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Abstract

Though flight deck automation has been well received by pilots and by the aviation industry, many automation human factors issues have been raised. In this study we surveyed a wide variety of sources, including pilots and other aviation experts, accident reports, incident reports, documentation on other studies of incident reports, and documentation on experiments, surveys and other studies, to identify and compile evidence related to 92 flight deck automation issues. We created a World Wide Web site (<http://flightdeck.ie.orst.edu/>) to make this information available to the aviation research, development, manufacturing, operational, and regulatory communities.

Introduction

Automation is the allocation of functions to machines that would otherwise be allocated to humans. The term is also used to refer to the machines that perform those functions. Current flight deck automation includes flight directors, autopilots, autothrottles, flight management systems, and centralized warning and alerting systems.

Flight deck automation has generally been well received by pilots (e.g., Wiener, 1989), and Boeing's *Statistical summary of commercial jet airplane accidents, worldwide operations* indicates that the hull loss accident rates for advanced technology (newer generation) aircraft are generally lower than those for comparable conventional (older generation) aircraft (Boeing, 1998). Yet, with

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the advent of advanced technology aircraft and the transfer of safety-critical functions away from human awareness and control, pilots, scientists, and aviation safety experts have expressed concerns about flight deck automation (e.g., Wiener, 1989; Sarter and Woods, 1994; Billings, 1997). These concerns include the possibility that automation may increase pilot workload, that pilots may lack an understanding of automation, and that automation may be unduly complex

Most recently, in response to such concerns, as well as to the occurrence of several accidents involving advanced technology aircraft, the U.S. Federal Aviation Administration (FAA) chartered a team to conduct a human factors study of the automation interfaces of current generation transport category airplanes. Their report (FAA Human Factors Team, 1996) acknowledges the existence of issues surrounding the safety of flight deck automation and makes broad recommendations to address those issues. Our research is in the spirit of those recommendations.

Problem, Objectives, and General Approach

The lack of a comprehensive list of flight deck automation issues has prevented a full understanding of the issues and a coordinated effort to address them using limited research, development, manufacturing, operational, and regulatory resources. Therefore, the objectives of our study were to:

1. develop a comprehensive list of flight deck automation human factors issues;
2. compile a large body of existing data and other evidence related to those issues; and

3. disseminate the list of issues and supporting data to the aviation research, development, manufacturing, operational, and regulatory communities.

Our general approach followed our objectives. In Phase 1 we identified issues and compiled citations of those issues and in Phase 2 we collected a large set of evidence related to those issues. We then created a World Wide Web site to make our findings widely available. The rest of this paper describes our methodology and summarizes our results.

Phase 1: Identification of Issues

To identify flight deck automation issues we compiled a list of possible problems with, or concerns about, flight deck automation, as expressed by pilots, scientists, engineers, and flight safety experts. We reviewed 960 source documents, including papers and articles from the scientific literature as well as the trade and popular press, accident reports, incident reports, and questionnaires filled out by pilots and others. We also surveyed 128 pilots and others experienced with flight deck automation asking them to describe their concerns. In these source documents, we found 2,428 specific citations of problems or concerns with automation and classified them into 114 issues (Funk, Lyall, & Riley, 1995). In Phase 1 we did not attempt to substantiate the claims made about flight deck automation problems. Rather, we merely identified and recorded perceptions of problems and concerns about automation that were identified in written documents, presentations, or other sources.

Phase 2: General Methodology

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In Phase 2 we used a wide variety of sources to locate and record evidence related to the issues identified in Phase 1. The sources we reviewed for evidence included documents describing accident investigations, incident report studies, scientific experiments, surveys and other studies. We also conducted a survey of individuals with broad expertise related to human factors and flight deck automation to obtain their judgements about the validity and criticality of the issues. We reviewed these sources for data and other objective information related to the issues. For each instance of this evidence we assessed the extent to which it supported one side of the issue or the other, and assigned a numeric strength rating between -5 and +5. We assigned a positive strength rating to evidence supporting that side of the issue suggested by its issue statement (supportive evidence) and a negative strength rating to evidence supporting the other side (contradictory evidence).

For example, consider the issue statement of issue065: "Pilots may lose psychomotor and cognitive skills required for flying manually, or for flying non-automated aircraft, due to extensive use of automation." If we found evidence in a source indicating that pilots lose manual flying skills due to extensive use of automation (at least under some circumstances), we recorded an excerpt from the source document and assigned this supportive evidence a positive rating, perhaps as great as +5. If we found evidence in a source indicating that pilots can and do maintain manual proficiency even with extensive use of automation (at least under some circumstances), we recorded an excerpt and assigned

this contradictory evidence a negative rating, perhaps as great as -5.

We developed detailed strength assignment guidelines for evidence from each type of information source. For example, in pilot surveys of automation issues, if at least 90 per cent of the respondents were in agreement with a statement consistent with an issue statement, we assigned a strength rating of +5. If at least 90 per cent were reported as agreeing with a statement contradictory to an issue statement, we assigned a strength rating of -5. To further assure consistency of strength assignment across analysts, both co-principal investigators (the first two authors) reviewed all strength assignments, making adjustments, if necessary.

For each instance of evidence found, we recorded in a database the related issue, an excerpt from the source document describing the evidence, the source document reference information, the type of aircraft and equipment to which the evidence applies (if specified), and a strength rating. During the process of collecting and recording evidence, we revised, updated, consolidated, and organized the issues, yielding a final set of 92 flight deck automation issues. Table 1 presents a subset of the issues (including each issue referred to in this paper). Each issue is listed along with its issue statement and the total number of instances of supportive and contradictory evidence found from all sources. The methods we used for identifying evidence (expert survey, accident reports, incident report studies, and experiments, surveys, and other studies) are described more

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completely in the following sections.

Table 1 goes here.

Evidence from Experts

We conducted a survey of experts to obtain their judgements about the validity and criticality of the issues identified in Phase 1. We used the results of the survey to begin compiling evidence related to those issues.

Method

We asked forty-seven individuals to participate in the survey based on their broad research or performance experience with human factors and flight deck automation. Thirty-six agreed to complete the survey, and 30 completed surveys were returned. The participants included pilots of several automated aircraft types, university researchers, airline management pilots, industry designers and researchers, and government regulators and researchers.

The survey requested general demographics information then presented 114 statements, one for each of the issues identified in Phase 1. Each statement was presented as an unqualified assertion. For example, on the survey the statement related to issue065 was as follows: "Pilots lose psychomotor and cognitive skills required for flying manually, or for flying non-automated aircraft, due to use of automation." (i.e., the qualifier "may" was removed from the statement of the issue). For each statement, the respondent was asked to rate their level of agreement that the assertion was true. The agreement rating was given on a scale from 1 (strongly disagree) to 3 (neutral) to 5 (strongly agree). There was also a

place to mark "cannot address" for each statement. In addition to the agreement rating, each statement was rated for criticality to flight safety from 1 (not critical) to 3 (moderately critical) to 5 (extremely critical). Additionally, there was a place for the respondents to indicate the type of information upon which they based their ratings for each issue. The seven choices for type of information were personal experience, experience of others, personal research data, research data of others, aviation literature, personal opinion, and other (with a space to fill in). The respondents were asked to mark all the types of information that applied.

Results

The responses to each statement were summarized. The six statements that resulted in consistently high agreement ratings from all respondents were:

- Pilots are required to monitor automation for long periods of time, a task for which they are perceptually and cognitively ill-suited, and monitoring errors are likely.
- Cultural differences are not adequately considered in automation design, training, certification, and operations. Because they are not considered, they have resulting effects on performance and how automation is used.
- Transitioning back and forth between advanced technology aircraft and conventional aircraft increases pilot training requirements.
- Although automation may do what it is designed to do, design specifications may not take into account certain unlikely

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but very possible conditions, leading to unsafe automation behavior.

- When two pilots with little automation experience are assigned to an advanced technology aircraft, errors related to automation use are more likely.
- Side sticks are not coupled with each other or the autopilot, reducing awareness of the other pilot's or the autopilot's inputs, resulting in reduced situation awareness and/or improper control actions.

Only one issue generated consistent responses disagreeing that it represents a problem: "Automation induces fatigue which leads to poor performance." The response distributions for the other 107 issues were not as clear cut as for these seven. Distributions ranged from being somewhat skewed to one side or the other (most in support of the problem), to being bipolar, to being almost flat. Several of the bipolar and flat distributions seem to have resulted from some ambiguity in the issue statements. We used the feedback from the survey respondents to clarify and modify issue statements.

The responses for each statement were summarized and included as evidence for that issue. Evidence was recorded for each issue dependent on the results of the agreement ratings. Evidence in support of an issue statement was designated with a strength rating associated with the percentage of responses of "agree" and "strongly agree" combined, and contradictory evidence was recorded based on the percentage of responses indicating "disagree" or "strongly disagree." These strength ratings, ranging from -5 to

+5, were consistent with the strength ratings we assigned to evidence obtained from other surveys we reviewed.

Evidence From Accident Reports

The conclusion of a qualified investigating board that some aspect of automation or its use contributed to the accident is a strong argument that an automation issue exists and needs to be addressed. This is the reason we believed it was important to review accident reports for evidence related to automation issues.

Method

We identified 34 aircraft accident reports we thought might contain evidence related to the flight deck automation issues from the literature, comments from the experts we surveyed, news media, and other sources. We were able to obtain 20 of these reports including reports for the following accidents: Aeromexico DC10-30, Luxembourg; Air Inter A320, Strasbourg, France; American Airlines B757, Cali, Columbia; China Airlines A300-B4-622R, Nagoya, Japan; Eastern Airlines L1011, Miami, Florida; and Trans World B707-331C, Jamaica, New York. We reviewed these reports for statements by the investigating board identifying one or more of the flight deck automation issues as contributing to the accident. In assigning strengths to this evidence, we considered how closely the investigating board's statements about their findings corresponded to a flight deck automation issue identified in our study, and the extent to which the investigating board suggested that the issue contributed to the accident (e.g., probable cause of the event, possible cause, etc.).

Results

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We found evidence related to flight deck automation issues in 17 of the 20 accident reports we reviewed. For example, the issue statement for flight deck automation issue106 is "Pilots may use automation in situations where it should not be used." We found supportive evidence for issue106 in five accident reports. One of these was the report on the accident that occurred when an American Airlines Boeing 757 crashed into mountainous terrain during descent near Cali, Colombia in 1995 (Aeronautica Civil of the Republic of Colombia, 1996). The investigating board wrote the following.

3. CONCLUSIONS ... 3.2 Probable Cause ... Aeronautica Civil determines that the probable causes of this accident were: ... 4. Failure of the flightcrew to revert to basic radio navigation at the time when the FMS-assisted navigation became confusing and demanded an excessive workload in a critical phase of the flight.

In the accident reports we found evidence related to 26 issues, including issue106. In addition to accident reports prepared by official investigating boards, we included in our review several accident reviews by other qualified individuals and teams (e.g., Mellor, 1994). Although we assigned lower strength ratings to evidence from such accident reviews, they were nevertheless a valuable supplement to evidence from the accident reports.

Evidence From Incident Report Studies

We included the review of incident report studies for evidence because, although individual aircraft incident reports can reflect

reporting bias, systematic studies of collections of reports can yield valuable safety information.

Method

We reviewed eight studies of Aviation Safety Reporting System (ASRS) incident reports, including one we conducted ourselves. In each of the incident studies we reviewed, the investigators selected a set of incident reports from the larger ASRS database (currently about 150,000 reports total) based on study-specific criteria, then reviewed the report narratives for information identifying and/or describing issues related to the purpose of their study (often including automation-related issues). We reviewed the investigators' summaries and conclusions in search of evidence for the flight deck automation issues identified earlier in our study. We rated the strength of this evidence based on the percentage of incident reports reviewed that supported or contradicted the statement of the issue.

Results

We found evidence in three of the eight incident studies we reviewed. As an example of our results, consider supportive evidence we found for issue133: "Training philosophy, objectives, methods, materials, or equipment may be inadequate to properly train pilots for safe and effective automated aircraft operation." In one of the incident studies, Palmer, Hutchins, Ritter, and Van Cleemput (1993) compared 50 conventional and 50 advanced technology aircraft altitude deviation reports. Thirty-four of the 50 advanced technology reports (68 per cent) suggested that training was a factor in the reported incident. We assigned a

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strength rating of +3 to this evidence. In the incident report studies we reviewed, we found evidence for 45 issues, including issue133.

Evidence From Experiments, Surveys, and Other Studies

We supplemented evidence from accident reports and incident studies with evidence from experiments, surveys, and other studies (including observation studies).

Method

We reviewed documentation from 18 experiments, 25 surveys (including our own), 15 observation studies, plus four other studies that represented a combination of approaches. In these documents we identified and recorded supportive and contradictory evidence as described above. Strength ratings depended on the type of study reviewed, the methodology and type of subjects used in the study, and the type of evidence yielded by the study.

Results

Experiments. We found evidence for the flight deck automation issues in 15 of the 18 experiment studies. One of the experiment studies yielded both supportive and contradictory evidence for issue105: "Pilots' understanding of automation may be inadequate for the performance of their duties." This was a study conducted by Sarter and Woods (1994) in which 20 airline pilots individually flew 60-minute scenarios on a B737-300 part-task trainer. At various points during each scenario the pilot was asked to perform or describe flight management system (FMS) tasks, and was asked questions concerning his/her FMS-related knowledge. The investigators described the following findings.

Immediately before receiving their takeoff clearance, pilots were asked what procedure they would use to abort the takeoff at 40 kts. ... 16 pilots (80%) ... did not mention that the autothrottles would have to be disconnected to prevent the throttles from coming back up again after manual intervention.

The same study yielded the following contradictory evidence: "in other cases a majority of pilots demonstrated an understanding of rather subtle automation features." Each of these two instances were assigned appropriate strength ratings. In the experiments we reviewed we found evidence for 17 issues, including issue105.

Surveys. We found evidence for automation issues in 24 of the 25 survey studies we reviewed. For example, consider issue013:

"Automation may reduce challenges that are the source of job satisfaction, which may adversely affect pilot performance." In Wiener's (1989) two-phase survey of Boeing 757 pilots he asked pilots to rate their level of agreement with the statement, "Sometimes I feel more like a 'button pusher' than a pilot." In Phase 1 of the study, 18 per cent of the pilots agreed or strongly agreed with the statement and in Phase 2 of the study, 19 per cent of the pilots agreed or strongly agreed with the statement. This is supportive evidence, albeit weak, for issue013. Most survey evidence related to issue013 was contradictory: most pilots like advanced technology airplanes. In the surveys we reviewed we found evidence for 55 issues, including issue013.

Observation studies. We found evidence for the flight deck

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automation issues in 10 of the 15 observation studies we reviewed. For example, consider the following evidence from Weiner (1993) related to issue112: "Procedures for data entry and programming automation may be unclear, overly difficult, complex, and time consuming. This may cause errors and delays that may lead to unsafe conditions."

When the crew attempted to create the waypoint by entering the coordinates (latitude, lat; and longitude, lon) into the legs page of the CDU [FMS Control Display Unit], they experienced considerable trouble due to the fact that the sequence of the clearance did not conform to the format required by the CDU. ... The crew tried one format after another, with growing frustration. Both were 'heads down' in the cockpit for a considerable time trying various formats for data entry.

In the observation studies reviewed we found evidence for 17 issues, including issue112.

Meta-Analysis

In our study we compiled a large amount of evidence on flight deck automation issues from a large number of sources. In an attempt to interpret this information, we conducted an analysis of this evidence. The objective of this meta-analysis was to summarize the evidence collected in Phase 2 to identify those issues that are problems in need of solutions, those issues that do not appear to be problems, and those issues which require more research. To accomplish this we ranked the issues based on several criteria, including the following:

1. number of citations -- the number of (possibly unsubstantiated) citations of each issue as a possible problem or concern, as found in Phase 1;
2. expert agreement rating -- the mean agreement rating given to each issue by the experts in our Phase 2 expert survey (that is, the extent to which the experts agreed with the statement suggested by the issue statement);
3. expert criticality rating -- the mean criticality rating given to each issue by the experts in our Phase 2 expert survey (that is, how critical to safety the experts felt the issue was); and
4. sum of strengths -- the sum of all evidence strength ratings for the issue (that is, a total "weight" of evidence on both sides of the issue.

We also created a composite ranking based on all four criteria: for each issue we summed its ranks for each criterion then produced a "meta-ranking" by sorting the issues in increasing order of this sum.

Considering only the overall "weight" of evidence on both sides of an issue, the sum of strength ratings from all of its evidence, the five issues with the greatest overall supporting evidence and the five issues with the greatest overall contradictory evidence are presented in Table 2.

Table 2 goes here.

After ranking the issues based on each of the individual metrics, we were interested in how they ranked when considering all of these criteria together. The five issues ranking highest and the five issues ranking lowest in the meta-ranking are

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presented in Table 3.

Table 3 goes here.

Discussion and Recommendations

In reviewing these results, the reader should keep in mind several limitations of our overall approach to evidence collection. First, while we attempted to include all published evidence related to flight deck automation issues available at the time of our study, we most likely missed some, and there is certainly unpublished evidence of which we were unaware. Second, the very nature of some of the issues and the nature of the sources we reviewed to discover evidence might have reduced the opportunity for obtaining contradictory evidence.

We consider those issues with the greatest overall supportive evidence (e.g., the first five issues in Table 2) and especially those issues ranking highest in multiple criteria (Table 3) as problems which require solutions. Scarce resources should not be expended on further efforts to show that they are problems -- the evidence already exists. Now the resources should be applied to developing solutions.

We believe that the issues with the greatest overall contradictory evidence (e.g., the last five issues in Table 2) are not significant problems at this time, and resources would be better used in solving other problems (see above) or further exploring unresolved issues. There are possible exceptions to this, one being issue079: "Automation may increase overall pilot workload, or increase pilot workload at high workload times and reduce pilot workload at low workload times, possibly resulting in

excess workload and/or boredom." This issue ranked eighth in number of citations collected in Phase 1, indicating that there is strong feeling that automation does increase workload in certain flight phases, which poses a safety hazard, yet it ranked second in overall contradictory evidence. This contradiction may be explained by considering the evidence about attentional demands separately from overall workload. Issue102 states: "The attentional demands of pilot-automation interaction may significantly interfere with performance of safety-critical tasks. (e.g., "head-down time", distractions, etc.)". Issue102 ranked highest in multiple criteria (see Table 3).

The Flight Deck Automation Issues Website

Our work has yielded a large body of information consisting of flight deck automation issues, unsubstantiated citations of the issues, supportive and contradictory evidence for the issues, and a bibliography of documents related to flight deck automation. To disseminate this information, we created a World Wide Web site (<http://flightdeck.ie.orst.edu/>). While we acknowledge that the quality, permanence, and accessibility of information on the World Wide Web are controversial, we believe that at this time the Web is the best means of making our findings accessible to those who can use it most effectively.

The website covers most of the topics in this paper, but generally in much more detail. In particular, the methodology for each component of Phase 2 (including strength rating assignment) is described more completely, a list of flight deck automation issues is presented, several taxonomies organizing the issues

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under different sets of categories are included, and access to a searchable, read-only version of our database is provided. Our intent is to make all of our findings accessible to individuals and organizations involved in aviation human factors research, flight deck design, flight deck procedure design, flight training, aircraft certification, accident and incident investigation, and other activities related to safe and effective commercial air transportation.

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Table 1. Full issue statements for all issues referenced in this paper. For each issue, the number of instances of supportive and contradictory evidence found are given.

issue	full issue statement	evidence instances (supportive, contradictory)	
issue013	Automation may reduce challenges that are the source of job satisfaction, which may adversely affect pilot performance.	4	6
issue025	It may be difficult to detect, diagnose, and evaluate the consequences of automation failures (errors and malfunctions), especially when behavior seems 'reasonable', possibly resulting in faulty or prolonged decision making.	6	1
issue046	Pilots may lack confidence in automation due to their experience (or lack thereof) with it. This may result in a failure to use automation when it should be used.	16	12
issue065	Pilots may lose psychomotor and cognitive skills required for flying manually, or for flying non-automated aircraft, due to extensive use of automation.	14	12

issue079	Automation may increase overall pilot workload, or increase pilot workload at high workload times and reduce pilot workload at low workload times, possibly resulting in excess workload and/or boredom.	19	25
issue083	The behavior of automation devices -- what they are doing now and what they will do in the future based upon pilot input or other factors -- may not be apparent to pilots, possibly resulting in reduced pilot awareness of automation behavior and goals.	18	4
issue092	Displays (including aural warnings and other auditory displays), display formats, and display elements may not be designed for detectability, discriminability, and interpretability. This may cause important information to be missed or misinterpreted.	32	7
issue102	The attentional demands of pilot-automation interaction may significantly interfere with performance of safety-critical tasks. (e.g., "head-down time", distractions, etc.)	9	3
issue105	Pilots may not understand the structure and function of automation or the interaction of automation devices well enough to safely perform their duties.	37	14
issue106	Pilots may use automation in situations where it should not be used.	10	1

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issuel08	Automation may perform in ways that are unintended, unexpected, and perhaps unexplainable by pilots, possibly creating confusion, increasing pilot workload to compensate, and sometimes leading to unsafe conditions.	16	5
issuel12	Procedures for data entry and programming automation may be unclear, overly difficult, complex, and time consuming. This may cause errors and delays that may lead to unsafe conditions.	13	3
issuel31	Pilots may become complacent because they are overconfident in and uncritical of automation, and fail to exercise appropriate vigilance, sometimes to the extent of abdicating responsibility to it. This can lead to unsafe conditions.	16	4
issuel33	Training philosophy, objectives, methods, materials, or equipment may be inadequate to properly train pilots for safe and effective automated aircraft operation.	25	12
issuel39	The presence of automation may reduce inter-pilot communication, possibly resulting in less sharing of information.	5	5
issuel56	Automation may induce fatigue, possibly leading to poor pilot performance.	3	4

Table 2. Partial listing of flight deck automation issues ranked by overall evidence (sum of strength ratings). See Table 1 for full issue statements.

rank	issue ID	abbreviated issue statement	sum of strengths
1	issue105	understanding of automation may be inadequate	+63
2	issue083	behavior of automation may not be apparent	+35
3	issue131	pilots may be overconfident in automation	+33
4	issue092	displays (visual and aural) may be poorly designed	+32
5	issue133	training may be inadequate	+31
		.	
		.	
		.	
88	issue156	fatigue may be induced	-6
89	issue139	inter-pilot communication may be reduced	-9
90	issue046	pilots may lack confidence in automation	-9
91	issue079	automation may adversely affect pilot workload	-11
92	issue013	job satisfaction may be reduced	-14

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Table 3. Flight deck automation issues ranking highest in multiple criteria. See Table 1 for full issue statements. cit = rank by number of (unsubstantiated) citations, agmt = rank by mean expert agreement rating, crit = rank by mean expert criticality rating, str = rank by sum of evidence strengths.

issue	abbreviated issue statement	cit	agmt	crit	str	sum	rank meta-
issue102	automation may demand attention	1	2	10	18	31	1
issue108	automation behavior may be unexpected and unexplained	3	23	18	8	52	2
issue131	pilots may be overconfident in automation	2	32	23	5	62	3
issue025	failure assessment may be difficult	16	6	17	26	65	4
issue083	behavior of automation may not be apparent	7	20	34	6	67	5
