MEASURING THE ECONOMIC VALUE OF AVIATION METEOROLOGICAL PRODUCTS *

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1. INTRODUCTION

The aviation system is one of the principal users of weather information. Assessing the benefits of weather information to aviation is important in a number of contexts:

1. Determining the priority of investments in aviation weather information via a vis other options for transportation and/or weather system investments;
2. Determining priorities for research, implementation, facility staffing and information distribution;
3. The allocation of roles and responsibilities between various government agencies and private industry for various functions, and
4. Use in forecasting to set thresholds (see, e.g., [Felton, 1991], [Andrews, 1993], and [Liljas and Murphy, 1994]).

With reduced government funding in a variety of areas related to aviation weather and with cost pressures on the users of the weather information (especially the air carriers), the importance of carefully performed benefits assessment has increased significantly in the past decade and is expected to become even more important in the near future.

Our discussion will focus on safety and delay reduction. In the case of safety, we will consider in some depth the case of the deployment of wind shear detection systems, while delay reduction will focus on results from recent studies of improved information on airport weather.

In each case, we will also identify issues related to other benefits assessments in these areas.

2. IMPROVED SAFETY

Safety of flight has always been of paramount importance to the aviation system and, in fact, the overall safety record of the U.S. air carriers in terms of deaths per passenger mile is far lower than any other transportation modalities. Nevertheless, air carrier accidents attract far more attention than most other transportation accidents that result in a similar number of casualties and hence have been a major preoccupation of the aviation weather system for a number of years.

2.1. Wind Shear Detection Systems

Accidents due to wind shear have been a major concern for many years, and at least five systems are in active development or being deployed at this time by the FAA and air carriers:

1. The Terminal Doppler Weather Radar (TDWR)
2. The enhanced Low Level Wind Shear Alert System (LLWAS)
3. The Airport Surveillance Radar-9 Wind Shear Processor and
4. Airborne wind shear detection radars [see articles in Delnore, 1994], and
5. Airborne “reactive systems” which detect sharp losses in an aircraft’s total energy [Bowles, 1990].

Additionally, combinations of these systems (e.g., TDWR and LLWAS will be deployed at some airports [Cole, 1994]).

The problem facing the FAA has been to identify which of the various ground based systems (including combinations of systems) is warranted at the various airports. The approach taken to resolve this issue was to compute the expected benefits of each combination at an airport with an equation of the type:

\[ \text{Benefit} = N_{\text{accidents}} \times C_{\text{accident}} \times P_{\text{effective}} \]  

where:

- \(N_{\text{accidents}}\) = expected # of wind shear accidents at an airport
- \(C_{\text{accident}}\) = expected cost of an accident at that airport
- \(P_{\text{effective}}\) = expected probability of preventing an accident by one or more systems

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1 For example, the “investment criteria” proposed by Bob Carr, Chairman of the Appropriations Subcommittee on Transportation [Carr, 1993] include “reduction in aircraft delay hours attributable to the item requested one year and three years after completion,” and the “value of other economic benefits, with description.”
This equation seems simple enough, and one would imagine that estimating the various quantities should be relatively straightforward given the good historical database on accidents and their costs (including payments to heirs, and airframe costs) and extensive testing results for the various systems at a number of sites.

However, the task proved not so easy. One of the major problems is the small number of air carrier wind shear accidents. There were accidents in 1982 and 1985, and then none until 1994. If one assumes that the likelihood of an air carrier accident per year was constant from 1980 to 1994, the small number of events means that there is a high degree of uncertainty as to the “true” accident rate.\(^2\) We note that there were no events from 1985 to 1993. Could this be chance (the probability of no events for seven years with an average rate of 0.23 accidents per year is about 20 percent) or is it a byproduct of:

1. Improved wind shear training for airline pilots, and/or
2. Use of prototype LLWAS and TDWR systems at airports (two occasions of “aircraft saves” by such systems occurred in that period at Denver), and/or  
3. Limited use of “reactive” wind shear detection systems on aircraft?

We cannot resolve these possibilities from the available data. However, the above discussion highlights the problem in benefits estimation for rare events where the underlying probabilities may be changing with time.

Assessing the various system’s effectiveness also was not easy. A relatively limited amount of wind shear measurements was available for the midwest (one year at Kansas City with a lower than average frequency of thunderstorm events) and none for the east coast. Results from the locations with many observations (e.g., Denver, Orlando, Huntsville/Memphis) were combined with climatological data and the understanding of microburst generation mechanisms to provide estimates for the full variety of locations.

The most difficult problem in assessing the ground-based benefit was to estimate the reduction in \(N_{\text{accident}}\) due to airborne “reactive” systems that alert only when a plane is already encountering a microburst. A key factor in accident avoidance with such systems is the response of pilots to a very rare alert. This ended up being resolved by analytical arguments using plausible assumptions on the time the pilot needs to compare alerts to other information and to spool up the engines [Gibson, 1992].

The results of benefits studies using equation (1) with the various assumptions and factors has been used as the principal FAA mechanism for determining deployments of the ground-based systems. However, as we have seen, arriving at well-supported benefits estimates for cases such as this was difficult at best, even though there was a very good record of accidents and over 10 site-years of testing at various locations with the principal competing systems.

3. IMPROVED SYSTEM EFFICIENCY/DELAY REDUCTION

The efficiency of operations in the aviation system is manifested in delays, cancellations, diversions, controller workload, scheduling integrity and payload. All of these have substantial economic impacts which warrant quantification. To illustrate the magnitude of the numbers, the estimated cost of delays to the air carrier system is $5B per year, of which 65 percent is generally attributed to weather.\(^3\) If a substantial fraction of this delay could be shown to be reduced by better weather information systems, it would clearly motivate very substantial investments in aviation weather systems.

3.1. Background Information

Table 1, from [Weber, et al., 1991], shows the results of extrapolating delay results for Chicago’s O’Hare airport during various weather events to a number of airports based on the differences in traffic into the airport.\(^4\) We see that there are major differences between the various airports in terms of the types of weather phenomena which lead to delays. The key question is the extent to which the delay that occurs is in fact avoidable.

Thunderstorms account for approximately 50 percent of the delay in Table 1. A common misconception is that thunderstorm delay is unavoidable because the airport is closed due to hazardous weather. Detailed studies of thunderstorm delay in the terminal

\(^2\) To illustrate, the likelihood function shows a peak at 0.23 accidents per year. However, the likelihood function at 0.11 accidents per year = likelihood function at 0.42 accidents per year = 0.5 of the peak likelihood function. This suggests that the true rate could easily be half as much as twice the observed rate if the rate were constant over that time.

\(^3\) A statement by Mr. L. Kieman of the FAA National Planning Division to the FAA National Capacity Indicator Forum, 1 Sept. 1994.

\(^4\) A subsequent comparison of delays per aircraft at O’Hare with delays at Minneapolis and Dallas-Fort Worth airports [Evans and Clark, 1993] suggested that the O’Hare results were not atypical.
area have shown that the bulk of the delay arises from difficulties in:

1. Planning terminal routes when planes must be vectored around storms,
2. Anticipating when runways will be usable,
3. Anticipating the opening and closing of the “gates” into and out of the terminal area, and
4. Matching the rates of flow into the terminal with the effective airport capacity as opposed to outright airport closure.

<table>
<thead>
<tr>
<th>AIRPORT</th>
<th>DAILY OPS</th>
<th>CLIMATOLOGY (Days per Year)</th>
<th>DELAYS &gt; 15 Min.</th>
<th>ANNUAL DELAY MIN X 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T-Storm</td>
<td>Hvy Fog</td>
<td>Lo Vis.</td>
</tr>
<tr>
<td>Chicago</td>
<td>2175</td>
<td>38</td>
<td>16</td>
<td>109</td>
</tr>
<tr>
<td>Atlanta</td>
<td>2156</td>
<td>50</td>
<td>30</td>
<td>136</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>1589</td>
<td>3</td>
<td>44</td>
<td>121</td>
</tr>
<tr>
<td>Dallas</td>
<td>1578</td>
<td>45</td>
<td>11</td>
<td>86</td>
</tr>
<tr>
<td>Denver</td>
<td>1438</td>
<td>41</td>
<td>10</td>
<td>57</td>
</tr>
<tr>
<td>San Francisco</td>
<td>1255</td>
<td>2</td>
<td>17</td>
<td>101</td>
</tr>
<tr>
<td>St. Louis</td>
<td>1178</td>
<td>45</td>
<td>11</td>
<td>156</td>
</tr>
<tr>
<td>Boston</td>
<td>1162</td>
<td>19</td>
<td>23</td>
<td>125</td>
</tr>
<tr>
<td>Phoenix</td>
<td>1142</td>
<td>23</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Detroit</td>
<td>1137</td>
<td>33</td>
<td>22</td>
<td>121</td>
</tr>
</tbody>
</table>

Another principal cause of delay is the reduction in capacity, with low ceiling and visibility conditions at airports which have closely spaced runways or other operational restrictions during instrument flight rules (IFR) weather. As in the case of thunderstorms, we are not referring here to very low visibility conditions such that landing at all is a problem. Rather, one typically cannot use the runways as efficiently as is done during visual flight rules (VFR) operations. Table 2 compares the scheduled arrivals at various airports with typical effective capacities during IFR conditions on the basis of worst-case arrivals in a one-hour period and on the basis of average arrivals between 8 AM and 9 PM. Clearly at a number of airports, the onset of IFR conditions must surely lead to either delays and/or cancellations and diversions.

Flows in the air system are determined by controllers and traffic management unit (TMU) personnel. The role of the terminal and enroute controllers is well understood. It should be emphasized that controllers typically are concerned about handling the aircraft that are currently in their area of responsibility, and hence are less concerned about the forecast weather.

<table>
<thead>
<tr>
<th>Highest Worst-Case Hourly Deficit</th>
<th>Highest Average Hourly Deficit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kennedy</td>
<td>Boston</td>
</tr>
<tr>
<td>42</td>
<td>16</td>
</tr>
<tr>
<td>Boston</td>
<td>Newark</td>
</tr>
<tr>
<td>36</td>
<td>10</td>
</tr>
<tr>
<td>O'Hare</td>
<td>Kennedy</td>
</tr>
<tr>
<td>35</td>
<td>5</td>
</tr>
<tr>
<td>Dallas</td>
<td>O'Hare</td>
</tr>
<tr>
<td>34</td>
<td>4</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>LaGuardia</td>
</tr>
<tr>
<td>27</td>
<td>3</td>
</tr>
<tr>
<td>Newark</td>
<td>6. O'Hare</td>
</tr>
<tr>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>Detroit</td>
<td>St. Louis</td>
</tr>
<tr>
<td>23</td>
<td>22</td>
</tr>
</tbody>
</table>

However, the role of TMU personnel in attempting to balance the air traffic demand with changes in the system capacity due to weather is not as well appreciated. There are TMU personnel at the Air Traffic Control Systems Command Center (ATCSCC)

\[5\] The effective IFR capacity for an airport can change significantly with different wind directions and speeds. The capacities shown here were typical restrictions imposed during the summer of 1994.
("central flow") as well as at each enroute center and also at major terminals. When weather affects a particular terminal, the terminal and adjacent enroute center TMU personnel typically will attempt to compensate by slowing traffic into the terminal area and perhaps holding close-in aircraft. Longer-lasting problems (especially those at major airports) may require national programs to delay a large fraction of the aircraft into a given airport, typically by imposing ground holds. Enroute weather problems may also be addressed by rerouting aircraft along paths that are less impacted by weather [Jesuroga, 1993a].

This planning role means that the TMU personnel must continually be anticipating weather impacts on operations rates throughout the aviation system. They are assisted in this task by a large real-time database which provides estimates of the expected traffic load and capacity in all sectors and key airports for each 15-minute period throughout a day based on facility estimates, flight plans, aircraft locations, and winds [Jesuroga, 1993b].

One of the major concerns in understanding delay causality and economics benefits is the “delay ripple” effect which arises when an aircraft is delayed on one leg of a flight (e.g., due to adverse weather), such that the next leg (and subsequent legs) flown by that aircraft that day also is delayed. In cases where the subsequent leg(s) are not weather impacted, the delay on the subsequent legs may not be attributed to terminal weather. DeArmon [1992] states that “delay ripple is in general pretty strong” and persists over a number of successive legs. Hartman cites a case where the number of passengers delayed (down line impact) due to delay ripple was 27 times greater than the initial number delayed [Hartman, 1993]. More typically, downstream delay has been estimated to be one to four times the initial weather delay.

3.2. Models for Delay

Delays can generally be modeled as a combination of a fixed delay (typically limited to a finite number of aircraft) and/or a variable queuing delay wherein the effective capacity of the airport (or enroute sector) is less than the demand for a period of time. The first situation can arise with a transient event (e.g., a group of aircraft must fly a longer route) where there is no reduction in the overall average rate of aircraft movement.

Figure 1 shows a simple example of the classic queuing situation where the weather reduces the capacity for some finite time. This simple queuing model can be used to address both air traffic control/airport reductions in effective terminal capacity and traffic management actions by interpreting:

1. The effective capacity as the minimum of the air traffic control/airport constraints on the traffic flow and the flow rate imposed by the TMU, and
2. The effective duration as the union of the actual weather event duration and the time period over which aircraft are not available to land due to traffic management holds.

Thus, for example, if an actual weather event lasts for two hours and creates a situation in which aircraft are held on the ground, the event may be viewed as continuing until the ground hold aircraft are released and arrive at the destination airport.

![Figure 1. Result for simple case.](image)

It is straightforward to show that the accumulated delay for all the aircraft involved in the incident shown in figure 1 is

\[ \Sigma \text{delays} = 0.5 T^2 \frac{(D - C_W)(C_V - C_W)}{(C_V - D)} \] (2)

From equation 2 we see that small increases in the effective capacity during a weather event, C_W, can produce larger proportional reductions in the accumulated delay. Since T is squared, reducing the effective duration of a weather event can also produce large delay reductions. For example, if a good short-term prediction enables the TMU to anticipate the end of a three-hour effective duration weather event a half hour earlier, the accumulated delay is reduced 31 percent.

Calculations of delay reduction using a refinement of the simple queuing model to include time-varying demands and effective capacity can be carried out using a common personal computer spreadsheet. This approach is very computationally efficient and
compares well with measured delays for the very limited number of cases analyzed to date.

Alternatively, one could simulate individual flights in the overall aviation system as is done with the NASPAC model [Frolov, 1989]. The advantage of such a simulation is that at the same time one could address downstream effects, including interactions between connecting flights and options that an airline might take to reduce delay impact on systems operations. However, the current models of this type are expensive to run and do not include any of the most interesting interactions.

Consequently, several simple models have been used to account for downstream effects. One of these is a closed form answer obtained by assuming that aircraft can make up a fixed amount of delay (e.g., 20 minutes) per leg flown. Boswell has developed a model in which the amount of delay made up per leg is a random variable and suggested how this could be used to determine a multiplier for initial weather delays to arrive at a total weather delay.

3.3. Application of Delay Models

A large study of terminal operations efficiency benefits has been carried out as a part of the Integrated Terminal Weather System (ITWS) development program. In this study, estimates were made for 28 situations involving both fixed delay reductions and queuing delay reduction by obtaining quantitative estimates from air traffic personnel (supervisors and TMUs) and airlines. The queuing model studies focused on increases in the effective arrival rates in the terminal area when thunderstorms impact the airport and on reducing the effective duration of low ceiling and visibility events by short-term predictions.

In both cases, the qualitative behavior suggested by equation (2) occurred:

1. Relatively small changes in $C_W$ (specifically 10 percent) can produce much larger proportional reductions in accumulated delay (e.g., 20-50 percent), and
2. Modest reduction in weather event effective duration (e.g., from 3 hours to 2.5 hours) by predicting the event end time can produce substantial changes in delay (e.g., 20-35 percent).

In retrospect, it was realized that a number of situations in which a fixed delay model was used (e.g., the benefit of anticipating a runway shift) should be considered instead of using the queuing model since there will be a queue that forms while the runway shift is being accomplished that does not instantly disappear when the shift has been accomplished. This highlights the need to carefully analyze the aviation operations to decide on the best model to use before asking the questions that will fill in the model details.

3.4. Other Areas of Economic Benefit

We should note that there have been extensive studies of the benefits of improved winds information for flight planning. Analyses in this area have extended to focus on the benefits of reduced fuel consumption by optimizing route choice. However, Lunnun [1993] has shown that even larger benefits arise from being able to operate with fewer fuel reserves than would have been required had one carried the reserves for a worst-case flight time on the flight leg in question.

This same issue of costs associated with excessive reserves arises also in eliminating unnecessary use of "occasional" or other conditional terms in the terminal forecast used in flight planning (see [Feltin, 1991] and [Fahy, 1993]). This further illustrates that a very detailed understanding of the aviation system operations (including FAA regulation impact) is needed to identify and quantify important economic benefits.

4. SUMMARY AND SUGGESTIONS FOR FURTHER STUDIES

In this paper, we have discussed two major areas of economic benefits associated with the aviation system: wind shear accident prevention and more efficient terminal operations during adverse weather. Preliminary work suggests that the efficiency of terminal operations is a fruitful area for additional indepth study. However, there are several topics that also warrant study that have not been discussed above.

4.1. The Benefits of Long-Term (e.g., Greater Than 2-3 Hours) Predictions

The bulk of the air carrier flights into U.S. airports are less than 2-3 hours. This suggests that short-term predictions will generally suffice to effectively adjust the flow into an airport or enroute sector to take advantage of the available capacity. So, what are the benefits for longer-term forecasts beyond the very small number of airports that are dominated by long-range flights?

For air carrier operations, the benefit would appear to lie in more nearly optimum planning for a day. How much is this worth? No analysis on this has been reported to date. Addressing this would appear to require interaction with airline operations planners to a much greater extent than has been the case for published studies to date.

For general aviation (GA) pilots, especially those restricted to VFR operations, longer-term predictions (e.g., 1-7 days) clearly help with trip planning. How can we measure the benefit for this? There also will be
a related safety benefit associated with helping the GA pilot avoid flying in deteriorating conditions. A major challenge in developing a model for these benefits is that GA flight planning is accomplished by many independent individuals using a wide variety of data sources to accomplish their planning.

4.2. Challenging Elements of Improved Efficiency Assessment

At a recent symposium on capacity indicators, it was noted that there are many allocation and assessment issues associated with improved efficiency of air system operations that need in-depth research. For example, should a delay due to strong headwinds be considered in assessing whether the aviation system capacity has improved? Does early arrival due to fortuitous tail winds constitute a negative delay? Where delay reduction is accomplished by a combination of systems (e.g., the weather system providing winds to a terminal automation system that helps terminal controllers), how should the benefit be allocated? How can reduced controller workload benefit be quantified? What is the cost of a canceled flight? What is the quantitative benefit of on-time performance in terms of passengers choosing to use air travel and/or a particular carrier?

REFERENCES


