

DEFINING CRITICAL POINTS FOR DYNAMIC AIRSPACE CONFIGURATION

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Keywords: *Critical Points, Airspace Structure, Airspace Complexity, Sector Design*

Abstract

Airspace boundaries are designed around air traffic flows and their crossing and merge points to reduce controller workload and maximize capacity. Redesigning airspace boundaries today is a lengthy process, heavily dependent on past experience and expert judgment. Therefore, the airspace boundaries remain fairly static and traffic flows tend to adhere to current airways. Traffic flows could be made more efficient by allowing them to change more dynamically adapting to congestion and weather. This would require airspace boundaries to be redesigned dynamically. This paper introduces a method for extracting the cross and merge points between dominant traffic flows from flight trajectories. These cross and merge points define a more flexible structure around which dynamic airspace boundaries may be designed. To evaluate the method, a set of cross and merge points are compared with current airway intersection points and airspace boundaries. Results show that critical points from flight tracks are comparable to airway intersections. This comparison suggests cross and merge points based on forecast trajectories and constraints may be useful for designing dynamic airspace boundaries for the future air transportation system.

1 Introduction

As the volume of en-route flight traffic increases, the problem of increasing or better utilizing airspace capacity is of growing concern. Dynamic Airspace Configuration research is fo-

cused on creating methods and algorithms that increase airspace capacity by redesigning airspace boundaries to reduce or redistribute controller workload and airspace complexity [1]. Human factors studies show that airspace structure, consisting of dominant traffic flows and the points where these flows merge and intersect, helps increase capacity [2, 3]. Air traffic controllers use airspace structure to lower cognitive complexity and enable them to control increasing numbers of flights at one time. Airspace boundaries are designed to accommodate these airspace structures to minimize controller workload and maximize airspace capacity. Occasionally, inefficient airspace boundaries are redesigned to accommodate standard flows that may change slowly over time. Flows are identified manually by looking at historical flight tracks in the airspace. Then airspace designers use expert judgment from past experience to define and analyze new airspace boundaries. This process takes several months. Therefore, only standard flows under "nominal" situations are accommodated, and the airspace structures and boundaries remain fairly static.

Static airspace structure may mitigate complexity in "nominal" situations, but in an "off-nominal" situation, such as bad weather or congestion, these same structures could actually add to complexity [4]. Reference [5] shows that reconfiguring airspace boundaries to complement severe weather reroutes can produce more evenly distributed and lower peak sector loads, improving workload distribution. This concept follows the same airspace boundary design process as today, but alternate airspace boundaries

are designed to accommodate a set of preconceived routing scenarios from the National Severe Weather Playbook. The National Severe Weather Playbook is a large set of rerouting scenarios designed to adapt to changes in the weather. The extent to which this concept can adapt to "off-nominal" situations is still fairly rigid. A method of defining dynamic airspace structure elements derived from forecast trajectories is needed to allow more flexible airspace boundary design.

This paper focuses on the points at which flows cross and merge. These points will henceforth be referred to as "critical points." A method is introduced for extracting critical points directly from flight trajectories. Critical points are identified by clustering individual crossing and merge points between a set of flight trajectories. These critical points along with other airspace constraints may be used to dynamically reconfigure airspace boundaries and improve controller workload distribution.

An outline of the paper is as follows. Section 2 explains the method of extracting critical points from flight tracks. Section 3 presents an analysis of critical points extracted from current day traffic with respect to airway intersections. Today's standard flows tend to adhere the static airways that are used to define flight plans. Therefore, it is expected that critical points derived from current day flight tracks will tend to be at airway intersection points. In addition, an analysis of a critical point's relative position to current airspace boundaries is performed to establish baseline sector design criteria.

2 Extracting Critical Points From Flight Trajectories

This section describes a method for extracting critical points from flight trajectories. Once flight tracks are extracted from raw data, pairs of flight tracks are compared to locate individual merging and crossing intersections. These merging and crossing points are then clustered separately to form merging and crossing critical points.

2.1 Identifying Trajectory Intersection Points

Every pair of flight tracks is compared to find individual crossing and merging intersection points. Figure 1 shows flight A compared to flight B. For each time sequentially ordered point

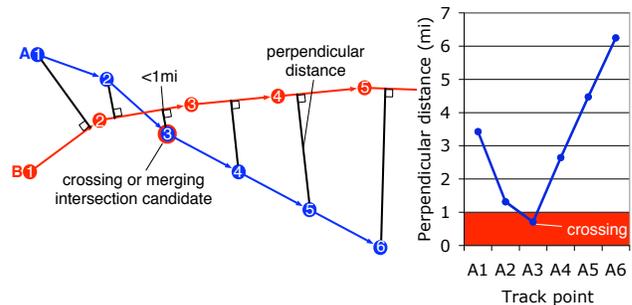


Fig. 1 Example comparison between two tracks.

in path A, the closest perpendicular distance to a segment on path B is computed. If this distance is less than one mile, the point is a candidate crossing or merge point. If there are three or less adjacent candidates, the point closest to the compared path is considered a crossing point. In Figure 1, only point A3 is closer than a mile to path B and so it is considered a crossing point. If there are more than three adjacent intersection point candidates, the two flights are considered to be following the same route for some time. If both paths begin at least one point before they occupy the same route, the first candidate is considered a merging point. Figure 2 shows a few more examples of perpendicular distance graphs resulting in different crossing and merging intersection results. There are three adjacent intersection candidates in Figure 2(a) within the threshold distance shown in red. The point with the minimum perpendicular distance is considered to be the crossing point. In 2(b), there are more than three adjacent intersection candidates. There is a point before the first candidate which has a perpendicular distance greater than one mile. Therefore this first candidate point is considered a merging point. There are also more than three adjacent intersection candidates in Figure 2(c) but

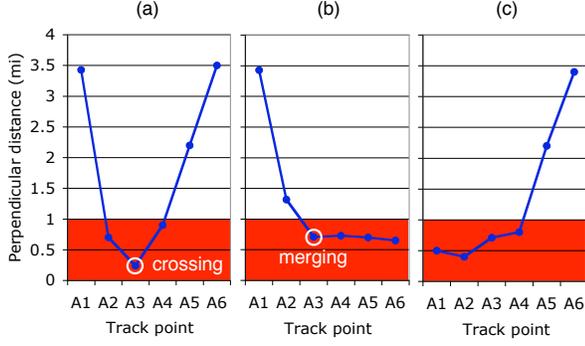


Fig. 2 Example comparison between two tracks.

the first candidate is also the first track point. Flight tracks may be filtered by altitude, regional location, or time before comparing. The flight path may have been truncated at point A1 and so A1 may not be a true merging point. Diverging points are not analyzed in this paper as they are not considered critical points for controller workload. Point A4 in Figure 2(c) would be considered a diverging point.

The comparison is such that, intersection points differ slightly when path A is compared to path B than when path B is compared to path A. Both intersection points are considered when identifying critical points. Figure 3 shows an example of how three flight tracks are compared to one another. Lines A (green), B (red), and C (blue) are three sets of flight tracks compared. The orange circles are the intersection candidate points within a mile of the compared track. Squares and diamonds are the points identified as crossing or merging respectively. Notice how one set of crossing points is chosen as the closer of two adjacent intersection candidates when A and C are compared. Also notice how all points downstream from the merging points of A and B are intersection point candidates.

Note that when comparing flight A to flight B, direction is only important for flight A in locating merging points. For example if B in figure 3 flowed in the reverse direction, A would still find a merging point when comparing to B and produce a distance profile similar to figure 2(b). But when B is compared to A, it will produce a

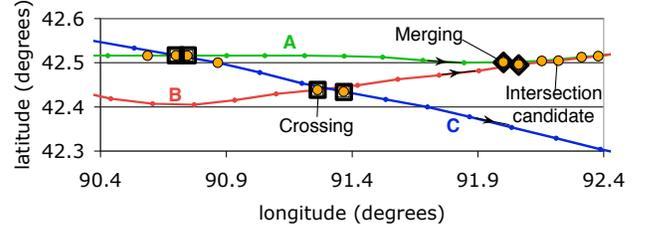


Fig. 3 Example of how multiple crossing and merging intersection points are detected when three flight tracks are compared to one another.

distance profile similar to 2(c) and so no intersection point will be found.

2.2 Merging Trajectory Intersections into Critical Points

Once every pair of flight trajectories has been compared, the intersection points must be merged into critical points. This is done by iterating over the following two steps. 1) A center of mass calculation is used to cluster points within a square region that sweeps across the space of original points and weight the resulting clustered points. 2) Lower weight clustered points are filtered if they are near enough to a clustered point with higher weight. This two step algorithm is repeated, refining the results of the previous iteration. A steady state is achieved when the clustering results are identical to the results of the previous iteration. These steady state clustered points are considered critical points.

2.2.1 Clustering Points

The center of mass calculation finds the average coordinate position of all points within a square region weighted by the point weight. The method of identifying trajectory intersections is such that there may be multiple intersections found at the same coordinates. The first iteration of the clustering algorithm is performed on these trajectory intersection coordinates weighted by the number of trajectory intersections they represent.

Let $\Lambda(c) = [\lambda_1(c), \lambda_2(c), \dots, \lambda_n(c)]$ be an array of longitudes and $\Phi(c) =$

$[\varphi_1(c), \varphi_2(c), \dots, \varphi_n(c)]$ be an array of latitudes. $p_i(c) = (\lambda_i(c), \varphi_i(c)) \forall i \in \{1, 2, \dots, n\}$ is the i th point of n points within a square region with center c . Let $W(c) = [w_1(c), w_2(c), \dots, w_n(c)]$ be the array of weights associated with these points. The center of mass clustered point coordinates for the square region centered at c is given as

$$p'(c) = (\lambda'(c), \phi'(c)) \quad (1)$$

$$\lambda'(c) = \frac{\Lambda(c) \cdot W(c)}{\sum_{i=1}^n w_i(c)} \quad (2)$$

$$\phi'(c) = \frac{\Phi(c) \cdot W(c)}{\sum_{i=1}^n w_i(c)} \quad (3)$$

This calculation is repeated for other square regions, sweeping across the space of points to be clustered. The sweep rate determines how much the square region is shifted for each new center of mass calculation. Let r be the sweep rate given by

$$r = s/\rho, \quad \rho \in \{2, 3, 4, \dots\} \quad (4)$$

where s is the length of a side of the square region and ρ is the sweep ratio. The ρ must be an integer greater than or equal to 2 so that every point is used in the same number of center of mass calculations and at least more than once. This enables the same point to be tested within multiple different s by s regions. In fact, each intersection point is included in a center of mass calculation exactly ρ^2 times. There are ρ^2 different s by s square regions that overlap each r by r square region. This is illustrated in Figure 4 for $\rho = 2$. A single r by r region is shown in red along with 4 different overlapping s by s regions shown in blue.

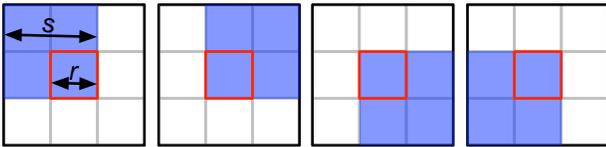


Fig. 4 For $\rho = 2$, there are $\rho^2 = 4$ different s by s square regions overlapping a single r by r square region.

Note how any point within the r by r region shown will be used, in part, to calculate 4 different $p'(c)$ coordinates and their weights. In order

to normalize the weight, the assigned weight of $p'(c)$ is given as

$$w'(c) = \frac{\sum_{i=1}^n w_i(c)}{\rho^2}. \quad (5)$$

2.2.2 Filtering Clustered Points

The point clustering process above will always yield one point for every s by s region covering the point space. Some of the lower weight points must be filtered to give more emphasis to higher weight points in subsequent iterations of the algorithm and to reduce the final number of critical points produced.

In some cases, different s by s regions may produce clustered points with identical coordinates. For example, this happens when the points within a single r by r region are the only points within the ρ^2 s by s regions that share that r by r region. The result is ρ^2 clustered points, each with $\frac{1}{\rho^2}$ the combined weight of the points in the r by r region. Therefore, before lower weight clustered points are filtered, all $p'(c)$ s that share the same coordinates are merged into one point (p) with summed weight ($w(p)$). The total coordinate weight for clustered point coordinates, p , is given by

$$w(p) = \sum_c w'(c) \quad \forall c \text{ s.t. } p'(c) = p. \quad (6)$$

Once coordinate weights have been adjusted in this way, lower coordinate weight points that are close enough to higher coordinate weight points are filtered. Of the ρ^2 center of mass calculations performed on these ρ^2 s by s square regions, filter all but the clustered point with the greatest coordinate weight.

Figure 5(a) shows the points in a $4r$ by $4r$ region and (b) shows the clustered points that resulted from a center of mass sweep with $\rho = 2$. The size of each blue point represents its weight. In (a) the red box shows the s by s region associated with center location 1 in red. Numbers 2 through 9 are placed in the center of the remaining 8 s by s regions that span this example. Notice that the shifting distance between s by s region centers is r . The resulting clustered points

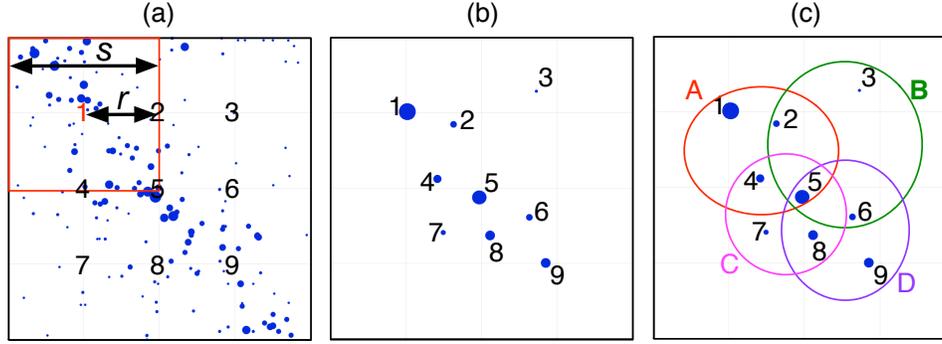


Fig. 5 Example of how intersection points are merged and filtered to form critical points.

in (b) are each labeled with the same number as the s by s region that created it. In this example there are 4 different groups of 4 s by s regions that overlap the same r by r region as depicted in Figure 4. These groups are shown in Figure 5(c) labeled A through D. The 3 lower weight clustered points are filtered from each group of 4. Clustered points $\{2, 4, 5\}$ are filtered from group A. Similarly, points $\{2, 3, 6\}$, $\{4, 7, 8\}$, $\{6, 8, 9\}$ are filtered from groups B, C, and D respectively. After these points are filtered, the only remaining clustered point is 1.

2.2.3 Algorithm Iterations

The algorithm iterates by creating new $\Lambda(c)$, $\Phi(c)$, and $W(c)$ arrays populated with the surviving clustered points from the previous iteration and their associated coordinate weights. Equations 5 and 6 play an important role in allowing the algorithm to repeat until it reaches a steady state. Sufficiently isolated points and their associated weights are unaffected by the algorithm and after several iterations, the algorithm will reach a steady state.

Consider the case where a single intersection point p with weight w exists in an r by r region and it is the only point within the $\rho^2 s$ by s regions that share that r by r region. This will result in ρ^2 clustered points at the same coordinates, each with weight $\frac{w}{\rho^2}$ by Equation 5. Equation 6 will then sum these weights to equal the original weight. If the clustered point is sufficiently isolated from other clustered points as not to be fil-

tered, it is ultimately unaffected by the algorithm iteration. In this way, the size of s determines how isolated a point must be and ρ determines the accuracy to which the point is placed. For the simple example shown in Figure 5, the algorithm reaches a steady state after the first pass.

Figure 6 shows a larger example of merging and filtering intersection points over several sweeps of the algorithm. In this example, crossing and merging points were processed independently. The blue and green points represent crossing and merging points respectively. The point size represents the relative weight of the point with respect to other points plotted. The routes that produced the original intersection points according to the method discussed in section 2.1 are also plotted as black lines. Figure 6(a) shows the original trajectory intersection points, and (b) and (c) show merged points after the first and second sweep of the algorithm respectively. Note in (a) how crossing points are far more numerous than merging points which results in much larger crossing points in (b) and (c) with respect to merging points. Also note how most of the point consolidation occurs in the first algorithm sweep.

3 Analysis of Current Day Critical Points

In order to evaluate the method proposed in this paper, a set of critical points identified from historical track data are compared with current airway intersection points and sector boundaries. Comparing critical points to the current day route

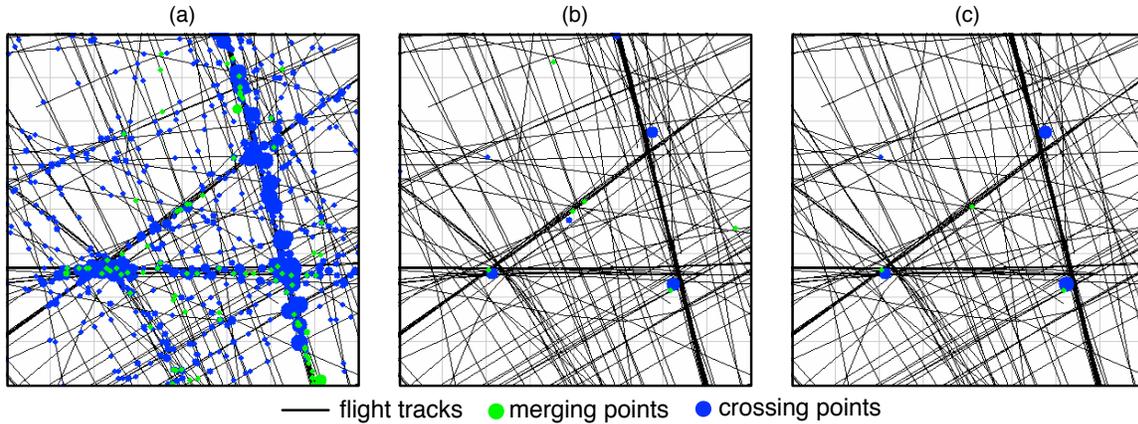


Fig. 6 Example of how intersection points are merged and filtered over several center of mass sweeps to form critical points.

structure and sectors helps to calibrate critical point weights for use with forecast trajectories, establish baseline sector design criteria, and identify areas where current flight tracks deviate from the current structure.

Major airway intersection points of the current route structure have a direct relationship with current sector design. Some considerations for sector design that are analyzed in this section include the number of large critical points or airway intersections in one sector [6] and their location with respect to sector boundaries.

3.1 Analysis Scope

One could use planned flight trajectories from flight plan data or actual trajectories captured by historical track data to produce critical points. Track data were used because flight plan data are too closely tied to the current airway structure. Track data present more accurate representations of flight paths actually flown. Research has shown that controllers faced with a high workload tend to adhere to the route structure more closely [7]. Therefore, it is expected that the critical points from tracks during the busiest hours of the day on a low weather day should follow the current airspace structure.

The track data used to generate critical points were taken from Aircraft Situation Display to In-

dustry "TZ messages" [8] for 4/17/2005, a low weather day. The track data were filtered to nation-wide cruise tracks above flight level 240 during the busiest four hours of the day, between 18:00 and 22:00 GMT. The sectors analyzed include 188 sectors that at least include flight levels 370 through 490. About 87% of the flight tracks considered are within this altitude range. Critical points for these tracks were generated using $s = 0.2$ degrees and $\rho = 2$. The algorithm reached a steady state in three iterations.

Current airway intersection points were extracted from airways published in the FAA's resource aeronautical data effective March 17th 2005 [9]. Any navigational aid or fix that appears in more than one airway is considered an intersection point. Note that airways alone without flight traffic, have no directionality and so crossing and merging airway intersections are indistinguishable. Each intersection point is given a weight equal to the number of airways in which it appears. This number ranges from 2 to 22 intersecting airways. The airway intersection weight is not affected by traffic density whereas the critical point weight is. The airway intersecting weight is multiplied by the surrounding flight density (number of flights within a $r(2\rho - 1) = 0.3$ squared region surrounding the $r = 0.1$ squared region containing the intersection) to make it comparable with critical point

weight. Similarly, the critical point weight can be normalized by dividing it by its surrounding flight density to create a weight that is more comparable with the airway intersection weight. But critical point and airway intersection results using this weight are less comparable. Therefore, the un-normalized weights reflecting traffic density are used in this analysis.

3.2 Merging vs. Crossing Critical Points

Critical points are generated separately for crossing and merging intersections. In general, critical points formed from crossings have much larger weights than critical points formed from merge points. This is because the method described in Section 2.1 detected far more crossing points than merge points. Recall that there is no minimum altitude difference when detecting crossing and merging points in this analysis. Merges are far more likely to occur at similar altitudes than crossings. Therefore, another analysis, detecting only intersections of flights within a minimum altitude difference of one another, may detect more merging critical points.

The maximum weights for crossing critical points, merging critical points, and airway intersections are 724, 354, and 2,068, respectively. In order to more easily compare the critical points and airway intersection weights, they are rescaled to weights between 0 and 10. Points with higher weight have greater effect on controller workload. Figure 7 shows a histogram of numbers of critical points and airway intersections by weights. The figure is scaled to easily view the smaller numbers of points with weights of 2 and higher. Numbers with weights between 1 and 2 reach the low hundreds and numbers with weights between 0 and 1 are in the thousands.

As seen in Figure 7, even with this scale adjustment, there are far fewer merging critical points with higher weight than crossing critical points. The crossing critical points are more similar in number to airway intersections. The few merging critical points that have substantial weight are very close to high weight crossing critical points but shifted slightly downstream of the

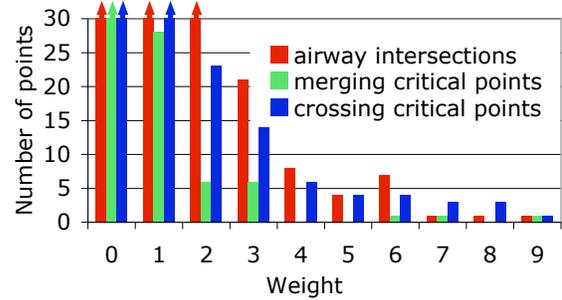


Fig. 7 Numbers of crossing and merging critical points and airway intersections by weight.

general flow. This is due to flights cutting corners when turning from one airway to another, merging in reality farther downstream from the airway intersection. Only two merging critical points with weight greater than 1 could not be paired with a crossing critical point within 15 miles, in histogram bins 1 and 2.

In general, merging critical points appear to get closer to their paired crossing critical points as weight increases. The merging critical point in histogram bin 7 is just 0.017 nautical miles away from its paired crossing critical point. There is no correlation between the weights of crossing and merging critical point pairs.

The three largest merging critical points with weights greater than 6 all appear in Jacksonville center. By contrast, the eleven largest crossing critical points with weights greater than 6 are spread throughout different East coast centers where traffic density is higher and more structured. Figure 8 shows the three largest merging critical points in Jacksonville Sectors 47, 69, and 75. Crossing and merging critical points and airway intersections are shown as blue, green, and red points respectively. Flight tracks are shown in black and sector boundaries in red. The two largest merging critical points are close to large crossing critical points and airway intersections in Sectors 47 and 75. Most of the traffic in these two sectors follow the Southeast coastline. The third largest merging critical point, found in Sector 69, has three times the weight as its closest crossing critical point. Each of these three sec-

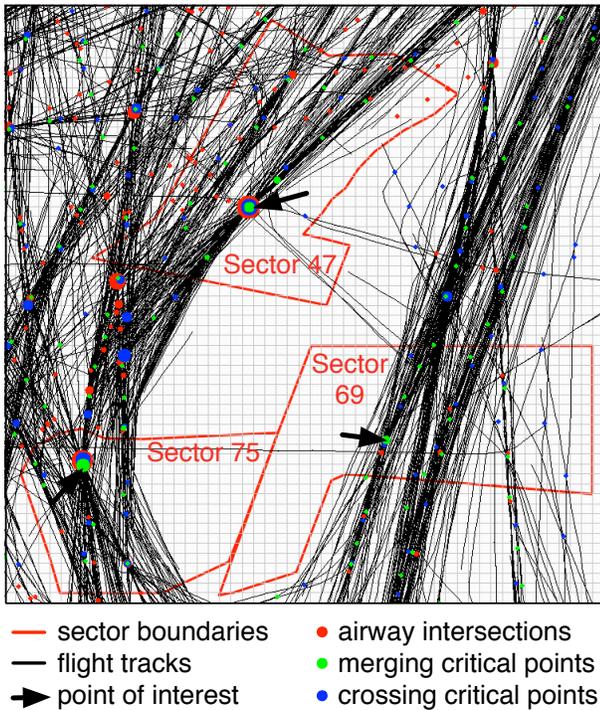


Fig. 8 The three largest merging critical points shown with crossing critical points and airway intersection points for three Jacksonville sectors.

tors have a high density of very structured routes with small intersection angles. Routes with small intersection angles are where large merge points are most likely to be detected because crossing routes at small angles may yield more than three adjacent points within one mile of each other, identifying the intersection as a merge point according to the method described in Section 2.1 .

3.3 Critical Points vs. Airway Intersections

Merging and crossing critical points are paired separately with their closest airway intersection within 15 nautical miles. Figure 9 shows a histogram of the percent number of merging and crossing points paired with airway intersections. All high weight critical points (weight ≥ 5) are paired with an airway intersection. Only two medium weight crossing critical points ($3 \leq \text{weight} < 5$) could not be paired. Figures 10 and 11 show these unpaired crossing critical points. Each figure shows flight tracks in black on the

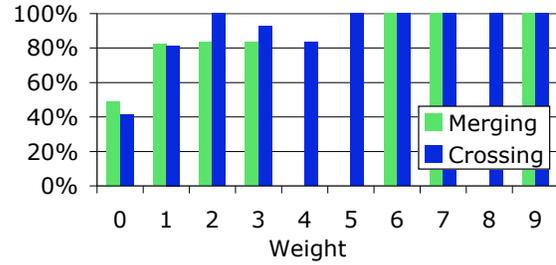


Fig. 9 The percent of merging and crossing critical points paired with airway intersections within 15 miles.

left and airways in black on the right. Notice in Figure 10 that airways do cross near the unpaired critical point, they just do not share a common navigational aid or fix so no airway intersection was identified. In Figure 11 the airways do not accurately represent the traffic flow. These are routes that fly over the Atlantic ocean between North Carolina and southern Florida. Flight traffic seems to follow oceanic routes more loosely and oceanic routes change often.

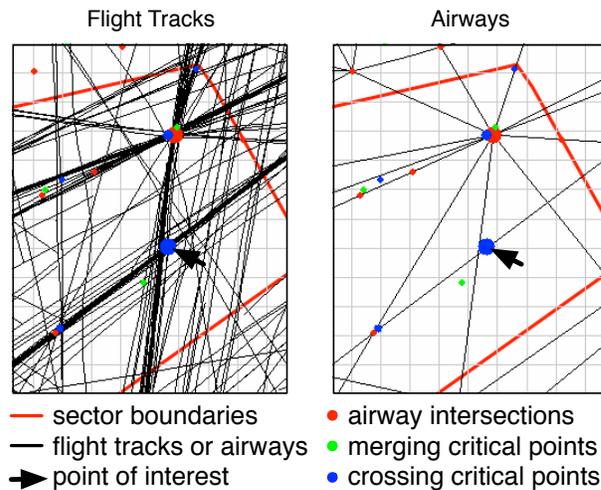


Fig. 10 Flight tracks and airways surrounding the unpaired crossing critical point near crossing airways without an intersection.

The average distance between crossing critical points and their paired airway intersections decreases as the critical point weight increases. The average distance for all crossing critical

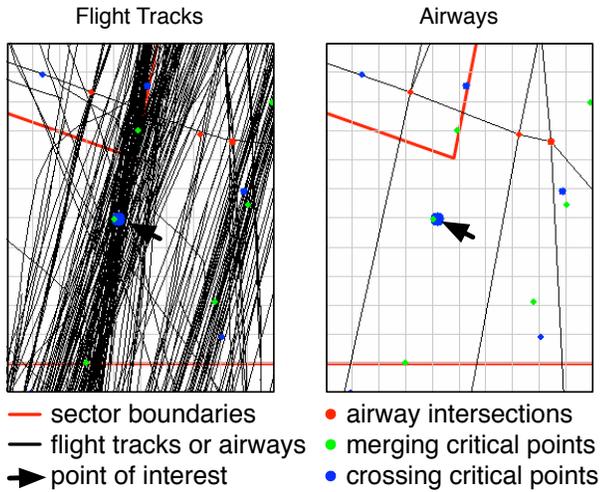


Fig. 11 Flight tracks and airways surrounding the unpaired crossing critical point where the traffic flow does not follow an airway.

points with weight greater than 5 is just 1.2 miles. This shows that the method described in Section 2 does a good job of placing crossing critical points at airway intersections where the current day flows intersect. The exceptions seen in Figures 10 and 11 illustrate how major flows and critical points cannot always be inferred from today's static route structure alone, even during times when traffic is most likely to conform to this route structure.

There is a 75% correlation between the weights of paired crossing critical points and airway intersections. But this high correlation is heavily influenced by the surrounding traffic density factor in airway intersection weights. The number of intersecting airways alone correlates only 35% with crossing critical point weights. Even though an airway intersection may intersect a large number of airways, the traffic flow around the intersection may not be close enough to form a critical point or not all of the intersecting airways might be used. Figure 12 shows the flight tracks and airways around a point with large number of intersecting airways. Notice how there are far more airways intersecting at this point than flight tracks utilize.

Merging critical points do not show any trend

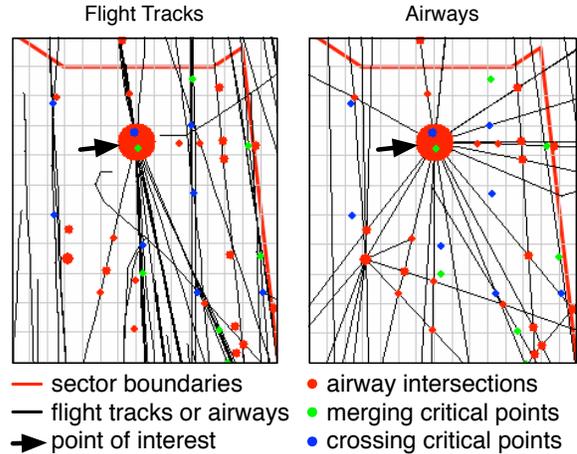


Fig. 12 Flight tracks and airways in sector ZSE46.

between weight bin and distance to paired airway intersections and they have only a 51% correlation with paired airway intersection weights. Because of the stronger relationship between crossing critical points and airway intersections, merging critical points are not considered in the remaining analyses.

3.4 Sector Analysis

This section analyzes the geographic relationship between critical point and airway intersection density within current sector boundaries. Three metrics that may be useful in designing sector boundaries around critical points are investigated. These metrics are the number of significantly weighted critical points in each sector, the closest distance of a critical point to the sector boundary, and the average distance between critical points within the same sector.

Sector metrics are averaged over the subset of sectors that contain both critical points and airway intersections to make them comparable. Figure 13 shows the number of sectors containing crossing critical points, airway intersections, and both crossing critical points and airway intersections with a weight greater than a given threshold. The number of sectors compared quickly diminishes as the weight threshold is increased. Figure 14 is a geographical representation of sectors showing the largest crossing critical point

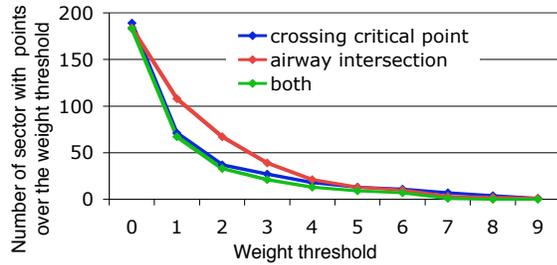


Fig. 13 Number of sectors containing crossing critical points, airway intersections, and both crossing critical points and airway intersections with weights greater than a given threshold.

and airway intersection weights for each of the 188 sectors analyzed. Low to high weights are

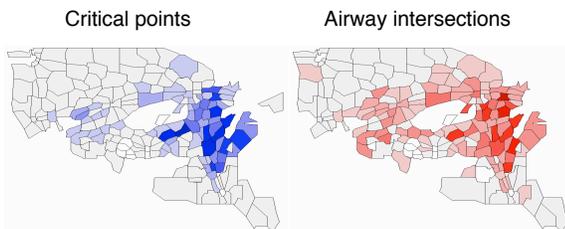


Fig. 14 The maximum weights for critical points and airway intersections in each sector.

represented by colors ranging from light to dark. Critical points and airway intersections have very similar geographic concentration of maximum weight on the East coast. This is due to the high traffic density and tighter route structure on the East coast.

The number of critical points in a sector may make a big impact on controller workload because each new critical point splits controller focus. Figure 15 shows the average and maximum number of crossing critical points and airway intersections in a sector. Only sectors containing both crossing critical points and airway intersections were included. The figure has been scaled to better show average numbers of points. Both the average and maximum number of crossing critical points and airway intersections per sector are very similar. This indicates that the

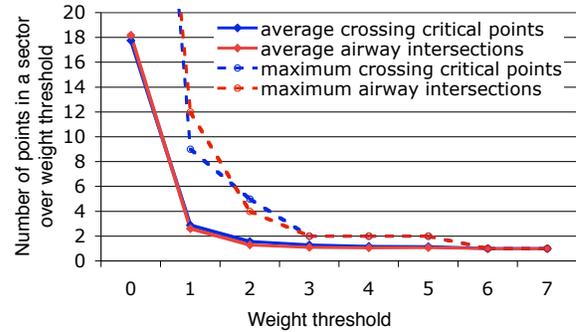


Fig. 15 The average and maximum number of crossing critical points and airway intersections for all sectors containing both types of points.

weight scaling matches well between crossing critical points and airway intersections. These data help evaluate at what weight threshold the critical point can be considered a controller focal point within the sector. Typically, there should not be more than one or two major focal points in a sector. Both average and maximum numbers of crossing critical points and airway intersections per sector are way too high for a weight threshold of 0. The average numbers for a weight threshold of 1 are more reasonable but not for maximum numbers. Ignoring points with weights less than 2 reduces the numbers of points within today's sectorization enough to be considered controller focal points.

The correlation between the numbers of crossing critical points and airway intersections in the same sector range from 54% to 73% for weight thresholds between 2 and 6. At higher weight thresholds, there are too few sectors to compare well.

The distance of critical points from the sector boundary affects the time a controller has to assess and control a flight's impact on the intersection traffic. For each sector, let α be the average closest critical point or airway intersection distance (miles) to the sector boundary weighted by $w(p)$. Let A be the average α for all sectors that had both critical points and airway intersections above a given weight threshold. Figure 16 shows A for crossing critical points and airway inter-

sections over different weight thresholds. The A

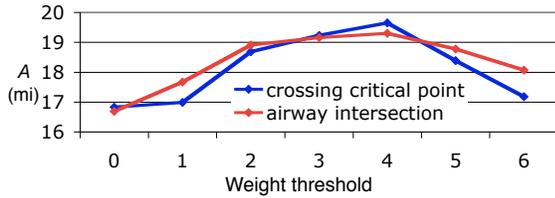


Fig. 16 Crossing critical point and airway intersection As for different weight thresholds.

for crossing critical points and airway intersections are very similar to each other. The highest distances are for points with weight thresholds 2 through 5 averaging around 19 miles. The main reason for placing airway intersections at least a minimum distance from a sector boundary is to allow controllers enough time to access and control a flight’s impact on the intersection traffic. If the minimum distance to the sector boundary is not along a significant flow path, the metric is less meaningful.

Like the distance of critical points from the sector boundary, the average distance between critical points within the same sector may impact how a controller deals with a critical point. The closer critical points are together, the more likely control actions involving those critical points will be lumped together. The distance between critical points in this analysis are already affected by the choice of s in Section 2.2. Let β be the average distance between critical points within the same sector weighted by $w(p)$. Let B be the average β for all sectors containing multiple points above a given weight threshold. Figure 17 shows crossing critical point and airway intersection Bs for weight thresholds between 0 and 5. Once again Bs are very similar between crossing critical points and airway intersections. All Bs are over 45 miles.

4 Conclusions

Comparing critical points to the current day airway intersections helps calibrate their weights so

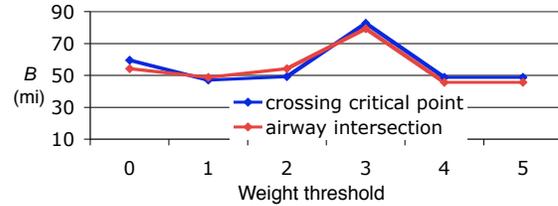


Fig. 17 Crossing critical point and airway intersection Bs for different weight thresholds.

they can be used in sector design with different flight trajectories. Then critical points based on forecast trajectories and constraints may be used to define dynamic airspace boundaries that change with the air traffic. This would minimize the need to impose traffic management restrictions and reduce controller workload.

This analysis shows that critical points (where dominant flows cross and merge) generated from current day flight paths are comparable to airway intersections. This shows promise for the method of defining critical points presented in this paper.

Crossing critical points far outnumbered and outweighed merging critical points. When critical points were scaled to a maximum weight of 10, the critical points with weight greater than 2 paired best with airway intersections and resulted in the most reasonable number of critical points within each sector. This analysis found average distances of critical point and airway intersection from sector boundaries around 19 miles and average distances between large weight points over 45 miles.

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References

- [1] Kopardekar, P., Bilimoria, K., Sridhar, B. 2007. Initial concepts for dynamic airspace configuration. In *7th AIAA Aviation Technology, Integration and Operations Conference*, Belfast, Northern Ireland.
- [2] Davison, H. J., Histon J. M., Ragnarsdottir, M. D., Major, L. M. and Hansman, R. J. 2003. Impact of operating context on the use of structure in air traffic controller cognitive process. In *5th USA/Europe ATM R&D Seminar*, Budapest, Hungary.
- [3] Cummings, M. L., Tsonis, C. G. and Cunha, D. C. 2005. Complexity mitigation through airspace structure. In *13th International Symposium on Aviation Psychology*, Oklahoma City, Oklahoma.
- [4] Athenes, S., Averty., Puechmorel, S., Delahaye, D., and Collet, C. 2002. ATC complexity and controller workload: trying to bridge the gap. In *International Conference on Human-Computer Interaction in Aeronautics*, MIT, Cambridge, Massachusetts.
- [5] Klein, A., Kopardekar, P., Rodgers, M. 2007. "Airspace playbook": dynamic airspace reallocation coordinated with the national severe weather playbook. In *7th AIAA Aviation Technology, Integration and Operations Conference*, Belfast, Northern Ireland.
- [6] Histon, J. M., Hansman, R. J., Aigoïn, G., Delahaye, D. and Puechmorel, S. 2002. Introducing structural considerations into complexity metrics". In *Air Traffic Control Quarterly*.
- [7] Busing, H. G. 2005. "Air Traffic Control Operating Modes and the management of Complexity". International Center for Air Transportation, Massachusetts Institute of Technology, Research Project under Prof. R. John Hansman.
- [8] Aircraft Situation Display To Industry: Functional Description and Interface Control Document. August 2000. Report no. ASDI-FD-001. Volpe Center Automation Applications Division, Cambridge, MA.
- [9] Federal Aviation Administration. Aeronautical Information Services. National airspace system resource aeronautical data. Effective March 17, 2005.