Modeling the Economic Impact of Adverse Weather into En Route Flights

Chuanwen Quan, Antonio A. Trani, and Sale Srinivas

A methodology is presented to quantify and minimize the effect of adverse weather on commercial and general aviation traffic. The method described uses two simple models, the Air Traffic Flow Model and the Adverse Weather Impact Model, to quantify the impact of adverse weather into regional airspace operations in the National Airspace System (NAS). The impact of adverse weather in aviation in system delays is well documented. Weather is a major source of delays in NAS. In the past 5 years, weather has accounted for 71.2% of all delays in NAS according to statistics compiled and published by the FAA. Adverse weather varies in extent from a few square miles to thousands of square miles. Besides causing delays, it affects the safety, comfort, and efficiency of aviation. Better models to manage air traffic under adverse weather conditions are needed. Ultimately, these models could be deployed as decision-support systems to aid air traffic personnel to divert traffic optimally in a real-time scenario.

If the claim that “all roads lead to Rome” was the key indicator of that city’s economic greatness in ancient times, a modern city’s equivalent claim would have to be “all air transportation lands here.” Air transportation has grown into a large industry. In the past, shipping, railway, and then highway systems have played vital roles in determining a city’s economic power. Today air transportation systems play a substantial role in national economies. The United States has the world’s largest aviation system. The U.S. population represents about 5% of the total world population, yet the people in the United States account for 43% of the world’s commercial air travel (1). In 2000, U.S airlines carried nearly 700 million passengers. That was nearly a 50% increase from those who flew in 1991. According to recent FAA forecasts, that number will grow to more than 1 billion by 2010. The total number of operations handled by the U.S. air traffic control (ATC) system continues to grow at a modest pace of 2% per year (2). By the year 2015, 45 million instrument-type flights could be handled by the FAA at various air route traffic control centers (ARTCCs) and terminal radar approach control centers (TRACONs) daily.

PROBLEM DEFINITION

The economic growth and record air travel demand during the 1990s and the last decades have created a lot of problems in air transportation industry. The FAA reported that delays increased 90% between 1995 and 2000. The total delays at the 15 largest airports in the National Airspace System (NAS) reached 361,619 h in 2000 (3). Adverse weather is a major source of delays in the NAS. In the past 5 years, weather has accounted for 71.2% of all delays in the NAS, according to statistics compiled and published by the FAA. When adverse weather occurs, flights may cancel and delay on the ground or aircraft are routed around these areas for safety and comfort reasons. Airlines and passengers incur an extra expense because of the cancellation and delay of flights or increased travel times and fuel consumption. According to the Air Transport Association, air traffic delays to airlines and passengers represented an estimated $6 billion in 2000 (4), or about $4.2 billion caused by weather. Besides delays, adverse weather affects safety. National Transportation Safety Board (NTSB) statistics from 1989 to 1998 indicate that 30% of the accidents in the NAS are caused by adverse weather conditions.

NATIONAL AIRSPACE SYSTEM AND ATMOSPHERE

National Airspace System

The NAS is a complex collection of systems, procedures, facilities, aircraft, and people. The NAS includes thousands of pieces of hardware equipment at hundreds of locations throughout the United States. These components compose one system that ensures safe and efficient operations. Thousands of people operate the equipment used to provide NAS services to system users who travel each day. More than 18,000 airports in the United States are also a significant part of the NAS infrastructure. The overall airspace in the United States is divided into 22 air route traffic control centers. Twenty of these centers control the air traffic above the continental United States. The airspace of each center is further divided into numerous sectors, which are generally small enough to be managed by a pair of air traffic controllers. Because air traffic is frequently congested in the vicinity of major airports, most large airports have an air traffic control tower or a TRACON facility or both. The main NAS users are air carriers, air cargo, commuter air carriers, air taxis, and general aviation, military, and civilian users (5).

Atmosphere

The atmosphere of the Earth may be divided into several distinct layers. The atmosphere nearest the Earth is divided into three basic layers: the troposphere, the tropopause, and the stratosphere. The troposphere is the layer that extends between 25,000 and 30,000 ft at the poles and 55,000 to 65,000 ft at the equator. There is a thin buffer zone between the troposphere and the next layer called the tropopause. The tropopause extends 13,000 ft above the troposphere.
and is characterized by a constant temperature versus elevation profile. The tropopause serves as a boundary layer trapping most of the moisture in the troposphere. The stratosphere exists and extends 105,000 ft above the tropopause. It is characterized by an inversion in the temperature gradient. Of the three layers, the troposphere is characterized by a negative temperature lapse rate with altitude and contains the highest concentration of water vapor. The troposphere is where all weather takes place. All adverse weather phenomena—such as thunderstorms, hurricanes, windshears, lightning, and icing—occur in this layer. Almost all aircraft activities are in the troposphere layer. Aircraft fly within the atmosphere and are wholly dependent on it for the generation of the aerodynamic forces that sustain and regulate flight. When adverse weather systems occur, the aircraft will struggle.

**Adverse Weather and Effects**

Adverse weather processes are very diverse in terms of their origin, physical nature, spatial and temporal scales, and intensity. However, from the point of view of their effect on aviation, they may be classified into five groups: (a) phenomena involving physical motion of air; (b) hydrometeorological phenomena; (c) phenomena inducing and facilitating ice formation on aircraft surfaces; (d) phenomena causing low visibility; and (e) phenomena involving atmospheric electricity (6).

The different types of adverse weather affect aircraft in fundamentally different ways, but their overall effect on aviation is a degradation in the safety, comfort, schedule keeping, and efficiency of operation.

**Safety**

When the effects of weather phenomena on aviation are considered, the safety aspect comes to mind first. This is because the first priority of any civilian aviation system is to ensure passenger safety. The fear of hazardous weather in the aviation safety context is not merely psychological. Numerous systematic studies have shown weather to be one of the main causes in a large number of aircraft accidents. In earlier years, when flight was dependent to a greater extent on visual clues, and accident investigation methods and tools were less developed, many fatal accidents due to a variety of factors including weather were often attributed to pilot error. With more scientific methods of accident investigation, the true extent of the effect of weather on aviation safety began to be realized. In recent times, weather has been established as a cause or factor in a large fraction of accidents across the entire spectrum of aviation activity.

**Comfort**

Although fatal air crashes, occurring periodically, are the most visible manifestation of the effect of adverse weather on aviation, weather factors influence aviation in many more subtle but profound ways, and on a more continuous basis. An important aspect of weather-aviation interaction relates to passenger comfort. Weather-induced rough flights, capable of causing passenger injuries in the cabin and serious passenger discomfort, are a matter of common experience even with today’s jetliner equipment. Rough flights are usually caused by atmospheric turbulence, either in association with clouds or rain activity, or under clear weather conditions (clear-air turbulence). Passenger discomfort may also result from sudden loss of height by airplanes encountering masses of air moving at speeds significantly different from the ambient air speed.

**Schedule Keeping**

An important area in which weather factors adversely affect aviation, especially the operation of scheduled airliners, is the punctuality of flights. Inclement weather adversely affects the operational readiness of runways and other airport facilities, as well as that of aircraft themselves, resulting in flight delays. Further, because flight schedules are serially arranged using common aircraft and routes, delays usually propagate even to areas unaffected by weather until they are absorbed by the slack supply function in the system. Because the emphasis in modern aviation systems is on efficiency, which usually implies a low slack or idle capacity, the cascading effect due to delays can be quite severe across the network. There is a strong effect of weather in disrupting flight schedules.

**Efficiency**

Aviation is a highly capital-intensive enterprise. Hence, there is an utmost emphasis on the efficient utilization of resources. In the context of aviation, resources are classed into four distinct groups: (a) the aircraft themselves, (b) the ground facilities that support their operation, (c) airspace resources, and (d) the human resources needed to pilot and support all aircraft and ground-handling resources. Weather adversely affects the efficient utilization of these resources.

The main indicators of operating efficiency of any aviation system are the traffic-handling capabilities of airports and air corridors, and the average fraction of time that individual aircraft remain in operation. Weather phenomena reduce the efficiency of aviation operations by adversely affecting the traffic-handling capacities of airports. Factors such as heavy rain, fog, strong crosswinds or wind gradients, heavy snow, and runway icing render entire airports or individual runways nonoperational for significant lengths of time, reducing the total number of takeoffs and landings permissible at these airports. In addition, adverse weather conditions may necessitate a higher degree of separation between aircraft in flight, reducing the traffic throughput rate along takeoff and landing corridors. Further, adverse weather may keep airport grounded for a larger fraction of time, resulting in lower utilization factors of both airports and aircraft (6).

**RESEARCH METHODOLOGY AND MODELS**

In the future air traffic management system, it is imperative to have a set of models to understand aircraft flows across regions of congested airspace. This is necessary to reduce the costs imposed on airspace users and service providers. Such models may serve as an advisory tool (a) to approve flight paths that offer minimum interaction with other flights caused by adverse weather systems and (b) to reschedule flights around adverse weather areas at a minimum cost to users and service providers.

Two computer models have been developed for this purpose using Matlab 5.3, a general engineering software package developed by Mathworks (7). The models developed are the Air Traffic Flow
Model (ATFM) and the Adverse Weather Impact Model (AWIM). ATFM determines ARTCC center and sector loads given a set of flight paths or flight tracks. AWIM uses the outputs of ATFM to determine the impact of adverse weather on en route flights and estimates detour costs (called extra costs here) around the adverse weather system. All models can be executed on any Windows 95/NT compatible PC, Macintosh, or Unix Workstation platforms without modifications due to their common interpreted language.

The models can be used for economic estimation analysis and in tactical decision-making mode. They could also be used for generating strategic and optimal paths to detour flights around adverse weather regions. ATFM generates inputs for AWIM, which in turn considers alternative flight paths for each designated flight based on safety and cost. It is advocated that standard airspace simulation models be used to estimate the impact of flight detours without any optimization features in place. This is useful because air traffic managers need to gauge the benefits of any model developed using accepted modeling and simulation tools. In other words, by comparing the results of simulation models such as RAMS, SIMMOD, or TAAM with the outcome of the Decision Support Flight-Planning Model (DSFM), one can judge the savings between the status quo and an optimized strategy, under future NAS operations.

ATFM requires a series of aircraft flight paths and the sector geometry as inputs. The model processes the information to determine the occupancy of each sector by different flights over time. The essence of the model lies in storing the adjacency information of sectors and identifying the sectors crossed by a flight path. AWIM uses the outputs of ATFM and adverse weather information (AWIN) data to detect the flights affected by the adverse weather first, then to generate new flight paths, and finally to estimate extra costs and generate revised flight paths. The interrelationships between these models are illustrated in Figure 1. ATFM analyzes individual flight paths from an origin to a destination airport and estimates time traversals over each sector encountered. This output is then used by AWIM to

![Diagram of ATFM and AWIM models](image)

**FIGURE 1** Air Traffic Flow Model (ATFM) and Adverse Weather Impact Model (AWIM) (SAR = system analysis recording, ETMS = En Route Traffic Management System, ACES = Adaptation Controlled Environment System, NARIM = National Airspace Resource Investment Model, AW = adverse weather).
assign an optimization route to the flights affected by the adverse weather and estimate the cost of the detour strategy.

**Air Traffic Flow Model**

**Model Assumptions**

The assumptions made in the development of ATFM are as follows.

- All flights are assumed to fly along straight lines between way points. (Dummy way points could be specified to further discretize curvilinear flight trajectories.)
- Two nodes that are less than 0.35 nautical miles apart are assumed to define the same point in the airspace. This assumption is made to correct for inaccuracies in data that sometimes assign different, slightly perturbed, locations to the same node and hence create vacuums within the airspace.
- A flight that moves along a common boundary of some sector modules is assumed to pass through only one of them. The choice is made based on selecting the currently occupied sector, if applicable, or arbitrarily otherwise (8).

**Flight-Path Generation**

The flight paths for a particular day were used for the purpose of analyzing these scenarios. Flight paths obtained from the FAA En Route Traffic Management System (ETMS) database and corresponding to the air traffic situation on November 12, 1996, were used for this purpose. To study future scenarios, extrapolated ETMS data for November 12, 2010 and 2015, were used to run the models. Whenever a flight trajectory is assumed to be independent of the ground-based navigation aids, a wind-optimized trajectory is adopted. Wind-optimized routing is the three-dimensional trajectory that will have the least possible impedance from the prevailing winds. In this context, great-circle routes between origin and destination airports are used.

**Sector Occupancy Determination**

A flight that crosses a sector will be detected by the model based on the adjacency information that is generated and stored during the preprocessing step. Because each sector is complex in shape, the analysis is done at the module level, and the result is translated to the sector level by considering the particular modules that make up the sector. Modules are sections of sectors as defined by the FAA Adaptation Controlled Environment System (ACES) sector database (9).

The model first identifies the initial module encountered by the flight. This may be the module that encompasses the originating airport. Sometimes the originating airport may not lie within the defined modules. In such a case, the model identifies the module through which the flight enters the defined airspace. Once the initial module through which the flight passes is detected, the point and time of exit are identified. The point is found by checking if the flight crosses any of the faces, the floor, or the ceiling defining the module, without merely glancing at it and remaining within the same module.

The program also identifies the way the flight exits the module, that is, if the flight exits across a face, or the floor, or the ceiling, or at a vertex, or across an edge. With this knowledge, and because module adjacency information is known, the next module into which the flight enters is determined. This process of identifying each traversed module and the corresponding occupancy time is continued until the flight reaches its destination. Next, the sectors through which the flight passes are identified by examining the modules that compose each sector. This provides information on all flights that cross a particular sector along with related occupancy times.

**Adverse Weather Impact Model**

**Model Development**

The main blocks that make up AWIM are shown in Figure 1. Two external blocks in this figure are inputs from ATFM: (a) sector occupancies and flight-path structures, and (b) adjacency information to local spatial relationships between neighboring sector models. The first task in AWIM is the extraction of flight proximity information. This is done through the creation of three data structures containing time, spatial, and sector adjacency information.

The AWIM data are generated according to the geometry of the adverse weather and the period of the adverse weather activity. The AWIM is a four-dimensional airspace polytope in shape, defined by its vertices, floor, ceiling altitudes, and time. Its shape can vary over time. For example, an aviation weather system might exist at certain size at time \( t \). Sometime later (at time \( t + \Delta t \) ), it might be larger or smaller or it might have disappeared. Real weather systems exhibit complex, three-dimensional shapes. To simplify the modeling task, weather patterns can be defined by a circle of radius \( R \) and centered at \( (X_0, Y_0) \). The third dimension of the AWIM region involves floor and ceiling boundaries. Because we are interested in modeling adverse weather phenomena, the floor is considered sea level and the ceiling corresponds to the highest flight level of commercial flight.

There are five basic processes in the AWIM model:

1. Building the AWIM weather region,
2. Extracting flights,
3. Detecting impacted flights,
4. Generating new flight paths, and
5. Estimating extra costs and choosing optimization path.

The following paragraphs describe in some detail each of these processes.

**Building the AWIM Region**

A subroutine is used to build the AWIM region and will perform the following tasks.

1. Find an AWIM centroid \( (X_0, Y_0) \) that is the weight average of all vertices and radius \( R \) that is the distance between the centroid and the farthest vertices from the centroid using the vertices data of the AWIM.
2. Construct the AWIM area to be a circle at the centroid \( (X_0, Y_0) \) and with radius \( R \). This is the approximate shape of the weather area for generating the detour flight-path problem.
Extracting Flights

Based on the output from ATFM, a subroutine is used to extract flight information, including flight way points and flight times.

Detecting Impacted Flights

To detect whether or not the flights are affected by the adverse weather during the adverse weather activity, the model will do the following:

1. Read flight way points and flight times,
2. Calculate the distances between every way point and centroid \((X_0, Y_0)\), and
3. Check which way points will be in the circle at that time by comparing the radius \(R\) and the distances.

The flight will not be affected if there are no way points in the circle. Otherwise, the flight is impacted by the adverse weather.

Generating New Flight Paths

The impacted flight will be rerouted around the adverse weather area. As shown in Figure 2, let \(P_0, P_1, P_2, \ldots\) and \(Q_0, Q_1, Q_2, \ldots\) be the original way points in a flight path. The first detour flight path is \(\ldots P_1 \rightarrow A \rightarrow E \rightarrow F \rightarrow B \rightarrow Q_1 \ldots\), the second detour flight path is \(\ldots P_1 \rightarrow E \rightarrow F \rightarrow Q_1 \ldots\), the third detour flight path is \(\ldots P_2 \rightarrow E \rightarrow F \rightarrow Q_2 \ldots\), and so on. The arrow \(\rightarrow\) represents from one way point to the next way point. If points \(Q_i\) and \(P_i\) are at the airport, the detour flight paths will use them repeatedly.

Estimating Extra Costs and Choosing Optimization Path

Using the fuel consumption standards for each aircraft type and passenger value of time, models can calculate the extra travel time based on the sector occupancy and costs for fuel consumption and passenger value of times for every new flight path, and then choose the minimum travel time and costs. This will be the optimum flight path generated.

MODELING RESULTS

Flights and Detour Trajectory Analysis

A hurricane near the coast of Florida is chosen as a case study. Figure 3a illustrates the output of the ATFM model, showing original flight trajectories. The flights are free through this area when there is no hurricane, but when a hurricane occurs, the flights are
Economic Analysis

Figure 5 indicates the total extra fuel and passenger-time costs due to flight detours around a hurricane in 1998 (5a) and 2015 (5b). HD in the figure stands for hurricane duration, and H stands for hour. From Figure 5a, the total extra costs for 3 h, 6 h, and 10 h are about $51,700, $115,000, and $225,000, respectively, when the hurricane is at original size. In 2015, the total extra costs are $185,000, $380,000, and $615,000 for 3 h, 6 h, and 10 h duration, respectively. The total costs are more than threefold the costs in 1998.

CONCLUSIONS AND RECOMMENDATIONS

These models and techniques have been synthesized to derive quick estimates of adverse weather impact for various levels of traffic. Some of the conclusions of this work are listed below.

- There would be moderate to substantial variations in traffic flow patterns across various ARTCC sectors in NAS. The introduction of flexible flight-planning rules expected as a result of free flight
would have different effects on the various ARTCCs according to their geographical location.

- The models developed provide valuable insights on traffic flow patterns around adverse weather.
- The AWIM has been successfully demonstrated with small-scale problems to predict flight detours around adverse weather areas. An estimation of cost savings through the implementation of the prescribed flight paths can be computed using the procedures outlined herein, given the data.

REFERENCES


Publication of this paper sponsored by Committee on Airfield and Airspace Capacity and Delay.