (ATM) System besides the current sectors. Figure 13 illustrates a schematic view of a HTS and existing sectors.

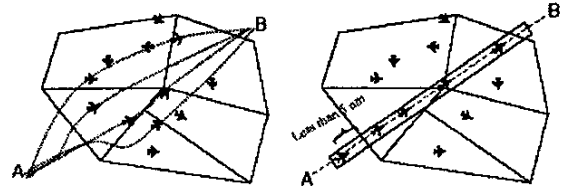


Figure 13. HTS Development Structures the Airspace

Aircraft Capabilities

As a minimum requirement, participating aircraft in the HTS should be equipped with Conflict Detection/Resolution (CD&R) tools, 4D Flight Management System (FMS), Station-Keeping equipments and CDTI for situational awareness. The separation responsibility could be transformed to the cockpit and ATC would be responsible for strategic planning (i.e. change the path of stream to avoid adverse weather). Also ATCs would assure that aircraft which are not equipped with required avionics do not enter a tube.

Flow Visualization

To determine the topology of a HTS network we need an abstract model of air traffic flow which visualizes the current traffic structure. We model the air traffic flow as a fluid, where each aircraft is assumed to be a particle of the fluid. Velocity of a small volume of the fluid is calculated as resultant of velocity vectors of each aircraft. Figure 14 illustrates a schematic view of the process. A small volume of the fluid contains 4 aircraft and resultant of the velocity vectors for each aircraft yields the velocity vector for the fluid (equation 1).

The aircraft position updates taken by radar hits in the Enhanced Traffic Management System (ETMS) has been used to calculate the velocity vectors for each aircraft during a 15 minute period. Having computed velocity vectors for small

elements of the fluid, a vector field of the fluid velocity is constructed and shown in Figure 15.

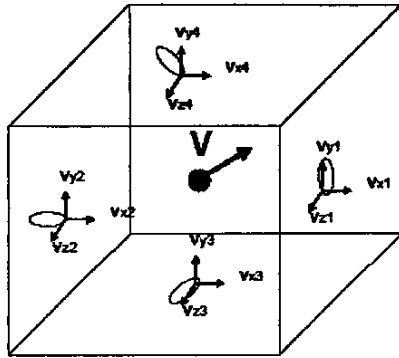


Figure 14. Velocity Vectors of Fluid Elements are Computed as Resultants of the Aircraft Velocity Vectors

$$\vec{V} = \sum_{i=1}^4 \vec{V}_i \quad (1)$$

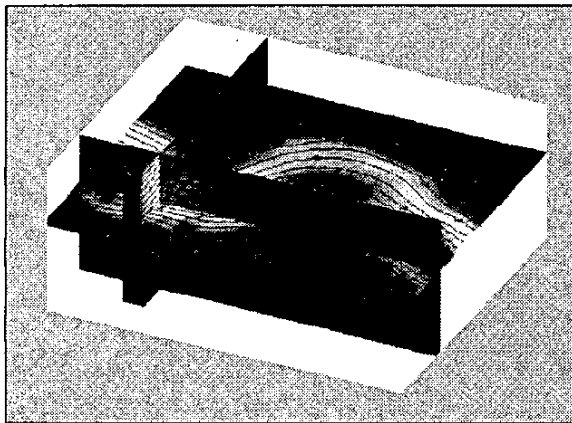


Figure 15. Aircraft Flow Visualization, Vector Fields of Aircraft Velocity

Another method for visualizing the traffic flow is to indicate divergence of the vector field by width of some tubes [11]. In Figure 16 same airspace is shown using tubes to indicate the flow velocity in a more rigorous way.

The aircraft velocity values in ETMS database are recorded as one dimensional numbers and there are many missing values in the database. Therefore to calculate the velocity vectors of each aircraft, we used position updates.

Such a flow modeling requires significant amount of computation for calculating the individual aircraft's velocity in 3D from position updates. We are currently extending this model for a larger airspace.

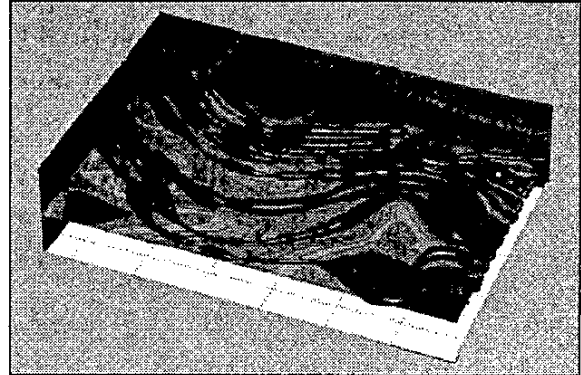


Figure 16. Construction of Tubes Based on the Velocity Vector Fields

Conclusion and Future Work

The issue of ATC workload as a critical capacity constraint is apparent. Without a revolutionary change, the ATM system could not efficiently handle the future growth in air traffic. Recent advances in avionics and data links provide capabilities for new concepts of operation. The HTS concept may potentially eliminate some of the system inefficiencies. However extensive studies in operational concept and feasibility of the HTS network are inevitable. Major areas of future research could be summarized as follows:

- 1 HTS Geometry Design
- 2 HTS Control Concept Research
- 3 Aircraft Capabilities and Equipage
- 4 Role of Human in HTS Operation
- 5 Failure Modes Research
- 6 Benefit and Cost Studies

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