OBSERVATIONS OF AIRCRAFT PROXIMITY TO WEATHER FOR USE IN REROUTING DECISION AIDS

by

Deborah S. Hyams

B.S., Aeronautics and Astronautics, 1997
Massachusetts Institute of Technology

Submitted to the Department of Aeronautics and Astronautics in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Aeronautics and Astronautics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1999

© Massachusetts Institute of Technology, 1999
All Rights Reserved

Author .................................................................

Department of Aeronautics and Astronautics

Certified by ............................................................

James K. Kuchar
Assistant Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by ............................................................

Jaime Peraire
Chairman, Department Graduate Committee
ABSTRACT

Information about pilot behavior in the presence of weather is needed if a decision aid is to be created to assist with enroute replanning. Specifically it is important to know how close pilots are willing to fly to various levels of precipitation. Two surveys and an analytical study were conducted in order to examine pilot preferences and behavior in enroute replanning decision making. The first survey involved a questionnaire on the world wide web and the second survey consisted of a more focused series of personal interviews. Replanning decisions in response to turbulence and weather were examined. Weather was determined to be the largest cause of pilot-initiated inflight replanning, and pilot reports appeared to be an influential information source in light weather. In moderate or severe weather the effects of pilot reports were decreased. Next, an analytical study was performed in which enroute flight track data archived from the Dallas Fort-Worth area was correlated with precipitation intensity data to assess pilot behavior in the presence of weather. Twelve hours of data during a cold-front passage were examined to generate statistics on pilot proximity to weather of varying intensity levels. This data also included the duration of the penetrations and the closest point of approach to each level of precipitation. The duration in more severe levels of weather was smaller than predicted by a simplified model of the weather. Also, the correlation between lead and following aircraft duration and proximity to weather was examined. A slight but insignificant trend for the following aircraft to spend less time in weather than the leading aircraft was discovered. However, it appears that the severity of the weather in the twelve hour period of interest was sufficiently severe to lessen the effects of the lead aircraft.

Thesis Supervisor: James K. Kuchar
Title: Assistant Professor of Aeronautics and Astronautics
Acknowledgments

This research was supported by the NASA Ames Research Center under Grant NAG-2-1111 and Contract NAS2-98012. The author is also appreciative of the support provided by the NASA Langley Research Center, including Sally Johnson, Mark Ballin, and Terry Abbott. I am also appreciative of the collaboration with Bill Corwin at Honeywell, and Geoff Gosling at the University of California, Berkeley. The pilot respondents to the survey also deserve thanks for their time and input.

There have been so many people who, through their time, feedback, and sometimes just mere presence, have helped me finish this thesis. It would be impossible to list them all, but I would like to acknowledge a few who have wholeheartedly supported me throughout this work.

First of all, Prof. Jim Kuchar, my advisor, always had time to look over another draft and answer some more questions. Thank you for your infinite patience with me. May you have future graduate students who understand all of the graphs the first time around.

Group 42 at MIT Lincoln Laboratory worked very hard to make sure everything was in working order for the flight track/weather precipitation data analysis. Their programming skills and incredible knowledge were invaluable. To Dale, Margo, and Beth, thank you for all of your hard work. Tina and Kim, thank you for showing me the yogurt machine.

The folks in the ICAT lab are the most responsible for what remains of my sanity. The Profs, John Hansman and JP Clarke, and the graduate students: Sanjay “future Ph.D.” Vakil, Todd Farley (who unfortunately had to leave in January), Yiannis Anagnostakis, Tom Reynolds, Dr. Richard Kornfeld, Mario Rodriguez, Lee Winder, Lee Yang, Terence Ping Ching Fan (who worked with me on the first survey), Laurence Vigeant-Langlois, and David Matsumoto. Thanks for making the workplace so much fun. Jennie and Marion also get huge KUDOS for all of their administrative support and Furby/G&S stories.

Go Club MIT!

My other workplace and home, Ashdown House, has always been important to me. To Vernon and Beth Ingram, the housemasters, thank you for your advice and your patience. It was great living in the community that you have worked so hard to create. I promise to come back and visit. Let's not forget the folks who live inside the dorm: I can't thank Tom Lee or Lynne Svedberg enough for their friendship and support. You both taught me things that I never could have learned from a thesis alone. You made grad school a true learning experience for me.

Pat Walton, thank you.

And of course I saved the most important acknowledgement for last. My family has unconditionally supported me throughout my life, despite the fact that I have put them through some especially trying times these past two years. Mom, Dad, and David, thank you for giving me the freedom to make my own decisions, and thank you for supporting me through them all. Also, Dave, thanks for moving to Boston.

And now, on to the thesis....
# Table of Contents

Acknowledgments ................................................................................................... 5 

List of Tables ........................................................................................................... 9 

List of Figures ........................................................................................................... 11 

1 Introduction .......................................................................................................... 13 

2 Background and Motivating Research ................................................................. 17 
   2.1 Model of the Replanning Process .................................................................. 17 
   2.2 Prior Research ............................................................................................. 20 
   2.3 Current Weather Information Sources ....................................................... 23 
   2.4 Brief Overview of Precipitation Levels ....................................................... 24 
   2.5 Integration of Hard and Soft Hazards ......................................................... 25 

3 In-flight Replanning Information Survey ............................................................. 27 
   3.1 Subject Selection .......................................................................................... 27 
   3.2 Ride Quality Pilot Reports ........................................................................... 28 
   3.3 Weather Case Scenarios .............................................................................. 34 
   3.4 Conclusions ................................................................................................ 38 

4 Proximity to Weather Analysis ............................................................................ 41 
   4.1 Objective/Impetus ....................................................................................... 41 
   4.2 Aircraft and Weather Data Collection ......................................................... 41 
   4.3 Data processing ........................................................................................... 42 
   4.4 Results ......................................................................................................... 44 
       4.4.1 Weather Conditions ........................................................................... 44 
       4.4.2 Example Aircraft Behavior ................................................................. 50 
       4.4.3 Overall Duration in Precipitation ....................................................... 54 
       4.4.4 Minimum Distance to Precipitation .................................................. 58 
       4.4.5 Leader and Follower Aircraft ............................................................... 60 
   4.5 Conclusions ................................................................................................ 63 

5 Summary .............................................................................................................. 65 

References .............................................................................................................. 69 

Appendix A ............................................................................................................. 71 

Appendix B ............................................................................................................. 85
List of Tables

Table 2.1: Precipitation Levels ...........................................................................................................24
Table 3.1: Turbulence Study Scenarios ............................................................................................29
Table 3.2: Weather Case Scenarios Test Matrix ..................................................................................35
Table 4.1: Expected and Observed Penetration Behavior .................................................................50
Table 4.2: Duration in Precipitation ..................................................................................................55
List of Figures

Figure 2.1: Model of the Replanning Process .............................................................. 18
Figure 3.1: Pilots’ Replanning Decisions: Scenarios 1-3 .............................................. 30
Figure 3.2: Pilots’ Replanning Decisions: Scenarios 3-5 .............................................. 32
Figure 3.3: Example Test Scenario ............................................................................. 35
Figure 3.4: AHP Results from Light Weather Scenarios (Lead on Route A) .......... 37
Figure 3.5: AHP Results for Moderate Weather Scenarios (Lead on Route A) .... 37
Figure 4.1: ZFW High Altitude En-route Sector .......................................................... 43
Figure 4.2: Percentage of Sky Covered by each Precipitation Level ....................... 45
Figure 4.3: Relative Coverage as a Fraction of Area of Level 2 Precipitation ...... 46
Figure 4.4: Weather Model for Expectation Calculations ......................................... 47
Figure 4.5: Weather Model for Expected Duration Calculations ............................ 48
Figure 4.6: Minimum Distance from Aircraft 0088 to Each Level of Precipitation .. 51
Figure 4.7: Duration in each Precipitation Level for Aircraft 0088 ......................... 54
Figure 4.8: Histograms of Average Duration in Precipitation Levels 2-5 ............... 56
Figure 4.9: Cumulative Minimum Distance to Precipitation Levels ....................... 58
Figure 4.10: Average Minimum Distance to Precipitation (All aircraft) ............... 59
Figure 4.11: Correlation between leader and follower duration in level 2 precipitation .... 60
Figure 4.12: Correlation between leader and follower duration in level 4 precipitation .... 61
Figure 4.13: Correlation between leader and follower proximity in level 2 precipitation ...... 62
Figure 4.14: Correlation between leader and follower proximity in level 4 precipitation ...... 62
Chapter 1

Introduction

Air carrier flight plans are the result of a careful balance between flight schedule, environment (winds, weather, and traffic congestion), and aircraft performance, designed to optimize the route so as to deliver the aircraft on time and with minimum fuel burn. However, these flight plans are based on forecast conditions and ideal flight patterns, and it is not uncommon for pilots to encounter unforeseen circumstances such as inclement weather, traffic conflicts, or a change in winds which may require replanning the original route. When these in-flight replans are required, pilots, together with Air Traffic Control (ATC) and the Airline Operations Center (AOC), decide upon an alternate course.

Weather is the most common cause of pilot-initiated in-flight replanning. To make an informed decision, pilots need access to relevant data. In the cockpit, pilots generally have more accurate local weather information than ATC and AOC. Therefore, when pilots have to reroute around weather they are often the deciding party, as opposed to ATC or the AOC.

With the increasing amounts of technological ability in the cockpit, it may be possible to create a decision aid to both display weather information in a more readily understandable format as well as to assist pilots with their enroute replanning decisions. Such a decision aid might be sophisticated enough to suggest routes similar to what the pilots might choose after integrating the information themselves. The reason that such a decision aid does not already exist has to do with the nature of weather as a hazard to safe flight as well as the nature of decision aids themselves.

Weather is a soft hazard, which means that it can be penetrated under certain conditions, such as when the weather is less severe. Also, pilots prefer to put a safety buffer between severe
weather and their aircraft. This safety buffer differs depending on which level of weather they are closest to. Due to these subjective constraints, it is difficult to determine pilots’ thresholds for soft hazards, and without thresholds it is difficult to incorporate them into a rerouting decision aid in a realistic manner.

In addition to traditional sources of weather information which are specifically supported by the Federal Aviation Administration (FAA), pilots also use information that they hear over the radio, known as Party Line Information (PLI) and weather radar displays. This short-term information is regarded by pilots as the most timely, accurate weather information available, and therefore affects their rerouting decisions.

The goal of this research is to address the use of weather information in the realm of enroute replanning decision aids. To this end, this thesis addresses several issues with regard to pilot preferences. Specifically the relationship between information sources and pilot preferences is discussed as well as the ultimate effect that the information plays in replanning decisions. A threshold specific question that is examined here is the question of how close pilots are willing to fly to various levels of precipitation. This information can then be used in a decision aid which might help create routes that are neither too close to weather (unsafe) nor too far from weather (inefficient). These questions were investigated using a two-part study. First, a survey and in-depth interview were used to determine several aspects of pilot decision-making behavior. Second, actual flight track data and weather intensity data were plotted to determine aircraft behavior in the presence of weather within a twelve hour period in May of 1997.

The outline of the thesis is as follows: Chapter 2 discusses background information for the research described in the thesis, Chapter 3 presents two surveys which gathered information about
pilot preferences and replanning decision-making, and Chapter 4 describes the study of flight track and weather intensity data. Finally, Chapter 5 gives a summary of the research and results.
Chapter 2
Background and Motivating Research

This chapter gives a brief description of some background information which is necessary to understand the research performed in the thesis. Section 2.1 describes a model of the replanning process, covering the mental process that pilots use to monitor and alter their current flight plan. Section 2.2 describes prior research which helped to form and motivate this thesis. Much of this work discusses pilots’ use of information in the cockpit, so it is important to understand where that information currently comes from. To this end, Section 2.3 describes the current weather sources which are available to pilots both in pre-flight and in-flight. Since much of the weather information that is given to pilots relies on definitions of precipitation, Section 2.4 gives a more detailed look at the definitions of precipitation levels, and Section 2.5 discusses different types of hazards to be modeled into a decision aid.

2.1 Model of the Replanning Process

Figure 2.1 shows a conceptual diagram of the general in-flight replanning process. This model was adapted and modified from two references (Abbott, 1993; Rogers, et al., 1998) in order to more explicitly depict the interactions between stages in the replanning process. As shown, there are four main components of this model that represent basic processes in replanning: Monitor, Assess, Formulate, and Modify. Although the focus here is on the cockpit, a similar model can represent the replanning processes in the AOC and ATC.

The first component in the model represents monitoring the current flight plan and the environment. Monitoring is the collection of information in order to determine the adequacy of
the current flight plan. This step involves gathering relevant information from cockpit instruments, pilot reports, AOC, ATC, and observation out the windscreen. While monitoring, the pilot is watching his or her current flight path for problems or hazards.

Once the appropriate information is available, the next step is to assess the value of the plan that is being monitored. Assessment encompasses integrating the various sources of information and determining whether a plan is adequate. Thus, while monitoring is generally a data-collection task, assessment is a higher-level process requiring a value system and judgment.

The decision as to whether a flight plan is adequate can be modeled as a comparison against some form of threshold of acceptability. This threshold includes factors such as regulations, safety, efficiency, airplane performance constraints, as well as subjective preferences. In practice, due to the large number of variables involved, it is difficult to determine an explicit description of this process for use in an expert system or decision aid.

If assessment of the situation indicates that the current flight plan is adequate, then the monitoring and assessment cycle is continued. If, however, assessment indicates that the plan is
inadequate (e.g., due to severe weather along the route of flight), the pilot will begin to formulate alternative plans. This task is similar to monitoring in that it primarily involves the collection of information needed to generate and evaluate deviations from the current flight plan. However, it differs from monitoring in that formulation of alternate routes is an active gathering of information in order to devise a new plan. This might include, for example, requesting ride reports or adjusting the weather radar elevation angle to examine precipitation returns at alternate altitudes. Potential changes in the flight plan must then be assessed in a manner similar to that discussed earlier. This assessment may result in the alternate plan being rejected, in which case further formulation and assessment cycling will be required.

Note also that the formulation task is not necessarily initiated only by recognizing a deficiency in the current plan. Pilots generally formulate and assess alternate flight plans as a matter of course during a flight, both to determine whether a more preferable route is possible and also to 'stay ahead of the aircraft' should replanning be required at a later time.

The final step in replanning is the modify step. Modifying, in this model, represents physically implementing the new plan (e.g., by conferring with ATC and by programming the Flight Management System). Depending on the flight conditions, the modification may involve negotiations with and consent of ATC and/or the AOC. Thus, should a proposed route change not be acceptable to ATC or AOC, additional iterations of assessment and formulation may be required. This hierarchy of decision-making is one area in which the current replanning process is inefficient: pilots may develop a tactical change in flight plan that subsequently is rejected by ATC or AOC, necessitating additional replanning. If ATC, AOC, and the flight crew are all more directly involved in decision-making early on, the frequency of such iteration may be reduced.
2.2 Prior Research

Prior research dealing with in-flight replanning issues can be divided into three separate categories: outlining of major research interests (Abbott, 1993; Rogers, et al., 1998; NASA, 1997), examination of information used by pilots (including which information sources pilots prefer and how the information affects their in-flight behavior) (Patrick, 1996; Midkiff & Hansman, 1992; Dershowitz, 1997), and development of replanning models and prototype expert systems (Robinson, et al., 1997; Nguyen & Ward, 1997, Abbott, 1993).

Of most interest to this thesis were the second and third categories of research. Specifically, some informational studies have focused solely on the amount and types of information available to pilots and how it affects their decision-making process. These studies looked at “Party Line Information” (PLI) that pilots receive by overhearing communications addressed to other aircraft on shared VHF voice frequencies. This information includes elements such as pilot reports of experienced weather conditions, traffic avoidance, and weather deviations.

One finding which was common to all of the PLI studies was the perceived importance of weather information reported by other pilots. One study performed a survey of active commercial pilots and asked them to rate different PLI elements in various stages of flight (Midkiff & Hansman, 1992). For the cruise portion of flight, ride reports and weather information received the highest importance ratings. In fact, across all phases of flight, weather situation information and ride reports were rated first and third in terms of importance, respectively. According to further results of the study, weather information and ride reports were two of the most accurate and available PLI elements. Also, in a following simulation study it was found that turbulence and weather deviations are extremely effective in inducing action responses from pilots (Midkiff...
& Hansman, 1992). Another survey of pilot perceptions of PLI information emphasized the pilots' need for specific traffic and weather information (Pritchett, 1994).

Still other research concentrated on the methods used by pilots to make decisions in high-risk situations (Dershowitz, 1997). According to this research, the majority of high risk situations reported by pilots were weather related. This research also highlighted the need to understand a pilot's information needs when designing decision aids. Understanding these needs will allow for the improved design of decision aid systems. If pilot reports and weather scenarios have a large influence on the in-flight replanning decisions then it is important to understand their influence so that it can be incorporated into a decision aid or at least so that a decision aid can be aligned as much as possible with pilots' mental models.

Additionally, another previous study investigated the effect of showing both traffic and weather information to both pilots and Air Traffic Controllers (Patrick, 1996). The outcome showed that communication was improved and enroute replanning decisions were more efficient when all involved decision-making parties had traffic and weather information. In those experiments, the integration of the traffic and weather information into an alternate flight plan was handled by the human decision-makers. Creating a decision aid to integrate the information for the decision-makers could allow a reduction in workload as well as an increase in efficiency.

Of the third category of research, in which researchers attempted to develop models of the replanning process and prototype expert systems, two studies were of particular interest. The first study, completed by Seagull Technology, Inc. developed a model of the replanning process by surveying pilots and modeling the weather avoidance problem with algorithmic route planning methods (Krozel, et al., 1997). Their goal was to determine an algorithmic method for efficiently guiding aircraft through and around weather in the terminal area (within 100 nmi of the airport).
One aspect of their survey was an attempt to determine how close pilots are willing to fly to weather. Overall weather penetration, duration in significant weather, and proximity to adjacent, more severe weather were all found to be very important to route acceptability. However, in terms of specific thresholds, they determined that routes passing through light green weather were acceptable while routes passing through red weather were unacceptable. More detailed thresholds may be needed for a realistic decision aid to be completed.

Another study, conducted at the MIT Lincoln Laboratory, looked at deviations and weather penetrations by aircraft which were entering the terminal area of DFW Airport (Rhoda & Pawlak, 1998). This research attempted to determine the effects of weather on pilots by observing and taking data from archived flight track and weather data. The findings of the study demonstrated that the closer that aircraft are to the airport, and the less information that they have about their environment, the more likely they are to penetrate higher levels of weather. These findings are not extractable to the enroute environment, however, because there are different expectations, information sources, and time limitations in the enroute sector.

The research discussed in this thesis was performed to answer several of the unanswered questions posed by the studies described in this section. For example, one of the issues which was not clear from previous work was the degree to which pilot reports induce or inhibit replanning decisions. Accordingly, this thesis presents the results of two survey efforts designed to investigate how turbulence and weather-related pilot reports affect pilot decision-making. Since the studies by Seagull and MIT Lincoln Laboratory about pilot behavior around weather was not directly extractable to the enroute area, a study was conducted to determine pilot behavior specifically in the presence of weather in the enroute sector.
2.3 Current Weather Information Sources

Pilots currently receive weather information both pre-flight and in-flight. One important aspect to note is that significantly more information is available during pre-flight planning than is available in the cockpit.

Much of pilots' pre-flight information comes from flight planning data received on paper from the airline dispatcher before pushback, including expected winds, turbulence, and weather conditions. In pre-flight, pilots have access to text encoded weather information (including recent weather reports from pilots), but they also have access, via flight service meteorologists, the world wide web and other popular media, to weather maps and current weather information. (FAA, 1985)

Weather information available in the cockpit is primarily available in text strings which are received over voice radio. Information regarding weather and turbulence conditions along the flight path are provided via VHF radio pilot reports and/or messages from ATC and the airline operations center (AOC). While in flight, pilots also have access to local precipitation from the weather radar, and on glass-cockpit aircraft, the current wind direction and magnitude. Weather radar presents a pictorial display of precipitation readings based on the radar reflectivity (as described in the Section 2.4). Limited traffic information is available through the Traffic Alert and Collision Avoidance System (TCAS) display, which shows proximate traffic using icons. Because of the lack of accurate information regarding environmental conditions along the flight path, pilots often rely on pilot reports (PIREPs), overheard on the radio, and the actions of other aircraft to aid in decision making. When information is received indirectly over the radio from other pilots' transmissions it is known as partly line information (PLI). As discussed in the previous
section, although PLI is unregulated, it is perceived as one of the most important sources of weather information.

2.4 Brief Overview of Precipitation Levels

Weather, specifically precipitation, is categorized into different levels designated as the National Weather Service (NWS) Video Integrator and Processor (VIP) 6-level Intensity Scale. The levels are defined with respect to the radar reflectivity factor, $Z$. $Z$ is a function of the amount of radar beam energy that is backscattered by a target and detected as a signal (or echo). DBz is the non dimensional “unit” of radar reflectivity. It represents a logarithmic power ratio (in decibels, or dB) with respect to $Z$. Higher values of $Z$ (and dBZ) thus indicate more energy being backscattered by a target. The amount of backscattered energy is generally related to precipitation intensity, such that higher values of dBZ that are detected from precipitation areas generally indicate higher precipitation rates. Six accepted definitions of weather intensity rely upon dBz for their characterization, as shown in Table 2.1.

Table 2.1: Precipitation Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>dBZ</th>
<th>Precipitation Type</th>
<th>in/hour</th>
<th>Radar Color Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-30</td>
<td>Light precipitation</td>
<td>0-0.2</td>
<td>light green</td>
</tr>
<tr>
<td>2</td>
<td>30-41</td>
<td>Light to moderate rain</td>
<td>0.2-1.1</td>
<td>dark green</td>
</tr>
<tr>
<td>3</td>
<td>41-46</td>
<td>Moderate to heavy rain</td>
<td>1.1-2.2</td>
<td>yellow</td>
</tr>
<tr>
<td>4</td>
<td>46-50</td>
<td>Heavy rain</td>
<td>2.2-4.5</td>
<td>orange</td>
</tr>
<tr>
<td>5</td>
<td>50-57</td>
<td>Very heavy rain; hail possible</td>
<td>4.5-7.1</td>
<td>dark orange</td>
</tr>
<tr>
<td>6</td>
<td>&gt;57</td>
<td>Very heavy rain and hail possible</td>
<td>&gt; 7.1</td>
<td>red</td>
</tr>
</tbody>
</table>
2.5 Integration of Hard and Soft Hazards

All decision aids can be broadly classified as either active or passive. Active systems generate discrete decisions or commands that are communicated to the operator with the intent of modifying the process' future state trajectory (e.g., a traffic conflict resolution command). Passive systems provide process and environment state information to the operator without explicit decisions being made by the automation (e.g., depicting precipitation levels on a weather radar display). Thus, an active system acts as an automated decision-maker (which may agree or disagree with the human operator's decisions), while a passive system acts as an automated decision supporter.

Currently, active alerting systems are in place that warn pilots of hard hazard collision threats such as traffic or terrain. Pilots also have passive weather radar displays that depict precipitation intensity. Due to the soft, complex nature of weather as a hazard, pilots have traditionally had to integrate weather information with other constraints when determining tactical routes. As more complex alerting systems are developed, it may be attractive to incorporate soft weather information in the decision aids, even if only at a fairly rudimentary level. Additionally, automated conflict resolution commands to pilots or air traffic controllers may be improved by reducing the likelihood that such a resolution command is not acceptable due to weather.

The potential to translate rerouting behavior into a form that could be incorporated into an automated decision aid was the motivation for this study.
Chapter 3
In-flight Replanning Information Survey

To better understand how pilot report information is used in the replanning process on the
flight deck, two surveys of active pilots were conducted. The first survey was written in
HyperText Markup Language (HTML) and was conducted via the world wide web. Users could
fill out the survey at their leisure using a web browser, and their responses were delivered via
anonymous E-mail to the experimenters. Additionally, the online format allowed for efficient
distribution to pilots around the world. The second, “follow-on” study was a more focused
version of the online study and further explored pilots’ preferences and decision-making behavior
through personal interviews.

3.1 Subject Selection

A hypertext link to the online survey was posted at several popular aviation websites,
including a general-interest web site that produces weekly newsletters to aviation enthusiasts
(www.avweb.com) and a site devoted to users of Flight Management Systems
(www.Neosoft.com/~sky/BLUECOAT). Because of the inability to control and verify the
background of respondents over the internet, several open-ended questions on the survey were
used to screen out non-pilots.

Over a three-week period, from mid-January to early February, 1998, a total of 309 valid
survey responses were received from the online study. These surveys came from a variety of
pilots with different levels of flight experience. The respondents were grouped into four
categories according to the highest level of flight rating obtained: Private, Instrument,
Among the 309 respondents, 91 (29%) were Air Transport Pilots. Because the focus of this effort was on airline in-flight replanning, the data discussed here include only the responses from the Air Transport Pilots. These pilots had an average of 9,678 total flight hours and an average age of 44 years. A complete summary of the survey responses for all pilot types is available (Fan, et al., 1998).

The follow-on study was completed by ten pilots during personal interviews. The results of the follow-on study is not statistically significant due to the small sample size, however, they can provide preliminary insight as to the use of pilot reports in in-flight replanning and pilot decision making behavior.

3.2 Ride Quality Pilot Reports

In the first part of the survey, pilots were presented with scenarios involving the prospect of turbulent weather. In each scenario, pilots were told that there was a region approximately 20 minutes ahead along their route of flight in which moderate chop (turbulence) had been reported earlier. Moderate chop is a state of continuous, rapid turbulence, which may be dangerous to unbelted passengers but is not dangerous for flight.

The scenarios were designed to test the possible effects of several parameters on pilot decision-making. The parameters were: presence of a lead aircraft, turbulence on the own aircraft, a pilot report of moderate chop from a lead aircraft, and an altitude change performed by a lead aircraft in response to turbulence. These scenarios are shown in Table 3.1. Only scenarios 1-5 were presented in the online survey. However, all 8 scenarios were presented in the follow-on study.
Table 3.1: Turbulence Study Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Turbulence on own A/C</th>
<th>Lead A/C Present</th>
<th>Moderate chop on lead A/C</th>
<th>Altitude change by lead A/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>8</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

In each scenario, respondents were asked to choose one of three options: proceed using the current flight plan, change the flight plan, or request more information. In addition, there was space for pilots to specify the type of information they would request and to give general comments with regard to the scenario.

In each of the first three scenarios, there were clearly-preferred courses of action that received a majority of support by the respondents (Fig. 3.2). Whether this preferred course of action was to continue with the current plan, replan, or to request more information depended on the specific scenario, as discussed below. Only results which are statistically significant at the 99% level are reported (p < 0.01).
Figure 3.1: Pilots’ Replanning Decisions: Scenarios 1-3

Scenario 1 was a control case, in which the subject’s aircraft was the only aircraft in the area. Pilot decision-making was therefore based solely on the prior report of turbulence 20 minutes ahead. In scenario 1, 63% of the pilots surveyed online indicated that they would request more information before deciding whether to continue with the current flight plan. In the follow-on study, all of the pilots also chose to ask for more information. This likely results from the ambiguous baseline condition in which the recency and scope of the turbulence report was not explicitly mentioned to the subject.

In scenario 2, the pilots heard via radio that another aircraft was flying approximately 5 to 10 minutes ahead of them on the same route and at the same flight altitude. However, this aircraft had not made a turbulence report. This scenario was designed to determine whether a lead aircraft could have an effect on pilot decision-making. In this scenario, pilot preference shifted significantly such that 83% indicated that they would continue on course. In the follow-on survey, half of the pilots chose to continue on course while the other half chose to ask for more information. From the online survey, it appears that the presence of a lead aircraft can have a significant influence on the pilots’ replanning decisions to proceed as planned. Additionally, from
talking to the pilots who completed the follow-on study, the information that they would request would be a ride report from the lead aircraft. Since none of the pilots indicated that they would change their flight plan, this implies that the pilots are reassured by the presence of another aircraft, presumably because they expect the lead aircraft to report turbulence when and if any is encountered. Thus, the lead aircraft acts as a surrogate ride quality sensor.

In scenario 3, the pilots heard a report that the lead airplane was experiencing moderate chop. Comparing scenario 3 with scenarios 1 and 2 allows evaluation of the effect of a pilot report from a lead aircraft. As in scenario 2, scenario 3 resulted in a significant change in pilot preference. In this case, slightly more than half (53%) indicated that they would request a change in flight plan. The remaining pilot preference was split approximately equally between requesting more information and proceeding as planned. In the follow-on survey, six pilots chose to change the flight plan while the other four asked for more information. This scenario shows that a pilot report of turbulence from a lead aircraft shifts pilot preference toward changing the flight plan. However, approximately 25% of the pilots indicated that they would request more information, suggesting that pilot reports, though useful, do not provide all of the information that is desired.

In scenario 4, the lead aircraft, in addition to the pilot report of moderate chop, also requested a change in altitude in order to improve ride quality. In this case, the additional impact of not only a pilot report, but also a turbulence avoidance maneuver can be determined. In this scenario, the fraction of pilots requesting a change of plan was slightly less than in scenario 3 (46%) for the online survey, as shown in Fig. 3.2. In the follow-on survey, seven pilots changed course and three asked for more information, which is only slightly different than in scenario 3. Apparently, a request for deviation due to turbulence does not carry much additional information over a
turbulence report alone, and therefore does not significantly change a decision to reroute. It may, however, factor into the type of rerouting that is requested.

![Figure 3.2: Pilots’ Replanning Decisions: Scenarios 3-5](image)

Finally, in scenario 5, the lead airplane was proceeding straight and had not reported any turbulence, but the subject’s airplane was experiencing moderate chop. This allowed for the exploration of the effect of actual (as opposed to predicted) turbulence on decision-making. A somewhat surprising result was obtained in response to scenario 5 (Fig. 3.2). Fewer pilots (33%) indicated that they would request a change in their flight plan in this case than had indicated they would do so in scenarios 3 (53%) or 4 (45%). In the follow-on study one pilot indicated that he would proceed as planned, seven chose to ask for more information, and the other two indicated that they would change flight plan immediately. From the online survey it seems clear that subjects were less willing to change the flight plan while they were experiencing turbulence than when the subject’s ride was smooth. The reason for this apparent contradiction is likely due to the
presence of the lead aircraft. Namely, a lead aircraft that is not reporting turbulence is interpreted to indicate that there is no turbulence at its location. Thus, in scenario 5, the subjects likely decided that the turbulence would abate in the near future, and thus a change of altitude might not be warranted. In contrast, although the subject’s ride was smooth in scenarios 3 and 4, the prospect of turbulence ahead, due to the pilot report, was sufficient to lead many subjects to request a change in flight plan.

The remaining three scenarios were not presented in the online survey; however, they were examined in the follow-on study.

Scenario 6 is the baseline condition for all of the cases in which turbulence was acting on the pilot’s own aircraft. In this scenario four of the pilots chose to change course immediately, five asked for more information, and the remaining pilot proceeded as planned. As in scenario one, the ambiguous results likely stem from the ambiguous baseline condition in which turbulence is forecast but no updates have been presented.

In Scenario 7, in which the lead aircraft reports turbulence, seven pilots changed course immediately, and three pilots asked for more information. In Scenario 8 the lead aircraft reported turbulence and asked for an altitude change. Eight pilots asked to change course immediately and two requested more information. Even with the small sample size available from the follow-on study it suggests that the presence of turbulence on their own aircraft causes pilots to give more weight to the reports of the aircraft ahead of them, especially when the report confirms what the pilot is experiencing on his own aircraft.

In addition to selecting between the three options, several subjects wrote comments regarding what additional information they would have liked to have had in the scenarios. The types of additional information requested included: alternate altitudes or flight paths with smoother air
(mentioned by 13 pilots of the 91); type of aircraft reporting the turbulence (by 10 pilots); spatial extent of the problem, or how long turbulent conditions would last (by 9 pilots); and the ride quality of other aircraft in the area (by 7 pilots). Other factors that would also be considered by the air transport pilots (as expressed in the additional comments for this question) include cabin concerns (i.e., whether meals are being served, mentioned by 5 pilots), the recency of the pilot report (mentioned by 3 pilots), fuel (mentioned twice) and penalty of diversion (mentioned twice). In the general comments section, diversion penalties, weather conditions, wind profile, airborne traffic, and cabin concerns (mentioned once or twice each) were also listed as other factors influencing the replanning decisions.

The effect of turbulence on the pilots’ own aircraft appears to make the pilot more cautious. As was suggested in the online study, it is almost as if the pilot report is a surrogate weather information source. The information from the follow-on study further develops that thought by adding that if the pilot’s own aircraft is flying in calm air then turbulence reports from the lead aircraft are taken more skeptically. However, when there is turbulence acting on their own aircraft, the pilots react more strongly to the reports and actions of the lead aircraft.

3.3 Weather Case Scenarios

The second part of the follow-on study was a study of the impact of pilot reports on replanning choices around a weather system. In the study, pilots were presented with a weather radar display and three route options (Fig. 3.4). The choice of Route A was to remain on their current path at 31,000 ft (FL310), which led directly into the weather, Route B was a climb of 4000 ft to FL350, and the third choice, Route C, was a deviation to the North around the weather
system at FL 310. Figure 3.4 is an example of a test scenario in which a report of moderate chop is being given by a lead aircraft on route A (as shown by the diamond symbol).

There were fourteen separate scenarios tested, and the order was counterbalanced with each pilot in order to compensate for learning effects throughout the study. The scenarios went through the following situations on each route: absence of a lead aircraft, presence of a lead aircraft, lead aircraft reporting light chop, and a lead aircraft reporting moderate chop (Table 3.2).

Table 3.2: Weather Case Scenarios Test Matrix

<table>
<thead>
<tr>
<th>Location of Lead Aircraft</th>
<th>Route A</th>
<th>Route B</th>
<th>Route C</th>
</tr>
</thead>
<tbody>
<tr>
<td>no lead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lead; no report</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lead; light</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lead; moderate</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The scenarios were presented with a light weather picture which showed an entirely green cell. Additionally, the scenarios involving Route A were repeated with a slightly worse weather display reading in order to explore the effect of harsher weather on the replanning process. This weather cell included some areas of yellow along the route of flight.

For each scenario in the weather radar case study, the pilot was asked to use the Analytical Hierarchy Process (AHP) to rate the route choices that were presented. The Analytical Hierarchy Process is used to obtain subjective preferences of multiple options. It provided a means of evaluating multiple design options using weighted ranking scales (Yang & Hansman, 1995). The process breaks up multiple options into a series of paired comparisons which are then recombined to produce an overall weighted ranking. Most importantly, AHP retains information about the relative size of the intervals between the rankings. So it is possible to know how much better one option is than another. The final result of AHP is a chart in which the dominance of an option is given by its area in the chart; the larger the area, the more dominant the option.

For all of the scenarios, route C was the most preferable option, with routes A and B taking up smaller portions of the graphs as in Figure 3.4. What these results mean, besides the fact that route C was the most preferable option of all three, however, is that route B was the second most preferable route, and route B was preferred about three times as much as route A. Figure 3.4 shows the results for the scenarios with light weather in which the lead aircraft, if there was one in the specific scenario, was on route A. The interesting result from these scenarios is the decreasing preference for continuing through the weather as the lead aircraft first reports light chop and then requests an additional altitude change. This supports the conclusions from the previous turbulence case scenarios that lead aircraft are used as surrogate ride quality sensors. When the lead aircraft indicates via radio requests that the weather is worse, the pilots use the new
information to replan their routes. Figure 3.5 gives the graphed results for the scenarios in which moderate weather was shown. Again, the preference for continuing through the weather
decreases as the lead aircraft reports light chop and then asks for an altitude change, however the decrease is not nearly as large as it was in the light weather scenarios. This suggests that pilot reports do not add as much additional information when the weather is more severe. When the weather is lighter it is more ambiguous to the pilots whether they should deviate or not. However, when the weather is more severe, pilots obtain enough weather information from radar, and pilot reports appear to hold less weight.

3.4 Conclusions

The results of the survey show that pilot reports play a significant role in decision-making related to turbulence. In fact, the lead aircraft is seen as a surrogate ride quality sensor. A pilot report of turbulence from a leading aircraft along the route of flight significantly alters the following-pilot's preference from “request more information” to “change flight plan”. The lack of a pilot report from another aircraft in an area of previously-reported turbulence likewise significantly alters pilot preference from “request more information” to “proceed as planned”. This implies that the lack of a pilot report may be interpreted as a report of “no turbulence.” An aircraft that issues a pilot report for turbulence and also requests a change in altitude does not significantly alter following-pilot preferences to change course over that which occurs when the pilot report alone occurs, suggesting that the deviation request does not provide much additional information over the ride report itself.

The results from the weather scenarios also support the conclusions drawn in the turbulence scenario. Pilot reports from other aircraft have a strong influence on which route a pilot is willing to take. If there is a report of turbulence within the weather system then the pilot is not willing to follow the route into the system. However, if a pilot is near a weather system with a lead aircraft
not reporting turbulence, then the pilot may be willing to penetrate the weather. Due to the hazards associated with penetrating severe weather, pilots are reluctant to penetrate areas which are shown as severe weather on their weather radar in spite of what any PIREP is saying. However, when weather is less severe, pilots are more willing to consider the option of penetrating weather and so they look to the PIREPs for any additional information that is not provided by the weather radar.

Overall, in the survey of pilots, weather concerns are cited as the most common initiators of replanning. Since PIREPs and weather radar are the only real-time local sources of weather information available to the pilot other than the view out the windsreen it makes intuitive sense that they are also the most commonly cited sources of information used during replanning.
Chapter 4
Proximity to Weather Analysis

4.1 Objective/Impetus

The results of the weather deviation portion of the follow-on survey clearly demonstrated the complicated nature of the decision-making process. For example, there appeared to be a relationship between the severity of weather and the usefulness of PIREPs. In order to understand more about pilot behavior in the presence of weather, and in order to translate subjective weather hazard risk into objective terms that could be incorporated into an automated decision aid, an analysis of pilot tendencies to deviate around weather was conducted.

4.2 Aircraft and Weather Data Collection

Courtesy of MIT Lincoln Laboratory, data was obtained for the hours of 2100 GMT on May 19, 1997 to 0900 GMT on May 20, 1997 from the Dallas Fort-Worth enroute sector, which spans 500 nmi from New Mexico across all of Texas. Both flight track data and weather precipitation data were analyzed. To restrict the analysis to enroute aircraft, only data for flights above 30,000 ft were used.

Flight track information is archived by the Federal Aviation Administration (FAA) for fifteen days. The data for days on which weather caused significant delays to the air traffic control system are then given to MIT Lincoln Laboratory. Flight track data is recorded by Air Route Surveillance Radars (ARSR), and although the data is updated every twelve seconds by the radar, the Host computer, which is the central processing system for air traffic control, “coasts” the data and provides six second updates for the controllers. The data used in this analysis were updated
every six seconds. The weather precipitation data was collected by the National Weather Service which collects weather data on NEXRADs (Next Generation Radar) stationed throughout the country. It was further processed by Weather Services International (WSI) and then archived at Lincoln Laboratory. The weather data was updated every five minutes for the full twelve hours of interest and provides the location of storms as well as the six precipitation levels.

4.3 Data processing

Data processing consisted of the following steps: First the flight track data and weather precipitation data were correlated into one coordinate system and movies were made of aircraft progress versus weather. Second, the weather was “contoured,” meaning that polygons were fitted to the edges of weather cells, and an algorithm was written to determine the distance from each aircraft to each level of weather. This algorithm also returned values for total duration in weather. Finally, data was extracted in order to determine the intensity of the precipitation as a function of altitude (termed echotops data).

The first step in processing the flight track and precipitation data, correlating the coordinate systems of the data types and plotting them together, was accomplished using Weather Shell, a program provided by MIT Lincoln Laboratory. This program made it possible to add the outlines of the high-level enroute sectors, state boundaries, jetways, and runways. Then these images were formed into continuous streams of data, or “movies” of the full twelve hours. Figure 4.1 is an image from one of the movies made with Weather Shell depicting traffic in the ZFW high altitude enroute sector. The white lines are state boundaries. The aircraft are labeled with their transponder codes, and they have trails behind them displaying their positions for the five minutes prior to the current reading.
As mentioned above, the traffic in the movies updated every six seconds, with the weather data updating every five minutes. With such a mismatch in update rates, if both the traffic and the weather started playing at time zero, then the error in the measurements of the minimum distance to weather for each aircraft could be significant after five minutes. In order to reduce the error in the measurements of aircraft proximity to weather, the timing of the weather updates was offset by 2.5 minutes. In this manner, the aircraft and weather data would be mismatched by no more than 2.5 minutes.

In order to take measurements, contours were made of the weather data. A contouring program, provided by MIT Lincoln Laboratory, created outlines of each of the various levels of weather. Contour vertices were plotted at every pixel on the edge of a weather cell (corresponding
to 1 km distances). Using these polygon data, the minimum distance from each aircraft to each level of weather was determined every six seconds.

Finally echotops information was extracted from the WSI data. Echotops information gives the altitude at which the dBz level is 18 dBz or higher (Level 1 weather or above). By correlating the echotops data with the flight track data, it is possible to determine whether the aircraft is flying within a storm. Unfortunately echotops information is only available for the TRACON area 200 km around the DFW airport, so, in this study, it is only used as a gauge for the general height of storms in the entire enroute sector. The echotops information indicates that the aircraft generally were below the tops of the weather.

4.4 Results

In order to focus on just those aircraft in the vicinity of weather, the results that are presented here include only those aircraft that entered weather of level 2 or higher. There are 2 main metrics used in this thesis, duration to weather and proximity to weather. Duration was defined as the accumulated time spent within a given level or a level of higher intensity. Time in level 2, for example, also included time spent in levels 3 or higher, and thus serves as a metric of the total time spent within a region of precipitation.

4.4.1 Weather Conditions

Figure 4.2 depicts the percentage of the sky that was covered by each level of precipitation during the twelve hour period of interest. The percentage is defined as the total area of each weather level divided by the total area of airspace.
Figure 4.2: Percentage of Sky Covered by each Precipitation Level

As shown in the figure, Level 2 covered the largest percentage of the sky, with a maximum of approximately 7% of the sky covered in Level 2 precipitation. Although level 2 precipitation only covered 7% of the sky it was scattered over several regions, and 32% of the aircraft penetrated level 2 weather. The amount of sky covered by each level decreases incrementally with each higher level of precipitation. Level 3 covers approximately half of the area of Level 2, and Level 4 covers approximately half of the area of Level 3, etc.

Figure 4.3 depicts the relative percentages covered by levels 3 through 5 relative to the area covered by level 2 over the complete time frame.
As shown in Figure 4.3, the weather improved slightly over the twelve hour period. This is apparent because the more severe levels covered smaller percentages as time progressed. Averaging the values in the graph over time for each level determined that level 3 covered 48% of the area covered by level 2 precipitation. Level 4 covered 23%, level 5 covered 9%, and level 6 covered 3%.

By modeling the weather as circular regions and assuming no deviation effects, we can roughly estimate the expected number of aircraft that would enter each level of weather and then compare it to the actual data. Figure 4.4 depicts the model of area that is used to compute the expected number of aircraft and expected duration of each aircraft in the various levels of weather.
Looking at Figure 4.4, assume that the large circle represents level 2 weather and that it has an area of 1. The shaded inner circle represents a more severe level of precipitation, for this example let us assume that it is level 3 precipitation, and is given the area fraction, \( A \). Assuming a uniform distribution of traffic and no diversion, the expected fraction of aircraft which will enter level 3 precipitation relative to those that will enter level 2 is the ratio of their diameters. Due to the relationship between radius and area, the expected fraction of aircraft which will enter level 3 precipitation, \( f \), is therefore equal to the square root of the area fraction, \( A \):

\[
 f = \frac{2r_1}{2r_2} = \frac{2\sqrt{A}}{\pi} = \sqrt{A}
\]

(1)
Furthermore, the expected duration ratio, \( r \), that an aircraft would spend in each level relative to level 2 can be computed using this model. Figure 4.5 depicts the duration, \( d \), that an aircraft spends within level 3 weather.

![Figure 4.5: Weather Model for Expected Duration Calculations](image)

The duration that an aircraft spends in the weather depends on where it crosses the circle. In particular, an aircraft passing a distance \( x \) from the center of the circle would have a duration of

\[
d = 2 \sqrt{(r_1^2 - x^2)}
\]

in that precipitation level. The expected duration in level 2 weather is then given by taking the average duration for values of \( x \) between 0 and \( r_2 \):

\[
\bar{d}_{\text{level2}} = \int_0^{r_2} \frac{2\sqrt{(r_1^2 - x^2)}}{r_2} \, dx = \frac{\pi r_2}{2} = \frac{\sqrt{\pi}}{2}
\]  

(2)
using the fact that $r_2 = \sqrt{1/\pi}$. The expected duration of the same group of aircraft in level 3 is found using the same method as for level 2, but must account for the fact that some aircraft never enter level 3. Thus the overall expected duration in level 3 is the average duration given an aircraft enters level 3 times the fraction of aircraft entering level 3:

$$d_{level3} = \left( \frac{\pi r_1}{2} \right) \sqrt{A}$$

(3)

The ratio of expected durations in level 3 precipitation relative to the duration in level 2 weather is then:

$$\tau = \frac{d_{level3}}{d_{level2}} = \frac{\pi r_1 \sqrt{A}}{\frac{\sqrt{\pi}}{2}} = r_1 \sqrt{\pi A} = A$$

(4)

since $r_1 = \frac{\sqrt{A/\pi}}{}$. So the total expected duration ratio in level 3, relative to the duration in level 2, is simply the area fraction, A.

Table 4.2 summarizes these relationships. The overall area covered by each level of precipitation is shown, relative to the area covered by level 2. Also shown are the expected and observed fractions of aircraft that entered each level, and the overall expected and observed average duration in each level.

The aircraft penetration and duration data will be explained further in Section 4.4.3.
<table>
<thead>
<tr>
<th>Precipitation Level</th>
<th>Area fraction</th>
<th>$f$ Expected to enter</th>
<th>Observed to enter</th>
<th>$\tau$ Expected duration</th>
<th>Observed duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (reference)</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>0.48</td>
<td>0.69</td>
<td>0.73</td>
<td>0.48</td>
<td>0.43</td>
</tr>
<tr>
<td>4</td>
<td>0.23</td>
<td>0.48</td>
<td>0.40</td>
<td>0.23</td>
<td>0.14</td>
</tr>
<tr>
<td>5</td>
<td>0.09</td>
<td>0.30</td>
<td>0.10</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>6</td>
<td>0.03</td>
<td>0.17</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
</tr>
</tbody>
</table>

As can be seen in Table 4.1, increasingly fewer aircraft entered levels 4-6 than would be expected based on the simplified geometrical model of weather. Also, the average duration spent in levels 3 and above was lower than would be predicted by the model. Although the model overestimates the number of entering aircraft for levels 4, 5, and 6, the model underestimates the fraction of aircraft to penetrate level 3 precipitation by 0.04. This indicates that the aversion to level 3 weather is not as strong as for higher levels of precipitation.

4.4.2 Example Aircraft Behavior

Figure 4.6 depicts the minimum distance from one example aircraft, transponder code 0088, to each level of precipitation as it flew across the enroute sector. As the aircraft entered the enroute sector it encountered a weather cell which included precipitation levels 2-6. As the aircraft flew through the weather cells, the minimum distance from the aircraft to precipitation increased with respect to each successive level of weather. The aircraft then exited that cell and flew northwest across the enroute sector and entered a second weather cell. The second cell did not include level 6 precipitation. Note that when the aircraft penetrated weather, it is shown as 0 distance in the plots.
Figure 4.6: Minimum Distance from Aircraft 0088 to Each Level of Precipitation
Figure 4.6: Minimum Distance from Aircraft 0088 to Each Level of Precipitation
Figure 4.6: Minimum Distance from Aircraft 0088 to Each Level of Precipitation

The jumps in data that are evident near 0600 GMT in some of the plots are due to the mismatch in update rates between aircraft and weather data. Although the weather was offset by 2.5 minutes to minimize error, in some cases the weather moved significantly or disappeared (as was the case with the level 5 precipitation) and caused a jump when the update occurred.

Additionally, as the aircraft flew through the weather cells, the duration spent in each level of precipitation decreased with each successive level of precipitation, as shown in Figure 4.7. As
discussed above, the increasing minimum distance and decreasing duration in successive levels of weather is indicative of weather factors. First, there was less weather for the pilot to encounter, and therefore the plane spent less time in and was farther away from the higher levels of weather, and second, the aircraft was purposefully diverted to avoid these areas of more severe weather as described in Table 4.1.

4.4.3 Overall Duration in Precipitation

1095 aircraft flew through the ZFW enroute sector between 2100 GMT on May 19, 1997 and 0900 GMT on May 20, 1997. Of those aircraft, 353 (32%) penetrated level 2 weather or higher. The average times the 353 aircraft spent in weather are depicted in table 4.2.
Table 4.2: Duration in Precipitation

<table>
<thead>
<tr>
<th>Weather level</th>
<th>Average duration in weather (sec.)</th>
<th># of aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>82.2</td>
<td>353</td>
</tr>
<tr>
<td>3</td>
<td>30.6</td>
<td>257</td>
</tr>
<tr>
<td>4</td>
<td>8.4</td>
<td>142</td>
</tr>
<tr>
<td>5</td>
<td>1.2</td>
<td>35</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

No aircraft penetrated level 6 precipitation. Figure 4.8 shows four histograms of the duration that aircraft spent in precipitation levels 2-5. The histograms only depict data from the 353 aircraft which penetrated level 2 weather.
Figure 4.8: Histograms of Average Duration in Precipitation Levels 2-5
Figure 4.8: Histograms of Average Duration in Precipitation Levels 2-5
As shown in the histograms, level 2 was the most frequently penetrated level, and aircraft spent the most time in level 2 precipitation. As the levels increase, the graphs shift to the left with more aircraft spending less time in the weather or not penetrating the higher levels at all. The graph for level 5, for example, demonstrates that 90% of the 353 aircraft did not penetrate level 5, and the aircraft which did penetrate spent 30 seconds or less in the weather.

4.4.4 Minimum Distance to Precipitation

Figure 4.9 shows the cumulative distribution of the minimum distance to each level of precipitation by all 1095 aircraft in the enroute sector. It is possible from this graph to determine

Figure 4.9: Cumulative Minimum Distance to Precipitation Levels
how close a certain percentage of pilots flew to the different levels of precipitation. For example, 50% of pilots flew within 1.0 nmi of level 2 precipitation, within 1.6 nmi of level 3 precipitation, within 2.9 nmi of level 4 precipitation, within 5.6 nmi of level 5 precipitation, and 50% flew within 13.2 nmi of level 6 precipitation. From this graph it is also possible to determine the fraction of pilots that penetrated each level of weather by looking at the 0-distance reading on the left-hand side of the graph. For instance, it can be seen that 32% of the aircraft entered level 2, as discussed in the previous section.

Figure 4.10 depicts the average minimum distance to each level of precipitation. While the increases in minimum distance are relatively small for levels 2 through 5, the distance between the aircraft and level 6 precipitation is almost twice the minimum distance to level 5.
4.4.5 Leader and Follower Aircraft

The last stage of the analysis was to choose pairs of leaders and followers and analyze whether the presence of a lead aircraft affected the following aircraft’s duration in or proximity to weather. A total of 33 leader/follower pairs were chosen subjectively using the “movies” that were created of the flight track data correlated with the weather precipitation data. If two aircraft, both traveling the same direction, started and finished crossing the sector at the same locations and one aircraft was ahead of the other, then they were considered a leader/follower pair. The altitude of the two aircraft were not compared (though both had to be above 30,000 ft). It is not possible to know if there was actual communication between the aircraft, as the audio tapes were not archived, however, it is assumed that the following aircraft had knowledge of the leading aircraft’s position and weather situation, either through PLI, specific ATC communication, or traffic display Figures 4.11 and 4.12 depict the correlation between leader and follower duration in precipitation levels 2 and 4, respectively.

![Graph showing correlation between leader and follower duration in level 2 precipitation](image)

Figure 4.11: Correlation between leader and follower duration in level 2 precipitation
The effect of the leader on the following aircraft’s behavior was not statistically significant in either level 2 or 4 precipitation. The solid line shown has a slope of 1 which would indicate no difference between the leader and follower aircraft. The dashed line demonstrates the actual correlation shown. Although the correlation was not statistically significant, it does, in both cases, demonstrate a slight tendency towards following the actions of the lead aircraft and to spend less time in the weather.

Similarly, the leaders did not have a statistically significant effect on the minimum distance that following pilots flew with respect to either level 2 or 4 precipitation. Figures 4.13 and 4.14 depict the correlation between leader and follower proximity for levels 2 and 4 respectively.
Figure 4.13: Correlation between leader and follower proximity in level 2 precipitation

Figure 4.14: Correlation between leader and follower proximity in level 4 precipitation
The correlation analysis demonstrates that there was almost an exact correlation between the distances that leaders and followers flew to precipitation levels 2 and 4. However, on average, the followers flew slightly farther away from precipitation, with the leaders flying an average of 12.1 nmi away and the followers flying 12.3 nmi away from level 2 precipitation and an average of 15.3 nmi and 15.7 nmi for leader and followers from level 4 weather, respectively. These differences are not statistically significant.

It is interesting to note that when the aircraft pairs were analyzed with respect to level 4 precipitation both the leaders and followers added an additional 3.3 nmi to their minimum distance from weather on average.

4.5 Conclusions

From the analysis of the flight track data and weather precipitation data it appears that the presence of a lead aircraft did not greatly reduce the amount of time that a following aircraft spends in either level 2 or level 4 weather. Additionally, the presence of a lead aircraft did not significantly influence how close a following aircraft would fly to either level 2 or 4 precipitation.

One explanation for these results is that the weather during this particular twelve hour period was severe enough to cause all pilots to deviate. As shown in the survey, when pilots were near moderate or severe weather, PIREPs (if any were given) were not a significant factor in decision making. In other words, the weather radar provided all of the necessary information to alert pilots to the weather severity. Since the weather in the twelve hour period used in the flight track and weather intensity analysis was severe, the leading aircraft diverted around it, despite the fact that there were no lead aircraft ahead of them (in most cases). The following aircraft would likely have made the same diversions whether or not there was a lead aircraft.
Chapter 5
Summary

Pilots frequently encounter unforeseen obstacles enroute that cause them to "reroute" or change their original flight plan. When these in-flight replans are required, pilots must integrate various information sources to determine the most efficient and safe route around the obstacle. With the increasing amounts of technological ability in the cockpit it may be possible to create a decision aid to both display weather information in a more readily understandable format than is currently available as well as to assist pilots with their enroute replanning decision aids. Several studies have shown that weather is rated by pilots as the most common source of in-flight replans. Accordingly, this thesis focused on pilot behavior in the presence of weather in the enroute sector. The ultimate goal is to gain an understanding of behavior around weather to incorporate into and improve decision aids.

In order to create such a decision aid, information is needed about pilot behavior in response to varying levels of precipitation. In order to collect this information two Dallas Fort-Worth (ZFW) enroute sector for twelve hours during a cold front passage.

Specifically information was collected about pilots' behavior using hypothetical precipitation and turbulence scenarios. Finally, the data analysis of the ZFW enroute sector examined the question of how close pilots are willing to fly to various levels of precipitation.

The survey of pilot preferences and decisions was conducted using a form posted on the world wide web. The survey requested input on potential cockpit enhancements and also probed pilot decision-making behavior through a series of in-flight scenarios. Over 300 responses were
obtained, of which 29% were Air Transport Pilots. 10 pilots participated in a follow-on survey consisting of person-to-person interviews.

The results of the survey show that pilot reports (PIREPs) can play a significant role in decision-making related to turbulence. In fact, the lead aircraft is often seen as a surrogate ride quality sensor and the lack of a pilot report may be interpreted as a report of “no turbulence.” From the analysis of the flight track data and weather precipitation data it appears that the presence of a lead aircraft near severe weather does not greatly influence the duration that the following aircraft spends in either level 2 or 4 weather. Additionally, the presence of a lead aircraft does not seem to influence how close a following aircraft will fly to either level 2 or 4 precipitation when near severe weather.

Therefore, more severe weather appears to reduce the impact of PIREPs. When weather is severe, then pilots gain enough information from weather radar to not consider the option of penetrating the weather. The PIREPs do not add any additional information. When weather is less severe, pilots have the option of penetrating, and so they look to the PIREPs for any additional information that is not provided by the weather radar.

In order to create a decision aid which would reliably aid pilots in their rerouting decisions it is important to look not only at the enroute sector but also at pilot behavior in the terminal area. Several studies have been performed in the terminal sector, so the results need to be correlated and verified. Additionally, it would be useful to correlate the distance and duration data with the type of aircraft that each piece of data came from. Smaller aircraft have different weather tolerances than larger aircraft do. That way a decision aid could be tailored to fit the specific type of aircraft in which it is being installed.
Weather is a complex hazard, and translating weather information into a form that can be used by an automated system is a challenge that will continue to be addressed by researchers in the future. As a preliminary step in this direction, however, the observations of enroute aircraft proximity to weather may be used to develop a simplified, prototype model of weather as a hazard. For example, based on the results of this study, level 6 might adequately be modeled as a hard hazard since no aircraft were observed to enter it. Levels 2 through 5, however, had some degree of softness since aircraft did penetrate them. A simplifying assumption is that pilots penetrated the weather only as far as they considered to be acceptable. Because radio transcripts or pilot reports were not available, it is not known whether any of the penetration events resulted in significant problems for the flight crews or posed other safety threats. The assumption at this stage is that all penetration events were acceptable to the pilots who flew them. With this assumption, another way of interpreting the duration data is that it defines the maximum amount of duration that would constitute an acceptable route through weather. For example, since no aircraft were observed flying more than 150 sec. through level 4 precipitation, a trajectory that involves more than 150 sec. of flight through level 4 would not be acceptable to any pilot. This assumption is reasonable given the fact that the pilots, on average, originally had significantly longer trajectories through each level of precipitation, but deviated to reduce that exposure according to the data in Table 4.2.

A decision aid created to assist with enroute replanning might be designed in several ways. There are at least two aspects at the core of the design questions. First there is the question of how the decision aid is going to be used. A decision aid could be created in which pilots could enter trial waypoints and the decision aid could analyze if this route would be acceptable based on current weather information. Another option is to have the decision aid continuously monitoring
the current plan, as in the model described in Section 2.1, and also assessing other routes to
determine if they are more efficient in terms of time or fuel burned. If the decision aid finds a
route which is both more efficient than the current route and also acceptable in terms of weather
hazards, it could alert the pilot. In order to be readily accepted by pilots, such a decision aid must
reflect the mental models held by pilots with respect to behavior around weather.

The second design issue is how the weather should be modeled in order to most accurately
reflect the pilots’ mental models. There are three ways in which a decision aid might incorporate
the weather data which was gathered in this analysis. The first would be to define certain levels of
weather which a decision aid would simply avoid as it would any hard hazard. The results from
this analysis suggest that level 6 should be treated as a hard hazard and avoided in this manner.
However, this method of creating a decision aid does not follow pilots’ apparent mental model of
less severe levels of weather as it would allow pilots to penetrate anything other than the level 6
hard hazard. The second method would involve creating a “safety buffer” around each level of
weather based on the average minimum distances that pilots flew around each level of
precipitation. The decision aid would only find routes to be acceptable if they do not violate this
safety buffer. The third method for creating a decision aid involves calculating the duration that an
aircraft would have to spend in each level of weather for a proposed route. If the duration is below
a certain maximum amount of time that pilots are comfortable with then the route would be
considered acceptable. Initial designs using this approach have already begun (Hyams, Matsumoto, et al., 1999), though additional research is warranted.
References


www.avweb.com

www.NeoSoft.com/~sky/BLUECOAT


Appendix A

Pilot Survey Form

The survey can be viewed on the web at <http://web.mit.edu/tpfan/www/survey1.html>. A hardcopy (edited) version of the survey is shown below.

MIT International Center for Air Transportation

Survey on Inflight Replanning Process

The International Center for Air Transportation and Aeronautical Systems Lab at Massachusetts Institute of Technology is conducting research into the inflight replanning process used by pilots (when the original flight plan needs to be modified). Your voluntary input through this survey is invaluable to us. You do not need to answer all questions if you do not feel comfortable.

The purpose of this survey is to better understand how PILOTS of POWERED AIRCRAFT make decisions and what information they use to make decisions. The survey is not timed, and should take about 20-30 minutes to complete. All responses are confidential and will not be released in connection with any of your individual background information.
Your time and effort in completing this survey are deeply appreciated.

We can be reached at tpfan@mit.edu or dshyams@mit.edu. Or by mail at:

Terence Fan and Debbie Hyam, MIT International Center for Air Transportation, Room 37-117, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Feel free to contact us if you have any further questions or if you would like to participate in any future experiments.

A.) BACKGROUND

These questions are intended to understand your flying background and experience level.

1. Total Flight Hours: ________

2. Actual Instrument Hours: ________

3. Pilot Ratings (mark all that apply):
   - Student
   - Private
   - Commercial
   - ATP
   - Instrument
   - Flight Instructor
   - Glider
Rotorcraft

Multiengine

4. Primary region (and country if outside of US) where you fly (eg: North East US, CONUS, etc.): ________

5. Your Age: ________

6. Your Sex: Male Female

7. What is the primary purpose of your flying (only one choice allowed):
   - Pleasure flying
   - Personal Travel
   - Business Travel
   - Corporate Flying
   - Flight Instruction
   - Air Carrier (Part 121) Flying
   - Part 135 Carrier Flying
   - Other: ________

8. Please list the three aircraft types that you frequently fly, starting with the most frequently flown: ________, ________, ________

B.) FLIGHT OBJECTIVES

Please rank the following flight objectives in order of importance from 1 to 5 with 1 being the most important and 5 being the least important:

   Safety ________
Ride Comfort ________
Fuel Efficiency ________
Schedule Adherance ________
Workload ________

If there is anything else that you would rate as a flight objective, please list here: ________

C.) INFORMATION CONVEYANCE

With respect to the aircraft type that you fly most (indicated in part A), please rate how well certain information elements are conveyed to the pilots in terms of availability (ability to have access to the information on demand), timeliness (degree to which the information represents the current situation), and usefulness (degree to which the information aids your replanning decision).

Rating: 1 denotes no improvements needed; 10 (max) denotes much improvement is needed

<table>
<thead>
<tr>
<th>Information</th>
<th>Availability</th>
<th>Timeliness</th>
<th>Usefulness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of precipitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity of precipitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neighboring Traffic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High terrain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location of turbulence reports</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind information</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional comments:</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

D.) REPLANNING PROCESS

1. What prompts you to evaluate alternative flight plans on your own initiative?

2. On average, for every 10 times that you evaluate the viability of an alternative flight plan, how many times do you actually diverge from the current flight plan?

_______ times
3. How often do you evaluate alternate flight plans by your own initiative while you are enroute to destination? (Choose only one)

   All the time

   Regularly

   Rarely

4. On average, out of 10 times that you actually decide to diverge from the current flight plan, for how many times do you wait:

   ______ Less 1 minute before requesting a re-route with ATC: times

   ______ 1-5 minutes before requesting a re-route with ATC: times

   ______ 5-30 minutes before requesting a re-route with ATC: times

   ______ More than 30 minutes before requesting a re-route with ATC: times

5. How often do you consider the following factors when formulating an alternate flight plan? (10 for always, 1 for never) Please rate also the importance of each of the following in a flight replanning decision (10 is of critical importance, 1 of little importance, more than one factor can have the same rating).

<table>
<thead>
<tr>
<th>Factors</th>
<th>How often?</th>
<th>Rate of importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind information</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nearby traffic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terrain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weather system (storm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbulence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Icing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Restricted airspace</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6. What information sources (e.g. displays, weather maps, PIREPs, flight service stations, etc.) do you consult to determine the need to replan, and in what order typically?
7. To what extent does the non-PIREP information you have usually agree with or conflict with pilot reports?

8. Which information source would you rely on if you have non-PIREP information that conflicts with pilot reports from an airplane similar to yours?

9. Have you ever been in a situation in which you relied upon the reports of the pilots ahead of you despite being given conflicting information? If so, please explain the situation here in as much detail as possible:

10. When you independently decide to change your plan, under what conditions is it typically an altitude change, a heading change or a change in speed. Please describe all three scenarios.

11. While replanning, what questions and under what circumstances do you typically ask the controller?

12. When the controller recommends a route change, what percentage of the time do you accept it as opposed to asking for another variation? Why?

13. If a display were created to assist pilots in the replanning process, what information would you like to see on it?
E.) CASE SCENARIOS

Case 1: Turbulence

A. Imagine yourself in enroute cruise, ATC informs you that "moderate chop" has been reported at your altitude in the airspace you are about to enter in 20 minutes. You would (choose the most applicable answer):

Request a change of flight plan

Request more information: 

Proceed as planned

Additional comments: 

B. At this point you hear from the radio that an airplane about 5 to 10 minutes ahead of you at the same flight altitude is proceeding along your current route of flight. No turbulence has yet been reported from this aircraft. You would (choose the most applicable answer):

Request a change of flight plan

Request more information: 

Proceed as planned

Additional comments: 

C. If you overheard that same airplane (about 5 to 10 minutes in front of you at the same flight altitude) is now reporting "moderate chop", you would (choose the most applicable answer):

Request a change of flight plan

Request more information: 

Proceed as planned
D. If that airplane that is reporting "moderate chop" is also requesting a change in flight altitude, you would:

Request a change of flight plan

Request more information: ________________

Proceed as planned

Additional comments: ________________

E. What if that airplane ahead of you is proceeding straight and has not reported any turbulence, but your airplane is experiencing "moderate chop"? You would:

Request a change of flight plan

Request more information: ________________

Proceed as planned

Additional comments: ________________

Case 2: Precipitation:

A. Imagine yourself in enroute cruise. You encounter a weather system in front of you, as shown on the navigation display below (horizontal situation indicator):
The weather extends to at least 2,000 ft above your flying altitude, and is about 20 minutes from your current location. You would (choose the most applicable answer):

Request a change of flight plan

Request more information: ____________________

Proceed as planned

Additional comments: ____________________

B. There is another airplane (similar type as yours) 15 minutes in front of you (with same heading about to enter the system) at your flight level (as shown in the diagram below). The pilots
of that aircraft have not said anything over the radio. (On the web, dark grey appears green, and light grey yellow)

Request a change of flight plan

Request more information: __________________________

Proceed as planned

Additional comments: __________________________

C. If the other aircraft that is about to enter the weather system is requesting a change in course on the radio, you would (choose the most applicable answer):

Request a change of flight plan

Request more information: __________________________

Proceed as planned
D. If no weather system is shown on the navigation display, but you overhear from the radio that the aircraft in front of you is requesting a detour around weather, you would (choose the most applicable answer):

- Request a change of flight plan
- Request more information: ______________________
- Proceed as planned

Additional comments: ______________________

F.) DISPLAYS:

1. How would you rate the desirability of displaying alternative flight plans in the navigation display (in addition to the current flight plan)? 10 denotes very desirable, 1 denotes not desirable at all: ______

2. If several alternate diversion courses can be displayed, what other information would you like to have to assist in your flight replanning decision? Please check all applicable:

- Expected fuel savings
- Expected time savings
- Expected ride quality
- Other - Please specify: ______________________

3. Would you be interested in having access to a 3-D wind model using the most current data available? 10 is very useful, 1 is not useful at all:

4. How would you rate the usefulness of each of the following means of displaying 3-D wind forecast information? 10 is very useful, 1 is not useful at all
Wind vector field (please see below for an example)

Effective tailwind contours (see below for example)

Selectable altitude range (ability to change altitude of interest for display)

Other features: _______________________

An example of a wind vector field (takes 20 minutes to travel to top of screen along the current flight plan, arrows in different colors):

An example of an effective tailwind contour (takes 30 minutes to travel to top of screen along the current flight plan, arrows in different colors):

G.) AUTOMATION:

Please indicate whether you would like the following replanning functions automated. Scale: 10 denotes a definite need; 1 denotes no desire to have that function automated.
1. Integrating information from pilot reports, etc., in the navigation display (e.g. ride quality rating).

2. Showing the intended paths of nearby aircraft in the display.

3. Incorporating more detailed weather information (e.g. wind forecast).


5. Letting pilots know if an alternative path incurs significant time or fuel savings.

6. Suggest a flight path (possibly different from original plan) that an "experienced" pilot would.

Additional Comments:

This is the end of the survey. Click the "Submit" button when you are done

Submit or Reset
There may be a delay after pressing the Submit button. Please be patient and do not press it more than once. Thank you!

Thank you very much for your time and assistance!
Appendix B

Raw Survey Results

Total Instrument Hours by Pilot Groups

<table>
<thead>
<tr>
<th>Instrument Hours</th>
<th>Air Transport</th>
<th>Commercial</th>
<th>Instrument</th>
<th>Private</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1,735</td>
<td>255</td>
<td>131</td>
<td>20</td>
</tr>
<tr>
<td>Median</td>
<td>770</td>
<td>100</td>
<td>85</td>
<td>3</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2523</td>
<td>574</td>
<td>143</td>
<td>65</td>
</tr>
</tbody>
</table>

Flight Objective Ranking by Pilot Groups

For Commercial Pilots (103 responses used):

<table>
<thead>
<tr>
<th>Objective</th>
<th>Average Ranking</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>1.09</td>
<td>0.45</td>
</tr>
<tr>
<td>Workload</td>
<td>3.22</td>
<td>1.07</td>
</tr>
<tr>
<td>Ride Comfort</td>
<td>3.46</td>
<td>1.16</td>
</tr>
<tr>
<td>Schedule Adherence</td>
<td>3.48</td>
<td>1.25</td>
</tr>
<tr>
<td>Fuel Efficiency</td>
<td>3.76</td>
<td>1.00</td>
</tr>
</tbody>
</table>

For Instrument Pilots (67 responses used):

<table>
<thead>
<tr>
<th>Objective</th>
<th>Average Ranking</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>1.07</td>
<td>0.50</td>
</tr>
<tr>
<td>Workload</td>
<td>3.00</td>
<td>1.142</td>
</tr>
<tr>
<td>Ride Comfort</td>
<td>3.27</td>
<td>1.05</td>
</tr>
<tr>
<td>Schedule Adherence</td>
<td>3.64</td>
<td>1.08</td>
</tr>
<tr>
<td>Fuel Efficiency</td>
<td>4.01</td>
<td>1.01</td>
</tr>
</tbody>
</table>

For Private Pilots (34 responses used):

<table>
<thead>
<tr>
<th>Objective</th>
<th>Average Ranking</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>1.06</td>
<td>0.34</td>
</tr>
<tr>
<td>Workload</td>
<td>2.97</td>
<td>1.03</td>
</tr>
<tr>
<td>Ride Comfort</td>
<td>3.09</td>
<td>1.08</td>
</tr>
<tr>
<td>Fuel Efficiency</td>
<td>3.47</td>
<td>0.93</td>
</tr>
<tr>
<td>Schedule Adherence</td>
<td>4.41</td>
<td>0.96</td>
</tr>
</tbody>
</table>
How often pilots evaluate alternate flight plans by their own initiative

Out of 10 times that pilots actually decide to diverge from an existing flight plan, the time lag before a request to re-route is made is as shown:
For Every 10 Times a Diversion Decision is Made

For Every 10 Times a Diversion Decision is Made

For Every 10 Times a Diversion Decision is Made

0 1-3 4-6 7-9 10
No. of times pilots wait for <1 mins to request clearance

0 1-3 4-6 7-9 10
No. of times pilots wait for 5-30 mins to request clearance

0 0.2 0.4 0.6 0.8 1
Ratio of Pilots

Air Transport
Commercial
Instrument
Private

Air Transport
Commercial
Instrument
Private
For Every 10 Times a Diversion Decision is Made

<table>
<thead>
<tr>
<th>Reasons</th>
<th>No. of Times Mentioned</th>
<th>Commercial</th>
<th>Instrument</th>
<th>Private</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather</td>
<td>97</td>
<td>57</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>24</td>
<td>13</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Winds</td>
<td>15</td>
<td>11</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Traffic at Destination</td>
<td>13</td>
<td>3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Mechanical Problems</td>
<td>12</td>
<td>5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>More Direct Routes</td>
<td>10</td>
<td>9</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Pireps of Poor Ride Quality</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Passenger Request</td>
<td>5</td>
<td>6</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Personal Plans</td>
<td>3</td>
<td>6</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Diversion to Alternate Airport</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Action</td>
<td>Conditions</td>
<td>Commercial</td>
<td>Instrument</td>
<td>Private</td>
</tr>
<tr>
<td>------------------------</td>
<td>---------------------</td>
<td>------------</td>
<td>------------</td>
<td>---------</td>
</tr>
<tr>
<td>Altitude Change</td>
<td>Turbulence</td>
<td>31</td>
<td>32</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Icing</td>
<td>51</td>
<td>27</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Weather System</td>
<td>28</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td>27</td>
<td>27</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Flight Conditions</td>
<td>12</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>To overfly system</td>
<td>7</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fuel</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Heading Change</td>
<td>Weather system</td>
<td>65</td>
<td>36</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Direct Routing</td>
<td>7</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Terrain</td>
<td>6</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Cumulonimbus</td>
<td>6</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Diversion to alternate</td>
<td>5</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Flight Conditions</td>
<td>4</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Traffic, airborne</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Turbulence</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Speed Change</td>
<td>Turbulence</td>
<td>34</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Traffic, airborne</td>
<td>6</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Traffic, destination</td>
<td>4</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fuel</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>ATC request</td>
<td>6</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Storm/weather system</td>
<td>5</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td>3</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

Rating of Importance of Factors Influencing the Flight Replanning Decision
Responses to the Turbulence Case by Pilot Group

<table>
<thead>
<tr>
<th>Question A</th>
<th>Ratio who changes course</th>
<th>Ratio who asks for more info</th>
<th>Ratio who proceeds as planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Transport</td>
<td>0.089</td>
<td>0.633</td>
<td>0.278</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.068</td>
<td>0.583</td>
<td>0.350</td>
</tr>
<tr>
<td>Instrument</td>
<td>0.110</td>
<td>0.521</td>
<td>0.370</td>
</tr>
<tr>
<td>Private</td>
<td>0.094</td>
<td>0.688</td>
<td>0.219</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question B</th>
<th>Ratio who changes course</th>
<th>Ratio who asks for more info</th>
<th>Ratio who proceeds as planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Transport</td>
<td>0.022</td>
<td>0.144</td>
<td>0.833</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.010</td>
<td>0.167</td>
<td>0.824</td>
</tr>
<tr>
<td>Instrument</td>
<td>0.014</td>
<td>0.068</td>
<td>0.919</td>
</tr>
<tr>
<td>Private</td>
<td>0.063</td>
<td>0.219</td>
<td>0.719</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question C</th>
<th>Ratio who changes course</th>
<th>Ratio who asks for more info</th>
<th>Ratio who proceeds as planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Transport</td>
<td>0.533</td>
<td>0.244</td>
<td>0.222</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.356</td>
<td>0.267</td>
<td>0.376</td>
</tr>
<tr>
<td>Instrument</td>
<td>0.264</td>
<td>0.333</td>
<td>0.403</td>
</tr>
<tr>
<td>Private</td>
<td>0.438</td>
<td>0.375</td>
<td>0.188</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question D</th>
<th>Ratio who changes course</th>
<th>Ratio who asks for more info</th>
<th>Ratio who proceeds as planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Transport</td>
<td>0.459</td>
<td>0.306</td>
<td>0.235</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.300</td>
<td>0.400</td>
<td>0.300</td>
</tr>
<tr>
<td>Instrument</td>
<td>0.452</td>
<td>0.233</td>
<td>0.315</td>
</tr>
<tr>
<td>Private</td>
<td>0.581</td>
<td>0.258</td>
<td>0.161</td>
</tr>
</tbody>
</table>
### Responses to the Precipitation Case by Pilot Group

<table>
<thead>
<tr>
<th>Question E</th>
<th>Ratio who changes course</th>
<th>Ratio who asks for more info</th>
<th>Ratio who proceeds as planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Transport</td>
<td>0.325</td>
<td>0.301</td>
<td>0.373</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.330</td>
<td>0.200</td>
<td>0.470</td>
</tr>
<tr>
<td>Instrument</td>
<td>0.243</td>
<td>0.157</td>
<td>0.600</td>
</tr>
<tr>
<td>Private</td>
<td>0.387</td>
<td>0.290</td>
<td>0.323</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question A</th>
<th>Ratio who changes course</th>
<th>Ratio who asks for more info</th>
<th>Ratio who proceeds as planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Transport</td>
<td>0.820</td>
<td>0.101</td>
<td>0.079</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.717</td>
<td>0.192</td>
<td>0.091</td>
</tr>
<tr>
<td>Instrument</td>
<td>0.671</td>
<td>0.247</td>
<td>0.082</td>
</tr>
<tr>
<td>Private</td>
<td>0.806</td>
<td>0.194</td>
<td>0.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question B</th>
<th>Ratio who changes course</th>
<th>Ratio who asks for more info</th>
<th>Ratio who proceeds as planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Transport</td>
<td>0.671</td>
<td>0.212</td>
<td>0.118</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.454</td>
<td>0.330</td>
<td>0.216</td>
</tr>
<tr>
<td>Instrument</td>
<td>0.507</td>
<td>0.282</td>
<td>0.211</td>
</tr>
<tr>
<td>Private</td>
<td>0.742</td>
<td>0.226</td>
<td>0.032</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question C</th>
<th>Ratio who changes course</th>
<th>Ratio who asks for more info</th>
<th>Ratio who proceeds as planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Transport</td>
<td>0.871</td>
<td>0.082</td>
<td>0.047</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.700</td>
<td>0.220</td>
<td>0.080</td>
</tr>
<tr>
<td>Instrument</td>
<td>0.722</td>
<td>0.194</td>
<td>0.083</td>
</tr>
<tr>
<td>Private</td>
<td>0.933</td>
<td>0.067</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Automation Desirability

If several alternate diversion courses can be displayed, the pilots were asked what other information they would like to have to assist in the flight replanning process.

<table>
<thead>
<tr>
<th>Question D</th>
<th>Ratio who changes course</th>
<th>Ratio who asks for more info</th>
<th>Ratio who proceeds as planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Transport</td>
<td>0.121</td>
<td>0.637</td>
<td>0.242</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.208</td>
<td>0.713</td>
<td>0.079</td>
</tr>
<tr>
<td>Instrument</td>
<td>0.297</td>
<td>0.581</td>
<td>0.122</td>
</tr>
<tr>
<td>Private</td>
<td>0.355</td>
<td>0.581</td>
<td>0.065</td>
</tr>
</tbody>
</table>

The pilots were asked if they would be interested in having access to a 3-D wind model using the most current data available.
The pilots were asked to rate the usefulness of each of the following means of displaying 3-D wind forecast information:

- wind vector field
- effective tailwind contours
- selectable altitude range
- other features (specifications requested).
Usefulness of Wind Vector Field Display

Usefulness of Effective Tailwind Display
Usefulness of Selectable Altitude

Usefulness of Other Features