INTERACTION OF AIRSPACE PARTITIONS AND TRAFFIC FLOW MANAGEMENT DELAY WITH WEATHER

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Abstract

The interaction of partitioning the airspace and delaying flights in the presence of convective weather is explored to study how re-partitioning the airspace can help reduce congestion and delay. Three approaches with varying complexities are employed to compute the ground delays. In the first approach, an airspace partition of 335 high-altitude sectors that is based on clear weather day traffic is used. Routes are then created to avoid regions of convective weather. With traffic flow management, this approach establishes the baseline with per-flight delay of 8.4 minutes. In the second approach, traffic flow management is used to select routes and assign departure delays such that only the airport capacity constraints are met. This results in 6.7 minutes of average departure delay. The airspace is then partitioned with a specified capacity. It is shown that airspace-capacity-induced delay can be reduced to zero at a cost of 20 percent more sectors for the examined scenario. While the first two approaches investigate the upper and lower bounds in terms of delay and number of sectors, the third approach investigates the tradeoff between the number of sectors and the delay by re-applying the traffic flow management using the re-partitioned sectors. In this approach, the weather constraints are reflected in the sector partitions, and the delay is shared between airspace and airports. The solutions discovered by this approach are 6.9 minutes of average delay with a 312 sector configuration and 8.1 minutes of delay with a 253 sector configuration. Results show that a sector design that is tailored to the traffic and weather pattern can reduce delay while reducing the number of sectors at the same time. However, airspace partitioning can only address the delays caused by airspace congestion. Even in the presence of convective weather, the airport capacity constraint causes the majority of the delay.

Introduction

The motivation of this study is to determine if airspace partitioning is helpful in reducing airspace-induced traffic flow management delays when aircraft are rerouted to avoid regions of convective weather. Earlier studies examined traffic flow decisions in conjunction with airspace partitioning [1–3]. In [3], a tradeoff study was performed on the number of nationwide sectors designed for traffic in a clear-weather day and the ground/departure delays needed for accommodating the traffic demand. Results showed that most of the delays are caused by airport arrival and departure capacity constraints. All delays caused by airspace capacity constraints can be eliminated by re-partitioning the airspace. It was determined that 360 high-altitude sectors, which are approximately today's operational number of sectors of 373, are adequate for delays to be driven solely by airport capacity constraints for the current daily air traffic demand. In addition, simulations of traffic growth of 15 percent and 20 percent with forecast airport capacities in the years 2018 and 2025 showed that delays will continue to be governed by airport capacities. In clear-weather days, for small increases in traffic demand, increasing sector capacities will have almost no effect on delays.

This paper is an extension of the previous study described in [3]. It is one of the first studies to investigate the system-wide impact of weather combined over a full day period with traffic flow management and airspace partitioning. In addition, the approach in this study is based on actual geometric weather reroutes that are independent of the sector configuration.

Three approaches are presented to study the interaction between airspace partitioning and delaying flights in the presence of weather. In the first approach, only traffic flow management is applied using sector configuration from a clear weather day to establish a baseline. In the second approach, traffic flow management is applied to find

routes and schedules that satisfy only the airport capacity constraints. The airspace is then re-partitioned so that no additional delay is caused by the congestion in the airspace. This approach establishes the upper bound in terms of cost and benefit, because it results in the smallest delay with the largest number of sectors. In the third approach, the sectors are re-partitioned as in the second approach but the design capacity is raised to control the number of sectors. With these sector designs, traffic flow management is applied again with both the airport and airspace constraints to find delays. This approach shows the most practical solution. The sector design reflects the traffic pattern and weather, and delay is shared between airport and airspace while keeping reasonable numbers of sectors.

The main conclusion of the study is that airspace partitioning can help reduce delays that are caused by the congestion in the airspace when flights are rerouted around weather; however, the majority of delay is still caused by airport capacity constraints.

The rest of the paper is organized as follows. "Description of Tools" section describes the airspace partitioning tool, rerouting algorithm, air traffic simulation tool, and a departure scheduler used in this study. The multi-step approaches are described in "Approaches" section. Results of the study are presented in "Results" section. Finally, the main findings are summarized in the "Conclusions" section.

Description of Tools

This section provides a summary of four tools used for generating the results of this study. The following sub-sections describe the Voronoi-diagram-based sector partition method used for partitioning the airspace into sectors, a procedure for creating routes using streamlines around blocking weather, the Airspace Concept Evaluation System (ACES) that was used for simulating the air traffic, and the first-come first-served (FCFS) scheduler for computing departure times needed for traffic flow management.

Sector Partitioning Method

The airspace partitioning method recursively uses a Voronoi diagram to optimize airspace partitions [4]. The objectives of the optimization include maximizing average flight-time through the sector, relocating the sector boundaries away from major flows and major flow crossings, balancing the number of aircraft in the sectors, and maximizing the crossing-angle between the flight paths and the sector boundaries. The constraint is that the maximum number of aircraft in the sector at any time be at or below the specified capacity value.

Figure 1 shows an example of an airspace partition obtained using the procedure described above. The figure shows a horizontal slice of the sectors at a single 24,000 feet altitude level. Although not shown in the figure, some of the partitions have vertical divisions. This example shows a total of 283 sectors at altitudes 24,000 feet and above generated for a peak-traffic count of 21 aircraft per sector.
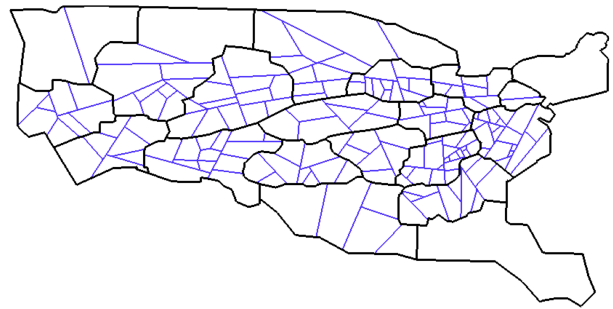

Figure 1. Example of Airspace Partitioning

Weather Avoidance Routing

The weather rerouting tool creates streamlines around weather using principles from fluid mechanics, and then uses them as routes. In ideal two-dimensional fluid flow past stationary obstacles, a streamline shows the direction a fluid element travels. Streamlines are tangent to the velocity vector of the flow. Hence, streamlines smoothly avoid obstacles and do not cross them; therefore they are a reasonable solution for weather avoidance.

The rerouting tool creates a grid around weather cells and solve the two-dimensional Laplace equation using finite-difference method to get the streamlines. For each weather block, the routes are created in four directions: north-south, east-west, northeast-southwest, and northwest-southeast. Among the four, the direction that is closest to the original route is selected. For each direction, multiple streamlines exist that avoid the weather cell. As a streamline gets

closer to the weather cell, it tends to follow the exact contour thus creating the 'hugging' problem. In the current rerouting tool, a streamline that is a certain distance away from the weather cell boundary is selected to ensure that the route does not hug around the weather. Figure 2 shows an example of streamlines flowing in east-west direction that smoothly flow around the weather polygons.

For the current study, weather cells are combined every hour. That is, all the regions swept by the weather during a one-hour period are combined to form a larger stationary weather cell to avoid. Although combining weather-constrained area has a potential of creating unnecessarily large area to avoid, it makes the reroutes robust that the same route is guaranteed to clear the weather for one hour. This property will play an important role later when the routes are selected by the departure scheduler.

The weather data comes from National Convective Weather Forecast (NCWF). The regions where the NCWF Hazard Scale level is three and above are considered to be the areas to avoid.
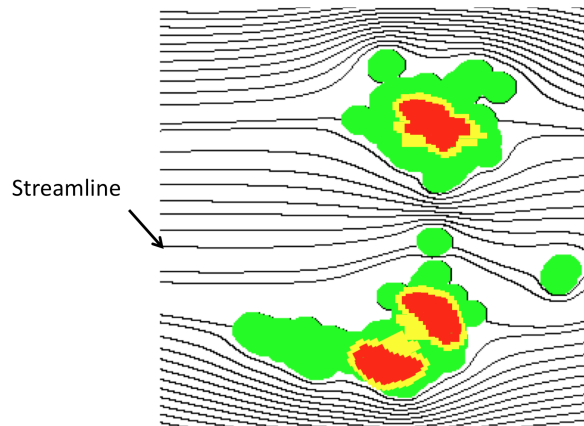

Streamline

Figure 2. Streamlines around Weather Cells

Airspace Concept Evaluation System

ACES is a gate-to-gate simulation of air traffic at local, regional and national levels. It was developed at NASA Ames Research Center [5]. ACES simulates flight trajectories using aircraft models derived from EUROCONTROL's Base of Aircraft Data (BADA) [6] and traffic data consisting of departure times and flight-plans obtained from the recorded Airline Situation Display to Industry (ASDI) files.

Typical ACES outputs are arrival and departure counts at airports, traffic-counts in sectors and system performance metrics including arrival, departure, en-route and total delays. Validation studies [7-8] have shown that ACES generates delays and metrics similar to those observed in the real world.

In this study, ACES was used for simulating traffic without airport and airspace capacity constraints. The resulting output data, which includes departure time, entry and exit time for the sectors along the route, and the arrival time for each flight, were then used for generating inputs for the departure scheduler, which is discussed in the next sub-sections.

Departure Scheduler

Traffic flow management is performed through a departure scheduler that delays the flights on the ground to satisfy the airport capacity constraints represented by aircraft departure and arrival rates and airspace capacity constraints represented by maximum numbers of aircraft in sectors [9].

The departure scheduler is based on the FCFS scheduler used for the earlier study [3]. One fundamental difference is that the route depends on the departure time in the presence of weather because the weather changes with time. The new rerouting-enabled departure scheduler first computes delay with a given route. The route is valid for a range of departure times within which the route is guaranteed to clear the weather. If the computed delay is within this range, the route is selected. If the delay is out of range, the process is repeated with the next route.

Figure 3 shows the concept of choosing different routes at different departure times due to weather movement. In the figure, "Route 1" represents the route that the flight has to take to go around the weather, "Weather 1," if this flight is delayed on the ground between zero and one hour. If the delay becomes larger than one hour, it can be expected that the weather will change to "Weather 2" thus the route also has to change to "Route 2."
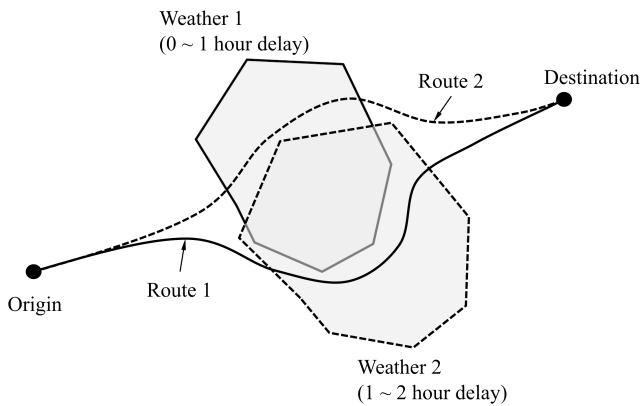
Figure 3. Routes Avoiding Weather

In this study, five candidate routes are used. These routes are generated assuming the flight can be delayed on the ground from zero to 30 minutes, from 30 minutes to one hour, from one to two, from two to three, and from three to four hours. The first two routes are valid for 30 minutes each and the next three routes are valid for one hour each. The scheduler first tests the route that corresponds to zero to 30 minutes delay. If the computed delay is less than 30 minutes, this route is selected and the scheduler continues with the next flight. If the computed delay is more than 30 minutes, the scheduler tests the second route that corresponds to 30 minutes to one hour delay. This process is repeated until the correct match between the route and delay is found. If the delay exceeds four hours the fifth route is used.

In the previous study, the scheduler did not permit any change in the transit times. This rigid constraint can cause inefficient delay allocation in both airports and sectors. For example, a sector might have a 30 minute long open slot to accommodate a flight. However, if this flight needs 30.1 minutes of transit time to traverse this sector, it has to be further delayed until an open slot that is longer than 30.1 minutes becomes available. To address this issue, the FCFS scheduler was enhanced based on the closed form solution process in [10]. Transit time for each sector can be reduced up to one percent and increased up to five percent. One percent reduction in the transit time can be achieved by increasing the speed by one percent. Five percent increase in the transit time can be achieved by combining speed reduction and path stretching. The one percent speedup and five

percent slowdown are conservatively chosen so that they are well within the performance boundary of any aircraft type. The transit time variation might not be practical in current operations, but can be useful when the four-dimensional trajectory concept is deployed in the future.

Approaches

This section describes the procedures that are used to perform the analyses using the previously described tools. Flight plans around weather are generated by the streamline rerouting tool. Interaction between the airspace partitioning and traffic flow management delay is studied by imposing convective weather from May 26th, 2011 on the high volume traffic of May 3rd, 2007. In the following studies, delay refers to the ground delay that is caused by airspace and airport congestion. The extra flight time caused by rerouting around weather compared to the clear-weather route is discussed in the results section but is not included as delay.

Generating Routes around Weather

Flight plans for May 3rd, 2007, a clear-weather day, are used as the input to the weather rerouting procedure. A clear-weather day flight plan was chosen because it can represent nominal traffic demand without weather rerouting. The procedure generates five reroutes for each flight using convective weather data from May 26th, 2011. These five reroutes are generated assuming all the flights are uniformly delayed on the ground by zero, one-half, one, two, and three hours respectively. The procedure is summarized in Figure 4. A smaller 30 minute spacing for the first two routes is due to the fact that most of the delays are less than 30 minutes.
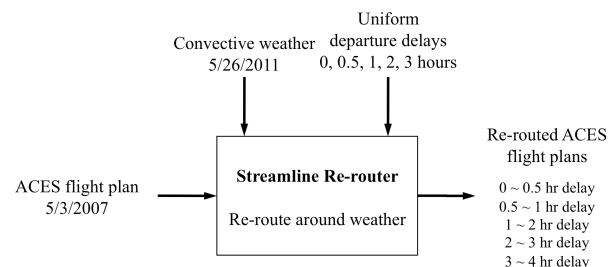

Figure 4. Streamline Tool Generate Five Reroutes

Figure 5 shows the weather over the continental US at 21:25 UTC on May 26th, 2011. As can be seen from the figure, the eastern part of the US is covered by convective weather. Yellow, orange, and red colors indicate level three, four, and five respectively in the NCWF Hazard Scale.

In this study, the weather is assumed to extend all the way to the top of the Class A airspace. Consequently, no flights are permitted to fly over the weather regardless of the altitude. This can be considered as a worst case scenario.
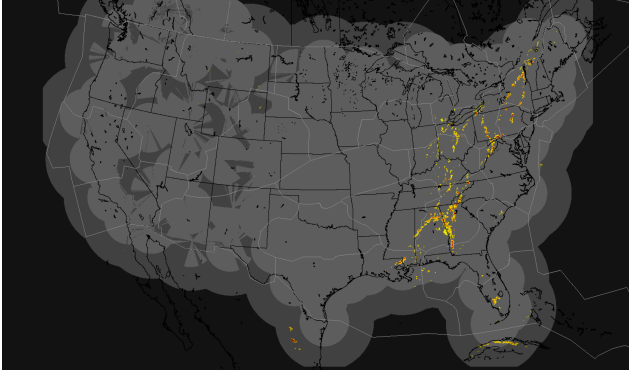

Figure 5. Convective Weather Regions

Historic Sector Data

To establish a point of reference, delays are computed using the actual sector data of May 2007 and Aviation System Performance Metrics (ASPM) airport capacity data of May 3rd, 2007. The sector data contain the actual sector polygons with corresponding capacity values. As shown in Figure 6, the five sets of routes generated using the rerouting procedure are separately simulated using ACES with the sector data to obtain the transit times. The FCFS departure scheduler computes the necessary ground delays that satisfy all the specified sector and airport capacity constraints.
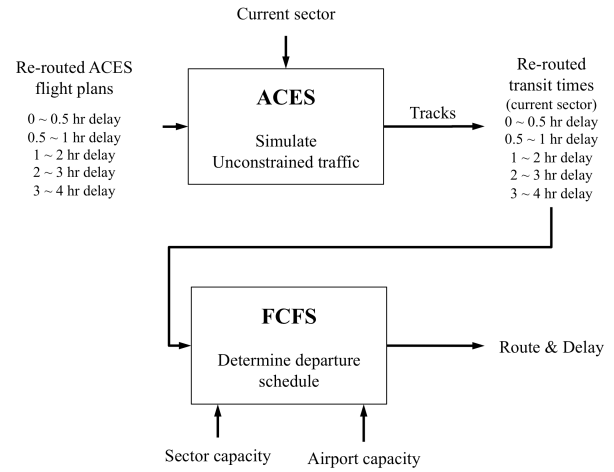

Figure 6. Delays Computed for Historic Sectors

Method I: Traffic Flow Management Delay

The first approach for studying the interaction of airspace partitioning and delaying flights in the presence of weather is summarized in Figure 7. This approach represents a solution by the traffic flow management only. First, unconstrained tracks are generated by an ACES simulation with the clear weather day flights. Since the ACES simulation is unconstrained, sector data are not required for this simulation. Using these tracks, the Voronoi-diagram-based partitioning tool generates sectors with a given peak-traffic count value. The procedures in the previous sub-section are repeated using these re-partitioned sectors. It should be noted that, the sectors are generated by the Voronoi-diagram-based partitioning tool without regards to any of the weather rerouting characteristics. Their role is to be a surrogate of current day sectorization with the following two properties: the same sector capacity for all high altitude sectors and a single unconstrained low altitude sector per center. The former property is required so that consistent comparison can be made to the subsequent studies in terms of the number of sectors and delays. The latter property is required because this study only investigates the impact of high altitude sector constraint.
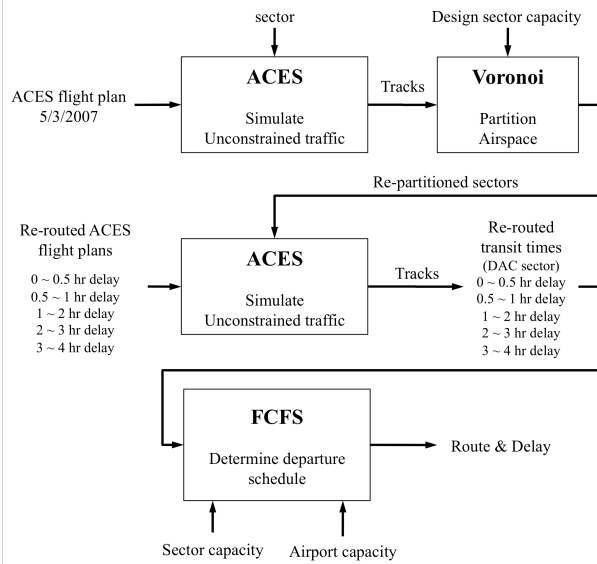
sector | Design sector capacity

ACES
Simulate Unconstrained traffic

Tracks

Voronoi
Partition Airspace

ACES flight plan 5/3/2007

Re-partitioned sectors

Re-routed ACES flight plans

0 ~ 0.5 hr delay
0.5 ~ 1 hr delay
1 ~ 2 hr delay
2 ~ 3 hr delay
3 ~ 4 hr delay

ACES
Simulate Unconstrained traffic

Tracks

Re-routed transit times (DAC sector)
0 ~ 0.5 hr delay
0.5 ~ 1 hr delay
1 ~ 2 hr delay
2 ~ 3 hr delay
3 ~ 4 hr delay

FCFS
Determine departure schedule

Route & Delay

Sector capacity | Airport capacity

Figure 7. Delays Computed for Re-partitioned Sectors

Method II: Re-partitioning Using Traffic Flow Managed Solution

Figure 8 describes the second approach for studying the tradeoff of airspace partitioning and delaying flights in the presence of weather. First the FCFS scheduler computes the departure times and routes assuming only airports constraints. With these schedules, the tracks are simulated using ACES. These tracks are fed into the Voronoi-diagram-based partitioning tools with design capacity that is identical to the one used for the previous approach. As the partitioning tool creates sectors so that there is no delay caused by sector capacity constraints, this solution represents the lower bound of the delay. The cost of this lower bound of delay is an increased number of sectors.
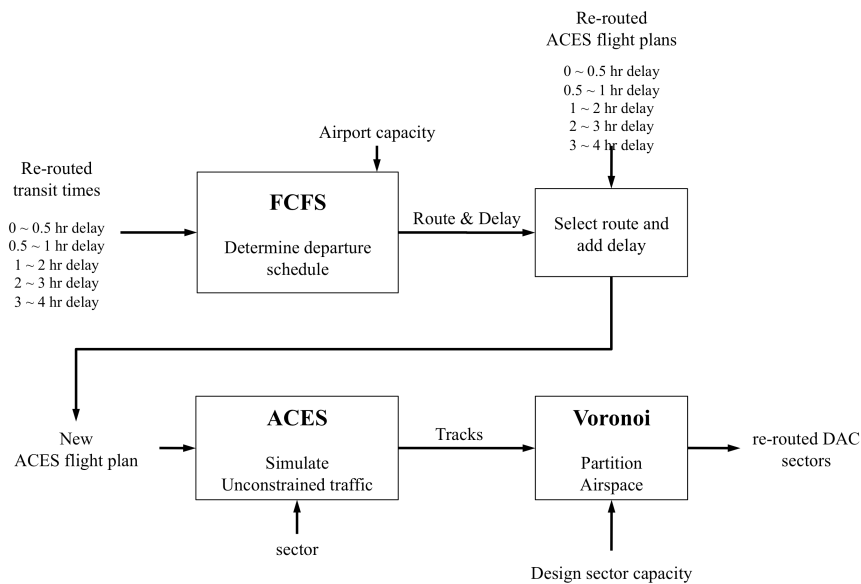

Re-routed ACES flight plans

0 ~ 0.5 hr delay
0.5 ~ 1 hr delay
1 ~ 2 hr delay
2 ~ 3 hr delay
3 ~ 4 hr delay

Airport capacity

Re-routed transit times

0 ~ 0.5 hr delay
0.5 ~ 1 hr delay
1 ~ 2 hr delay
2 ~ 3 hr delay
3 ~ 4 hr delay

FCFS
Determine departure schedule

Route & Delay

Select route and add delay

New ACES flight plan

ACES
Simulate Unconstrained traffic

Tracks

Voronoi
Partition Airspace

re-routed DAC sectors

sector

Design sector capacity

Figure 8. Re-partitioning using TFM Solutions

Method III: Traffic Flow Management using Re-partitioned Sectors

While approaches in the previous sub-sections provide the upper and lower bounds of delay and the associated cost in terms of the number of sectors, they may not be the best solutions. To examine practical solutions in which the number of high-altitude sectors does not exceed the current operational number of around 370, an approach similar to the previous study [3] is used. Sectors are created by the Voronoi-diagram-based partitioning method using the tracks and schedules that satisfy the airport capacity constraints as in Figure 8. The difference is that design capacities larger than the actual capacity are used for creating sectors. By adjusting the design capacity, it is possible to control the number of sectors and to keep the number below the current operation. With these sectors, traffic flow management is applied again using FCFS scheduler with the original sector capacity to obtain the delays caused by airport and airspace capacity constraints.

Results

This section describes the results obtained using the approach discussed in previous section.

Weather Reroutes

Figure 9 shows the distribution of additional airborne time due to rerouting around the regions of convective weather. The additional airborne time is defined as the total flight time of the rerouted flight minus the original flight time. Among the 47,984 flights, around 25,800 flights are rerouted, and the average additional airborne time is 14.7 minutes for the rerouted flights, and the overall average is 7.9 minutes. As shown in the figure, about 50 percent of rerouted flights have additional flight time less than 15 minutes. For the 18 percent of the rerouted flights that show reduced flight time is due to the original routes being not direct.

Note that about 130 flights have unrealistic additional flight time exceeding 2 hours. These exceptionally long reroutes are due to forcing the streamline rerouting tool to find a reroute regardless of the weather situation. In real life operations, flights that require extreme reroute are very likely to be cancelled.
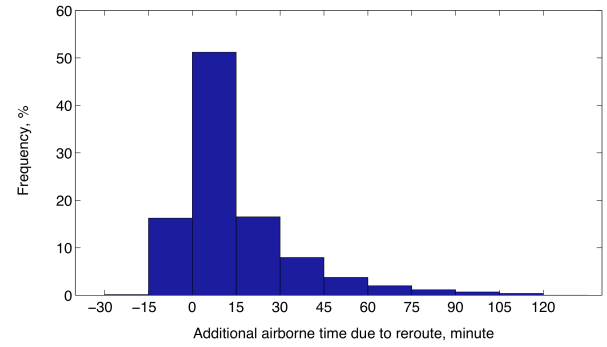

Figure 9. Additional Airborne Time Distribution

Historic Sectors

To establish a point of reference, simulations were performed using the historic sector data. The sector data from May 2007 have a total of 1,254 sectors. Among them, 1,216 sectors are constrained with an average capacity of 17.4. Note that low altitude sectors also have capacity constraints.

Table 1. Average Delays for May 2007 Sectors

Weather Condition	Clear	Severe	Severe
Airport Capacity	Clear	Clear	Severe
Speed Off	10.0	11.1	12.2
Speed On	6.8	8.2	8.8

Table 1 summarizes the per-flight delay results in minutes. Compared to the airport capacity of the clear weather day of May 3rd, 2007, using the airport capacity of the actual severe weather day of May 16th, 2011 increased the average delays by about ten percent, which shows the impact of airport capacity reduction due to weather. The last row of the table shows that, by allowing moderate speed variations, delays can be reduced. Throughout the following results, it is shown that, if aircraft are allowed to adjust sector transit times by

adjusting speeds or stretching the paths, the average delay can be reduced by around 30 percent.

The average ground delays for the clear weather day of May 3rd, 2007 with its corresponding airport capacity are 6.8 and 10.0 minutes respectively for with and without speed variations. The results indicate that delays are mostly governed by airport capacity constraints. Presence of weather adds about two minutes of extra delay on average.

Method I: Traffic Flow Management Delay

The re-partitioning with clear-weather, unconstrained traffic resulted in 335 high altitude sectors with a capacity of 18. Low altitude sectors are assumed to be unconstrained. Table 2 shows the per flight delays. This result will serve as the baseline for upcoming comparison. Observe that the number of sectors at 335 is lower than the 360 reported in [3]. This is due to a 10 percent reduction in traffic volume after it was later determined that there were duplicate flights in the previous study. This error has since been corrected for this follow-on study. Table 2 shows a trend that is very close to the one shown in Table 1, which is about one extra minute of average delay due to the use of the airport capacity from the severe weather day and about 30 percent decrease in the average delay if speed variation is allowed.

Table 2. Average Delays for Re-partitioned Sectors

Weather Condition	Severe	Severe
Airport Capacity	Clear	Severe
Speed Off	10.6	11.7
Speed On	7.6	8.4

Table 3 compares the delay statistics with the previous study. The second column is from [3] corrected for the reduced traffic volume. In this table, results with no speed variation are shown, since speed variation was not allowed in the previous study. The table shows that the weather slightly increases mean, median, and standard deviation of the delay.

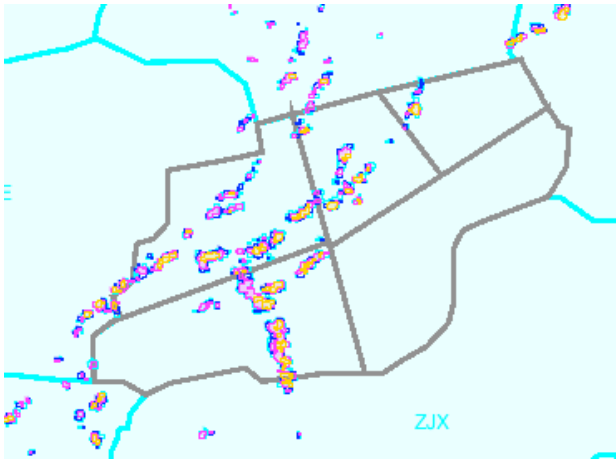**Table 3. Comparison of Delay Statistics**

Metric	No Weather	With Weather
Total # Flights	48,126	47,984
# Flights with > 15 min. Delay	8,973	10,388
Mean Delay, minute	10.0	11.7
Median Delay, minute	2.3	2.4
Standard Deviation, minute	19.5	21.6
Maximum Delay, minute	399	171
Total Delay, hour	8,019	9,318

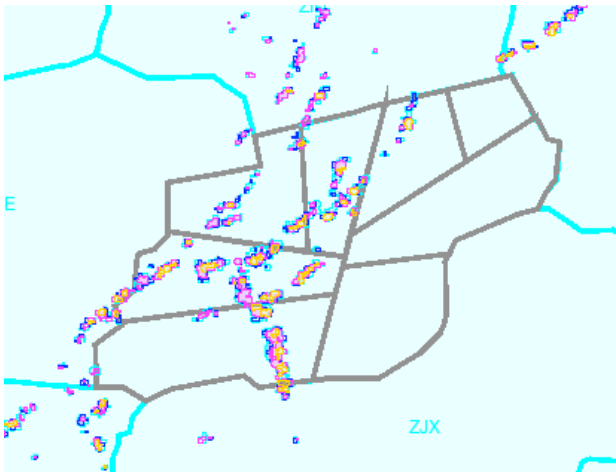## Method II: Re-partitioning Using Traffic Flow Managed Solution

As the impacts of speed variation and the airport capacity reduction due to weather turned out to be consistent in the two previous sub-sections, all the following results will use only the airport capacity from the severe weather day. Traffic flow management will always allow the speed variation of speeding up by one percent and slowing down by five percent.

Even in the presence of weather, if only airport capacity constraints are applied, the average delay is 6.7 minutes. For a clear weather case, the average delay for this non-duplicate flight set is 6.8 minutes. Note that the delay is 8.4 minutes with the sector capacity constraints. This result implies that with enough sector capacity, it is possible to reduce the delay from 8.4 to 6.7 minutes.

To make the sectors not cause any delay, the re-partitioning algorithm created 402 sectors with a design capacity of 18. That is 67 extra sectors compared to the previous case of re-partitioning using clear-weather, unconstrained traffic. This solution represents the lower bound of delay with the upper bound of cost and is likely to be unrealistic.

(a) ZTL Partitions for Baseline Configuration

(b) ZTL Partitions for 402 Sector Configuration

Figure 10. ZTL Partitions

Figure 10 compares the sector partitions at Atlanta Center (ZTL). It can be observed that when the airspace is re-partitioned to accommodate weather, the number of sectors increased.

Method III: Traffic Flow Management using Re-partitioned Sectors

In the previous sub-section, a design capacity of 18 was used for generating sectors. If the same tracks that are scheduled to satisfy airport constraints are used with design capacities of 21 and 24, 312 and 253 high altitude sectors are created respectively by the Voronoi-diagram-based partition tool. If the actual number of aircraft in a given sector is examined, most of sectors show several short time periods where the count is actually equal to the design capacities. If the capacities of these sectors are then reduced to 18, the average delay is 6.9 and 8.1 minutes respectively. Compared to the baseline case of 335 sectors with 8.4 minutes of delay, both the solutions shows simultaneous reduction in the delay and the number of sectors.

Figure 11 shows four data points from the current study and one data point from the clear weather case. With the 335 sector configuration and without weather, the average delay is 6.8 minutes. For all four cases, all the sectors have a capacity of 18. When the number of sectors are 335 and when those sectors are not designed for the specific weather, observe that the weather increases the delay by 1.6 minutes. To completely avoid the delay due to the sector-capacity constraint, the number of sectors needs to be increased by 67. However, by re-partitioning using higher capacity values of 21 and 24 and then applying the traffic flow management at the actual capacity value of 18, both the delay and the sector capacity can be reduced.
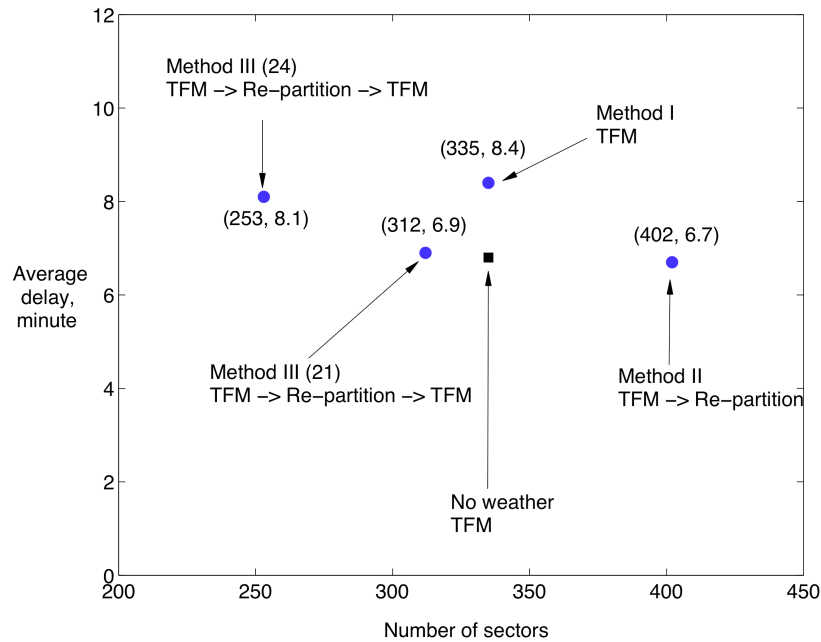
Figure 11. Summary of the Results

Conclusions

In this study, the interaction of airspace partitions and traffic flow management delay in the presence of weather is investigated. Because the weather forces the flights to be rerouted causing congestion in the vicinity of weather, airspace capacity constraint has a role in the delay. It was discovered that if the clear-weather airspace partition is used without any re-design, the average delay increases by about 1.6 minutes. It is possible to reduce this delay back to the clear-weather level, but it requires more than 20 percent increase in number of sectors, which is not practical. However, by allowing a reasonable amount of airspace-capacity induced delay accompanied by the re-design, 6.9 and 8.1 minutes of average delay can be achieved with 7 and 24 percent reduction in the number of sectors respectively. It is demonstrated that re-partitioning the airspace can reduce the delays caused by the congestion in the airspace due to weather, while reducing the number of sectors at the same time. Nevertheless, the majority of the delay is still caused by the airport capacity constraints.

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30th Digital Avionics Systems Conference
October 16-20, 2011