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AVIATION WEATHER REQUIREMENTS IN THE AIR TRAFFIC MANAGEMENT SYSTEM

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1. INTRODUCTION

Weather has a major impact on the safety, efficiency, and capacity of aviation operations. Runway acceptance rates and other capacity metrics are reduced in instrument meteorological conditions (IMC). According to some studies, 40–65 percent of delays that U.S. domestic airlines experience are attributable to adverse weather, at annual costs estimated to range from \$4–5B per year (NRC, 1995; Evans, 1995). Accidents and incidents continue to be caused by adverse weather. Passengers are inconvenienced by flight cancellations or diversions due to weather, and are uncomfortable or may even be injured when turbulence is encountered during a flight. The expected future growth in air traffic will only exacerbate all these conditions, imposing constraints on the ability of the airlines to meet growing demand while improving safety and efficiency.

Worldwide growth estimates for the air transport industry over the next 15–20 years are relatively modest, on the order of a few percent per year (Boeing, 1997a). These growth projections assume that there are no technical or procedural constraints that will limit the expansion of commercial aviation operations. Increasingly, however, the perception is growing that these assumptions are not correct, and that indeed significant changes will be needed in the air traffic management (ATM) system if the expected increase in traffic demand is to be met (Chew, 1997). These changes will come in the form a modernized National Airspace System (NAS) that will rely on new communications, navigation, and surveillance (CNS) technologies and ATM operational concepts (e.g., Free Flight; Boeing, 1997b).

To what degree weather may constrain future growth in the NAS is not well known in a strict, quantifiable sense, but notionally the problems appear to be significant. To this end, the CNS/ATM Analysis group within the Boeing Commercial Airplane Group (BCAG) has been collecting and

analyzing information on the impact of weather on the ATM system. The objective of this effort is to take a top-down look at the aviation weather system to develop technical and business-relevant information on the role of weather in the ATM system. The goal of the study is to identify and develop requirements for aviation weather information that can lead to effective investments and operational benefits.

2. ASSUMPTIONS AND DEFINITIONS

Our efforts to date have been focused mainly on issues related to weather impacts on capacity and efficiency in the NAS. This is not to downplay the requirements for safety, but the purpose of the present study is to explore the operational and economic benefits that weather information can provide. Safety concerns will always be the overriding constraint, and no requirement related to capacity or efficiency will be developed that comprises the requirements for safety. Thus, our intent is to develop the linkages between traditional aviation weather services, which have historically addressed safety issues, and future requirements for weather information.

An important assumption that has guided this work is based on the premise that a potential solution to the capacity problem may be sought in reducing aircraft separations (Boeing, 1997b). Safely reducing separations through all phases of flight without increasing controller or flight crew workload may become an important driver in the development of new CNS/ATM technologies and procedures. Accurate knowledge of meteorological conditions will be an important element of many of these technologies. For example, the Center-TRACON Automation System (CTAS) and airborne flight management systems (FMS) require accurate forecasts of four-dimensional (4-D) winds and temperatures for aircraft trajectory synthesis.

The distinction between capacity and efficiency is not always clear. For the purposes of this study, capacity and efficiency are defined as follows:

- **Capacity:** The theoretical maximum flow rate of aircraft that can be accommodated in a given time period by the system or one of its components,

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given requirements for separation standards. **Throughput** is the actual flow rate realized in operation, which never exceeds capacity, and is often much less.

- **Efficiency:** A measure of how close a real operation is to achieving ideal flight, expressed in terms of actual cost, or the degree to which the ATM system penalizes operations, relative to the cost of an ideal or optimum operation. An “ideal flight” is one in which a theoretically minimum cost is incurred between origin and destination, assuming no constraints due to traffic, weather, or procedural issues. Factors which affect efficiency include flight route, fuel usage, delays, and procedural restrictions.

From an economic perspective, efficiency is primarily a *cost* issue. If the application of “better” weather technologies can improve efficiency in the ATM system (e.g., by reducing delays during adverse weather or shortening flight times by using preferred routes), then the costs per operation can be reduced (through lower fuel costs, fewer diversions and cancellations, etc.). The definition of system capacity, on the other hand, is primarily a *revenue* issue. It goes directly to how many flights the airlines can schedule and what they can charge for their services. The high fixed costs of the airline industry, the relatively low marginal costs to carry additional revenue-generating payloads, and the strong sensitivity of sales to price (elasticity) implies that the airlines will almost always look for ways to increase the number of operations to carry more passengers and cargo (Crandall, 1995). Even if higher capacities create new inefficiencies, the increased revenue may more than offset any new costs. Thus, new technologies that carry a high technical risk for success may lead to potentially significant increases in capacity and hence revenue to the airlines and airports. Understanding trade-off’s between efficiency and capacity, and their affects on investment decisions in aviation weather technology, is an important issue that does not appear to have been addressed yet in NAS planning efforts.

A recently formed industry-government forum called the CNS/ATM Focus Team (C/AFT) has proposed metrics for assessing NAS performance. C/AFT is gathering economic, technical, and risk data, and developing methodologies for use by airlines, air traffic service providers, government agencies, and industry to determine an economic-driven strategy for CNS/ATM deployment.¹ The

C/AFT metrics include predictability, flexibility, access, delay, and efficiency:

- **Predictability:** The extent to which the system allows users to know when they will arrive based on when they depart.
- **Flexibility:** The extent to which users are able to use the system the way they want to, with an absence of constraints.
- **Access:** The extent to which users are able to access airports, airspace, and related aviation services.
- **Delay:** A measure of the time required for an operation relative to an optimum (not scheduled) time, e.g., the difference between the estimated time of arrival (ETA) under optimum conditions, and the actual time of arrival (ATA).
- **Efficiency:** A measure of the impacts of system performance on direct operating costs from the perspective of a single flight.

An important concept is that delay by itself is not an adequate measure of how well the system is performing nor how well user needs are being met. Thus, using delay as a sole measure of NAS performance will underestimate the benefits of CNS/ATM improvements. Weather is a factor in each of these metrics to a greater or lesser degree, and it is important that the right data be collected to determine the impacts of weather on system performance.

3. FUNCTIONAL STRUCTURE OF THE AVIATION WEATHER SYSTEM

A functional structure of the ATM system that is based on the concept that system capacity is inextricably linked to separation standards is shown in **Figure 1** (Boeing, 1997b), along with a conceptual model showing how aviation weather information is mapped into the separation function. We have identified three areas where aviation weather information is needed, which are characterized by decreasing look-ahead times: **AOC and NAS Planning** (hours to 1–2 days), **Separation and Sequencing** (5–20+ minutes), and **Safety** (< 5 minutes). This paradigm is intended to capture both the current aviation weather system and future requirements that address the need for rational approaches to setting separation standards. The key findings to draw from Figure 1 include the following:

- The majority of the meteorological information that is required primarily affects system efficiency, capacity, and throughput. This is not

¹ See <http://www.boeing.com/commercial/caft>.

Aviation Weather Functional Structure

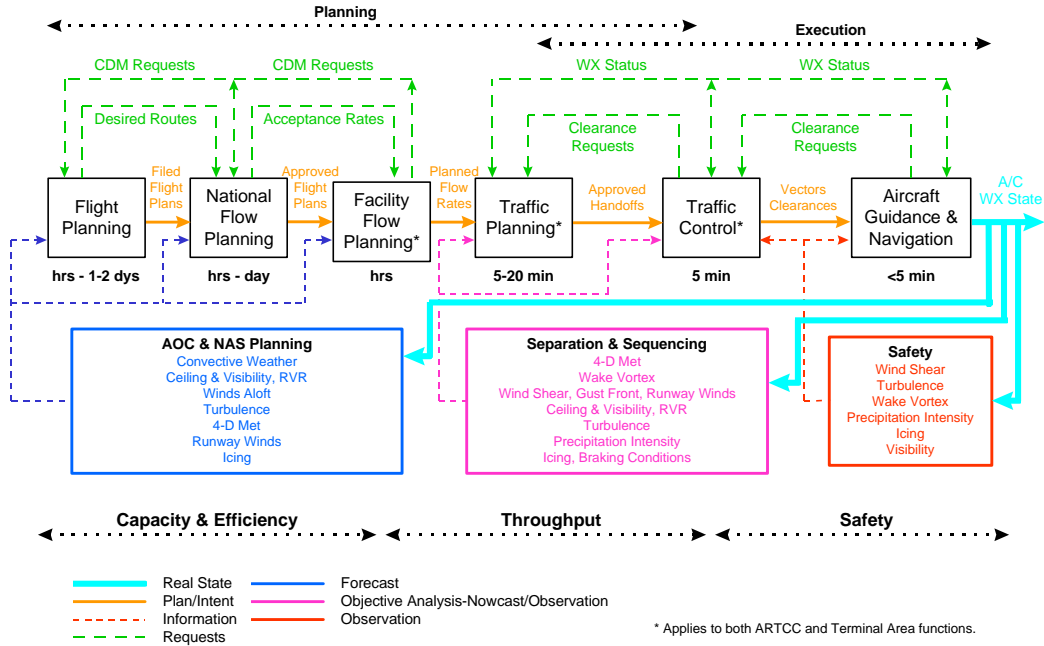


Figure 1. Functional structure of the aviation weather system.

to downplay the requirements for safety, but until an aircraft is about to encounter a potentially hazardous weather condition, the safety aspects of weather are part of the planning and separation and sequencing steps. These in turn are measured in terms of operational efficiency and throughput in the system.

- The AOC and NAS planning function affects system efficiency, and helps establish daily capacity in the NAS. This planning process relies almost exclusively on forecasts.
- The weather information generated in the separation and sequencing function affects system throughput. This function relies primarily on diagnostic analyses of observations and nowcasts. In today's aviation weather system, the focus is mainly on mitigating impacts when adverse weather is occurring (i.e., IMC conditions). In the mid- to far-term, with the advent of systems like CTAS and operational concepts like conflict probe, the focus will shift more to routine operational decisions regarding how to move aircraft through the system on a continuous basis, i.e., during Visual Meteorological Conditions (VMC) as well as IMC.
- The safety function relies almost exclusively on observations, which are made by both ground-

based and aircraft sensors. Quick detection of the threat with very low false alarm rates, and timely and meaningful dissemination of warnings to stakeholders are key requirements.

- The order in which meteorological information is presented in each functional area corresponds to a first cut on its priority to stakeholders.

When one examines the structure of the aviation weather system and the technologies that support it, it appears that the paradigm being used by stakeholders in the system for non-safety related constraints and requirements can be stated as follows:

- Weather is mainly an efficiency problem and economic costs created by delay (including diversions and cancellations) are the primary metric for tracking system performance.
- The benefits to be gained from investments in weather technologies that support tactical ATC operations (e.g., 20-30+ min. look-ahead times) are greater than those that can be realized from systems that provide information for use in the longer-term, strategic planning phases of flight operations.
- Most of the constraints take place in the terminal area, when adverse weather produces IMC flight conditions. Convective weather is the most

important source of delay and should be given the highest priority.

- A standardized, one-size-fits-all approach to technology development and deployment is best suited to meet system requirements.
- Transmitting graphical weather products to the cockpit will improve efficiency in the system, and will drive the requirements for datalink insofar as they are affected by the need to exchange weather information between the ground and the air.

While this paradigm contains elements that are largely correct, our findings lead us to propose a somewhat different paradigm for constraints and requirements related to efficiency and capacity:

- Weather impacts on system performance need to be tracked in terms of predictability, flexibility, user access, delay, efficiency. Using delay as the only metric of system performance underestimates the costs of weather constraints on NAS operations and the benefits to be gained from improved weather information.
- Constraints on efficiency and capacity due to weather arise during the AOC & NAS Planning function, because it is at this stage when key decisions are made regarding facility throughput and delay management. This leads to a high priority requirement for accurate forecasts of weather and winds on a region-by-region basis on time scales of 3-6+ hours, especially by the AOC's, that is not currently being met.
- Once aircraft are airborne, tactical weather information related to the Separation and Sequencing function and operations in the extended terminal area (e.g., within 200 nm. of the airport) is needed to maximize throughput. Two categories of weather information are needed to fulfill this requirement: 1) terminal area weather information, which the Integrated Terminal Weather System (ITWS) is designed to provide; and 2) four-dimensional gridded winds and temperatures to support the en route transition function, for which a requirement does not yet exist.
- Meteorological conditions affect NAS performance in all phases of flight operations. To increase system throughput, accurate knowledge of current and expected meteorological conditions during both IMC and VMC will be needed. This will be especially important in dense terminal airspace, where precision four-dimensional guidance and navigation may be used to help

reduce intervention rates and the spacing buffers that are added to basic separation standard. Developing methods that improve forecasts of ceiling and visibility should be a high priority requirement.

- There are significant local and seasonal differences in weather conditions (e.g., local wind systems, varying ceiling and visibility, frequency and intensity of convective weather) that can make regional (as opposed to national) weather forecasting solutions highly effective.
- Performance requirements (e.g., accuracy, uncertainty, resolution, availability) for aviation weather technologies and information have not been developed yet, and will be needed in the future to bound the performance of CNS/ATM tools and procedures applied to separation assurance functions.
- Requirements for 2-way exchanges between the aircraft and the ground of digital information on aircraft trajectories and meteorological conditions will be important for the successful implementation of new flow management functions and aircraft navigation and guidance capability. This may prove to be an important driver of the requirements for datalink capabilities.

4. SUMMARY OF KEY FINDINGS

The primary finding from the Boeing study can be stated as follows: *improved weather information is a critical element for increasing capacity in the National Airspace System.* This conclusion may seem overly simplistic, but the fact is that we have found that requirements do not yet exist for aviation weather information and technologies aimed at meeting demands for future traffic growth. Historically the primary requirement driving the development of the aviation weather system infrastructure has been safety, but technologies aimed at improving safety are not sufficient to meet requirements for increasing capacity (or improving efficiency). As a result, requirements for aviation weather information have not been successfully linked to economic benefits generated by increased capacity. With this conclusion as our primary working premise, **Table 1** presents a brief, prioritized synopsis of the key findings from the study, and indicates the ATM system performance metrics that apply to each area.

A first step to develop requirements for aviation weather information is to develop a comprehensive baseline of the current "as is" state of the system vis-

Table 1. Summary of the key findings from the Boeing Aviation Weather Study, based on the premise that improved weather information will be needed to increase capacity.

Rank	Finding	ATM System Performance Metrics
1.	A comprehensive baseline is needed that describes the “as is” state of operations in the NAS today with respect to weather constraints on capacity and efficiency.	Predictability Flexibility Access Efficiency Delay
2.	Weather information is needed in three functional areas to increase capacity and improve efficiency (look-ahead times are in parentheses): <ul style="list-style-type: none"> • AOC & NAS Planning (hrs to ½-1 day) • Separation & Sequencing (5-20 min.) • Safety (<5 min.) 	Predictability Flexibility Access Efficiency Delay
3.	To increase capacity and improve throughput, better weather information is needed in the planning phases of AOC & NAS operations. Improved forecasts of ceiling and visibility conditions is a high priority requirement that is not currently receiving enough attention. Better forecasts of expected convective activity continues to be an important requirement. Regional (as opposed to national) weather forecasting systems can be highly effective.	Predictability Flexibility Delay Efficiency
4.	Performance requirements (e.g., accuracy, uncertainty, and availability) are needed for 4-D gridded meteorological information.	Flexibility Access
5.	Meteorological conditions strongly influence wake vortex decay and transport. Additional research is needed to characterize atmospheric conditions that affect vortex behavior.	Predictability Access Flexibility
6.	The two-way exchange of weather information between the aircraft and the ground will likely become more important as the NAS evolves to accommodate increased traffic.	Flexibility Efficiency Delay
7.	Real-time weather information is needed in the extended terminal area (e.g., 150-200 nm.) to improve throughput during both IMC and VMC.	Efficiency Delay
8.	Better methods are needed to predict, detect, and avoid clear air turbulence.	Flexibility Efficiency
9.	More upper-air observations may be needed to help meet requirements for the accuracy of forecasts and nowcasts.	Predictability Flexibility Access
10.	Airlines want flexible weather avoidance methods in exchange for their investments in improved weather information systems.	Flexibility Efficiency

a-vis weather impacts on air carrier operations. Such a baseline would describe, for example, the amount of delay (including diversions and cancellations) attributable to weather as a function of weather condition, location, time, and system demand.

An important finding from the present study is that this baseline does not yet exist. Likewise, good

economic data and analyses of the costs of weather in the ATM system are also not available. The studies that have been conducted to date were informative but were judged insufficient for developing requirements for future aviation weather systems. Part of the problem is that delay data are not kept in any systematic way in the NAS for delays of less than

15 minutes duration. This makes it difficult to track economic consequences and to monitor efficiency and throughput in the system. A high priority recommendation from this study is that such baseline information should be developed to ensure that effective decisions are made on investments in the aviation weather system. Without this baseline, future developments of the NAS infrastructure will be made without appropriate requirements for weather information to meet demands for increased traffic flows and improved efficiency. It is possible, indeed likely, that the findings from this study will change once such a baseline is developed. With this in mind, the key conclusions and recommendations from the study are summarized below:

- Changes in the aviation weather system in the next 15-20 years will be evolutionary, not revolutionary. There are no “silver bullets” on the horizon that will significantly improve forecast accuracy overnight or rapidly fill holes in current observing networks. There are, however, requirements for aviation weather information that have not been identified or fully defined in the NAS architecture, but which could probably be met with reasonable development efforts. Among these are the development of high resolution regional-scale forecasting systems. Such systems may be needed to resolve local processes that influence ceiling and visibility conditions and the initiation and decay of convective activity, and to produce four-dimensional gridded meteorological data with the accuracy and specified uncertainty needed to satisfy performance requirements for trajectory synthesis.
- To increase capacity and improve throughput, better weather information is needed in the planning phases of AOC & NAS operations. Improving forecasts of ceiling and visibility conditions is a high priority requirement that is not currently being satisfied. Better forecasts of convective activity continues to be an important requirement. As noted above, there are significant local and seasonal differences that can make regional-scale forecasting systems (as opposed to national systems) highly effective in this regard.
- Increasing system capacity by safely reducing separations implies that access to the system will be performance based. For weather, this will lead to new requirements for the performance of both ground-based and airborne systems that generate and/or use weather data. One of these requirements will likely involve augmenting weather information, especially forecast data, with

measures of the uncertainty or reliability of the information (e.g., 95 percent confidence limits).

- Meteorological conditions, especially vertical distributions of winds, temperature, and turbulence, play an important role in the rate of dissipation of wake vortex circulations and in the transport of vortices near the ground. Present wake separation requirements that are based only on aircraft type and weight can be conservative and reduce throughput during IFR conditions. Additional research is needed to develop requirements for meteorological information to support wake turbulence separation criteria.
- Weather is not “easy.” Stakeholders need to be realistic on the level of performance that can be achieved and the costs to do so. A reasonable goal may be to define the amount of uncertainty that is minimally acceptable (e.g., ± 1 hr. error in forecasts of changes in ceiling height or visibility conditions), and to estimate the cost to achieve this degree of performance.

5. REFERENCES

- Boeing (1997a). 1997 Current Market Outlook, Seattle, WA, March.
- Boeing (1997b). Air Traffic Management Concept Baseline Definition. NEXTOR Report # RR-97-3, Seattle, WA, October 31.
- Chew R. (1997). Free Flight - Preserving Airline Opportunity. Presented at C/AFT Meeting, March 19-20, Seattle, WA.
- Crandall R.L. (1995). The unique U.S. airline industry. In Handbook of Airline Economics, First Ed., D. Jenkins, ed., Aviation Week Group, McGraw-Hill Companies.
- Evans J. (1995). Measuring the economic value of aviation meteorological products. 14th Conference on Weather Analysis and Forecasting, Dallas, TX, Jan. 15-20.
- NRC (1995). Aviation Weather Services, a Call for Federal Leadership and Action. National Research Council. Washington DC.

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