

# BENEFITS OF COLLABORATIVE FLOW MANAGEMENT DURING CONVECTIVE WEATHER DISRUPTIONS

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## Abstract

This paper presents a flexible modeling methodology that is designed to assess a range of operational concepts for collaborative flow management. The particular focus is on the problem of airline schedule recovery in conditions where airspace sectors are capacity limited due to convective weather events. This model is embedded in a dynamic simulation environment, the Boeing National Flow Model (NFM), representing the US National Airspace System (NAS). The airline schedule recovery model is based on an optimization formulation that allows a representation of adaptive airline behavior in current and future operations. The schedule recovery options considered include ground delay, pre-departure re-routing and flight cancellation. Included is a NAS-wide benefits analysis of convective weather operations enabled by increased automation capability and exploring the benefits of improved forecasting capabilities. The modeling effort also included, for comparative purposes, the development of a baseline representation of current convective weather system response in the NFM, using delay data obtained from the Airline Service Quality Performance (ASQP) database. The results indicate a significant benefits potential for increased automation support and improved convective weather forecasts for the future NAS operation.

## Introduction

Flow management is a significant component of the air traffic management service both in the United States and in Europe. Increasing traffic growth is likely to continue to outpace capacity enhancements, and weather disruptions will continue to cause reductions in capacity at airports and in the airspace. Thus, flow management's role in balancing capacity and demand is likely to continue to grow.

The US system is experiencing a growing need to protect airspace sectors from overload, particularly due to convective weather systems. Thus, flow management in the US is taking on an increasing role in coordinating strategies to avoid sector overloads.

Participation in decision-making in flow management in the US has for many years included a significant involvement by airspace users, through the Collaborative Decision Making (CDM) paradigm. CDM includes data exchange and shared automation tools for both the airline operations control (AOC), the ATC system command center (SCC) and traffic management in ATC en route centers (ARTCC). It is clear that a significant extension to the flow management service will be needed in coming years. This extension will need to consider a more complete set of constraints, i.e. combined airport and airspace constraints, a complete set of delay, re-routing and cancellation options, and maintain the real-time collaboration between service provider and airspace users. The FAA and US airlines launched a new initiative in the summer of 2006, called the Airspace Flow Program [1], which takes the first automation-supported step toward assigning ground delay to flights due to a restriction in the airspace.

The work presented in this paper is focused on a system-wide application of an optimization-based approach to re-plan traffic flow when both airport and airspace constraints are predicted. This is an application of a sophisticated modeling methodology for flow management and airline schedule recovery, which is part of the Boeing National Flow Modeling (NFM) tool. The NFM is a major component of the Boeing ATM preliminary design toolset [2][3], aimed at supporting trade studies on ATM operational concepts and architectures in early phases of major modernization steps. The paper presents a description of the weather modeling methodology, the planning algorithms used for this study, and the methodology used to approximate a baseline model of current convective weather operations. Analysis results show the potential NAS-wide benefits for a single day of convective weather operations with a range of concept and weather forecasting assumptions.

## Related Work

The history of US flow management and CDM is summarized in [4], describing the fundamental tenet of SCC allocating resources and individual users (e.g., airlines) deciding how to most effectively use their allocation. The limitations of current US en route flow

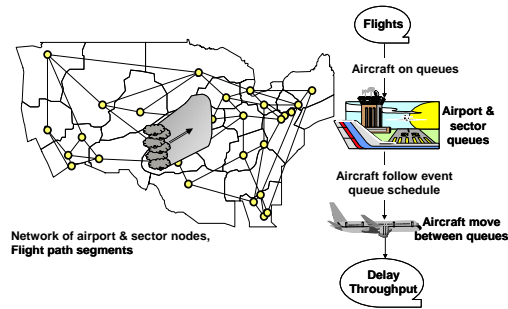
management initiatives such as miles-in-trail restrictions are discussed in [5], and optimization is proposed as the most viable methodology to tackle the combined airport and airspace problem. The significant efficiency benefits achieved after CDM was implemented are discussed in [6]. The issue of uncertainties in forecasting is treated in [7], with a conclusion that periodic schedule peaks over predicted capacity will compensate for possibly conservative forecasts. The issue of equity in ground delay strategies is discussed in [8], and [9] makes a strong case for the near-term need to tackle the multi-resource flow problem in the US. Development of the Collaborative Routing Coordination Tool (CRCT) is documented in [10], with a focus on a graphical user interface and automatic assessment of sector demand vs. capacity under manually selected re-routing scenarios. The operational benefits enabled by improvements in convective weather forecasting using the Corridor Integrated Weather System are described in [11] and [12] proposes a methodology for assessing the benefits of newly fielded weather or ATM systems. A concept of operations using a probabilistic decision tree to take into account the uncertainties in convective weather forecast is introduced in [13]. Strategies for generating weather avoidance routes in an arrival management scenario are compared in [14], and [15] describes requirements for the future system in the context of network centric operations (NCO).

The development of the Boeing National Flow Modeling capability started in 2001 [16]-[17], with the aim of exploring the performance of a variety of flow management operational concepts. The NFM has proven to be a versatile tool for flow management trade studies, and the work reported in this paper is focused on a NAS-wide benefits assessment where the NFM is tuned to emulate current convective weather operations to establish a system performance baseline.

## Modeling

### *The National Flow Model Simulator*

The Boeing National Flow Model (NFM) is an event-based simulator that represents the delay behavior of aircraft and ATC flow operations. As shown in Figure 1, the NAS is represented by a network topology made up of nodes and segments. Included are nodes for airports with landing and take-off rates, nodes for sectors with transit capacities using actual geometries, segments that make up flight plans with airways and waypoints, and actual weather with associated forecasts derived from historical archives.



**Figure 1. National Flow Model Overview**

Runs typically include a full day of scheduled flights from the Official Airline Guide (OAG), from ETMS derived schedule, or future schedules generated from a predictive model. The simulator dynamically moves aircraft along the network of routes between nodes. If the demand for take-offs or landings exceed airport capacities, then the aircraft queue is processed in a First-in-First-out (FIFO) order. En route capacity is determined by maximum occupancy, as specified by the FAA Monitor Alert Parameter (MAP) [18] for each sector. If demand exceeds the maximum occupancy, aircraft queue at the sector boundary and are also processed in FIFO order.

At various points during an NFM simulation of a single day, there exists an opportunity to re-plan the flight schedules for the remainder of the day. This is particularly relevant in the event of a capacity outage such as that caused by convective weather. The NFM contains re-planning modules for ground delay programs (i.e., Ration by Schedule, RBS) and, also, modules for airline schedule recovery. In this paper, the focus is on collaborative flow management involving airline schedule recovery. These concepts are described in the subsequent section.

In any case, the flight schedule is executed with or without re-planning options and, as a primary output, delays are measured relative to the original flight schedule. The NFM measures arrival delay as actual gate arrival time minus scheduled gate arrival time, as defined in the input traffic schedule. These schedules may include block time padding of schedules to help ensure nominal on time performance. The schedules are also tail-routed so that the NFM may consider the impact of delay propagation.

### *Airline Schedule Recovery*

This paper describes the analysis of a general and flexible concept for collaborative flow management for a large system such as the US National Airspace System (NAS). The concept includes collaboration between a central authority, which allocates airport and airspace capacities, and

distributed applications for re-planning airline schedules in the face of capacity reductions due to weather events or other system constraints. In this context, a disruptive event, such as convective weather, triggers a re-planning process which begins with the development of a forecast of available capacities for the remainder of the planning horizon. The planning horizon is typically taken to be the remainder of the current day of scheduled operations and the capacitated system elements include airport departure rates, airport arrival rates, and sector occupancy limits. The central authority uses this forecast of available capacities to develop, through a collaborative process, an equitable allocation of these capacities to the airlines using the system. Each airline then utilizes a distributed airline schedule recovery application to develop a re-planned schedule using ground delays, flight cancellations, and pre-departure re-routes, in order to minimize delays or delay costs (or, equivalently, maximize the value of the re-planned schedule) while adhering to the allocation of forecast capacities. This re-planning process may be repeated at multiple points throughout the day.

The NFM includes a module called the Airline Schedule Recovery Model (or AOC Model) to analyze the performance of these collaborative flow management concepts. A primary input to the model, besides the original tail-routed airline schedule, is an allocation of forecast airport and airspace capacities. The primary output of the model is a new flight schedule in which, for each flight, there is a decision to fly the flight as originally scheduled, cancel the flight, or re-plan it. Re-planned flights are assigned a new (delayed) departure time and/or a new flight plan (re-route) based upon the available routes. The schedule is constructed by the model to optimize an objective function and, at the same time, be feasible with respect to the capacity constraints. In the general case, the input schedule is tail-routed and additional constraints having to do with the feasibility of flying the re-planned schedule are also imposed. There is no consideration of crew schedules or maintenance constraints in the current model.

An optimization approach for implementing the schedule recovery problem is described in detail in [16] and [17]. The problem of developing equitable allocations of forecast capacities is also discussed in [16]. A simplification or specialization of the model to the departure problem is covered in [19]. The objective function may be used to maximize the value of the re-planned schedule (i.e., maximize the total effective seat miles, [16]) or to minimize total delays subject to capacity constraints. The approach can also be used to minimize total delays weighted by the individual

flight values or to minimize total delay costs as described later in this paper. Other objective functions may also be used as long as they satisfy flight independence, that is, the outcome for each flight must be scored in a way that is independent of the way in which other flights are re-planned.

### ***Comparison to Flow Initiative***

The FAA Airspace Flow Program (AFP), which went into operation in early summer 2006, relies on the first FAA operational automation capability to compute ground delay solutions to constraints in the airspace [1]. Traffic Management Unit (TMU) specialists are able to define regions of airspace as Flow Evaluation and Flow Constraint Areas, and the ETMS system will generate a list of all flights predicted to transit through the areas during a specified period. The Flight Schedule Monitor (FSM) produces a demand prediction for the area, which may indicate a need to issue an Airspace Flow Program if demand is predicted to substantially exceed expected capacity. This will result in ground delays assigned to affected flights, and when this occurs flight operators have the option to re-file their flight plan for a different route to avoid the congested area.

As described above, the AFP currently only considers one region of airspace when re-planning user schedules, and possible interactions with other AFP's or airport ground delay programs are handled through a series of precedence rules. Table 1 shows a comparison between the features of the AFP and the functionality available for analysis in the NFM.

<b>Characteristic</b>	<b>Airspace Flow Program</b>	<b>NFM Schedule Recovery</b>
Control Strategies	Delay	Delay, re-route and cancellation
Multiple constraints	One constraint dominates through precedence rules	Coordinated across all constraints
Airspace capacity	Flow rate (polygon, line, sector, box)	Sector occupancy
Impact on other resources	Not considered	All airport and airspace constraints are observed

**Table 1. Comparing AFP and NFM Functions**

### ***Weather***

The NFM contains modules for representing actual weather and weather forecasts. A summary of these capabilities is presented here with more details available in [20]. Actual weather can be represented by sequences of weather radar images on specific dates from historical archives. In the

case of weather forecasts, the model can make use of the Aviation Weather Center’s Collaborative Convective Forecast Product (CCFP) [21] which is in current operational use by the FAA and airlines and is also available from archives. Boeing has also developed a Convective Weather Forecast Replicator (CWFR) which is, essentially, a parametric forecasting model. The CWFR starts with actual historic weather and geometrically creates a forecast replica around it according to error parameters that the modeler can adjust to represent varying forecast quality. Thus the CWFR allows for the exploration of the benefits of improved weather forecasting capabilities in a parametric fashion. In this paper, we make use of the actual weather, the CCFP forecast, and also, for comparative purposes, the perfect forecast.

The weather forecast uncertainty observed with today’s weather systems causes difficulties in balancing system utilization. This in turn introduces operational risk, resulting in an overly conservative delay response. The purpose of the convective weather model (CWM) is to represent the random

dynamics of convective weather and the associated uncertainty impacts on available capacity, both for forecasted and actual capacities. The CWM’s outputs are actual and forecasted NAS resource capacity reductions that vary dynamically in time. The presence, or prediction, of weather in a sector will reduce the actual capacity of the sector, potentially increasing the likelihood of congestion.

Figure 2 illustrates the functional architecture of the convective weather model (CWM). The path emanating from the “Actual Weather Radar Images” block across the top of the diagram represents the actual weather and its effect on actual resource capacities. Archived weather can also be used to generate replications of weather forecasts. The arrow emanating downwards from the “Actual Weather Radar Images” block indicates that archived weather is made available to the Convective Weather Forecast Replicator (CWFR) algorithm, whose various steps are represented by the processing blocks in the lower part of the diagram.

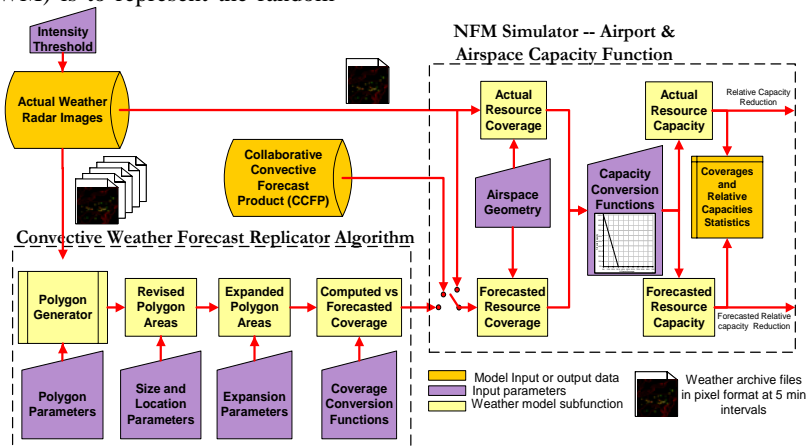


Figure 2. Weather Processing in the NFM

There are several differences between forecast and actual weather. Actual weather files are provided at 5-minute intervals to update the weather state in the simulation. The forecasts are generated using a forecast update cycle such as the CCFP’s four-hour cycle (in effect in 2001 but has been changed since). The computation of weather coverage is different for actual and forecast weather. For actual weather, coverage is computed inside the polygonal area representing a sector or inside a predefined circular area around an airport. For forecast weather, an intermediate step inside the CWM generates weather forecast polygons and their weather coverage.

In the NFM, it is desired to compute the effective capacity of a sector in the presence of

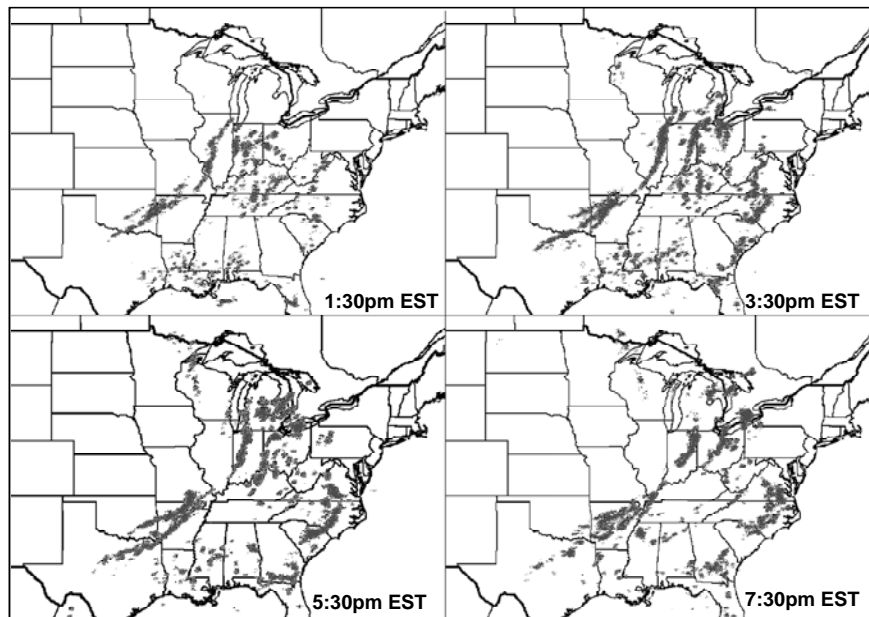
weather. When a weather polygon intersects a sector (or, similarly, an airport), the coverage of this sector by weather is assumed to be the product of the weather coverage value of the weather polygon and the proportion of the sector that is intersected by the weather polygon. For example, if a weather polygon has a 70% weather coverage, and it intersects 80% of a sector, it is assumed that the sector has a 56% coverage (70% x 80%) uniformly distributed throughout its area. An additional function, discussed in the Analysis section (see Figure 4), relates this coverage to the relative capacity of the sector. Using the simulation capability and its associated weather model, it is possible to examine the issues associated with improved forecasting capabilities. Figure 2 illustrates how the CWM can switch between

CCFP, CWFR, or actual weather to represent the associated forecasted capacity reductions. By using the actual weather radar images, the simulation can represent perfect weather forecasting performance. By using the CCFP, the CWM represents the performance of current forecasting technology. Improvements in today's forecasting technology can be represented in the simulation by judicious choices of the CWFR error parameters.

## The Weather Scenario

The weather scenario that was used in this analysis is actual convective weather from June 14,

2000. This day was chosen due to the intensity of the weather system on that day. There was a storm with a radar intensity of category 3 (and above) that primarily disrupted the mid-west at peak hours of air traffic. The data for this system was obtained from the Aviation Weather Center in the form of digital images of weather radar returns, available in 5-minute intervals. Some images of the progress of this weather system are shown in Figure 3. As the figure illustrates, multiple weather fronts developed and progressed through the afternoon and early evening.



**Figure 3. Progress of the storm on the afternoon of June 14, 2000**

## Analysis

The purpose of this analysis is to measure the benefits potential for increased flow management automation on a single bad convective weather day. The concept evaluated is the distributed airline schedule recovery concept described in earlier sections. The bad convective weather day was selected to be June 14, 2000 as described in the previous section. The Boeing future schedule generation capability was used to create scenarios for comparison from y2000, 2010, and 2020. For y2000, historical data can be used to measure the performance of the baseline system (current practice) on that day. The same data can also be used to “baseline” (i.e., tune or calibrate) the schedule recovery model so that it produces results that are similar in effectiveness to existing practice. In this way, an attempt can be made to project the benefits of greater automation to future time periods and increased traffic levels.

In the distributed airline schedule recovery concept, the airlines can make use of pre-departure planning options including planned ground delays, flight cancellation, and (optionally) pre-departure flight re-routing thru the airspace. Thus, once a baseline level of system performance is established, the analysis can show the extent to which these levels of automation can improve on the baseline system performance. The analysis was conducted for current levels of weather forecasting capability (as modeled by the CCFP forecast) and, also, for perfect forecasting.

The establishment of the baseline system performance is critical and was accomplished using historical statistical data for the selected bad convective weather day (June 14, 2000). Actual convective weather data, along with the CCFP forecast for this day had been available to Boeing as part of previous internal studies involving the NFM. Actual delay and flight cancellation statistics for that day were analyzed using the Airline Service

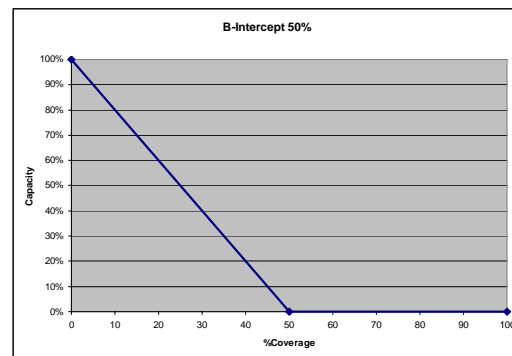
Quality Performance (ASQP) database which can be accessed through the Bureau of Transportation Statistics (BTS) web access site. Since the data available in the ASQP database contains only statistics for major airlines, this exercise was done using the subset of ASQP data that could be best matched up with corresponding flights in the year 2000 OAG schedule used in the NFM analysis. Additionally, the airline schedule recovery model and the model of conversion from weather coverage to system capacity were “tuned” to create a baseline model that behaved similarly to the current system on the day in question. These parameter settings were found through an extensive parametric analysis, so that when the entire set of airline schedules were run through the NFM, the delay and cancellation statistics for the eight airline subset would be in approximate agreement with the ASQP statistics for that day. In this way, the benefits analysis could then be extrapolated to future time periods using the baseline model. Though not rigorous, it is believed that this approach can give some idea of the benefits potential for future time periods.

Since there has been substantial progress in the development of effective automation associated with ground delay programs, and since airport capacity is fairly well understood, the parameters that were tuned pertained primarily to the airspace or pertained to the model relating weather coverage to capacity. Two baseline models (W and BW) were analyzed:

- **Baseline W** (“white” planner): ignores the airspace during the schedule re-planning process. Attention is paid to the airports and their forecast capacities and a plan is created that adheres to the allocated forecast airport capacities. But the airspace capacities are assumed to be infinite for the purposes of planning. Actual airspace capacities are enforced in executing the plan.
- **Baseline BW** (“black and white” planner) treats the airspace, but crudely. It assumes that the planning process first categorizes airspace sectors, for a particular time-slice, as black or white (closed or open) and then makes a plan that adheres to the allocated forecast airport capacities but uses only white sector-time-slice combinations. So, it is like the white planner except that strategies are not allowed to make use of the black (shut-down) sector-time-slice combinations. Again, the actual airspace capacities are enforced in executing the plan.

Besides manipulating the planning process to achieve a baseline, there is also the possibility of tuning the model that converts weather coverage to system capacity. Actual weather is generally

described at the “pixel” level and it is simply assumed that weather of a certain intensity or greater (which we will call bad weather) at a pixel location creates an environment that is unsafe for air travel. In the case of actual weather a calculation is made to compute the fraction of all the pixels associated with a given sector that are experiencing bad weather. This fraction is called the coverage associated with the sector. Coverage is transformed into relative sector capacity by a function like the one shown in Figure 4. The relative sector capacity is then multiplied by the sector MAP value in order to compute the maximum number of airplanes that can occupy the sector at the given time. In our studies, we have looked at conversion functions of the form shown in Figure 4 but have experimented with different values of the x-intercept, referred to as B-int. The figure illustrates the case in which B-int is 50%.



**Figure 4. Translation from Weather Coverage to Relative Capacity**

The situation is similar in the case of weather forecasts, as opposed to actual weather. Weather forecasts are expressed in terms of polygons of convective weather. Each polygon is given a coverage value which expresses the percent of the polygon that is covered by bad weather. The conversion of these weather forecasts into sector capacity involves an analysis of the intersection of the polygons with the sector geometry. A calculation is made to determine the fraction of the sector covered by bad weather. This calculation is based upon what parts of the sector are covered by which polygon and what the coverage is associated with each intersection. Then Figure 4 can be used to compute the relative capacity for the sector which is then converted to capacity using the MAP value for the sector as described above.

The situation, for both actual and forecast weather, is similar for airports and, in fact, simpler because the airport is assumed to be a point instead of an area. Relative capacity is converted to capacity again using Figure 4 but using maximum airport arrival and departure rates taken from the FAA OEP forecast.

In this analysis, the delay and cancellation statistics must be converted to delay cost. The components of the cost values are expressed as dollars per airplane seat as follows:

- Cancellation cost = \$29.21 /seat
- Airplane plus crew operating cost = \$6.67 /seat /hr
- Percentage of operating cost for crew = 31.62%
- Passenger value of time = \$18.59 /seat /hr

This data was taken from [22] which provided values for different equipment types. We have used the values averaged across all equipment types to simplify the analysis. The passenger value of time component assumes a 65% average load factor. In addition to the cost of cancellation quoted above it is assumed that passengers must rebook their flights and that a four hour additional passenger rebooking cost is attributed for each passenger on the cancelled flight. The above cost values can be recast in the following terms:

- Arrival delay cost = \$20.70 /seat /hr  
[=(0.3162 x 6.67) + 18.59]
- Cancellation cost = \$103.57 /seat [=29.21 + (4 x 18.59)]
- Airborne delay cost = \$4.56 /seat /hr  
[=.6838 x 6.67]

The airline schedule recovery model within the NFM was modified to optimize directly on the delay and cancellation costs described above.

### Methodology – Baseline W

As described in the previous section, the baseline W is associated with the “white” planner. Airport capacity is allocated and re-plans are created which optimize the effectiveness of the re-planned schedule. Airspace sector capacities are ignored in the planning process but are enforced in the NFM simulation of executing the schedules. Airplanes are required to stay in queues at sector boundaries when sector capacity is exceeded. The primary parameter that is tuned for baseline W is the B-int value associated with the conversion from coverage to relative capacity. This, essentially, controls the amount of capacity in the system. An attempt was made to find a value for B-int that came close to matching the ASQP results for the selected eight airlines. An additional parameter, called the cancellation penalty multiplier was also utilized. This parameter was used as a multiplier on cancellation cost.

Figure 5 shows these results and shows that a selection of B-int=22.5% with a cancellation penalty of 0.8 comes as close as possible to matching on total delay cost and cancellations. The

figure shows that an extremely close match is achieved with respect to both metrics.

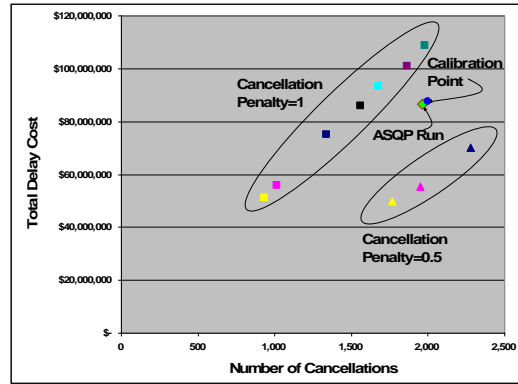


Figure 5. Parameter Selection for Baseline W

### Methodology – Baseline BW

Baseline BW is the black-and-white, “BW”, planner. As described earlier, in the BW planner certain sector-time-slice combinations are not allowed to be used in the re-planning process. A new parameter “BW” is introduced and represents a threshold for the ratio of forecast capacity to maximum available capacity for a sector. When the ratio falls below this threshold value then the sector-time-slice combination is labeled “black” and is not allowed to be used in the re-planning process. The tuning for baseline BW mainly involved manipulating the BW and B-int parameters as shown in Figure 6. The cancellation penalty parameter was also used but values very close to 1.0 worked best. Overall, the best match was found for parameter values of BW=.473 with B-int=0.5. A summary of the results are shown in Figure 6.

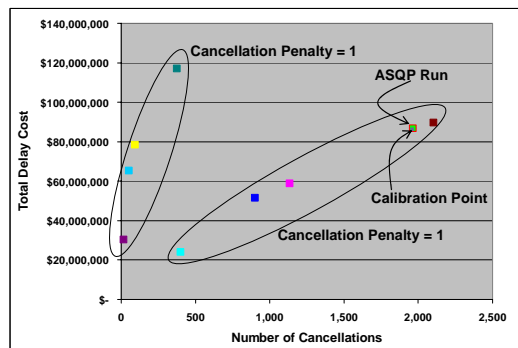


Figure 6. Parameter Selection for Baseline BW

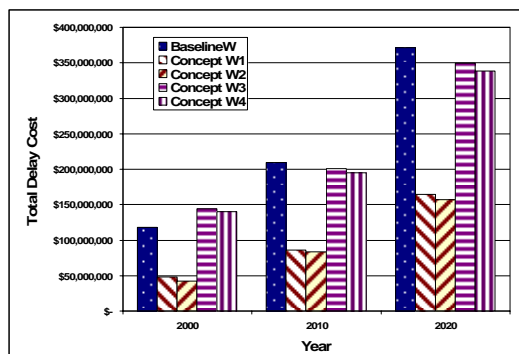
Again, the figure shows that an excellent match is achieved in terms of both total delay cost and total number of cancellations. Note, however, that a significantly different value of B-int is employed than in the case of Baseline W.

## Results

In this section we show the benefits analysis results, comparing the distributed airline schedule recovery concept with the baseline system performance (measured using the calibrated baseline models) for the single bad weather day confronted by traffic schedules for the years 2000, 2010, and 2020. The comparisons were made for the following system concepts:

0. Baseline with CCFP forecast (W, BW)
1. Schedule recovery with perfect forecast but without re-routing (W1, BW1)
2. Schedule recovery with perfect forecast and re-routing (W2, BW2)
3. Schedule recovery with CCFP forecast but without re-routing (W3, BW3)
4. Schedule recovery with CCFP forecast and re-routing (W4, BW4)

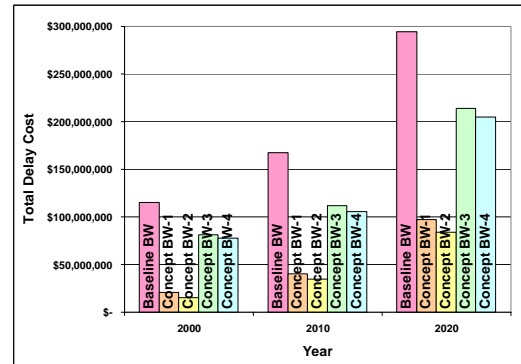
Figure 7 shows the results for baseline W. Interestingly concepts W3 and W4 perform slightly worse than the baseline in y2000 and only slightly better than the baseline in y2010 and y2020. In other words, the CCFP forecast is not really adequate to support the greater automation capabilities associated with concepts W3 and W4. However, the combined effect of the increased automation of the schedule recovery application, along with the perfect forecasting, produces a benefit of nearly \$75M for a single day with y2000 traffic levels and over \$200M benefit for a single bad weather day in y2020. Thus, the results show tremendous potential for the benefits of improved forecasting. The benefit for re-routing is currently shown to be relatively small but this is believed to be the result of an inadequate set of alternative routes employed in this analysis. A primary objective of future work (beginning early in y2007) will be to explore the benefits of pre-departure re-routing with improved route databases and, also, the benefits of post-departure re-routing with dynamic flight plan generation.



**Figure 7. Delay Cost Comparison for Baseline W**

Similarly, Figure 8 shows the results for baseline BW. In this case, the benefits are even

larger and there is benefit even when weather forecasting is at the level of the CCFP. Staying with the CCFP level of forecasting, the benefits range from about \$30M in y2000 to about \$90M in y2020. With perfect forecasting the results are worth about \$100M in y2000 and about \$200M in y2020. Again, all benefits results are for a single bad weather day.



**Figure 8. Delay Cost Comparison for Baseline BW**

In summary, two different baselines have been created and analyzed. The first, baseline W, is based on the “white” planner and was successfully calibrated to closely match the ASQP statistics on total delay cost and total cancellations. This baseline showed substantial benefits under assumptions of improved weather forecasting but did not perform well with the CCFP forecast. On the other hand, the second baseline BW, is based on the “black-and-white” planner and was also successfully calibrated to closely match the ASQP statistics and can deliver significant results under all conditions including the CCFP forecast. Single-day benefits of \$30-\$100M were possible with the CCFP forecast with much greater benefits for improved forecasting. As a final note, it is our belief that the baseline BW is the more realistic of the two approaches since it accounts, in the planning process, for reduced airspace capacities due to convective weather. Note that this is not the case for baseline W in which the planning process is carried out without regard to airspace capacity issues. Thus, baseline BW appears to be closer to current practice.

Although neither baselining approach employs an actual model of current practice, and therefore is not rigorous, it is believed that these approaches can provide insight into the nature and magnitude of potential benefits for greater flow management automation and improved forecasting capabilities. The overall conclusion is that the schedule recovery application has an extremely large potential to deliver results. Yet, without a doubt, this advanced concept, with its great benefits potential, is



technically complex and would require major changes to the current operational concept and automation functionality.

## Summary and Next Steps

This paper presented an analysis of NAS-wide benefits for flow management and airline schedule recovery if more sophisticated automation support and improved weather forecasts were to be made available. The analysis was done using the Boeing National Flow Modeling capability and its airline schedule recovery module, which was tuned to include a representation of the delay performance of current convective weather operations. Analysis results show that significant cost savings can be achieved when automation support is used to optimize and automate the response thru the combined use of delays, cancellations, and re-routing strategies during a convective weather event. Next steps will focus on improved route databases for pre-departure re-routing and post-departure re-routing with dynamic flight plan generation.

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## Key Words

Air traffic management, flow management, airline schedule recovery, collaborative decision making, optimization, modeling, simulation.

## Author Biographies

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Michael L. Carter has over twenty years experience as an applied mathematician with the Boeing Company. He has created software for a wide variety of Boeing applications, developed general-purpose mathematical algorithms, integrated complex engineering applications, and implemented advanced multidisciplinary design optimization (MDO) software. He is a senior member of the Computational Mathematics group of the Mathematics & Computing Technology organization. He has recently done extensive work in (1) developing and analyzing schedule recovery algorithms for effective re-planning of flights to minimize air traffic delays, and (2) utilizing MDO software to significantly enhance a process for designing airplane wings.

Aslaug Haraldsdottir is a Technical Fellow with The Boeing Company and has 26 years of experience in the areas of air traffic management operational concepts and analysis, dynamic systems modeling, simulation and control theory. Her current interest is in air traffic management system operational concepts, technical performance and system architectures for high-density airspace. She is part of the Boeing Commercial Airplane Air Traffic Management team, which currently has a primary focus on near-term improvements in air traffic operations in domestic airspace through air-ground integration and applications of high-performance navigation.

Bruno W. Repetto holds Doctoral and Masters degrees in Operations Research from Carnegie Mellon University, and is a member of the Institute for Operations Research and the Management Sciences (INFORMS), and the Society for Industrial and Applied Mathematics (SIAM). He is a member of the Operations Research group of the Mathematics & Computing Technology organization at Boeing, where he has developed and collaborated in the development of models for airline applications and aircraft manufacturing applications. Before joining Boeing in 2000, he held positions as systems analyst and research scientist at companies in the energy industry and the consulting sector for the steel industry. His interests are in the theory and practice of discrete mathematics and combinatorial optimization.