Differences in Aircrew Manual Skills in Automated and Conventional Flight Decks

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Aircraft flight decks have become highly automated in an effort to maximize aircraft performance, increase terminal area productivity, and reduce fuel costs. Whereas flight deck automation offers significant operational advantages over older conventional flight decks, unintended side effects due to automation have been observed. Among these concerns is the possible change of pilot basic skills in automated aircraft. The differences, if any, in manual flight skills between aircrews assigned to conventional and automated flight decks were examined. Commercial airline crew members flying the conventional transport aircraft or the automated version were observed during line-oriented flight training. Aircraft state and pilot control inputs were recorded for analysis. An observer simultaneously evaluated secondary task accomplishment. Significant differences in manual control inputs were found, particularly during abnormal operations. The results have implications concerning modification of aircrew recurrency training, standard operating procedures, and flight deck resource management to further optimize aircrew performance and safety in automated flight decks.

The increased capabilities of modern transport aircraft, complexity of operations in today's congested environment, and recognition of human limitations have spurred aircraft designers to automate flight decks. Modern aircraft require more skillful handling because of their speed, weights, and the criticality of flight regimes. Furthermore, standard instrument departures, standard terminal arrivals, and noise abatement procedures have become more complex, placing increased demands on pilot and aircraft performance.

Among the many possible assets of flight deck automation are the ability to increase overall system efficiency by improving terminal area productivity and fuel economy and simultaneously increasing safety levels. Specifically, Wiener (*1*) suggests the following advantages that flight deck automation offers:

- Increased capacity and productivity,
- Reduction of manual work load and fatigue,
- Relief from routine operations,
- Relief from small errors,
- More precise handling of routine operations, and
- Economical use of machines.

Undeniably, automation has extended the capabilities of aircraft, but the complexity of piloting has correspondingly increased. An industrywide study (*2*) produced the *National Plan To Enhance Aviation Safety Through Human Factors Improvements* and identified the following issues that need attention with regard to automated aircraft:

- Introduction of unanticipated failure modes;
- Potential for substantially increasing "head-down" time;
- Reluctance of flight crews to take over a malfunctioning system;
- Complacency, lack of vigilance, and boredom in pilots;
- Increases in terminal area work load;
- Incompatibility with present air traffic control (ATC) system;
- Difficulty in recovering from automation failure; and
- Deterioration of pilot basic skills.

Flight deck automation has rapidly changed the nature of the flying task by placing a number of computer-based devices at the pilot's fingertips, thereby replacing the demand for manual control. Management and line pilots are both concerned about a possible change in flying skills due to the use of automation. More than half of the Boeing 757 pilots and 77 percent of the McDonnell Douglas MD-88 pilots interviewed by Wiener et al. (*3*) stated concerns about the possible loss of aviation skills with too much automation.

The concerns of these pilots are not without merit. The man-machine interface has been cited in recent accidents of automated aircraft (*4–10*). Fifty-six percent of all nonfatal, pilot-caused accidents are caused by defective perceptual motor activities, such as aircraft control, judging distance and speed, and so forth (*11–12*). Nagel (*13*) notes that the bandwidth a pilot can achieve is very much a function of the degree to which the control skill is practiced. Furthermore, an analysis of U.S. Air Force accident rates during training (*14*) indicates that the accident rate temporarily spikes immediately following leave periods, leading to the conclusion that the complex skills required to pilot a jet aircraft must be practiced at regular intervals to maintain proficiency.

Experienced line and management pilots believe that pilots must maintain their basic flight skills because of several factors present in today's operational environment. First, very few will question the concept that skills, especially the complex skills required to fly transport jet aircraft, must be regularly practiced to maintain a proficient level.

Second, in today's congested airspace with rapid-fire clearances, it is not at all uncommon for flight crews to become so task-saturated with attempting to program the last-minute changes into the flight management systems (FMS) that many crews have found it much easier and safer to simply revert to manual control.

Third, with the increase in high-density traffic at congested airports, last-minute speed and altitude adjustments will continue to increase, thus causing the frequent "slam-dunk" maneuver that places a premium on the aircrew's ability to maximize the performance of the aircraft in a high–work load environment. Hendricks (*15*) states that such maneuvers place a premium on the pilot's basic aircraft motor skills, perceptual skills, and judgment.

Fourth, physical flying skills are one of five critical elements of situational awareness. Schwartz (*16*) states that flying the aircraft remains the highest order of priority, regardless of other demands

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on a pilot's attention. Maintaining flying proficiency allows a pilot to devote less mental energy to flying the aircraft, thus allowing more attention to be devoted to other needs.

Flight deck automation will be implemented into increasing numbers of commercial aircraft. The subject of this investigation is to determine what differences exist in manual skills between aircrews of conventional and automated aircraft.

OBJECTIVES

This study seeks to complement other studies involving automated flight decks so that future training programs and operating procedures may be updated to increase the safety and efficiency of future air transport systems.

Therefore, this study seeks to determine the following research questions:

- To what degree do manual flying (aircraft control) skills differ between aircrews in automated and conventional flight decks during normal and abnormal operations in terminal airspace?
- To what degree do navigational skills differ between aircrews in automated and conventional flight decks during normal and abnormal operations in terminal airspace?
- If differences exist, to what extent do they affect flight safety?

METHODOLOGY

Experimental Subjects

This study was designed as a one-factor experiment divided into two independent groups: conventional flight deck pilots and automated flight deck pilots. All participants were commercial airline pilots holding airline transport pilot certificates and employed by a single major airline. A total of 48 subjects (24 aircrews; 12 aircrews from each type of aircraft) were evaluated. The groups were classified according to the type of aircraft flown. For experimental purposes, the two aircraft were considered virtually equal in all other parameters except for the degree of automation used in the flight deck. Measurements were taken of both captain and first officer flight performance during simulator training.

All data collection was performed during an afternoon time period to reduce circadian effects for aircrew members who live in various regions throughout the continental United States.

Population Demographics

Aircrews evaluated in this study were chosen by the sponsor airline's crew scheduling department on the basis of the need for annual training required by the Federal Aviation Regulations (FAR). The schedule is primarily dictated by date of hire of the aircrew members. The investigator had no control over aircrew scheduling. There is no method of aircrew assignment that would bias the backgrounds of either the conventional or automated group.

Total flight experience and experience in the specific type of aircraft did not differ markedly between the two groups. Table 1 summarizes the distribution of experience for both groups.

Experimental Device

This investigation was conducted using Phase III six-degree-of-freedom motion simulators of the commercial transport aircraft. The simulator cabs were equipped with instrumentation for VFR and IFR takeoff and landing tasks as well as throttle, gear, and flap controls to accommodate a wide variety of in-flight maneuvers. The cabs were also equipped with hydraulically actuated control loaders, programmed to give the desired dynamic force-feel characteristics of each aircraft during the takeoff and landing phases of flight.

The pilots in the cab were provided with visual, aural, and motion cues. The visual cues gave a 50-degree-wide collimated display to both pilots. A field of view of 150 degrees wide and 40 degrees high was produced using three calligraphic projectors, each driven from three computer-generated image channels.

Measures of Manual Performance

Maneuvers

Pilots of both groups, as part of their annual training, are required to accomplish certain maneuvers. This investigation studied the following terminal area maneuvers:

- Takeoff and initial climb (normal),
- Continued takeoff with engine failure and initial climb,
- Instrument landing system (ILS) approach and landing (normal), and
- Single-engine ILS approach and landing.

Dependent Variables

Crew performance is currently assessed according to four major areas. Communications process and decision behavior, team building and maintenance, work load management and situational awareness, and overall technical proficiency are the four major markers of crew performance. Adherence to FAR/ATC directives, stick and rudder skills, checklist usage, and systems knowledge are the areas graded within overall technical proficiency (*17*).

TABLE 1 Summary of Subject Experience

	"Conventional"		"Automated (hand flown)"	
	Mean	S.D.	Mean	S.D.
Total Time (Captains)	16,250	4,450	16,700	5,200
Total Time (F/O)	8,500	5,900	8,070	6,500
Time in Type (Capt.)	4,540	1,250	4,100	1,200
Time in Type (F/O)	2,440	720	2,430	800

The full range of crew performance markers was evaluated as part of the overall study. However, this report addresses only the stick and rudder portion of overall technical proficiency. Analysis of crew performance markers and operational errors is currently under way and will be reported in future publications.

For purposes of this report, the dependent variables used for evaluating individual pilot performance included aircraft state variables and pilot control inputs. The following aircraft state and pilot control variables were evaluated:

- Aircraft pitch and bank attitude;
- Aircraft indicated airspeed, heading, and altitude;
- Aircraft displacement from glide slope and localizer; and
- Pilot control inputs (elevator, throttles, ailerons, and rudder).

At the start of each of the aforementioned maneuvers, an observer (who was present in the simulator during the training sessions) initiated an algorithm in the simulator's software that made a hard-copy record of the aircraft and pilot inputs for later analysis. The selected parameters were recorded at 10 Hz over the time interval.

Aircraft net deviations across the time interval were calculated as the deviation of the instantaneous pitch-and-bank angle from the time-averaged value. This provided a measure of the closeness with which the pilot maintained the average aircraft pitch and bank throughout the maneuver. The time-averaged value was calculated using the signal's root-mean-square across the time interval.

Confidentiality

All information was immediately coded for security reasons so that no one set of data could be traced back to an individual. The data bases were secured and personal identifiers removed before publication and release of any findings. No information regarding any individual crew member will be released and individual information is maintained only with coded identification numbers.

Test of Statistical Significance

The t-test was used as the measure of statistical significance. The experimental null hypothesis for this study assumed no difference between the two population means. Specifically, this tests the following hypothesis:

$H_O: \mu_1 - \mu_2 = 0$

Using the Cochran-Cox method, the value of t required for an $\alpha = 0.05$ level of significance is 2.069. An observed value of t greater than 2.069 is grounds to reject the null hypothesis.

FINDINGS

Normal Takeoff Performance

During normal takeoffs, the automated crew members exhibited an average of 7.4 pitch oscillations after rotation from takeoff while establishing climb-out speed, whereas conventional crew members exhibited an average of 3.2 pitch oscillations. Automated crews exhibited a mean of 4.3 bank overshoots in turning to the assigned heading on takeoff, whereas conventional crews exhibited a mean of 0.8 overshoots. Maximum bank angle deviations during climb out averaged 14.5 degrees for the automated crews versus 3.2 degrees for conventional crews. Conventional aircrews averaged a 40.0-ft deviation from the assigned altitude on level off, whereas automated crews averaged 150.2 ft.

Table 2 summarizes point estimates of the mean, 95 percent confidence interval estimates, and t-tests of statistical significance of net airspeed, pitch, bank, and heading deviations from assigned values during the maneuver. Clearly, these show significant differences between the means of the two groups and present sufficient evidence alone to reject the null hypothesis.

Normal ILS Approach

Numerical analysis of landing parameters included a summation of the deviation of the airspeed, glide slope position, localizer position, bank angle, and pitch attitude from nominal values (Table 3).

With the autothrottle disengaged, automated crews showed a root-mean-square deviation of 13.6 knots from the final approach speed, with individual maximum deviations ranging from 15.8 knots fast to 13.3 knots slow. Conventional crews showed an average deviation of 5.2 knots, with individual maximum deviations ranging from 0 to 8 knots. The mean of the deviations for the conventional and automated groups was 257.8 and 928.8 knots-sec, respectively. The conventional group again showed less variation within the group than the automated group. This leads one to question what other factors may account for the difference in performance within the automated group.

From an operational standpoint, airspeed deviation is perhaps the most significant finding of this study. Without a forward-mounted camera to detect eye motion, it is unknown whether the automated group's instrument scan had largely left the airspeed indicator out of their scan. Certainly, the cause for this deserves further study.

The average area of the glide slope deviation across the time interval was 11.8 and 24.6 deg-sec for the conventional and automated groups, respectively. Conventional and automated aircrews demonstrated 22.1 and 50.2 deg-sec deviation from the nominal

TABLE 2 Summary of Normal Takeoff Performance

	"Conventional"		"Automated (hand flown)"	
	mean	95% int.	mean	95% int.
Airspeed Deviation (knots-sec)	214.8	$202.1 < \mu < 227.5$	534.2	$517.9 < \mu < 550.5$
Pitch Deviation (deg-sec)	23.0	$21.7 < \mu < 24.2$	45.5	$42.7 < \mu < 48.3$
Heading Deviation (deg-sec)	207.9	$193.0 < \mu < 222.8$	498.3	$480.4 < \mu < 516.2$
Bank Deviation (deg-sec)	129.4	$119.8 < \mu < 138.9$	244.2	$229.6 < \mu < 258.7$

TABLE 3 Summary of Normal ILS Performance

	"Conventional"		"Automated (hand flown)"		t*
	mean	95% int.	mean	95% int.	
Airspeed Deviation (knots-sec)	257.8	248.0< μ <267.5	928.8	846.1< μ <1011.5	15.97
Glide Slope Position (deg-sec)	11.8	11.16< μ <12.3	24.6	21.8< μ <27.3	8.70
Localizer Position (deg-sec)	26.0	24.5< μ <27.5	54.0	50.2< μ <57.8	11.68
Bank Deviation (deg-sec)	67.7	64.0< μ <71.4	207.7	193.5< μ <221.9	9.66
Pitch Deviation (deg-sec)	22.1	21.0< μ <23.1	50.2	47.5< μ <52.8	9.58

pitch attitude during the normal ILS approach. The findings of greater glide slope and pitch attitude deviations by the automated group correlate with each other.

Localizer and bank attitude data show similar trends. The root-mean-square value of the deviation from the centerline of the localizer was 26.0 and 54.0 deg-sec for the conventional and automated groups, respectively. Mean bank deviations were 67.7 and 207.7 deg-sec for the conventional and automated groups.

The *t*-test values between the means were 15.97 for airspeed, 8.70 for glide slope, 11.68 for localizer, 9.66 for bank, and 9.58 for pitch differences. Clearly, all parameters indicate enough difference between the group means to reject the null hypothesis.

V-1 Continued Takeoff Performance

Performance measurements of aircrew performance during the V-1 continued takeoff, summarized in Table 4, display similar trends reported earlier in the normal takeoff section. Conventional aircrews showed smaller airspeed and pitch deviations during this critical maneuver than during normal takeoffs. The areas of airspeed deviations during normal and V-1 takeoffs were 214.8 and 199.4 knots-sec, respectively. This would indicate heightened awareness by the aircrews of the criticality of this maneuver, and the ability of the crew member to fly the aircraft even more precisely with respect to pitch and airspeed control. Heading and bank control suffered somewhat though during the engine-inoperative climb. This is not unexpected due to the large yawing moment produced by asymmetrical thrust.

Automated group performance displayed greater deviations from assigned parameters than the conventional group. The means of the areas of the airspeed deviations are 793.3 and 199.4 knots-sec, respectively, for the automated and conventional groups. Pitch motions demonstrate similar differences between 64.6 and 21.4 deg-sec for the automated and conventional groups.

Heading deviations were 232.1 deg-sec in the conventional group versus 618.8 deg-sec in the automated group. Bank deviations were 146.0 deg-sec in the conventional group versus 304.4 deg-sec in the automated group.

Tests of statistical significance yielded *t* values of 15.1 for airspeed deviations, 15.78 for pitch deviations, 14.76 for heading deviations, and 9.29 for bank deviations. These values of *t* are more than sufficient to reject the null hypothesis.

Unlike the conventional group, which showed only small increases in deviations during this maneuver compared with the normal takeoff, the automated group's performance showed a large increase in deviations from assigned parameters. The automated group's mean area of the airspeed deviation increased from 534.2 to 793.3 knots-sec. The automated group's mean pitch deviation increased from 45.5 to 64.6 deg-sec, corresponding to the airspeed deviations.

Directional control difficulties during the V-1 continued takeoff maneuver were also manifested by larger heading deviations and bank. Heading deviations within the automated group increased from 498.3 deg-sec during the normal takeoff to 618.8 deg-sec during the engine-failure V-1 continued takeoff maneuver. Bank deviations showed similar trends, increasing from 244.2 to 304.4 deg-sec.

Engine-Inoperative ILS

Table 5 summarizes the differences in aircrew performance during the single-engine ILS maneuver. The conventional group showed very little change in airspeed, glide slope, and localizer control between the normal and single-engine ILS. Airspeed deviations were 257.8 versus 257.9 knot-sec between the normal and single-engine ILS maneuvers. Glide slope deviations were 11.8 and 11.9

TABLE 4 Summary of V-1 Takeoff Performance

	"Conventional"		"Automated (hand flown)"	
	mean	95% int.	mean	95% int.
Airspeed Deviation (knots-sec)	199.4	185.8 < μ < 212.9	793.3	757.3 < μ < 829.3
Pitch Deviation (deg-sec)	21.4	20.1 < μ < 22.7	64.6	62.3 < μ < 67.0
Heading Deviation (deg-sec)	232.1	215.2 < μ < 249.0	618.8	599.5 < μ < 638.0
Bank Deviation (deg-sec)	146.0	135.8 < μ < 156.3	304.4	291.2 < μ < 317.5

TABLE 5 Summary of Single-Engine ILS Performance

	"Conventional"		"Automated (hand flown)"		t*
	mean	95% int.	mean	95% int.	
Airspeed Deviation (knots-sec)	257.9	$247.3 < \mu < 268.5$	989.2	$944.4 < \mu < 1033.9$	15.56
Glide Slope Position (deg-sec)	11.9	$11.2 < \mu < 12.6$	25.9	$24.6 < \mu < 27.2$	9.19
Localizer Position (deg-sec)	27.1	$25.5 < \mu < 28.7$	61.9	$59.3 < \mu < 64.5$	11.09

deg-sec, and localizer deviations were 26.0 versus 27.1 deg-sec for the normal and single-engine ILS maneuvers, respectively.

The automated group showed larger increases in performance deviations during the single-engine ILS compared with its performance during the normal ILS. Airspeed deviations increased from 928.9 to 989.2 knot-sec. Glide slope deviations increased from 24.6 to 25.9 deg-sec, and localizer deviations increased from 54.0 to 61.9 deg-sec.

Comparison of the performances of the conventional and automated aircrews during the single-engine ILS yields findings similar to previous maneuvers. Airspeed deviations were 257.9 knots-sec for the conventional group and 989.2 knots-sec for the automated group. Means of the glide slope deviations were 11.9 deg-sec for the conventional group versus 25.9 deg-sec for the automated group. Localizer deviations were 27.1 deg-sec for the conventional group and 61.9 deg-sec for the automated group.

Test of statistical significance yielded t values of 15.56 for airspeed deviations, 9.19 for glide slope deviations, and 11.09 for localizer deviations. Each of these values is sufficient to reject the null hypothesis.

Additional Observations

Whereas this study was structured around the evaluation of aircraft state parameters, the following observations were recorded during this study. None of the conventional flight deck crews allowed the aircraft to drift far enough off course centerline so that a full-scale course deviation indication occurred. However, 80 percent of the automated crews allowed this to happen. These deviations compromise the No Transgression Zone for parallel runway approaches, which requires intervention by air traffic controllers. Twenty percent of the automated crews continued a descent on the approach despite having a full course deviation indication.

Significant and potentially hazardous errors were committed by automated aircrews (40 percent) during level-off at the minimum descent altitude and subsequent descent to the runway environment, which indicate continued problems with the man-machine interface. Inappropriate modes were used to descend, resulting in destabilized approaches with significant sink rates close to the ground, or incorrect numbers were placed in the flight management system.

During last-minute clearance amendments in terminal airspace, many of the automated aircrews attempted to reprogram the FMS, whereas conventional aircrews simply relied on older but simpler methods to comply with the new clearance. Nearly one-third of the events involved both flight deck crew members attempting to reprogram the FMS at the same time. The observer noted that no one was monitoring the aircraft during this segment, nor was any flight deck member scanning for traffic outside the flight deck. The flight crews who most successfully handled last-minute clearance amendments simply turned off the autopilot with the yoke switch and flew the aircraft as a conventional aircraft.

It was also noted that 20 percent of the automated aircrews, when they became disoriented during manual maneuvers, attempted to turn the aircraft back over to autopilot control. The autopilot would not accept aircraft control under these circumstances because the aircraft was out of appropriate airspeed limits. It was clear that this subpopulation relied on the automation to take over when their manual skills were tasked to the limit. As stated in the introduction, flight deck automation should be viewed as an aid to, not a replacement of, aircrew performance.

Though not part of the original experiment, during visual approaches to landing pilot-instructors would command (through the simulator's visual software) a small aircraft to appear in the windscreen moving left to right. None of the automated aircrews spotted the intruder, whereas nearly all (11 out of 12) of the conventional aircrews did.

CONCLUSIONS AND RECOMMENDATIONS

Tests of statistical significance confirm observations that significant differences exist between the manual performance of the automated and conventional groups. Analysis of aircraft state parameters leads to the conclusion that pilots of automated aircraft, while flying manually during these maneuvers, consistently exhibited greater deviations from assigned courses and parameters and greater deviations from nominal pitch-and-bank attitudes. Occasional deviations were great enough to present a hazard to the safety of that aircraft and others in the terminal area.

Approach and Landing Conclusions

Destabilized Approaches

The most significant differences were found to occur during the approach and landing phases. It is industry practice to tolerate very little airspeed deviation from the recommended value during approach and landing. The FAA's Practical Test Standards for the Airline Transport Rating allow only a 5-knot margin faster than the recommended final approach speed. The Practical Test Standards also require a stabilized final approach with no more than one-quarter scale deflection of either the glide slope or localizer. National Transportation Safety Board (NTSB) accident records (*18–24*) list unstabilized approaches as a factor in a disproportionate number of accidents, further confirming the importance of stabilized approaches. Ninety-one percent of the automated aircrew members did not conform to the airspeed requirements, and 27 percent of the automated group did not meet the localizer standard when manually flying normal ILS approaches.

The safety consequences, especially in terminal airspace, of these larger deviations deserve attention and suggest intervention strategies to prevent automated aircrew manual performance from diverging further from conventional aircrew performance. Variations in airspeed during final approach result in changing aim points during the very dynamic process of landing, where a great majority of major mishaps occur. This makes it more difficult for the pilot to predict the actual touchdown point.

Short-Term Intervention Measures

Perhaps the simplest solution to this problem is to encourage automated aircrew members to manually fly a certain percentage of departures and arrivals. Whereas that seems to be the clear-cut solution to the entire question of this study, the researcher is unconvinced that the entire difference in performance is solely due to the lack of practice by the automated group. Or stated another way, the researcher is concerned that this simple recommendation addresses only a symptom and not the underlying causes.

Since the need to fly a stabilized approach is so critical, this study recommends not only short-term intervention measures that will decrease performance deviations but also a series of investigations that will fully examine the effects of flight deck automation on all aspects of the air transportation system for the long term.

In the short term, this study recommends a judicious balance of automatic and manual departures and arrivals to optimize safety and maintain pilot manual skills. Crew resource management must be amended specifically for the automated flight deck. It is recommended that when automated aircrews are flying manual approaches, the pilot not flying (PNF), in addition to monitoring automated systems, must also closely monitor the pilot flying (PF) and make appropriate recommendations if aircraft parameters begin potentially unacceptable trends.

Flight crew training must emphasize approach stabilization. Airline operators must define criteria for acceptable, stabilized approaches with nonpunitive policies that mandate go-arounds for approaches not stabilized by 500 ft.

It is recommended that ATC recognize the need for stabilized approaches and minimize last-minute airspeed and altitude adjustments for aircraft intercepting the final-approach course. Automated aircraft should be given sufficient intercept angles to the final-approach course. In addition, the use of slam-dunk maneuvers, which require maximum performance of the aircrew, must be discouraged for these aerodynamically clean aircraft.

Long-Term Intervention Measures

The effects of the current ATC system on the use of automated flight decks must be examined. Findings from this study and others suggest that pilot work loads increase for automated aircrews during maneuvers in terminal airspace, partly due to the incompatibility of automation with the current ATC system. The design of the future ATC system must take into account how to interface efficiently and safely with automated flight decks.

Controlled Flight into Terrain Implications

Twenty percent of the automated crews continued a descent on the approach despite having a full course deviation indication. Protection from collision with obstacles is ensured only when the aircraft is within the lateral and vertical limits of the ILS. No protection is guaranteed when the aircraft is outside these limits.

Controlled flight into terrain (CFIT) accidents are the leading category of accidents in the commercial transport and business classes. From 1975 through 1989, 68 air carrier CFIT accidents occurred worldwide (*25*). From 1986 through 1990, 36 of 40 CFIT air carrier accidents occurred during approach or landing. All 36 accidents occurred during periods of instrument meteorological conditions or reduced visibility.

Automated flight decks are equally represented in the CFIT accidents. Navigational error, misreading of charts, misunderstanding of clearances and procedures, and simple distraction have been identified as causal factors. In the long term, a full-scale examination of the CFIT phenomena should be conducted, including the effects of flight deck automation on crew situational awareness and crew coordination.

In the short term, this study recommends complete installation of the latest version of the Ground Proximity Warning System worldwide and thorough aircrew training to ensure proper response by aircrews.

Single-Engine Operations

Swept-wing aircraft are strongly coupled between rolling and rudder input. Very slight rudder inputs, especially with a failed engine, can produce significant bank angles. Whenever the throttle is adjusted, a corresponding rudder movement must occur. This, in turn, can produce a banking motion that many times was not compensated for by the automated aircrews. Because of problems with rudder inputs, the aircraft pitch-and-bank attitudes were never stabilized. In addition, very significant airspeed deviations (10 knots) below the final approach speed occurred in 60 percent of the automated aircrews.

Whereas it is certain that at one time most of the aircrews had well-developed control coordination skills, it is apparent that conventional aircrews were proactive in control inputs, as opposed to the reactive control inputs made by automated aircrews.

Man-Machine Interface

The frequency and severity of errors committed by aircrews interfacing with the FMS observed during this investigation are cause for concern. Analysis of operational errors is currently under evaluation and will be reported in future publications.

Since a number of accidents have shown the man-machine interface as a causal factor (*16–10*), this finding strongly suggests further study into the design and use of autopilot systems as an aid to the pilot, rather than reliance on the pilot to make up for deficiencies in systems design.

It is cause for concern that the PNF now has the capability to make inputs into the mode control panel of the FMS, which can completely render useless the efforts of the PF, at times producing irreversible and potentially hazardous errors. It is recommended that future automated systems be designed so that an erroneous input or inadvertent mode selection by the PF or the PNF cannot create a potentially hazardous condition, especially during the approach phase of flight.

Automated aircrews continued to demonstrate misunderstandings of the operations performed in each mode of the autopilot, particularly during the approach phase of flight. System designers have not anticipated the effect of such systems on the full range of aircrew performance. As recently as November 1994, a major international manufacturer of automated aircraft, in response to seven fatal mishaps involving the man-machine interface with its automated aircraft, is suggesting that airlines change the aircrew training curriculum. Whereas training seems to be the typical corrective action within the industry, a true systems safety method would suggest that future autopilot designs be more error tolerant. Training and procedures, both of which rely on the human element, should be the last layer of protection to minimize error. Elimination of the hazard, incorporation of protective devices, and incorporation of warning devices are much more effective for minimizing error and should be used by airframe manufacturers and airline management before relying on flight deck training and procedures.

Near Midair Collision Implications

Though not part of the original experiment, during visual approaches to landing pilot-instructors would command (through the simulator's visual software) a small aircraft to appear in the windscreen moving left to right. None of the automated aircrews spotted the intruder, whereas nearly all (11 out of 12) of the conventional aircrews did. This is cause for concern, given that terminal airspace is already very congested and future proposals will place arriving aircraft at even closer intervals to parallel or converging runways. The probability of midair collision in higher traffic densities will increase in the future ATC environment. It will become even more important for aircrews to maintain a vigilant scan for other air traffic. This deserves immediate attention. Whereas an investigation dedicated solely to this problem is certainly warranted, this study recommends that short-term intervention strategies be considered for operational aircrews.

Further Study

In addition to the recommendations pointed out in this section, the limitations of this study suggest that this preliminary study be used to develop a full mission scenario in which the full range of aircrew performance markers is measured and analyzed. Such an effort would necessitate the inclusion of at least two appropriately trained evaluators to assess aircrew performance. It would also be preferable to videotape the events for later analysis.

As stated in the introduction, the deterioration of pilot manual skills is one of the noted concerns with flight deck automation. If it is assumed that the manual skills of the two groups were equal upon assignment to their respective fleets, then one can surmise that the manual skills within the automated group have diminished over time. However, to more exactly address this question, a long-term study measuring the manual skills of automated aircrews over time is required.

Because of the greater variance in performance within the automated group, other variables, such as pilot total time, pilot background (type of aircraft flown in past, etc.), percentage of flight time in manual versus automated modes, number of hand-flown approaches in the last 6 months, and time in type should be compared in future reports to determine whether any of these parameters may cause a statistically significant variation in performance within the automated population. An analysis of variance investigation will then be possible to determine the methods by which automated crews are best able to maintain manual proficiency.

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