TRANSPORTATION RESEARCH RECORD

No. 1480

Aviation

Public-Sector Aviation Issues

Graduate Research Award Papers 1993–1994

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
WASHINGTON, D.C. 1995

Transportation Research Record 1480
ISSN 0361-1981
ISBN 0-309-06118-0
Price: $22.00

Subscriber Category
V aviation

Printed in the United States of America

Sponsorship of Transportation Research Record 1480

TRB Selection Panel for Graduate Research Award Program on Public-Sector Aviation Issues
The panel evaluates applications from graduate students and recommends candidates for awards on the basis of academic accomplishments, references, experience, career goals, and proposed research (quality of concept, approach, and potential value to the public sector of aviation).
Chairman: Gerald S. McDougall, Southeast Missouri State University
Raymond A. Ausrotas, Paul S. Biederman, John B. Fisher, Susan H. Godar, Richard S. Golaszewski, Beverly M. Huey, F. Roy Madgwick, Francis P. Mulvey, Joseph P. Schwieterman

FAA Liaison: John F. Hennigan, Jr.

Transportation Research Board Staff
Robert E. Spicher, Director, Technical Activities
Larry L. Jenney, Senior Program Officer, Aviation (through January 31, 1994)
Joseph A. Breen, Senior Program Officer, Aviation
Nancy Doten, Senior Secretary
Nancy A. Ackerman, Director, Reports and Editorial Services
Norman Solomon, Editor

The organizational units, officers, and members are as of December 31, 1994.

Transportation Research Record 1480

Contents

Foreword

The papers in this volume are reports on research topics chosen by graduate students selected for awards from a nationwide competition under the Eighth Graduate Research Award Program on Public-Sector Aviation Issues (1993–1994). The program is sponsored by the Federal Aviation Administration and administered by the Transportation Research Board. Its purpose is to stimulate thought, discussion, and research by those who may become managers and policy makers in aviation. The papers were presented at the 74th Annual Meeting of TRB in January 1995. The authors, their university affiliations, faculty research advisors, and TRB monitors are as follows.

Richard A. Charles, a master's candidate in urban studies–transportation at Georgia State University, explored the use of advanced avionics to improve air traffic system capacity and the prospect of public funding for airline equipment acquisitions. His faculty research advisor was Atef Ghobrial of the College of Public and Urban Affairs, Georgia State University. TRB monitors were Thomas J. Vild, Aerospace Management Consultant, and James P. Fernow of the MITRE Corporation.

Suzanne M. Dawes, a Ph.D. candidate at the University of Southern California, conducted research on an integrated framework to analyze coordination and communication among aircrew, air traffic control, and maintenance personnel. Her faculty research advisor was Najmedim Meshkati of the Institute of Safety and Systems Management at the University of Southern California. TRB monitors were Gerald S. McDougall of Southeast Missouri State University and Robert Helmreich of the NASA/University of Texas/FAA Aerospace Crew Research Project in Austin, Texas.

Gina T. Galante, a master's candidate at the University of Southern California, made a preliminary identification of factors causing pilots to disconnect the flight management systems in glass cockpits. Her faculty research advisor was Diane Damos of the Institute of Safety and Systems Management at the University of Southern California. TRB monitors were William E. Gehman of the Michigan Aeronautics Commission and Earl L. Wiener of the University of Miami.

Jody Hoffer Gittell, a Ph.D. candidate at the Massachusetts Institute of Technology, examined the cost/quality trade-offs in the departure process of the major U.S. airlines. Her faculty research advisor was Thomas A. Kochan of the Sloan School of Management at MIT. TRB monitors were Francis P. Mulvey of the U.S. General Accounting Office and Joseph P. Schwieterman of DePaul University.

Elyse Golob, a Ph.D. candidate at Rutgers University, investigated the impact of deregulation on investment and production strategies in the commercial aircraft industry. Her faculty research advisor was Ann Markusen, Director of the Project on Regional and Industrial Economics at Rutgers University. TRB monitors were John B. Fisher of Ohio State University, William Swan of Boeing Airplane Company, and Adrian LeRoy of Douglas Aircraft Company.

Patrick R. Veillette, a Ph.D. candidate at the University of Utah, investigated the differences in aircrew manual skills in automated and conventional flight decks. His faculty research advisor was Rand Decker of the Department of Civil Engineering at the University of Utah. TRB monitors were Lemoine Dickinson, Jr., of Failure Analysis Associates and Beverly Huey of the National Research Council, National Academy of Sciences.

Rachel N. Weber, a Ph.D. candidate at Cornell University, studied the issue of accommodating gender differences in the cockpit design of military and civilian aircraft. Her faculty research advisor was Judith Reppy, Director of Peace Studies at Cornell University. TRB monitors were Richard Pain of TRB and Susan H. Godar of the Economics Department, St. Mary's College of Maryland.

Using Advanced Avionics To Improve Air Traffic System Capacity and the Prospect of Public Funding for Airline Equipment Acquisitions

RICHARD A. CHARLES

The ability to accommodate the continued growth of air travel by expanding the associated landside infrastructure is constrained by environmental factors and financial deficits. By application of the latest technology to airplanes, however, system improvements that can bring substantial reductions in public-sector costs are possible. How to fund such beneficial improvements is a difficult question. The need for better data than have been developed on air traffic system capacity, the potential benefits of new technologies, and the need to reorder some development program priorities are described. A rationale for evaluating the prospect of public funding for airline equipment acquisitions is suggested. A key element of the approach to achieving these objectives is the presentation of data developed internally by several airlines individually (some of which are proprietary and are presented with sources available on request) and by individual industry observers and authorities. These data are useful in estimating the magnitude of findings that might be expected if research is conducted on a system level.

Constraints placed on the air traffic system (ATS) as a result of airway system design and low-visibility operating restrictions became widely recognized in the late 1960s. Many of these advances were developed to address, in particular, delays generated by ATS capacity limits. A common feature of these efforts was their sponsorship almost exclusively by the private sector. Airlines funded the technology advances, in effect, through their ongoing purchases of new airplanes and equipment at increasingly higher prices.

New developments were also undertaken occasionally by the private sector in an attempt to circumvent the limitations of the established system. One example is the use of Flight Management System (FMS) technology to improve system capacity, which resulted in the establishment of some 80 FMS approaches in the United States and was entirely an airline initiative.

The air carrier industry is now evolving toward satellite-based navigation, which is, in effect, a radio navigation system. It offers greater accuracy and reliability than past systems and makes possible, for the first time, decommissioning of virtually the entire ground-based navigation infrastructure. The ability to implement systemwide direct routings will depend, as in the past, on changes to the air traffic control (ATC) system—in philosophy as well as in structure. The potential high accuracy of the satellite-based system also makes its application possible as the basis for approach operations, conducted with advanced optical systems, in which low-visibility landing operations may be conducted without the extensive airport infrastructure improvements otherwise needed to support such operations. (Development of the related optical technology is not being adequately supported or advanced by the federal government.)

Substantial financial benefits are possible from satellite-based operations and will accrue to the nation's economy as well as to air carriers. Decommissioning the groundside navigation infrastructure and avoiding capital outlays for airport improvements constitute a major benefit to the public sector, made possible by relocating navigation and ATC functionality from the ground to the airplane. Doing so, however, may place an intolerable financial burden on airlines, whose bleak financial circumstances at least partly reflect their continuing efforts to recover from the destabilizing effects of airline deregulation. It is in this context that public funding for initial equipment acquisitions by air carriers should be considered. Concurrently, development programs in process should be reviewed and discontinued where they are found to be inferior to the capabilities of satellite-based navigation or optical landing technology. All available funding can then be focused on the most beneficial programs. The potential benefits to airlines exceed industry losses and are, therefore, central to the health of the industry.

FAA has launched a broad range of initiatives intended to exploit the many possibilities offered by a global navigation satellite system (GNSS), including improved oceanic and domestic en route navigation, approach and landing, and airport surface operations. Domestic GNSS applications are being increasingly emphasized, and FAA schedule projections for GNSS implementation are being revised favorably. A system-level effort should now be initiated to measure the financial, economic, and social benefits of the new technology base for domestic air transportation. In this manner, the returns to society on the substantial investment needed—one which the airlines are not in a position to make by themselves—can be evaluated.

Airline costs reside in such areas as excessive fuel burn, crew pay, and excessive aircraft overhead (technical and administrative) per flight segment. Costs to the economy are in productivity losses, excessive use of resources (fuel, etc.), higher transportation costs (fares), and, where navigation technology is concerned, financial support of an obsolete groundside infrastructure that demonstrates poor reliability, and for which low production quantity components are becoming prohibitively expensive.

Constraints on ATS capacity are considered the most serious problem facing the future of U.S. commercial aviation. Slowdowns in the system adversely affect both domestic and international air

Department of Aviation Management, Georgia State University, Atlanta, Ga. 30303.

commerce and are a detriment to economic growth. Congestion and delays in the United States have been estimated to cost the domestic economy in excess of $10 billion annually (*1*). On an international scale, it has been estimated that a delay of 1 min/hr for a single Boeing 747 costs the world's economy $1 million per year (*1*).

FAA efforts to advance ATC automation have focused on the Advanced Automation System (AAS), which may need redirection of its technical and philosophical components to accommodate system changes now on the horizon.

Policy related to the navigation technology factor, as a constraining mechanism on the air traffic system, is the focus of this paper.

CURRENT ATC SYSTEMS

En route Operations

The primary radio navigation system in the United States is a network of airways defined by VOR ground stations. The principal shortcomings of the system are indirect routing; the feeder-arterial quality of its structure, which funnels traffic onto crowded airways and leaves much available airspace unused; and angular inaccuracy (the relationship between distance from a station and positional accuracy).

Before availability and acceptance of the Global Positioning System (GPS), FAA's approach to improving the en route structure focused on modernizing ATC equipment and updating procedures to streamline operations within the constraints of existing system design. With GPS has come an awareness of the air traffic management (ATM) concept. Use of GPS for direct navigation can only have a meaningful impact on system capacity if it is supported by an ATM structure designed to accommodate direct navigation on a system level.

Terminal Area and Approach Operations

A number of constraints related to terminal area navigation currently serve to limit the amount of traffic that can be accepted into a terminal area before measures are introduced that produce delays. The inferior accuracy and slow sweep speeds of existing terminal area surveillance radar systems contribute to conservative spacing practices. Local area environmental policies and ordinances lead to suboptimum routings. Some routings are optimized on the basis of landmark recognition. Aircraft that rely on VOR or ILS signals for terminal area navigation must abandon such routings in instrument conditions. Also, VOR and ILS signals are subject to interference from atmospheric and geographical phenomena, including multipath anomalies.

Development of the MLS was, in part, an attempt to deal with terminal area capacity problems. The system enabled curved or segmented approaches under MLS guidance, as a means to address environmental concerns and the ability to retain irregular approach paths in instrument conditions. MLS also provided vertical guidance and a much higher degree of immunity from interference than that afforded by VOR or ILS. MLS was capable of providing sufficient accuracy for Category IIIb approach operations. The cost for each runway-end installation of MLS was estimated at approximately $1 million.

FAA is now directing and participating in efforts to develop GPS for precision approach operations comparable with those possible with MLS. Updated primary radar systems with trend projection and conflict alert software are still planned for use in enhancing terminal area operations.

Airport Surface Operations

Current plans to improve ATC's ability to deal with surface traffic are based on a new primary radar system that offers greater accuracy and faster sweep-display update rates, known as ASDE-3 (airport surface detection equipment). ASDE-3 radar systems will cost approximately $4.5 million per installation.

En Route Capacity

The elements of the existing en route system that most affect capacity include the structure of the airways system and the accuracy of existing navigational aids, in combination with the characteristics of ATC surveillance equipment.

Airways System Structure

Tremendous capacity improvements and financial savings are possible in direct routings and the ability to fly at optimum altitudes. The fuel penalty for flying at other than optimum altitudes has been estimated to be in excess of $150 per hour. A Boeing 747, for example, which operates 3,600 hr per year, could reduce its fuel burn by $540,000 annually (*2*, p. 12).

United Airlines estimates that using satellites for direct routing in domestic operations might reduce flight times by 1 percent and 3 million mi per year (*3*, p. 53). United's domestic departures in 1992 (720,592) (*4*, p. 12) comprised 10.5 percent of the total number of U.S. Air Transport Association (ATA) member domestic departures (6,866,325) (*4*, p. 2) of that year. If the relationship of United's departures to the ATA-member total is extended to miles flown, it can be estimated that domestic route miles flown by ATA-member airlines might be reduced by more than 28 million per year as a result of direct routing supported by GPS.

Another major airline estimates that direct routing of domestic flights will save almost $340 million annually as a function of direction of flight and flight at optimum altitudes and winds (see Table 1). [These data were provided by an airline representative at a committee meeting of the Air Transport Association in 1994. The airline (Airline A) requested that its identity not be published but agreed to be identified as the source upon specific request. Source of the data will be provided upon request.] This airline also estimates the value of productivity gains that would be realized as a by-product of operationalizing the savings shown in Table 1 at $1.6 billion in annual profit.

If the savings in Table 1 are applied proportionally to other U.S. (ATA-member) airlines on the basis of annual departures, the resultant potential domestic industry savings approach $4 billion.

A third major airline (*6*) has estimated savings and contributions to increased system capacity on the basis of modeled city-pairs (see Table 2). [These data were provided in 1994 by an airline representative who requested that the airline identity not be published. The airline (Airline B) agreed to be identified as the source upon specific request. Source of the data will be provided upon request.]

Table 2 indicates that the largest potential savings, as a percentage of total trip resources, will be realized on shorter stage lengths. Savings for longer trips are, however, significant.

TABLE 1 Airline A Losses due to Inefficient Routing and Altitude, Domestic U.S. Operations, 1993

	Quantity	Unit Cost	Total
Enroute Losses[1]			
Indirect Routes	4,995,482	$60	$299,728,920
Delays[2]	362,341	$60	$ 21,740,460
Cruise Inefficiency[3]			
Altitude, Winds	25,750,000	$0.66	$ 17,098,000
Total:			$338,567,380

[1]Enroute losses are measured in minutes.
[2]Includes execution and delays.
[3]Cruise inefficiency is measured in gallons.

Airline B extended the Table 2 data to its entire fleet and domestic route structure. It estimated that a systemwide fuel savings of 8 percent was reasonable—$117 million annually, at current prices. Time savings were also estimated at 8 percent and expressed in terms of aircraft variable cost at $155 million. Additional ATC-related savings were calculated, which included the expected effects of reduced delays (ground and air), conducting approach, landing, and taxi operations under low-visibility conditions at the same rates as under visual conditions, and the elimination of speed restrictions below 10,000 ft. These measures are expected to produce an additional $230 million, bringing the total to more than $500 million annually.

Navigation and Surveillance Accuracy

The basic navigational accuracy of GPS-derived position information is superior to that of VOR-based signals. En route accuracy currently supported for GPS is on the order of ±100 m, with substantial improvements possible. In addition, GPS navigation data are not angular and are therefore not position dependent.

Automatic dependent surveillance (ADS) describes a system by which GPS-derived position information (with additional aircraft and environmental data, as desired) is data-linked via satellite or terrestrial connections to ATC and displayed on a conventional azimuth-oriented display, referred to as "pseudo-radar." The implicit accuracy of ADS is extremely high and independent of the angular distance inaccuracies associated with primary radar.

In combination, the navigational and surveillance accuracies of GPS and ADS far exceed those associated with VOR and primary radar and can be expected to have a substantial effect on U.S. air traffic system capacity by making reduced separation standards possible in en route operations. Current development work aimed at implementing ADS as early as possible has only recently included domestic applications and oceanic operations.

One recent measure is a proposal by FAA to fund $200 million for the acquisition of ADS broadcast devices by the general avia-

TABLE 2 Airline B Estimated Savings from Direct Routing by City-Pair

	City-Pair			
	A	B	C	D
Current Distance[1]	218	1,758	888	749
Potential Distance[2]	160	1,686	857	704
Savings (nm)	58	72	31	45
Savings (%)	27	4	3	6
Current Enroute Time[3]	44	238	130	108
Potential Enroute Time[4]	32	228	126	102
Savings (min)	12	10	4	6
Current Fuel Burn (lbs)	8,580	38,270	21,300	18,300
Potential Fuel Burn (lbs)	6,107	36,470	20,200	16,650
Savings (lbs)	2,473	1,800	1,100	1,650
Potential Fuel Savings (%)	29	5	5	9
Potential Time Savings (%)	26	4	3	6

[1]Current distance is the average actual distance flown due to current routing practices, expressed in nautical miles.
[2]Potential distance assumes optimum (direct) routing, expressed in nautical miles.
[3]Current enroute time is the average actual time required for the flight due to current routing practices, expressed in minutes.
[4]Potential enroute time assumes optimum (direct) routing, expressed in minutes.

tion fleet, based on recognition of the fact that a system in the United States based on ADS surveillance will not work without the full participation of the general aviation community.

American Airlines has estimated that reduced flight times made possible as a result of surveillance accuracies associated with ADS, including both oceanic and domestic operations, are expected to save $5 million in fuel costs (at current prices) and $4 million in crew costs. RTCA has estimated that improvements related to ATC's more precise knowledge of aircraft position, from capabilities such as ADS, could save airlines some $13.2 billion between 1995 and 2015 (*3*, p. 53).

Terminal-Airport Capacity

For air carrier operations, from the perspective of navigational and surveillance accuracy, airport capacity is most affected by configurational characteristics of the runway and taxiway system, procedures affected by environmental ordinances, and facilities enabling operations in conditions of low visibility—in the air and on the ground.

Runway-Taxiway System

Techniques used to model runway capacity have evolved over the years from probabilistic to more simulationlike.

For computing the effects of runway interdependency in the case of parallel runways, operations in instrument meteorological conditions (IMC) may be classified as either "independent parallel" or "dependent parallel" approaches. In general, independent parallel approaches can be conducted in IMC on parallel runways in the United States that are spaced at least 4,300 ft apart. For parallel runways that are spaced closer than 4,300 ft, dependent parallel approach operations are conducted in which lateral (diagonal) spacing between aircraft on parallel approach paths and longitudinal (in-trail) spacing for aircraft on approach to the same runway must be maintained. Airport capacity will be increased where it is possible to maintain independent runway approach operations despite reductions in visibility below visual conditions (visual meteorological conditions).

Where parallel runways that operate in the dependent case can be changed to operate in the independent case, a capacity improvement from as low as 29 operations per hour to as much as 57 operations per hour can be achieved, an increase of almost 97 percent.

The Aviation System Capacity Plan has determined that of the top 100 U.S. airports, 30 could benefit from improved capacity as a result of independent parallel instrument flight rules (IFR) approaches, 18 could benefit from dependent parallel IFR approaches, 53 could benefit from dependent converging IFR approaches if a prospective converging runway display aid were used, 32 would gain capacity benefits from independent converging IFR approaches, and 13 would gain increased capacity from triple IFR approaches (*5*, p. 7-2).

The most significant improvements to airport capacity in this area are currently envisioned to be as a result of adding new runways, extending existing runways, and arranging spacing to allow independent arrival and departure streams. Capacity increases are estimated at between 33 and 100 percent, depending on airport configuration (*5*, p. 2-13). At the same time, it is acknowledged that "significant capacity gains can be achieved at airports with closely spaced parallel runways if the allowable runway spacing for conducting independent parallel instrument approaches can be reduced" (*5*, p. 5-5). Further, "analysis and demonstrations have indicated that the separation between parallel runways could be reduced if the surveillance update rate and the radar display accuracy were improved, and special software was developed to provide the monitor controller with alerts" (*5*, p. 5-5). This approach to improving airport capacity through reduced runway separation standards relies on conventional radar surveillance, with a faster update rate to reduce the time required for ATC to perceive a potential conflict, aided by conflict alert software.

Independent parallel instrument approaches can currently be conducted at approximately 15 airports in the United States where runway separation is at least 4,300 ft. Building triple parallel approach facilities would increase capacity by 50 percent. Building quadruple parallel approach facilities would increase capacity by 100 percent. Using existing radar technology, but with an azimuthal ccuracy of 5 milliradians and an update rate of 4.8 sec, this would require a 5,000-ft runway separation (*5*, p. 3-4).

Table 3 gives capacity differences for selected runways (data provided by FAA). Table 4 gives estimated savings, in time and dollars, associated with independent parallel operations at the airports described in Table 3 (data provided by FAA).

In determining the classification of approaches at a given airport/runway system as dependent or independent, computer simulations and flight simulator sessions are run in place of mathematical modeling. Diagonal spacing is defined at maximum in coordination with in-trail spacing requirements. Key variables used to test approach operations for classification as independent include the time and airspace required for "blunder" detection and coordinated corrective action by ATC and the flight crew. The time sequence includes (a) commission of the blunder (e.g., a sudden, inappropriate heading change), (b) recognition of the blunder by ATC, (c) communication of corrective measures by ATC to the errant flight crew, and (d) execution of corrective control inputs by the flight crew.

As a means for improving azimuthal accuracy, FAA is testing a final monitor aid that will provide accuracy within 1 to 2 milliradians, but still with only a 4.8-sec update rate. FAA is also testing a precision runway monitor (PRM) radar with high azimuth and range accuracy and update rates of 0.5 to 2.4 sec. Capacity improvements are expected as a result of these systems, supporting independent approaches to parallel runways separated by 3,400 ft, and down to as low as 3,000 ft (*5*, p. 5-5).

One technology option exists, however, with the potential for changing the variables used and process itself, and should be explored. This option offers greater accuracy, is less expensive to implement and support, and is based on combining GPS approach navigation with ADS surveillance and GPS-based collision avoidance cockpit displays.

By enhancing the accuracy and update rate of existing collision avoidance systems with nonangular GPS-based data, the accuracy of the TCAS display can support its use as the basis for colocating the blunder detection function in the cockpit. The time required for blunder detection by ATC would then be virtually eliminated (relegated to backup, coordination, and advisory), and the requirement for initial communication to the flight crew by ATC would be replaced with immediate recognition and action by the flight crew. (ATC would remain in the information loop for coordination of other traffic.) This methodology can be implemented at significantly lower cost than the PRM (radar-based) methodology in

TABLE 3 Potential Capacity Improvements Using Existing Runways in Arrivals per Hour, Dependent Versus Independent Operations

Airport	Runways	Centerline Spacing (ft)	Dep. Parallel Capacity	Indep. Parallel Capacity
Dallas Love	31R/31L	2,975	35.9	52.8
Baltimore	10R/10L	3,500	37.0	52.0
Houston	8L/8R	3,500	50.8	76.2
Kennedy	4R/4L	3,000	36.9	49.0
Portland, OR	28R/28L	3,100	35.5	52.6
Minneapolis	11R/11L	3,380	35.5	49.2
Phoenix	8R/8L	3,400	34.6	48.4
Memphis	36R/36L	3,400	35.2	49.2
Salt Lake City	16R/16L	3,500	36.2	50.8
Raleigh	5R/5L	3,500	35.4	49.2
Detroit	3L/3C	3,800	36.6	50.2
Ft. Lauderdale	27R/27L	4,000	34.7	48.0
AVERAGE CAPACITY			37.0	52.3
OVERALL CAPACITY INCREASE			41.3%	

development, both in initial investment and in long-term support. Perhaps most important, it has the potential to modify approach evaluation methods, yield capacity increases greater than those currently anticipated by conventional methods, and improve operational safety.

Low-Visibility Operations—Airborne

Of all delays greater than 15 min, 66 percent are caused by weather (27 percent by terminal volume). These delays are largely the result of instrument approach procedures that are much more restrictive than visual procedures (*5*, p. 1-15) and result in restriction of the airport's capacity. Of some 12,000 airports in the United States, only 40 are Category III equipped to support operations in visibility conditions less than those associated with basic IFR. (Europe has some 170 Category III capable airports.) One airline estimates its direct annual cost of diversions, cancellations, and passenger misconnects related to weather at $28.9 million (source of data supplied on request).

The use of GPS for approach and landing guidance in conditions below Category I, such as Category II (runway in view at 100 ft, 1,200 ft or less visibility) and Category III (potentially all the way to 0/0), is currently in the development stage. There is little doubt

TABLE 4 Estimated Annual Savings, Independent Parallel Approaches, 2000

Airport	Annual Delay Savings (hours)	Annual Delay Savings ($ millions)
Dallas Love	24,820	$ 39.9
Baltimore	15,768	25.4
Houston	6,534	10.5
Kennedy	5,877	9.5
Portland, OR	438	0.7
Minneapolis	36,135	58.1
Phoenix	17,155	27.6
Memphis	62,014	99.8
Salt Lake City	17,776	28.6
Raleigh	66,065	106.3
Detroit	1,570	2.5
Ft. Lauderdale	2,628	4.2
TOTALS	256,780	$413.1

that GPS guidance adequate for Category III operations is technically feasible. Successful autolands have been demonstrated at Category IIIB standards without the use of pseudolites, kinematic phase tracking, or enhancement from other aircraft systems. Differential GPS (DGPS) correction uplinks with C/A code tracking and carrier phase smoothing algorithms only were used. Category III required navigation performance was met within comfortable margins using a NASA Boeing 737-100 (*6,* p. 1).

In support of current plans for enhancing system capacity through airport infrastructure improvements, FAA and airport capacity design teams identified 23 "delay-problem" airports (exceeded 20,000 hr of annual delay) in 1991, 17 of which are constructing or planning new runways or extensions. Since then, 33 airports were forecast to exceed 20,000 hr of annual delay by 2002, of which 25 now have plans for construction of new or extended runways. Some runway upgrades are planned to meet Category III requirements, but not all. Of the top 100 airports in the country (on the basis of number of departures), 62 have proposed new or extended runways. The cost of these efforts combined exceeds $7.7 billion (*5,* p. 7-3). Even if carried out, their effect on system capacity will be substantially less than is possible by technologically superior alternatives.

For example, the Lambert–St. Louis International Airport Capacity Enhancement Plan, completed in 1988, was designed to increase IFR capacity to VFR capacity (*5,* p. 4-3). Included among the recommendations were construction of one new runway, conversion of a taxiway to a runway, three taxiway extensions, relocation of a cargo area, installation of a Category III ILS, installation of new radar for surveillance of surface operations (ASDE-3), and relocation of the Air National Guard facility (*5,* p. C-55). The new Category III ILS makes additional approaches possible in low-visibility conditions only at a single runway end and applies only to airplanes and carriers equipped with and certified for autoland or head-up display (HUD) system operations. Older air carrier airplanes and regional operators cannot equip cost-effectively for these types of operations.

When simply substituting GPS for ILS, Category III operations continue to require runway system and geographical upgrades to support the sophisticated and expensive automatic landing systems, normally associated with only the newest and most expensive air carrier airplanes, or the advanced HUD. The use of HUD for manually flown operations to Category III minimums has been demonstrated through the in-service experience of Alaska Airlines (*7,* p. 27). HUD reduces the need for expensive autoland systems but still relies on the presence of the groundside Category III infrastructure.

There is a potential means by which Category III operations can be successfully carried out, with equal if not greater safety than in the past, while almost completely avoiding expensive runway upgrades and eliminating reliance on autoland operations. This approach can also enhance the use of older air carrier airplanes still in service and support the participation of operators using smaller aircraft, such as regional carriers. It is a system that can make it possible to execute approaches and landings in Category III conditions at Category I facilities. The system is the enhanced vision system (EVS) that, if successfully developed, can enable flight crews to see the runway environment through intervening clouds and fog.

The development of EVS technology, in combination with GPS-ADS and autoland operations, offers the possibility of either hand-flown or automatic approaches to Category III minimums, on Category I runways, independent of ground-based navigation aids, runway lighting and marking, and most geographical constraints. EVS is broadly accepted as a promising technology for monitoring GPS-based position. A number of industry experts are confident of its potential for accomplishing Category III landing operations at Category I facilities. Its potential for enhancing safety, improving system capacity, and making it possible to avoid billions in airport infrastructure improvements and upgrades clearly calls for priority for its evaluation and timely development.

The baseline requirement for an EVS system has been established as giving the flight crew the ability to execute a landing and rollout, either manually or through autoland, from an approximate position of Category I minimums (200/½) "regardless of prevailing atmospheric visibility" (*8,* p. 2). Specifically, the EVS operational requirement is to enable low-visibility operations to at least Category IIIA, on Category I runways, with visual identification of runway references in accordance with the requirements of FAR 91.175 (c)(3) (*8,* p. B1). Cost to the service provider (FAA) will be considerably less than existing precision landing systems, with much greater potential benefits. Cost to the user, however, could be as much as the theoretical retrofit of a fail-operational autoland system. In the case of regional airlines, prices in that range can exceed the value of the airplane (*9,* p. 58). If EVS technology is not made available for substantially less, neither regional airlines nor the majors will be able to afford it.

The findings of the Working Group on Enhanced and Synthetic Vision indicate that FAA does not have a current research and development effort on EVS technology in place and that it has a "requirement to promote safety and provide certification support for users and industry when such support is requested" (*8,* p. 2). It found that the industry wants FAA's participation, particularly in the area of human-machine interface, and that funding may also be required. Ultimately, the report stated that the FAA should "encourage, support, participate and enable, industry and users to proceed in an expeditious manner to safely and efficiently take advantage of this technology" (*8,* p. 3).

Low-Visibility Operations—Ground

It has been estimated that nearly 80 percent of all flights are delayed from 1 to 14 min in the taxi-in/taxi-out phase of flight (*5,* p. 5-1). For a Boeing 747-400, 15 min of unnecessary ground running time is worth $550 in direct operating costs (at current prices) (*2,* p. 12). United Airlines estimates the annual cost of departure delays at $100 million (*10,* p. 49). Another estimate indicates the annual cost of delays on the surface as follows: gate delays (due to flow control, ATC, or airport), 580,000 min with a value of $14.5 million; taxi delays (outbound and inbound), 7,300,000 min with a value of $256.8 million; a total of $271.3 million (source of data supplied on request). Further, as mentioned earlier, 23 airports exceeded 20,000 hr of annual flight delay in 1991. The average cost to airlines of these delays, at $1,600/hr, was $32 million for each airport.

Current FAA plans to address surface traffic levels of the present and future are contained in the Airport Surface Traffic Automation (ASTA) program, which includes the use of DGPS but is also based on a new primary radar for ground surveillance, ASDE-3, and the automation of radar returns through a software system known as the airport movement safety system (*5,* p. 5-2). Originally contracted in 1985, ASDE-3 has been delayed by a series of software and hardware development problems.

Use of DGPS and ADS alone for management of airport surface traffic was successfully demonstrated at Daytona Beach by three aircraft as part of the ASTA program (*3,* p. 55). The pure DGPS-ADS approach offers potentially better accuracy, is far less expensive, and offers compatibility with DGPS-ADS-based en route and approach technology. ASDE-3 systems are being implemented, however, to replace the ASDE-2 systems installed in the 1960s. The first 40 ASDE-3 systems are being commissioned. Thirty-five more are planned by September 1995. ASDE-3 installations cost approximately $4.5 million each (*11,* p. 41). FAA acknowledges that ASDE-3 will not be available at all airports because of cost considerations and that "it is important, therefore, to develop affordable sensors to provide a reliable surveillance source for terminal operations and to support automation development and airport capacity initiatives" (*5,* p. 5-13).

FUNDING CONSIDERATIONS

Airline

United Airlines has estimated annual operating losses related to ATC delays, system capacity limits, weather problems, cancellations, and a number of other flight inefficiencies variously at $500 million (*12,* p. 43), $630 million (*10,* p. 47), and $647 million (*3,* p. 53). On the basis of United's share of total ATA-member domestic departures, the $647 million United loss can be extended to a value of $6.2 billion annually for all ATA-member airlines, an amount that can be substantially reduced by GPS navigation, in combination with ADS and EVS technologies.

Foreign operators are experiencing losses from a variety of similar ATS problems. Lufthansa reported in 1990 that 17 percent of delays were related to ATC start-up operations, 19 percent of delays occurred in airborne operations, and the total cost of delays for the year was $92 million (*13,* p. 11). Air France reported an annual cost from congestion of $70 million (*13,* p. 11). Other estimates have suggested that GPS alone can save airlines $5 billion annually in fuel and other costs (*12,* p. 36).

Autoland operations based on GPS position data are independent of ILS signals but still require the presence of other landside Category III infrastructure elements. As mentioned earlier, successful autolands have been demonstrated to Category IIIB standards. Still to be resolved are integrity, continuity, and availability of the signals, and possible added accuracy requirements that may be imposed by FAA.

Public Sector

The contribution of the air transport industry to total world output was estimated in 1989 at some $700 billion. Air traffic system inefficiencies have a significant effect on the domestic and world economies.

Table 5 gives a conservative estimate of some annual public-sector costs associated with support of various ground systems used today for domestic navigation and surveillance of aviation operations. The data include labor (estimated at 40 percent), rents, utilities, spare parts, and flight inspections. Runway costs, such as lighting, are not included.

Decommissioning of the ground systems indicated in Table 5 would save, then, conservatively, $0.25 billion annually in public-sector costs. Decommissioning is feasible with the implementation of GPS and ADS.

By comparison, the infrastructure needed to support domestic GPS en route navigation consists principally of 20 to 30 DGPS ground monitor stations (30 to support Category I approaches throughout the United States) (*14,* p. 46), which might be estimated to cost between $100,000 and $200,000 each. Support costs will be a small fraction of those for older systems. To support ADS surveillance, a small number of additional ADS Mode-S communications ground stations may also be required. Software and hardware upgrades to ATC display and computer systems to accommodate GPS and ADS should be available within current ATC budgets, in such planned resources as the AAS.

CONCLUSION AND RECOMMENDATIONS

The air traffic system again suffers from overcrowding and undercapacity; upgrading the air navigation system will provide substantial relief. The best technical approach and the most cost-effective solution appear to be the same, essentially calling for relocating navigational resources from the ground to the airplane. To do so burdens airlines with an impractical investment requirement.

It appears equitable and appropriate that some form of public funding be applied to airline acquisition of the most cost-prohibitive and effective elements of the new technology, such as

TABLE 5 Estimated Annual Support Costs Associated with Navigation and Surveillance Ground Equipment, 1992[1]

System	Units in Service	Average Unit Cost	Total Annual System Cost
VOR/DME	1,039[2]	$86,000	$89,354,000
ILS	1,159[3]	81,000	93,879,000
NDB	1,575[4]	13,000	20,475,000
Surveillance Radar	--	--	50,000,000
TOTAL			$253,000,000

[1]Interview by author with Mark Kipperman, Science Applications International Corporation, January 17, 1994, Washington, D.C.
[2]1,039 total *(5),* 950 operated by FAA *(5).*
[3]1,159 total *(5).*
[4]1,575 total, 728 operated by FAA *(5).*

the enhanced vision system, to bring the benefits associated with it to airlines and the public. In addition, the investment made by airlines in older-technology airplanes, which is continuing, will be better preserved by retrofit of the new technology. Extending the useful life of those airplanes will benefit traditional airlines, low-cost start-up carriers, and the traveling public.

On the basis of indicators described in this research, it appears that by developing and implementing GPS for en route navigation and approach/landing, operations, complemented in both cases with ADS and EVS, we might expect the following:

- A reduction of 28 million mi flown in domestic operations by ATA-member airlines (increasing system capacity);
- Annual savings of $10 billion for the domestic economy;
- Elimination of more than $250 million annually for support of existing navigation ground facilities;
- Reduction of a $32 million annual cost generated by delay problem airports;
- Elimination of a $4.5 million per installation cost for ASDE-3 radar systems;
- Reduction of the $7.7 billion currently planned for airport infrastructure improvements; and
- Airline savings that are estimated at between $300 million and $500 million annually, for major carriers.

The price for avionics (1995 dollars) to equip an air carrier airplane with GPS, ADS, and EVS capable of the operations described in this paper, could approach $1 million per aircraft (interview with G. K. Knoernschild, Rockwell International, March 22, 1994). On December 31, 1993, there were 4,596 turbojet air carrier airplanes in the United States (*15*) and 2,208 airplanes operated by regional airlines in passenger service in the United States (interview with W. Coleman, Regional Airline Association, July 26, 1994).

To fit all the 6,804 airplanes with full-capability systems would require a total investment of $6.8 billion. [A substantially smaller number of retrofits can be expected, however, due to differences in equipage (e.g., FMS, autoland) and aircraft age, in some cases.] As mentioned earlier, for example, a runway upgrade program (such as that described for St. Louis) results in added accessibility by only a relatively small number of sophisticated aircraft. The promise of EVS would make St. Louis accessible to all equipped aircraft. In the absence of some form of public funding, the benefits of EVS, as currently envisioned, will probably not be realized at all.

ACKNOWLEDGMENTS

The research in this paper was supported by a grant provided by the FAA and administered by TRB as part of the Graduate Research Award Program for the preparation of research papers on aviation policy issues. The author thanks TRB monitors James P. Fernow, MITRE Corporation; Thomas J. Vild, Aerospace Management Consultant; Mark Kipperman, Science Applications International Corporation; Cap. Robert Buley, Northwest Airlines; Andrew Flood, Collins Air Transport Division, Rockwell International; and TRB program coordinators Larry L. Jenney and Joseph Breen for their direction, encouragement, and invaluable assistance in the production of this paper. In particular, gratitude is expressed to Atef Ghobrial of Georgia State University for his wisdom and guidance in aviation policy research.

REFERENCES

1. Boeing Motion Picture/Television. *Flightpath to Prosperity.* Produced and directed by Boeing Support Services. 1994. 10 min. Videocassette.
2. Martin, M. The Fuel Factor. *Aeronautical Satellite News,* Feb.–March 1992.
3. Nordwall, B. D. Digital Data Links Key to ATC Modernization. *Aviation Week and Space Technology,* Jan. 10, 1994.
4. *Air Transport 1993—The Annual Report of the U.S. Scheduled Airline Industry.* Air Transport Association, Washington, D.C., 1993.
5. *1993 Aviation System Capacity Plan.* Report DOT/FAA/ASC-93-1. Federal Aviation Administration, U.S. Department of Transportation 1993.
6. Rowson, S. V., G. R. Courtney, and R. M. Hueschen. Performance of Category IIIB Automatic Landings Using C/A Code Tracking Differential GPS. Presented at 1994 *National Technical Meeting, The Institute of Navigation,* Jan. 24–26, 1994.
7. Adams, C. HUDs in Commercial Aviation. *Avionics,* Nov. 1993.
8. Buley, R. *Working Group on Enhanced and Synthetic Vision Report to the FAA Research, Engineering, and Development Advisory Committee.* Washington, D.C. 1994.
9. Nordwall, B. D. Regions Scrutinize Benefits Before Upgrading Avionics. *Aviation Week and Space Technology,* May 9, 1994.
10. Lyon, M. W. A Matter of Control. *Airline Business,* June 1994.
11. Phillips, E. H. First ASDE-3 Radar Begins Operations at Seattle. *Aviation Week and Space Technology,* Jan. 3, 1994.
12. Moorman, R. W. Delaying the GPS Promise. *Air Transport World,* Sept. 1993.
13. Woolley, D. Costing Congestion. *Aeronautical Satellite News,* Feb.–March 1992.
14. Hart, D. C. Wide Area Augmentation for GPS. *Avionics,* March 1994.
15. *World Jet Airplane Inventory End 1993.* Boeing Commercial Airplane Company, Seattle, Wash., April 20, 1993.

Integrated Framework To Analyze Coordination and Communication Among Aircrew, Air Traffic Control, and Maintenance Personnel

SUZANNE M. DAWES

Human error has been cited as a factor in many aviation incidents. Increased automation has not decreased the number of incidents related to human error, but rather has introduced new classes of errors. These errors often result from a lack of coordination and communication among the crew—not only the aircrew but air traffic controllers and ground personnel. It is proposed that an individual's decision style is one tool that can be used to examine the coordination and communication among these team members. Using an advanced aircraft simulator, test pilots flew a generic flight including takeoff, climb, cruise, approach, and landing under both normal and emergency operations. Decision styles were shown to affect work load ratings, the amount of information used during a segment of flight, and the amount and complexity of written information provided.

Aviation incidents related to human factors are of increasing public concern. Despite improvements in the sophistication and reliability of technology, the percentage of human error–related incidents and accidents has not decreased. As stated in the FAA's *National Plan for Aviation Human Factors,* "Human error has been identified as a causal factor in 66% of air carrier accidents, 79% of commuter fatal accidents and 88% of general aviation fatal accidents" (*1*). Other large-scale accidents—such as Chernobyl, Three Mile Island, Bhopal, Vincennes, Avianca Flight 052 (*2*), and Dryden—illustrate the "consequences of poor human factors planning in the design and operation of complex systems" (*3*). Attempts have been made by various agencies such as the FAA, National Aeronautics and Space Administration (NASA), and Department of Defense to address this concern. However, "these efforts have not been organized into an overall plan that addresses the comprehensive nature of human factors issues in the operation and maintenance of all types of aircraft, in air traffic control system operation and maintenance and the interface between the air and the ground" (*1*).

The objective of this research was to apply an additional technique for the assessment of human performance in aviation. The first step in this process was to develop a conceptual framework of skill-, rule-, and knowledge-based decision making between primary players [aircrew, air traffic controllers (ATCs), and maintenance personnel] (*4,5*). The second step studied the impact that different decision styles had on the performance of aircrews. Within this framework, the team structure of individuals in the cockpit was examined in detail, as were the effects of different team combinations on performing routine (skill- and rule-based) decision making versus unknown or emergency (knowledge-based) decision making.

Industrial and Systems Engineering, University of Southern California, University Park GER 240, Los Angeles, Calif. 90089-0193.

WORK LOAD

As the development of advanced aircraft systems continues, it is apparent that these new systems are becoming increasingly complex. The availability of computer-aided imagery and data-processing capabilities has paved the way for the introduction of even more complex and sophisticated hardware. As a result of these technical improvements, the aircrew must process greater amounts of information and make decisions in extremely complex environments. Stresses such as fatigue, cultural variables, cost, schedule constraints, and regulatory constraints combine to produce sustained high work load demand on aircrews.

Problems with mental work load occur routinely in aerospace. Overloading situations are known to have occurred in military combat aircraft, commercial jet aircraft, and air traffic control. Any one of the current measures of work load may not be sufficient to address concerns, such as information management and crew coordination. Automation is one solution that is often pursued. However, automation may not represent an optimum remedy because monitoring is still required, and usually conventional or manual backup must be provided (*6*). In addition, it has been shown that although automation eliminates certain classes of errors, it can also introduce new classes of errors. These errors are often in the form of not detecting when the human must reenter "the loop," in some cases resulting in errors whose consequences are more severe than the ones eliminated by the automation (*7*).

Subjective measures are direct or indirect queries of operators regarding their opinion of work load level involved in a task (*8*). Reid et al. (*9*) discuss some of the reasons for using multidimensional subjective measures of work load. Practical reasons for subjective measures as a component of a comprehensive work load test are the relative ease of administration, widespread acceptability, minimal instrumentation, and nonintrusiveness with performance of the primary task.

One highly used method for subjective measurement is the subjective work load assessment technique (SWAT) (*10*). SWAT was designed specifically to assess human mental work load by asking operators how hard they are working. In order to develop SWAT, researchers defined work load as primarily comprising three dimensions: time load, mental effort load, and psychological stress load. Each of the three dimensions has three levels corresponding roughly to high, medium, and low loading. Each of the three dimensions contributes to work load during performance of a task or a group of tasks. All three factors may or may not be correlated. For example, one can have many tasks to perform in the time available (high time load) but the tasks may require little concentration (low mental effort). Likewise, one can be anxious and frustrated (high stress) and have plenty of spare time between relatively simple tasks. This rating of workload is based on direct estimate or comparison estimate of the work load experienced at a particular time.

CREW RESOURCE MANAGEMENT

Research on crew coordination and communication, more commonly known as crew resource management (CRM), has indicated that both initial and recurrent training in CRM lead to continuing improvement in crew performance over time (*11*). Helmreich and Foushee (*12*) provide the following definition: "CRM includes optimizing not only the person-machine interface and the acquisition of timely, appropriate information, but also interpersonal activities including leadership, effective team formation and maintenance, problem-solving, decision making, and maintaining situation awareness."

Cockpits have evolved from single-seat aircraft to cockpits with multiple crew members and advanced technology. Additional crew members were initially perceived as backup for the pilot. However, as aircraft design advanced, aircrews were increasingly required to work as a team to maintain effective performance (*12*). To this end, CRM research has expanded its boundaries beyond the cockpit to include flight attendants, ATCs, maintainers, and ground personnel. As Kanki and Palmer (*13*) state, "There can be no doubt that operating modern aircraft is a high-stakes profession with lives invested in every flight. It is therefore reasonable to assume that communication plays an important part of this human activity as it does in all others where individuals are trying to accomplish common goals and separate tasks."

As Helmreich and Foushee (*14*) state, three categories of variables affect group performance: input, process, and outcomes. Input variables include the individual with the knowledge, skills, and abilities brought to the situation and group variables such as structure, size, cohesiveness, and environmental factors. Process factors reflect the interpersonal and technical coordination found in group interactions. Outcome factors define the dimensions of success or failure of the task conducted. Figure 1 shows the major factors that influence the way groups behave and ultimately the outcome of each flight.

Research on accidents found that crews must cope simultaneously with multiple tasks at the group level. Groups differ in their ability to complete these tasks. Reports from the National Transportation Safety Board implicate crew judgment and decision making in 47 percent of fatal accidents (*15,16*).

DECISION STYLES

Cognitive styles are defined as learned thinking habits that act as components of an individual's personality system. Cognitive style represents an individual's information-processing model; the way she or he receives, stores, processes, and transmits information (*17,18*).

Schroeder et al. developed a human information-processing model that suggests that environmental pressures (or load) systematically affect the complexity of information processing of individuals in an inverted U-shaped function (*19,20*). Maximum information use is found under a moderate environmental load, and a decline is seen under overload and underload conditions.

Driver and Streufert (*21*) and Driver and Mock (*22*) used this information processing and cognitive style model as the basis for a decision style theory. A decision style is developed along two dimensions: information use and focus. Focus is a continuous dimension ranging from unifocus to multifocus. The unifocus style takes the data provided and applies them to a single solution of a decision alternative, whereas the multifocus style takes the same

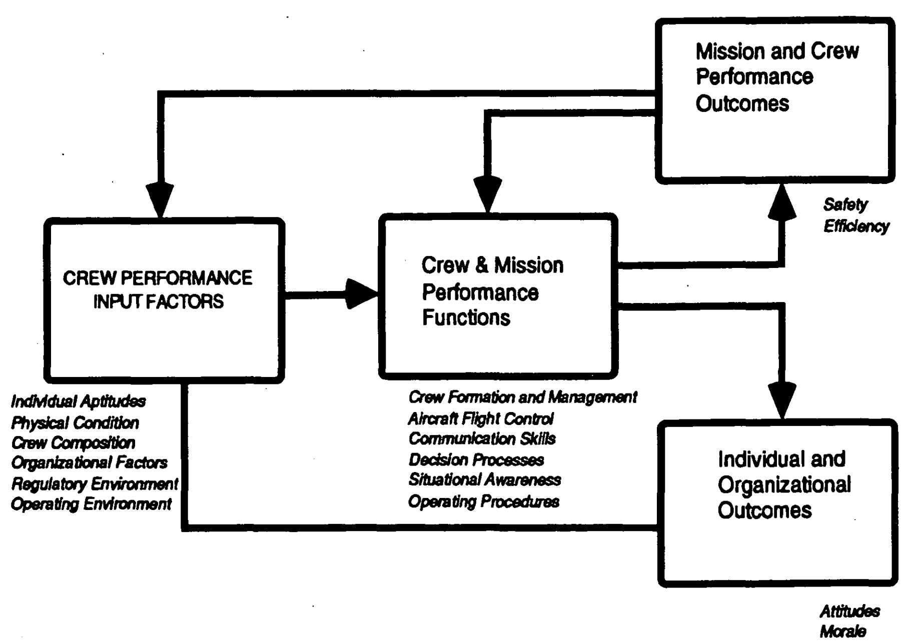

FIGURE 1 Effective crew performance (*14*).

amount of data and integrates them into several outcomes simultaneously. In the model, information use is the amount of information the decision maker seeks in making a decision and is split between two types: satisficers and maximizers. Satisficers use just enough information to generate an answer. Maximizers use as much information as possible to generate a solution. The dimensions of decision style are characterized by five decision styles: decisive, flexible, hierarchic, integrative, and systemic. This relationship is shown in Figure 2.

An individual who uses only enough data to generate a sufficient answer has a decisive decision style. For individuals within this category, once a decision is made, it is final. No attempt is made to reevaluate or review additional data. Individuals using this style are concerned with speed, efficiency, consistency, and achievement of results.

In the flexible decision style, the individual also uses a minimalist approach in seeking just enough data to make a decision. In this case, data are used to generate multiple conclusions that are subject to new data, reevaluation with new data, and the generation of a new solution. Driver and Rowe (*17*), Driver et al. (*23*), and Driver (*24*) state that the flexible style is typically associated with speed, adaptability, and a certain intuitiveness.

The hierarchic style seeks the maximum amount of information available to make a decision. This information is analyzed meticulously or reviewed to create the best solution. Once the solution is obtained, it is implemented with a contingency plan, but is essentially resistant to change. This style is often characterized as rigorous, precise, analytic, and even perfectionist (*23*).

The fourth style—the integrative decision style—like the hierarchic style, uses a maximum amount of information. However, at the same time, this decision maker generates a number of possible solutions. Synthesis is key to understanding this decision style. The integrative style is viewed highly inventive, emphatic, and cooperative. Individuals who do not use an integrative style often view those who do as indecisive.

A fifth decision style is systemic. This individual appears to embody both a hierarchic and integrative decision style. Initially, this decision maker uses a hierarchic approach exploring all options. However, as additional information is presented, this individual is able to integrate it into earlier information as a hierarchic would. The new information results in a prioritized option list. Systemic individuals appear to be more methodical and careful than those with an integrative style, but more open than those with a hierarchic style.

The use of decision style models has many implications for decision making under real-world, time-pressured operating conditions. In mental task performance, different styles consistently demonstrate distinctly different reactions (e.g., perceived difficulty) to the same task load levels and environmental demands (*25–27*).

SKILL-, RULE-, AND KNOWLEDGE-BASED DECISION MAKING

The lowest level of decision making is skill-based decision making, which tends toward decisions based on learned skills. The next higher level of decision making is rule-based decision making, which is often characterized by a single-response situation based on predefined rules of how the situation should be handled (*28–30*). Orasanu (*15*) and Wiener et al. (*31*) further divide rule-based decision making into two types of decisions. The first category is the go–no go decision. An example would be a rejected takeoff arising from "cargo door lights, runway traffic, compressor stalls and/or overheat lights" (*15*). The second category is the recognition-primed decision (*32*). In this situation, the decision maker would first interpret the cues as belonging to a particular event and then select an appropriate response on the basis of experience. A recognition-primed decision would be made in the case of a fuel leak where preestablished parameters must be considered (i.e., how much fuel remains, the rate of fuel loss, and how long the aircraft can continue flying). From this information, the closest appropriate airport must be identified and perhaps an emergency declared (*15*).

The highest level of decision making is knowledge-based decision making. Knowledge-based behavior occurs when the decision maker finds no preexisting structured procedure for the current incident or when the external circumstances allow deep reasoning about the system configuration and evolving phenomena. The decision maker knows intuitively that it is impossible to have a script for every possible circumstance. A script is defined as the product of individual knowledge, operation experience, operational policies, and applicable procedures. Individuals operating on a knowledge basis typically rely on logical reasoning, intuition, and creativity to generate rules for the existing situation. However, when responding to an unfamiliar emergency, they execute control activities based on logical reasoning.

Historically, when an "event" occurs, pilots analyze the event and use a defined hierarchy or procedure to make a decision. This means

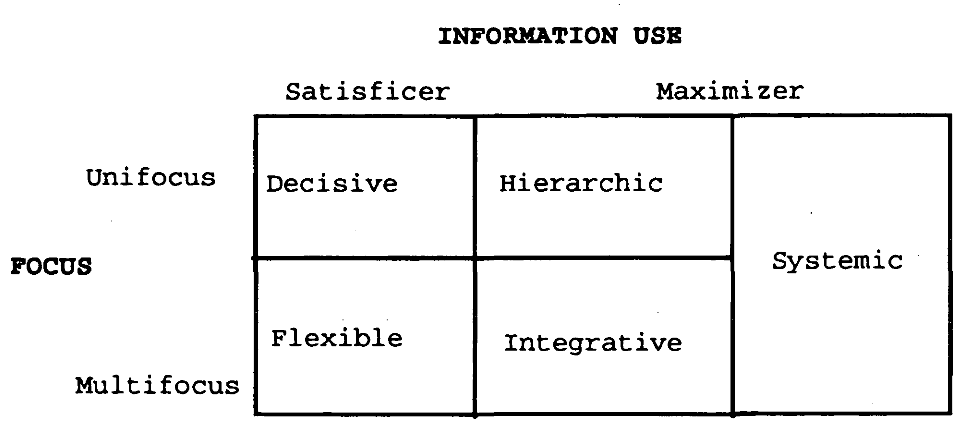

FIGURE 2 Decision style (*23*).

that both expected (changes in displays due to decreased altitude) and unexpected events (low fuel when the pilot thought the fuel level was higher) undergo the same type of processing. Rasmussen (*28*) reported that as the degree of familiarity decreases, the need for the crew to work as an integrated team increases. Thus, the pilot must make the transition from skill-based (automatic) and rule-based (procedures) to knowledge-based (unknown or unfamiliar territory) decision making, simultaneously moving from performing individual to team tasks.

Knowledge-based decisions can be made for either well-defined or ill-defined problems (*29*). Well-defined problems include option selections and scheduling decisions; ill-defined problems include nonprocedural activities and creative problem solving. Crews operating with ill-defined problems often try to "diagnose" what is occurring and may be unable to define the problem exactly. In such cases, there is often no prescribed procedure for identifying or solving the problem nor a script for the crew to follow. Such cases may require external input, for example, from air traffic controllers. Because of the ambiguity of the situation, no one correct or best solution is available to the crew (*15*).

Attempts have been made to reduce crew decision making by automating systems and establishing standard procedures and checklists that serve to cover anticipated failures or emergencies (*7*). However, even with such automated systems, increases in decision making often occur as a result of adverse weather conditions, unanticipated events (loss of subsystems), or heavy air traffic. While we can categorize these decisions, in reality, for any given flight situation, crews use a combination of skill-, rule-, and knowledge-based decision making (*15*).

RESEARCH STUDY

This research examined the impact of decision style of team members on team performance. It was hypothesized that the more unifocused the decision style, the lower the work load ratings for both rule- and knowledge-based decision making. It was also hypothesized that subjects with a unifocus decision style would see fewer display changes and provide fewer written comments than the multifocus subjects.

The independent variables for this study were segment type (takeoff, departure, cruise, instrument approach, and landing), task difficulty (rule based versus knowledge based), and team structure (decisive, flexible, hierarchic, integrative, and systemic). The dependent variables were work load ratings, number of display changes, and number of written comments from a postflight questionnaire.

Subjects

Crew members consisted of qualified flight crew personnel who had completed basic aircraft system training. Each crew member was properly attired with standard-issue flight equipment.

Apparatus

A high-fidelity six-degree-of-freedom motion base flight mission simulator with a CT-5A visual system for simulation of advanced aircraft was used during this test. The simulator cockpit had a two-person configuration. The left-seat person was primarily responsible for flying the aircraft, whereas the right-seat person was responsible for navigation, threats, and weapons delivery.

Procedure

Before the beginning of the experiment, all crew members completed a base SWAT sort. In addition, crew members who volunteered completed a decision style questionnaire.

Crew members were randomly assigned to teams. All simulator sessions were observed via the operator communications console located within the same general area as the simulator.

Each crew reported to the flight/mission simulator 1½ hr before the beginning of the sortie. Crew members were met by the evaluation conductor and briefed on the mission and requirements of the evaluation. Upon completion of the sortie, they were asked to participate in a 1-hr debriefing.

Work load ratings were collected throughout the sortie. Delayed SWAT ratings were collected at the debriefing to verify the ratings provided during the flight. In addition, each crew member completed a questionnaire to collect subjective information on the various segments of flight and crew coordination and communication during the sortie. Data were collected on the type and location of display used by each crew member during each flight segment.

Crews were randomly assigned to receive alternative rule-based (R) and knowledge-based (K) segments. Half of the crews were presented R-K-R-K-R segments and half were presented K-R-K-R-K segments.

RESULTS

Since the SWAT scale development yielded a Kendall W of 0.7528, a group scale was developed. Crew member decision style is summarized in Table 1.

Ten crews completed the simulator session in which each sortie comprised five segments: takeoff, climb, cruise, approach, and landing. Twenty-five total crews were available during the time allocated for study; however, 15 of the crews completed only some of these five segments of flight because of training needs, subsystem evaluations, and time constraints. Only data for the crews completing all five segments were included in the analysis of results. The average work load values for left and right seaters are given in Figures 3 and 4, respectively. In 100 percent of the cases, the work load increased for knowledge-based scenarios.

The data were analyzed to compare information need as a function of decision style. The number of display changes was used as the measure of information need. This analysis indicated that information maximizers (hierarchic, integrative, or systemic decision style) had a greater number of display segment changes for any segment than did satisficers (decisive and flexible decision style). In all five segments, information maximizer pilots had a greater average number of display changes than did information satisficer pilots. The takeoff and landing segments were both statistically significant. For the right seater, the WSO, information maximizers had a greater number of display changes than WSOs who were information satisficers in three out of the five segments. Multifocus individuals (flexible, integrative, and systemic decision styles) generally had more display changes than unifocus (decisive, hierarchic) individuals. In all segments the pilots who were multifocus had a greater

TABLE 1 Crew Member Decision Style

Crew #	Left Seat - Pilot (primary/backup)	Right Seat - WSO (primary/backup)
1	Decisive/--	Systemic/Decisive
2	Decisive/Integrative	Decisive/Integrative
3	Systemic/Flexible	Integrative/Hierarchic
4	Integrative/hierarchic	Systemic/Decisive
5	Integrative/Hierarchic	Decisive/Integrative
6	Flexible/Systemic	Decisive/Hierarchic
7	Systemic/Decisive	Hierarchic/Decisive
8	Hierarchic/Integrative	Systemic/Flexible
9	Hierarchic/Integrative	Decisive/Systemic
10	Integrative/Flexible	Integrative/Flexible

number of display changes than those who were unifocus. The differences were statistically significant for all segments with the exception of landing. In three out of the five segments, multifocus WSOs had a greater number of display changes than their unifocus counterparts. Table 2 summarizes the average number of display changes.

No significant differences were found between the number of comments or number of display changes by segment type (rule or knowledge based). In 80 percent of the segments for pilots and 60 percent of the segments for WSOs, the knowledge-based scenarios had a higher number of comments and display changes than did the rule based. The only segment in which there was a statistically significant difference was the case of the cruise knowledge-based segment for the WSOs. This was due in part to the selection of the knowledge-based scenario. That is, the task selected at the time of the study was not the final procedure for completing the task, thus the increased number of comments.

The number of comments made on the postflight questionnaire was also different as a function of individual decision style. In 80 percent of the segments for pilots and 60 percent of the segments for WSOs, multifocus individuals made a greater number of comments than their unifocus counterparts. Information maximizers also provided more written comments than did information satisficers. The comparison of written comments is provided in Table 3.

The types of comments made by each group are of particular interest. In general, the comments of those who were unifocus were related directly to the tasks completed during the segment and, in many cases, attempted to explain that the work load was probably lower than they reported. In contrast, those with a multifocus orientation discussed and provided a much more exacting and lengthy discussion. A sampling of comments is presented in Figure 5.

Another difference was that those with a unifocus orientation never discussed segments for which they had provided a low work load rating. However, those who were multifocused provided comments even when the work load was rated satisfactory. A sampling of these comments is provided in Figure 6.

Differences in work load ratings were found between individuals who were unifocused and multifocused. In 80 percent of the segments, multifocus individuals rated work load higher than did unifocus crew members for both rule- and knowledge-based tasks. No significant differences were found between the two groups for rule-based tasks; however, significant differences were found for takeoff, climb, and cruise for the WSOs. A comparison of the work load ratings of the two groups is given in Figure 7.

CONCLUSION AND FUTURE RESEARCH

The results of this study indicate that the decision style of an individual plays a role in experiencing and thus rating the mental work

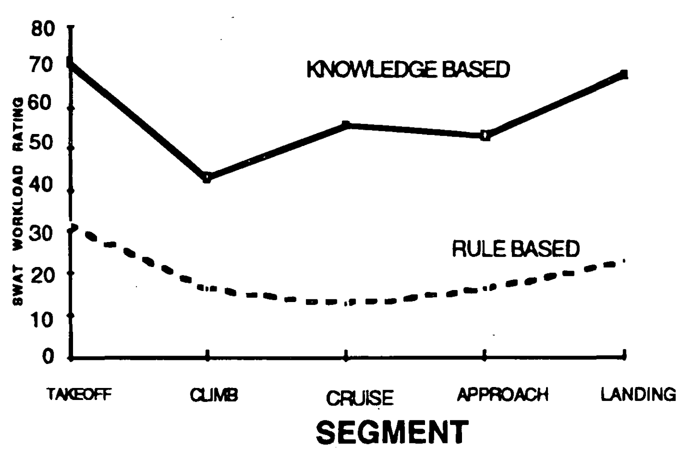

FIGURE 3 Pilots—work load rule- and knowledge-based decision making.

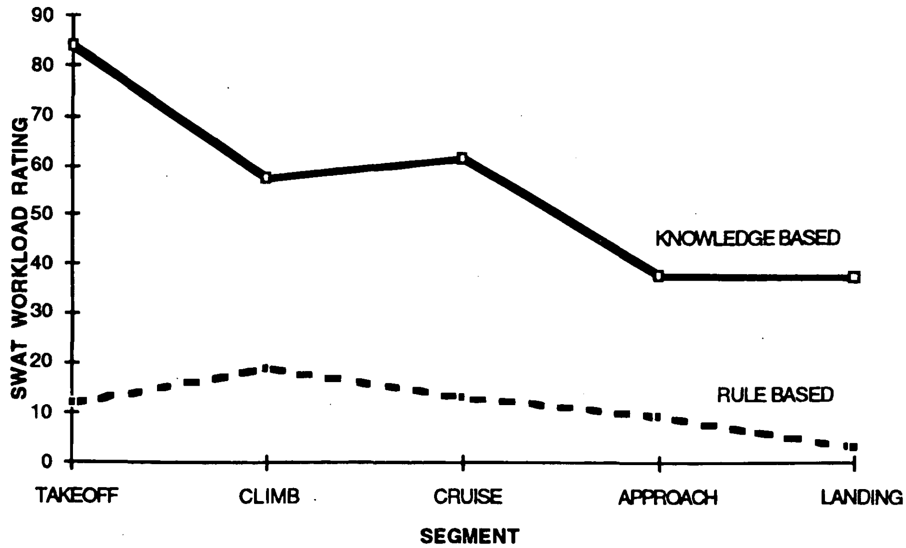

FIGURE 4 WSO—work load rule- and knowledge-based decision making.

load associated with various tasks. The differences in the subjective rating of unifocus versus multifocus styles arose from the crew members' perceived difficulty with the mental tasks. Perceived difficulty of a strictly cognitive task is a partial function of the "subjective complexity" of the subject and is also influenced by the components of the environmental load imposed on the crew member. The crew members—depending on their decision styles—had a different perception of the environmental load, then the different style-dependent subjective ratings were predictable. For instance, the unifocus crew members (decisive and hierarchic) had a consistent increase from rule- to knowledge-based tasks, whereas multifocus crew members (flexible, integrative, and systemic) had a larger increase from rule to knowledge based. In both the rule- and knowledge-based segments, multifocus crew members reported higher work load ratings than did unifocus crew members. These findings were supported by an increase in the number of display changes and number and complexity of written comments for multifocus crew members.

These findings are important for those involved in the design and operation of advanced aircraft. Using unifocus individuals to evaluate the initial design of these systems may result in higher work load ratings than would be obtained by examining the subject pool as a group. Multifocus individuals also provide a level of detail in terms of written comments that is far more useful than their unifocus counterparts, whose comments focus solely on the task as currently designed. The use of the multifocus crew members' "what if"

TABLE 2 Average Number of Display Changes

	Pilot				WSO			
Segment	Satisficer	Maximizer	Unifocus	MultiFocus	Satisficer	Maximizer	Unifocus	MultiFocus
Approach	0.333	1.286	0.500	1.333	0.500	0.330	0.500	0.333
Climb	0.667	0.714	0.250	1.000	0.500	0.667	0.750	0.500
Cruise	0.000	0.429	0.000	0.500	0.000	0.833	0.500	0.500
Approach	0.333	0.714	0.250	0.833	0.750	0.667	0.500	0.833
Landing	0.000	0.571	0.250	0.500	0.000	0.667	0.250	0.500

TABLE 3 Average Number of Written Comments

	Pilot				WSO			
Segment	Satisficer	Maximizer	Unifocus	MultiFocus	Satisficer	Maximizer	Unifocus	MultiFocus
Approach	0.667	1.000	0.500	1.167	0.500	0.333	0.500	0.333
Climb	0.667	0.571	0.250	0.833	0.500	0.667	0.750	0.500
Cruise	0.000	0.714	0.250	0.667	0.000	0.833	0.500	0.667
Approach	0.000	0.714	0.500	0.333	0.750	0.667	0.500	0.833
Landing	0.333	1.000	0.500	0.833	0.000	0.667	0.250	0.500

Unifocus Comments

With the a/r only 30 minutes from takeoff the workload here is probably artificially high

Simulator lighting and visual presentation increased workload over normal daytime levels

Multifocus Comments

Time control was somewhat confusing due to the implementation of xxx but the early late indication on display is helpful.

The display is helpful but several button pushes are necessary to keep up to speed on the threat in relation to your flight plan. Changing ranges, declutter schemes and updating display is time consuming while navigating through the threat

Attention to controls and displays increases due to the transition. All displays have lots of information to cross check

FIGURE 5 Unifocus versus multifocus comments.

or "what else" questions provides valuable information to designers of these systems before their operational use. Whereas the work load ratings are higher for multifocus crew members, their increased use of the information available (especially for integrative and systemic) appears to provide the crew member with more of the information that oftentimes is needed to diagnose the situation. Whereas there were no deviations from established procedures in this study, it is hypothesized that in future studies with knowledge-based scenarios that evolve over the duration of an entire flight compared with one segment of flight, we will see differences in performance from the different decision styles. Another area that needs further investigation is the specific verbal communication patterns between the different combinations of crews. Observation indicates that the more multifocus and information maximizing a crew member, the more likely he or she will be to both seek and share information. The ability of a crew member to seek necessary and sufficient information, both written and verbal, is critical to maintaining safety of flight.

ACKNOWLEDGMENTS

This research was financially supported by the Graduate Research Award Program, sponsored by the FAA and administered by TRB. The author would like to thank Larry L. Jenney of TRB, Joseph A. Breen of TRB, Robert L. Helmreich of the NASA/University of Texas/FAA Aerospace Crew Research Project, and Gerald S. McDougall of Southeast Missouri State University for their com-

Maintaining envelope is intensive and normal for this phase of flight

Climb with autopilot is easy to maintain

The early/late indication on the display is helpful

Information is good and available during this phase of flight

FIGURE 6 Multifocus comments with low work load ratings.

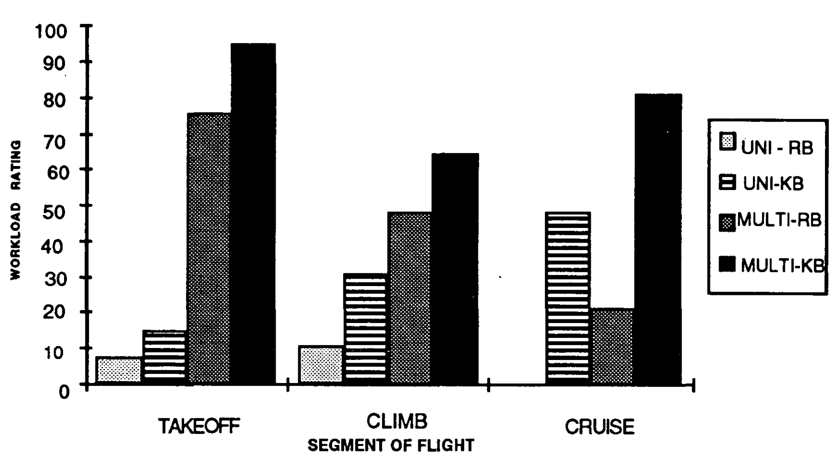

FIGURE 7 WSO—unifocus versus multifocus work load ratings.

ments. The support of the Institute of Safety and Systems Management, University of Southern California, has been invaluable, especially the support and encouragement of William Petak and Najmedim Meshkati. The author is also grateful to the Northrop Grumman Corporation, specifically the managers of the System Safety and Human Factors Department, Gerald R. Doria and James R. Francis, for their assistance in completing this research.

REFERENCES

1. *National Plan for Aviation Human Factors.* Vol. 1. FAA, U.S. Department of Transportation, April 1991.
2. Helmreich, R. L. Anatomy of a System Accident: The Crash of Avianca Flight 052. *International Journal of Aviation Psychology,* 1994.
3. *Human Factors, Management and Organization.* Draft digest. International Civil Aviation Organization Circular. Feb. 1993.
4. Hendrick, H. W. Macroergonomics: A Concept Whose Time Has Come. *Human Factors Society Bulletin,* Vol. 30, No. 2 1987, pp. 2–3.
5. Meshkati, N. Integration of Workstation, Job and Team Structure Design in Complex Human-Machine Systems: A Framework. *International Journal of Industrial Ergonomics,* Vol. 7, 1991, pp. 111–120.
6. Wierwille, W. W., and J. G. Casali. Mental Workload Estimation—An IE Problem. *IE Ergonomics News,* Vol. 17, No. 3, Winter 1983, pp. 1–4.
7. Wiener, E. L., and D. C. Nagel (eds.). *Human Factors in Aviation.* Academic Press, San Diego, Calif., 1988.
8. Wierwille, W. W., and R. C. Williges. *Survey and Analysis of Operator Workload Assessment Techniques.* S-78-101. Systemetrics, Inc., Blacksburg, Va., 1978.
9. Reid, G. B., C. A. Singledecker, T. E. Nygren, and F. T. Eggemeier. Development of Multidimensional Subjective Measures of Workload. *Proc., Human Factors Society,* 1982, pp. 403–406.
10. Reid, G. B., and T. E. Nygren. The Subjective Workload Assessment Technique: A Scaling Procedure for Measuring Mental Workload. In *Human Mental Workload,* (P. A. Hancock and N. Meshkati, eds.), Elsevier Science Publishers B.V., Amsterdam, Netherlands, 1988.
11. Helmreich, R. L. Future Directions in Crew Resource Management Training. *ICAO Journal,* Vol. 48, No. 7, 1993, pp. 8–9.
12. Helmreich, R. L., and H. C. Foushee. Why Crew Resource Management? Empirical and Theoretical Bases of Human Factors Training in Aviation. In *Cockpit Resource Management* (E. L. Wiener, B. G. Kanki, and R. L. Helmreich, eds.), Academic Press, San Diego, Calif., 1993, pp. 3–45.
13. Kanki, B. G., and M. T. Palmer. Communication and Crew Resource Management. In *Cockpit Resource Management* (E. L. Wiener, B. G. Kanki, and R. L. Helmreich, eds.), Academic Press, San Diego, Calif., 1993, pp. 99–136.
14. Helmreich, R. L., and H. C. Foushee. Group Interaction and Flight Crew Performance. In *Human Factors in Aviation* (E. L. Wiener and D. C. Nagel, eds.), Academic Press, San Diego, Calif., 1988, pp. 189–227.
15. Orasanu, J. M. Decision Making in the Cockpit. In *Cockpit Resource Management* (E. L. Wiener, B. G. Kanki, and R. L. Helmreich, eds.), Academic Press, San Diego, Calif., 1993, pp. 137–172.
16. Orasanu, J. M. Lessons from Research on Expert Decision Making on the Flight Deck. *ICAO Journal,* Vol. 48, No. 7, 1993, pp. 20–22.
17. Driver, M. J., and A. J. Rowe. Decision-Making Styles: A New Approach to Management Decision Making. In *Behavioral Problems in Organizations* (C. L. Cooper, ed.), Prentice-Hall, Inc., Englewood Cliffs, N.J., 1979.
18. Driver, M. J. Decision Styles and Organizational Behavior. *The Review of Higher Education,* Vol. 6, No. 4, 1983, pp. 387–406.
19. Shroeder, H., M. J. Driver, and S. Streufert. *Human Information Processing.* Holt, Rinehart, and Winston, New York, 1967.
20. Driver, M. J. Individual Decision Making and Creativity. In *Organizational Behavior,* (S. Kerr, ed.), Grid Publishing Inc., Ohio, 1979.
21. Driver, M. J., and S. Streufert. Integrative Complexity: An Approach to Individuals and Groups as Information Processing Systems. *Administrative Science Quarterly,* Vol. 14, 1969, pp. 272–285.
22. Driver, M. J., and T. J. Mock. Human Information Processing, Decision Style Theory and Accounting Information Systems. *The Accounting Review,* July 1975, pp. 490–508.
23. Driver, M. J., K. R. Brousseau, and P. L. Hunsaker. *The Dynamic Decision Maker.* Jossey-Bass Publishers, San Francisco, Calif., 1993.
24. Driver, M. J. Person-Environment Metastability: Decision Style Reliability. Presented at Joint National Meeting of ORSA-TIMS, Milwaukee, Wis., 1979.
25. Meshkati, N., and M. J. Driver. Individual Information Processing Behavior in Perceived Job Difficulty: A Decision Style and Job Approach to Coping with Human Mental Workload. In *Human Factors in Organizational Design and Management* (H. W. Hendrick and O. Brown, Jr., eds.), Elsevier Science Publishers B.V., Amsterdam, Netherlands, 1984.
26. Meshkati, N. *A Conceptual Model for Assessment of Mental Workload Based on Individual Decision Styles.* Ph.D. dissertation. University of Southern California, Los Angeles, 1983.
27. Meshkati, N., and A. Loewenthal. The Effects of Individual Differences in Information Processing Behavior on Experiencing Mental Workload and Perceived Task Difficulty: A Preliminary Experimental Investigation. In *Human Mental Workload* (P. A. Hancock and N. Meshkati, eds.), Elsevier Science Publishers B.V., Amsterdam, Netherlands, 1988, pp. 269–288.
28. Rasmussen, J. Mental Models and the Control of Action in Complex Environments. In *Mental Models and Human-Computer Interaction* (D. Ackerman and M. J. Tauber, eds.), Elsevier Science Publishers B.V., Amsterdam, Netherlands, 1990, pp. 41–69.
29. Rasmussen, J. Skills, Rules, and Knowledge: Signals, Signs, and Symbols and Other Distinctions in Human Performance Models. *IEEE Transactions on Systems, Man and Cybernetics,* Vol. SMC-13, No. 3, May–June 1983, pp. 257–266.
30. Rasmussen, J. Deciding and Doing: Decision Making in Natural Context. In *Decision Making in Action: Models and Methods* (G. Klein, J. Orasanu, R. Calderwood, and C. Zsambok, eds.), Ablex, Norwood, N.J., 1993.
31. Wiener, E. L., B. G. Kanki, and R. L. Helmreich. *Cockpit Resource Management.* Academic Press, San Diego, Calif., 1993.
32. Klein, G. A. A Recognition-Primed Decision (RPD) Model of Rapid Decision Making. In *Decision Making in Action: Models and Methods* (G. Klein, J. Orasanu, R. Calderwood, and C. Zsambok, eds.), Ablex, Norwood, N.J., 1993.

Preliminary Identification of Factors Causing Pilots To Disconnect the Flight Management Systems in Glass Cockpits

GINA T. GALANTE

Research in cockpit automation has indicated that pilots sometimes have difficulty understanding and operating cockpit automation systems. Problems with operating automated systems or the need to reprogram systems has the potential to keep pilots looking inside the cockpit during critical phases of flight when, in fact, they should be looking outside the cockpit. An alternative to reprogramming the automation, particularly the flight management system, is either to turn the automation completely off or to reduce the level of automation to the basic autopilot. Observations indicate, however, that pilots often do not turn off the automation when lengthy reprogramming is required. The identification of specific conditions under which pilots disconnect cockpit automation was made to determine whether they disconnect it when it is appropriate to do so. Examination and analysis of a field study of automation use from a major air carrier data base containing observational activities of crews were conducted. Second, the National Aeronautics and Space Administration's Aviation Safety Reporting System data base was queried. Third, pilots from major air carriers were surveyed to ascertain their decisions to disconnect the automated systems during flight and the circumstances affecting those decisions. Several common factors were found to affect pilots' decisions to disconnect automated systems. These multiple factors were pilot experience, work load, rapid air traffic control–issued changes, automation performance, weather, equipment failures, and congested airspace. These factors support prior automation research findings by others investigating various automation issues.

Automation-assisted flight has been used routinely in civil air transport since the end of World War II (*1*). Recently, fly-by-wire aircraft have been introduced with advanced control systems, flight management computers to aid navigation and flight path, and automated subsystem management computers that alleviate the crew of all routine subsystem management tasks (*1*).

Though modern aircraft may be easier to fly than the less advanced aircraft of the past, pilots must keep track of much more information than ever before. Pilots must know where they are and where their destination is located and be aware of environmental threats such as weather, terrain, and other aircraft (*2*). In addition, they must know the state of their aircraft, its systems, and consumables. The nature of most of the information they must monitor and control is dynamic and unpredictable.

Originally, automation was designed and introduced into the cockpit to aid pilots in performing information gathering, management, and control tasks (*1*). Automation of the flight deck was seen also as a way to drive human error out of the cockpit or "automate human error out of the system" (*3*).

The idea of automating as much as possible was very popular in the 1970s and early 1980s (*1*). Increased safety and pilot work load reduction were the expected benefits of automation in the cockpit (*1*). However, in the mid-1970s automation was beginning to be viewed as a possible source of problems in accidents and incidents in the aviation industry (*1,4*). The rapid introduction of automated technologies into the cockpit resulted in critical analyses from the aviation community regarding the use of automation. This introduction of automation was made possible by the increasing sophistication of microprocessor technology and display systems (*5*).

The benefits and pitfalls of cockpit automation have been under analysis for the last two decades. From the earliest investigations of cockpit automation, skepticism was expressed concerning the overall value of automation. One of the first published articles by Wiener and Curry (*3*) asks whether human error can truly be eliminated through automation. The temptation to design out human error, thereby reducing costly accidents and incidents, was nearly irresistible to engineers. Some researchers, however, had begun to ask whether automation had passed its ideal point. By the late 1970s, the U.S. government led by Congress directed the National Aeronautics and Space Administration (NASA) to examine human factors in cockpit automation (*4*).

Institute of Safety and Systems Management, University of Southern California, Los Angeles, Calif. 90089-0021.

PURPOSE

The purposes of the research presented here are to identify the conditions under which pilots disconnect cockpit automation and to determine whether they disconnect it when it is appropriate to do so. The research was conducted in three major segments. The first involved a field study of automation use from a major air carrier. The second involved analyzing the NASA's Aviation Safety Reporting System (ASRS) data base. The third and final segment involved conducting selected interviews followed by surveys with pilots from various air carriers.

BENEFITS OF AUTOMATION

Wiener (*6*) has also outlined eight benefits or reasons behind the use of cockpit automation, three of which are mentioned below.

Work load reduction is considered a primary incentive for the use of automated devices in cockpits. Work load reduction is viewed as a necessity for a variety of reasons, including the assumption that pilots prefer to be relieved of routine manual control and mental arithmetic. The alleviation of routine tasks is supposed to allow pilots time to oversee the flight and to be effective in emergencies. Another reason for work load reduction is to increase the time pilots can spend scanning or looking out the cockpit, rather than performing tasks that require looking inside the cockpit.

However, a research study of 200 Boeing 757 pilots conducted by NASA indicates that automation actually increased work load (*7*). Another reason for work load reduction is the change from three-pilot to two-pilot crews. Researchers report that the designers should be aware that each automated device creates its own scanning demand. Automation may not be increasing the time spent looking out the cockpit.

Increased flight precision and maneuvers created a need for conserving valuable and increasingly busy airspace. The economical use of airspace will require aircraft to travel closer together than ever before. Precise flight paths and maneuvers will allow for precision navigation; lateral, vertical, and longitudinal speed; and effective spacing of aircraft arrivals and departures.

Display flexibility has permitted designers to display information in many innovative ways. Software-generated displays allow pilots to configure their displays in a flexible, personalized manner. The problem is that the amount of information displayed may become overwhelming.

AUTOMATION PROBLEMS

Many problems are cited as a result of automation. Recently, it has been reported that pilots and researchers believe that the benefits of automation are debatable (*8*). Mecham reports that the idea that automation was introduced into the cockpit without adequate scientific study or empirical data is becoming increasingly popular (*8*). It has also been claimed that inappropriately designed automated systems are placing aviation safety at risk (*9*). Several other issues have been raised regarding automation and its potential problems.

Work Load

Although work load reduction is seen as a major benefit of automation in the cockpit, some researchers and pilots report that work load is not reduced in the busiest and most critical flight segments, such as during climb or descent into terminal areas (*10*). These flight segments become increasingly intense when air traffic control (ATC) issues changes. Some pilots report that they have never been busier than in glass cockpits even though automation promised to reduce work load (*10*). Reported research findings, however, do not clearly support either work load reduction or work load increase (*11*). In a recent study, pilots disagreed about the issue of work load (*12*). Half of the pilots surveyed reported concerns that automation actually increased work load. The respondents believed that work load was increased during flight phases that already have high work load and decreased work load in flight phases that have low work load (*12*). Crews also reported that in times of high work load, they turned the automation off and returned to manual modes of flight because they did not have time to reprogram and take advantage of the automation. This situation has been called the paradox of automation (*12*).

Loss of Manual Flying Skills

Pilots are reported to be concerned about overreliance on automation leading to a deterioration of basic flying skills (*13,14*). In one study of 200 Boeing pilots, nearly half reported that they were concerned about the possible loss of manual aviation skills because of too much automation (*7*). The study also indicated that 90 percent of the pilots reported that they hand-fly part of every trip to maintain their flying skills. Similarly, a study of pilot attitudes toward cockpit automation found that pilots are concerned about the loss of flying skills (*15*).

Along with the possible loss of flying skills due to overreliance on automation, some pilots report concerns about the reluctance to take over from an automated system. This reluctance often continues even when there is overwhelming evidence that something is wrong. The nature of these expressed concerns are self-assessments of personal performance and, therefore, cannot be relied upon as objective measures of actual flight performance in the operational environment (*11*).

Feelings of Disassociation from the Aircraft

The current generation of advanced cockpits has extensive computer processing of data from aircraft subsystems before presentation to the pilot (*15*). This processing has the capability of divorcing the crew from the raw data and, consequently, the state of the aircraft. In a study conducted by Wiener (*6*), pilots reported that they sometimes feel they are "along for the ride." Pilots also state that the problem is not insufficient work load but the feeling that they are "out of the loop." These statements refer to feelings that pilots report when the automation takes over and makes decisions without them. This feeling of disassociation has reportedly caused pilots and crews to "program" their way out of a problem rather than to deactivate the automation and fly the aircraft manually (*6*).

Situation Awareness

This feeling seems to be related to the frequently used term "situation awareness." Sarter and Woods (*9*) define situation awareness as "all knowledge that is accessible and can be integrated into a coherent picture, when required, to assess and cope with a situation." The loss of situation awareness can be potentially disastrous in the cockpit.

One common factor that seems to contribute to the loss of situation awareness is weak feedback from the automation displays and interfaces (*16*). Other clues that indicate a loss of situation awareness are failures to meet targets, undocumented procedures, departure from standard operating procedures, violation of minimums and limitations, no one flying the aircraft, and no one looking out the window (*17*).

Trustworthiness

Trustworthiness of automation is a problem that has been identified in automation research. Human trust in automation has been described by Riley (*2*) as the operator's subjective estimate of the probability that the next decision or action made by the automation will be correct. The problem of trustworthiness revolves around automation errors caused by system failures. The unreliability of an automated system can result in a system that is more costly to use, increases work load, and decreases safety. In general, however, automated systems are highly reliable (*4*).

Inappropriate Feedback and Interaction

Automation is often powerful enough to take over control of many complex tasks, but it is not powerful enough to handle the variety of abnormalities that can arise in the flight environment (*18*). The problem is that under normal operating conditions automated systems function in a manner that keeps human operators isolated from the moment-to-moment activities of the aircraft and controls. Therefore, when critical situations arise that cannot be handled by automation, the crew must be able to step in and recover the situation. Norman (*18*) suggests that problems are inappropriately blamed on automation being too powerful when, in fact, the real problem is that automation is not powerful enough.

Computer Changes

Reprogramming flight management computers during flight has been cited as a serious cause for concern. The results of a 3-year NASA study report that pilots are concerned about the tendency for crews to spend too much time looking heads-down or inside the cockpit while reprogramming flight computers (*7*). During the most critical phases of flight, pilots report excessive work load with the slightest change in their flight path (*10*). Pilots have also reported that it takes the undivided attention of one pilot to reprogram the computers (*7*). Pilots also claim that computer-driven cockpits demand a high degree of proficiency and are unforgiving to inexperienced pilots (*19*). Many of the computer devices used in cockpits will accept entries only in a certain format. Hughes (*19*) mentions that pilots can slip 10 mi behind the aircraft in their thinking in a very short time.

Pilot Interface

With increasing automation, pilots can become monitors of automated systems rather than aircraft controllers (*20*). The use of automated systems mandates that the interface be designed to take optimum advantage of human capabilities and the object controlled. The combination of manual and automatic control must be flexible (*21*). A review of research by Bergeron and Hinton (*20*) indicates several guidelines for good pilot interfaces with aircraft automation: aircraft status information and feedback should be simple, natural, and precise; flight-critical information should be continuous; control consoles should minimize the number of inputs; and routine and noncritical operations should be automated.

Training

Training issues are also shown to be potential sources of problems. There is a temptation for cost-conscious management to reduce training costs because they see the pilots' job as simpler with the aid of automated devices (*22*). Tullo (*22*) states that the opposite should in fact be happening. Researchers have found that pilots of glass cockpit aircraft indicate that they could use more training on how to use the numerous features of the complex autoflight and flight management systems (FMS) in glass cockpits (*12*). Another study conducted on pilot training for advanced cockpits found that automation has not reduced training needs (*14*). Pilot training should continue to emphasize system knowledge and simulator training but also additional education in the critical concepts of flight deck management (*22*). The Airbus Industrie subsidiary Aeroformation that directs Airbus training enforces the idea that crews need to maintain basic flying skills despite very high levels of automation (*23*).

RESEARCH ON AUTOMATION DISCONNECTS

Regardless of the problems associated with automation, there has been general acceptance of the use of automated systems on the flight deck (*11*). Automation also has been well received by pilots. The findings of several surveys and studies indicate that most pilots prefer to fly technologically advanced aircraft rather than the older, less sophisticated types (*11*). These findings lead to the conclusion that automation will continue to be used in cockpits and will probably increase in sophistication. Despite the increasing interest in cockpit automation, few empirical data are available about automated cockpit systems (*16*). Therefore, further detailed research into specific problems facing automation in the cockpit is clearly needed. The following research examines just one of the numerous problems associated with automation use.

Previous research indicates that pilots sometimes have difficulty understanding and operating cockpit automation systems (*16*). Problems with operating the system or the need to reprogram it have the potential to keep pilots flying heads-down, that is, looking inside the cockpit rather than flying heads-up, or looking outside the cockpit. An alternative to reprogramming the automation, particularly the FMS, is either to turn the automation completely off or to reduce the level of automation to the basic autopilot. Casual observations indicate, however, that pilots often do not turn the automation off when lengthy reprogramming is required (*24*).

The purposes of the research presented here are to identify the specific conditions and factors under which pilots disconnect cockpit automation and to determine whether they disconnect it when it is appropriate to do so. Three different techniques were used to investigate automation disconnects. The first segment of research involved a field study of automation use from a major air carrier. The second involved analyzing the data base available through NASA-ASRS. The third involved selected interviews followed by surveys with pilots from various air carriers.

FIELD STUDY OF AUTOMATION USE

The purpose of using this data base was to identify the conditions present when pilots disconnect the FMS and assess the appropriateness of their actions. The data base consisted of in-flight data gathered from 20 three-day trips with airline crews from a major air carrier, totaling 200 legs. The individual behaviors of the captains and first officers were recorded in the form of activity codes. The activity codes were collected every 7.5 sec. Data collection of each leg of a trip began from the takeoff roll of the aircraft to cruise altitude and then from top of descent to the arrival gate. Therefore, each leg had four segments: climb under and over 3050 m (10,000 ft) and descent under and over 3050 m (10,000 ft). The activity codes include behaviors such as hand-flying the aircraft while the autopilot was disengaged, looking out the window, manipulating the FMS, looking inside the cockpit, speaking to ATC, engaging the autopilot, and manipulating control wheel steering. The codes represent four types of activities: eyes, hands, communication, and global. The codes also represented only observable behaviors. The thought processes behind pilot responses could only be inferred. Therefore, any theorized pilot reasoning behind the activities codes was purely speculative.

Descriptive Categories

Approximately 40 out of the total 200 legs were identified as containing instances where pilots connected and disconnected the automation more than once during a flight. These unusual occurrences of engaging and disengaging automation multiple times in one leg accounted for roughly 20 percent of the total legs. These instances were then analyzed individually and inferences were made to categorize them into nine groups. The activities surrounding these automation codes were also investigated to identify any factors surrounding these disconnects.

Categorizing the 40 legs yielded 57 instances of automation disconnects. The 57 instances were individually analyzed and categorized. The results of categorizing the data led to the formation of nine descriptive groups. Figure 1 shows the nine descriptive categories of automation disconnect and their corresponding percentage of disconnects.

Control Wheel Steering

The control wheel steering (CWS) manipulation category refers to the pilot's use of CWS as a lower level of autopilot control. In these instances, the pilot only reduced the level of automation to CWS and then returned to the basic autopilot function rather than completely disconnecting all automation. This category accounts for 18 percent of all instances. Inclusion of an incident in this category was determined by the presence of a CWS code followed shortly by an autopilot code.

Unexpected Automation Performance

The category of unexpected automation performance of the describes instances in which pilots appeared to be surprised by the performance of the automation. This category accounts for roughly 18 percent of disconnects. This category includes MCP selection errors or programming errors. Included in this group are incidents of multiple MCP activity codes occurring before, during, and after automation disconnects. That the automation is not performing as expected or desired can only be inferred by the surrounding activity codes. The reasons behind the unexpected activity codes also can only be inferred because of the nature of this observational data base. It is impossible to determine whether the automation is responding in a surprising manner to the pilot's inputs because of correct or incorrect programming selections, incorrect data input, equipment failures, or inadequate system knowledge. The multiple reprogramming attempts by pilots are also plausible explanations for these codes.

Work Load

The category of work load was responsible for nearly 14 percent of automation disconnects. Inclusion of an instance in this category was determined by numerous activity codes in relatively small amounts of time surrounding the disconnect. An example of an incident that would be included in this category is multiple ATC calls occurring with numerous MCP inputs at a high–work load phase of flight at a particularly busy airport.

Equipment Failure

Equipment failures were responsible for nearly 11 percent of automation disconnects. This category includes any malfunction of any automated flight system, including the autopilot, autothrottle, or automated navigation systems. Inclusion of an incident in this category was determined by notes or citations of equipment failures made by the observer or by inference from the activity codes surrounding the automation disconnect.

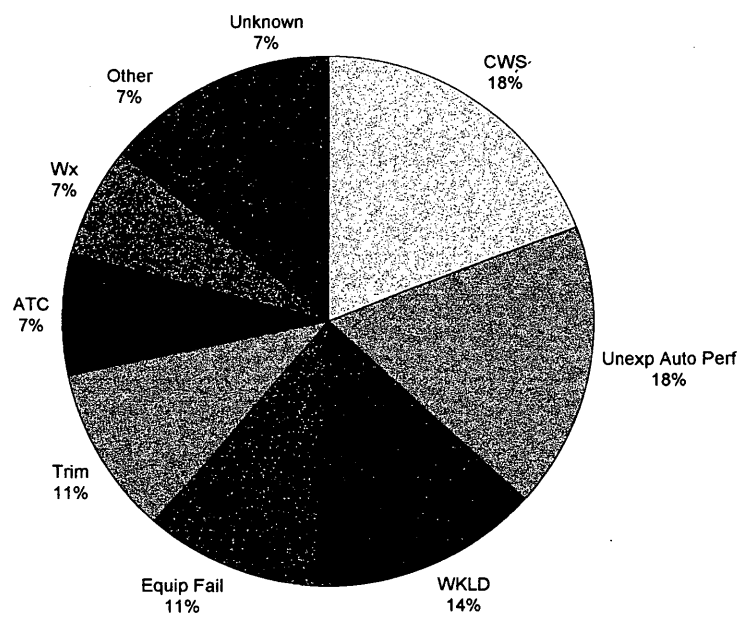

FIGURE 1 Percentages of automation disconnects from air carrier data base.

Trimming

Trimming the aircraft accounted for approximately 11 percent of the disconnect occurrences. Instances were assumed to belong to this category if rudder activity codes closely followed the automation disconnect.

ATC

The ATC category of automation disconnects includes altitude deviation, speed corrections, and any ATC-related issue or change made to the pilot by ATC. This category accounts for roughly 7 percent of all automation disconnects. Inclusion in this category was determined by ATC activity codes occurring before the automation disconnect and by inferences drawn from surrounding activities.

Weather

Weather-related disconnects were responsible for 7 percent of occurrences. Instances of automation disconnects were placed in this category when pilots encountered weather conditions resulting in flight through clouds or notification of impending flight through problematic weather conditions. Typically, this category includes instances when pilots appeared to be navigating around weather.

Other

The "other" category accounts for 7 percent of disconnects. This category includes disconnects that cannot be placed into any of the other categories and occur only once. An example is an autothrottle disconnect that occurred when an aircraft needed to wait on the runway after preparing to depart because of delayed landings.

Unknown

The "unknown" category is responsible for 7 percent of all incidents. A disconnect was included in this category if its cause could not be determined. The activity codes surrounding the disconnect did not supply any information that could lead to categorizing the incident into any of the other eight descriptive categories.

Flight Segment

An analysis of automation disconnects occurring in various flight segments was conducted for all incidents. The flight segment containing the highest percentage of disconnects was the descent above 3050 m (10,000 ft). Approximately 35 percent of all incidents fell into this category. The flight segments of climb under and above 3050 m (10,000 ft) represented 23 and 26 percent of all disconnects, respectively. The segment of descent under 3050 m (10,000 ft) contained only 15 percent of automation disconnects.

The analysis of this data base has permitted the identification of incidents in which automation was engaged and disengaged more than once per leg. Approximately 40 legs, or 20 percent, were found to include disconnects. The nature of this observational data base allows only the categorization of automation disconnects according to descriptive categories, as well as flight segment. The reasoning behind pilot motives to disconnect or reconnect the automation was not explicitly made known through the data collection techniques. Inferences, however, have been made regarding reasons for the disconnects and reconnects.

NASA-ASRS DATA BASE

The second segment of this research involved analyzing the data base available through NASA-ASRS. Searches and analyses were conducted on all automation disconnect reports for all aircraft types as well as on specific aircraft type reports. This was necessary because of the data base aircraft type de-identification format. The following types of aircraft were queried individually: A-320, Boeing 747-400, and Boeing 757/767. The remainder of this discussion will focus on the searches and analyses from the requests of all aircraft type and Boeing 757/767 disconnect reports.

Search Request on All Automation Disconnect Reports

The results of this search produced a list of automation-related incidents referencing disconnects for all aircraft types. A total of 300 reports was made available from the NASA-ASRS office. The reports were narrations of incidents and accidents related to the disconnection of automated systems.

An analysis of these reports was conducted on the aircraft falling into the following weight classes: large transport [68 100–136 200 kg (150,001–300,000 lb)], heavy/large transport [more than 136 200 kg (300,000 lb)], and wide-body [more than 136 200 kg (300,000 lb)]. From these weight classes, 57 automation disconnects were found relevant to this research. The analysis of these remaining reports then allowed grouping of the incidents into categories. Seven categories emerged from the analyses of these reports. Figure 2 shows the categories and percentages of automation disconnect from the NASA-ASRS search.

In each of the three weight categories, equipment failures accounted for approximately 50 percent of all automation disconnect incidents. Across all three weight categories, weather and turbulence was the second largest category and was responsible for roughly 22 percent of the incidents. ATC-related issues, such as altitude deviations or changes, accounted for 9 percent of all disconnects for the three weight classes. The Other category was responsible for 11 percent of all incidents. The Unknown category accounted for 4 percent of disconnects. The remaining categories—trimming an aircraft and pilot selection errors—each accounted for 2 percent of disconnects.

Search Request on Boeing 757/767-Type Reports

The search request conducted on Boeing 757/767 was referenced by key words, such as two engines, advanced cockpit, 68 100–136 200 kg (150,000 to 300,000 lb), and more than 136 200 kg (300,000 lb). This search request generated 300 Boeing 757/767 type reports.

The analysis of these reports found 22 incidents that contained references to automation disconnects. The reports were classified into six categories, as shown in Figure 3. The largest category was equipment failures with 31 percent of all disconnects. Selection and programming errors, the second largest category, contained 18 percent of reported disconnects. The categories of ATC and approach issued changes, Other, and Unknown each accounted for 14 percent of total automation disconnects. The smallest category, accounting for 9 percent, consisted of weather- and trimming-related disconnects.

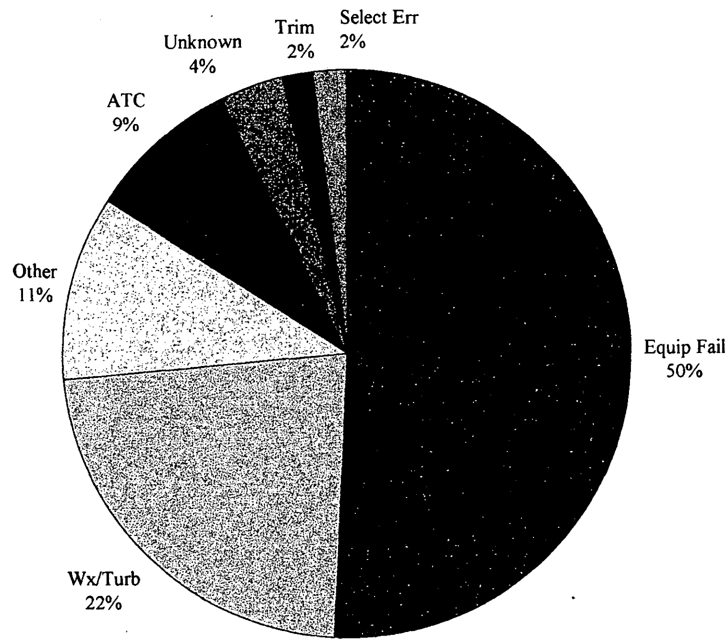

FIGURE 2 Percentages of automation disconnects from NASA-ASRS search of all reported automation disconnects.

INTERVIEWS AND SURVEYS

The third segment of research involved selected interviews followed by surveys with pilots from various air carriers. The interviews were used to develop the survey questions and format. The survey was used to question pilots directly about their decision to disconnect the automated systems during flight, the circumstances surrounding the disconnects, and the factors and parameters affecting their decision to disconnect the automation. The interviews and surveys also served to obtain pilots' attitudes and opinions concerning cockpit automation. Surveys were distributed to three major air carriers: 30 to Air Carrier X, 25 to Air Carrier Y, and 15 to Air Carrier Z. The survey distribution parameters were limited to 757/767 captains and first officers.

Demographic Information

The survey yielded 42 respondents. Seventy percent of the respondents held the position of captain on their current aircraft. The mean total flight hours of the pilots was 13,700, and mean months on the Boeing 757/767 was 36. The mean age of the pilots was 48.

Experience

Ninety-five percent of respondents indicated that they disconnect automation to maintain their flying skills. Roughly 40 percent indicated that they disconnect automation and hand-fly their aircraft at least once every leg. When asked if they used automated systems more, less, or no differently as they have become more experienced in flying their current aircraft, 7 percent said they used them less, and 43 and 50 percent said they used them the same or more, respectively. The mean number of hours pilots felt it took them to feel very comfortable with their current aircraft's automation was 160. Fifteen percent of pilots responded that their flight time to comfort was in excess of 500 hr. Ten percent of pilots responded that they use memory aids to help them with the automation in their aircraft. Of the 10 percent who used memory aids, half were first officers with a maximum of 11,000 hr.

Training

When asked whether they had received enough initial training on the automation in their cockpits, 17 percent of the pilots indicated that they did not feel they had been given enough training. Of these 17 percent, 30 percent were first officers with fewer than 9,000 total flight hr. Similarly, 25 percent of pilots responded that when they changed to their current aircraft, they found the automation difficult to use. Eighty percent of these pilots were over the age of 50 and all were captains.

Reliability

Fifty-five percent of pilots indicated that they had disconnected the autopilot or autothrottles because they were concerned about the reliability of the automation. Seventy-four percent of pilots responded that they had experienced failures of autopilot components on their aircraft.

Work Load and Automation Management

When pilots were asked if they disconnect the automation in high work load environments, 67 percent answered that they disconnect when the work load is high. Sixty-seven percent responded that it takes more time to program the autopilot in high work load phases of flight than it does to disconnect the automation and hand-fly the aircraft. When asked if they had ever programmed or reprogrammed the automation when in retrospect they should have dis-

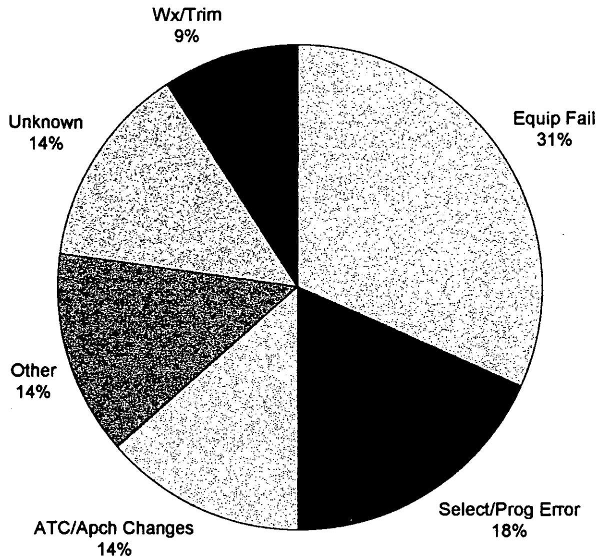

FIGURE 3 Percentages of automation disconnects from NASA-ASRS search of Boeing 757/767-type reports.

connected the automation and hand-flown the aircraft, 79 percent responded that they had. Ninety percent of pilots claimed that they made an error when programming the FMS, MCP, and so forth and had to disconnect either the autopilot or autothrottles. Twenty-four percent of pilots also indicated that they have had to disconnect the automation because they did not understand the automation, error message, or modes. Of these pilots, half had less than 12 months on the aircraft.

Approach and En Route

Pilots responded that several factors influence their decision to disconnect automation during approach. Figure 4 shows these factors in the approach and en route phases of flight. Multiple ATC changes were the most frequently cited factor that affected pilots' decisions to disconnect automation during approach. This factor was cited by 31 percent of respondents. Work load was the second most frequent factor affecting automation disconnects. This factor accounted for approximately 26 percent of responses. Weather was cited by 24 percent of pilots as an important factor. Pilot experience with automation accounted for 19 percent of the factors affecting the decision to disconnect during approach.

When pilots were asked if they had ever had to disconnect automation during an approach and then had to reconnect, 55 percent claimed they had. When pilots were asked if there were any external factors that affected their decision to disconnect automation en route, several factors were cited (see Figure 4). Pilot experience with automation was the most commonly cited factor affecting the decision to disconnect en route. This factor accounted for approximately 31 percent of disconnects. Multiple ATC changes were the second most frequently cited factor—accounting for 27 percent—affecting pilots' decisions to disconnect. Weather and busy airspace were two other factors cited by pilots and accounted for 24 and 18 percent of factors affecting disconnects, respectively.

Other

When pilots were asked if they ever disconnect the automation to increase passenger comfort, 38 percent responded that they do disconnect for comfort. Thirty-six percent of respondents reported witnessing unusual autopilot procedures or techniques in other pilots. When asked if they had ever noticed any instances when other pilots should have disconnected the automation but did not, 57 percent responded they had.

CONCLUSIONS

This research used three techniques to identify the specific conditions under which pilots disconnect cockpit automation. These three approaches consisted of examining and analyzing a major air carrier data base containing observational data of pilot crew activities,

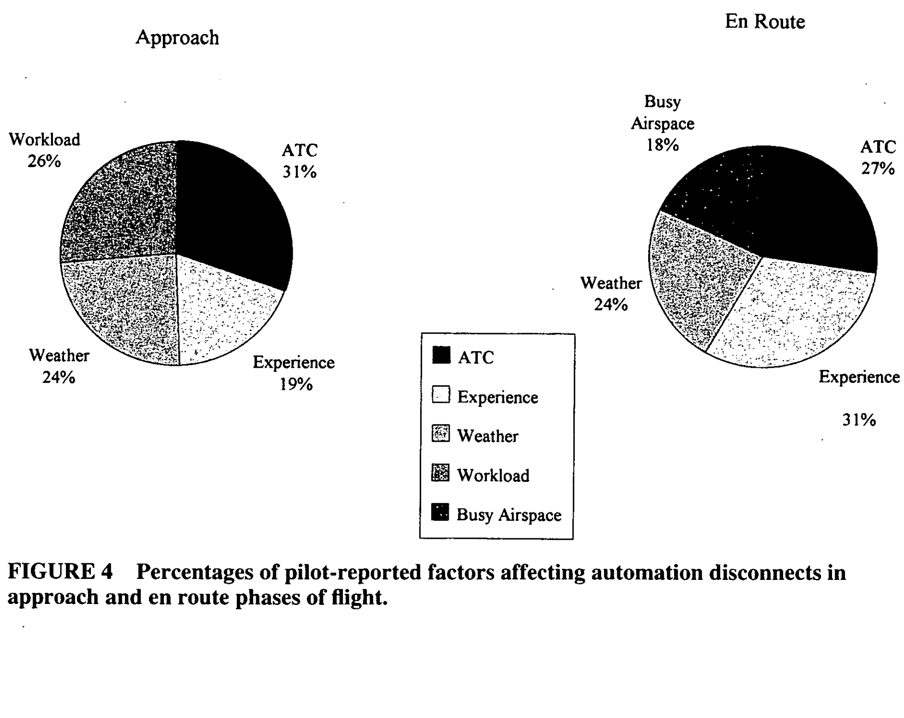

FIGURE 4 Percentages of pilot-reported factors affecting automation disconnects in approach and en route phases of flight.

querying and analyzing a variety of searches from the NASA-ASRS data base, and conducting selected interviews and surveys with pilots from major air carriers about their decisions to disconnect the automated systems.

These three research segments revealed multiple factors that influence pilots' decisions to disconnect automated systems. Pilot experience, work load, multiple and rapid ATC-issued changes, automation performance, weather, equipment failures, and busy airspace are factors that affect pilots' decisions to disconnect automation. The largest portion of automation disconnects was determined to occur in the descent above 3050 m (10,000 ft) flight segment. The surveys indicated several factors related to specific automation issues, including reliability, experience, training, and work load, which affect pilots' decisions to disconnect automation.

The findings support other research on various automation-related issues. For example, investigators have found that pilots report disconnecting automation once per trip to maintain their flying skills (*14,15*). Findings in this research also support those from Sarter and Woods (*16*) indicating that a large number of pilots on the Boeing 757 are surprised by the automation or do not understand all the modes and features of the FMS. These results also support prior research that had found that pilots disconnect automation during high work load phases of light (*12*).

This research focused on just one of many important automation-related issues. Because of the lack of empirical data on these issues, research investigating automation and pilots' use of automation needs to be continued.

ACKNOWLEDGMENTS

This research was financially supported by the Graduate Research Award Program sponsored by the FAA and administered by TRB. The author would like to thank faculty advisor Diane L. Damos from the University of Southern California for invaluable guidance and support. The author would like also to thank Joseph Breen of TRB, William E. Gehman of the Michigan Aeronautics Commission, Earl L. Wiener of the University of Miami, and Elizabeth Lydall, Bryan Coolican, and Jack Welsh for their comments and encouragement.

REFERENCES

1. Billings, C. E. *Human-Centered Aircraft Automation: A Concept and Guidelines.* NASA Technical Memorandum 103885. Ames Research Center, Moffett Field, Calif., 1991.
2. Riley, V. *Psychological Issues in Human Interaction With Automated Systems.* University of Minnesota, 1990.
3. Wiener, E. L., and R. E. Curry. Flight-Deck Automation: Promises and Problems. *Ergonomics,* Vol. 23, No. 10, 1980, pp. 995–1011.
4. Wiener, E. L., and D. C. Nagel eds. *Human Factors in Aviation.* Academic Press, San Diego, Calif., 1988.
5. Boehm-Davis, D. A., R. E. Curry, E. L. Wiener, and R. L. Harrison. Human Factors of Flight-Deck Automation: Report on a NASA-Industry Workshop. *Ergonomics,* Vol. 26, No. 10, 1983, pp. 953–961.
6. Wiener, E. L. Beyond the Sterile Cockpit. *Human Factors,* Vol. 27, No. 1, 1985, pp. 75–90.
7. Hughes, D. Glass Cockpit Study Reveals Human Factors Problems. *Aviation Week and Space Technology,* Vol. 8, 1989, pp. 32–36.
8. Mecham, A. German Center Studies Cockpit Automation. *Aviation Week and Space Technology* Vol. 12, 1993.
9. Sarter, N. B., and D. D. Woods. Situation Awareness: A Critical but Ill-Defined Phenomenon. *International Journal of Aviation Psychology,* Vol. 1, No. 1, 1991, pp. 45–57.
10. Hughes, D. Pilots, Research Studies Give Mixed Reviews to Glass Cockpits. *Aviation Week and Space Technology, March* 23, 1992, pp. 50–51.
11. Braune, R. J., S. E. Infield, P. M. Harper, and K. W. Alter. Human-Centered Requirements for Advanced Commercial Transport Flight Decks. *Proc., 35th Annual Meeting of the Human Factors Society,* Santa Monica, Calif., 1993, pp. 88–92.
12. Palmer, E. A., E. L. Hutchins, R. D. Ritter, and I. van Cleemput. *Altitude Deviations: Breakdowns of an Error-Tolerant System.* NASA Technical Memorandum 108788. Ames Research Center, Moffett Field, Calif., 1993.
13. Phillips, E. H. Pilots, Human Factors Specialists Urge Better Man-Machine Cockpit Interface. *Aviation Week and Space Technology,* Vol. 11, March 23, 1992, pp. 67–68.
14. Orlady, H. W., and W. A. Wheeler. Training for Advanced Cockpit Technology Aircraft. *Flight Safety Foundation: Flight Safety Digest,* 1993, pp. 8–12.
15. McClumpha, A. J., M. James, R. G. Green, and A. J. Belyavin. Pilots' Attitudes to Cockpit Automation. *Proc., 35th Annual Meeting of the Human Factors Society,* Santa Monica, Calif., 1991, pp. 107–111.
16. Sarter, N. B., and D. D. Woods. Pilot Interaction with Cockpit Automation: Operational Experiences with the Flight Management System. *International Journal of Aviation Psychology,* Vol. 2, No. 4, 1992, pp. 303–321.
17. North, D. M. Airbus Pilot Training Center Stresses Task-Sharing, Good Communications as a Key to Flying Advanced Aircraft. *Aviation Week and Space Technology,* March 23, 1992, pp. 63–64.
18. Norman, D. A. The "Problem" with Automation: Inappropriate Feedback and Interaction, Not "Over-Automation." *Philosophical Transactions: Royal Society of London,* Vol. B-327, 1990, pp. 585–593.
19. Hughes, D. Pilots Support 767 Automated Cockpit, but Cite Mismatch with ATC System. *Aviation Week and Space Technology,* March 23, 1992, pp. 52–55.
20. Bergeron, B. S., and B. S. Hinton. Aircraft Automation: The Problem of the Pilot Interface. *Aviation, Space, and Environmental Medicine,* Vol. 56, 1985, pp. 144–148.
21. Berestov, L. M., S. Y. Boris, V. V. Gorin, and V. V. Rogozin. Role of Human Factors Widening in New Aircraft Design. *ICAO Bulletin,* Dec. 1989, pp. 21–24.
22. Tullo, F. *A Look Into the Future: What Will the Pilot's Role Be in the Cockpit of the 21st Century?* 1990.
23. Lenorovitz, J. M. Airbus Stresses Cockpit Management, Coordination in Transition Training. *Aviation Week and Space Technology,* February 10, 1992, pp. 29–30.
24. Eldredge, D., S. Mangold, and R. S. Dodd. *A Review and Discussion of Flight Management System Incidents Reported to the Aviation Safety Reporting System.* Volpe National Transportation Systems Center, 1992.

Cost/Quality Trade-Offs in the Departure Process? Evidence from the Major U.S. Airlines

JODY HOFFER GITTELL

Higher costs should lead to higher quality, according to conventional thinking. In airline departures, longer scheduled turnaround times and higher per passenger airport staffing levels should lead to better on-time performance, customer satisfaction, baggage handling, and safety. To test the foregoing hypothesis, a unique longitudinal measure of scheduled turnaround time for the 10 major U.S. carriers was used, controlling for aspects of product complexity such as flight length, passengers per flight, cargo per flight, meal service, and percentage of passengers who connect. Longer turnaround times and higher staffing levels are found to be associated with worse on-time performance, customer satisfaction, baggage handling accuracy, and safety, controlling for product complexity. In addition, individual airlines vary greatly in the efficiency with which they use turn time and staffing resources to achieve these outcomes. Field research suggests that longer turnaround times are a form of organizational slack that detracts from organizational learning. Conversely, quick turnaround strategies may have an organizational learning spillover effect on other departure outcomes. The traditional logic suggests a trade-off between cost and quality such that turnaround time and staffing must be increased to improve on-time performance, baggage handling, customer satisfaction, and safety. The new logic suggests that low levels of resource use can lead to better outcomes, with the support of organizational practices conducive to learning. Toyota introduced this logic into the automobile industry with its just-in-time inventory system; Southwest has introduced it into the airline industry.

Traditionally, there is some trade-off within each industry between the cost and quality of its products or services. Part of an individual company's strategy is the choice of where to operate along that boundary. But organizational learning fostered by total quality management, process redesign, and the reduction of buffers has been used by companies in some industries to mitigate this trade-off. When these practices are used in a key process, they can become an important source of competitive advantage and alter the competitive dynamics of that industry. For example, in the automobile industry, Toyota was the innovator in the 1980s and set a new standard for achieving higher quality (in the sense of product reliability) at a lower cost, a standard that other Japanese and U.S. producers have since adopted (*1*). This paper presents evidence that Southwest Airlines has set a new standard in the airline industry for higher quality at lower cost, potentially changing the competitive dynamics of the industry.

Sloan School of Management, Massachusetts Institute of Technology, 50 Memorial Drive, Cambridge, Mass. 02142-1347.

HORIZONTAL COORDINATION AND REDUCTION OF TIME OR INVENTORY BUFFERS

Learning-intensive practices in the automobile and airline industries include two mutually supportive elements: (a) horizontal coordination based on teamwork and communication among frontline workers who perform different functions and (b) the reduction of time or inventory buffers. Each of these will be treated briefly.

Horizontal Coordination

Coordination is a problem that arises from specialization and the division of labor. It is a problem that every organization must solve. Coordination can be achieved primarily at the top of a vertical, hierarchical organization in which each functional group is relatively autonomous from the others. Or it can be achieved horizontally at each level of a relatively flat organization, across frontline employees and at each level of management. They are two distinct organizational designs, each with a set of supporting human resource and other practices that foster a distinct set of employee behaviors (*2*).

Horizontally coordinated organizations are thought to have certain competitive advantages over hierarchically coordinated ones in their ability to achieve higher quality at lower cost by achieving faster cycle times and by providing a more coherent interface with customers. These organizations can change the nature of competition in an industry by pushing out the cost/quality frontier rather than making cost/quality trade-offs along an existing frontier. Evidence has been found in the garment industry as well that "the strategic shift to greater coordination shifts the placement of the traditional 'cost/service' curve to a more favorable position" (*3*, p. 13).

Some set of organizational practices—work organization, human resource, and performance measures—appears to be needed to support horizontal coordination. A related project (based on observations, interviews, and surveys at four airlines) identifies some potential elements of this set (*4*). In the area of work organization, cross-functional teams or case managers can be used as coordinating mechanisms. These mechanisms shift the structure of accountability, authority, and the flow of information from vertical to horizontal. In the area of human resources, selection and training are used to develop generalists or, alternatively, specialists who can communicate across functional boundaries. Job rotation is also used in some contexts to achieve broader knowledge. In the area of performance measures, shared outcome measures and group rewards are used to foster teamwork and communication. Finally, the evidence also suggests the importance of mechanisms for resolving conflicts and reducing status boundaries between functional groups.

Reduction of Time or Inventory Buffers

In addition to these organizational practices, one of the supporting characteristics for horizontal coordination that helps to achieve both cost and quality gains is the reduction of buffers. In hierarchical coordination, in-process time or product inventories are used as buffers between stages of work to protect each functional area from the need to communicate with and resolve problems with other functional areas (*5*). Horizontal coordination is fostered by the reduction of buffers, which reveals problems, forces communication and learning across functions, and is conducive to continuous improvement of product or service quality. Reducing buffers has the secondary effect of reducing costs, so that organizations that do it successfully are able to offer customers lower-cost and higher-quality products and services.

Cost-Quality Breakthrough

In the airline industry, carriers that use shorter scheduled turnaround times should have better outcomes for on-time arrivals, customer satisfaction, baggage handling, and safety without resorting to excess staffing, if they have also instituted practices that support horizontal coordination. This would support the argument that longer turnaround times are a form of organizational slack that detracts from cross-functional learning and that quick turn strategies have an organizational learning spillover effect on other departure outcomes. The old logic suggests a trade-off between cost and quality such that turnaround time and staffing must be increased to improve on-time performance, baggage handling, customer satisfaction, and safety. The new logic suggests that low levels of resource use can lead to better outcomes, with the support of organizational practices conducive to learning. Toyota introduced this logic into the automobile industry with its just-in-time inventory system; Southwest Airlines, it is argued, has introduced it into the airline industry.

DEPARTURE PROCESS

The departure process is one of the core processes of an airline's operations. Its success or failure, repeated hundreds of times daily in dozens of locations, can make or break an airline's reputation for safety and reliability. It is also perhaps the most complex process that an airline performs on a repeated basis. The complexity of the departure process varies according to the carrier's product mix and division of labor. At American Airlines, which has a typical product mix and division of labor for a major commercial air carrier, the departure process requires the direct or indirect input of 12 departments. At the point of departure, the process requires rapid coordination among nine groups of frontline employees—ramp workers, mechanics, ticket agents, gate agents, skycaps, caterers, operations agents, flight attendants, and pilots—most of whom report to separate departments. Flights at American Airlines are currently turned around with a minimum scheduled time of 35 min (for the MD80)—from gate arrival to gate departure—whereas comparable flights (Boeing 737) are turned around with a minimum scheduled time of 15 min at Southwest.

A departure is successful from the customer's point of view if it does not involve unnecessary hassles and if it results in a safe, on-time arrival of the customer and his or her baggage. On-time arrival is generally found to be passengers' most important criterion for the quality of air travel (*6,7*). A departure is successful from the airline's point of view if these customer outcomes are achieved in a cost-effective way.

Scheduling To Reduce Departure Delay

Airlines attempt to reduce departure delay without mishandling bags, without treating customers rudely, and without resorting to overstaffing. Often they do this by improving the management and coordination of employee effort. Alternatively, however, they reduce departure delay by expanding scheduled turnaround time—adding buffers, as it were, to the schedule. Interviews with station managers and aircraft schedulers suggest that this latter practice is common.

These buffers are costly, however. Extra turnaround time increases the overall length of a flight for passengers who are continuing through the hub, which makes a flight less attractive and makes it appear lower on travel agents' screens (reduces "screen presence"). Extra turnaround time also increases the ground time of aircraft, which is costly. This is an especially important consideration on short-haul routes, where turnaround time is a higher percentage of total time.

Finally, extra turnaround time may even reduce rather than increase on-time departures, the integration of customer service, and productivity. If extra turnaround time serves as a buffer in the system that reduces the pressure for learning and problem solving, airlines with higher turnaround times may experience lower rather than higher outcomes, just as manufacturing processes with more in-process inventories have been found to experience more frequent defects and lower productivity (*8*).

Isolating the Influence of Coordination and Product Complexity

The goal here is to identify the components of turnaround time and departure delay that are influenced by the coordination of the work process, those that are influenced by a carrier's strategic choices about product mix, and those that are beyond the control of any individual carrier.

Turnaround time and transit time together account for an aircraft's total time in service. Turnaround time is the time from arrival at the gate until departure from the gate, and transit time is the time from gate departure to gate arrival at the down-line station. Reducing either one increases the number of flights an aircraft can make in a given day, thereby increasing the revenue generated by that aircraft. But reducing them below what the organization can reliably achieve risks late arrivals, which dissatisfies customers and causes further delays throughout the system.

Turnaround time can be usefully thought of as having three components (see Table 1). Every carrier has a systemwide minimum scheduled turnaround time (TURN1): the minimum period of time in which stations are expected to prepare an aircraft for departure. TURN1 varies for each plane type—larger planes have a longer TURN1—and differs for international flights, where more meals must be loaded and so forth. Often the total scheduled turnaround time is greater than the minimum, for reasons discussed later, but TURN1 is the period in which a station is expected to turn a plane around whenever a flight is running late and needs to be turned

TABLE 1 Components of Turn Time, Transit Time, and Delays

TURN1	Minimum scheduled turnaround time. The turnaround time an airline reverts to when the incoming plane arrives late, based on the minimum feasible time to turn the aircraft.
TURN2	Scheduled buffers. Extra time scheduled beyond the minimum scheduled turnaround time, to increase the likelihood of staying on schedule.
TURN3	Scheduled connect time. Extra time scheduled beyond the minimum scheduled turnaround time, to allow passengers to connect.
TRANS1	Taxi time at originating station.
TRANS2	Flight time.
TRANS3	Taxi time at destination station.
DELAY1	Delay caused by coordination problems among station personnel or between station personnel and flight crew.
DELAY2	Delay caused by weather or airport congestion.
DELAY3	Delay caused by passenger accommodation.

around as soon as reasonably possible. If a flight comes in late, the station is charged with a late departure only if it takes longer than the TURN1 for that plane and flight type to turn it around.

TURN1 also varies across carriers, even for the same plane and flight type, because of considerations like whether the airline carries freight and mail. For example, Southwest increased its TURN1 from 10 to 15 min in the late 1980s in large part because it began to carry freight and mail. TURN1 also varies across carriers depending on the speed at which the organization is geared up to turn the plane around. For example, TURN1 is 15 min at Southwest and 35 min at American. This depends in part on practices like equipment standardization and product simplification and whether flight attendants or special crews clean the planes. TURN1 also depends on the efficiency of the work process, it is argued, particularly the quality of cross-functional coordination.

There is a second component of scheduled turnaround time called buffer time (TURN2). It is added selectively to a schedule when a particular flight is always late in departing due to various problems in preparing the plane for departure and when it is considered less costly to add buffer time than to risk the late departures or to fix the problems. But when a flight is late in arriving from the up-line station, the scheduled turnaround time reverts to TURN1, and the station must do without the buffer time to avoid being charged with a delay.

A third component of scheduled turnaround time—connect time (TURN3)—depends a great deal on the route structure. In a hub-and-spoke system, where flights are scheduled to converge at a central location, transfer passengers, and continue to final destinations, additional ground time is scheduled at hub cities to allow passengers to connect and at spoke cities to time flights to converge back at the hub at the same time. Point-to-point route systems may schedule in some connect time at cities where passengers often connect, but they minimize the need for TURN3 by scheduling more frequent flights so that transfers do not require convergence and by designing the route structure so that continuing passengers have numerous ways to reach the same destination.

Transit time has three components. The first—taxi time (TRANS1)—begins as soon as the aircraft pushes back from the gate and continues until takeoff. The other components of transit time are flight time (TRANS2) and taxi time at the down-line station (TRANS3). Delays can occur in any of the three components because of airport congestion or weather but are relatively uncontrollable. Some carriers try to reduce TRANS1 by choosing airports that are less congested. This component of turnaround time is somewhat related to a carrier's route structure since a hub-and-spoke carrier does the kind of peak scheduling that contributes to airport congestion. But even point-to-point carriers may be affected by the congestion caused by hub-and-spoke carriers if they use hub airports. Other than changing airports or decreasing the peaking of one's schedule, increasing the scheduled transit time is often the only viable response to transit delays.

There are three primary kinds of nonscheduled turnaround time, or delays. The first is from lack of coordination of some kind (DELAY1). The second is from weather or airport congestion that prohibits the aircraft from pushing back from the gate (DELAY2).

The third is a discretionary delay made to accommodate passengers from another flight when the transfer time was not sufficient, or passenger delay in embarking or disembarking due to other problems (DELAY3).

Increasing the efficiency of the work process allows a carrier to reduce minimum scheduled turnaround time (TURN1) and buffer time (TURN2) and to reduce delays that result from a lack of coordination (DELAY1). But improved coordination does not reduce transfer time (TURN3), transit time, or delays due to congestion (DELAY3) since these are driven largely by the scheduling required to support the hub-and-spoke route structure and the airport congestion that results from it. These other kinds of turnaround and transit time are also costly to carriers, but because they are not affected by organizational efficiency they are not considered here. They are built-in costs of the hub-and-spoke system—presumably costs that are outweighed by the benefits of hubbing. The larger debate about hub-and-spoke versus point-to-point is heated and complex and will not be directly addressed here.

ANALYSIS AND FINDINGS

The following sections describe findings on product complexity, cost levels, and quality outcomes for the 10 major U.S. carriers, using longitudinal data from September 1987 through May 1994. The variables used in the analysis are given in Table 2. Their sources are given in Table 3. A detailed discussion of the selection and derivation of these variables can be found in a data appendix, available from the author upon request.

Differences in Product Complexity

Before we can compare cost levels or quality outcomes for the 10 major U.S. carriers, it is necessary to understand and adjust for differences in their products. Clearly, there is a demand for both a more and a less complex product. We do not want to assume that either is superior, nor do we want to bias our measure of efficiency in

TABLE 2 Variable Descriptions (Sample: U.S. Major Airlines' Domestic Systems, September 1987 to May 1994)

Name	Description	Mean	Std Dev	Obs
COSTS				
Turn Time	Minutes of scheduled aircraft time at the gate, for through flights.	43.1	11.4	737
Staffing	Airport employees (excluding maintenance) per thousand daily passengers.	125.9	37.8	810
Cost Index	((Turn Time/ avg(Turn Time) + Staffing/ avg(Staffing)) x 100) / 2	100.0	24.4	737
QUALITY				
Late Arrivals	Percent of flights that arrive more than 15 minutes late, disregarding mechanical delays.	19.3	6.7	810
Complaints	Departure-related customer complaints per million passengers.	15.5	24.4	810
Lost Bags	Mishandled bags per thousand passengers.	6.4	2.2	810
Deviations	Pilot deviations per thousand departures.	29.6	34.4	810
Qual Index	(4 * 100)/(Late/avg(Late) + Comp/avg(Comp) + Lost Bags/avg(Lost Bags) + Dev/avg(Dev))	131.8	69.7	810
PRODUCT COMPLEXITY				
Passenger	Passengers per departure.	72.0	12.2	810
Length	Thousands of miles flown per departure.	634.2	136.3	810
Cargo	Ton miles of freight and mail flown per departure.	724.4	450.8	810
Connects	Percent of passengers who connect.	38.2	12.0	810
Meals	Meal expenditures per passenger ($).	4.13	2.03	810

TABLE 3 Data Sources (Sample: U.S. Major Airlines' Domestic Systems, September 1987 to May 1994)

Name	Source
COSTS	
Turn Time	Official Air Line Guide Scheduling Data, archived by the Federal Aviation Administration
Staffing	Form 41, Schedule P10, U.S. Department of Transportation
QUALITY	
Late Arrivals	Air Travel Consumer Report, Table 1, U.S. Department of Transportation
Complaints	Air Travel Consumer Report, Table 3, U.S. Department of Transportation
Lost Bags	Air Travel Consumer Report, U.S. Department of Transportation
Deviations	National Transportation Safety Board, FAA Pilot Deviation Subsystems
PRODUCT MIX	
Passenger	Traffic Digest of Statistics: Commercial Air Carriers, International Civil Aviation Organization
Length	Traffic Digest of Statistics: Commercial Air Carriers, International Civil Aviation Organization
Cargo	Traffic Digest of Statistics: Commercial Air Carriers, International Civil Aviation Organization
Connects	Origin and Destination Survey Data, Average Coupons, U.S. Department of Transportation
Meals	Form 41, Schedule P7, U.S. Department of Transportation

favor of a less complex product. Ultimately, we want to compare apples with apples—not apples with oranges. Number of passengers per departure, length of flight, cargo carried, percentage of connections, and degree of meal service all reflect types of product complexity that affect the relative ease of the departure process. Airlines that offer a more complex product are therefore expected to require more scheduled turn time and more airport staffing per passenger.

Important differences are evident on Table 4. The average number of passengers per departure ranges from about 50 (for Alaska Air and Southwest) to about 85 (for United and American). These differences are not due mainly to load factors, which vary little across carriers, but rather to difference in average aircraft size.

Average leg length varies according to whether a carrier offers primarily a short- or long-haul product. Southwest and USAir are at the bottom of the distribution with 376 and 482 mil per flight, respectively. American and United lead the group with 785 and 810 mil per departure, respectively.

Cargo carried varies substantially across the major carriers in this period, with Southwest again at the low end, carrying only 7 percent of the industry average mail and freight. Northwest and United are at the high end with each carrying twice the industry average.

Percentage of passengers who connect is especially low for Southwest, with only 12 percent compared with an industry average of 38 percent. Southwest is the least hubbed of all the carriers, with a linear or point-to-point route structure. America West and Alaska Air approximate this structure most closely at 32 percent and 24 percent of connections, respectively. Delta is the most hubbed carrier, connecting 53 percent of its passengers, with American and Northwest close behind at 46 percent and 49 percent, respectively.

Finally, in meal expenditures per passenger, Southwest is also at the extreme low end, spending only $0.18 per passenger on average. American and Alaska Air have the highest expenditures, at $5.99 and $7.35 per passenger, respectively.

A trend analysis of these variables (not shown here) indicates that for the major carriers as a whole, each measure of product complexity has been increasing over the period.

Actual Turn Time and Staffing Levels

These carriers also differ significantly in the levels of turn time and airport staffing over this period (Table 5). Southwest Airlines has

TABLE 4 Differences in Product Complexity* (Sample: U.S. Major Airlines' Domestic Systems, September 1987 to May 1994)

	Passenger mean(SD)	Length mean(SD)	Cargo mean(SD)	Connnects mean(SD)	Meals mean(SD)
Alaska	50.8 (6.5)	586.1 (37.6)	679.7 (75.6)	24.1% (2.1)	$7.35 (0.93)
American	86.1 (7.5)	784.5 (51.8)	779.0 (201.5)	46.4% (1.6)	$5.99 (0.52)
AmWest	72.8 (7.5)	557.7 (77.8)	348.8 (145.9)	31.6% (2.3)	$2.01 (0.54)
Continental	72.4 (6.6)	749.0 (29.8)	700.0 (82.2)	40.2% (3.5)	$4.44 (1.65)
Delta	79.4 (7.1)	622.5 (7.7)	704.1 (63.7)	52.7% (3.0)	$4.46 (0.32)
Northwest	71.3 (7.3)	670.2 (39.3)	1501.0 (194.6)	48.8% (2.1)	$3.80 (0.53)
Southwest	51.0 (34.3)	375.9 (4.6)	51.0 (34.3)	12.1% (1.1)	$0.18 (0.05)
TWA	72.9 (6.3)	704.2 (18.2)	976.9 (87.3)	43.9% (2.0)	$4.62 (0.05)
United	85.8 (7.6)	810.0 (24.2)	1310.6 (100.2)	40.5% (1.4)	$4.90 (0.43)
USAir	61.5 (4.9)	481.7 (30.1)	192.6 (48.1)	41.7% (5.4)	$3.55 (0.91)
Total	72.0 (12.2)	634.2 (136.3)	724.4 (450.8)	38.2% (12.0)	$4.13 (2.03)

* See Table 2 for definitions of these five components of product complexity.

the lowest turnaround time by far; at 17.3 min it uses only 40 percent of the industry average. Southwest is followed by Alaska Air at 33 min and America West at 41. At the high end is Northwest, which turns planes in 55 min—28 percent above the industry average. TWA, United, and American have slightly lower turn times than Northwest.

In staffing, Southwest is at the low end again, employing an average of 65 airport personnel per 1,000 passengers enplaned daily, relative to an industry average of 126. America West follows closely with 77 airport employees per 1,000 passengers daily. Delta, American, TWA, and Alaska lead in staffing levels with more than 150 airport employees per 1,000 passengers enplaned daily.

Effect of Product Complexity on Turn Time and Airport Staffing

Differences in product complexity are expected to account for some of the differences in carrier levels of turn time and airport staffing. Length of trip influences the length of the fueling process and the number of bags to be loaded. The number of passengers boarded increases the staff and time required for check-in, baggage handling, and boarding. The amount of cargo loaded affects the time and staff required for handling. The degree of meal service likewise affects the time and staff required for handling. Connecting passengers require staff for transferring bags, checking them in, and rerouting them in case of missed connections. Connections also require additional scheduled turn time to allow a group of flights to meet up.

Table 6 gives the effects of these five elements of product complexity on turn time and airport staffing. As expected, flight length, cargo, and connections increase the amount of scheduled turn time (Column 1). The number of passengers and degree of meal service also increase the amount of scheduled turn time (equation not shown here), but their effects are overwhelmed and reversed by the other factors. Once individual carrier effects are accounted for, flight length, cargo, and connections continue to increase the needed turn time (Column 2).

Meals and flight length both have significant positive effects on airport staffing levels per passenger, controlling for individual carrier differences (Column 4). But the number of passengers per departure actually reduces rather than increases per passenger staffing needs. This likely arises from the tendency of carriers to conserve on staffing by using the same number of gate agents, ticket agents, and baggage handlers to staff a larger flight—it just takes longer. Also, once individual carrier effects are accounted for, cargo and connections have no systematic effects on staffing requirements.

From the coefficients on trend, it is clear that both turn time and staffing requirements have increased significantly over this period,

TABLE 5 Turn Time and Airport Staffing (Sample: U.S. Major Airlines' Domestic Systems, September 1987 to May 1994)

	Turn Time		Staffing		Cost Index**	
	Actual mean(SD)	Adj* mean(SD)	Actual mean(SD)	Adj* mean(SD)	Actual mean(SD)	Adj* mean(SD)
Alaska	33.0 (5.0)	40.2 (2.2)	153.2 (34.9)	109.6 (9.4)	98.7 (16.5)	90.0 (4.7)
American	50.8 (5.6)	46.4 (2.3)	156.8 (23.6)	171.7 (9.4)	121.3 (13.0)	121.7 (4.9)
AmWest	41.1 (4.0)	44.6 (2.3)	77.2 (11.0)	86.9 (9.4)	78.1 (7.2)	86.1 (4.8)
Continental	46.4 (2.8)	43.1 (2.2)	108.6 (14.7)	102.0 (9.4)	97.0 (6.9)	90.3 (4.8)
Delta	46.7 (4.5)	44.2 (2.2)	162.5 (19.2)	175.9 (9.4)	118.3 (7.3)	120.8 (4.8)
Northwest	55.1 (3.4)	47.2 (2.3)	132.3 (16.2)	130.0 (9.4)	116.1 (7.3)	106.1 (4.8)
Southwest	17.3 (2.0)	30.0 (2.7)	65.2 (6.1)	78.3 (9.4)	45.8 (2.7)	65.8 (4.9)
TWA	51.2 (4.7)	46.8 (2.3)	154.4 (19.3)	151.4 (9.4)	120.3 (10.6)	114.3 (4.7)
United	50.0 (4.7)	42.3 (2.2)	134.4 (15.7)	150.7 (9.4)	110.8 (7.8)	108.6 (4.8)
USAir	41.6 (2.5)	47.0 (2.2)	114.0 (20.3)	102.4 (9.4)	93.4 (9.2)	95.0 (4.6)
Total	43.1 (11.4)	43.1 (5.4)	125.9 (37.9)	125.9 (34.6)	100.0 (24.4)	100.0 (17.3)

*Adjusted for differences in product mix. See Table 6 for derivation.
**Cost Index includes turn time and staffing. See Table 2 for derivation.

over and above the increases one would expect from product complexity alone. This trend may result from competition among the airlines to achieve high rankings on the quality outcomes measured by the U.S. Department of Transportation over this period.

Adjusted Turn Time and Airport Staffing Levels

Coefficients from Columns 2 and 4 were used to compute turn time and staffing adjusted for these key aspects of product complexity and individual airline differences. The adjusted measure of turn time tells us how long a carrier's turn time would be if it had the average industry product mix. Likewise, the adjusted measure of airport staffing tells us how many airport personnel would be employed per passenger by a particular carrier if that carrier had the typical industry product mix.

Comparing the adjusted measures with the original measures (Table 5), we get a more accurate portrayal of the between-carrier differences in turnaround times and staffing. Southwest still has the lowest turnaround time, even adjusting for the simplicity of its product, but at 30 min its turn time is 70 percent of the industry average rather than only 40 percent before adjustment. Some of the difference in Southwest's actual turn time is clearly due to its very simple product. Adjusted turn times are also higher than the actual turn times for the other airlines with relatively simple products—Alaska Air, America West, and USAir—particularly for USAir. Considering the relative simplicity of its product, USAir has one of the longest turn times in the industry. The airlines with relatively complex products—United, Delta, Northwest, American, Continental, and TWA—have adjusted turn times that are lower than their actual turn times. United's adjusted turn time is particularly low, at 42 min, showing that, relative to its product, it has the speediest turnaround after Southwest and Alaska Air.

Once the effect of product complexity on airport staffing is accounted for, Southwest still has the leanest staffing in the industry at 78 employees per 1,000 passengers per day. Clearly, some though not all of Southwest's staffing efficiencies are due to its simpler product. Alaska Air has the most elaborate meal service and has among the highest airport staffing levels. But adjusted for that meal service, its airport staffing levels are among the leanest, following Southwest, America West, and USAir. The most highly staffed carriers, even accounting for the complexity of their product, are

TABLE 6 Effect of Product Complexity on Turn Time and Airport Staffing (Sample: U.S. Major Airlines' Domestic Systems, September 1987 to May 1994)

	Turn Time coefficient (t-stat)		Staffing coefficient (t-stat)	
	1	2	3	4
Trend	0.040	0.048	0.000	0.216
	(6.00)	(6.84)	(0.00)	(6.91)
Passenger	-0.129	-0.019	-0.624	-1.942
	(6.65)	(0.96)	(6.09)	(21.89)
Length	0.036	0.029	-0.008	0.567
	(13.81)	(5.82)	(0.63)	(2.62)
Cargo	0.004	0.005	0.011	0.002
	(7.61)	(3.93)	(3.83)	(0.28)
Connects	0.590	0.229	1.190	0.069
	(34.86)	(4.63)	(13.16)	(0.32)
Meals	-0.976	-0.931	9.780	1.867
	(8.27)	(5.12)	(15.83)	(2.39)
Constant	6.67		82.410	
	(6.42)		(15.06)	
Alaska		12.94		195.42
		(4.94)		(16.95)
American		18.97		257.51
		(5.12)		(15.76)
AmWest		17.42		172.69
		(6.49)		(14.53)
Continental		15.68		187.86
		(4.61)		(12.50)
Delta		16.78		261.73
		(5.05)		(17.89)
Northwest		19.92		215.83
		(6.02)		(14.88)
Southwest		2.95		164.19
		(1.53)		(19.30)
TWA		19.53		237.23
		(5.97)		(16.45)
United		14.88		236.48
		(4.12)		(14.92)
USAir		19.82		188.21
		(7.39)		(15.92)
Adj Rsquared	87%	92%	64%	84%

Note: Coefficients are retained from columns 2 and 4 to compute adjusted turn time and staffing.

American and Delta, respectively, at 172 and 176 employees per 1,000 daily passengers. Notably, these two carriers have engaged in projects to reduce airport staffing in 1994 and 1995.

In the final columns of Table 5, turnaround time and staffing are combined into a cost index (see derivation on Table 2), which will be used for subsequent analyses.

But neither turnaround time nor staffing, actual or adjusted, alone or in combination, itself suggests efficiency or inefficiency. They can only be judged by their effects on outcomes. The following section offers a brief review of the quality outcomes that are most closely tied to the departure process—on-time performance, customer complaints related to the departure process, baggage handling accuracy, and safety. The final sections address the relationship between the key inputs—turnaround time and airport staffing—and quality outcomes.

Quality Outcomes

There is some variation in on-time performance across the 10 major carriers (Table 7). United has the poorest record of on-time performance for the period as a whole, with 23 percent of its flights arriving late (at least 15 min past scheduled time of arrival). TWA, Continental, Delta, and USAir belong to the same performance group, with 21 percent of their flights arriving late. Southwest and America West lead the group with late rates of about 15 percent. Six of the 10 carriers improved on-time performance for the period as a whole—Northwest, Southwest, and Alaska had the greatest rates of improvement for the industry. Both Northwest and Southwest, notably, have competed for the distinction of being first in on-time performance in the 1990s and have used the distinction as a marketing tool.

TABLE 7 Differences in Outcome Quality (Sample: U.S. Major Airlines' Domestic Systems, September 1987 to May 1994)

	Late Arriv mean(SD)	Complaint mean(SD)	Lost Bags mean(SD)	Deviate mean(SD)	Qual Index* mean(SD)
Alaska	18.4	3.1	6.4	18.8	187.6
	(6.5)	(7.1)	(1.5)	(50.1)	(77.0)
American	18.7	11.5	6.1	42.4	107.3
	(5.3)	(6.5)	(2.0)	(28.3)	(33.2)
AmWest	14.9	11.7	6.6	14.8	159.3
	(6.0)	(7.3)	(2.6)	(29.8)	(63.6)
Continental	21.4	31.9	6.4	43.9	91.2
	(5.7)	(44.2)	(1.5)	(38.2)	(37.9)
Delta	21.4	5.4	6.4	33.9	121.6
	(5.7)	(4.1)	(1.7)	(25.4)	(37.5)
Northwest	17.9	24.0	6.7	30.4	119.4
	(6.6)	(41.7)	(2.0)	(28.4)	(54.3)
Southwest	14.5	4.4	3.9	11.1	229.9
	(6.5)	(4.2)	(0.6)	(17.3)	(88.7)
TWA	21.2	39.2	7.6	33.1	81.8
	(6.4)	(24.4)	(2.7)	(42.4)	(40.2)
United	22.9	13.6	6.8	38.1	103.0
	(6.3)	(10.2)	(2.1)	(33.3)	(36.9)
USAir	21.2	10.5	6.8	30.0	116.4
	(6.4)	(8.5)	(2.2)	(21.5)	(40.1)
Total	19.3	15.5	6.4	29.6	131.8
	(6.7)	(24.4)	(2.2)	(34.4)	(69.7)

*Quality Index is the reciprocal of late arrivals, customer complaints, baggage mishandling and safety deviations. See Table 2 for derivation.

The variation across airlines in customer satisfaction, as measured by the thousands of passengers per departure-related complaint made to the U.S. Department of Transportation, is greater than the variation in on-time performance. Alaska Air, Southwest, and Delta received only 3.1, 4.4, and 5.4 departure-related complaints per million passengers, respectively, over this period. On the low end, TWA, Continental, and Northwest received 39, 32, and 24 complaints per million passengers, respectively, for the same period. Every airline experienced significant declines in customer complaints over the period, particularly the three with the most complaints.

Baggage mishandling rates for the period as a whole ranged from 3.9 mishandled bags per 1,000 passengers at Southwest to 7.6 for TWA. Every airline except Southwest experienced significant improvement in this area over the period.

Safety outcomes, measured as pilot deviations per thousands of flight departures, vary substantially across airlines over this period. Southwest and America West made the fewest deviations per departure over this period, whereas American and Continental made the most.

The quality index is constructed from these four measures of quality outcomes of the departure process (see Table 2 for its derivation). Southwest and Alaska Air have the strongest performance along these four dimensions for this time period, whereas TWA is weakest.

Effects of Turnaround Time and Staffing on Quality Outcomes

Turnaround time, staffing, and quality outcomes do not tell us much about efficiency. Even when we adjust the inputs for differences in product complexity, they are still just inputs. And quality outcomes are just outputs. To learn about efficiency, we need to look at the effect of the inputs on the outputs. First, for airlines as a whole over this period, do on-time performance, customer satisfaction, baggage handling accuracy, and safety require higher levels of turn time and airport staffing? Second, how much on-time performance, customer satisfaction, baggage handling accuracy, and safety can be achieved with a given level of turnaround time and airport staffing? These questions lead us to the central hypothesis of the paper.

Instead of the trade-off traditionally expected between costs and quality—where higher quality is achieved with higher costs—we find that over this period higher quality was achieved with lower costs (Table 8). The negative trade-off is significant even once costs are adjusted for differences in product complexity (Column 2). For the industry as a whole, the logic of cost and quality has shifted.

TABLE 8 Higher Quality at Lower Costs (Sample: U.S. Major Airlines' Domestic Systems, September 1987 to May 1994)

	Cost Index** coefficient (t-stat)	Adj Cost Index*** coefficient (t-stat)
	1	2
Trend	0.348 (10.07)	0.276 (11.16)
Qual Index*	-0.197 (17.17)	-0.134 (16.37)
Constant	111.8 (1.82)	106.2 (81.6)
Adj Rsquared	30%	29%

*Quality Index is the reciprocal of late arrivals, customer complaints, baggage mishandling and safety deviations. See Table 2 for derivation.
**Cost Index includes turn time and staffing.
***Adjusted for differences in product mix. See Table 6 for derivation.

TABLE 9 Differences in the Ratio of Quality Achieved to Costs Expended (Sample: U.S. Major Airlines' Domestic Systems, September 1987 to May 1994)

	Quality/Cost* mean (SD)	Qual Index** mean (SD)	Cost Index*** mean (SD)
Southwest	354.1 (1.30)	229.9 (88.7)	65.8 (4.9)
Alaska	208.6 (0.84)	187.6 (77.0)	90.0 (4.7)
AmWest	187.8 (0.70)	159.3 (63.6)	86.1 (4.8)
USAir	121.8 (0.40)	116.4 (40.1)	95.0 (4.6)
Northwest	108.8 (0.51)	119.4 (54.3)	106.1 (4.8)
Delta	102.7 (0.31)	121.6 (37.5)	120.8 (4.9)
Continental	102.1 (0.41)	91.2 (37.9)	90.3 (4.8)
United	95.3 (0.33)	103.0 (36.9)	108.6 (4.8)
American	91.1 (0.27)	107.3 (33.2)	121.7 (4.9)
TWA	72.1 (0.34)	81.8 (40.2)	114.3 (4.7)
Total	145.5 (1.02)	131.8 (69.7)	99.5 (17.3)

*(Quality Index/Cost Index)
** Quality Index includes ontime, customer satisfaction, baggage handling and safety.
***Cost Index includes turn time and staffing and is adjusted for differences in product mix.

Across individual airlines, there are substantial differences in the ratio of quality achieved to costs expended (Table 9). For the most part, airlines with lean operations over this period relative to their product's complexity—that is, those with low adjusted costs—have also achieved the best quality outcomes relative to those costs (Figure 1).

DISCUSSION OF RESULTS

Is there a cost/quality trade-off in the departure process? Clearly there is, but in the opposite direction of the trade-off traditionally expected. Higher quality is associated with lower, not higher, costs over this period. For some airlines, quality was achieved at a low expenditure of turnaround time and staffing relative to product complexity. For others, the expenditure was substantially higher.

The role of product complexity has been carefully accounted for. The product offered by the airlines became substantially more complex over this period in ways that increased the complexity of the departure process and consequently the need for turnaround time and staffing. But the use of these resources in many cases increased out of proportion to the complexity of the product.

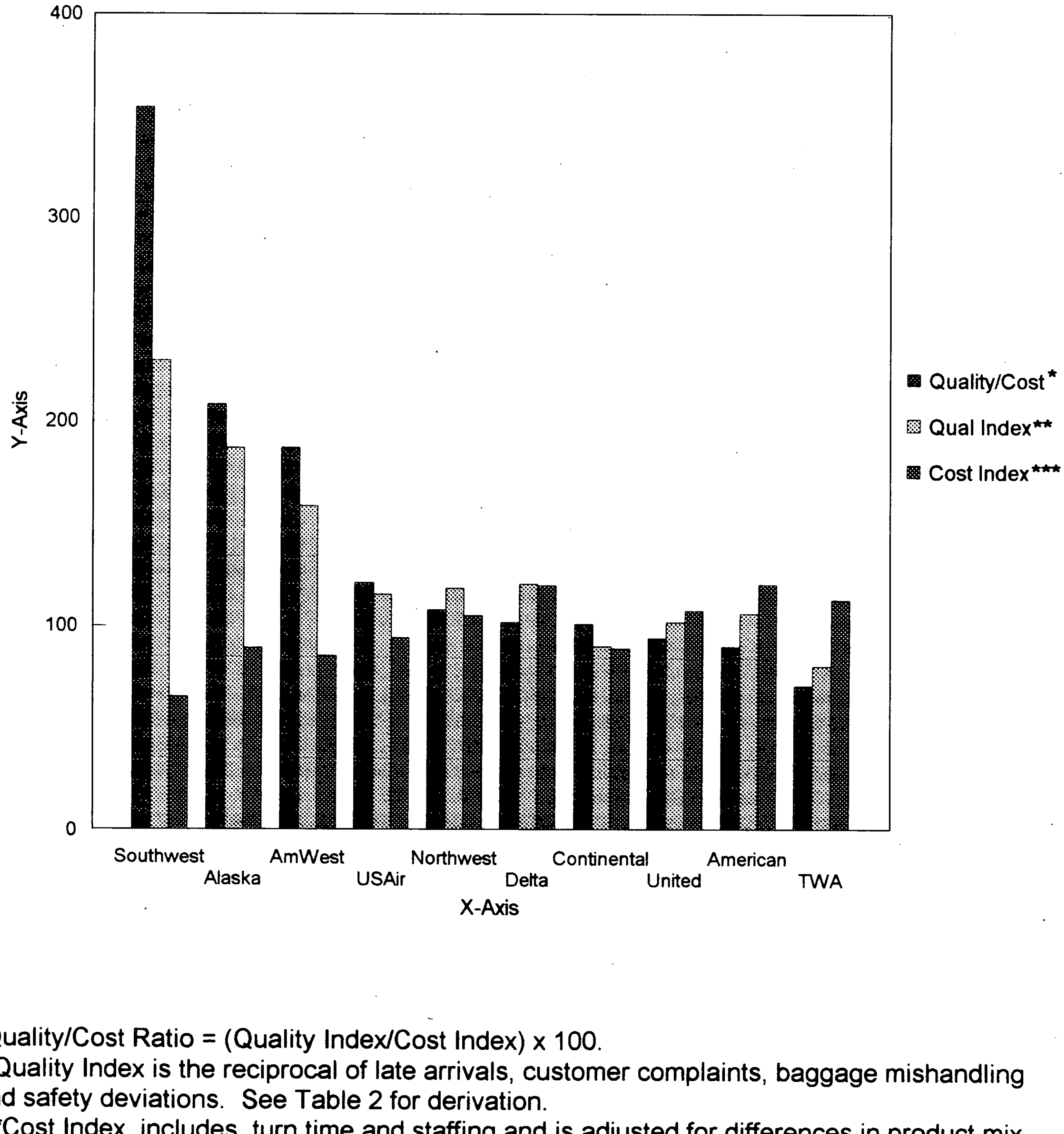

FIGURE 1 Ratio of quality achieved to costs expended (sample: U.S. major airlines' domestic systems, September 1987 to May 1994).

These findings lend support to this paper's central hypothesis—that excess resources can serve as organizational slack that lead to less efficient resource use, and vice versa, perhaps because they tend to be used as substitutes for organizational learning. Both turnaround time and staffing have the potential to play this role in the departure process. Over the period observed, among the major U.S. carriers, both turnaround time and per passenger airport staffing served as organizational slack.

For practitioners, these findings raise new questions. What are the organizational practices that allow lean resources to be used effectively? Lean resources in the form of less ground time and leaner staffing could inspire teamwork across functional groups to "get the job done," or the added stress could simply engender unproductive conflict and a deterioration of service. Other research suggests that Southwest has developed a set of organizational practices that build cohesion and common goals across groups, allowing the stress to be used in a productive way (*4*). These practices include horizontal coordination based on communication and teamwork across functional groups, combined with the reduction of time and staffing buffers. As more organizations in the airline and other industries press toward the limit in dropping excess resources, these kinds of practices may be the critical determinant of whether expected outcomes are achieved.

ACKNOWLEDGMENTS

The author gratefully acknowledges the support given by the Transportation Research Board, National Research Council, for this research. The author is also enormously grateful to Gary Mihalik of FAA for preserving the *Official Airline Guide* data on line from the early 1980s to the present and for furnishing it. This paper is a tribute to his patience. Thanks also to Charles Bradford of FAA for guiding me through the construction of the turnaround time variable and to Tim Ryan of FAA for assisting with the data transmission. Finally, the author thanks TRB monitors Frank Mulvey and Joe Schwieterman for useful feedback and Carlton Wine of FAA and Joseph Breen of TRB for their support of this effort.

REFERENCES

1. Womack, J., D. Jones, and D. Roos. *The Machine that Changed the World: The Story of Lean Production.* Rawson-MacMillan, New York, 1990.
2. Aoki, M. Horizontal Versus Vertical Information Structure of the Firm. *American Economic Review*, Dec. 1986.
3. Hammond, J. H. *Coordination as the Basis for Quick Response: A Case for "Virtual" Integration in Supply Networks.* Harvard Business School Working Paper, Cambridge, Mass., 1992.
4. Gittell, J. H. *Crossfunctional Coordination and Human Resource Systems: Evidence from the Airlines Industry.* Ph. D. dissertation. Massachusetts Institute of Technology, Cambridge, 1995.
5. Galbraith, J. *Designing Complex Organizations.* Addison-Wesley, 1973.
6. J. D. Power and Associates. *Domestic Airline Business Traveler Satisfaction Study.* Nov. 1993.
7. Bowen, B. D., D. E. Headley, and J. R. Luedtke. *Airline Quality Rating.* NIAR Report 91-11. National Institute for Aviation Research, Wichita State University, Wichita, Kans., April 1991.
8. MacDuffie, J. P., and J. Krafcik. Integrating Technology and Human Resources for High Performance Manufacturing: Evidence from the International Auto Industry. In *Transforming Organizations* (T. Kochan and M. Useem, eds.), Oxford University Press, New York, 1992.

Impact of Deregulation on Investment and Production Strategies in the Commercial Aircraft Industry

ELYSE GOLOB

The impact of the Airline Deregulation Act of 1978 on the U.S. aircraft manufacturing industry is investigated. The ways in which the removal of fare and route restrictions precipitated a restructuring of the investment and production strategies of the two major domestic airframe manufacturers are explained. On the basis of a series of interviews with informants in the airline and aircraft manufacturing industries, it is concluded that deregulation has affected the commercial aircraft industry in four significant ways: (a) fleet analysis procedures were transformed following deregulation, (b) the emergent hub-and-spoke system precipitated major fleet reconfigurations, (c) there was a rise in manufacturer and institutional financing and leasing agreements, and (d) airlines were saddled with aging and multiple-model fleets. Manufacturers have responded to these developments by assuming an increased share of the risks associated with aircraft acquisition, incorporating customer concerns in aircraft design, and reducing capacity while increasing productivity.

The Airline Deregulation Act of 1978 has had a significant effect not only on the industry it was designed to reform but also on the aircraft manufacturing industry. Whereas the removal of fare and route restrictions resulted in a protracted upheaval of the airline industry, it also precipitated a restructuring of the investment and production strategies of the two major domestic airframe manufacturers. Recent evaluations of deregulation's impact, however, have focused on the increased competition among airlines, labor-management relations, and measurements of consumer benefits, including pricing, service, and safety (*1–4*). Aircraft industry studies, while acknowledging the effect of deregulation on such areas as airline purchasing power and changes in equipment demands, call for further research on this topic (*5–8*).

This study finds that deregulation has had a profound impact on the U.S. commercial aircraft industry in four significant ways: (a) fleet analysis was transformed after deregulation as airlines began to view aircraft as resources to operate rather than assets to own, (b) the growth of the hub-and-spoke system precipitated substantive fleet reconfiguration, (c) the removal of government-sanctioned price increases in response to the escalating cost of aircraft led to a rise in manufacturer and institutional financing and leasing agreements, and (d) increased competition and mergers among the airlines have resulted in aging fleets and a trend toward fleet rationalization.

American manufacturers have responded to these developments in several ways. Over the past 15 years, Boeing and McDonnell Douglas have assumed an increased share of the risks associated with aircraft acquisition by providing manufacturer financing, flexibility in delivery dates, and extended maintenance and support agreements. Several events, however, that have occurred simultaneously with deregulation have had a significant impact on the industry: increased foreign competition from Airbus, economic recession, and the curtailment of spillover effects from military production following defense cutbacks (*9–13*). Since aircraft manufacturers have also undertaken various strategies to meet these challenges, including internationalizing aircraft production and improving productivity through cost-cutting efforts such as computerized design and development, the singular effects of deregulation are difficult to ascertain.

Furthermore, demand in the airline industry fluctuates in cycles of approximately 8 years. Reluctant to acquire aircraft at the bottom of a cycle, airlines prefer to reduce their risk by placing orders at the last minute, thereby taking advantage of the good deals and short lead times offered by manufacturers. When considering the industry as it comes out of the second full cycle following deregulation, one must differentiate between short-term decisions undertaken in response to cyclical factors and long-term structural effects due to the lifting of government restrictions by examining the pattern of orders during the full range of time.

METHODOLOGY

To determine the effect of deregulation on the production and investment strategies of domestic aircraft manufacturers, interviews were conducted with two primary groups of informants in the airline and aircraft manufacturing industries. In addition, leasing company personnel and institutional financiers were interviewed. The first set of interviews involved fleet planners and aircraft acquisition personnel in six domestic airlines: American, Delta, and United, the "Big Three"; USAir and Continental, generally considered "outsider" companies; and Southwest, a highly successful and much imitated company. Table 1 gives the major characteristics of these companies, including revenue passenger miles, market share, load factor, and operating profit margin. Airline profits are a result of high system load factors. A 68.5 percent load factor for a domestic carrier such as Southwest is considered high, whereas 68.6 percent for United, an international carrier, is not. A load factor below 65 percent, shown by the four remaining airlines, is considered dangerous.

Although deregulation is one of many factors affecting the competitive status of U.S. aircraft manufacturers, the use of a carefully prepared interview format enabled the researcher to isolate the

Rutgers University, B-119 Lucy Stone Hall, New Brunswick, N.J. 08903.

TABLE 1 Selected Profile of U.S. Airline Industry: Revenue Passenger Miles, Market Share, Load Factor, and Operating Profit Margin, 6 Months 1994

Company	Revenue Passenger Miles (000s)	Market Share (%)	Load Factor (%)	Operating Profit/ Loss (000)*
United	50,271,243	21	68.6	19,000
American	46,778,707	19.6	62.7	(162,000)
Delta	41,524,629	17.4	64.7	(180,000)
Continental	19,553,427	11.8	62.3	8,495
USAir	18,426,175	7.7	62.3	(33,116)
Southwest	10,496,351	4.4	68.5	71,557

* 4th Quarter, 1993

Source: Aviation Daily May 31, 1994 p. 340; July 21, 1994 p. 118.

impact of deregulation from other causes. The interviews focused on four areas:

- Effect of deregulation on the airline's equipment needs, including fleet planning and selection criteria;
- Effect of deregulation on the airline's buying patterns, including financing, discounting, payment options, delivery schedule, buying versus leasing, absorption of development costs, and launch customer relationship;
- Perceived response of U.S. manufacturers to airline needs; and
- Assessment of the ongoing impact of deregulation on the airline industry.

The second round of interviews with aircraft manufacturers, including marketing researchers, financial officers, strategic planners, and production managers, concentrated on the following four issues:

- Changes in customers' needs following deregulation, including customer base (new versus old airlines, leasing companies), operating practices (hub-and-spoke), buying patterns (financing, timing), and equipment needs (types, options);
- Marketing practices due to changes in customer needs, including product line and depth and demand forecasts;
- Production and investment practices due to changes in customer needs, including capital financing, outsourcing, production rates, and technology versus economics as a driving force in aircraft design; and
- Transfer of risk from airlines to manufacturers, including flexible delivery schedules and increased support and maintenance agreements.

DIMENSIONS OF THE COMMERCIAL AIRCRAFT INDUSTRY

The design, development, and production of a civilian transport aircraft are fraught with risk. Total launch costs for a new aircraft are estimated at $4 billion to $6 billion and entail a 5- to 6-year negative cash flow. Because of these enormous start-up costs, a successful aircraft does not achieve its break-even point for 10 to 15 years. In addition, numerous factors external to the manufacturing process affect the product's sales levels, including recession, political developments, and fuel costs. Manufacturers cope with these extraordinary costs through reliance on cash flow from older models, reconfiguration of existing models to meet new market demands, and cross-subsidization from military sales. A portion of this risk is assumed by the launch customer in the traditional airline-aircraft relationship. During the early stages of the program, two or three customers make a firm commitment to buy the new plane and provide progress payments to the manufacturer of 20 to 30 percent of the launch costs. In return, the launch customer receives a discounted price and is able to incorporate its suggestions into the design of the aircraft.

The high risks, immense economies of scale, and costly barriers to entry have traditionally limited the commercial aircraft industry to two or three major players. The changing market share is a result of multiple factors, including the increase in global traffic, the rising importance of offset deals, political developments, and trade policies. Table 2 provides an overview of the year-end world market shares and new aircraft sales of the three dominant manufacturers—Boeing, Airbus, and McDonnell Douglas—for 1992 and 1993.

The effects of the Airline Deregulation Act of 1978, designed to restructure a regulated oligopolistic industry into a more competitive one, were soon apparent to the commercial aircraft manufacturers. Although the removal of price and route structures created new forms of competition, it did not eliminate the oligopolistic nature of the airline industry. Whereas some carriers exited as others emerged and restructured, the identities and market shares of the largest firms—with a few notable exceptions—remained relatively stable.

Economies of scale and the long-term nature of the product and technology constrained the airlines' ability to function as players in a spot market. Following deregulation, firms continued to behave as oligopolists, watching and matching each other's actions rather than responding to market signals. This allowed airlines to aggressively assert their oligopolistic power over the aircraft manufacturers, reinforcing the bilateral oligopoly between the two industries. How-

TABLE 2 Major Aircraft Manufacturers' Market Share and New Sales—1992 and 1993

COMPANY	MARKET SHARE (%) 1992	1993	NEW AIRCRAFT SALES (%)* 1992	1993
BOEING	59.6	60.4	64.2	86.6
AIRBUS	17.0	25.3	37.0	14.0
MCDONNELL DOUGLAS	23.4	14.3	0.0	0.0
TOTAL**	100.0	100.0	101.2	100.6

*Nine months 9/30/92 and 9/30/93

**Figures do not always equal 100% due to negative results at McDonnell Douglas.

Sources: Prudential Securities, 3/24/94; 1/13/94.

ever, the negative profits and stock price declines resulting from the recurrent price wars and the infiltration of new entrants into well-established routes affected the airlines' ability to purchase and finance new aircraft.

IMPACT OF DEREGULATION ON AIRCRAFT DEMAND

Fleet Analysis

The transformation of airline transportation from a state-regulated utility into a competitive market structure changed the way airlines approached aircraft acquisition. Before deregulation, purchase analysis was fairly straightforward as the airline identified its mission and determined the requisite number of planes. Using a push-down analysis, each new plane purchased replaced the former top-of-the line model and pushed the next aircraft down in position until the last plane in the fleet was sold. The stability in the marketplace allowed the airline to confidently forecast the future in a regulated era during which its market share was "god given."

Deregulation altered the fleet selection process radically. Fleet introduction, a 30-year commitment spanning the life cycle of the aircraft, became precarious in a deregulated environment where the industry changed in 3- to 5-year spurts. As fleet planners constantly reevaluated short-term route dynamics and updated the existing fleet, it became increasingly difficult to get rid of nonapplicable aircraft and to compensate for bad decisions. Airlines developed extensive models for strategic planning that analyzed markets, types of service, and plane-to-route allocations. By the mid-1980s, however, use of these models declined as airlines found it difficult to achieve this high degree of flexibility and began to search for a new source of competitive advantage.

At the same time, changes in the tax credit laws in 1985 made money available from outside the industry, and leasing companies became major players as airlines sought to avoid long-term ownership risk. As a result, the airlines began to view aircraft not as assets to own but as resources to operate. As profits declined, the deregulated airlines became even more obsessed with cost control. Low-cost new entrant carriers such as People Express forced incumbent airlines to seek fuel-efficient, two-engine, two-pilot aircraft that offered significantly improved seat-mile costs over prevailing models. Other airlines chose to reengineer rather than replace older aircraft. For example, a number of carriers have purchased hush kits for DC-9 aircraft rather than new planes to meet FAA's Stage 3 requirements.

As airlines became reluctant to absorb the development costs of new technologies that offered no return on their investment, the decision to acquire new models became more dependent on economic than technological criteria. Airline planners interviewed indicated that technology must increasingly buy its way into the plane, or as one informant remarked, "We're not going to be an aeronautical benevolent society anymore." As the commercial aircraft industry has matured since the 1970s, technological advances have decreased. Airline officials indicated that no significant technological breakthroughs are considered necessary at the present time, and their key concern remains the acquisition of serviceable, durable, and reliable aircraft at a reasonable price. Finally, fleet-planning decisions involve factors other than traffic demand, price, and technology. Exogenous issues such as the personalities of the deal makers play a crucial role at the moment of sale. As one insider observed, "In the end, the chairman of my airline speaks to the chairman of Boeing. If he likes the aircraft he's shown, we'll buy it."

Fleet Reconfiguration and the Hub-and-Spoke System

Under regulation, fleet change depended on two factors: the age of the fleet and the awarding of new routes. Traffic was streamlined as airlines flew wide-bodied planes across the country. Because the major form of competition among regulated carriers was frequency, load factors tended to be low compared with current levels. As airlines sought to increase efficiency in serving new routes, the shift from point-to-point service to a hub-and-spoke network accelerated as traffic was consolidated between hub cities and fragmented from spokes to hubs. Although the hub-and-spoke system required smaller aircraft, airlines found themselves saddled with fleets of wide-bodied planes designed for a regulated era. Despite attempts to reconfigure fleets to accommodate different passenger loads, many airlines experienced the dumbbell effect in that they possessed a disproportionate amount of large and small planes.

Two factors contributed to the expansion of the hub-and-spoke system following deregulation. First, airlines sought to manage the increasing volume of travel more efficiently by pooling passengers through hubs and offering more flights per day between hub and nonhub centers. Second, companies used pricing to monopolize nonhub travel where they were the sole carrier. Contrary to popular wisdom, however, the hub-and-spoke system is neither a creation nor a sine qua non of deregulation. Delta's hub-and-spoke system, using feeder traffic from regional airlines into its Atlanta hub, predated deregulation. Southwest, on the other hand, has traditionally eschewed the hub-and-spoke strategy. While its competitors abandoned linear service, Southwest remained a short-haul carrier using the 737 exclusively and adding flights when demand increased. Furthermore, a recent report indicates that most passenger trips in the U.S. domestic hub-and-spoke system do not use connections. Of all domestic flights, 69 percent in 1979 and 63 percent in 1989 involved direct trips (private correspondence with Boeing, August, 1994).

Manufacturer and Institutional Financing and Leasing

After deregulation, airlines could no longer ask the government for fare increases when aircraft prices rose. Instead, they turned to the manufacturer for financing assistance, discounting, and additional givebacks in the form of support and maintenance services. During the regulatory era, airlines committed to orders and decided how to finance them as the delivery date approached. In most cases, one-half to two-thirds of the assets were purchased by the airlines, with one-third financed through leases and mortgages. As one 30-year veteran reminisced, "Aircraft purchase was a lot of fun in the old days. I just took a check out and purchased the airframe."

In the 1980s, there was a sustained change in the marketplace not attributable to the economic recession. Airlines found it increasingly difficult to pay for purchases out of their own earnings, whereas banks became reluctant to finance acquisition. As a result, manufacturers began to offer substantial discounting as well as a commitment to finance. In addition, companies turned to leasing agreements to take advantage of available tax credits. Today both McDonnell Douglas and Boeing provide backstop financing and guarantee credit at market rate. The use of financing, however, varies substantially from company to company. Whereas manufacturer financing is important for new entrants and foreign companies, it is often uneconomical for major domestic carriers who prefer institutional lenders. The notable exception to this trend is Southwest, which pays out of its own cash flow and has not used manufacturer financing since its initial B-737 purchase in the early 1970s. In addition to financing assistance, airlines increasingly seek concessions from the manufacturer in other long-term costs, such as product support and training.

Aging Aircraft and Fleet Rationalization Strategies

Deregulation unleashed a competition among the airlines that weakened their overall financial position at the same time that aircraft prices were rising. As the price gap between new and old aircraft economics widened, it became more profitable for airlines to retain older planes with comparable operating costs. In 1988, 28 percent of the U.S. fleet was more than 20 years old, a 21 percent increase since the end of regulation (*14*).

The merger and acquisition frenzy in the airline industry following deregulation left many companies with an inefficient fleet containing many different aircraft types and subtypes. Additional training costs, lost working time, spare parts inventory, and service needs made the maintenance of these fleets prohibitively expensive. For example, each model requires its own flight simulator at a cost of $15 million. Over the past few years, several airlines have announced a strategy of fleet simplification or rationalization to reduce the fleet to four or five types. The final choice of commonality, influenced by the high cost of replacement models, will have a significant impact on aircraft purchases in the coming decades. Table 3 provides an analysis of the jet fleets of selected airlines, including aircraft types, fleet size, top models, and average age for the first quarter of 1994. Today, all carriers with the exception of Southwest have upward of eight models, including subtypes.

TABLE 3 Jet Fleet Analysis, Selected Major U.S. Carriers—First Quarter 1994

AIRLINE	Aircraft Types	Total Fleet	Top 4 Models*	Average Age (Years)
American	9	689	MD-82, B727 B767, DC-10	8.3
Continental	9	297	B737, B727 DC-9, A-300	13.9
Delta	8	555	B727, MD-8 B757, B737	9.7
Southwest	1	160	B737	7.7
United	8	573	B737, B727 B757, B747	10.8
USAir	10	477	B737, DC-9 F-100, B757	11.3

*Models include subtypes; models listed in descending order.

Source: Aviation Daily July 6, 1994, p. 25.

In summary, deregulation has had several apparent effects on aircraft demand. The search for a new competitive advantage has encouraged airlines to view planes as resources to operate rather than as assets to own. The resultant focus on cost consciousness, in addition to changing tax laws and the maturation of jet technology, has affected fleet acquisition decisions. Also, the expansion of the hub-and-spoke network produced a mismatch between existing fleets and those required for new route structures. Finally, declining airline operating profits precipitated an increase in manufacturer and institutional financing, a trend toward refurbishing rather than replacing older aircraft, and the initiation of fleet rationalization strategies.

RESPONSES OF AIRCRAFT MANUFACTURERS

The precarious financial condition of the deregulated domestic airlines has forced the two major domestic commercial aircraft manufacturers, Boeing and McDonnell Douglas, to assume a greater share of the risks associated with aircraft acquisition, including manufacturer financing, flexibility in delivery dates, and improved maintenance and support agreements. In 1978, McDonnell Douglas created a separate financial division, McDonnell Douglas Finance Corporation (MDFC), to disengage its sales and financing operations. This move was undertaken after officials determined that the financing concessions associated with sales had shifted the burden back onto the manufacturer. In addition, as an autonomous subsidiary with a diversified financial portfolio, MDFC had greater borrowing power, which translated into better benefits for its customers.

Aircraft manufacturers have been forced to adjust to the increase in deferrals and cancellations since deregulation. Whereas it is unusual for manufacturers to accept cancellation without significant penalty, the lack of new orders has made them more willing to rearrange delivery schedules to avoid the dreaded "whitetail," an ownerless aircraft. Because of the long lead time associated with final assembly due to parts procurement from a large supplier base, schedule changes are more flexible further away from delivery. The period of time in which the manufacturer locks in the customer is very tight, and it is extremely expensive to make a change within that window. Manufacturers are generally most flexible 8 to 10 years in advance, and somewhat less so 2 to 3 years before delivery. As one manufacturer explained, "If the delivery date is too flexible, it costs the manufacturer. Instead we drive flexibility down to the suppliers. Although penalizing them was our former philosophy, we now offer incentives to make them more flexible."

The unstable profit levels and reduced cash flow associated with deregulation have influenced airlines to off-load the high cost of keeping, operating, and maintaining aircraft. Carriers pressure manufacturers to partner on cost reduction through lower support costs, spare parts supply, and contributions to engineering expenses. Whereas other aircraft industry activity is not directly attributable to deregulation, its impact should not be discounted. The increased oligopolistic power of the carriers has allowed them to insist that manufacturers accommodate more differences in aircraft production than previously. Although Boeing has traditionally resisted this suggestion as a matter of cost, in recent years it has attempted to position itself as the company responsive to customer needs through a greater awareness of aircraft operating costs. As one fleet planner remarked, "Boeing's mantra for the past two years has been 'life cycle cost.' " Furthermore, deregulation is only one of several factors increasing the pressure on manufacturers to lower production costs. Cutthroat competition among the carriers has produced downward pressure on prices and sales for both airline tickets and aircraft purchases. Today, both Boeing and McDonnell Douglas are reducing capacity and reorganizing to shorten production cycles, and the lead time for building a new aircraft has been shortened to 12 to 18 months from 2 years.

CONCLUSION

Deregulation, the principal cause of the ongoing upheaval in the airline industry, has had a protracted impact on the production and investment strategies of the commercial aircraft manufacturers. Whereas air carriers rapidly reorganized and restrategized to capture market share and sustain profitability, aircraft manufacturers responded more slowly to the changing demand because of long production and product cycles. In addition to the uncertainties posed by an unstable domestic market, these firms were subject to the multiple pressures of international competition, declining defense sales, and foreign offset deals.

By opening up the industry to competition, deregulation drove out weaker carriers, such as Eastern and PanAm. The oligopolistic rush to reconfigure after the removal of price and route structures resulted in some poor choices on the part of individual airlines leading to overcapacity. The mid-1980s was an unstable time for the industry, as major carriers grew faster than demand justified. Airline financial officers, unable to cut labor costs due to high union wages, attempted to increase growth and revenues through expanded service and acquisitions. At the same time, out-of-work employees and cheap aircraft from bankruptcies lowered the barriers of entry for new participants. As one informant stated, "The assets wouldn't be there at cheap prices if not for the protracted death of other companies."

Following the initial shakeout, the remaining airlines continued to undergo a major corrective process in an attempt to stabilize prices and decrease operating costs. A new wave of start-ups such as Kiwi, Valuejet, Reno, and Markair are following a niche market strategy, whereas niche carriers such as Southwest have become bread-and-butter companies driving out established carriers in certain routes. At the close of the second down cycle since deregulation, airlines are beginning to experience renewed profitability and positive cash flows as costs come under control because of lower fuel prices, slowly rising wages, and low interest rates. In the U.S. domestic market, traffic and load factors have increased since the price wars of 1992 with fares climbing 15 to 20 percent by 1993. Industry observers, however, believe that the sector will continue to evolve and restructure with no stable form emerging in the next decade.

The historical correlation between aircraft orders and airline profits reinforces the cyclical nature of the business. Following an upturn in traffic cycle, airline planners realize the need for additional capacity and place orders for new aircraft.

Because of the long-term nature of aircraft manufacturing, however, improved airline results take time to translate into strong orders and shipments. Thus, whereas demand for commercial aircraft is strongly tied to airline profits, the delay between order and delivery means that initial shipments occur several years later, by which time the cycle may have reversed itself. In addition, aircraft acquisition decisions are trend-oriented as airlines follow the buildup of orders to ensure slots and match the competition. Overproduction occurs as carriers find themselves with too many aircraft during periods of declining profits and begin to cancel.

The attempt to fully use existing facilities results in excess capacity. Manufacturers and airlines produce more products and services than are warranted by market demand. Rather than eliminate capacity on both sides until prices cover costs, market forces favor overproduction especially when the downturn is expected to be short lived and capacity problems are predicted to emerge. In the words of one airline representative, "There are too many aircraft chasing too many people with negative effects on the carriers." Manufacturers, in turn, complain that deregulation has had a long-lasting effect on the airlines left with "no ground rules." Cyclical declines in orders and rises in cancellation rates force manufacturers to cut back employment in their own facilities as well as in their supplier base. New aircraft orders have declined from the record years of the late 1980s, and delivery schedules have been extended. In response, Boeing reduced its work force and cut its production rate during 1993 from 32.5 to 23 airplanes per month (*15*). McDonnell Douglas, following a niche market strategy based on growth and profit rather than market share, also made extensive cutbacks in its labor force and has cut production levels to 36 planes in 1994 compared with 140 in the prerecession years.

Deregulation has produced a new competitive environment in which the focus of airlines is on short-term revenues. The continuing oligopolistic nature of the industry, in which airlines cut fares to increase traffic and passenger loads, minimizes long-term profits. To raise the capital necessary to purchase new aircraft in up cycles, airlines must achieve stable levels of profitability. This leads to renewed demands for cost controls in aircraft acquisition and a shifting of risk onto the manufacturers. As a result, manufacturers are forced to assume a greater share of financing, provide flexibility in delivery dates, and offer improved maintenance and support agreements. These developments may once again change in the upcoming cycle as financing requirements decline because of increased profitability. In addition, some analysts predict a trend toward dehubbing as hubs prove too costly to operate. If this proves true, airline fleets will once again be burdened with wrong-sized aircraft (*16*). Finally, Stage 3 government requirements are expected to accelerate purchasing requirements as noise becomes an economic issue. Stage 2 aircraft, comprising 47 percent of the domestic fleet, are subject to U.S. usage requirements, including nonaddition rules and mandatory compliance with Stage 3 by 2000. Since compliance is possible by reengineering or hush kitting, however, order forecasts are uncertain.

The issue of who owns the capital and who owns the risk in the airline industry is critical for current policy and requires further research. Empirical analysis can indicate whether manufacturers are using more capital than previously in response to airline requirements. If manufacturers are bearing an increasing share of the airlines' risks, are their returns proportionally greater than the risk-free returns for capital in the past? In addition, the growing role of leasing companies must be examined to determine whether this trend indicates a desire by manufacturers to capture the tax benefits of depreciation in times of declining airline profitability or a natural move in the marketplace. In addition, a public policy in which government or industry rationalizes production temporarily during down cycles to preserve capacity may play a role in preventing distortions due to the airline industry's cyclical nature; or as one informant cynically remarked, "If the industry should be reregulated, let them regulate the production rates."

ACKNOWLEDGMENTS

Funding for this project has been provided by TRB under the Eighth Graduate Research Award Program on Public-Sector Aviation Issues. The author would like to thank the following for their comments: Bill Swan, Adrian LeRoy, John Fisher, Ann Markusen and Candace Howes, as well as numerous individuals in the airline and commercial aircraft industries who generously shared their time and insights.

REFERENCES

1. Bailey, E., D. Graham, and D. Kaplan. *Deregulating the Airlines.* MIT Press, Cambridge, Mass., 1985.
2. Dempsey, P. *Flying Blind: The Failure of Airline Deregulation.* Economic Policy Institute, Washington, D.C., 1990.
3. Morrison, S., and C. Winston. *The Economic Effects of Airline Deregulation.* Brookings Institute, Washington, D.C., 1986.
4. Shepherd, A. The Airline Industry. In *The Structure of American Industry* (W. Adams, ed.), MacMillan, New York, 1990.
5. *The Troubled Airline Industry: Its Impact on Aircraft Manufacturers and the U.S. Economy.* Aerospace Industries Association, 1993.
6. Bluestone, B., P. Jordan, and M. Sullivan, *Aircraft Industry Dynamics.* Auburn House, Boston, Mass., 1981.
7. *The U.S. Commercial Aircraft Industry and Its Foreign Competitors.* MIT Commission on Industrial Productivity, Cambridge, Mass., 1988.
8. Seitz, F. *The Competitive Status of the U.S. Civil Aviation Manufacturing Industry.* National Academy Press, Washington, D.C., 1986.
9. Markusen, A., and J. Yudken. *Dismantling the Cold War Economy.* Basic Books, New York, 1992.
10. McIntyre, I. *Dogfight: The Transatlantic Battle Over Airbus.* Praeger Press, Westport, Conn., 1992.
11. Mowery, D. *International Collaborative Ventures in U.S. Manufacturing.* Ballinger Publishing, Cambridge, Mass., 1988.
12. Newhouse, J. *The Sporty Game.* Knopf, New York, 1982.
13. Tyson, L. *Who's Bashing Whom? Trade Conflict in High Technology Industries.* Institute for International Economics, Washington, D.C., 1993.
14. Valente, H., and McGinley. Should Airlines Scrap Their Oldest Planes for the Sake of Safety? *Wall Street Journal,* May 6, 1988, p. 1.
15. Velocci, A. Industry Scorecard '93: Transition Testing Top Firms' Mettle. *Aviation Week and Space Technology,* Vol. 128, No. 22, 1993, pp. 62–69.
16. Prudential Securities Report on Boeing. Jan. 13, 1994.

Differences in Aircrew Manual Skills in Automated and Conventional Flight Decks

PATRICK R. VEILLETTE

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

Department of Civil Engineering, 3220 Merrill Engineering Building, University of Utah, Salt Lake City, Utah 84112.

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.

ACKNOWLEDGMENTS

The author expresses gratitude to FAA for its sponsorship of the Graduate Research Awards Program and to Barbara Kanki of NASA's Ames Research Center, which supported the first year of the research. The author is indebted to Beverly Huey, Lemoine Dickinson, Larry Jenny, Nancy Doten, and Joe Breen of the Transportation Research Board for their help and guidance. The author is especially grateful for the full cooperation of the many professional aircrews who willingly participated in this study and to the management of the major airlines, who were cooperative and supportive of this research effort.

REFERENCES

1. Wiener, E. L. Cockpit Automation. In *Human Factors in Aviation* (E. L. Wiener and D. C. Nagel, eds.), Academic Press, Inc., New York, 1988, pp. 433–461.
2. *National Plan To Enhance Aviation Safety Through Human Factors Improvements.* Human Factors Task Force, Air Transport Association of America, April 1989.
3. Wiener, E. L., T. R. Chidester, B. G. Kanki, E. A. Palmer, R. E. Curry, and S. E. Gregorich. *The Impact of Cockpit Automation on Crew Coordination and Communications.* NASA CR 177587. National Aeronautics and Space Administration, 1991.
4. Cockpit Coordination, Training Issues Pivotal in Fatal Approach-to-Landing Accident. *Accident Prevention,* Vol. 51, No. 1, Jan. 1994.
5. Mecham, M. Autopilot Go-Around Key to CAL Crash. *Aviation Week and Space Technology,* May 9, 1994, p. 31.
6. *Aviation Accident Report of Eastern Air Lines Flight 401, Miami, Florida, 29 December 1972.* Report NTSB-AAR-73-14. National Transportation Safety Board, Washington, D.C., 1973.
7. *Aviation Accident Report of Aeromexico DC-10-30, XA-DUH, Over Luxembourg, Europe, November 11, 1979.* Report NTSB-AAR-80-10. National Transportation Safety Board, Washington, D.C., 1980.
8. *Aviation Accident Report of Scandinavian Airlines System, DC-10-30, John F. Kennedy International Airport, New York, February 28, 1984.* Report NTSB-AAR-84-15. National Transportation Safety Board, Washington, D.C., 1984.
9. *Aviation Accident Report of China Airlines 747-SP, N4522V, 300 Nautical Miles Northwest of San Francisco, California, February 19, 1985.* Report NTSB/AAR-86/03. National Transportation Safety Board, Washington, D.C., 1986.
10. *Aviation Accident Report of Continental Express (Jet Link) Embraer 120 Brasilia, Flight 2733, 29 April 1993.* National Transportation Safety Board, Washington, D.C., 1994.
11. Jensen, R. S., and J. Adrion. *Aeronautical Decision Making for Instrument Pilots.* Aviation Research Associates, Columbus, Ohio, 1985.
12. Billings, C. E., and W. D. Reynard. Human Factors in Aircraft Accidents: Results of a 7-year Study. *Aviation, Space, and Environmental Medicine,* 1984, pp. 960–965.
13. Nagel, D. C. Human Error in Aviation Operations. In *Human Factors in Aviation* (E. L. Wiener and D. C. Nagel, eds.), Academic Press, Inc., New York, 1988, pp. 263–303.
14. *Road to Wings: Special Report of Accidents in Air Training Command.* Air Training Command, Randolph AFB, San Antonio, Tex. (undated).
15. Hendricks, W. R. ATC Effect on Stabilized Approaches. *Journal of the Airline Pilots Association,* March–April 1993, pp. 28–31.
16. Schwartz, D. Training for Situational Awareness. *Journal of the AirLine Pilots Association,* May 1993, pp. 20–23.
17. Foushee, H. C., and R. L. Helmreich. Group Interaction and Flight Crew Performance. In *Human Factors in Aviation* (E. L. Wiener and D.C. Nagel, eds.), Academic Press, Inc., New York, 1988, pp. 189–228.

18. *Aviation Accident Report of Delta Air Lines DC-9, N3323L, Chattanooga Municipal Airport, Chattanooga, Tenn., November 27, 1973.* NTSB Report NTSB-AAR-74-13. National Transportation Safety Board, Washington, D.C., 1974.
19. *Aviation Accident Report of Kennedy Flight Center, Gates Lear Jet Model 23, N866JS, Byrd International Airport, Richmond, Virginia, May 6, 1980.* NTSB Report NTSB-AAR-80-12. National Transportation Safety Board, Washington, D.C., 1980.
20. *Aircraft Accident/Incident Summary of Eastern Air Lines DC-9, N8948E, Pensacola Regional Airport, Pensacola, Florida, December 27, 1987.* National Transportation Safety Board, Washington, D.C., 1988.
21. *Aviation Accident Report of Atlantic City Airlines, Inc., DHC-6, Twin Otter, N101AC, Cape May County Airport, New Jersey, December 12, 1976.* NTSB Report NTSB-AAR-77-12. National Transportation Safety Board, Washington, D.C., 1977.
22. *Aviation Accident Report of McDonnell-Douglas Corporation DC-9, N980DC, Edwards Air Force Base, California, May 2, 1980.* NTSB Report NTSB-AAR-82-2. National Transportation Safety Board, Washington, D.C., 1982.
23. *Aviation Accident Report of Trans-Colorado Airlines Flight 2286, Fairchild Metro III, SA227, N68TC, Bayfield, Colorado, January 19, 1988.* National Transportation Safety Board, Washington, D.C., 1989.
24. *Aviation Accident Report of Central Airlines Flight 27, Hughes Charter Air, Gates LearJet Model 25, N51CA, Newark International Airport, Newark, New Jersey, March 30, 1983.* NTSB Report NTSB-AAR-84-11. National Transportation Safety Board, Washington, D.C., 1984.
25. *Statistical Summary of Commercial Jet Aircraft Accidents, Worldwide Operations, 1959–1984.* Boeing Commercial Airplane Company, Renton, Wash., 1985.

Accommodating Difference: Gender and Cockpit Design in Military and Civilian Aviation

RACHEL N. WEBER

Primarily on the basis of interviews, the treatment of gender is compared as a human factors consideration within military and civilian aviation. Defense and civilian cockpits have traditionally been built to specifications based on male anthropometry and may embody a physical bias against women and smaller-statured men. Defense and commercial divisions of airframe manufacturers rely on similar computer modeling techniques and anthropometric data to accommodate a targeted population of pilots. However, the design of defense aircraft tends to be highly regulated, and more efforts have been taken to ensure that a larger pool of otherwise eligible pilots is accommodated by future systems, such as in the Joint Primary Aircraft Training System. Within very loose FAA guidelines, commercial manufacturers are responsive to their customer airlines, most of which are not concerned with accommodating women pilots unless they fear liability for employment discrimination. Commercial manufacturers also do not possess adequate anthropometric data about the civilian female pilot population. Because of defense budget cutbacks, a changing social context, and a broader political mandate, the public sector has a responsibility both to facilitate the transfer of knowledge from military to civilian aviation and to concern itself with the equity issues involved in accommodating female pilots.

To examine issues concerning women and technology, social scientists commonly rely on two approaches (*1*). The first approach questions women's access to particular technologies. In the context of aviation, one would ask questions regarding women's upward mobility in the profession; for example, are women limited because they are not trained, socialized, or permitted to fly certain aircraft? Solutions to these problems would lie in eroding barriers to these boundary markers, such as easing women-in-combat exclusions or providing scholarships for women to attend flight training school.

The second approach—which informs the subject of this paper—questions the technology itself. Are cockpits designed to accommodate women's bodies? Is a particular flight deck "gender neutral" or is male bias embodied in the actual design, in the engineering specifications? How can biased technologies be altered to become more "women friendly"?

Such questions are receiving attention within the military as human factors practitioners at the Pentagon attempt to determine whether the Joint Primary Aircraft Training System (JPATS), the primary aircraft trainer used by the Navy and Air Force, embodies a bias against women and smaller-statured pilots. After successful completion of mandatory JPATS training, student pilots advance to intermediate trainers and then to aircraft-specific training. Therefore, if women cannot "fit" into the JPATS cockpit or if the cockpit does not "fit" women pilots, they will be unable to pursue aviation careers in the Navy or Air Force. Other defense aircraft as well as ships and protective clothing are also receiving such scrutiny (*2*).

Department of City and Regional Planning, Cornell University, Ithaca, N.Y. 14853.

Human factors work conducted in the military has significant ramifications for civilian aviation. For example, limits on participation by women in military flying roles may inhibit career prospects in civilian aviation since many airlines still prefer pilots with military training. Civilian aircraft may also embody similar biases against women's bodies because they have been designed for a primarily male pilot population. Because of the significance of these man-machine systems, this paper will examine the treatment of gender as a human factors consideration within military and civilian aviation. It will outline the methods used by the military to determine whether cockpits are women friendly and compare these methods with research conducted on this human factors issue in civilian aviation.

Because there is a dearth of literature in this area, this paper relies heavily on interview studies and the interpretation of internal documents. Interviews were conducted with human factors specialists at major airframe manufacturers, public-sector research laboratories, and regulatory agencies. Qualitative research, compared with more empirical policy analysis, allows one to engage the ideological assumptions embedded within the policy debates. Such an approach seeks not only to understand the effects of technological change on society but also to ask which social factors have shaped technological change.

BIAS IN DEFENSE AIRCRAFT

Defense systems have traditionally been built to male specifications (*3*). Since women tend to be shorter and have smaller limbs and less upper-body strength, some may not be accommodated by such systems and may experience difficulty in reaching controls and operating some types of equipment (*4*). To understand how women's bodies become excluded by design, it is necessary to examine how current weapon systems are designed with regard to the physical differences of their human operators.

The best technology is useless if it is incompatible with the capabilities and limitations of its users. As such, Department of Defense acquisition policy mandates that human considerations be integrated into design efforts to improve total system performance by focusing attention on the capabilities and limitations of the human operator.

To integrate the soldier, sailor, and airman into current design practices, the military relies on human factors theories, also called "human engineering" or "ergonomics," which address human characteristics, expectations, and behaviors in the design of items that people use. During World War II, human factors became practiced as a distinct discipline by the U.S. military when it became apparent that new and more complicated types of military equipment could not be operated safely or effectively and could not be maintained adequately by many well-trained personnel (*5*). An effort was directed to design equipment that would be more suitable for human anthropometry.

Anthropometrics refers to the measurement of dimensions and physical characteristics of the body as it occupies space, moves, and applies energy to physical objects as a function of age, sex, occupation, ethnic origin, and other demographic variables. The military has routinely measured and categorized different body dimensions to standardize the design of weapons systems. The U.S. Army Natick Research Development and Engineering Center "1988 Anthropometric Survey of Army Personnel" is the most recent compilation of these data. The Natick Survey contains data on more than 180 body and head dimension measurements of a population of more than 9,000 soldiers. Age and race distributions match those of the June 1988 active duty Army, and minority groups were intentionally oversampled to accommodate anticipated demographic shifts in Army population.

In the application of anthropometric data, systems designers rely on Military Standard 1472, Human Engineering Design Criteria for Military Systems, Equipment and Facilities. As with the use of military specifications in defense procurement, these guidelines are critical to developing standards that reflect the military's needs and goals and are ultimately embodied in the technology. These guidelines suggest the use of 95th and 5th percentile male dimensions in designing weapons systems, if the accommodation of 100 percent would incur trade-off costs out of proportion to the additional benefits to be derived. However, determining what is a "trade-off cost" and when such costs are too high can be an arbitrary process.

Accommodation becomes more difficult when more than one physical dimension is involved, and several dimensions need to be considered in combination. Difficulties arise from the interrelationships between and among the dimensions, some of which have low correlations with each other (e.g., sitting height and arm length). For example, in military applications approximately 52 percent of Navy aviators would not be accommodated by a particular cockpit specification if both the 5th and 95th percentiles were used for each of the 13 dimensions. To determine whether operators of different shapes and sizes can be accommodated in weapons systems, human factors specialists rely on advanced two- and three-dimensional modeling techniques. However, the changing anthropometry of the military population has not altered the tools available to determine female accommodation; the Air Force, for example, does not possess female mannequins, choosing instead to cut the arms of male dummies.

Because women are often smaller in all physical dimensions than men, the gap between a 5th percentile woman and the 95th percentile male can be very large. Women who do not meet requirements are deemed ineligible to use a variety of military systems. Before the operating requirements became so stringent, women pilots adapted their bodies to the technology. They mounted wooden blocks on the bottoms of their boots to reach the rudder pedals of the T-37 and used pads on their seats.

In the case of the JPATS trainer, minimum anthropometric requirements needed to effectively operate such an aircraft were considered, and specifications were written to reflect such requirements. For example, "the ability to reach and operate leg and hand controls, see cockpit gauges and displays, and acquire external vision required for safe operation" was considered critical to the safe and efficient operation of the system. The five critical anthropometry design "drivers" were determined to be sitting height, functional arm reach, leg length, buttock-knee length, and weight (JPATS Cockpit Accommodation Working Group Report, May 1993, unpublished data).

Original JPATS specifications included a 34-in. minimum sitting height requirement to safely operate cockpit controls and eject. This specification was based on sitting height minimums in the current aircraft fleet and reflected a 5th percentile male standard. However, at 34 in., anywhere from 50 to 65 percent of the American female population is excluded because female sitting heights are generally shorter than those of males. Therefore JPATS, as originally intended, accommodated the 5th through 95th percentile male but only approximately the 65th through 95th percentile female.

NEGOTIATING ACCOMMODATION IN THE MILITARY

When former Secretary of Defense Les Aspin announced the administration's policy on women in combat in April 1993, he sought to implement a congressional mandate that would permit women to compete for all assignments in aircraft, including those aircraft engaged in combat missions. Although the new policy gave women a greater combat aviation role and was intended to permit their entry into many new assignments, the aircraft associated with the new assignments precluded the directive from being implemented. That existing systems could contain a technological bias against women's bodies despite the congressional mandate for accessibility alarmed policy specialists at the Pentagon. This contradiction would potentially embarrass a new administration, which was caught off guard with the gays-in-the-military debacle and was trying to define a working relationship with an antagonistic Pentagon.

Instead of fitting the man to the machine as was the norm, it was seen to be necessary to fit the machine to the (wo)man. Stipulating new operational requirements of users would also entail changing the technology. In May 1993, the Under Secretary of Defense (Acquisition) directed the Assistant Secretary of Defense (Personnel and Readiness) to develop a new sitting height threshold that would accommodate at least 80 percent of eligible women. He delayed release of the JPATS draft request for proposal until a new threshold could be documented.

This move led to the development of the JPATS Cockpit Accommodation Working Group within the Pentagon, which included representatives from the Air Force and Navy JPATS program offices as well as from service acquisition, personnel, human factors, and flight surgeon organizations. After months of deliberation, the working group determined that a reduction of the sitting height requirement by 3 in. would accommodate approximately 82 percent of women (JPATS Cockpit Accommodation Working Group Report, May 1993, unpublished data).

Reducing the envelope to 31 in. would require significant cockpit modifications, largely because ejection equipment significantly restricts the ability to adjust the seat. In addition, there was the possibility that the aircraft nose, rudder, and other flight controls would also need to be substantially modified to accommodate a smaller person. Further, since ejections at smaller statures and corresponding body weights have yet to be certified for safety, test articles and demonstrators would need to be developed to ensure safe ejection

(E. Dorn, Memorandum on JPATS Cockpit Accommodation Working Group Report, Oct. 19, 1993, unpublished data).

As debates continued in the press and within the working group during 1993, the possibilities for technological variety began to close down. In the JPATS case, administrative closure was achieved when the 1994 Defense Authorization Bill was passed. The bill included a provision preventing the Air Force, the lead agency in the purchase of the JPATS, from spending $40 million of a $41.6 million trainer budget unless the Pentagon altered the cockpit design (*6*). John Deutch, then the Under Secretary of Defense, wrote in a memorandum legitimizing the problem of accommodation of women in defense aircraft:

> I believe the Office of the Secretary of Defense (OSD) should continue to take the lead in addressing this problem. Other platforms in addition to aircraft should be considered as well. We must determine what changes are practical and cost effective in support of SECDEF policy to expand combat roles for females. I request that you take the lead in determining specification needs. Further, you should determine the impact of defense platforms already in production and inventory. (J. Deutch, JPATS Cockpit Accommodation Working Group Report, Dec. 2, 1992, unpublished data)

The impetus for changing the sitting height requirement and the JPATS itself arguably came directly from Congress and the president. However, this assertion does not discount the contributions made by several organizations within the Pentagon and the services, which, cognizant of the bias inherent in defense aircraft, were exploring alternatives to such technologies. For example, the Human Systems Integration (HSI) departments in the Office of the Secretary of Defense have consistently focused on integrating human factors into the preacquisition process of weapons procurement. Pentagon acquisition policy requires program managers during the acquisition phase to document what human system risks exist in predecessor or comparable systems, what studies and analyses are planned to identify or mitigate human risks, and the status of these efforts before each milestone decision review. Subsequently, HSI submits its assessments to the Defense Acquisition Board. It is through this process that the lack of accommodation of women by JPATS and design flaws inherent in other systems have been raised for senior-level deliberation and resolution before the systems have gone into actual production.

RELATIONSHIP BETWEEN HUMAN FACTORS IN MILITARY AND CIVIL AVIATION

The synergy between national security needs and civil aviation—both aircraft manufacturers and air transport—has been well documented. Military objectives shaped the American aircraft industry; indeed, the structure of the industry today is a consequence of earlier government procurement policies (*7*). Military-funded research and development, particularly in propulsion technology, has benefited commercial aircraft. Many of the earlier civilian airplanes were converted from military aircraft. On the other hand, technology developed for commercial requirements has had significant military applications, including such examples as the CF6 turbofan engine, flight-management systems, and improved fuel efficiency. In addition, the civil transport system is often perceived as a reserve military fleet in the event of a wartime emergency (e.g., during Operation Desert Storm).

As such, much of the technology base, supplier base, skills, and processes used by defense and civil aircraft are held in common. The principal commercial airframe producers all rely on substantial military sales. Often the divisions responsible for military and civilian work are physically and organizationally separate, but a high degree of labor mobility and technology exchange may exist.

Since World War II, the military has traditionally taken the lead in human factors research. Indeed, the field developed as attention was given to the "knob and dial" types of problems associated with designing control devices and visual instruments that could be used more rapidly and accurately. The range of operating requirements and the need to understand the characteristics of the user population before acquisition led the services to begin collecting and classifying data about the military population (*8*). Today, the Army's Natick Research and Development Command and the Air Force Systems Command's Human Systems Division at Wright-Patterson Air Force Base in Ohio still provide the most accurate anthropometric data.

Those in civilian aviation are considered to lag behind their military colleagues in the general field of human factors research. With specific regard to the accommodation of female pilots, many believe that the military has taken the lead in evaluating (wo)man-machine interaction. Located at the intersection of technology, economics, and labor relations, the issue of female accommodation in the private sector has been framed in a very different manner.

ACCOMMODATING WOMEN IN COMMERCIAL AIRCRAFT

Manufacturers are unsure of the total population of women commercial pilots, let alone their body dimensions. The number of women earning their air transport rating in the United States has increased by 325 percent since 1980. However, the percentage of women pilots is still approximately 3 in the United States and significantly lower worldwide (*9*). The FAA Statistics and Forecast Branch maintains information on the number of women pilots who have a current medical certificate and a pilot license. In 1993, 39,460 women held both the certificate and license out of a total of 665,069 pilots (*10*). However, these figures do not reflect the number of women actually employed as commercial pilots. In 1990, the Air Line Pilots Association stated that there were approximately 900 women pilots (out of a total of 43,000) at 44 of the airlines where it had members at that time.

Despite their similar origins, the cockpit technology encountered in civilian aviation differs substantially from that found in the military. The function that the human being is intended to perform and the types of mechanisms provided for him or her in the control processes also differ. For example, the extreme rates of acceleration experienced in military cockpits require elaborate restraining devices. Such restraints must be designed for the anthropometric characteristics of the intended users. The main complaints with the JPATS center on ejection seats and the need to provide safe ejection to lighter individuals.

In contrast, commercial aircraft do not reach the same high speeds as military planes, nor do they contain ejection seats. The seats in a commercial cockpit are adjustable to meet the varied comfort and safety requirements of the users. Thus, certain characteristics, such as height, weight, and strength, do not have the same valence in commercial aviation as they do in the military. Many argue that commercial aircraft can accommodate a more variable population because the operating requirements are not as stringent as in the military.

The location of various controls on the commercial flight deck, however, may disadvantage women and smaller-statured men. Although the seats are more adjustable, individuals with smaller functional arm reach and less upper-body strength may still experience difficulties manipulating controls. When women are sitting on the left, some complain that they cannot reach controls on the right side. Although electrical and hydraulic systems require smaller forces to actuate, reach concerns become increasingly important during manual reversion.

Major airframe manufacturers have integrated human factors as part of their initial concept and design process and have designed flight decks for both men and women pilots since the early 1980s. The methods that human factors practitioners in the commercial world use to determine accommodation are quite similar to those used by the military, many having been developed by internal defense divisions or borrowed directly from the public-sector research laboratories. Contractors experiment with various computerized human modeling packages (i.e., CATEA, GENECONN, CREW CHIEF, COMBIMAN) during the preliminary design stages. With the use of such programs—most of which run in conjunction with computer-aided design systems—engineers are able to analyze visibility and reach in a proposed cockpit design. Such programs create three-dimensional graphic representations of pilots that can be adjusted to different body sizes and proportions on the basis of accumulated anthropometric data from the Army surveys. Since the Army data contain both male and female standards, the various programs do not differ significantly in their ability to model women. However, cockpits are generally designed for a population with a range of 25th percentile military women to 99th percentile military men.

Although military and commercial engineers use similar methods and data, the pilot populations may differ. In other words, the fact that commercial aviation relies on anthropometric data representative only of military populations could pose a problem. Many agree that at present the largest obstacle in overcoming design bias against women pilots is the lack of comprehensive anthropometric data for civilian female populations.

The only available civilian data are very old. For female measurements, some manufacturers still use a 1940 Department of Agriculture survey conducted for clothing dimensions. These data are not extensive enough for use in designing large, complex interfaces, such as cockpits. Conducting a survey of civilian pilots would be expensive and time consuming; it appears that no one financially strapped airline company is willing or able to undertake such a project now.

Human systems specialists suspect that more variability exists in the civilian pilot population because civilian airlines have less restrictive eligibility requirements and a more expansive age range than the military. For example, commercial airlines do not maintain the same limits on body weight and height. In the military, most pilots are between 21 and 35 years old, whereas commercial airlines employ an older population, primarily former servicemen. In the past, commercial pilots received their training in the military, whereas now the trend is to filter through private flight-training schools. This results in a less standardized commercial pilot population, one that might not be represented in the anthropometric data culled by the military.

Once the cockpit design moves to the production stage, manufacturers rely on a working group of active pilots in their mock-up studies and verification analyses. Boeing chooses men and women of different shapes and sizes and asks them to reach to the extremes of the cockpit. McDonnell Douglas interviews the pilots themselves as well as their union to get feedback about accommodation. Distinguishing between comfort and accommodation is one of the main problems facing human factors practitioners. Comfort problems might include backaches, circulation problems, wear spots on elbows, and inadequate room for legs in contrast to accommodation concerns, such as the ability to fully see and perform necessary pedal work.

The process of designing and developing a cockpit is different for each manufacturer and for each aircraft. Because commercial airframe manufacturers design for many different customers, they must incorporate the preferences of each individual customer airline into their designs. Unlike defense contracts, the only regulations that standardize the design of the cockpit with respect to human factors come from FAA and are found in FAR Part 25.777C:

> The controls must be located and arranged with respect to the pilot seats so that there is full and unrestricted movement of each control without interference from the cockpit structure or the clothing of the minimum flight crew (established under 25.1523) when any member of this flight crew from 5′2″ to 6′3″ in height is seated with the seat belt and shoulder harness (if provided) fastened.

The regulations make no mention of the gender of the intended user but manufacturers interpret them to include both male and female pilots.

Many believe that the FAA guidelines are limited by their lack of enforcement and by their ambiguity—for example, height may not be the sole design driver or determinant of accommodation. Nonetheless, manufacturers are required to write a report, complete with mock-ups and models, stating that the design complies with FAA physical requirements. However, FAA is often unable to verify that smaller pilots would be accommodated because it is attending to other more critical design issues.

Manufacturers are responsive to their carrier customers within the FAA guidelines; they consider the accommodation of women and smaller-statured people in any design, but just how much of an issue it becomes—how big the envelope, how adjustable the seat—is based on the particular customer's preference. Few customer airlines are concerned with accommodating women pilots specifically, but some have made queries pertaining to height requirements and other human factors issues. The European airlines tend, on the average, to be more savvy about human-machine interface and ergonomics. For example, KLM has sophisticated human factors capabilities and is known for considering the "social" impacts of design. Whether one can attribute this sensitivity to the relative strength of unions or to the traditions of social democracy is open for debate.

Domestic airlines may inquire about physical stature in the context of labor relations. Manufacturers are occasionally contacted by the carriers' legal departments, which fear that the airlines will be sued for employment discrimination because height and strength requirements for pilots are so high as to exclude a significant number of women. For example, a woman pilot trainee who failed a simulator test might claim that the airline, and the aircraft itself, are biased against those with less upper-body strength. The airlines fear that they will be unable to justify such requirements as bona fide occupational qualifications critically related to job performance. Airlines have contacted private anthropometric consultants to help redefine height criteria to avoid allegations of sex discrimination.

Airframe manufacturers are also sensitive to the perception that as the ethnic and racial makeup of the nation changes, the accommodation of smaller men will become increasingly necessary. In addition, the prospect of foreign sales, both military and commercial, to countries with different-sized populations makes accommodation an important economic consideration. In the first paragraph of a memorandum to the Under Secretary of Defense (Acquisition), Assistant Secretary of Defense Edwin Dorn stressed that

> a reduced JPATS sitting height threshold will also expand accommodation of shorter males who may have previously been excluded from pilot training. For potential foreign military sales, this enhances its marketability in countries where pilot populations are of smaller average stature. (E. Dorn, Memorandum on JPATS Cockpit Accommodation Working Group Report, Oct. 19, 1993, unpublished data)

However, most foreign countries—excluding those of Western Europe—are not concerned with these types of human factors issues and rarely inquire about cockpit accommodation. In addition, international anthropometric data are very difficult to compile or access. Foreign militaries, often the repositories of such data, are hesitant to release their information for national security reasons.

Those airframe manufacturers who also build defense aircraft have been sensitized to the issue of accommodation in commercial planes. Government contracts are much more specific in their design requirements and are beginning to specify the need for the accommodation of women. Contractors try to stay one step ahead of the Pentagon to win their share of a decreasing number of procurements. For example, McDonnell Douglas has been an advocate of female accommodation for years because it foresaw that the women-in-combat exclusion would eventually be eliminated. Its human factors division invested heavily in human factors research to be better positioned to win government contracts.

CONCLUSION

Some argue that the issue of design accommodation is not about women but about the ways in which aircraft have evolved over the past 80 years. Most of the current inventory was designed before women had entered the profession. As Reppy (*11*) notes, "Closure in the design of these [technologies] ha[d] been reached in a time and context in which the idea of women as potential users was not considered; in effect, the current technologies were born gendered." A cycle was created whereby an older population of predominantly male pilots defined the design of new aircraft, which, in turn, defined the operational requirements for new pilots. The new generation of pilots—women included—must distinguish between legitimate operational requirements instituted for safety and efficiency purposes and the residue of male bias from decades as a single-sex profession.

Others argue that design accommodation is not a gender issue, but one solely concerned with size and stature. Physical systems and accoutrements cannot be designed for the typical human because humans come in different shapes and sizes. Smaller-statured individuals—male and female—are discriminated against in design, but women, who are smaller on the average, tend to suffer disproportionately. Men's and women's bodies are biologically different, but women must "pass" as men to have legitimate claim to certain professions and technologies. Women pilots are left with a quandary: do they prove that they can meet male standards or do they work to change the standards and the technology because the standards tend to disproportionately exclude women?

As airlines downsize and the competition for pilot positions increases, few women or smaller-statured pilots are likely to complain about any perceived lack of accommodation and demand special treatment. Private airframe manufacturers are accountable to their airline customers, many of whom either are not concerned about this issue or do not receive sufficient input from their line pilots. Customers have traditionally been more concerned with profit or payload motives, such as the number of passenger seats and cargo capacity, than with cockpit requirements (*12*). In addition, there is speculation that the JPATS project will be delayed indefinitely or abandoned because of budgetary constraints.

The civilian public sector may be the proper channel through which issues of design accommodation can be addressed and regulated. An editorial in *Aviation Week and Space Technology* (March 30, 1992) claims that "only the federal government is likely to pursue the high-risk type of basic research that is needed to keep the aerospace industry on the forefront of human factors knowledge." Such research at FAA and NASA is funded at only approximately $45 million per year despite 65 percent of air transport accidents being attributable to human factors and flight crew error.

In the absence of other initiatives, it may be the role of FAA not only to investigate the potentially discriminating effects that design may have on women's opportunities in the pilot profession but also to facilitate the transfer of knowledge from military to commercial sectors in this area (*13*). Design accommodation of women offers tremendous opportunity for technology transfer to civilian transportation because the military, with its stringent specifications, sensitizes engineers to the inclusion of women in design. Often this kind of transfer occurs internally between the commercial and defense divisions within the same company. Individuals who work on both sides encourage a cross talk in techniques and expertise.

However, more public-sector involvement in creating effective coupling between all areas of research and development that are pertinent to both military and civil systems is warranted. The world-class capabilities of the Department of Defense laboratories need to play a key role in the strategies for human factors research in the civilian sector. Cooperative research and development agreements, which have given the laboratories a mandate to expand their ties with industry, would allow their researchers to develop consortia of airlines, airframe manufacturers, and consultants to create a more comprehensive data base of civilian dimensions. One informant suggested that such an arrangement be pursued to conduct a comprehensive collection of civilian female anthropometric data.

Whereas once federal research and development funds were allocated to enhance the capacity of high-tech weapons systems, the emphasis in the past decade has shifted somewhat to the use of human resources to maximize the efficiency of such systems. In light of defense cutbacks and changing social contexts, the public sector also needs to take a more active regulatory role in equity maximization. Regulating the accommodation of a larger pool of pilots in the concept and design phase would ensure a more equitable outcome than relegating such issues to the logic of the market and the courts.

ACKNOWLEDGMENTS

The author wishes to thank TRB for providing the opportunity to conduct this research and the following people for their valuable assistance: Larry Jenney, Joseph Breen, Judith Reppy, Richard Pain, Susan Godar, Nina Richman-Loo, and John Slocum. In addition, the author wishes to thank those who were interviewed for this project: Patricia Beardsley, Statistics and Forecasts, Federal Aviation Administration; Joseph Bert, Private Human Engineering Consultant; Bruce Bradtmiller, Anthropology Research Project; Bill Buchholz, Commercial Airplane Engineering, Boeing; James Danaher, National Transportation Safety Board; R. Curtis Graeber, Commercial Airplane Engineering, Boeing; Sharon Hecht, Commercial Airplane Engineering, Boeing; Mark Hoffman, Federal Aviation Administration; Tom Malone, Carlow and Associates; Thomas McCloy, Federal Aviation Administration; Kathy McClosky, Human Engineering Division, Armstrong Laboratory, Wright-Patterson Air Force Base; Joe McDaniel, Human Engineering Division, Armstrong Laboratory, Wright-Patterson Air Force Base; Steven Merriman, Aircraft Analysis Group, McDonnell Douglas; Richard Pain, Technical Activities, Transportation Research Board; Nina Richman-Loo, Human Systems Integration, Department of Defense; and Conway Underwood, Commercial Airplane Engineering, Boeing.

REFERENCES

1. Wacjman, J. *Feminism Confronts Technology.* Pennsylvania State University Press, University Park, Pa. 1991.
2. Key, E., E. Fleischer, and E. Gauthier. Women at Sea: Design Considerations. *Proc., 30th Annual Technical Symposium on the Association of Scientists and Engineers,* April 8, 1993.
3. Binkin, M. *Who Will Fight the Next War: The Changing Face of the American Military.* Brookings Institute, Washington, D.C., 1993.
4. McDaniel, J. Strength Capability for Operating Aircraft Controls. Presented at Annual International Industrial Ergonomics and Safety Conference, San Antonio, Tex., 1994.
5. McCormick, E., and M. Sanders. *Human Factors in Engineering and Design.* McGraw-Hill, Inc., New York, 1982.
6. Maze, R. Fitting Seats for Women. *Navy Times,* Oct. 25, 1993.
7. Simonson, G. R. (ed.). *The History of the American Aircraft Industry.* MIT Press, Cambridge, Mass., 1968.
8. Noe, A. Medical Principle and Aeronautical Practice: American Aviation Medicine to World War II. Ph.D. dissertation. University of Delaware, 1989.
9. Gilmartin, P. Women Pilots' Performance in Desert Storm Helps Lift Barriers in Military, Civilian Market. *Aviation Week and Space Technology,* Jan. 13, 1992.
10. *U.S. Civil Airmen Statistics.* FAA APO-94-6. Office of Aviation Policy, Plans and Management Analysis, Federal Aviation Administration, 1993.
11. Reppy, J. New Technology in the Gendered Workplace or Why Pushbutton Weapons Have Not Increased Women's Participation. Presented at the Workshop on Institutional Change and the U.S. Military: The Changing Role of Women, Cornell University, Ithaca, N.Y., Nov. 13–14, 1993.
12. Sexton, G. Cockpit-Crew Systems Design and Integration. In *Human Factors in Aviation* (E. Weiner and D. Nagel, eds.), Academic Press, San Diego, 1988.
13. *National Plan To Enhance Aviation Safety Through Human Factors Improvements.* Air Transport Association of America, Human Factors Task Force, 1991.