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# THE FUTURE NATIONAL AIRSPACE SYSTEM: DESIGN REQUIREMENTS IMPOSED BY WEATHER CONSTRAINTS

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## Abstract

In this paper, we present design requirements for the future National Airspace System (NAS) focusing on the most fundamental constraint imposed on this system – namely, the effects of weather. We begin by performing a problem-space analysis in order to classify weather related problems across NAS domains: surface, terminal, and en route. We then identify a set of core ideas that address many of the weather constraints in these domains. The core ideas include flexible traffic management, coupled traffic and weather prediction, and human factors issues that relate to establishing and maintaining common situation awareness between the various decision makers in the NAS. From these core ideas, we discuss a set of functional requirements for the future NAS to enable it to be more robust to the impact of weather and its uncertainty on capacity.

## Introduction

Weather is a major limiting factor in the NAS today, accounting for roughly 70% of all traffic delays[1]. In recent years, a significant increase in the number of weather-related delays has occurred, particularly during the convective weather season (mid-May through mid-September), as indicated in **Figure 1**. Because we cannot control the weather and because safety must be maintained in the presence of weather-related hazards, our ability to predict the weather and its influence on capacity is critical towards designing the future NAS.

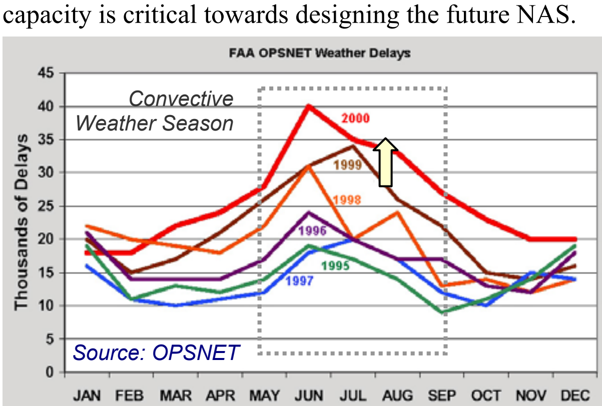



**Figure 1:** Yearly weather-related delay data highlighting the trend toward increased delays during the convective weather season.

As presented in **Table 1**, hazardous weather events such as convective weather (e.g., lightning, tornados, turbulence, icing, hail, etc.), extreme weather (hurricanes, blizzards), low visibility (fog, haze, clouds), clear air turbulence, snow (including snow removal from runways and aircraft de-icing), and wind shifts/wind shear (affecting safe takeoff and landing) pose challenges to the NAS on a nearly daily basis. As indicated in **Figure 2**, which compares the number of weather and non-weather related delays in 2000, every day is different with a wide variety of weather effects impacting the NAS. Something as simple as wet runways can cause a major airport (e.g., Chicago O'Hare) to lower its Airport Arrival Rate (AAR) due to the reduced ability of aircraft to brake during landing.

Because Traffic Flow Management (TFM) and airline scheduling are interconnected across the NAS, such impacts are not isolated to individual aircraft in weather-prone areas. Rather, since delays at one point tend to naturally ripple through the NAS, weather-related impacts at one location can propagate to affect a significantly larger portion of the NAS. An obvious example of this is the current use of Ground Delay Programs (GDPs) in which aircraft at various origin airports are held on the ground due to constraints expected in the future at a destination airport.

TFM technology, procedures, and systems provide a structured and strategic way to smooth demand and maintain flows ahead of time, minimizing the extent of control and maintaining organized flows through constrained resources. However, in the absence of perfect weather and demand predictions, the current system often must resort to tactical reactions (e.g., excessive airborne holding and/or rerouting) resulting in excessive workload on controllers and pilots alike.

The realizable capacity of the NAS is ultimately limited to its ability to accommodate safe and efficient travel under *all* weather conditions across all domains (surface, terminal area, and en route). The key to greater capacity in the NAS lies in our ability to accurately predict and adjust the future state of NAS traffic in concert with predictions related to weather and its effects on aircraft, flight routes, and airport surfaces. Further, these actions must take place on a timescale consistent with critical NAS response times.

**Table 1.** Aviation Weather Hazards.

| Phenomena | Risk to Pilot/Passengers and/or Aircraft |
|---|---|
| Fog/Haze/Smoke | Visibility hazard; Pilot has difficulty with landing, taxi, or take off. |
| Clouds | Visibility hazard; Pilots not trained to fly according to Instrument Flight Rules (IFR) may become disoriented, possibly leading to loss of control. |
| Thunderstorms | Hazards associated with thunderstorms include: lightning, hail, heavy rain, wind gusts, microbursts, CIT, tornadoes, waterspouts, and icing. See below for the effects of these. |
| Hurricane | Hurricanes combine the hazards of gusts, strong winds, and heavy rain. Problems associated with severe convection (turbulence, tornadoes, etc.) occur over a wide-spread area. |
| Lightning | Could temporarily blind a pilot; Can cause physical damage to airframe or avionics. |
| Hail | Causes physical damage to the windshield, wing leading edges, and other aircraft surfaces. Physical damage could lead to loss of control of aircraft. Could cause physical damage to aircraft while parked or taxiing. Not much of a visibility hazard. |
| Heavy Rain | Associated mainly with thunderstorms, but could also come from stratiform clouds. Could be a visibility hazard for the pilot. Could degrade engine performance for jets. Could cause flooding at airports or cause hydroplaning during landing or take off. Also has a minor impact on aerodynamics performance (loss of lift). |
| Icing (Clear, Rime, or Mixed) / Graupel / Sleet | Degrades aerodynamics performance causing loss of climb or possibly tail instability. The stall speed increases, the lift decreases, and the drag increases - an airplane flies contrary to pilot expectations. Some jet engines cannot tolerate a lot of ice crystals – engine flame out is possible. Ice particles can clog engine filters. Blocks of ice on leading edges of wings can break off and enter a tail mounted engine. Intermittent icing may be associated with thunderstorms and convection and continuous icing may be associated with stratiform clouds. When associated with convection, icing adds to the risks associated with thunderstorms and with stratiform or continuous icing, it adds to the risks associated with reduced visibility. |
| Wind Shifts | A sustained change in the wind, which again can cause problems during takeoff and landing if the runway configuration/take off direction is not adequately addressed. |
| Wind Gusts | A quick change in the wind speed and/or direction. Can cause control problems during takeoff or landing. Gusts at take off quickly degrade aerodynamics and can cause fatal accidents. |
| Jet Stream | Turbulence regions may exist near jet stream boundaries. |
| Convective Induced Turbulence (CIT) | CIT is caused by the instability and resulting up and down drafts. Could physically damage the aircraft if strong enough. Even light turbulence causes passenger discomfort. Extreme turbulence could cause physical injuries to pilot/passengers who are not wearing seat belts. |
| Clear Air Turbulence (CAT) | CAT could damage aircraft if strong enough. Even light turbulence causes passenger dis-comfort. Extreme turbulence could cause physical injuries to pilot/passengers not wearing seat belts. Generally caused by wind shear in the atmosphere where no clouds are present. |
| Mountain Waves | Fast changes in vertical wind velocity, eddy currents, and rotors could cause turbulence or shifts in wind that greatly affect aircraft aerodynamics. Frequently results in moderate or greater turbulence. Could lead to loss of aircraft control or at the extreme, structural failure. |
| Microburst / Wind Shear | Wind shear is dangerous to aerodynamics and can cause loss of control or uncontrolled impact with the earth. Microbursts are a specific kind of wind shear which results in an increase in performance, a downdraft and a strong decrease in performance, possibly leading to loss of control and uncontrolled impact with the earth. |
| Tornado / Waterspout | High vorticity wind conditions associated with the tornado / waterspout are very dangerous. Very difficult to control the aircraft potentially leading to loss of aircraft. Wind and/or flying debris can damage or destroy aircraft on the ground (even if tied down or in hangers). |
| Snow | Could be a visibility hazard (white out) for the pilot, possibly causing loss of control. Likely (possibly) to be coupled with icing. If snow on the aircraft is not removed before take off, could degrade aerodynamics performance. Snow/ice on runways could cause an aircraft to slide off the runway during landing, taxi, or take off. |
| Blizzard | Blizzards combine the hazards of wind gusts, icing, and heavy snowfall. Reduced visibility may adversely affect the pilot. |
| Volcanic Ash | Visibility hazard if near the eruption. Could damage engine parts leading to flame out and scratch/pit wind shield leading to loss of visibility for pilot. Encounters with volcanic ash can destroy the airplane even if landed safely. |

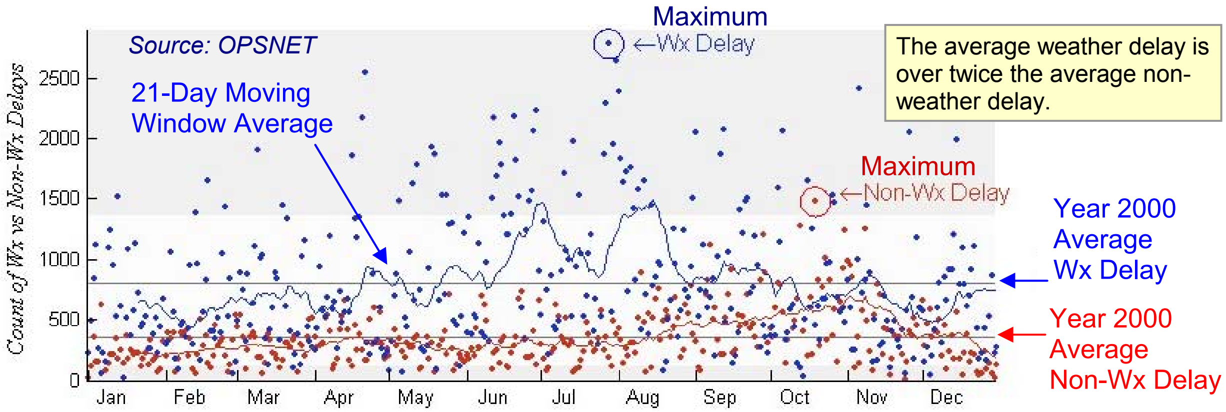



**Figure 2.** Every Day is Different – Weather vs. Non- Weather Related Delays in 2000.

A number of efforts by the FAA, NASA, RTCA and private industry have been targeted toward the development of future Concepts of Operation for the NAS. These include the FAA's Operational Evolution Plan[2] (OEP), Free Flight Concept[3], and NAS Architecture[4] v4.0, NASA's Distributed Air/Ground Traffic Management Concept[5], the RTCA NAS Concept of Operations[6,7], and the Boeing capacity-driven concept[8]. Each of these efforts provides different levels of detail regarding aspects of the future NAS ranging from information infrastructure to TFM to sensor and navigation requirements. However, all of these concepts will be limited in their impact on increasing NAS capacity if weather remains the critical constraint. Accordingly, our focus is on adding to the concept of operations for the future NAS, regardless of which evolutionary path it might take, such that it is more robust to the effects of weather as compared to the current NAS.

In this paper, we begin by describing a number of classes of weather-related problems that impact the efficiency of current NAS operations. In doing so, we highlight not only significant weather effects, but their primary impacts on NAS operations. We then present a number of ideas which address these root causes, leading to the specification of functional requirements for a future NAS. These requirements lead to a NAS that is more robust to uncertainty and more capable of maintaining throughput (which is lost today due to various inefficiencies) during weather constraints. Finally, we present some enabling technologies which may address the specified functionality.

## Weather Related Problem Situations in the NAS

Our "All Weather Concept of Operations" has been motivated by analyzing a series of problem situations that exist in the current NAS. This analysis leads to the development of guidelines for new operational procedures, roles and responsibilities, and/or Decision Support Tools (DSTs). The problem space of interest is defined by the "cross product" between the types of weather "problem situations" and the operational domains, as illustrated in **Figure 3**. We define the NAS operational domains as:

- Surface – Areas involved with gate operations, taxiways, and runways, including "non-movement" areas, which may be gate areas where non-Air Traffic Control[9,10,11] (non-ATC) service providers perform gate and ramp operations;
- Terminal Airspace – Terminal airspace is the area delegated by the ARTCCs to the Terminal Radar Approach Control (TRACON) for the provision of approach and departure sequencing, typically within the range of a "fast-sweep" radar sensor (around 40 to 60 miles). Note that sometimes ARTCCs provide approach control services to non-TRACON equipped airports, but this is generally not the case for busier airports;
- En Route Airspace – En route airspace controls the traffic between terminals, where aircraft are in cruise or transitional (climbing out or descending into airports) phases of flight.

Note that the impact of particular weather "problem situations" in a given domain is often the imposition of additional constraints on neighboring domains. To address this, we consider problems which span both small and large spatial extents as well as with different look-ahead time requirements for TFM initiatives. Finally, we do not claim to have identified all possible problem situations; however, we have focused on many of the most frequent or most severe capacity-limiting problem situations.

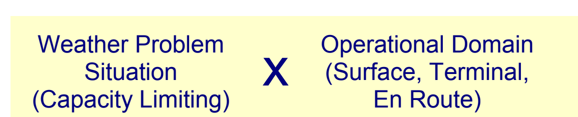



**Figure 3:** The trade space for the exploration of Core Ideas.

**Weather Adversely Affecting Airport Surfaces**

The following examples describe surface problem situations in which weather in the terminal area adversely affects the capacity of an airport. In each example, we describe not only the weather event, but also the impact that it has on conditions in the NAS.

Each of the problem situations described below can have purely local (isolated) effects or both local and global (propagating) effects. As an example of the latter, note the pivotal role that San Francisco International Airport (SFO), a non-hub airport, plays in the hub-and-spoke operations of several airlines. When low visibility conditions are present at SFO, as is common in the case of morning fog (marine layer), arrival and departure delays propagate to cause en-route congestion that affects other air sectors and airports as well. When problems occur simultaneously at the nearby Oakland and/or San Jose airports, or at other airports with departures to SFO, the problems are compounded.

Surface Situation 1: Shifting Wind Direction Changes the Runway Configuration

A sudden change in runway configuration due to unpredicted or poorly predicted changes in wind direction (and/or the presence of wind shear or micro-burst warnings) results in high workload and added delays while aircraft are re-routed to new arrival fixes and runways. This may also result in a runway configuration selection that is non-optimal for the current conditions and traffic complexity, in which case, additional arrival and departure delays may occur. Such a situation can occur when the ATC tower tries to predict likely future conditions, picking a runway configuration that is less sensitive to wind shifts – potentially at the expense of throughput in the event that the weather event doesn't actually materialize. Generally, the impacts of such events on NAS operations include:

- Wind direction is such that it requires a configuration change
- If timing of wind shift is not predicted properly, then aircraft currently in queue for a now inactive runway need to be taxied to an active runway
- Aircraft still at gates will need to be assigned to different runways
- Aircraft on final approach may need to execute a missed approach procedure
- Aircraft outside of arrival metering fixes must be re-routed to new fixes
- Departures using the new configuration must wait until terminal airspace has "stabilized" (e.g., remaining arrivals clear of departure corridors).

The impact on capacity varies depending on the condition. In general, a runway configuration change adds delay to both arrivals and departures, reducing capacity during the transition. However, the steady state effect of a change in configuration may be to increase, decrease, or leave unchanged the achievable arrival and departure rates at a given airport.

Surface Situation 2: Low Visibility

Reductions in visibility and Runway Visual Range (RVR) due to fog, haze, snow, etc. negatively impact surface operations in the NAS in many ways, including:

- Ground and Local Controllers unable to discern exact positions of aircraft (see **Figure 4**)
- Controllers cannot discern the order of flights in a queue at the runway or spot location
- Increased separations are required between aircraft to maintain safety as relative distances are hard to monitor
- Runway crossing is more difficult as it relies on controller visual judgment of gaps
- Pilots ability to see airport signage and pavement markings is significantly reduced, leading to a reduction in awareness of actual surface position
- Pilots have more difficulty seeing other aircraft or knowing their exact position in a queue
- Controllers must often rely on pilot-reported positions, which may be in error
- Inability to conduct closely spaced (or parallel) approaches.

The impacts on capacity are as follows. Pilot uncertainties regarding position lead to a reduced taxi speed; simultaneously, controller uncertainty regarding aircraft position results in increased runway crossing times and thus taxi delays. Surface movement inefficiency "backs up" to the runways, reducing both AAR and ADR (Airport Departure Rate). Elimination of closely-spaced parallel approaches, common during low visibility, further lowers the AAR.

**Figure 4:** High and low visibility conditions recorded from a control tower (Sacramento International Airport).

Surface Situation 3: Aircraft Requiring De-icing

De-icing (e.g., **Figure 5**) is a cumbersome procedure requiring time, equipment, de-icing fluid, and personnel that impacts capacity in terms of departure rates. Ice accumulation on aircraft wings and control surfaces must be removed. The extent of the capacity reduction depends, in a large part, on the availability of equipment and personnel and the location of the de-icing pads relative to the gates and runways (some airports de-ice at the gates, while others use a remote de-icing pad). Once aircraft are de-iced, they must takeoff within a given time period (typically 15 minutes) or be re-treated. The impact on capacity is primarily related to the time consumed by the de-icing process, namely any additional taxi time to/from remote de-icing pads plus the service time required to apply the de-icing treatment. This impact manifests itself as departure delays – the extent of which is determined by the efficiency of the process. Note that since passengers on commercial flights expect flights to be boarded as scheduled, there is little opportunity for airlines to board aircraft early to "make up" for the time needed for de-icing (assuming it could be predicted). An indirect capacity impact is related to the need to expedite the departures for aircraft which have been de-iced to avoid the need for re-treatment – which can impact the required inter-arrival spacing on mixed use runways.

**Figure 5:** De-icing operations increase the time required between flights and reduce airport capacity (Detroit International Airport).

Surface Situation 4: Snow, Ice, Slush, Water on Runway

Slick conditions on the airport surfaces can reduce aircraft braking and directional control. Complicating the situation is the fact that braking conditions are not necessarily the same on all parts of a runway, due to its length. Impacts of this problem on NAS surface operations include:

- Increased runway occupancy time as aircraft must rollout to the last runway exit
- Ceasing of Land and Hold Short Operations (LAHSO)
- Some shorter runways may not be usable
- Temporary runway closure due to the need for removal of accumulated snow, and
- Impaired visibility of surface pavement markings and lighting from the flight deck.

The impacts on capacity are as follows. A reduction in options of runway exits impacts taxi routing flexibility, potentially leading to arrival taxi delays (or at least increased taxi times) and possible surface congestion. With an increase in runway occupancy time, there will be a corresponding AAR reduction due to the need for increased inter-arrival spacing. This reduction is exacerbated by the closure of runways for snow removal and when certain runways are unusable due to poor braking action. The inability to utilize LAHSO procedures further impacts capacity by limiting the ability of controllers to coordinate operations between dependent runways.

## Weather in the Terminal (or Transition) Airspace

The following problem situations describe weather constraints that partially or completely limit capacity in a portion of the terminal (or transition) airspace.

Terminal Situation 1: Convective Weather Cells Affecting Arrival or Departure Streams

The direct arrival route to an arrival fix can often be obstructed by convective weather (e.g., **Figure 6**). To mitigate this problem, current NAS procedures allow pilot requests to deviate aircraft around weather. This procedure is followed assuming the controller sees that the cell is small enough that deviations will remain within the arrival airspace sector and will not impact departing aircraft in neighboring sectors. If a large weather cell or multiple weather cells pass by the arrival and departure flows streams in a way that both arrivals and departures are affected simultaneously, then the TFM problem is coupled. Usually, there is a preference given to the arrivals to make their way through the weather while the departures are put in a ground hold (introducing departure delays). This is the case when arrivals have to pass through airspace that is typically reserved for departures. It does not take much airspace complexity before the arrival fix is shut down.

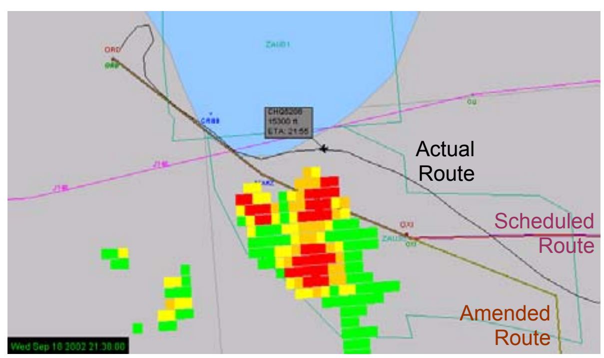



**Figure 6:** A weather cell affects the arrival traffic causing an aircraft to request a pilot deviation due to weather (Chicago O'Hare International Airport, 9/18/02).

The impacts on NAS operations include:

- Weather avoidance deviations impact the time at which flights will cross arrival metering fixes introducing arrival delays and adding complexity and uncertainty to the sequencing and spacing of arrivals to runways.

- If departures are put into ground holding, then departure delays are introduced.
- If the arrivals cannot get through, then they may be temporarily put into airborne holding – which can have the effect of propagating upstream to the ARTCC as airborne holding stacks fill up.
- If departures are favored because there is a need to release aircraft from the airport (e.g., to prevent gridlock), then arrivals are put into airborne holding or re-routed to another corner-post.
- Diversions to alternate airports must be performed if necessary.

The impact on capacity is primarily related to the delays (arrival and departure) introduced by weather avoidance maneuvering.

Terminal Situation 2: Weather Constraints Initiating Arrival/Departure Strategic Trade-offs (30-60 Minute Lead Time for Planning)

When there is sufficient lead time ahead of a weather constraint, for instance 30 to 60 minutes, there is a need to act upon user priorities regarding different arriving and departing flights, and to increase throughput by making better use of capacity that is often unused in the current NAS during such situations. In these cases, there is sufficient time to plan a solution and to re-route aircraft with corner-post swaps, tunneling maneuvers, and other plans. The impacts on NAS operations are as follows:

- With sufficient time to plan, departure aircraft do not have to hold for arrivals; weather avoidance may be accomplished by using different departure fixes and tunneling maneuvers to allow departure aircraft to tunnel under weather constraints and arrival flows.
- Corner-posts may be temporarily re-assigned for arrivals to better accommodate the situation.
- Some aircraft will be put into circular holding to build up a buffer while corner-post swaps are used to re-allocate the arrival demand.
- Diversions to alternate airports must be performed if necessary.

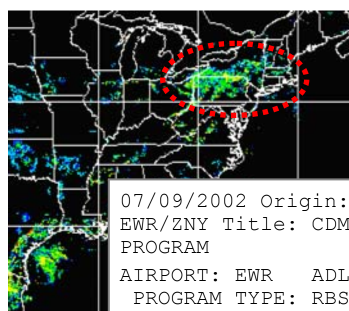
The impact on capacity is primarily related to the delays (arrival and departure) introduced by refueling for departure fix changes and tunneling maneuvers (if required), weather avoidance maneuvers, and delays caused by the above traffic management initiatives.

Terminal Situation 3: Weather Constraints Impact Arrival Airspace Capacity (1-4 Hr. Horizon)

Weather may impact the terminal airspace for an airport (or the airport surface) and reduce but not prohibit arrivals. As indicated by the excerpt from an Air Traffic Control System Command Center (ATCSCC) log in **Figure 7**, a GDP may then be initiated in order to control the arrival flow. While the GDP is intended to reduce the number of flights arriving at the airport in a given time period, it may also indirectly reduce en route traffic in a region impacted by weather that is near that airport. While a GDP allows flights to be swapped within an airline or across airlines in order to fill the available arrival slots with the most "valuable" flights, a GDP may not be very precise in its impact – due in large part to uncertainties in estimating en route times. As the weather in **Figure 7** illustrates, controlling arrivals by setting an overall AAR to deal with en route or terminal area weather may be imprecise. In this case, routes from the South do not appear to be directly impacted by weather, but are included within the scope of the GDP, likely as a means of limiting flow through the airspace and providing maximum flexibility for re-routing of impacted flows around the weather. The impacts on NAS operations are as follows:

- GDPs may adversely impact aircraft that are not at all affected by the weather
- GDPs may cause cancellations of aircraft that are not allocated a time of departure within the acceptable schedule limitations of the airlines
- GDPs may hold aircraft on the ground hours prior to the weather event; with imprecise strategic weather predictions; this does not allow airline users the option to take off and be ready to land if the weather does not fully materialize.

The impact on capacity is highly dependent on the accuracy of long-term weather forecasts. In the absence of accurate long-term weather forecasts, a conservative approach is taken today and cancellations and delayed flights translate into lost capacity.



07/09/2002 Origin: ATCSCC Facid: EWR/ZNY Title: CDM GROUND DELAY PROGRAM
AIRPORT: EWR   ADL TIME: 15:47Z
PROGRAM TYPE: RBS PP
ARRIVALS ESTIMATED FOR: 091800Z - 100159Z   PROGRAM AAR: 37
ALL CENTERS ARE INCLUDED IN THE PROGRAM.  EXEMPTED AIRPORTS: NONE
MAXIMUM DELAY:87 AVERAGE DELAY:42
REASON:WEATHER,SUPPORT OF SWAP

**Figure 7:** Weather impacting flights into EWR from the West, but not from the South (7/9/02).

## En Route Weather Constraints

The following problem situations describe how weather activity in en route airspace may adversely affect capacity.

En Route Situation 1: Unanticipated Clear Air Turbulence (CAT) or Icing

Small pockets of CAT or icing may appear over a major jet route without warning on a controller's radar. Predicting CAT or icing conditions today is very difficult. In this situation, the sector controller relies on Pilot Reports (PIREPs) to identify impassable airspace. PIREPs may vary with respect to the severity of the CAT and the physical profile of the constraint region may be changing quickly. Therefore, it is difficult for controllers to apply the same control to all aircraft passing over the same region. Controllers may add large safety margins to the weather constraint region to account for the uncertainties. Since major flows of aircraft are often spaced tightly to achieve maximum throughput, the flow of traffic behind the deviating aircraft must be spaced to accommodate a re-joining of that aircraft back into the stream. The impacts on NAS operations are as follows:

- Airspace complexity increases as adjacent flows of traffic may be affected by deviations
- Added controller workload to handle pilot deviation requests and insure flow separation
- Variation in pilot requests to deviate around turbulence (topside, bottomside, left, or right). This results in a wide band of tightly spaced traffic whose aircraft must adjust speed to allow for deviations and maintain integrity of the flow.

The impact on capacity is primarily related to the inefficient use of airspace. Frequent altitude changes used to avoid CAT may saturate flight levels clear of CAT and thus reduce the effective capacity of the impacted airspace.

En Route Situation 2: Convective Weather, High Tops

Localized convective weather may materialize as a cluster of convective weather cells and block a primary jet route. Consider when the weather reaches tops high enough that aircraft cannot climb over. Aircraft are forced around the weather and must be shifted from one jet route to another. There are certain fixes at which this route changes can occur based on the NAS jet route intersections. When the weather is not forecasted accurately (e.g., when the Collaborative Convective Weather Forecast Product (CCFP) forecast is in error), the opportunity to change jet routes may pass. The impacts on NAS operations are as follows:

- Congestion along jet routes clear of the weather constraints may saturate the airspace nearest the constraint, causing higher complexity to such airspaces and higher workload for controllers
- Jet routes may be shut down
- Delays result from re-routes around weather.

The impact on capacity is primarily related to inefficient routing. A missed opportunity to change jet routes from one that is impacted by convective weather can result in flow-reduction measures such as Miles-in-Trail (MIT) restrictions, En Route Spacing Programs (ESPs), or Ground Stops (GS), each of which reduces en route capacity.

En Route Situation 3: Multiple Clusters of Weather Cells within the Same Center

Localized convective weather often appears in discontinuous patches, blocking a wide region of airspace but providing narrow corridors through which aircraft could possibly pass (e.g., **Figure 8**). When these corridors are still passable by aircraft, controllers must maintain sufficient clearance between aircraft to allow them the ability to deviate around moving hazardous weather without conflict with nearby flows. Due to the dynamics of weather, air traffic controllers, dispatchers, and pilots must watch carefully to avoid new weather cells, and anticipate weather cell growth/decay rates. The relatively fast (and difficult to predict) nature of convective weather dynamics make this a particularly challenging problem. Controllers monitor PIREPs to determine the severity of turbulence and icing conditions in the corridor. The impacts on NAS operations are as follows:

- Congestion grows along the routes within and upstream of weather impacted airspaces.
- With imprecise weather forecasts, some traffic must be tactically re-routed due to unpredicted convective weather while other routes temporarily shut down will be reopened because the predicted weather did not persist.
- Delays result from MIT restrictions imposed on weather impacted jet routes and re-routes around weather constraints.

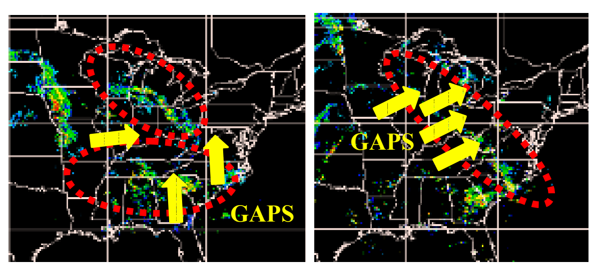



**Figure 8:** Dispersed weather with gaps between hazardous weather cells.

The impact on capacity is, as with the previous problem situation, primarily related to inefficient routing. Controllers keep the risk of conflict to a minimum by controlling the number of aircraft in the corridor, typically, with very high MIT restrictions which has an obvious negative impact on throughput.

En Route Situation 4: Large Impassable Lines of Weather from Canada to the South

Consider data from an actual occurrence, as in **Figure 9**, for a front extending from Canada south into Texas is expected to close East-West routes for 6 hours, forcing East-West traffic to be moved south into ZHU. The front is expected to impact the East corner-posts at DFW, thereby also impacting arrivals and departures at DFW and DAL airports. The likelihood that the front will be solid from Canada to Texas is judged to be moderate (40-60%). There is a modest chance that the front will develop holes in the line down in ZFW that will allow flights to cross East-West. The implication of this prediction is that, in addition to the obvious disruptions of all East-West traffic and ZFW arrivals and departures, if a solid front does develop from Canada to ZFW, then overflights will have to be moved through ZHU airspace, potentially impacting departures from ZHU airports. The impacts on NAS operations are as follows:

- Congestion along playbook play routes is extreme due to the limited number of re-route solutions available with very large weather constraints.
- Diversions may result at airports that did not have GSs or GDPs in place due to lack of accurate weather forecasting.
- Significant delays result from re-routes around weather constraints.
- Significant cancellations may result due to lost connections from delays.

The impact on capacity is affected by the inability to predict long term weather constraints, making it difficult to thin the overstream traffic and ZFW arrivals appropriately).

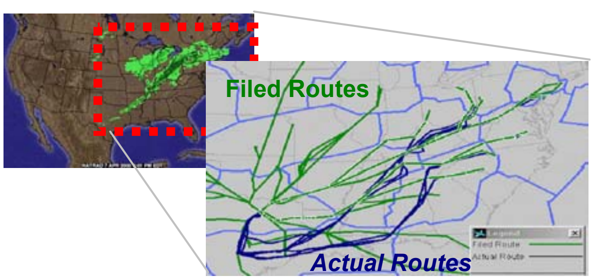



**Figure 9: A large weather system extends across the Midwest causing major re-routes.**

**Other En Route Weather Problem Situations**

Additional classes of en route weather-related problems include the following:

- Icing conditions may cause difficulty for smaller aircraft (e.g., General Aviation (GA)) that do not have the equipment to invoke anti-icing en route. With unequipped aircraft, icing regions need to be avoided, and thus, the aircraft may need to be re-routed, causing a less efficient flow en route.
- In addition to turbulence regions existing nearby jet streams, extremely strong jet streams cause problems with airline schedule integrity since aircraft flying with the jet stream will be early and those flying against the jet stream will be delayed. This can cause a breakdown of hub and spoke connectivity. In the worst case, some flight arrive late causing missed connections or cancellations.
- In another weather effect, hurricanes and tropical storms may cause large portions of the NAS to be subject to large areas of convective weather and large quantities of rain which may cause flooding. Airports in the affected region are expected to have large numbers of cancellations and re-routes around the weather system may be expected for several days until the storm system dissipates.
- Finally, volcanic ash, while not occurring very frequently in the NAS, can cause major capacity problems as it is hazardous to fly through and blocks off very large regions of airspace, thus, reducing en route capacity. The extent and intensity of ash distribution is influenced by winds.

Furthermore, additional problem situations may exist that have not been discussed in this brief summary.

**Core Ideas for Increasing Capacity**

Our analysis of the aforementioned classes of problems across the various domains of the NAS has led to the development of a number of "Core Ideas", illustrated in **Figure 10**, that we feel are important in shaping the future NAS. These core ideas represent the changes in philosophy or approach to operations required in order to build in the desired robustness to weather and its uncertainty.

Core Idea 1: Flexible Traffic Management Around Weather Constraints

This core idea identifies control techniques for managing traffic through and around weather. The concept is to optimize flow around hazardous weather constraints given uncertainty in the nature (extent, penetrability) of these constraints. These control techniques span across all domains and cover all time-horizons of control ranging from long-term strategic planning to short-term tactical reaction. The goal is to identify flexible control methods and procedures that strive for clear weather throughput during all-weather conditions. Functions proposed to achieve this objective include:

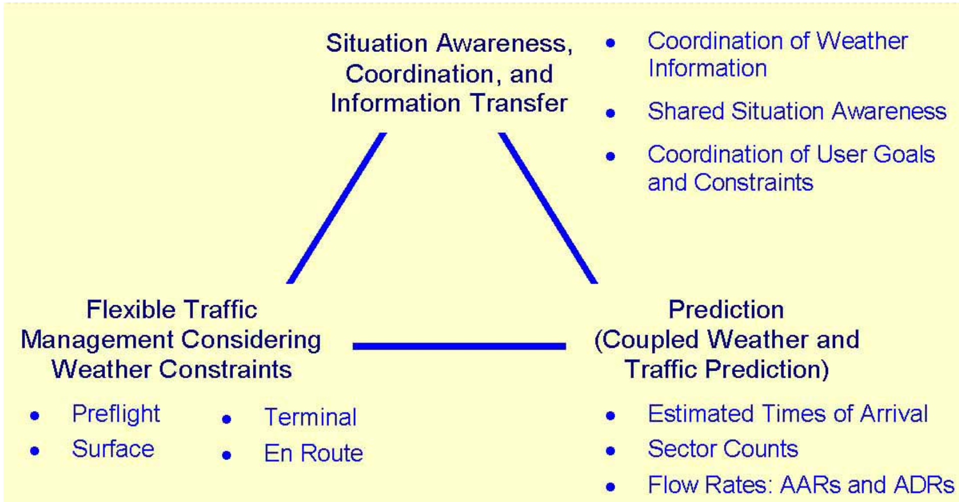



**Figure 10:** The "Core Idea Triad".

- Pre-Flight Planning – Strategic adjustment of demand in the NAS is required to mitigate TFM demand/capacity imbalance issues before most flights take off. A strategic plan of operations takes into account reduced AARs due to weather constraints. Ground holding strategies (including current airport-based GDPs as well as proposed enhancements such as fix-based, range-based, and multi-airport GDPs), re-routes, and playbook plays (which may be re-designed daily by tweaking the current playbook plays to better conform to the predicted weather) for the day are determined using up to 6 hour weather predictions. Note that the ultimate success of this long-term planning is contingent both on the accuracy of published airport AARs relative to what the airport surface and terminal airspace can actually achieve over a given time period and the ability of the air traffic system to deliver planned traffic during execution. The AAR used for national flow planning must be developed based on predicted weather and scheduled demand for both arrivals and departures (as they must share taxiways, runways, and gates) and should be robust to uncertainties in each of these inputs. Equity (and more importantly, fairness) relative to the distribution of delay across different classes of NAS users (e.g., within major carriers and between scheduled, on-demand service providers, and GA flights) must also be factored into the allocation of resources[12].
- Precise Control of Take Off Time to Address TRACON Weather Constraints – Tactical adjustment of take off time is required to optimally time aircraft releases into overhead streams, coordinate a runway configuration change due to wind shifts, hold aircraft temporarily when weather avoidance paths of arrivals block departures, and control take off times for first-tier GSs or first-tier GDPs. Strategic adjustment of take off time is used to control second-tier (or greater) GSs and GDPs, as well as fix-based GDPs. Note that precise control of take off time requires considerable planning of surface movements, including de-icing procedures, so as to enable flights to hit slots without unduly sacrificing surface throughput (e.g., if a constrained flight blocks an unconstrained flight's path to the runway).
- Weather Avoidance DSTs for Transition Airspace – For maximum capacity, the transition airspace requires arrival and departure traffic to deviate around weather without impeding the strategically planned AAR or ADR. When arrival flows that are avoiding weather cannot be maintained without the traffic crossing over into departure corridors, then the definition of the departure corridor needs to be adjusted to accommodate weather avoidance without affecting the AAR or ADR, or the departure traffic flow must be interrupted with a ground hold for a minimal amount of time. If departure traffic must be favored (e.g., to prevent airport gridlock), the minimal amount of airborne holding must be applied to an arrival stream such that the departure flow can perform weather avoidance without loss of ADR. A DST is required that aids the traffic manager in developing these solutions and resolving inherent tradeoffs between different strategies.
- Weather Avoidance DSTs for En Route Aircraft – En route aircraft require weather avoidance algorithms that take into consideration multiple dimensions of variability. Weather avoidance may be accomplished by flying over, around, below, or weaving safely through hazardous weather

constraints. Furthermore, aircraft flight plans (e.g., downstream portions of planned trajectory) can be adjusted (extended or shortened) temporally so that the time the aircraft interacts with a weather constraint can be controlled to benefit the aircraft / airline. Flow constrained areas may be required to organize high-density flows with manageable complexity.

- Coordination of Large Scale TFM Plans – Complex large scale weather systems require playbook plays that take into account user preferences while also taking into consideration the 4D, temporally changing geometry of the weather. New playbook plays and range-based Coded Departure Routes (CDRs) that are designed daily (shaped by specific predicted weather shapes) can optimize traffic flow, given weather prediction uncertainties. These playbook plays can also be tactically adjusted when weather predictions provide better information during the course of the day.

Core Idea 2: Coupled Weather and Traffic Prediction

This core idea identifies methods for predicting traffic movement through and around weather. Prediction of weather and traffic effects must seamlessly extend from relatively precise tactical information for short time horizons to probabilistic strategic information for long-term time horizons. DSTs (covering all flight phases in all operational domains) must incorporate consistent predictions of the traffic/weather and/or constraints imposed by the weather. As demonstrated by Evans[13], there is a need to couple storm predictions with traffic flow and traffic conflict DSTs. This is critical for maximizing capacity in each operational domain and for planning and coordinating future traffic management decisions. The goal is to identify prediction methods and supporting technologies that provide the best look ahead for making effective decisions during weather impacted days in the NAS. The following functions are proposed:

- Broadcast of Updated ETAs – The ETA for an aircraft to touchdown, to a metering fix, to a sector crossing, center crossing, or to any fix location is required to allow TFM to adjust sequencing, scheduling, and flow constraints and for aircraft to meet Required Times of Arrival (RTAs). ETAs must take into account the expected weather avoidance routes and weather-related constraints.
- Sector Count Prediction – Accurate sector count predictions (and flow complexity within a sector) are required to address controller workload concerns and to spatially distribute demand to minimize the impact of potential weather-related bottlenecks.
- Estimation of AAR and ADR – AARs and ADRs must be estimated based on the strategic weather forecast and corrected based on the tactical weather forecast and TFM initiatives in effect. Flight cancellations should be estimated as a consequence of predicted ADRs.

Core Idea 3: Shared Situation Awareness

Shared situation awareness among all members of the user triad (Flight Deck (FD), Air Traffic Service Provider (ATSP), and Airline Operational Control (AOC)) must be crafted in a constructive manner. It is required that the underlying weather/traffic prediction logic, DST adaptations, and user interface technologies are compatible with the human operator's interpretive skills and action-taking/implementation capabilities. The goal is to identify types of interfaces, roles, responsibilities, and procedures that support effective decision-making during weather impacted conditions in the NAS. The following functional requirements represent a first attempt at reaching this goal:

- Coordination of Weather Information – Data fusion is needed to combine surface observations, satellite sensor data, radar weather data, wind and temperature measurements collected from aircraft (e.g., through the Meteorological Data Collection and Reporting System (MDCRS)), PIREPS, and on-board weather radar. This fused, consistent information must be made available to the FD, AOC, and ATSP.
- Shared Situation Awareness – To support shared situation awareness, the distribution and presentation of fused weather information to all in the user triad must be timely, efficient, easy to comprehend, and intuitive. Both current state conditions and projections of future conditions are required. The current CCFP is a first attempt at achieving such a shared, consensus description.
- Accommodation of NAS User Goals and Constraints – Shared situation awareness and information exchange deals with only one aspect of the need to improve coordination between the ATSP and NAS users. In addition to attempting to increase throughput, a second need is to accommodate the business concerns of NAS users. This will require the development of DSTs that are informed of the user constraints (e.g., fuel onboard, arrival priority, etc.) and procedures for fairly dealing with this information.

Note that these three Core Ideas are co-dependent. Core Idea 1 cannot be achieved without sufficient prediction of traffic and weather, as stipulated in Core Idea 2. Furthermore, shared situation awareness cannot be achieved in Core Idea 3 without an accurate view of the future, as provided by the prediction capability described in Core Idea 2.

## Requirements / Enabling Technologies

In this section, we describe some requirements/ enabling technologies that support these core ideas.

### Enabling Technology: Improved Weather Prediction and Sensing

In the future, improved sensing of weather across the entire NAS is required, as well as improved prediction of weather over both short and long time horizons. A variety of technologies (e.g., the Integrated Terminal Weather System (ITWS) and Corridor Integrated Weather System (CIWS)) are currently being developed to provide some of this weather information. Improvements are likely to result from a combination of sensed weather information including:

- Surface Observations – for winds aloft, temperatures, pressures, dew point, precipitation levels, visibility, ceiling, and cloud cover
- Upper Air Observations – for winds, temperatures, pressures, and water vapor
- Weather Radar Measurements – for storm location, size, growth, decay, and motion
- Satellite Measurements – visible, infrared, etc.

The greatest need is in terms of better long-term weather forecasting in the range of 2-6 hours look ahead. These long-term forecasts may best be achieved as a series of probabilistic weather forecasts.

### Enabling Technology: Improved Airport Surface Planning and Control

The introduction of DSTs to improve the flow of traffic on the airport surface and to coordinate traffic flow on the surface with flows aloft will improve the efficiency of airport operations under adverse weather conditions. This will alleviate delays caused, for example, when departures must be held due to downstream merging constraints and MIT restrictions. Such tools will enable accurate use of tunneling maneuvers.

These DSTs may incorporate probabilistic weather forecasts and demand estimates to enable traffic flow managers and controllers to identify the best time for runway configuration changes and to maximize the likelihood of meeting controlled departure times (Expect Departure Clearance Times (EDCTs)) to conform to weather constraints. Such tools will bridge the gap across the current information "divide" between the ATSP and NAS users (e.g., airlines) to provide a common view of current and predicted future surface traffic. This shared view will serve as a framework for collaboration to maximize the use of weather-impacted surface resources consistent with user preferences. A Surface Management System (SMS) being developed by NASA Ames Research Center, in cooperation with the FAA, is progressing in this direction[14]. Integration of surface-domain tools with en route and terminal area tools (extending the ideas of Atkins and Hall[15]) is required to provide even further improvements in the ability for the airport surface to handle the dynamic, time-varying constraints imposed by weather.

### Enabling Technology: DSTs to support Improved Airspace Utilization

Flexible methods for designing weather avoidance paths in the transition airspace are required to provide continuous flows around weather to airport metering fixes. If the arrival and departure weather avoidance routes are coupled, methods that allow for the arrival and departure flows to be adjusted with "variable waypoints" are possible, as depicted in **Figure 11**. With "variable waypoints", jet routes can be altered dynamically throughout the day as weather constraints change. Such routes will allow for continuous flow of traffic to airport metering fixes.

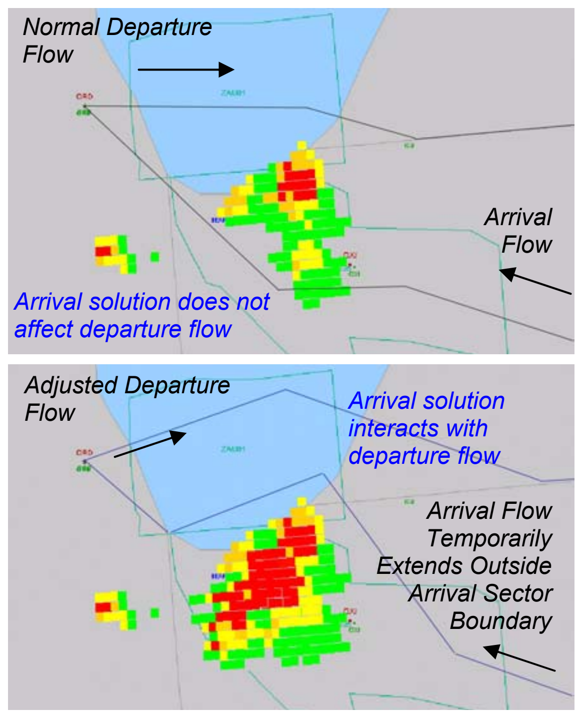



**Figure 11.** Example solutions to the transition airspace weather avoidance problem.

En route aircraft require weather avoidance algorithms that take into consideration multiple dimensions of variability. Weather avoidance may be accomplished by flying over, around, below, for example, as illustrated in **Figure 12**, or by safely weaving through hazardous weather constraints. In the future, a method of planning 2-6 hour TFM initiatives based on probabilistic weather information is needed. Furthermore, aircraft flight plans can be adjusted temporally so that the time the aircraft interacts with a weather constraint can be timed to benefit the aircraft/airline. Flow Constrained Areas (FCAs) may be set up to allow "parallel jet routes" to progress across the FCA without crossing over each other, but allowing for a high-capacity, low-complexity traffic flow across the FCA, as shown in **Figure 13.**

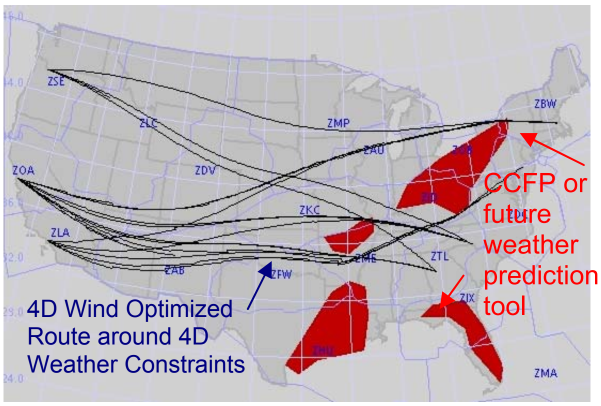



**Figure 12.** 4D wind optimized paths[16] designed to avoid large weather constraints.

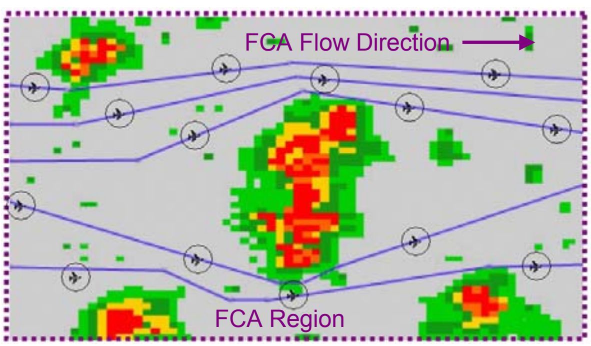



**Figure 13.** Parallel jet routes designed to avoid weather within a flow constrained area.

Enabling Technology: Trajectory Prediction that Couples Traffic and Weather Constraints

Accurate sector count predictions are required to address controller workload concerns and to spatially distribute the expected sector demand. As illustrated in **Figure 14**, when weather is present within a sector, the effective number of aircraft that can be safely accommodated is reduced. Sector capacity limits must allow for such a reduction in the number of aircraft planned to enter a sector. Development of reliable mechanisms for predicting the likely reduction of sector capacity due to forecast weather (e.g., an airspace penetrability likelihood) is required in order to balance the need for complexity-reducing flow management with the users' desire to avoid unnecessary delay due to re-routing around what they perceive to be "passable" weather.

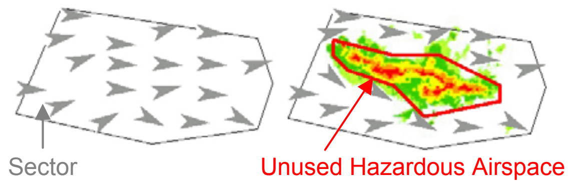



**Figure 14.** Notion of high airspace utilization (left) versus reduced airspace utilization (right) due to weather constraint.

Similarly, the ETA for an aircraft to touchdown to a metering fix, sector crossing, center crossing, or to any fix location is required to allow TFM to adjust sequencing, scheduling, and flow constraints and for aircraft to adjust their controls to meet Required Times to Arrival (RTAs), if applicable to the control laws of the future. ETAs at various points in space must take into account weather avoidance and weather-related constraints as described by Krozel[17], et al, and depicted in **Figure 15**, in which probabilistic information is used to estimate runway ETA given weather.

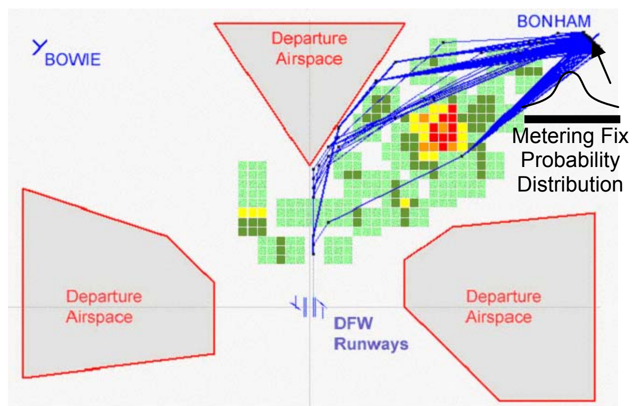



**Figure 15.** Algorithmic solutions to weather avoidance problems can determine statistical properties that generate potential future traffic flows and ETAs tuned from historical ETAs.

Enabling Technology: New Pilot / Controller Displays

The envisioned Operational Concept requires weather and weather-avoidance routing information to be displayed in a way that reinforces shared situation awareness between all the stakeholders. For example as shown in **Figure 16** and **Figure 17**, new displays currently in Research and Development (R&D) such as advanced Head-Up Displays (HUDs), Electronic Moving Map (EMM), Synthetic Vision (SV), and Augmented Reality (AR) displays may allow each member of the AOC/ATSP/FD triad to view weather-related information in a conformal, perspective/3D view. Such displays, or other innovations of the future, are required to support operations in low or zero visibility.


**Figure 16.** HUDs and EMM Displays can improve the efficiency and safety of surface operations during low/zero visibility conditions.

Integrated weather and traffic information on controller and pilot displays are becoming a reality. For example, the Weather and Radar Processor (WARP) is a Federal Aviation Administration (FAA) computer network that puts NEXRAD radar weather data onto ARTCC controller displays. WARP also collects, formats and distributes weather information to supervisors and weather professionals to help them advise pilots of hazardous weather. WARP provides the meteorologist in the Centers the data and communications to help predict areas, routes, or single airports where bad weather will slow traffic. WARP shares raw data, forecasts, and weather displays with other FAA programs. In addition, ITWS and CIWS displays are now being deployed into the ATCSCC and ARTCCs. Future displays will require, for a shared situation awareness, that the command center and ARTCCs share on their displays a view of the predicted weather as well as nowcasts.

Similar technology is starting to make its way onto the flight deck. Weather data link services today provide NEXRAD weather data and METARS to the flight deck. Weather data can be displayed in textual or graphical format, and pilots can request it at their current location, their destination, or anywhere in between. In the future, the pilot and controller must have the same nowcast and forecast weather information displayed to them (perhaps in different formats) such that they share common situation awareness.

## Conclusions

In this paper, we have described a number of different weather phenomena and their impact on operations in the NAS on the airport surface, in terminal airspace, and through the en route environment. From these various classes of weather-related problems, we abstracted out a triad of core ideas describing key changes in operational philosophy and procedures required in order that the future NAS be less susceptible to the impact of weather. Our claim is that the key to a more robust NAS capable of adapting to minimize the negative impacts of weather on capacity include: flexible traffic management capabilities, improved weather and traffic (coupled) prediction, and increased situation awareness and incorporation of user preferences. We have instantiated these core ideas through the specification of a number of functional requirements for the future NAS. Subsequent research currently planned includes the development of modeling capabilities to emulate the impact of these functions on NAS behavior in a number of different weather scenarios with varying levels of complexity and uncertainty. Requirements for weather prediction and traffic prediction capabilities will be established through simulation.


**Figure 17.** Augmented Reality (AR) systems, currently in R&D, may be available by 2015 to allow airport local and ground controllers to work in weather avoidance, low and zero visibility conditions.

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