

Design Analysis of Corridors-in-the-sky

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Corridors-in-the-sky is a new airspace structure designed to accommodate high density traffic by grouping flights with similar trajectories. Less air traffic controller workload is expected than with classic airspace structures. Thus, corridors-in-the-sky may increase national airspace capacity and reduce flight delays. To evaluate/design corridors-in-the-sky, besides identifying locations, their utilization, altitudes, and impacts on non-corridor traffic need to be analyzed. Although not providing complete analysis, this paper chooses a single corridor and presents analyses of its spatial and temporal utilization, impact on the remaining traffic, and the potential benefit caused by off-loading the traffic from underlying sectors. Methods developed to assist the analysis are described. Analysis results visualize the utilizations of the corridor, suggest the number of lanes, and show the possibility of deploying corridors dynamically. It is shown that combined lane options would be a better choice to lower the impact on non-corridor users compared with other options. Finally, analysis shows significant reduction of peak aircraft count in underlying sectors with only one corridor enabled.

I. Introduction

Corridors-in-the-sky, also referred to as tubes, have been proposed¹ to accommodate increasing and fluctuating traffic volume with designs based on traffic demand. They are expected to increase the airspace capacity and reduce delays. Corridors can absorb high-density traffic flows that have similar trajectories. Less controllers' workload may be demanded with corridors than with classic airspace structures due to the organized traffic flow. If automation is involved, such as advanced equipment for self-merging and self-spacing, the associated controllers' workload may be negligible.

Many studies have been conducted to design/evaluate corridors or corridor networks. Alipio et al.² and Yousefi et al.³ initially proposed to construct corridors between city-pairs. Sridhar et al.⁴ developed a corridor network interconnecting airports in clusters seeded by major airports to impact a significant amount of traffic. Gupta et al.⁵ refined a corridor network based on airport clusters using optimization based on Mixed Integer Programming (MIP) according to the cost of deviations. In previous work,⁶ a method that combines the Hough transform and Genetic Algorithm was proposed to find corridor candidates based on great circle trajectories. Hering⁷ proposed the "Freeways" because of the different structure of Europe. The "Freeways" are corridors that try to pass through, or as close as possible to, enlarged major airport areas. Furthermore, Hoffman et al.⁸ analyzed a list of design and operational issues for corridors. Sheth et. al.⁹ compared different corridor designs based on several developed metrics. All of above the research focuses on finding/analyzing 2D corridors, but more realistic concerns need to be addressed to move the design and evaluation of corridors forward. This work discusses some missing issues, such as number of lanes, altitude allocations of corridors, and how these will affect the benefits/costs of corridors. Capacity constraints at airports, separation assurance for the flights in the corridors, and the impact of weather conditions are still neglected in this work.

This study chooses a single corridor from previous work⁶ and presents analysis of its spatial and temporal utilization through which the number of lanes can be derived. To construct a 3D corridor, a metric measuring the number of crossings between remaining flights and the corridor is used as performance. A cell-decomposition method is proposed to make crossing detection a hundred times faster than the brute-force method. This paper starts with an introduction of the corridor model. Next, it presents the analysis

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of operations in the corridor, from that the number of lanes can be derived. Then the impact on remaining traffic is discussed, meanwhile the effect of the allocation of altitudes is described. The final section analyzes the possible benefits in underlying classic sector by deploying corridors based on the reduction of the peak aircraft count.

II. Corridor Model

Although the analysis presented in this paper can be applied to other corridor models, without loss of generality, a single corridor from previous work⁶ is studied. In this model, a method that combines the Hough transform and Genetic Algorithm was developed to identify 2D locations of corridors. Flights were assumed to fly great circle flight trajectories. The schedule was based on flight plans from April 20, 2007. A flight was allowed to fly on a corridor if it had less than 5% extra flight distance compared with its shortest path distance. The method was applied to optimize the corridor location such that the number of corridor-attendees was maximized under the constraint of 5% extra flight distance. The output corridors were ranked according to the number of attendees. Figure 1 shows the top 60 candidates that can accommodate 44% or 13,015 flights. The colors indicate the number of attendees in different corridors and vary with its geographical location.

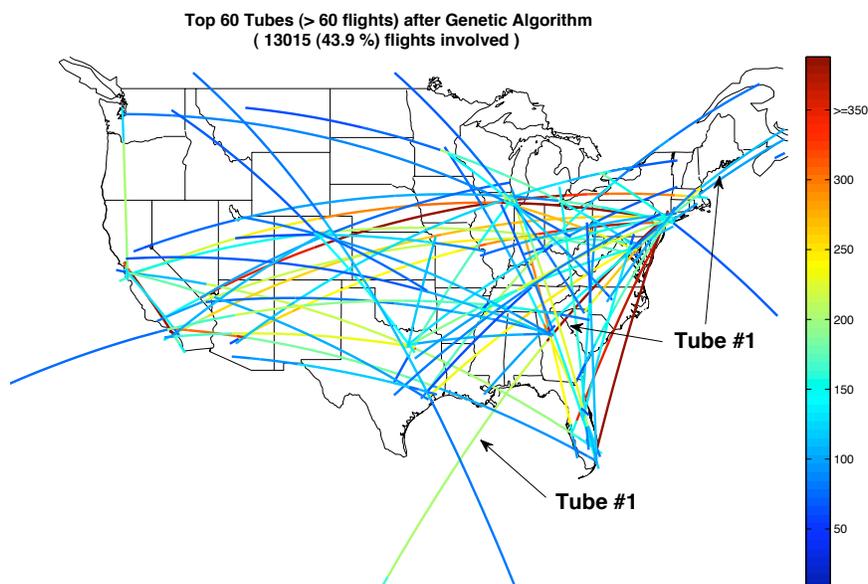


Figure 1. Top 60 corridors ranked by number of attendees

The candidate (see the right figure in Fig. 2) with the most attendees (774 flights during entire day) was chosen for analysis. All generated corridors, including this one, follow great circle trajectories. A corridor attendee was assumed to join in and exit from a corridor perpendicularly, as shown in the left figure in Fig. 2. This is the worst case, since other intersection angles will generate less extra distance. As an initial set-up, this model will be used for calculations through the paper.

III. Operations in Corridors

There could be many ways for measuring utilization of a corridor, such as the number of attended flights. But, they may not answer how crowded are the flights and what is the minimum number of lanes needed. The utilization has to be analyzed in a temporal and spatial manner. Therefore, a space-time map based on studies in ground transportation^{10, 11} is developed.

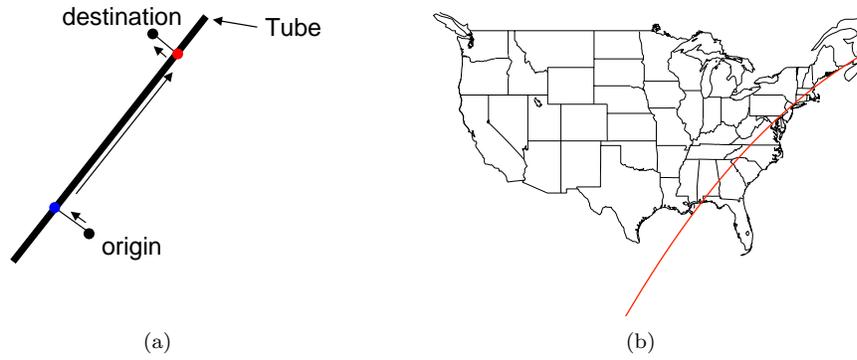


Figure 2. Corridor Model. (a) An example of how a user joins and exits a corridor. (b) the corridor picked for analysis

A. Space-time Map

To generate a space-time map, a spatial scale is needed. An origin is first defined at one end of the corridor. Then points on the great circle corridor are located according to their distances from the origin. As shown in Fig. 3(a), the upper end is the origin, and the scale along the corridor corresponds to distances (in nautical miles) from the origin.

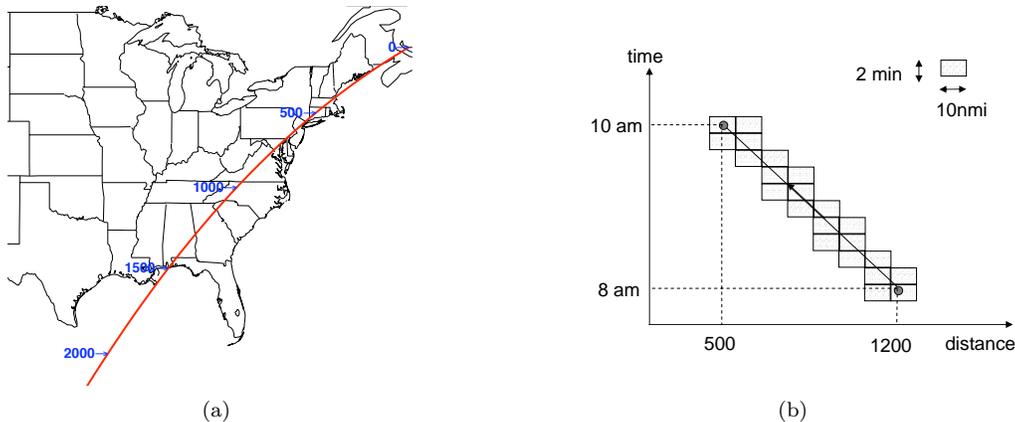


Figure 3. Space Time Map. (a) A corridor with scale. (b) Sketch of Space-time Map

Next, a space-time map is set up. If the schedule, entry and exit points, and speed of a flight is known, a flight can be represented as a curve on it. If the speed of the flight is assumed to be constant, the curve becomes a straight line whose slope is the speed. Figure 3(b) shows the space-time map and a straight line corresponding to a flight. From the line, it can be seen that the flight joined the corridor at the coordinate of 1,200 nmi (close to Atlanta) at 8 AM and exited at the corrdiante of 500 nmi (close to New York) at 10 AM. Then, this space is descretized into grids. Each grid is 10 nautical miles in width and 2 minutes in height. A grid can be looked on as a safety zone in which only one flight is allowed. Since a flight can be anywhere in the occupied grid, the size of grids is doubled based on classic safety requirement. If the line intersects a grid, the grid will be incremented by one. Figure 3(b) shows the grids that are intersected by the sample curve.

Although the speed of a flight in the corridor is assumed to be constant, it is applicable to have flights with varied speeds when necessary. In that case, a straight line will be replaced by a curve which corresponds to the varied speeds. Furthermore, uncertainty of the schedule, speed, and entry location can be taken into account to generate a probabilistic space-time map for corridor operations.

B. Analysis of Operations

Using the method described above, the space-time map of 774 flights in corridor No.1 is generated. Typical speeds of different aircraft types are chosen. Entry and exit locations are computed following the rule of “entering and exiting perpendicularly”. The flight schedules are used as the basis for time. The resulting map is shown in Fig. 4. As described in the last section, each grid accumulates the times occupied by flights. High pixel value of a grid means high occupancy, which is represented by hot color. Cooler colors represent lower occupancy. The hottest grids have 7 flights showing up simultaneously. Considering the separation rule, at least 7 lanes might be needed for these spots.

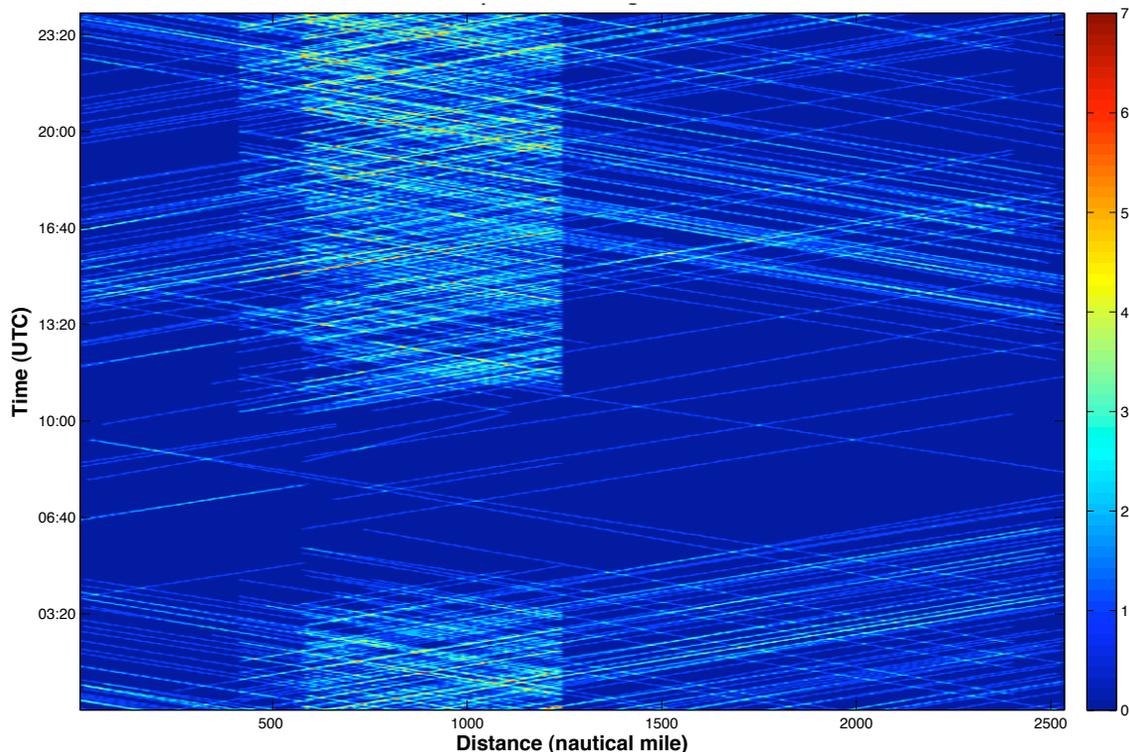


Figure 4. Space Time Map for Corridor No. 1

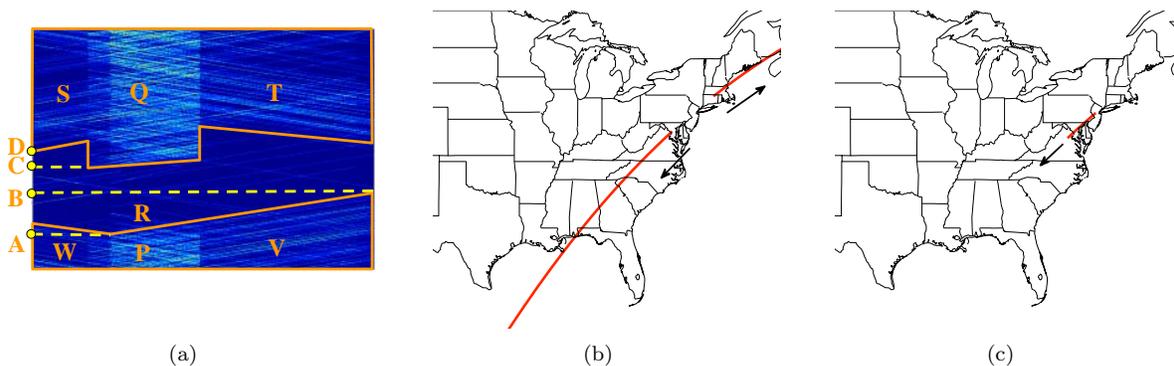


Figure 5. Dynamic Corridor. (a) partition for constructing a dynamic corridor. (b) snapshot of the corridor at UTC time 03:29 (somewhere between time stamp A and B). (c) snapshot of the corridor at UTC time 10:32 (after time stamp C).

In Figure 5(a), there are only a few flights in the dark blue region *R*, whereas heavy traffic occurs in the brightest regions *Q* and *P* between 500 nmi and 1,250 nmi during the daytime. It may not be necessary to

construct a corridor for the region of R . A dynamic corridor may be opened to follow the first flight of heavy traffic and ended with the last flight of heavy traffic. By setting up a threshold for triggering a corridor, regions in the space-time map can be defined, where that corridor is active. Fig. 5(a) shows a sample region included in orange frames specifying a dynamic corridor. Starting at 3 : 20 UTC (time stamp A), the full length corridor will be shrunk gradually from the location at 500 nmi towards the two ends. At 6 : 00 UTC (time stamp B), the corridor will be totally deactivated. At 10 : 00 UTC (time stamp C), the corridor will be gradually activated again. It will start from the location at 500 nmi. At 14 : 00 UTC, the entire corridor will be fully activated. Fig. 5(b) and 5(c) present snapshots of the dynamic corridor.

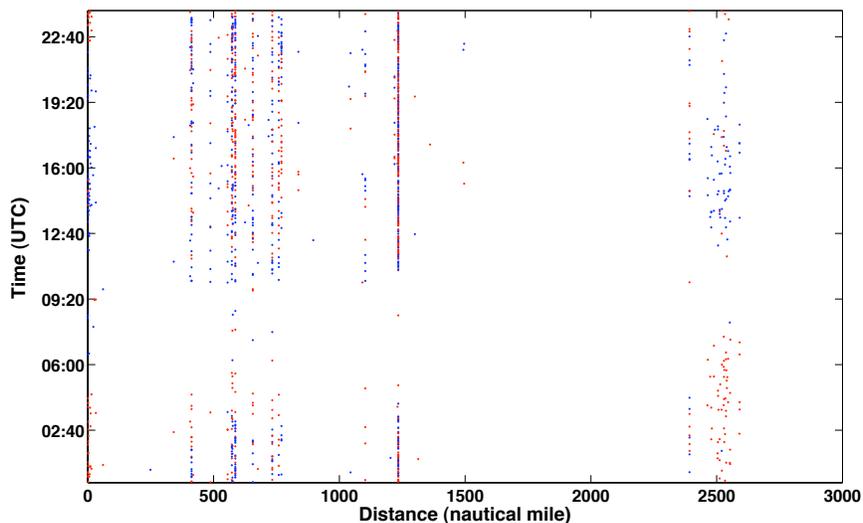


Figure 6. Space-Time Distribution of Entries and Exits

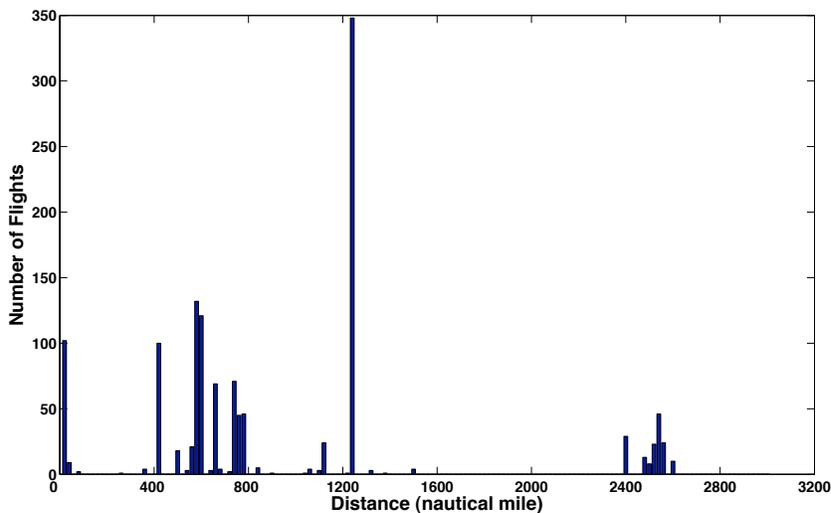


Figure 7. Histogram of Distribution of Entries and Exits

Fig. 6 shows the space-time locations of the entries and exits. The blue points represent entries and the red points represent exits. This figure visualizes when and where a flight would enter or exit the corridor in terms of its schedule. For example, before 09 : 00 UTC, many flights will join the corridor from the location of 2, 500 nmi, which is somewhere above the Gulf of Mexico. This suggests that only one entry ramp is needed at that location at that time period. While after 12 : 40 UTC, because most flights would exit through this position, one exit ramp should be enough. To further check the entry and exit clustering natures, the

spatial coordinates histogram is presented in Fig. 7. Along the corridor, several locations accommodate the majority of the entries and exits. This indicates that only a few ramps should meet the demand and the assumption of entering and exiting corridors anywhere doesn't necessarily introduce large number of ramps. The distribution and histogram can be used to guide construction of ramps in the future.

IV. Impact on Remaining Traffic

Another important operational issue that needs to be investigated is the impact on non-corridor users. If a significant number of flights are absorbed by corridors, the underlying sectors will have more capacity. But the traffic in underlying sectors will be forced to cap or tunnel if the corridor airspace is assumed to be impenetrable. Therefore, a corridor lane option that has less impact on crossing traffic will be preferred. This section will analyze the impact and provide suggestions on lane options for the sample corridor. In the analysis, the safety zone is defined as 5 nmi horizontally and 1000 ft vertically.

A. Cell-Decomposition Method for Detecting Crossings

On April 20, 2007, there were more than 50,000 flights. In the track data, the trajectories are composed of one-minute flight segments. Therefore, the number of flight segments are many times more than the number of flights in the daily track data. Because the crossing detection is not a one-time task, significant checks might be expected. For instance, an optimal altitude needs to be determined based on an exhaustive search, or the crossing detection may be integrated into optimization for designing corridors. Thus, although brute-force can detect the number of crossings in feasible time, a fast or real-time method to detect crossings is desired.

The quad-tree cell decomposition method has been used in robot path planning problems.¹² It constructs an obstacle-free solution space for building a shortest path in the presence of obstacles. Its theory can be applied in the crossing detection problem to rule out most unrelated flight segments. To apply quad-tree cell-decomposition, a rectangular region, which includes the entire US continent, is defined. The rectangular region is called the root cell. The rule is to decompose the cell into 4 quadrants if it contains designated "obstacles". This decomposition process is recursively executed until a defined depth level is reached or there are no quadrants with obstacles. The pseudo code of the cell decomposition is shown in Figure 8.

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Procedure CELLDECOMP(TreeDepth, CurrDepth, Cell, Obstacles)
;; TreeDepth is predefined and CurrDepth is initialized as 0;
begin
  j ← CurrDepth;
  while j < TreeDepth and Cell is Mixed do
    ; When a cell intersects Obstacles, it is 'Mixed'. Otherwise 'Empty';
    Decompose Cell into four sons {NW, NE, SW, SE};
    j ← j - 1;
    for each c ∈ {NW, NE, SW, SE} do
      CellDecomp(TreeDepth, j, c, Obstacles);
end

```

Figure 8. CellDecomp Algorithm

The following is the procedure for using quad-tree cell-decomposition to detect crossings:

1. Define a depth level and location of a corridor.

2. Preprocessing : Perform cell-decomposition with flight segments as obstacles in the entire NAS up to the given depth level. Then every cell at the deepest level is associated with a list of flight segments.
3. Decomposing : Perform cell-decomposition with the corridor as an obstacle up to the given depth level so that the corridor is associated with a list of leaf cells (cells with the smallest size).
4. Checking : For each leaf cell associated with the corridor, check its associated flights to see if the flights intersect with the corridor. If yes, count the number of distinct flights.

Fig. 9(a) displays the decomposed cells for National Airspace System (NAS) traffic with depth level 6 as in step 2. Because the flights are all over the US continental region, most of the cells reach the deepest level. Only a few cells at the left-bottom part are big because there were no flight records. Fig. 9(b) shows the decomposed cells for given corridor as in Step 3. Cells around the corridor are small. Since cells in step 2 are mapped with the cells in step 3, only flight segments associated with these small cells in step 3 will be considered for checking. This is expected to significantly lower the number of flights that needs to be examined.

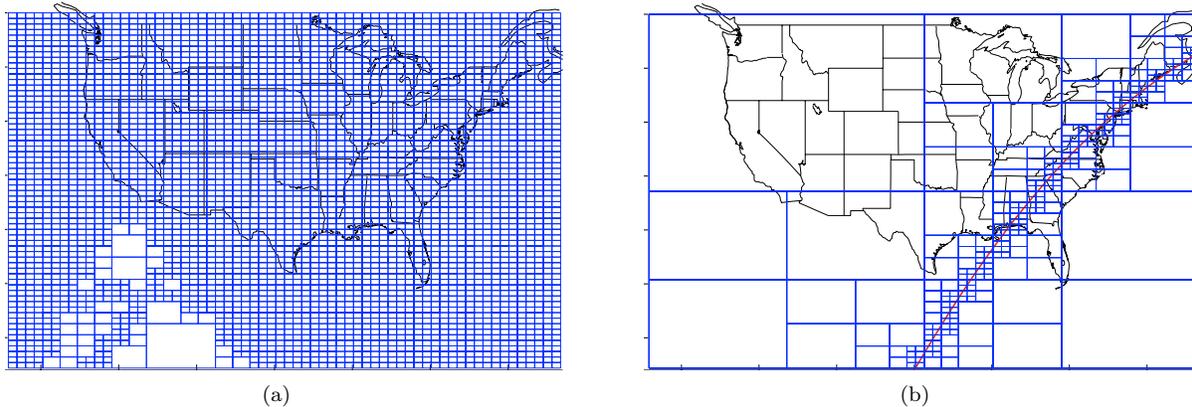


Figure 9. Cell-Decomposition for Detecting Crossings. (a) Preprocessing in Step 2. (b) Decomposition of the corridor in Step 3

B. Crossing Detection Performance

To check the performance of the crossing detection, the track data on April 20, 2007 is utilized, and the brute-force method is used as baseline. All flights above FL290 will be checked. According to the data, there are 3,454,185 flight segments above FL290. The sample case will be, given a corridor at FL310, check the number of crossings between non-corridor traffic and the corridor. The brute-force method can take advantage of the altitude range by only considering the flight segments between FL300 and FL320, But the number of flight segments in that range is as high as 205,222.

The experiments were run on a Mac machine with an Intel dual core CPU at 3.0 GHz. By applying the brute-force method, it takes 8.6 s to find the solution. While using quad-tree cell decomposition method, it can take as little as 0.048 s, which is 180 times faster than the the brute-force method. The reason is that brute-force wastes a large amount of time on checking flight segments far from the corridor. Figure 10 presents the relative performance when the number of tree depth is increased to 8. Depth 7 and 8 have the same computational time. It is noted that depth level 8 can not gain any more benefit over depth 7. That is because the cell sizes at depth 7 are already comparable to the size of one-minute flight segments. Further decomposing cells can not rule out more flight segments. Figure 11 shows the preprocessing time for different depth levels. Since the tree only needs to be built once, the long preprocessing time should be negligible when the detection needs to be performed many times. Based on these two figures, depth level 7 is recommended when performing cell-decomposition for detecting crossings. With a computation time of 0.048s, this method can be incorporated into the optimization to find good corridor candidates that also minimize crossings of non-corridor traffic.

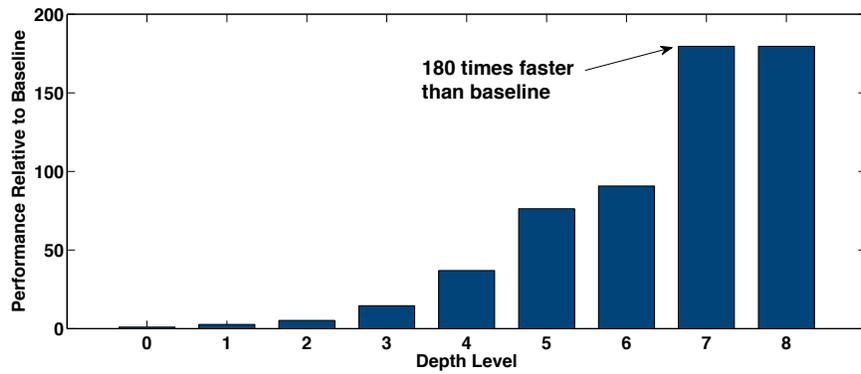


Figure 10. Relative Performances of Crossing Detection

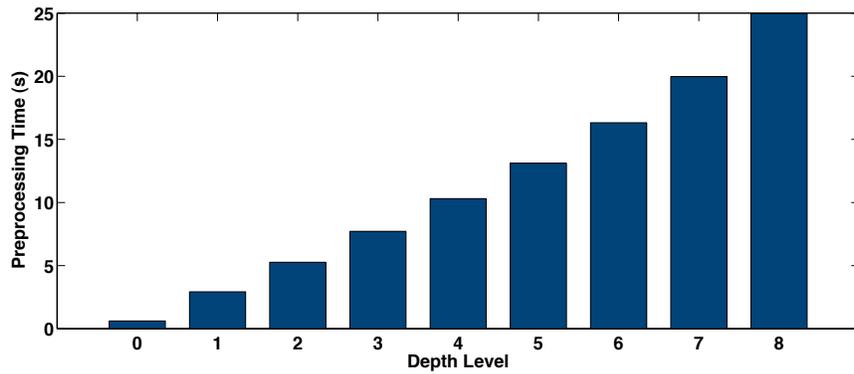


Figure 11. Preprocessing Time

C. Lane Options

Section III.B indicated that at least 7 lanes might be needed for the given corridor. If corridors are expected to be impenetrable, it is desired to find a lane option that minimizes the number of crossing flights. The cell-decomposition method described above is used.

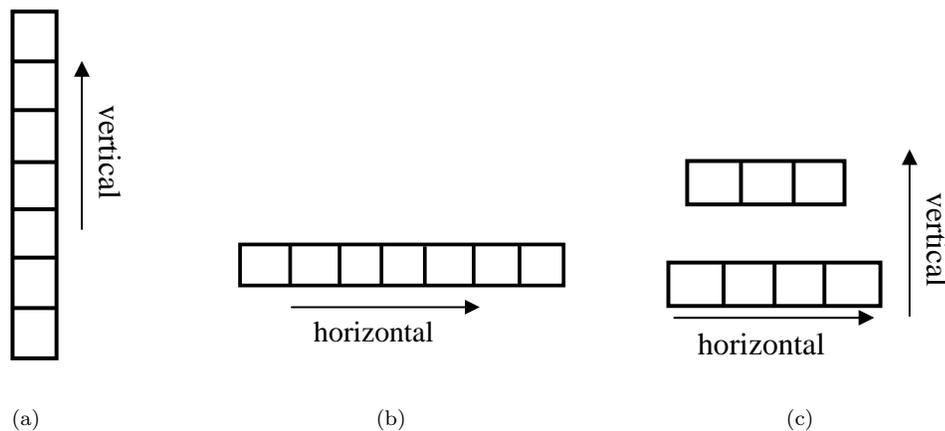


Figure 12. Corridor Cross Sections of Lane Options. (a) Stacked Lanes. (b) Side-by-side Lanes. Right: Combined Lanes.

The middle part of the corridor from the location of 500 nmi to the location of 1250 nmi is studied using three lane options. Fig. 12(a) shows vertically stacked lanes. Fig. 12(b) displays side-by-side lanes. While Fig. 12(c) shows a combined option, with a 3-lanes at one altitude and a 4-lanes at another altitude.

Figure 13 presents the comparison of these three lane options. Three sets of stacked lanes are shown as horizontal lines that cover 7 altitudes range, respectively. To simplify the figure, “combined” lanes are shown for four different altitudes chosen for the 3-lane part. The 4-lane part is allowed to vary between FL290 and FL410. The 3-lane altitudes for combined lanes 1, 2, 3, and 4 are FL410, FL350, FL340, and FL290, respectively.

Contradicting one’s intuition, except at super-high altitudes, the side-by-side lane option is the worst according to the number of crossing flights. Although it has low crossings at super high altitudes, these altitudes may not be feasible for all corridor users. The stacked lane options have relatively low crossings, but since they block seven consecutive altitudes, this option may cause high cost for non-corridor traffic to cap and tunnel. The combined options that have one part at high altitude and another at low altitude seem attractive. They have relatively low numbers of crossings and provide corridor users the flexibility of choosing two different altitudes. Although, these don’t serve as final analysis, they provide insights of the impact on remaining traffic. There are big differences in the impacts if different lane options are chosen.

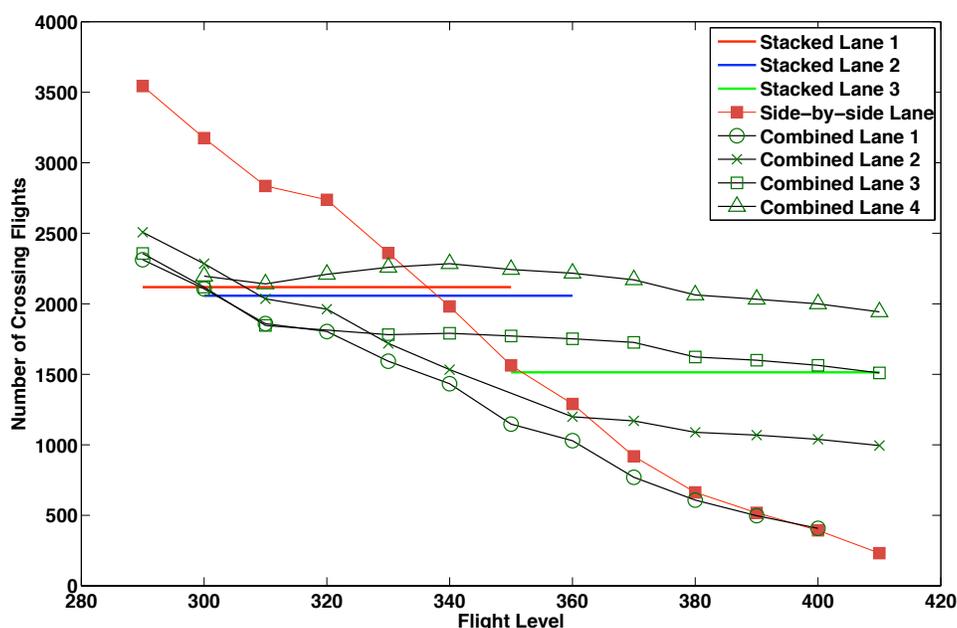


Figure 13. Comparison Among Different Lane Options

V. Initial Benefit Analysis

Based on previous research,¹ one possible advantage of having corridor airspace is to increase overall airspace capacity. As a preliminary study, the benefit and cost will be discussed based on the reduction of the peak aircraft count and the number of crossings, respectively. From the analysis in above sections, if the corridor is enabled, the number of crossings would be around 2,000 (see Fig. 13), which is dependent on the lane profile.

The peak aircraft count will be used as an approximate measure of complexity. The corridor and its underlying sectors are shown in Fig. 14. The peak aircraft count is first examined for the sectors without the corridor. Next, to study the peak aircraft count of sectors when the corridor is enabled, the corridor traffic is simply removed from the sectors. The time history of the peak aircraft count of Washington Center high sector ZDC72 with and without the corridor are shown in Fig. 15 with a blue and red curve, respectively. The difference of these two is shown with a green curve. The difference of traffic has coincided peaks with overall traffic (the blue curve) in ZDC72. Thus, the average reduction of the peak aircraft count due to enabling the corridor is as high as 26.1%.

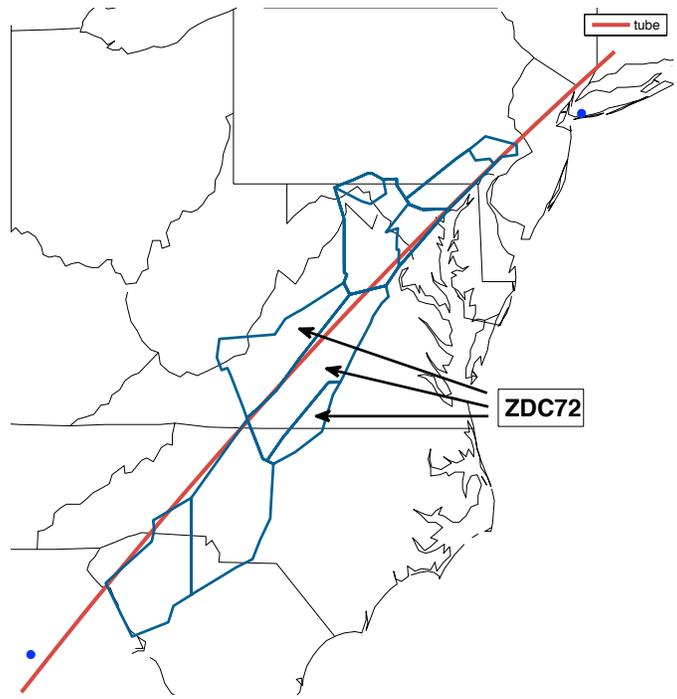


Figure 14. Underlying Sectors

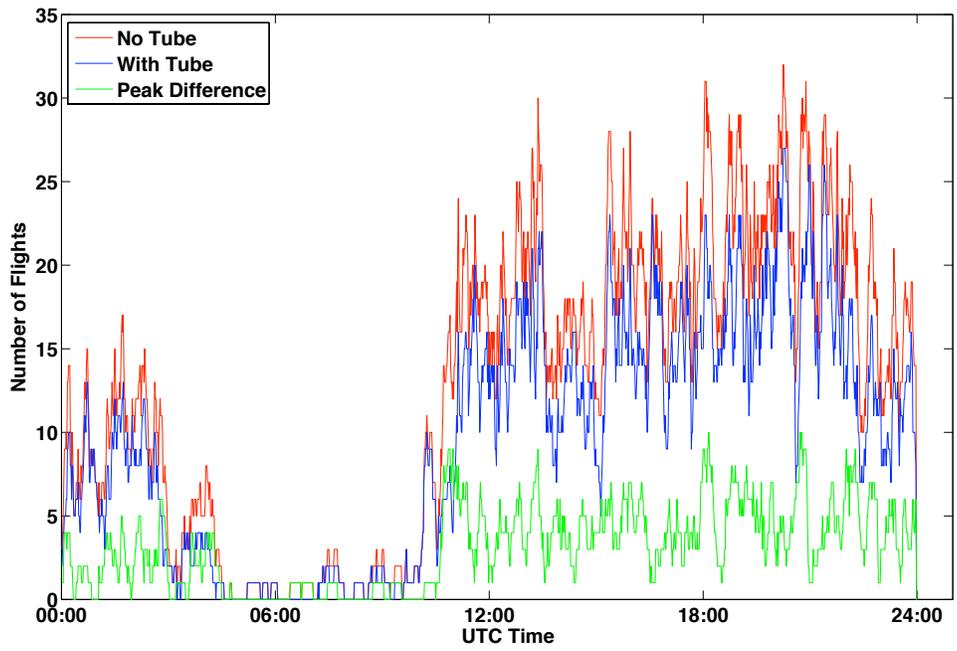


Figure 15. Peak Aircraft Count in ZDC72

In fact, similar situations happen in other sectors with this corridor enabled. The results show that Sectors ZDC04, ZTL28, and ZNY09 have 17.4%, 27.3%, and 24.1% reduction of the peak aircraft count, respectively. Thus, the corridor concept seems to be a positive solution to increase the NAS capacity.

VI. Conclusion

A single corridor design is analyzed in this work. To examine and visualize the utilization of this corridor, a space-time map was developed. It can be used to guide construction of dynamic corridors and to suggest the minimum number of lanes. A quad-tree cell-decomposition was developed to speed up the crossing checks by a factor over one hundred. This method can be used to minimize crossings in the initial corridor design. In the discussion of lane options in terms of minimizing crossings, it was found that combining multiple lanes at multiple altitudes reduces the number of crossings and provides flexibility for corridor users. The analyses of corridor utilization and impact on the remaining traffic is important for understanding or evaluating corridors. They actually can be integrated into the initial corridor design.

Preliminary benefit analysis was discussed based on the peak aircraft count and the number of crossings. Results show around 25% reduction of the peak aircraft count in underlying sectors if only one corridor is enabled. Crossings can be low if a combined lane option was used. This benefit analysis provides new metrics for corridor airspace. In the future, research will focus on how flights would be operated in corridors. Feasible simulations will be carried out based on these design information of a corridor, such as 2D locations, preferred altitudes, lane option, and ramp locations.

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