P10.3 IMPROVING AIR TRAFFIC MANAGEMENT DURING THUNDERSTORMS[†]

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1. ABSTRACT

This paper discusses inter-related studies and development activities that address the significant challenges of implementing Air Traffic Management initiatives in airspace impacted by thunderstorms. We briefly describe current thrusts that will improve the quality and precision of thunderstorm forecasts, work in progress to convert these forecasts into estimates of future airspace capacity, and an initiative to develop a robust ATM optimization model based on future capacity estimates with associated uncertainty bounds. We conclude with a discussion of the thunderstorm ATM problem in the context of future advanced airspace management concepts.

2. INTRODUCTION

Thunderstorms significantly reduce both terminal and en route airspace capacity. Resulting delays have increased substantially in the past decade due to increased en route congestion. Current technology cannot provide reliable long-term forecasts of the aviation impact of thunderstorms. Even when good short-term forecasts are available, the current air traffic management system often can not effectively exploit them to improve network flow because of workload and airspace management difficulties. As a result, air traffic managers employ conservative delaying procedures to minimize the possibility that aircraft will encounter thunderstorms along their route of flight. Based on FAA delay statistics, we estimate that thunderstorm related flight delays cost the commercial airline industry $2B annually in direct operating expenses.

Aviation planners anticipate a need for at least a two-fold increase in the capacity of the air transportation system in the next twenty years. Achieving this increase during fair weather conditions will require better utilization of the inherent capacity of en route airspace. If current and increased future demand is to be managed effectively during thunderstorms, we must also develop better storm forecast technologies and more flexible and less labor intensive air traffic management procedures that can allow dense streams of aircraft to safely bypass convective weather cells by efficiently utilizing all available airspace.

Necessary elements of a more effective ATM approach for maintaining capacity during thunderstorms are:

(i) Forecasts of the position, intensity, movement, height, and growth trends of thunderstorms generated in fine time steps that span the zero to six hour window necessary for flight planning and weather avoidance. These forecasts must include parameters that facilitate the generation of a corresponding forecast of the range of possible capacity reductions in impacted airspace;

(ii) Capacity models for converting the weather forecasts into time-varying estimates of the capacity reductions in affected en route sectors, terminal airspace, and airports. These estimates must include uncertainty bounds;

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(iii) Strategy generation tools that automatically generate optimal ATM strategies that account for these time-varying capacity estimates to reroute traffic around thunderstorm-impacted airspace or, when necessary, impose minimally disruptive ground and/or airborne delay programs;

(iv) Airspace capacity enhancements so that an aircraft can be quickly and flexibly rerouted to avoid weather without exceeding workload or capacity limits. New approaches to aircraft separation assurance are being investigated that can overcome current controller workload constraints and safely support higher densities and greater routing complexity, particularly in en route airspace.

This paper discusses efforts underway to develop or enhance capabilities in each of these areas. Coupled with accurate, multi-hour forecasts of future airspace demand, the capabilities listed above will provide a basis for a more robust ATM system that can substantially reduce the disruptive effects of thunderstorms.

3. THUNDERSTORM FORECASTING

A number of operational thunderstorm forecast products have been developed to assist in air traffic management. The Collaborative Convective Forecast Product (CCFP) (Fahey and Rodenhuis, 2004) is a manually generated 2, 4 and 6 hour national forecast issued every two hours by the NWS Aviation Weather Center. It provides a graphical representation of areas of potential convection and, for each such area, estimates of the percent area the storms will cover and forecast confidence. The operational effectiveness of CCFP has been limited by both forecast errors and by difficulty in "translating" the weather forecasts into airspace capacity estimates by human air traffic management specialists. At times, areas with low coverage and low confidence forecasts of thunderstorms have been treated as "no fly zones", sometimes resulting in unnecessary ground delay programs or other ATM initiatives such as extensive reroutes of aircraft.

Several closely-related, automated forecast products are in use at major ATC facilities. These algorithms track existing thunderstorms and generate forecasts based on extrapolation of movement, and growth and decay trends. The National Convective Weather Forecast (NCWF) Megenhardt et al., 2000) provides 0-1 hour forecasts of thunderstorm positions on the Traffic Situation Display (TSD) used by terminal and center air-traffic management specialists. Higher resolution Terminal (TCWF) and Regional Convective Weather Forecasts (RCWF) are also in use at major terminals and en route centers (Dupree et al., 2005), and have proven to provide substantial capacity benefits (Robinson et al., 2004). The RCWF includes a thunderstorm height forecast – important for assessing high-altitude jet route blockage – and both products score their forecast skill in real-time so as to provide users a continuously-updated measure of forecast confidence.

Figure 1 shows the RCWF user display which includes a depiction of current precipitation coverage and vertical extent. The RCWF is available at 15 minute forecast-time increments covering the interval 15 minutes to 2 hours, and each of these eight forecasts is updated automatically on a five minute cycle as new weather radar inputs are obtained. It is important to note that the RCWF forecasts capture the structure (e.g. convective element scale, line orientation) of the current storm measurements from which they are extrapolated, and are presented with very high spatial and temporal resolution. This allows users of the forecast to assess anticipated future impacts of thunderstorms on individual jet routes, terminal arrival and departure transition areas and airports. The RCWF is a key product delivered by the Corridor Integrated Weather System (CIWS) to traffic management specialists at major northeastern US en route and terminal ATC facilities.

High resolution numerical weather predictions (NWP) models (Weisman et al., 2004 and Weisman et al., 2005) provide explicit forecasts of convective fields over the multiple-hour interval needed for tactical and strategic air traffic management. Continuing improvements in resolution, model-physics and data assimilation capabilities have increased the convective-scale forecast skill of these models substantially. Because model "spin up time" limits the accuracy of very short term (0-3 hour) forecasts, NWP is less accurate than extrapolation-based forecasts for short time horizons. Many investigators have posited that future 0-6 hour automated forecast products will involve a blend of data extrapolation approaches (0-3 hour) and NWP methods (2-6 hours) (Wolfson et al., 2004 and Wilson et al., 2005).

Uncertainty in thunderstorm forecasts has typically been characterized via “area probability” within the forecast regions. Loosely, this is to be interpreted as the probability that a specific location within the forecast region will be experiencing a convective storm with high radar reflectivity at the forecast-valid time. Equivalently, this probability can interpreted as the fractional area within the forecast region that will be experiencing such a storm at the forecast valid time. These probabilities can be estimated manually based on the forecaster’s interpretation of atmospheric convective potential, or they can be derived from NWP models using multiple runs to form an “ensemble” of explicit forecasts which are then converted to area probabilities. Weygandt and Benjamin (2005) discuss a 0-6 hour convective probability forecast based on NWP ensemble techniques.

Unfortunately, “area probabilities” are not readily translated into estimates of future airspace capacity reduction because the traffic flow impact is strongly dependent on the location, orientation and spatial scale of the convection within the forecast area. This is illustrated in Figure 2, where the route blockage model described in Section 3 has been used to calculate the distribution of fractional route blockage for different U.S. en route sectors, using an ensemble of weather cases with similar fractional area coverage by high reflectivity convective storms. The distributions of blockage within individual sectors are broad and vary considerably amongst the sectors, indicating that details of the individual storms’ structures and the sector air route structures have a strong impact on the amount of blockage. We conclude that multi-hour “probabilistic” convective forecasts must characterize distributions of many relevant storm parameters, not simply fractional area coverage, and that it will be necessary to develop sector-specific models to translate the convective forecasts into estimates of capacity loss.

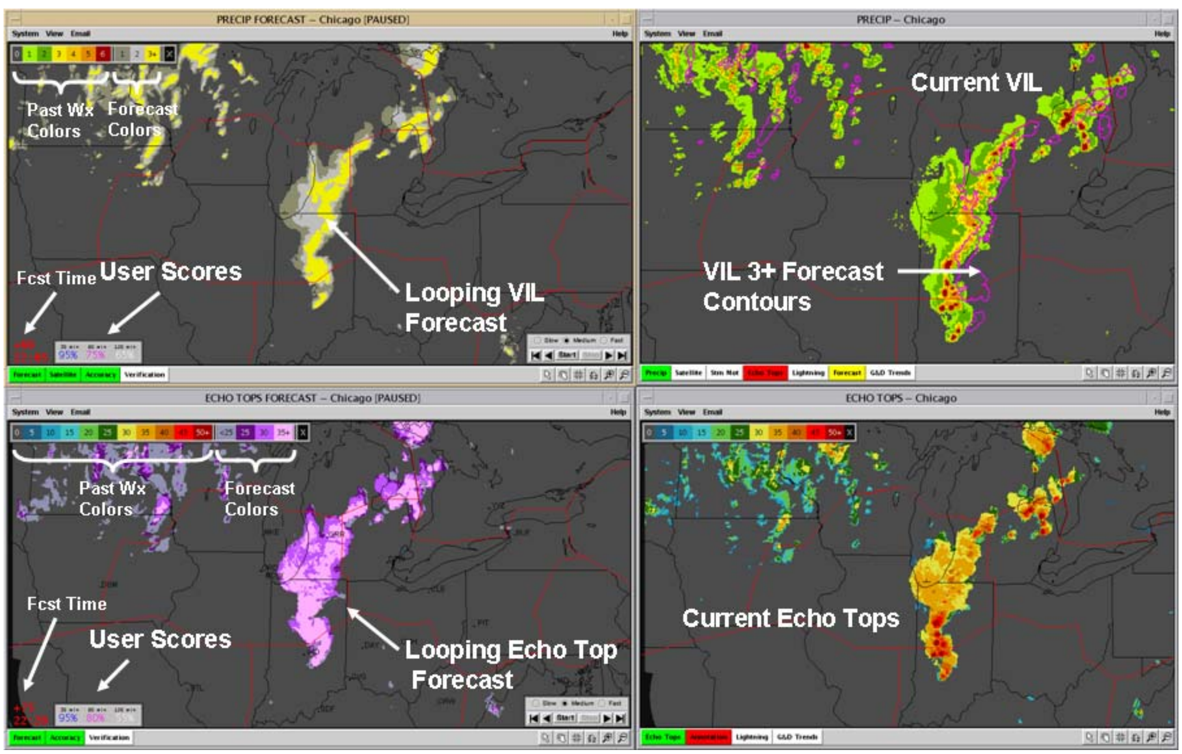

Figure 1. Regional Convective Weather Forecast (RCWF) generated by the Corridor Integrated Weather System. The Vertically Integrated Liquid (VIL) precipitation forecast is in the upper left panel: yellow areas depict regions of forecast convection. Storm height as estimated from radar “echo tops” are forecast in the lower left panel. Current depictions of these same parameters are shown in the two right hand panels.

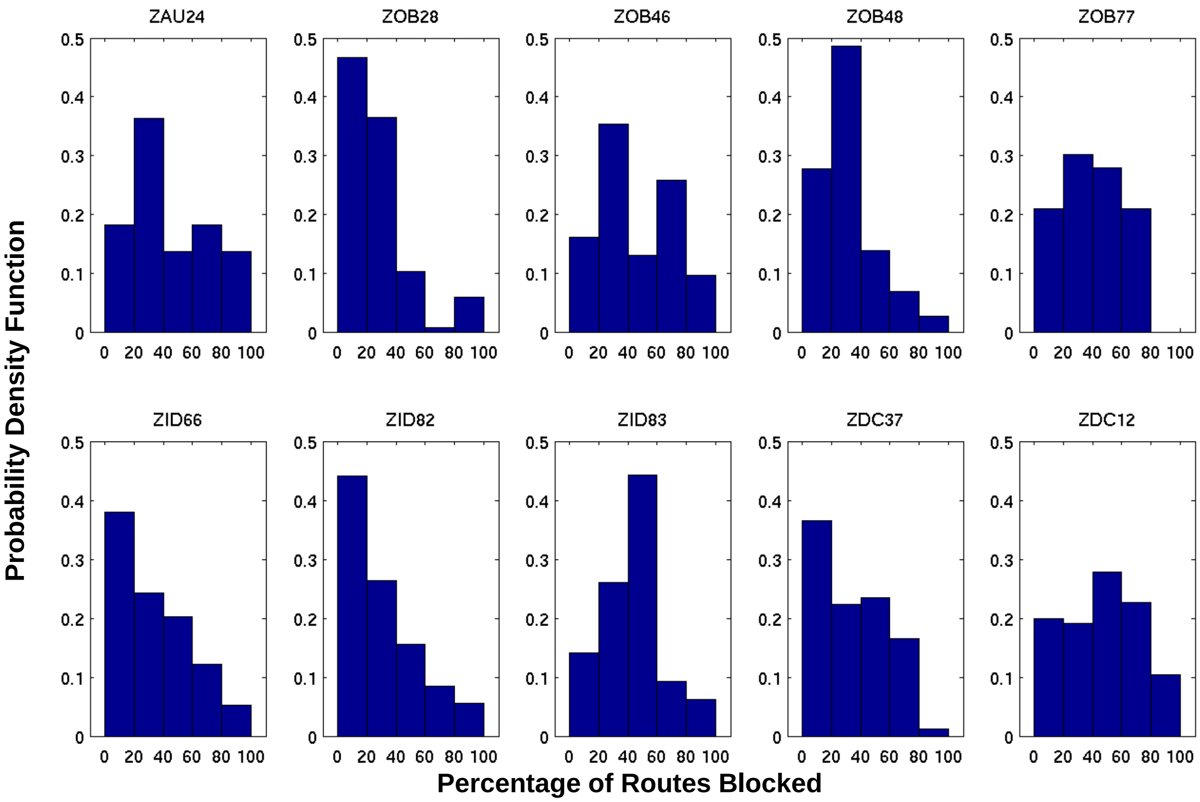

Figure 2. Distribution of the percentage of routes blocked in 10 congested en route sectors in the northeastern U.S. The distributions are for an ensemble of east-west oriented line storms exhibiting area coverage within the sectors of 30%-50%.

4. MODELING THE AIRSPACE CAPACITY IMPACTS OF THUNDERSTORMS

This section describes initial work to quantitatively model the impacts of thunderstorms on en route sector capacity. This work utilizes weather radar measurements of thunderstorm vertically integrated liquid water (VIL) and maximum altitude extent (radar "echo top" or ET) to estimate route blockage (RB) for each individual route within a sector. The individual route blockages are then combined to provide an average route blockage measure for the sector. The model we describe can also be used to estimate future en route capacity if high-resolution, short-range "deterministic" thunderstorm forecasts such as RCWF are used as input. Extension of the model to the long range, "probabilistic" forecast problem is discussed at the end of this section. Development of corresponding models for terminal area and airport capacity impacts will be described in future publications.

The ten ATC sectors referenced in Figure 2 were chosen for RB modeling due to differences in geographic location, size, route orientation and route complexity. These sectors include high traffic areas within the Indianapolis (ZID) and Cleveland (ZOB) centers, major north-south transit routes within the Washington (ZDC) center, and a Chicago (ZAU) center sector responsible for transcontinental traffic over the Midwest. A total of 60 high altitude jet route segments within these sectors were utilized in developing the RB models.

These route segments were sub-divided into lengths of roughly 55 km (0.5^{o} latitude) and assigned a width of 8 km. A blockage score for each subdivided segment was determined via a linear combination of measured radar echo overlap parameters. These parameters capture the intensity of the radar echo, the extent (partial or total) to which the echo overlays the route segment and the altitude extent of the echo. The weighting factors were determined empirically through a study of operations in New York City airspace and interactions with FAA air traffic managers and controllers. The blockage score for the route segment was taken to be the maximum of the subdivided segment blockage scores[1].

Figure 3 is a snapshot of capacity reductions in the ten en route sectors during thunderstorm activity. Shown are the high-altitude jet routes used in the model and the averaged RB (i.e. assumed capacity reduction) for each sector. The widths of the jet route lines denote the scheduled demand for each route at the time of this analysis. This analysis has been performed automatically at 5 minute time steps for twenty convective weather events within the CIWS domain to develop a large data base of time-varying sector capacity estimates. These are being further analyzed to refine and validate the capacity-reduction estimation model, and as input for initial evaluations of the ATM optimization model described in Section 4.

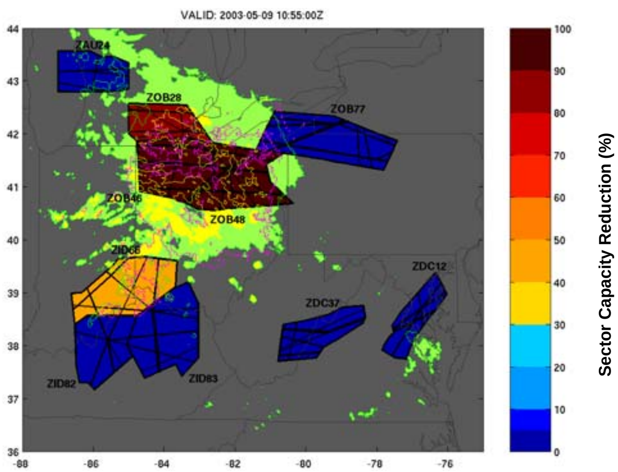

Figure 3. Example output of the RB-based sector capacity model described in the text. The input weather radar VIL field is shown using yellow to denote areas where the VIL exceeds the convective weather threshold. The purple contours are areas where radar ET exceeds 32,000 feet.

Characterizing the uncertainties of these capacity estimates, even in a post-analysis mode where the weather fields are known exactly, will be a major, ongoing element of our studies. In the remainder of this section we comment on the challenges of estimating nominal future sector capacities and associated uncertainty bounds when the input is a thunderstorm forecast with its own inherent uncertainties.

4.1 Ensemble-Forecast Based Uncertainty Estimates

The RB model described above utilizes high-resolution fields of measured or forecast thunderstorm VIL and ET. Such "deterministic" forecast fields are available as explicit outputs from the short-range, extrapolation based RCWF, although the CIWS user interface makes it clear that the RCWF forecasts may have large uncertainties for forecast times greater than one hour (especially when the convection is characterized by "disorganized" air mass storms). Some NWP models (especially those that have the ability to explicitly model initiation, growth and decay of individual cells) may have forecast fields with sufficient spatial resolution and precision to be used as an input for explicit route blockage calculations.

When the forecast accuracy is not high enough to be treated as "deterministic", an uncertainty estimate for the RB capacity model could be calculated by suitably combining RB estimates generated individually from the members of an ensemble of forecast runs. For NWP-based forecasts, methods for perturbing initial conditions and/or model parameters so as to span the uncertainty bounds of the forecast have been discussed in the literature (Atger, 1999 and Walser et al., 2004). Hohti et al. (2005) discuss analogous techniques for short-range extrapolation-based forecasts. For RCWF, algorithm parameters controlling the convective scale separation, motion tracking and growth/decay trending could be perturbed over plausible intervals so as to generate an ensemble of high-resolution extrapolation-based forecasts.

Although computationally demanding, an ensemble-based approach would be straightforward to implement and is certainly viable for case study analysis. At minimum, this can provide valuable insight into the tractability of establishing meaningful uncertainty bounds for future capacity estimates, and the case study analysis will provide valuable perspectives on alternative approaches.

[1] The use of the maximum of the subdivided segment blockage scores upper bounds the capacity loss on the route. If one considers the time variation of the subdivided segments blockage scores relative to the positions that an aircraft would be in as a function of time (i.e., determining whether there are 4D intersections of the aircraft and convective cells), one generally obtains a higher effective capacity. This refinement to capacity calculations is used by the Route Availability Planning Tool (RAPT) (DeLaura and Allan, 2003) and will be considered in follow on studies.

4.2 Statistically-Based Uncertainty Estimates

Martin and Evans (2005) suggest an approach to deriving the probability density function (PDF) of sector route blockage (RB) from a thunderstorm forecast, using convolutions of more readily determined PDFs. The PDF of RB, conditional on a probabilistic weather forecast, F, can be determined as:

$$P(RB|F) = \int P_1(RB|\underline{W}_C)\, P_2(\underline{W}_C|F)\, d\underline{W}_C \qquad (1)$$

Where:

P(RB|F) is the PDF of RB in an ATC sector given a thunderstorm forecast with parameters F. Example forecast parameters could be area coverage, mean storm height, storm type (airmass, lines), parameters characterizing the orientation of lines and a forecast confidence metric;

$P_1(RB|\underline{W}_C)$ is the PDF of RB given that actual thunderstorm parameters are $\underline{W}_C$ (a vector). The elements of $\underline{W}_C$ can include the same types of parameters utilized for F, but will generally support a larger set and convey more detail on storm characteristics. Having specified a set of thunderstorm parameters $\underline{W}_C$, this conditional PDF can be determined using the RB blockage model described previously and a large thunderstorm data set that spans the plausible domain of $\underline{W}_C$;

$P_2(\underline{W}_C|F)$ is the PDF of actual weather $\underline{W}_C$ given that a thunderstorm forecast with parameters F was made. The model for $P_2(\underline{W}_C|F)$ can be developed from meteorological validation of the probabilistic forecast that will be input to the capacity model (Mahoney et al., 2002).

By integrating the product of the P_1 and P_2 terms with respect to the continuous variable $\underline{W}_C$, one obtains the probabilistic forecast of RB conditional on F. An advantage of determining P(RB|F) by the above approach as opposed to empirically assessing the actual RB for many issued forecasts, is that only meteorological validation needs to be redone (that is, the model for $P_2(\underline{W}_C|F)$ is regenerated) if a different forecast technique is utilized.

Table 1. Summary of results of a pattern classification analysis

Sector Route Blockage (RB) Classification Results				
RB Interval	**# of Samples**	**High VIL Error**	**ET>25KFT Error**	**Best Combination Error**
[0-20%)	21287	11.60 %	8.21 %	**2.85 %**
[20-40%)	2578	77.89 %	69.67 %	**37.18 %**
[40-60%)	1691	73.95 %	76.95 %	**35.93 %**
[60-80%)	884	70.52 %	73.41 %	**32.37 %**
[80-100%]	515	56.12 %	71.43 %	**15.31 %**
	26955	24.51 %	21.60 %	**9.36 %**

Martin and Evans (2005) used a pattern classification technique to determine the parameter set $\underline{W}_C$ that provides the greatest explanatory capability for variation in RB. When considered individually, weather parameters characterizing the area coverage of high topped thunderstorms or the area coverage of high VIL had the greatest explanatory power. Significant improvement in explanatory power was obtained if both of these parameters were used, along with additional parameters characterizing, for example, the coverage and orientation of line storms. Table 1 lists the classification errors – that is the percentage of cases assigned to the wrong route-blockage bin -- for these single parameter and "best combination" thunderstorm characterizations. It is seen that multiple parameters must be used to characterize the thunderstorm activity if reasonably accurate estimation of route blockage is to be achieved across the full range of fractional blockage values.

Ongoing efforts to implement this statistical capacity model will utilize CIWS measurement fields to develop more robust representations of the functions $P_1(RB|\underline{W}_C)$. Automated tools for processing the large number of storm cases required to populate these models will be required, followed by careful validation that the model for route blockage --given actual weather parameters -- agrees well with the actual usage of routes in convective weather. Additionally, there will need to be coordinated work with the developers of convective weather forecasts to develop validated models for the performance of the forecasts (i.e., validated models for $P_2(\underline{W}_C|F)$).

5. ROBUST OPTIMIZATION OF GROUND HOLDS, IN-FLIGHT DELAYS AND REROUTES

Bertsimas and Stock-Patterson (1998) described a mixed-integer programming (MIP) model that addresses the traffic flow management problem (TFMP) in the presence of weather induced capacity constraints. The National Airspace System (NAS) is characterized as a set of airports interconnected via en route sectors. Each airport and en route sector is assigned time varying aircraft capacities. Individual flights are modeled as traversals of sectors forming paths between pairs of origin and destination airports. The model specifies the valid paths, along with minimum sector traversal times, so that aircraft speed is accounted for. The model solution yields not only the optimal cost (in terms of minimal in-flight and ground delays) but also the "flight plan" for each flight -- takeoff and landing times, and arrival times at each sector along its path. Using 1990's state-of-the-art MIP solvers and hardware, Bertsimas and Stock-Patterson (1998) showed that TFMP problems of significant size (six major airports, with three thousand flights over a sixteen-hour period) could be solved optimally using only a few minutes of computation time.

The Bertsimas-Stock-Patterson (1998) TFMP model is based on the assumption that future airspace capacity is known with certainty. We have recently commenced efforts to extend the formulation to the realistic situation where future airspace capacity is uncertain, owing for example to imperfect thunderstorm forecasts. Two principal methods have been applied to the problem of addressing data uncertainty: stochastic programming and robust optimization. Stochastic programming is difficult to apply to problems on the scale of TFMP, since it addresses data uncertainty by mapping probabilistic variation to a large number of distinct scenarios, each of which amounts to a separate mathematical programming problem which must be solved independently in order to determine which one yields the best solution. As an alternative, Bertsimas and Sim (2003) have shown that the robust optimization approach can yield near-optimal solutions to MIP formulations of network flow problems without the explosive increase in model size associated with stochastic techniques.

Robust discrete optimization can be applied to the TFMP as follows. Rather than specify the exact capacity of sector S at time t as S(t)=C, the capacity is given as a range $S(t)=[C_l,C_u]$, where C_l is a lower bound on expected capacity and C_u is the maximum capacity. In addition, a "robustness level" parameter Γ specifies the maximum number of sectors whose capacities are expected to meet their worst-case bounds. As examples:

(i) forecasts for a narrow thunderstorm line caused by frontal forcing would suggest a relatively small value for Γ (set by the maximum expected length of the line) and values for C_l and Cu in affected sectors that are respectively near-zero, and near the fair weather capacity limit. This capacity range reflects the expectation that en route sectors through which the front is passing may be completely blocked, but that the timing of the frontal passage is uncertain;

(ii) forecasts of widespread, airmass convection would suggest larger values for Γ, but a higher value for the worst-case capacity estimate C_l.

Using robust discrete optimization, the TFMP can be solved without being overly conservative, or requiring that all possible scenarios be considered individually. Although robust discrete optimization has not previously been applied to the air traffic flow management problem, Bertsimas and Sim (2003) show that in a wide variety of network flow problems, appropriate selection of data uncertainty intervals and the robustness level Γ can yield model solutions which are close to the optimal "perfect-information" solutions, with low probability of violating network capacity constraints.

After developing the robust optimization model for the TFMP, we plan to assess its utility using thunderstorm event data archived via the Corridor Integrated Weather System (CIWS) prototype. Actual weather, RCWF forecasts and data on scheduled demand and implemented delay programs will be archived and analyzed *a posteriori* to determine the potential benefits of automated, objective ATM procedures. This analysis should clarify important issues such as:

(i) the cost function against which optimization is performed. Bertsimas-Stock-Patterson (1998) used a linear function of ground and enroute delay costs for individual flights. From the airline industry perspective, however, it is likely that multiple short airplane delays are significantly less disruptive than a small number of delays which significantly exceed 15 minutes in duration. For example, Beatty et al. (1999) show that "downstream" impact increases nonlinearly with the length of the initial delay.

(ii) required computational resources. Formulating the (deterministic) TFMP for the entire NAS requires solving a model which contains approximately 1000 en route sectors, dozens of major airports, over 10000 sector traversal paths, and thousands of multi-hop commercial flights per day. Analysis is needed to confirm that advances in hardware and optimization software over the past decade are sufficient to solve NAS-sized MIP problems;

(iii) the validity of a fixed-route assumption. The Bertsimas-Stock-Patterson (1998) TFMP formulation assumes a static network through which aircraft travel from origin to destination. However, even casual inspection of measured aircraft flight data indicates that aircraft do not always traverse predefined routes, particularly in terminal airspace. Since the TFMP model does not account for this flexibility, the computed "optimal" result may be too conservative in many cases.

6. INCREASING THE INHERENT CAPACITY OF EN ROUTE AIRSPACE

In order to fully exploit the planning capabilities of the future system, the basic aircraft routing and separation assurance functions must be enhanced to permit greater aircraft densities and less dependence upon fixed airspace structures. One concept that demonstrates how this can be done is NASA's Advanced Airspace Concept (AAC) as described by Erzberger (2004). The AAC would substantially increase the capacity and flexibility of control in en route airspace by basing control on a set of 4D trajectories that would be validated, monitored, and updated as required by ground-based computers. In some airspace flexible separation and routing might be accomplished by distributed air-to-air separation techniques (Prevot et al., 2005). By eliminating controller workload associated with sector handoff coordination and with aircraft separation tasks these concepts remove the primary factor determining the current operational limit on traffic density and the ability to reroute in a fully flexible manner.

Andrews et al. (2005) demonstrated that by fully exploiting available 4D trajectories, the AAC would allow aircraft density in congested en route sectors to be increased by more than a factor of 4 without introducing conflicts. Further analysis indicated that defined level-of-safety goals could be maintained by the AAC in the presence of fault scenarios such as non-conformance and computer outages. Because the AAC envisions sectors that are several times greater than those in use today, weather rerouting could be accomplished more readily, with fewer sector boundary crossings and reduced coordination workload.

The AAC appears to be consistent with the approaches for mitigating thunderstorm impacts described in this paper. Planning of conflict-free, 4D aircraft trajectories requires that thunderstorm-induced capacity reductions in en route or terminal airspace be considered in tactical time frames. The thunderstorm forecast technologies described in this paper will support airspace capacity reduction estimates with moderate to high accuracy in the tactical time frame. A first-order assignment of aircraft reroutes and (if necessary) in-flight delays or ground holds can be developed and continuously updated using a stochastic optimization model of the type described in Section 4. The resulting plan would be coordinated with aircraft and implemented by the AAC trajectory revision logic to ensure simultaneous attainment of separation of traffic and separation from hazardous weather.

Figure 4 (Erzberger 2004) illustrates how AAC might achieve dynamic response to the need for thunderstorm re-planning. In the situation illustrated, two aircraft have requested deviations to avoid flying through thunderstorms on their original planned routes of flight. Within a few seconds, the AAC trajectory analysis logic determines that the requested reroutes are in conflict with each other, as well as with a third aircraft behind the thunderstorms. The system proposes modified trajectories that eliminate the conflicts. To assure that the modified reroutes likewise avoid the convective cells, the trajectory analysis engine employs a continuously updated depiction of current and forecast thunderstorm cell positions that span the reroute planning horizon. The planned routes are continually monitored for convective cells that appear unexpectedly, and a re-planning process is triggered if a potential hazard is detected.

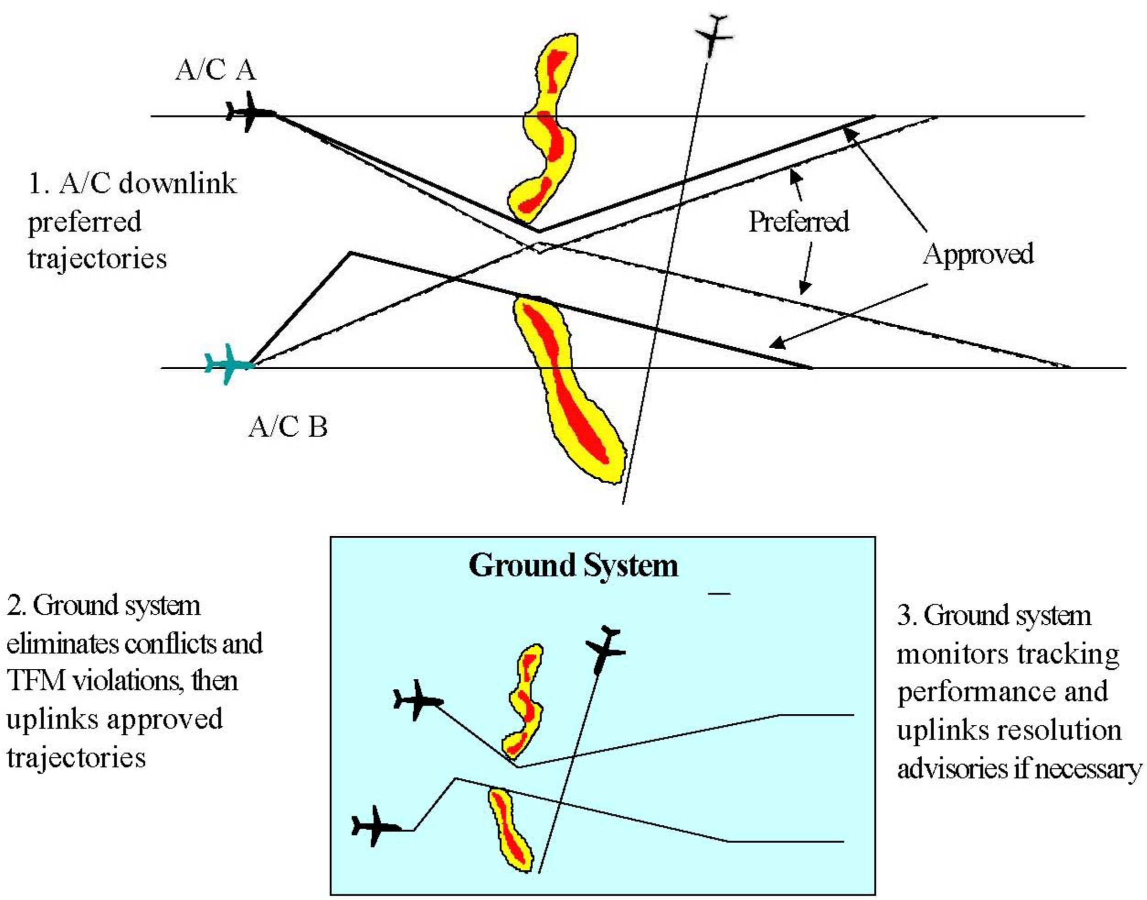

Figure 4. Illustration of AAC flexible rerouting around thunderstorms. From Erzberger [2004].

A key issue in developing the trajectory in this situation is how large a buffer need be provided around forecast thunderstorm positions. Both route generation and route monitoring will require an explicit model for pilot preferences[2] in avoidance of convective cells. The FAA Aeronautical Information Manual (Spence, 2004) suggests that pilots avoid thunderstorms characterized by “intense radar echo” in en route airspace by at least 20 miles. Rhoda, et al. (2002) observed, however, that air carrier pilots often fly over storms in the Memphis ARTCC airspace if the aircraft altitude is at least 5kft higher than the storm radar echo tops. DeLaura and Evans (2005) found similar behavior in Indianapolis ARTCC airspace. When the storm’s radar echo tops extended near to or above flight levels, they observed a median deviation around storms of about 15 nmi. Terminal area studies of pilot behavior (1999) indicated that a large percentage of aircraft will penetrate high reflectivity cells when within 10 nmi of the airport. High reflectivity cells were avoided at longer distances, but typical storm deviation distances were not determined. More extensive studies of pilot preferences for convective storm avoidance in both highly congested (e.g., New York, Washington and Cleveland ARTCCs) and less congested airspace (e.g., Atlanta and Denver ARTCCs) are needed.

Pilot behavior will likely change as anticipated innovations for the future system are implemented. Pilots will continue to evaluate storms largely from weather radar, visual observation, and reports from nearby pilots; and the decision on how close to fly to a specific storm will involve factors such as aircraft loading, passenger and crew status, the wind environment, and carrier cost-benefit issues such as passenger comfort, schedule, and fuel status. But the Advanced Airspace Concept will be able, within a few seconds, to generate new conflict-free weather-safe routes consistent with both system standards and pilot preferences. Thus, pilots and controllers can be less concerned than they currently are about workload and latency issues in re-routing.

The relationship between advanced separation concepts (such as the AAC or airborne self-separation) and convective weather is a topic worthy of considerable research. One important question to be answered is how much benefit the associated flexibility and capacity advances would provide in reducing today’s summer storm delays.

7. SUMMARY AND DISCUSSION

This paper has described work that addresses the Air Traffic Management problem as affected by thunderstorm-induced capacity constraints. We highlighted the Regional Convective Weather Forecast (RCWF) as an example of a very high resolution forecast product that can be used to quantitatively estimate future capacity reductions in individual en route sectors or terminal areas. Significant ongoing effort is needed, however, to optimally match meteorological forecast parameters to the needs of the airspace capacity models that will be the input to future ATM systems. For example, the frequently encountered “area probability” forecast was shown to provide insufficient information for estimating airspace capacity. In the authors’ opinions, support for research on coupling meteorological forecasts and airspace capacity models is inadequate, given the complexity of the problem and its importance to the goal of achieving significantly enhanced capacity in the future.

We described a computationally tractable approach for optimizing thunderstorm-induced airplane reroutes, in-flight speed adjustments, and ground holds so as to minimize delay costs. Work is ongoing to extend previous work to the realistic situation where future airspace capacity reductions caused by thunderstorms are known only approximately, and with increasing uncertainty at longer planning horizons. This approach provides an automated, objective, wide-area planning engine that could significantly increase the capability of the ATM system to take advantage of available airspace during thunderstorms.

Finally, we noted synergism with NASA’s Advanced Airspace Concept that would utilize automated trajectory planning and coordination to substantially increase the capacity of airspace. Conflict-free trajectory planning will require continuously updated estimates of current and future weather-induced capacity constraints. In addition, strategies for addressing inevitable uncertainties in future airspace demand and capacity must be developed. A key common assumption in the

[2] We assume here that the current policy of the pilot having principal responsibility for avoidance of hazardous weather (as opposed to the FAA taking on that responsibility) will continue in the future. New aircraft have weather radars that permit 3 D storm measurement and visualization. Additionally, the pilots have unique insights into storm severity from visual observations of storm cloud features at close range that are not available to ground based systems.

weather work and the AAC development is the need for substantial processing and control infrastructure to establish optimal, wide-area solutions.

8. REFERENCES

Andrews, J., J. Welch and H. Erzberger, 2005, Safety Analysis for Advanced Separation Concepts, 6th Eurocontrol/FAA ATM R&D Seminar ATM-2005, Baltimore, MD.

Atger, F., 1999, The Skill of Ensemble Prediction Systems, Monthly Weather Review 127, 1941-1953.

Beatty, R., R. Hsu, L. Berry, J. Rome, 1999, Preliminary Evaluation of Flight Delay Propagation Through an Airline Schedule, Air Traffic Quarterly, 7, 259-270.

Bertsimas, D. and S. Stock-Patterson, 1998, The Air Traffic Flow Management Problem with En Route Capacities, Operations Research, 46, 406-422.

Bertsimas, D. and M. Sim, 2003, Robust Discrete Optimization and Network Flows, Mathematical Programming Series B, 98, 49-71.

DeLaura, R., and S. Allan, 2003, Route Selection Decision Support in Convective Weather: A Case Study of the Effects of Weather and Operational Assumptions on Departure Throughput, Budapest, Hungary, 5th Eurocontrol/FAA ATM R&D Seminar ATM-2003, http://atm2003.eurocontrol.fr/.

DeLaura, R. and J. Evans, 2005, An Exploratory Study of Modeling En Route Pilot Convective Storm Flight Deviation, Lexington, MA, Massachusetts Institute of Technology, Lincoln Laboratory, Project Report NASA/A-6.

Dupree, W., M. Wolfson, R. Johnson Jr., R. Boldi, E. Mann, K. Theriault Calden, C. Wilson, P. Bieringer, B. Martin, H. Iskenderian, 2005, FAA Tactical Weather Forecasting in the United States National Airspace, Toulouse Nowcasting Conference.

Erzberger, H., 2004, Transforming the NAS: The Next Generation Air Traffic Control System, 24th International Congress of the Aeronautical Sciences.

Fahey, T. and D. Rodenhuis, 2004: “Continual evolution of CCFP-User needs for extended range prediction, 11th Conference on Aviation, Range, and Aerospace Meteorology, Hyannis, MA.

Hohti, H., M. Peura and J. Koistinen, 2005, Radar Based Ensemble Nowcasting of Precipitation, World Weather Research Program Symposium on Nowcasting and Very Short Range Forecasting, Toulouse, France.

Mahoney, J.L., J.K. Hederson, B.G. Brown, J.E. Hart, A. Loughe, C. Fischer and B. Sigren, 2002: The Real-Time Verification System (RTVS) and its Application to Aviation Weather Forecast, 10^th Conference on Aviation, Range, and Aerospace Meteorology, 13-16 May, Portland, OR.

Martin, B. and J. Evans, 2005, Results of an Exploratory Study to Model Route Availability in En Route Airspace as a Function of Actual Weather Coverage and Type, Lexington, MA, Massachusetts Institute of Technology, Lincoln Laboratory, Project Report NASA/A-7.

Megenhardt, D., C. K. Mueller, N. Rehak, and G. Cunning, 2000: Evaluation of the National Convective Weather Forecast Product. Preprints *9th Conference on Aviation, Range, and Aerospace Meteorology,* Amer. Met. Society, Orlando, Florida, pp 171-176.

Prevot, T., T. Callantine, P. Lee, J. Mercer, V. Battiste, W. Johnson, E. Palmer and N. Smith, 2005, Co-operative Air Traffic Management: A Technology Enabled Concept for the Next Generation Air Transportation System, 6th USA/Europe Seminar on Air Traffic Management Research and Development, Baltimore, MD.

Rhoda, D. and M. Pawlak, 1999, An Assessment of Thunderstorm Penetrations and Deviations by Commercial Aircraft in the Terminal Area, Lexington, MA, Massachusetts Institute of Technology, Lincoln Laboratory, Project Report NASA/A-2.

Rhoda, D., E. Kocab and M. Pawlak, 2002, Aircraft Encounters with Convective Weather in En Route vs. Terminal Airspace above Memphis, TN, Portland, OR, 10th Conference on Aviation, Range, and Aerospace Meteorology, American Meteorological Society.

Robinson, M., J. Evans, B. Crowe, D. Klingle-Wilson and S. Allan, 2004, *CIWS Operational Benefits 2002-3: Initial Estimates of Convective Weather Delay Reduction,* Lexington, MA, MIT Lincoln Laboratory Project Report ATC-313.

Spence, C., 2004, Aeronautical Information Manual/Federal Aviation Regulations, McGraw Hill.

Walser, A., D. Luthi and C. Shar, 2004, Predictability of Precipitation in a Cloud-Resolving Model, Monthly Weather Review 132, 560-577.

Weisman, M. L., C. Davis, and J. Done, 2004: The Promise and Challenge of Explicit Convective Forecasting with the WRF Model, Preprints 22nd

Conference on Severe Local Storms, Amer. Met. Society, Hyannis, MA.
Weisman, M. L., W. Wang, C. Davis, 2005: Experiences with 0-36 hour Explicit Convective Forecasting with the WRF-ARW Model. 2005 WRF/MM5 Users' Workshop, June 27-30, National Center for Atmospheric Research, Boulder, CO.
Weygandt, S. and S. Benjamin, 2005, Hourly RUC Convective Probability Forecasts Using Ensembles and Radar Assimilation, World Weather Research Program Symposium on Nowcasting and Very Short Range Forecasting, Toulouse, France.
Wilson, J., C. Mueller, M. Xu, J. Pinto and J. Sun, 2005, Combining Radar Echo Extrapolation and NWP Techniques for 1-6 Hour Convective Storm Forecasts, World Weather Research Program Symposium on Nowcasting and Very Short Range Forecasting, Toulouse, France.
Wolfson, M., B. Forman, K. Calden, W. Dupree, R. Johnson Jr., R. Boldi, C. Wilson, P. Bieringer. E. Mann, and J. Morgan, 2004, Tactical 0-2 Hour Convective Weather Forecasts For FAA, 11th Conference on Aviation, Range and Aerospace Meteorology, Hyannis, MA.