Dynamic Allocation and Benefit Assessment of NextGen Flow Corridors

Abstract—A flow-based modeling approach is proposed to identify candidate airspace for high-density flow corridors. The input to the model is a set of projected user-preferred, wind optimal, and unconstrained 4D trajectories (4DT). We compute Velocity Vector Fields (VVF) in the 4D space-time and cluster the velocity vectors both in time and space to define flow of aircraft when they fly their preferred trajectories under high capacity conditions. A sliding time window is implemented to dynamically create and optimize corridors’ coordinates based on the changes in preferred trajectories. From this process we compute a NAS-wide corridor network that mimics the dynamics of user preferred trajectories. In operational setting, flights will have the option of joining a corridor that is closest to their optimal trajectory. Using NAS-wide simulation, we assess the benefit of corridor network by comparing efficiency gained by joining the corridor network against extra distance traveled to join the network. We show that much of the overall corridors benefit may be gained by creating very few corridors.

I. INTRODUCTION

Recent advances in Communication Navigation and Surveillance (CNS) technologies are changing operating conditions of the Air Traffic Controller (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 equipment 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. These new features provide flexibility for airspace designers to implement new classes of airspace that are capable of accommodating multiple times more traffic than the current airspace structures.

One of the new classes of airspace introduced within NextGen is Corridors-in-the-Sky [1]. It is defined as a region of airspace, generally a long and narrow pathway, in which aircraft move in common direction or trajectory and along parallel lanes. Strictly speaking, by this definition, today’s jet routes qualify as corridors with their capacity determined based on minimum separation distances in different dimensions. Corridors can be viewed as a type of reserved airspace within which ATC provides neither separation services nor authorization to enter. Those two functions would overlap only in the corridor transitional areas, near the entry and egress points of the corridor.

The term corridor covers a range of operational concepts proposed by researchers such as High Volume Tube Shaped Sectors (HTS)[2], tubes[3], [4], [5], [6], highways-in-the-sky[7], and Dynamic Multi-track Airways (DMAs)[8]. While corridors do not have to be restricted to high altitudes, they find their most natural home in high-altitude airspace. Three of the prominent characteristics of NextGen corridors that would distinguish them from today’s airways are:

- Allowance for multiple (parallel) lanes of traffic;
- Capitalization on advanced CNS technology to enable changes in methods of separation, such as self-separation that potentially reduces separation standards within the corridor, or enables flying in formation;
- Dynamic activation rules to add or remove corridor structures, as needed, throughout a day.

A well-designed corridor reduces the airspace complexity and increases airspace capacity by minimizing interference from crossing traffic. In the corridor, there might be several parallel lanes to increase its capacity, breakdown lanes to accommodate avionics failures and passing lanes to accommodate aircraft with different performance characteristics operating in the same corridor. This benefits the corridor users directly by enabling them to use tighter separation between aircraft safely, boosting the capacity of the corridor and providing more flexibility in choice of slots for prospective corridor users.

A corridor can be static or dynamic. The corridor may be dynamically shifted to avoid severe weather or to take advantage of favorable winds. Moreover, it may only be utilized during certain times of the day or in response to certain triggers. In a dynamic corridor, the 3D trajectory of its centerline is a function of time and the corridor’s length may stretch or shrink during the day. Moreover, the start and end of the corridor may change during the corridor’s lifetime. This information must be fed to the Air Navigation Service Provider (ANSP) and be available for the aircraft flying that corridor. For instance, whenever a large number of flights are scheduled to be traveling from New York to Chicago within an hour, a pre-defined corridor might be turned ON and used to speed their journey, then deactivated for the rest of the day.

Yousefi et al.[2] performed statistical analysis of city-pair traffic and showed that 33 percent of the total scheduled
flights are operated between about 10 percent of the city-pairs. These city-pairs were identified as backbones of the airspace system and it was concluded that increasing the capacity of these routes could significantly improve the total system capacity. Additionally authors modeled the air traffic as flow of a fluid, where aircraft are the particles of the fluid. The velocity vectors for small volumes of airspace were then calculated as the resultant velocity vectors for individual aircraft. Accordingly, vector fields of the fluid velocity were created. It was proposed that the analysis of vector fields topology can be used to determine the geometry and location of potential corridors.

Sridhar et al. [4] used clustering techniques using today’s traffic to group the airports in close proximity of each other and construct corridors by connecting these groups of airports via great circle routes. Xue et al. [5] used Hough transformation to cluster the great circle routes between city-pairs into corridors and performed analysis of NAS-wide deviation from great circle routes required to join the corridor network. Hoffman et al. [6] constructed a corridor network by connecting major metroplex airports. Finally, Wing et al. [8] performed regional pooling of airports using different distance criteria and constructed DMAs by connecting pools of airports via great-circle routes.

In this paper, we attempt to analyze the dynamics of corridor network and include this in our design methodology. Specifically, we predict the periods that corridors should be active or how their centerline should dynamically change in response to changes in demand profile and weather disruptions. We develop a method that dynamically identifies high-density sections of the airspace that can benefit from new corridors. Similar to the proposal by Yousefi et al. [2] we model the aircraft flow and then group the major traffic flows based on a predetermined set of proximity parameters and finally insert corridors along the flows’ center of gravity. Furthermore, through NAS-wide simulation of traffic and using a futuristic 2.0X traffic forecast, we perform benefit assessment of corridor network in terms of system-wide recovered delay.

The paper is organized as follows: Section II, presents the steps and the mathematical model for designing a dynamic corridor backbone over a desired section of airspace. Section III discusses the cost/benefit analysis in terms of the total length of corridors implemented and the percentage of NAS-wide delay recovered. Finally, Section IV summarizes conclusion, briefly describes the possible implementation scenarios, and indicates next research steps.

II. CORRIDOR ALLOCATION METHODOLOGY

The following are the design criteria we seek to address in our methodology:

- A corridor is expected to be the principle and best route between two en route points and therefore its location should roughly align with user-preferred and wind-optimized trajectories.
- We assume that aircraft inside a corridor do not observe en route delay. This may be possible if we design corridors with sufficient lanes to accommodate the assigned traffic.
- Technically the more corridor we place in the system, the more delay will be recovered. However, in some areas the traffic density is not high enough to justify placement of corridors. Hence, projected corridor utilization must be considered as a design parameter.
- Only aircraft that are equipped with advanced avionics for self-separation are allowed to enter the corridor network.
- Corridor coordinates should be dynamic in time and an activation rule should be defined based on projected traffic density.

Using these criteria we first determine the optimal location of corridors and update their location based on the changes in user preferred trajectories. The following subsections describe the steps of our methodology.

As a final step, our algorithm suggests the best trajectory (including inside and outside a collection of corridors) that an aircraft could fly to observe minimum en route delay.

The following subsections describe the steps in our algorithm to design corridor backbone.

A. User-Preferred Trajectories and Traffic Forecast

Our main design criterion is to place the corridors close to user-preferred trajectories. Hence the first step is to generate futuristic unrestricted 4DTs including equipage forecast. The equipage data is needed to indicate which aircraft are capable for self-separation. We used a schedule data that was evolved from a baseline schedule of 3/28/2007 to 2.0X using FAA’s 2007 Terminal Area Forecast (TAF) reports. This data was fed to NASA’s Future Airspace Concept Evaluation Tool (FACET) to calculate wind-optimal trajectories. Finally, equipage data was fused to these trajectories and this unconstrained data is used as input to our analysis. Details of this data preparation process can be found in the cited references[9].

B. Flow Modeling based on Velocity Vector Field

In this section we develop a flow-based approach to identify candidate airspace for corridors. The space-time comprising of the earth sphere plus its exterior and time is a 4-manifold with boundary denoted by $M$. Let $Tr$ denote all the aircraft trajectories in the 4-manifold $M$ for an indefinite period of time. To each point on $Tr$, a tangent velocity vector is associated that follows the direction of the trajectory and indicates the velocity of the aircraft on that trajectory. For locations with no trajectory passing through them a zero vector is assigned. Note that in reality, at each point in space-time there can be only one aircraft and therefore only one velocity vector.

We explain below that the proposed algorithm works even if some trajectories calculated from flight plans coincide at some points. However, to establish a sound mathematical background for this problem, it is assumed that any absolute conflict in trajectories is resolved beforehand.
Equivalently, for a flight $i$ at time $t$, the 4D position vector $r_i(t)$ and 4D velocity vector $v_i(t)$ are related as follows:

$$r_i(t) = (x_i(t), y_i(t), z_i(t), t)$$

$$v_i(t) = \left(\frac{dx_i(t)}{dt}, \frac{dy_i(t)}{dt}, \frac{dz_i(t)}{dt}, 1\right)$$

(1)

(2)

where $x_i$, $y_i$, and $z_i$ denote the aircraft’s position components in Cartesian coordinate system.

The above characterization is the definition of a VVF on the 4-manifold $M$. Lambert conformal conic projection is used to create a VVF over 4D space-time. By presenting the magnitude of each velocity vector in terms of the distance to create a VVF over 4D space-time. By presenting the

C. Discretization of Velocity Vector Field

As a first step to make data suitable for numerical analysis, the user-preferred flight trajectories, $Tr$ are sampled every $T$ units of time starting from $t = 0$. The discretized version of the VVF is obtained by the set of velocity vectors defined for these sample points. Selection of $T$ is based on the trade off between computational speed and accuracy of the results.

Each sampled data item includes four positions and three non-trivial velocities. These seven attributes are sufficient to create a VVF over 4D space-time. By presenting the magnitude of each velocity vector in terms of the distance the associated flight travels per sampling period $T$, we can immediately identify the flight trajectories in the VVF.

**Fig. 1. VVF for FL280 to FL310 from 00:00 to 03:00 Zulu in 6-Minute Increments.**

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**Fig. 1. VVF for FL280 to FL310 from 00:00 to 03:00 Zulu in 6-Minute Increments.**

Figure 1 demonstrates a sample projection of VVF over the latitude-longitude-time space for three hours of sample data from 00:00:00 Zulu over the continental US. Only aircraft flying at flight levels FL280 to FL310 are included. As shown in the figure, for a high sampling rate, the resulting graph will be a close approximation of trajectories.

D. Clustering Velocity Vectors

Each non-zero velocity vector in the VVF is identified by the seven-element state vector $s = (t, r, \theta, \phi, v, \alpha, \gamma)$ representing the sampling time, the position of its origin, and its speed and heading. $t$ is the sampling time measured in number of elapsed time steps $T$ from a reference point. $r, \theta$ and $\phi$ identify altitude, latitude, and longitude respectively. $v$ identifies the ground speed, and $\alpha$ and $\gamma$ denote the horizontal and vertical headings of the aircraft. This state vector is augmented by a weight factor $\omega$ that will carry some information from the clustering process. All the state vectors in the VVF are originally assigned a weight of 1. The heart

of our methodology is to identify the state vectors that are adjacent and cluster them to one corridor element.

To define vector adjacency, we need an operation to measure the distance between two state vectors. We follow the same notation for norm $\|\|_1$ as specified by Dowek et al.[10]

**Definition 1:** A vector norm $\|\|_1$ is an operation from vectors to real numbers that satisfies the following criteria for any two vectors $s_1$ and $s_2$ and any scalar $k$:

1) The zero vector, 0, has zero norm; every other vector has a positive norm.
2) Scalability: $\|k s_1\| = \|k\|\|s_1\|$
3) Triangular inequality: $\|s_1 + s_2\| \leq \|s_1\| + \|s_2\|$

We define two norm operators $\|\|_1$ and $\|\|_2$ consistent with the above definition:

$$\|s_1 - s_2\|_1 = \max \left(\frac{|t_1 - t_2|}{T + 1/2}, \frac{|r_1 - r_2|}{R}, gcd(\theta_1, \phi_1, \theta_2, \phi_2), \frac{|\alpha_1 - \alpha_2|}{A}, \frac{|\gamma_1 - \gamma_2|}{\Gamma}\right)$$

(3)

$$\|s_1 - s_2\|_2 = \max \left(\frac{|t_1 - t_2|}{T + 1/2}, \frac{|r_1 - r_2|}{R}, \frac{\text{latD}}{\Theta}, \frac{\text{lonD}}{\Phi}, \frac{|\alpha_1 - \alpha_2|}{A}, \frac{|\gamma_1 - \gamma_2|}{\Gamma}\right)$$

(4)

gcd is the great circle distance between two points on the surface of earth. latD and lonD calculate the lateral and longitudinal distances of two velocity vectors with respect to their mean heading. The arbitrary variables $T, R, \Theta, \Phi, V, A, \text{and } \Gamma$ are separation requirement parameters and are determined based on design criteria. $\|\|_1$ is used with $T = 0$, when we are grouping the vectors at each time step. $\|\|_2$ is used when we are grouping the elements of potential corridors in the sliding window protocol described in the next section.

**Definition 2:** Two state vectors $s_1$ and $s_2$ are considered neighbors if and only if:

$$\|s_1 - s_2\| \leq 1$$

(5)

**Definition 3:** A set of state vectors is called a bundle and is identified by $B$.

**Definition 4:** The neighbor list of a state vector $s_i$, denoted by $NL_i$, is defined as:

$$NL_i = \{s_k : \|s_i - s_k\| \leq 1\}$$

(6)

Note that state vector $s_i$ is included in its own neighbor list.

**Definition 5:** A complete neighbor list $CNL$ is a set of state vectors that is the union of all the neighbor lists of its members:

$$CNL = \{s_k : \forall s_i \in NL_k \Rightarrow s_i \in CNL\}$$

(7)

Generating $CNL$ is an iterative procedure of searching for the neighbors of the current members and adding the newly
found state vectors to the bundle until all the members have been tried.

Procedure 1: Generating the CNLₖ around a state vector sₖ, known as the seed of the bundle:
1) Initialize CNLₖ with the state vector sₖ
2) For each sᵢ ∈ CNLₖ calculate the following:
   • Generate NLᵢ
   • Update CNLₖ by concatenating it with the set NLᵢ − CNLₖ

Proposition 1: The following condition always holds:

\[ \text{if } sᵢ \in \text{CNLₖ} \Rightarrow \text{CNLₖ} = \text{CNLᵢ} \quad (8) \]

Procedure 2: Partitioning a set of state vectors S in a 4D section in space-time:
1) Maintain a check list Cl for all members of S
2) For each sₖ ∈ S calculate the following:
   • If Cl(sₖ) = 1 continue with the next member
   • Otherwise generate CNLₖ
   • Set Cl(sᵢ) = 1 for all sᵢ ∈ CNLₖ
3) Proposition 1 ensures that the outcome of partitioning is indifferent to the initial seed location, and that the intersection of any two distinguished CNLs is empty:

\[ \text{CNLᵢ} \cap \text{CNLₖ} = \emptyset \Leftrightarrow \text{CNLᵢ} \neq \text{CNLₖ} \quad (9) \]

Definition 6: The Center of Gravity (CoG) of a bundle B is a state vector that is the weighted average of all its members:

\[ \text{CoG} = \frac{1}{ω_{CG}} \sum_{k} ωₖsₖ, \quad (10) \]

where k is the index of all sₖ ∈ B, ωₖ is the weight of each state vector, and ω_{CG} = \sum k ωₖ is the weight associated with CoG vector.

Definition 7: A CoG bundle is a set of state vectors that all its members are in the neighbor list of its CoG vector:

\[ B_{CG} = \{sₖ : \|sₖ - \text{CoG}\| ≤ 1\} \quad (11) \]

Proposition 2: The CoG of two disjoint bundles B₁ and B₂ can be obtained by:

\[ \text{CoG} = \frac{1}{ω_{CG1} + ω_{CG2}} (ω_{CG1}s_{CG1} + ω_{CG2}s_{CG2}) \quad (12) \]

where ω_{CG1} and ω_{CG2} are the weights of the two bundles respectively.

Procedure 3: Generating a CoG bundle around state vector sₖ:
1) Initialize CoGₖ with the state vector sₖ
2) Calculate the CoG vector s_{CG} for the set
3) Generate neighbor list NL_{CG} for s_{CG}
4) If \( NL_{CG} \cap \text{CoGₖ} = \emptyset \) then terminate the procedure
5) Otherwise update CoGₖ by concatenating it with the set \( NL_{CG} \cap \text{CoGₖ} \)
6) Go back to step 2.

Procedure 4: Breaking a complete neighbor list CNL to a set of CoG bundles:
1) Calculate CoG vector s_{CG} for the set
2) Order the members of CNL in descending order by their distance from s_{CG}
3) Pick sₖ from the head of CNL
   a) Calculate the CoGₖ for state vector sₖ
   b) Remove CoGₖ from CNL
   c) Go back to step 1 until CNL = \emptyset

Figure 2 demonstrates the steps in calculating CoG vector at each time step for two adjacent flights.

E. Sliding Window Framework

We are now equipped with necessary structure and tools to design corridors element by element by clustering the aircraft state vectors. We first identify areas in the space-time with high level of congestion. Due to the random nature of NAS and unpredictable parameters, the actual 4D trajectory is always diverted from the filed flight plan. If all the probability density functions (pdf) of the random variables are known, it is possible to obtain the chance of separation violation for any two aircraft. In this paper, we do not intend to obtain pdf for deviation of each aircraft from its centerline. Instead to account for the underlying uncertainty, we consider multiple times minimum required separation to identify the regions with potential violation and cluster the state vectors accordingly.

The second step in the design procedure is to calculate dynamically the attributes of each corridor element as listed below:

- Coordinates of the corridor’s centerline
- Number of parallel lanes of traffic
- Activation time period
- Aircraft speed range

Assume at time step t a corridor network already exists. Consider a sliding time window of size \( T_{aw} \) starting at the
processing time step $t$. The goal is to update the corridor backbone by adding additional corridor elements or removing or modifying existing corridors elements based on the preferred flight trajectories in this time window. If a corridor element is not highly occupied for some $T_{ka}$ period of time, it becomes inactive. $T_{ka}$ is known as the keep alive time.

When the new state vectors that are entering the sliding time window have slight deviation from some corridor elements, it is not possible to know if the deviation is in response to weather parameters, or simply due to association of the flight with a new origin destination pair. Therefore to create a stable corridors, clustering and CoG calculation is done according to the weighting of each element. Each corridor element is weighted based on the average flow rate it is accommodating.

We must also distinguish between desired 4DT and planned 4DT. At any time step, each aircraft files its desired optimal 4DT in the unconstrained airspace and the optimal 4DT that it plans to fly considering the structure of the corridor backbone and other constraints. In other words, depending on the location of the corridors more flight may change their planed 4DT to benefit from those corridors, however, the optimal design of corridors is done according to the VVF obtained from the desired 4DT of all the aircraft.

Corridor network is designed in the following high-level steps:

1) Create the VVF from the desired 4DT of all the aircraft
2) At a time step $t$, collect the state vectors for $T_{sw}$ units of time in the future.
3) For each time step in the sliding window, calculate all the distinguishable $CNL$s with time separation parameter set to zero $T = 0$ and norm definition $||\cdot||_2$. The other separation parameters are design parameters that must be chosen for optimum cost/benefit tradeoffs. 
4) Break the $CNL$s to the minimum set $CoG$ bundles and calculate the flow rate for each bundle.
5) Replace all the $CoG$ bundles with their associated $CoG$ vector $s_{CoG}$.
6) In the new VVF, for all the data in the sliding window, calculate all the distinguishable $CNL$s using the norm definition $||\cdot||_2$. Set the time separation parameter to the size of sliding window $T = T_{sw}$, this is equivalent to collapsing the 4D potential corridor elements over the time domain. Also, set the lateral separation $\Theta$ to distance separation $D$ in $||\cdot||_1$. The longitudinal separation parameter $\Phi$ is set to half of the average speed of any two state vectors. The other parameters are the same as in $||\cdot||_1$.
7) Break the new $CNL$s to the minimum set $CoG$ bundles and calculate the flow rate for each bundle. The set of associated $CoG$ vectors $s_{CoG}$ with high usage over time are good candidates for permanent 3D corridors.
8) Filter out the low-flow rate elements based on the design parameter flow-rate threshold $FR_T$.
9) Update the corridor backbone with the remaining corridor elements:

   a) For each $CoG$ vector $s_{CoG}$ from the sliding window, search in the corridor backbone for a neighboring corridor element $s_{CB}$
   b) Replace $s_{CB}$ with the $CoG$ vector of the two adjacent vectors
   c) If there was no neighbor, add the new $CoG$ bundle to the corridor backbone

10) Backbone structure is broadcast back to all aircraft.
11) Set $t = t + 1$ and go back to step 2.

By grouping the state vectors inside the sliding window, we can calculate the average traffic flow per unit of time. Moreover, the minimum required longitudinal separation of aircraft in a corridor determines the capacity of each lane; therefore the number of required lanes in each corridor element can be calculated based on the average flow rate in the corridor.

Note that depending on the accuracy of the weather forecast, the time-specific corridor elements may be published a few hours ahead of their activation.

F. Deployment Scenarios

To obtain the optimal corridors, we assume that each flight would file a desired unconstrained trajectory and an actual planned trajectory which is calculated based on the current structure of airspace and its associated constraints. Planned trajectory may divert from the optimal route because it may benefit from an existing corridor. However, corridor design in each time step, must be calculated according to their desired route.

Based on the 7 separation parameters, we can create an overlapping grid up to 7 dimensions. The goal is to minimize the search computation for finding neighbors to each state vector. The size of each dimension of the grid cell is multiple number of the separation parameter for that dimension. In the first step, each state vector is mapped to one of these grid cells, based on its parameters. To find the neighbors, we only search for other state vectors within that cell and its neighboring cells.

G. Navigational Reference System Grid

The FAA has proposed the Navigational Reference System (NRS) as part of the high-altitude airspace redesign initiative [11]. The NRS is a set of waypoints located on a regular grid of latitude/longitude coordinates, and is used for flight planning and navigation. The grid’s origin is at the Equator south of Greenwich, England. The NRS waypoints currently have a resolution of 30 minutes of latitude and 2 degrees of longitude. In its final version, the grid resolution will be 10 minutes of latitude and 1 degree of longitude.

We assume that within NextGen the NRS grid will be used as a referencing system and corridors should be published as a collection of consecutive NRS waypoints. Therefore, after generating the corridor network backbone, we map each corridor segment to its closest link in NRS grid.

III. RESULTS AND DISCUSSIONS

In this section we use a sample traffic forecast and generate corridor networks using the defined processes. Furthermore,
we assess the trade-off between NAS-wide delay reduction as a result of employing efficient corridors, against the extra distance flown to join the corridor network.

A. Corridor Network Generation

We use the unconstrained, user preferred, and wind-optimal 4DTs generated in Section II-A and generate corridor backbone. Figure 3 depicts the time step clustering of VVF for one hour of flight schedule at 15 Hour Zulu time for all aircraft flying Continental United States (CONUS) at flight levels FL290 and above. For clustering the state vectors, separation parameters are set to: \( T = 0 \), \( R = \infty \), \( D = 32 \text{nm} \), \( \Theta = 5^\circ \), \( \Phi = 5^\circ \), \( V = 30 \text{ Knots} \), \( A = 5^\circ \), \( \Gamma = \infty \). We have not set any separation limit in altitude. As depicted by the figure, velocity vectors almost cover the entire airspace but many of these routes are not flown frequently. Aircraft flying the same origin/destination but over different time periods may fly completely different routes that are optimized for wind-data at that specific time of the day. Note that some trajectories associated with different Origin/Destination may be merged for part of their path when they get close enough.

In Fig. 4, the 4D VVF has been collapsed over its time dimension to obtain the potential corridor elements, and calculate the percentage of time each corridor element is occupied over time. In Fig. 5 the corridor elements have been mapped to NRS grid and data is filtered to exclude the corridor elements that have been occupied by flow rates of less than 10 aircraft per hour. Now the goal is to identify the potential 4D corridor elements that are highly utilized over time.

Time usage of potential corridor backbone has been illustrated in Fig. 6. Utility is calculated as the percentage of aircraft flying the corridors over time. \( FR_T \) is set at 10 aircraft/hour. As the flow rate is increased, the percentage of aircraft that are naturally in the corridors reduces. Figure 7 illustrates the scenario that the \( FR_T \) has been raised to 25 aircraft per hour and corridors are mapped to NRS grid.

It is apparent from these figures that higher values for \( FR_T \) result in less dense corridor network. Figure 8 illustrates the
Timestep: 15 Hour UTC

29− 38
38− 53
53− 71
71− 94
94−128

Fig. 7. Corridor Backbone for Flight Levels FL290 and Above with \( FR_T = 25 \).

percentage of active corridors for different values of \( FR_T \). For example for \( FR_T = 25 \), total length of corridor backbone is reduced to only 52,000 nm or roughly 10 coast-to-coast corridors. This indicates the fact that there are certain flows of aircraft in the NAS that carry a large portion of overall traffic and enhancing the en route efficiency of these flows (i.e. by employing corridors) would result in significant system-wide throughput enhancement. Next we show that creating corridors along these major flows may deliver much of the overall NAS-wide delay reduction.

Fig. 8. Percentage of Active Corridors vs. Flow Rate Threshold.

B. Corridor Benefit Assessment

In this section we describe a methodology for evaluating the benefit of corridors in reducing NAS-wide delay. Consider two routing options between two en route points A and B, as shown in Fig.9. Aircraft can fly the direct route between two points and observe delay as a result of sectors’ limited capacity; \( delay(A, B) = \sum_{j=1,2,5} d_j \), where \( d_j \) is the en route delay observed in sector \( j \). Alternatively, aircraft can fly extra distance to join and leave a corridor element and therefore observe delay; \( delay(A, B) = \sum_{j=1,2,5} d_j' \), where \( d_j' \) is the delay due to excessive distance flown. Comparison of these two delay values indicates the optimal trajectory for each flight and whether it is efficient for them to join corridors. This assumes that corridors have enough capacity to allow aircraft to fly their optimal cruising speed.

The delay incurred to join corridors can be calculated using the distance between user preferred 4DTs and optimal cruising speed for each aircraft. However estimating the en route delay requires more detailed computation. For that we use NAS Simulation and Queuing Model (NSQM) which is a NAS-wide discrete time simulation model developed to provide a level playing field for evaluating and comparing Traffic Management Initiatives (TMI) strategies [12]. NSQM uses predetermined sector capacity values and applies airport holding, airborne delay, and re routes to maintain sectors’ demand under admitted capacities. We define sector capacities based on historical usage; for additional information on how nominal sector capacities are defined refer to Myers et al. (2008)[13].

Using the NSQM we define an inefficiency factor, \( f_{si} \), for each sector as the total delay incurred divided by the total dwell time for all the flights going through each sector for the 24 hours of unconstrained 4DTs. This inefficiency factor indicates the average delay that each flight observes per unite time while crossing each sector. Finally, having these inefficiency factors for each sector, we can compute the delay that each sector will impose on each flight without a need for further NSQM runs.

We use the unconstrained wind optimal 4DTs to perform the above calculations. For different values of flow rate threshold, \( FR_T \), we generate corridors and map them on NRS grid. Then using the sector inefficiencies we determine the optimal trajectory for each aircraft by comparing the delay incurred with or without joining corridor segments. Finally, we compute NAS-wide delay as a function of total corridor length. The results of this analysis is summarized in Fig. 10. For different corridor lengths, the recovered NAS-wide delay is plotted as percentage of delay reduction from baseline no-corridor case. Higher values for \( FR_T \) result in less dense backbone of corridors. For example for \( FR_T = 25 \), total length of corridor
backbone is reduced to only 52,000 km or roughly 10 coast-to-coast corridors. For this value, still about 60% of aircraft are inside the corridors at any time step and delay is reduced by about 60%. From this point, as we create more corridors (by decreasing FR_T), the rate of increase in recovered delay declines. This is an important observation and indicates that much of the overall corridor benefit can be gained by creating few corridors.

Publishing the corridors and deploying new procedures for interaction of corridor and non-corridor traffic is a costly exercise for the ANSP, especially when corridors are changing dynamically. However our analysis shows that few corridors should deliver significant benefit and this may justify creation of few major corridors within NextGen.

The issue of ATC workload as a critical capacity constraint is apparent. Without a revolutionary change, the ATM system will not efficiently handle the future growth in air traffic. Recent advances in avionics and data links provide capabilities for new concepts of operation. Corridors-in-the-Sky is one such concept that is also proposed within the NextGen ConOps.

Objective methodologies are needed to dynamically compute the topology of the corridors. We have modeled the air traffic similar to flow of a fluid, where aircraft are the particles of the fluid. Contiguous corridors are created by connecting the high density and usage corridor elements which indicate high flow rate traffic. Then we map the resulting corridors to NRS grids. Using a set of unconstrained 4DTs, we presented sample corridor networks for different values of corridor flow rate threshold.

We used detailed NAS-wide simulation to assess the benefit of corridor network in recovering overall airborne delay. We show that much of the overall corridors benefit may be observed by creating very few corridors in the NAS.

Due to many parameters affecting the user-preferred routes, we believe that the optimal design of corridors and scheduling of flight plans should be performed iteratively. Unconstrained user preferred 4DTs may be fed to our algorithms to produce a corridor network. Then aircraft may decide to alter their routes to join some segments of corridor network. This new flight plan is passed to corridor design algorithm to update the corridors. This procedure should be iterated until an optimal corridor backbone and optimal flight plans are obtained.

Only aircraft with certain equipage level are capable of flying in corridors. As a result, once a corridor is activated, all the aircraft without the necessary equipments must be rerouted out of corridors. Future work may analyze the additional system-wide cost due to this re-routing.

Our analysis was based on the assumption that system is quite predictable up to a timeframe T_p, during which there is no uncertainty in aircraft intent. Future work may consider data beyond T_p with lower validity weight.

Corridors are really the evolution of existing RNAV Q-routes. The existing Q-routes are published based on airline requests without an objective methodology for identifying their optimal location in the NAS. The methodologies presented herein may also be used to calculate the optimal configuration of Q-routes.

IV. CONCLUSION AND FUTURE WORK

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