Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009)

The Impact of Severe Weather on Sector Capacity

Lixia Song, Daniel Greenbaum, Craig Wanke
The MITRE Corporation
Center for Advanced Aviation System Development
McLean, Virginia 22102
lixia@mitre.org
dpg@mitre.org
cwanke@mitre.org

Abstract—**It is well-accepted that sector capacity is reduced when severe weather is present in the sector. However, no accepted algorithms for calculating the capacity under severe weather impact have been developed. We have proposed methods to estimate the impact of severe weather on sector capacity. These methods introduced three types of weather impact index: 2D weather coverage, 3D weather avoidance field coverage, and flow-based sector capacity reduction ratio. This paper discusses the correlations between the sector throughput and these three sector weather impact indexes with statistical analysis of the historical data. The statistical correlation between the actual sector throughput and the sector weather impact indexes reveals the current operation of the Air Traffic Management system and suggests the acceptable algorithm for calculating the capacity under severe weather impact.**

Keywords-Traffic flow management, sector capacity, sector weather impact index, flow capacity, traffic flow pattern

I. INTRODUCTION

In the U.S. National Airspace System (NAS), en route Traffic Flow Management (TFM) is the function which balances air traffic demand against available airspace capacity, to ensure a safe and expeditious flow of aircraft. However, airspace capacity is difficult to estimate and predict. In today's NAS, there is no automation tool to predict sector capacity, since there is no established and accepted indicator of sector capacity. The current Enhanced Traffic Management System (ETMS) [1] provides a congestion alerting function which uses peak one-minute aircraft count as a sector congestion alerting criterion (the "Monitor Alert Parameter," or MAP). This is not meant to be a measure of airspace capacity, but rather a threshold which, when exceeded by predicted demand, alerts traffic managers to examine the sector for potential congestion. The actual capacity of a sector is dependent on the complexity of the traffic flows within, as well as the presence or absence of hazardous weather.

In most cases, the presence of severe weather in a sector significantly increases the sector controller's workload and lowers the amount of traffic controllers can safely handle [2]. Many flights will want to avoid areas of severe weather, compressing the traffic into a smaller area, making it more difficult to separate aircraft and maintain safety. Flights may ask for last-minute maneuvers to stay clear of the weather, or to thread a path through gaps in the weather system, or to turn back if they cannot get through. Managing these maneuvers adds to the controller's workload since each new flight path has to be checked for potential future problems. Controllers may need to keep traffic density low near weather so they can grant last minute requests to maneuver and at the same time maintain safe separation between flights. However, the controllers' major task does not change under severe weather impact; the primary task is still moving the traffic from the previous sector to the next sector safely and efficiently. To better manage controllers' workload when sectors are impacted by severe weather, traffic flow managers need to understand the available airspace controllers can still use to accomplish this task.

This paper studies the relationship between the actual sector capacity and the available sector airspace under severe weather impact. The available airspace in a sector can be estimated in several ways, from simply considering only consider the precipitation severity of the weather to a multi-factor approach that considers the pilot deviation behavior around the weather and the blockage of each flow in the sector. These methods of estimating the available sector airspace under severe weather impact are introduced in the weather impact indexes section in this paper. The estimated actual sector capacity is explained in the following section. The effect of the weather impact factors, the echo top of the severe weather, the pilot deviation behavior around the weather, and the flow blockage in the sector, on the actual sector capacity are discussed in the rest of the paper.

II. BACKGROUND

Sector capacity as an indicator of controllers' workload threshold is not a single value even on clear weather days, since controller workload is not only a function of the number of aircraft, but also a function of traffic complexity. Therefore, a new approach to sector capacity prediction [3] was developed for airspace congestion management, in which traffic complexity is captured with traffic flow patterns. Traffic flow patterns are described with clustered flow features, which are more predictable and perturbation-resistant than metrics which rely on single-aircraft events or aircraft-to-aircraft interactions. NAS sectors typically exhibit a small set of common traffic flow patterns, and different patterns represent different levels of traffic complexity. In higher-complexity conditions, it takes fewer flights to generate high workload for the controller team, and thus the sector capacity is lower.

Estimating the future capacity of the NAS in the presence of weather has many difficulties. One difficulty is that weather forecasts all have some degree of inaccuracy. This is compounded by the problem that minor differences in how weather develops can lead to major differences in the impacts on the NAS. Small storms located at critical locations can have more impact than larger storms in less critical locations. Another problem is that each flight can be impacted differently. Many of the westbound flights in a sector may be blocked, while several northbound flights can make it through. Flights at 27,000 feet may have to deviate, while flights at 34,000 feet can fly over the storms without changing course. These factors mean that capacity is not strictly independent of demand; the trajectories and altitude profiles of flights that plan to use the airspace can significantly alter how many flights can be managed in a sector.

Several methods of estimating sector capacity under severe weather impact have been developed [4]. These methods introduced three sector weather impact indexes: 2D precipitation intensity at and above level three weather coverage (will be referred as 2D weather coverage in the rest of the paper), 3D weighted sector Weather Avoidance Altitude Field (WAAF) coverage (to be referred as 3D WAAF coverage), and the flow-based *ReducedSectorCapacityRatio.*

III. WEATHER IMPACT INDEXES

The Corridor Integrated Weather System (CIWS) is used in this paper to calculate the weather impact indexes. CIWS is a MIT Lincoln Laboratory (MITLL) weather product, which provides accurate and high update rate information on storm locations and echo tops with one-kilometer (km) spatial resolution [5]. The precipitation intensity of the severe weather is characterized by the Vertically Integrated Liquid (VIL) metric in CIWS. Weather areas with measured VIL at and above level three corresponds to heavy and extreme precipitation (at and above 40 dBZ) in current Federal Aviation Administration (FAA) terminology.

A. 2D Weather Coverage

VIL at and above level three (VIL3+) coverage in a sector is an important indicator of weather impact on sector capacity [6]. Without the help of automation, traffic managers often estimate the VIL3+ coverage in a sector by themselves and predict the reduction of the sector capacity based on their own experience. Thus, the first weather impact index will be examined in this paper is the percent of the sector area covered by weather with VIL at and above level three, which will be referred as 2D weather coverage in the rest of the paper. Figure 1 shows the number of flights passing through an example sector in 15 minutes plotted against the percent of the 2D sector weather coverage. As shown in the figure, the maximum traffic count generally decreases as the weather coverage increases.

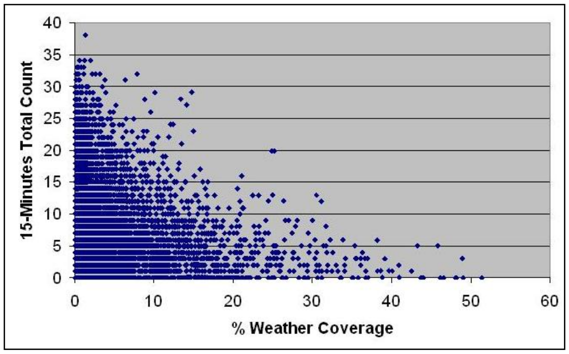

Figure 1. Sector throughput observation

B. 3D WAAF Coverage

The 2D sector weather coverage does not take into account the echo tops. Echo tops will likely be a large factor for high and super high altitude sectors, where many flights may be able to fly over certain storms. Another key element to factor in is the pilot avoidance behavior near severe weather. Flight through a severe weather area may be acceptable to some pilots and not to others. This acceptance is likely a function of many other factors such as operator experience and training, risk aversion or acceptance, airline policy, the existence of alternate options, and the expected amount of time that will be spent in the severe weather hazard space. Research is taking place on the behavior of pilots near severe weather. MITLL has developed their first Convective Weather Avoidance Model (CWAM1), which models the pilot deviation behavior in and around severe weather as a function of explanatory variables (such as reflectivity level and echo tops) by observing actual flight tracks around severe weather cells [7]. Note that the CWAM1 is the initial model and a MITLL is developing CWAM2 and CWAM3 [8].

With echo tops and the pilot deviation behavior model, the weather area in a sector that most aircraft would avoid can be identified. The deviation decision model in [7] shows that most aircraft fly *delta*Z above the 90th percentile of the echo top height in the 16X16 km^2 neighborhood, where *delta*Z is a function of the VIL3+ weather coverage in the 60X60 km^2 neighborhood. There are two versions of this function, deterministic and probabilistic. With the deterministic version of CWAM1, the *delta*Z is certain given the VIL3+ weather coverage in the 60X60 km^2 neighborhood; the weather avoidance altitude of each pixel (1x1 km^2, the resolution of CIWS) in a sector is then the *delta*Z plus the 90th percentile of the echo top height in the 16X16 km^2 neighborhood [9]. With the probabilistic version of CWAM1, the *delta*Z is a range attached with a probability. For example, if the VIL3+ weather coverage in the 60X60 km^2 neighborhood of the cell is between 0.7 and 0.8, and the difference between the flight altitude and the 90th percentile of the echo top height in the 16X16 km^2 neighborhood of the cell is ranged from -2,000 to 2,000 feet, then 80 percent of pilots would deviate around the cell. Given a probability of deviation threshold (e.g., 0.8), the weather avoidance altitude of each pixel can be calculated as follows:

1) Calculate the percentage of VIL level 3 above pixels in the 60 km neighborhood around the pixel (e.g., 75%).
2) Calculate the 90th percentile of the echo top height from the 16 km neighborhood of the pixel (e.g., 32,000 feet).
3) Find the range of *delta*Z from the probabilistic CWAM1 (table 1) with the percentage of VIL level 3 above pixels calculated in Step 1 and the given probabilistic threshold (e.g., *delta*Z is between -2,000 and 2,000 feet given VIL coverage to be 75% and the probability threshold to be 0.8).
4) The weather avoidance altitude of the pixel is the addition of *deltaZ* and the 90th percentile of the echo top height calculated in Step 2.

TABLE 1. PROBABILISTIC CWAM1 LOOKUP TABLE

%VIL DeltZ	0 to 0.1	0.1 to 0.2	0.2 to 0.3	0.3 to 0.4	0.4 to 0.5	0.5 to 0.6	0.6 to 0.7	0.7 to 0.8	0.8 to 0.9	0.9 to 1
<-10	0.9	0.9	0.9	0.9	0.9	1	1	1	1	1
-10 to -6	0.8	0.8	0.8	0.9	0.9	1	1	1	1	1
-6 to -2	0.6	0.7	0.7	0.8	0.8	0.9	0.9	1	1	1
-2 to 2	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8
2 to 6	0.2	0.3	0.4	0.4	0.5	0.6	0.6	0.6	0.6	0.6
6 to 10	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.4
>10	0	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3

(based on personal communication with MITLL CWAM1 development team)

To be able to compare the effect of different deltaZ on sector capacity, the lower end of deltaZ, which is most aggressive and gives the highest capacity, and the higher end of deltaZ, which is most conservative and gives the lowest capacity, are used from Step 3 to calculate the weather avoidance field of the pixel in Step 4. In addition, to compare the effect of different probability of threshold on sector capacity, two different probabilities of threshold are given (0.6 and 0.8) to calculate the weather avoidance field of each pixel. Thus, five types of WAAF are generated based on the deterministic and probabilistic CWAM1:

- Deterministic WAAF (will be referred as WAAF-D in the rest of the paper)
- Aggressive WAAF with probability of threshold to be 0.6 (to be referred as WAAF-A6)
- Aggressive WAAF with probability of threshold to be 0.8 (to be referred as WAAF-A8)
- Conservative WAAF with probability of threshold to be 0.6 (to be referred as WAAF-C6)
- Conservative WAAF with probability of threshold to be 0.8 (to be referred as WAAF-C8)

The weather avoidance altitude field also indicates that the avoided weather size, shape, and location vary with altitude. Since aircraft fly at different flight levels in the sector, it is important to understand how the weather would impact each flight level of the sector. Thus, a sector is sliced into 1,000 foot altitude bands. For example, sector ZID66 covers an altitude range of 23,000 to 33,000 feet, so ZID66 will have 10 altitude bands, from band 23 to band 32. A pixel in band x needs to be avoided if the weather avoidance altitude of that pixel is greater than x. The percentage of weather avoidance area for each sector altitude band can then be calculated through dividing the number of avoided pixels by the total number of pixels in each sector altitude band. The percentage of sector WAAF coverage is then the weighted sum of the percentages of weather avoidance area for each sector altitude band, where the weights reflect the observed usage of flight levels in the sector. That is,

$$\begin{aligned} &Sector\mathrm{WAAF}Coverage \\ &= \sum_i w_i \times BandCoverage(i) \\ &w_i : Weight on\, Altitude Band\, i \end{aligned} \tag{1}$$

The altitude weights are important. If we assume that altitude usage is uniform in sectors, the impact of a storm with 30,000 foot echo tops in a sector that handles flights from 24,000 to 35,000 feet will be overestimated. The majority of the flights in that sector will be free of the weather near the top of the sector. Altitude usage is also important in deciding what to do about very high altitudes, such as altitudes above 40,000 feet. In many cases these altitudes will be above the weather impacts, but assuming that flights in the sector will be using these altitudes with the same frequency of other altitudes would be incorrect, since very few aircraft can operate at these altitudes. Figure 2 shows an altitude usage profile over the entire NAS for the month of June 2007. Here the usage is measured in flight-minutes at each altitude.

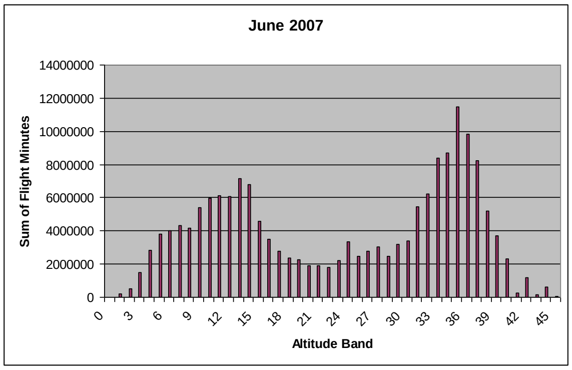

Figure 2. NAS altitude usage profile

The distribution of altitude usage is mostly determined by flight efficiency. We have assumed that this distribution will hold in most en-route airspaces. If so, a single distribution can be used for most sectors. Some sectors may not match this altitude usage distribution well, and may require special handling with sector specific profiles. In this analysis, the altitude profile shown in Figure 2 was used for all NAS sectors. To evaluate the benefit of weighing the altitude band coverage with the NAS-wide altitude profile, the equally-weighted 3D WAAF coverage is also calculated, that is, each altitude band is treated to be equal in (1).

C. Flow-Based ReducedSectorCapacityRatio

In addition to the size of the weather area or more accurately the WAAF area, the sector capacity is also highly correlated with the shape and location of the weather or WAAF area. Small storms located at critical locations can have more impact than larger storms in less critical locations. Figure 3 shows an example sector being impacted by the same shape and the same size weather. But the sector is impacted at different location in Case A and Case B. In Case A, the storm is located at a critical point, the major flows with most of the sector traffic on them are blocked. While in Case B, only the minor flows are impacted. The sector capacity reduction should be different for Case A and Case B. Thus, the third weather impact index is introduced to capture the flow and flow pattern impact in a sector [9]. As described in [9], flows in a sector are defined to be the sector transit triplets (entry sector – current sector – exit sector).

Under the severe weather impact, each flow (or triplet) blockage (or available ratio of flow capacity) is decided with the minimal-cut (*mincut*) of the flow given the weather avoidance altitude field in the sector [9, 10]. For example, one flow for sector B is A-B-C (Figure 4), which shows the flow is from sector A, through B, and into sector C. Each altitude band of a sector is a polygon. The yellow blocks in the figure are the WAAF area in the sector altitude band. Based on the generalized max-flow min-cut theorem, the capacity of flow A-B-C at each altitude band in sector B is dictated by its bottleneck, the *mincut* from the top edge **T** to the bottom edge **B** of sector B avoiding the WAAF areas (*Wmincut*). The top edge **T** and the bottom edge **B** is the portion of the sector boundary clockwise and counterclockwise between the source edge **S** (the sector boundary shared by sector A and sector B) and the destination edge **D** (the sector boundary shared by sector B and sector C).

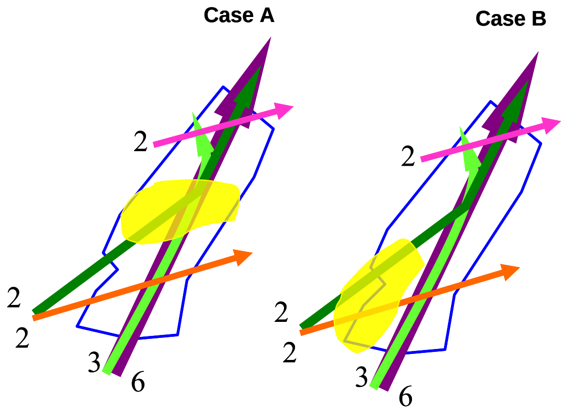

Figure 3. Example sectors under severe weather impact

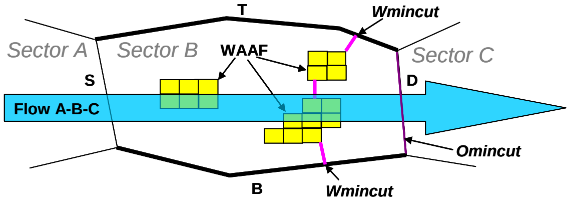

Figure 4. Flow capacity restricted with mincut

The *AvailableFlowCapacityRatio* is the flow *mincut* ratio calculated with the following equation,

$$AvailableFlowCapacityRatio = \min_i \frac{Wmincut_i}{Omincut_i} \tag{2}$$

Where $Wmincut_i$ is the *mincut* at altitude band i with WAAF area; and $Omincut_i$ is the *mincut* at altitude band i without WAAF area. The *ReducedSectorCapacityRatio* is the weighted average of the reduced capacity ratio of all the flows in the predicted traffic flow pattern. That is,

$$ReducedSectorCapacityRatio = 1 - \sum_{j=1}^{m} W_j \times AvailableFlowCapacityRatio \tag{3}$$

Where m is the total number of flows; and W_j is the weight on flow j, which is the number of aircraft on flow j divided by the total number of aircraft in the sector.

IV. ESTIMATED ACTUAL SECTOR CAPACITY

As we discussed in the previous sections, sector capacity as an indicator of controllers' workload threshold is dependent on the complexity of the traffic flows within the sector, as well as the presence or absence of hazardous weather. No one really knows what the actual sector capacity should be for each 15-minute period. The historical total number of flights the sector handled in a 15-minute period (sector throughput) can give us some knowledge on the sector capacity under current operational environment. However, many variables that control the sector capacity are difficult to isolate when collecting the historical sector throughput.

The study in [6] estimated the weather impacted capacity for a sector to be the upper bound of the sector throughput in all cases with the same weather coverage in the sector. The upper bound of the sector throughput could both underestimate and overestimate the sector capacity. What has been through the sector is not the same as what can be handled in the sector. In many cases there are not enough flights that are planned to fly through the sector at the time of the observation to achieve the maximum throughput. In other cases flights are hampered from reaching the sector due to weather or congestion in other sectors. Also demand in a sector could be lightened due to Air Traffic Management initiatives that have anticipated the weather. There can be other cases where the observed throughput is higher than what a weather impacted sector can expect to handle. This can happen when special traffic patterns are implemented to move flights around weather. These patterns may limit merging and crossing traffic in critical sectors to allow higher throughput than would be possible with the typical traffic patterns. Also, there can be other cases where the controller workload was higher than acceptable, sometimes due to unexpected rapid weather development.

In this study, we collected all the observations of actual sector throughput in June and July 2007. Observations were filtered out when a sector had low predicted demand one hour before the observation. This filter attempts to eliminate cases where the ATM system is reducing traffic in anticipation of the weather. ATM initiatives typically happen more than one hour before an event, and can be overly restrictive due to the uncertainty in forecasting weather impacts.

The rest of the observations are then binned according to the sector weather impact indexes. The bin sizes were carefully chosen to reflect the varying ranges of the different indexes, so that sample sizes were similar across the indexes when computing correlations. Most of the observations fall between 0% and 20% for 2D weather coverage and between 0% and 50% for 3D WAAF coverage, while flow-based *ReducedSectorCapacityRatio* observations range up to 100%. So, the filtered sector throughput observations were binned by every 2% of 2D weather coverage, every 5% of 3D WAAF coverage, and every 10% of flow-based *ReducedSectorCapacityRatio*. Within each bin of sector throughput observations, the top two and bottom two data points are deleted as outliers. The high throughput outliers may represent cases where workload was unacceptably high or cases where special high throughput flow patterns were used. The estimate of the actual sector capacity for each weather coverage bin is calculated from the 95th percentile of the throughput values if there are more than five data points in the bin.

V. LINEAR CORRELATION BETWEEN THE ESTIMATED ACTUAL SECTOR CAPACITY AND THE WEATHER IMPACT INDEXES

For the first set of analysis, we used the WAAF generated based on the deterministic CWAM1 (WAAF-D) to calculate the 3D WAAF coverage and the flow-based *ReducedSectorCapacityRatio*. Forty-eight high sectors from four northeast air traffic control centers (New York [ZNY], Washington [ZDC], Indianapolis [ZID], and Cleveland [ZOB]) have been selected for comparing the weather impact indexes. For these sectors, the linear correlations for the following variables are examined:

- Between each of the three sector weather impact indexes (2D weather coverage, 3D WAAF coverage, and the flow-based *ReducedSectorCapacityRatio*) and the estimated actual sector capacity
- Between the 95th percentile of the flow throughput (assumed to be the estimated actual flow capacity) and the *AvailableFlowCapacityRatio* for the top three major flows of the sector
- Between the estimated actual sector capacity and the major flow *AvailableFlowCapacityRatio*

The reduced sector capacity under severe weather impact is heavily dependent on the operational usage of the sector. In general, statistically-significant linear correlations were found between the estimated actual sector capacity and the three sector weather impact indexes. None of the three sector weather impact indexes has the strongest linear correlation with the estimated actual sector capacity for all the sectors examined. Figure 5 shows the 48 sectors we examined. The sectors are color coded to show the sector weather impact index that has the strongest linear correlation with the estimated actual sector capacity.

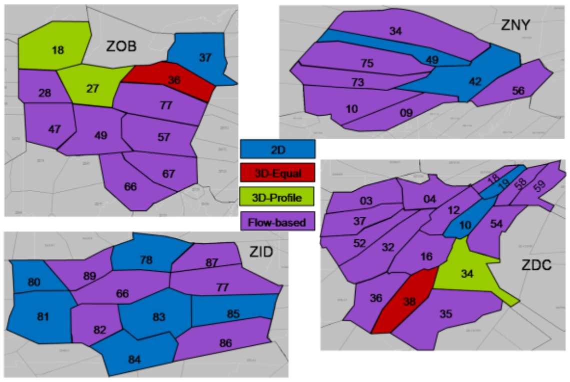

Figure 5. The sector seather impact index with the strongest linear correlation with the estimated actual sector capacity

The purple sectors are the sectors where the flow-based *ReducedSectorCapacityRatio* has the strongest linear correlation with the estimated actual sector capacity. Sectors where equally-weighted 3D WAAF coverage has the strongest correlation are shown in red, and sectors where altitude-weighted 3D WAAF coverage has the highest correlation are shown in olive. The blue sectors are where the 2D weather coverage has the strongest linear correlation with the estimated actual sector capacity.

Generally, flow-based *ReducedSectorCapacityRatio* has the strongest linear correlation with the estimated actual sector capacity in sectors with dominant flows. Figure 6 shows the linear correlations of an example sector (ZDC12) with a dominant flow (DC16-ZDC12-ZDC18). The sector weather coverage for the red line is the 2D weather coverage, for the blue line is the equally-weighted 3D WAAF coverage, for the green line is the altitude profile (as shown in Figure 6) weighted 3D WAAF coverage, and for the purple line is the flow-based *ReducedSectorCapacityRatio*.

Comparing the blue dots with the red squares in Figure 6, the correlation between the estimated actual sector capacity and the 3D equally weighted WAAF coverage (0.7922) is stronger than the correlation for the 2D weather coverage (0.6620). It shows that the deterministic CWAM1 works well in ZDC12 since WAAF is built upon the deterministic CWAM1. Comparing the olive triangles with the red squares in Figure 6, the altitude profile in Figure 2 added some value to the correlation for the 3D WAAF coverage (0.8658 vs. 0.7922). Comparing the purple stars with the rest in Figure 6, the correlation for the flow-based *ReducedSectorCapacityRatio* is stronger than the correlations for the other sector weather impact indexes (0.9460 for flow-based vs. 0.6620 for 2D).

For the sectors with dominant flows, the 95th percentile of the dominant flow throughput has strong linear correlation with the *AvailableFlowCapacityRatio* of the dominant flow, but not for the other flows.

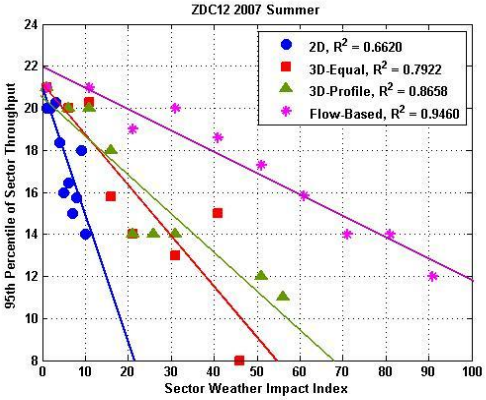

Figure 6. The linear correlation for ZDC12

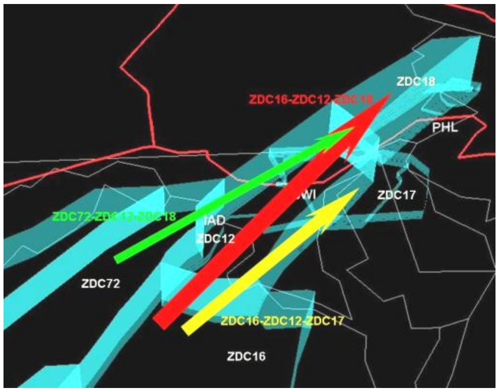

Figure 7. ZDC12 major flows

ZDC12 is a high sector that handles most of the traffic arriving EWR, LGA and PHL. Figure 7 shows the top three major flows through ZDC12, ZDC16-ZDC12-ZDC18 (red), ZDC16-ZDC12-ZDC17 (yellow), and ZDC72-ZDC12-ZDC18 (green). ZDC16-ZDC12-ZDC18 is the dominant flow of sector ZDC12. During the severe weather impact, the *AvailableFlowCapacityRatio* for ZDC16-ZDC12-ZDC18 has strong linear correlation with the 95th percentile of the flow throughput, but not for the other two flows. Figure 8 shows the linear correlations of the *AvailableFlowCapacityRatio* for the three major flows with their 95th percentile of the flow throughput.

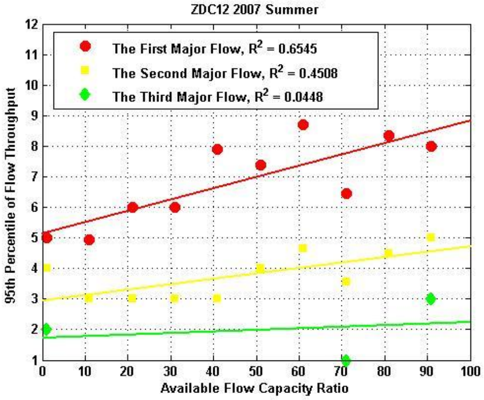

Figure 8. ZDC12 Top Three Flows Throughput

This result reveals the sector's current operational usage during severe weather impact. To reduce controller workload and improve sector efficiency during severe weather impact, ZDC12 continued to handle all traffic on the dominant flow ZDC16-ZDC12-ZDC18 while traffic on the other flows was reduced or eliminated. To verify this observation, some in-house previous controllers and traffic flow managers were interviewed. Their explanation about how they handled the traffic during the severe weather impact matches the results shown in Figure 8 and Figure 9. Figure 9 shows the estimated actual sector capacity of ZDC12 as the function of the AvailableFlowCapacityRatio of ZDC16-ZDC12-ZDC18. As shown in Figure 9, there is strong correlation between the AvailableFlowCapacityRatio of ZDC16-ZDC12-ZDC18 and the estimated actual sector capacity (0.7106), stronger than the correlation for the 2D weather coverage (0.6620).

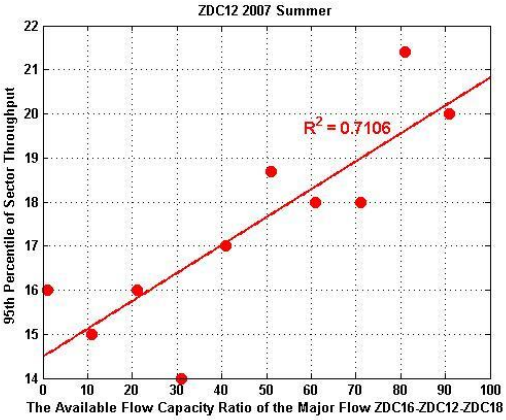

Figure 9. Sector capacity vs. flow capacity

For the sectors in which deterministic CWAM1 does not work well, the 2D weather coverage has the strongest linear correlation with the estimated actual sector capacity (blue sectors in Figure 5) since both 3D WAAF coverage and the flow-based *ReducedSectorCapacityRatio* are based on the deterministic CWAM1 in this set of analysis. For these sectors, we calculate the flow-based *ReducedSectorCapacityRatio* again with additional four types of WAAF (WAAF-A6, WAAF-A8, WAAF-C6, and WAAF-C8 as defined in the 3D WAAF coverage section) based on the probabilistic CWAM1.

All the blue sectors in Figure 5 turn to purple with some types of WAAF calculated with the probabilistic CWAM1. For example, the flow-based *ReducedSectorCapacityRatio* calculated with WAAF-A8 (Flow-A8 in Figure 10) has the strongest linear correlation with the estimated actual sector capacity for ZID85, as shown in Figure 10.

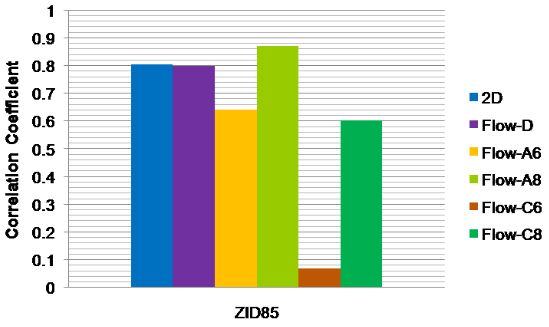

Figure 10. Comparison of different types of WAAF for ZID85

WAAF-A8 is the WAAF calculated with the probabilistic CWAM1 by setting the probability threshold to be 0.8 and deltaZ to be aggressive (the lower end). And the Flow-C6 in Figure 10 means the flow-based *ReducedSectorCapacityRatio* calculated with WAAF-C6, by setting the probability threshold to be 0.6 and deltaZ to be conservative (the higher end) of the probabilistic CWAM1. Flow-D is the flow-based *ReducedSectorCapacityRatio* calculated with the deterministic WAAF. But for ZID83, the flow-based *ReducedSectorCapacityRatio* calculated with WAAF-C8 has the strongest linear correlation with the estimated actual sector capacity, as shown in Figure 11.

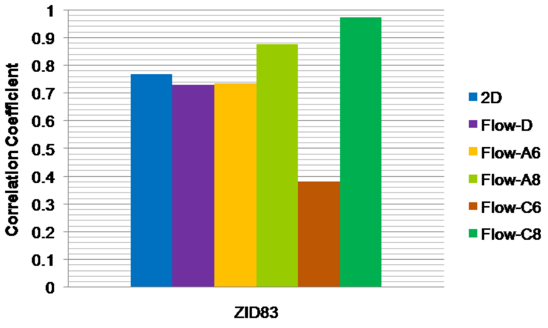

Figure 11. Comparison of different types of WAAF for ZID83

As shown in Figure 11, for ZID83, both Flow-A8 and Flow-C8 have better linear correlation with the estimated actual sector capacity than Flow-D. But Flow-C8 is significantly better than the others.

Figure 5 also shows that the 3D WAAF coverage has the strongest linear correlation with the estimated actual sector capacity for some of the sectors (red and olive sectors in Figure 5). These are the sectors with the dominant flows to be transitioning (climbing or descending) flows. When calculating the mincut of the transitioning flows in the calculation of the flow-based *ReducedSectorCapacityRatio*, the transitioning flows are projected to the level flows that go through the middle points of the lines connecting the average entry and exit points of the transitioning flows [7]. This treatment of the transitioning flows in the flow-based model may be the reason that the 3D WAAF coverage has stronger linear correlation with the estimated actual sector capacity than the flow-based *ReducedSectorCapacityRatio* for the sectors with the dominant flows to be transitioning flows. Further analysis is necessary to make this conclusion.

For sectors where the 3D WAAF coverage has the strongest correlation with the estimated actual sector capacity, sometimes the best approach was to use equally-weighted altitude bands (red sectors in Figure 5), and sometimes the NAS-wide altitude usage profile-weighted approach worked better (olive sectors in Figure 5). The reason is that the NAS-wide altitude usage profile does not match the sector altitude usage profile very well for some sectors. Figure 12 compares the altitude usage profile of ZOB36 and the NAS for the altitude band range of ZOB36.

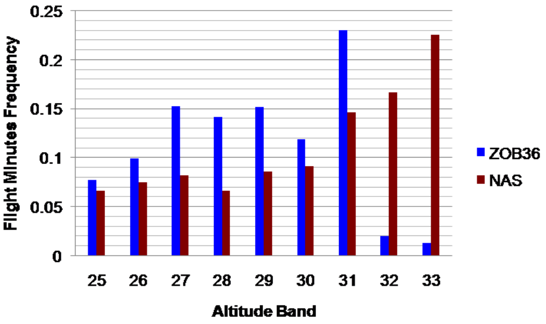

Figure 12. Altitude profile comparison between ZOB36 and NAS

As shown in Figure 12, the extreme case is for altitude bands 32 and 33. Altitude bands 32 and 33 are the least frequently used in ZOB36, while they are the most frequently used over the NAS. Further research is necessary to determine whether using sector-specific altitude profiles would improve the correlations for the 3D WAAF coverage index.

VI. CONCLUSION

Three sector weather impact indexes are introduced in the paper. The actual sector capacity is estimated to be the 95th percentile of the 15 minutes sector throughput with the help of some filters to filter out the low demand and overload cases. The linear correlations between the three sector weather impact indexes and the estimated actual sector capacity are analyzed for the 48 high-altitude sectors from four Northeast U.S. centers (ZNY, ZDC, ZID, and ZOB).

None of the three sector weather impact indexes has the strongest linear correlation with the estimated actual sector capacity for all 48 high sectors we analyzed with the deterministic CWAM1, although for the sectors with dominant flows, the flow-based *ReducedSectorCapacityRatio* always has the strongest linear correlation with the estimated actual sector capacity. Under severe weather impact, the *AvailableFlowCapacityRatio* of the dominant flow has strong linear correlation with the 95th percentile of the flow throughput and the estimated actual sector capacity, but not for the other flows. This indicates that, in sectors with dominant flows, a primary method of dealing with weather impact is to reduce or eliminate secondary flows through the sector in favor of traffic along the dominant flow direction.

For sectors where deterministic CWAM1 does not work well, the 2D weather coverage has the strongest correlation with the estimated actual sector capacity. For these sectors, the flow-based *ReducedSectorCapacityRatio* is calculated again with four different types of WAAF based on the probabilistic CWAM1. In every case, better correlations were found using the flow-based *ReducedSectorCapacityRatio* calculated with some type of WAAF based on the probabilistic CWAM1. However, the type of WAAF needed to get the best correlation varied across the sectors.

The historical data tells us what has been but not what should be. The statistical correlation between the actual sector throughput and the sector weather impact indexes reveals the current operation of the ATM system. Further research is necessary on predicting the sector capacity under severe weather impact, to tell what the sector capacity *should* be. This is needed, for example, to evaluate new airspace designs. One of the key research questions is how to translate the *AvailableFlowCapacityRatio* to the *AvailableSectorCapacityRatio*, considering the complexity due not only to traffic patterns but also due to weather impact. The analysis in this paper also reveals the directional (flow) capacity usage in the current operational environment. Automated traffic congestion resolution systems might be able to use directional flow capacities, in addition to sector capacities, in developing efficient responses to weather disruptions. So, another important research question is: how can flow capacity be better-predicted and used in both current and future operational environments?

REFERENCES

[1] *Enhanced Traffic Management System (ETMS) Reference Manual, Version 7.5*, Report No. VNTSC-DTS56-TMS-004, Volpe National Transportation Systems Center, U.S. Department of Transportation, November 2002.

[2] Masalonis, A.J., Callaham, M.B., Figueroa, Y., and Wanke, C.R. Indicators of airspace complexity for Traffic Flow Management decision support. *12th International Symposium on Aviation Psychology*, Dayton, OH, 2003.

[3] Song, L., Wanke, C. and Greenbaum, D., "Predicting Sector Capacity for TFM," *7th USA/Europe Air Traffic Management Research and Development Seminar*, Barcelona, Spain, 2-5 July 2007.

[4] Song, L., Wanke, C. and Greenbaum, D., Methodologies for Estimating the Impact of Severe Weather on Airspace Capacity, *American Institute of Aeronautics and Astronautics (AIAA) 2008-8917*, *8th AIAA Aviation Technology, Integration, and Operations Conference*, Anchorage, Alaska, 14-19 September.

[5] Weber, M., Evans, J., Wolfson, M., DeLaura, R., Moser, B., and Brian Martin, B., Improving Air Traffic Management During Thunderstorms, *12th Conference on Aviation, Range, and Aerospace Meteorology,* Atlanta, GA, 29 January - 2 February 2006.

[6] Davis, E., Hargroves, B., and Holden, T. *The Effect of Convective Weather on Sector Capacity*. MITRE Product MP 05W0000200, The MITRE Corporation, McLean, VA, September 2005.

[7] DeLaura, R., and Evans, J., *An Exploratory Study of Modeling Enroute Pilot Convective Storm Flight Deviation Behavior*, MIT Lincoln Laboratory Project Report NASA/A-6, 26 June 2006.

[8] DeLaura, R., Robinson, M., Pawlak, M., and Evans, J., Modeling Convective Weather Avoidance In Enroute Airspace, *13th Conference on Aviation, Range and Aerospace Meteorology*, New Orleans, LA, January 20-24, 2008.

[9] Song, L., Wanke, C. and Greenbaum, D., Predicting Sector Capacity under Severe Weather Impact for Traffic Flow Management, *American Institute of Aeronautics and Astronautics (AIAA) 2007-7887*, *7th AIAA Aviation Technology, Integration, and Operations Conference*, Belfast, Northern Ireland, 18-20 September.

[10] Krozel J., Mitchell, J., Polishchuk, V. and Prete, J., Capacity Estimation for Airspaces with Convective Weather Constraints, *AIAA Guidance, Navigation, and Control Conference*, Hilton Head, SC, August 2007.

DISCLAIMER NOTICE

The contents of this material reflect the views of the authors. Neither the FAA nor the Department of Transportation makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein.

AUTHOR BIOGRAPHY

Dr. Lixia Song holds S.B and S.M. in Solid Mechanics from Hunan University, S.M. in Aerospace Engineering from University of Minnesota, and Ph.D. degree in Aeronautical Engineering from the Massachusetts Institute of Technology

She is a Lead Modeling and Simulation Engineer with The MITRE Corporation's Center for Advanced Aviation System Development in McLean, Virginia, USA.

Dr. Song's research includes decision support systems analysis and integration, estimation and control, optimization.

Dan Greenbaum holds an M.S. in Computer Science from the George Washington University, an M.E. in Systems Engineering from the University of Virginia, a J.D. from Cornell Law School, and a B.A. from the University of Pennsylvania.

He is a Lead Software Systems Engineer with The MITRE Corporation's Center for Advanced Aviation System Development in McLean, Virginia, USA.

Mr. Greenbaum's work includes developing software to model air traffic and related human decision making.

Dr. Craig Wanke holds S.B, S.M., and Ph.D. degrees in Aeronautical Engineering from the Massachusetts Institute of Technology

He is a Senior Principal Engineer at MITRE, specializing in simulation and modeling with The MITRE Corporation's Center for Advanced Aviation System Development in McLean, Virginia, USA.

Dr. Wanke has worked for the past 15 years on decision support systems for cockpit and air traffic management applications.