TRANSPORTATION RESEARCH

RECORD

No. 1257

Aviation

Public-Sector Aviation Issues

Graduate Research Award Papers 1988–1989

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1990

Transportation Research Record 1257
Price: $12.00

Subscriber Category
V aviation

Mode
4 air transportation

Subject Areas
12 planning
14 finance
15 socioeconomics
21 facilities design
51 transportation safety
52 human factors
53 vehicle characteristics
54 operations and traffic control
55 traffic flow, capacity, and measurements

TRB Publications Staff
Director of Publications: Nancy A. Ackerman
Senior Editor: Naomi C. Kassabian
Associate Editor: Alison G. Tobias
Assistant Editors: Luanne Crayton, Kathleen Solomon, Norman Solomon
Production Editor: Kieran P. O'Leary
Graphics Coordinator: Karen L. White
Office Manager: Phyllis D. Barber
Production Assistant: Betty L. Hawkins

Printed in the United States of America

Library of Congress Cataloging-in-Publication Data
National Research Council. Transportation Research Board.

Public-sector aviation issues : graduate research award papers
1988–1989.
p. cm.—(Transportation research record, ISSN 0361-1981 ; no. 1257)
ISBN 0-309-05012-X
1. Aeronautics. I. National Research Council (U.S.). Transportation Research Board. II. Series.
TE7.H5 no. 1257
[TL553]
388 s—dc20
[387.7] 90-41736
CIP

Sponsorship of Transportation Research Record 1257

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 and other qualifications.
Chairman: Francis X. McKelvey, Michigan State University
John W. Fischer, Vicki L. Golich, Greig W. Harvey, Alice Herman, Sally D. Liff, Dorn C. McGrath, Jr., Dennis W. Mewshaw, Michael C. Moffet, Ronald W. Pulling, Agam N. Sinha, Ted Tedesco, Karl R. Zaeske

FAA Liaison: James Veatch

TRB Staff
Aviation Specialist: Larry L. Jenney
Program Coordinator: E. Thomas Burnard
Senior Secretary: Marcela O. Deolalikar

The organizational units, officers, and members are as of December 31, 1989.

Transportation Research Record 1257

Contents

Foreword

The papers in this Record are reports on research topics chosen by graduate students selected for awards from a nationwide competition under the third (1988–1989) Graduate Research Award Program on Public-Sector Issues. The papers were presented at the 69th TRB Annual Meeting in January 1990. The authors, their school affiliations, their faculty research advisors, and their TRB monitors are as follows.

Donald C. Galligan, Jr., a master's degree candidate at the University of Iowa, explored the problems and benefits of development of airports' excess lands. Faculty research advisor is John W. Fuller, professor of urban and regional planning. TRB monitors are John W. Fischer, Congressional Research Service, and Michael C. Moffett, American Association of Airport Executives.

Donna R. McLean, a master's degree candidate at Indiana University, investigated areas in which general aviation safety can be improved. Faculty research advisor is Clinton V. Oster, Jr., director, Transportation Research Center. TRB monitors are Vicki L. Golich, Pennsylvania State University, and Dennis W. Mewshaw, National Association of State Aviation Officials.

Maureen A. Pettitt, a Ph.D. candidate at Claremont Graduate School, examined cockpit-crew crisis decision making. Faculty research advisor is Charles T. Kercher. TRB monitors are William Edmunds, Air Line Pilots Association, and Richard F. Pain, TRB transportation safety coordinator.

Michael J. Roemer, a Ph.D. candidate at the State University of New York, Buffalo, analyzed the use of an automatic landing system to enhance aircraft tracking and control strategies. Faculty research advisor is D. Joseph Mook, Department of Mechanical and Aerospace Engineering. TRB monitors are Greig W. Harvey, Eakin, Harvey, Skabardonis, Inc., and Agam N. Sinha, the MITRE Corporation.

Terry A. Ruhl, a master's degree candidate at the University of California, Berkeley, identified alternatives to decrease runway occupancy, and thereby increase airfield capacity. Faculty research advisor: Adib Kanafani, Institute of Transportation Studies. TRB monitors: Francis X. McKelvey, Michigan State University, and Ronald W. Pulling, Ronald W. Pulling Associates.

The Graduate Research Award Program is sponsored by the FAA and administered by TRB. It was created to stimulate thought, discussion and research by graduate students who may become future managers and policy makers in civil aviation.

Land Use Controls and Policy for Airport Development

DONALD C. GALLIGAN, JR.

Many factors contribute to congestion in the airports and airways infrastructure, and many solutions have been proposed to correct this situation. Many experts agree that with the market the way it is now, airline transportation congestion will increase unless prompt action is taken. One way to increase capacity of the system is to expand and upgrade the entire system. This is an expensive proposition, so new sources of revenue will need to be utilized in order to facilitate this change. One old source of revenue that is being discovered anew is development of airports' excess lands with light industrial and commercial projects to fund part of the airports' operating and capital costs. The problems and benefits associated with this form of development are explored.

Traditionally, airports have drawn revenues from several sources. User fees, like landing fees and federal excise taxes, have been sufficient to sustain airport operations in most cases. Since deregulation in 1978, the hub-and-spoke system has contributed to a major congestion problem at many airports. There are several ways to combat this problem: pricing, greater use of secondary and reliever airports, segregation of airport uses, upgrading and expanding the airports and airways infrastructure, and reregulation, as well as others. All of these solutions are unpopular with some segment of society; there are no panaceas for solving the airport congestion problem. Traditionally federal and local political processes have encouraged and supported the most capital intensive, and least intrusive method for handling transportation problems. The method, or combination of methods, employed to ease the congestion problem in U.S. airports will not be cheap, and new sources of revenue will need to be tapped. The focus of this paper is how some airports are developing nonaeronautical-use lands to generate revenues from leased property.

LITERATURE REVIEW

Few publications addressing this topic were found. Of those found, all but one were published after 1987. Two very large data bases, American Business Institute Inform and National Technical Information Services, a government publications data base, were searched extensively. Both include data on airport development; from a list of thousands of publications, only two articles were relevant. The computer searches, as well as searches of the law, business, urban and regional planning, and main libraries at the University of Iowa and discussions with representatives from Apogee Research Inc., a public works consulting firm; the American Association of Airport Executives (AAAE); and TRB, generated only a handful of articles, books, and special reports that remotely had anything to do with financing airports through alternative land uses.

AAAE is now conducting a seminar for airport executives on this subject. In the seminar materials, El Paso International Airport developed a case study documenting its experience with land use financing. The airport's grounds were developed quite extensively, with a multitude of diverse uses such as manufacturing, warehousing, office complexes, government facilities, retail shops, miscellaneous commercial uses, hotels, and a golf course. The rent from these properties constitutes approximately 25 percent of El Paso's total revenues (*1*). Of course, not all airports can develop in such an extensive manner as in El Paso, with its 7,000 acres of land, but many smaller airports are finding development of excess land to be a good source of revenue.

BACKGROUND

Fort Lauderdale Executive in Florida; Reading Municipal in Pennsylvania; John Wayne Municipal in Orange County, California; and Hawkins Field in Jackson, Mississippi are a few of the small airports that have discovered the industrial park to be a good source of revenue. Although this is a fairly common form of airport development, the majority, including general aviation airports, have no nonaviation development of any type. Still other airports have excess lands but are prohibited from this type of development, depending on how the land was obtained. If an airport buys land without federal assistance, it is not bound by any restrictions, other than those for safety. If, however, an airport has obtained its excess lands with federal assistance, there can be restrictions on how these lands are used.

There are three principal ways in which airports acquire land with federal assistance. First, land may be purchased through the Airport Improvement Program (AIP), formerly the Airport Development Aid Program (ADAP), formerly the Federal Aid to Airports Program (FAAP). Second, land may be acquired through conveyance of property owned by the federal government that has been declared surplus to its needs. In this case, "airport purpose" includes land essential, suitable, or desirable for the development, operation, or maintenance of a public airport. Unlike grant-funded land, it allows for acquisition of property needed to develop sources of revenue from nonaviation business at a public airport. Third,

Department of Urban and Regional Planning, Jessup Hall, University of Iowa, Iowa City, Iowa 52242. Current affliation: North Bannock Metropolitan Planning Organization, 1651 Elvin Ricken Drive, Pocatello, Idaho 83201.

land can be acquired by conveying nonsurplus federal property (*1*, p. 1.1). For airports that have acquired excess lands through AIP or by conveying nonsurplus federal property, development of nonaeronautical revenue-producing projects is difficult at best because land acquired with federal grant money cannot normally be used to generate nonaeronautical revenues. The AIP program provides for conveyance of aeronautical-use land, and land obtained through conveyance of federal nonsurplus property is strictly for aeronautical purposes (*1*, pp. 1.2–1.3).

Surplus property may be designated as revenue-producing land in two ways. First, upon original conveyance of the land, FAA would determine which land would be used to produce revenue. Second, property originally conveyed for aviation use might be changed to revenue-producing use as a result of changes in aeronautical needs, that is, if the airport's master plan shows that aeronautical conditions have changed. For FAA to approve such a redesignation, the present and future aeronautical needs of the airport must be enhanced. Only FAA is authorized to change the use of surplus land from aeronautical to nonaeronautical use to support revenue production (*1*).

FAA makes its decision based on an application filed by an airport in accordance with Federal Aviation Regulation (FAR) Part 155—Release of Airport Property from Surplus Property Disposal Restrictions:

> This Part applies to the releases from terms, conditions, reservations, or restrictions in any deed, surrender of leasehold, or other instrument of transfer or conveyance (in this Part called "instrument of disposal") by which right, title, or interest of the United States in real or personal property was conveyed to a non-Federal public agency under section 13 of the surplus property act of 1944 to be used by that agency in developing, improving, operating, of maintaining a public airport or to provide a source of revenue from non-aviation business at a public airport.

There are many legal and administrative hurdles in developing an airport's excess lands. Most of these are in the form of FARs. One piece of legislation, however, has had a profound impact on airports in terms of development of excess lands and how those lands are developed. That piece of legislation is the Surplus Property Act of 1944.

Surplus Property Act of 1944

During World War II, the U.S. government seized control of many airports and the lands surrounding them and built many more to help in the national defense. At the end of the war these airports were turned over to states and local municipalities through the Surplus Property Act of 1944, which contains many provisions concerning the sale or lease of surplus property. The act states as its objectives:

> (h) to assure sale of surplus property in such quantities and on such terms as will discourage disposal to speculators or for speculative purposes; (q) to prevent insofar as possible unusual and excessive profits being made out of surplus property; (s) to dispose of surplus Government-owned transportation facilities and equipment in such manner as to promote an adequate and economical national transportation system; and (t) except as otherwise provided, to obtain for the Government, as nearly as possible, the fair value of surplus property upon its disposition.

These rather general objectives have been put into practice through FAA executive order 5190.6, which gives guidelines to FAA officials for objecting to proposed airport developments.

Through the Surplus Property Act of 1944, many municipalities purchased airports for $1, to make the sale legal and binding. There were strings attached, however, in the form of the national emergency clause, which allows the military to seize control of any public facility deemed necessary for national defense. All public airports and their excess lands are subject to this clause.

FAR Part 150

In many instances the FAR Part 150 noise compatibility study is a good place to start for an airport considering nonaviation development. The Part 150 regulations came about as a result of the Aviation Safety and Noise Abatement Act of 1979, and cover a broad range of topics concerning how FAA reviews the study, which airports are mandated by law to do a Part 150 study [defined by section 502(17) of the Airport and Airways Improvement Act of 1982]. The document contains discussions of the use of aircraft operational controls versus land use controls and which combination of the two gives the greatest reduction of noise, what the level of federal involvement in the local planning process should be, voluntary versus mandatory planning, level of public involvement, and many other issues central to noise abatement.

Table 1 shows what FAA has designated as appropriate land use based on aircraft noise levels. The Part 150 document is certain to point out that this table in no way constitutes any sort of policy sponsored by the FAA, and is in no way binding; however (*2*, p. 10), "Table 1 describes compatible land use information for several land uses as a function of yearly day-night average sound level values. The ranges of these values in Table 1 reflect the statistical variability for the responses of large groups of people to noise."

This type of development may not be workable at some airports. The airport case studies presented here all deal with relatively large general aviation or international airports in metropolitan areas. This type of development might not work for an airport that is located in a rural setting and at which 30 aircraft and no jets are based. There are location and size parameters for the type of development that an airport can attract. If the location of the airport is not pleasing to potential tenants, this type of development may be impossible.

For example, the Iowa City Municipal Airport in Iowa City, Iowa, has a 26-acre lot zoned for light industrial development and would like to attract a low traffic level of use to the area. This proposed development must overcome several obstacles. First, Iowa City is a community of only 50,000 people, with an unemployment rate of 0.8 percent. Effectively, there is no unemployment in the area, meaning that any firm deciding to locate there would have trouble finding employees or would need to draw from surrounding communities by offering higher wages, vanpooling, or other incentives.

Another factor is that the city has invested a lot of money in a company that is trying to locate firms in the industrial park on the opposite side of town from the airport. Thus, the city is not going to do anything to encourage industrial development at the airport. Another hurdle is the limited activities

TABLE 1 LAND USE COMPATIBILITY WITH YEARLY DAY-NIGHT AVERAGE SOUND LEVELS

Land Use	Yearly Day-Night Average Sound Level in Decibels					
	65-	65+	70+	75+	80+	85+
RESIDENTIAL						
Residential other than Mobile Homes Y	N	N	N	N	N	
Mobile Home Parks	Y	N	N	N	N	N
Transient lodgings	Y	N	N	N	N	N
PUBLIC USE						
Schools	Y	N	N	N	N	N
Hospitals and nursing homes	Y	25	30	N	N	N
Churches, auditoriums, concert halls	Y	25	30	N	N	N
Government services	Y	Y	25	30	N	N
Transportation	Y	Y	Y	Y	Y	Y
Parking	Y	Y	Y	Y	Y	N
COMMERCIAL USE						
Offices business and professional	Y	Y	25	30	N	N
Wholesale-retail-building materials.	Y	Y	Y	Y	Y	N
Retail trade -general	Y	Y	25	30	N	N
Utilities	Y	Y	Y	Y	Y	N
Communication	Y	Y	25	30	N	N
MANUFACTURING / PRODUCTION						
Manufacturing, general	Y	Y	Y	Y	Y	N
Photographic and optical	Y	Y	25	30	N	N
Agriculture(not livestock)& forestry	Y	Y	Y	Y	Y	Y
Livestock farming and breeding	Y	Y	Y	N	N	N
Mining and Fishing	Y	Y	Y	Y	Y	Y
RECREATIONAL						
Outdoor arenas and spectator sports Y	Y	Y	N	N	N	
Outdoor music shells, amphitheaters	Y	N	N	N	N	N
Nature exhibits and zoos	Y	Y	N	N	N	N
Amusement, parks, resorts, camps	Y	Y	Y	N	N	N
Golf courses, stables ,water sports	Y	Y	25	30	N	N

Key to Table 1
Y=Yes
N=No
25, 30= Land used and related structures generally compatible; measures to achieve noise level reduction or 25, 30 Db must be incorporated into design and construction of structure

Source: Federal Aviation Regulation Part 150 document.

that a town that size has to offer. Iowa City is fortunate to be the location of the University of Iowa, which attracts some cultural activities to the city and increases the likelihood that firms will locate there. An average town of 50,000 people may not have the type of amenities that firms look for when choosing a location. Yet another obstacle compounding the troubles of the potential airport development is that Cedar Rapids Airport, 30 mi north of Iowa City, has longer runways, commercial service, and a larger economic base because of its location in a city with a population of about 120,000, and it is also looking for industrial development.

CASE STUDIES

Reading Municipal Airport in Pennsylvania, Scottsdale Municipal Airport in Arizona, and Dallas/Fort Worth International Airport (DFW) in Texas were selected as case studies for analysis. Reading Municipal Airport is run by an airport authority and has an industrial park and a foreign trade zone. Scottsdale Municipal Airport is operated by the city of Scottsdale. It has no development on its grounds, but contiguous to the airport is an industrial park, an extensive airpark complex that has over 1,000 employers and 10,000 employees. The industrial park also has direct taxiway access to the runway in a "through-the-fence" operation. DFW opened in 1974 and is the newest major airport in the United States. This airport was opened on less than half its 18,000 acres, with thousands of acres set aside for nonaviation sources of revenue. These three airports were selected because they all have several different revenue sources, origins, and administrative structures, which will provide for the broadest coverage of the issues discussed here.

Reading Municipal Airport Authority

Reading Municipal Airport is an 865-acre parcel located in Bern Township, Brooks County, Pennsylvania. The airport has two runways, the longer of which is 6,350 ft and is being expanded to 7,000 ft. The shorter runway is 5,150 ft. The airport has all navigational aids and an FAA-operated control tower, which operates from 5:30 a.m. to 12:00 p.m., with the terminal building open during the same hours. There are five

fixed-base operators (FBOs) located on the airport, and around 180 aircraft are based there, 40 of which are corporate. The Reading airport is served by two carriers, U.S. Air through Allegheny Commuter, and United through United Express. Last year the airport had approximately 140,000 operations, of which about 13,000 to 15,000 were commercial.

In 1977, a new administration was put in place at Reading Municipal Airport, and one of its main goals was to turn some surplus industrial land into a modern industrial park. First, the administration asked FAA to authorize the designation of three areas on the airport property as land surplus to aviation use, in compliance with the conditions in the deed from the War Assets Administration.

The banks refused to loan the airport authority money to finance the capital improvements necessary to prepare the infrastructure in their industrial park unless the land could be exempted from the national emergency clause. In order to get this release, the airport authority had to file an application for release under FAR Part 155—Release of Airport Property From Surplus Property Disposal Restrictions, subsection 155.9—Release from War or National Emergency Restrictions. Approximately 200 acres was designated for nonaviation use. The land to be developed was three sections, each of which was on a different side of the airport.

The airport administration was required to write a narrative describing why they wanted the land released, do a complete environmental assessment of the entire area, and show that the new land use was in concert with the master plan. That information was sent to the U.S. Department of Defense for approval, according to FAR Part 155, subsection 155.9 paragraph (b), which states, "A release from the terms, conditions, reservations, or restrictions of an instrument of disposal that might prejudice the needs or interests of the Armed Forces, is granted only after consultation with the Department of Defense."

This airport development was unique because the airport authority was the developer for the infrastructural improvements. They put the contracts out for bids, and followed the state government requirements for developers to accomplish the improvements. Funding for these improvements came from several sources. The airport authority contributed $460,000 for capital improvements, the Pennsylvania Department of Commerce gave community improvement funds, community development funds were contributed, and money was borrowed from local banks.

When leases were negotiated with tenants, the FAA district office made sure that proper compensation was being derived from the property. Appraisals are made for every piece of property while a lease is being negotiated with a tenant, and a 10 to 12 percent per year rate of return is established in the terms of the lease. This is escalated every few years to keep pace with inflation. The FAA district office releases the property from the reverter clauses on a per-lease, per-parcel basis.

The leases are long-term, anywhere from 25 to 80 years. When the lease expires, the building and all other development on the grounds revert back to the airport authority. All leases are negotiated on a net, net, net basis, which means that the lessee pays for all expenses after locating on the airport grounds. This includes taxes, insurance, maintenance, and other costs associated with operation and upkeep of the property. This way, for the airport no more costs other than collection of rent are associated with the property once the infrastructrual improvements have been made.

Reading airport has used many marketing strategies to fill property to be developed in the industrial parks. One such strategy is a school tax abatement program set up as an incentive to locate at the airport. The school tax in Reading is the major tax in the area, and the tax abatement system allows a 50 percent abatement the first year, 40 percent the second, and a 10 percent reduction each successive year until the sixth year, when the tenant pays full taxes. This marketing strategy has produced an incentive for tenants to locate at the airport and has given the airport bargaining power in negotiated leases.

Another marketing strategy the Reading airport is hoping to capitalize on is the establishment of a foreign trade zone (FTZ). Reading's FTZ blankets all three sections of the industrial park. If a tenant wants to store a package from overseas or wants to engage in some sort of foreign production contract, this can be facilitated by the FTZ operator at the airport.

In order to obtain an FTZ designation, the airport administration conducted a study to see whether it was warranted. The designation was found to be warranted and necessary for the area, so airport administration, in conjunction with the Reading Chamber of Commerce and the local manufacturers association, put together the FTZ proposal. FTZ designations are given by the Foreign Trade Zone Board of the U.S. Department of Commerce. In a lengthy process of hearings and justifications, it took Reading 5 years to receive its designation.

There are three reasons why the Reading airport authority worked through the long administrative process of acquiring the FTZ designation: (a) to better serve the businesses already located at the airport, (b) to have another marketing tool to attract potential tenants to the airport, and (c) to increase traffic at the airport. It was believed that more shipments would come into the airport (primarily freight) if Reading had an FTZ designation. If the FTZ proves to be a valuable marketing tool and more firms locate there because of it, the result will be even more traffic at the airport. The more firms that locate in the industrial park, the more revenues that can be made for the airport. These revenues can be used to offset operating expenses, or for capital improvements not funded by the FAA, or as matching funds for FAA-sponsored capital improvements.

Airport revenues come from industrial leaseholds, aviation, and residential and farming activities. Residental zoning is not a compatible land use; however, in this case, a small trailer court and a few original stone houses have been on the grounds for a long time. Their location is not particularly noisy, so that 5-acre area has been kept residential. Reading airport's operating income is about $1,200,000; of that, about $160,000 comes from industrial leasehold revenues.

Reading Municipal Airport Authority's goals are to provide the best services for the local community and to provide connecting flights to major metropolitan areas of the East Coast. Major connecting hubs now served are Philadelphia, Pittsburgh, and Dulles International Airport, near Washington, D.C. The airport brought in an additional carrier, which increased the frequency of commercial flights to various destinations. In April 1989, there was a 19 percent increase in passenger enplanements and a 15 percent increase the previous month. Revenues from leaseholds can help the airport

keep pace with increasing service demands resulting from congestion at Philadelphia's airport.

Scottsdale Municipal Airport

Scottsdale Municipal Airport is a 600-acre parcel that has one 8,250-ft runway, two parallel taxiways, parking aprons, the land and buildings for three FBOs, an airport terminal building, an FAA office building, and an FAA control tower with all navigational aids. Scottsdale Municipal has about 500 aircraft based at the airport, with about another 100 corporate aircraft in the industrial park.

The Scottsdale Municipal Airport/Airpark is a 2,000-acre commercial development and reliever airport in Scottsdale, Arizona. It contains the majority of industrial-zoned land in the city and employs over 10,000 people. The 2,000-acre airpark is only half developed at this time, and it holds the potential for many more jobs and substantially more value for the local economy. The airpark is privately owned and surrounds the municipal airport, which is owned by the city of Scottsdale.

Since the mid 1960s, the airpark development has grown to 1,000 acres of developed land, with three industrial parks and seven runway access points. Nearly 7 mi of taxiways links over 200 commercial and office buildings directly to the airport runway. Some airpark properties also feature private hangars and fuel farms, allowing companies that use aircraft on a day-to-day basis to operate and maintain their own aircraft and fuel supplies directly outside their office buildings.

Using an employment multiplier of 2.5, estimates by city economic development staff and Arizona State University show that the airpark has been responsible for creating over 20,000 new jobs elsewhere in the community and surrounding metropolitan area. They further estimate that the activities at the airpark are indirectly responsible for over $1 billion of value added to the community and surrounding metropolitan area annually. Airpark businesses are projected to generate more than $2 million in sales tax revenues each year for Scottsdale, as well as over $2 million in property tax—the equivalent of approximately 2,300 single-family homes. This was accomplished through master planning and effective zoning for the airport/airpark area.

Cooperation between local developers and city staff led to the creation of the Planned Commerce Park (PCP) zoning district, which allows for more mixed-use campus-style developments in parcels of 40 acres or more. Retail shops, service stations, restaurants, and other services were being located in Phoenix because of limited opportunities to locate in the Scottsdale airpark. Scottsdale's vision for the airpark is mixed-use developments that incorporate professional offices, research and development centers, corporate headquarters, appropriate retail and support services for workers in the airpark area, and residential and recreational/hospitality uses—all integrated into a large, campus-style development.

In Scottsdale's case it was imperative that the city staff running the airport understood the basic principles of economic development. It is short-sighted to say that "through-the-fence" operations hurt an airport by reducing fuel sales. On the contrary, these operations create a large amount of economic activity that flows into the city through other economic channels, such as property taxes, school taxes, city service contracts, sales taxes, and the like. Even though the airport may not get as much direct revenue through the sale of fuel, the city staff managing the airport realize that the economic impact of 10,000 jobs and over $1 billion of value added to the community will come back to the airport, and some already has.

All this airpark activity has meant an increased role for Scottsdale Municipal Airport. In this case it is difficult to assign a precise dollar figure to the airport's new role; however, the rapid development of this airport can be partially attributed to the airpark's being the major activity hub of the community. The airport had about 235,000 operations in 1989, up approximately 23 percent from the level in the 1988 fiscal year. The increased activity has paved the way for newly operating commercial flights out of the airport, as well as a new 99-ft FAA control tower that recently started 24-hour service. Scottsdale has also approved future expansion of airport terminal and parking facilities. The airport's first commercial service started in mid-June 1989, with commuter service to John Wayne Municipal Airport in Orange County, California.

Tourism is a very important industry in the Scottsdale economy. This is exemplified by two commercial hotels, a luxury resort, and championship golf course in the airpark area. Scottsdale wants to provide more commercial service to and from the area, and to provide day trips outside of Scottsdale to places like the Grand Canyon and Sedona to generate more tourism. This will mean an even greater role for the airport in the local economy and increase the position of the airport as central to the community's well-being.

Dallas/Fort Worth International Airport

Starting operations in 1974, Dallas/Fort Worth International Airport (DFW) is the newest international airport in the United States. The airport is owned jointly by the cities of Dallas and Fort Worth and is located far outside the corporate limits of both cities. It is currently surrounded by five autonomous communities—Irving, Arlington, North Richland Hills, Hurst, and Ewless. When it began operations in 1974, all airport facilities covered about 9,000 acres, with another 9,000 acres of land yet to be developed. Part of this land was to be developed for nonaviation use to produce revenue for the airport.

In 1974, the United States had just been through the Arab oil crisis, and the country was actively looking for its own sources of oil. Texas was one of the main oil-producing states in the nation. The U.S. oil industry experienced a boom in the late 1970s with the second round of oil price increases. With oil selling at $24 a barrel, the entire state of Texas was riding a wave of economic prosperity. With this prosperity came development, and in the early 1980s DFW began to develop economically because surrounding communities could supply support services and an employment base.

In late 1985 the bottom fell out of the oil industry. Oil that once sold for $33 a barrel hit a low of $16 a barrel, and many wells could not afford to produce at such low prices. Thus the boom years of the 1970s gave way to the bust years of the 1980s, and the Texas oil economy began to collapse. This is where the DFW development story ends. The airport's

facilities and planning administration believes that the five autonomous communities surrounding the airport would protest the development of excess lands at the airport because they cannot add any of that development to their tax base.

Further complicating the matter is that firms locating at the airport do not have to pay property taxes. This creates a huge incentive for firms to develop there, but the airport's facilities and planning administration perceives political pressure from the local governments of the surrounding communities not to develop with non-aeronautical-related land uses. This political situation has put the property and facilities planning department at the airport in the very precarious position of wanting to develop the property to add to the airport's revenues while being pressured by the surrounding communities to develop those lands with firms that they believe have a legitimate claim for locating at the airport. It is important to note, however, that no representative from the surrounding communities has expressed this point of view directly to the facilities and planning administration. It is simply the administration's perception that these consequences would occur if nonaeronautical development took place at the airport.

This means that the scope of projects allowed to locate at the airport has been severely narrowed. The property and facilities department is looking for the type of development that may not have a demonstrable need to be at the airport, but would not locate in the Dallas/Fort Worth area if it were not at the airport. The only nonaviation development that the airport has been able to locate on its excess land is an FTZ.

ANALYSIS

Political

As mentioned previously, DFW had planned to develop quite extensively with nonaviation land uses to help defray a portion of the airport's operating and capital costs. This idea has fallen on hard times, and it has become very difficult to locate a firm at the airport and avoid conflict with the surrounding communities. The DFW properties and facilities department has decided to proceed cautiously, trying to avoid negotiation with the surrounding communities regarding airport development.

The method that the DFW properties and facilities department has followed can be explained in terms of a "best alternative to a negotiated agreement" (BATNA) assessment. According to Susskind and Cruikshank (*3*, p. 81), "Negotiations hinge on this concept. No group should enter into a negotiation if what it can obtain outside the negotiation is better than what it is likely to get as part of the negotiation." When considering a potential development, the DFW properties and facilities department wants a BATNA to be higher than what would be expected from a negotiated agreement. Just as important as having a high BATNA is letting other potential negotiators know how high it is, avoiding the conflict entirely.

This is one way of explaining DFW's approach to developing its excess lands, but one has to wonder whether this is a prudent method to attract development. Certainly this method avoids conflict, but it also severely constricts growth and prospects for development of the airport property. Is it so important to avoid conflict when the costs may outweigh the benefits derived from the avoidance?

Perhaps if an open dialogue and working relationship were established with the surrounding communities, the overall goal of revenue production would be better served. One has to question whether more revenue could be produced for the airport if a dialogue were entered into with the surrounding communities. Coopting local representatives by allowing the surrounding municipalities to tax the development and have a voice in negotiating with tenants would greatly increase the pace and scope of development at the airport. There are certain firms that do not need to be located at the airport but would benefit greatly from being there, for example, any firm dependent on air freight for production.

Bringing the surrounding communities into the negotiations would greatly expand the range of potential tenants for airport development. This would speed the development process and give the surrounding communities a share in the benefits by allowing them to add the development or a portion of it to their tax base. Of course, taxes couldn't be so high as to negate any benefit a firm might gain from locating at the airport. The tenant would end up paying more to locate at the airport than would have been the case were the surrounding communities not included in the negotiations, but the added benefit in terms of reduced transportation costs could more than make up that difference.

Economic

In 1986 Scottsdale's airpark claimed roughly 30 percent, or $292,514,700, of the community's assessed value. The community receives 1 percent of this in property taxes, which is equal to $2,925,000 yearly tax revenues. This is the equivalent of 2,900 homes worth $100,000 each. It appears to be a wise strategy to develop around the airport in this manner because the majority of housing in Scottsdale is on lots of 1 acre or more, and the entire airpark is 2,000 acres, only 1,000 of which is currently developed. Thus, by zoning this property as a light industrial, commercial, research and development park, and planned commerce park, Scottsdale has managed to triple the revenues generated on this tract of land.

$$\$2{,}925{,}000 \times 2 \approx \$6{,}000{,}000 \div \$1{,}000$$
$$\approx 6{,}000 \div 2{,}000 = 3$$

In this equation it can be estimated that if the airpark were completely developed, the total property tax revenues would be about $6,000,000, or roughly twice the current tax revenues. If this is divided by $1,000, which is the property tax paid on one $100,000-home per year, 6,000 homes would have to be located on the property to get the same revenue as the airpark currently provides. Scottsdale, however, has developed largely on 1-acre residential lots, so the number of homes that could be located on the land in the airpark is about 2,000. Thus, revenue production has been increased by a factor of 3. This does not take into account the cost of developing around an airport with incompatible land uses, which would have costs associated with it, making this type of light industrial development even more cost efficient.

As stated previously in the Scottsdale Municipal Airport case study, it is difficult to quantify the effects that the airpark

has had on the airport. However, the airport has stayed a remarkably sound influence in the community and has strengthened its overall importance to the community's economic well-being. The airport's increased importance to the community was recently demonstrated by the community's agreement to build the airport a new terminal and upgrade the parking facility.

In Reading, Pennsylvania, the total cost to the airport authority of the infrastructure improvements was about \$460,000. This investment provides \$160,000 a year in rent from leased property. A present value analysis can be done using the following formula:

$$PV = A/i \tag{1}$$

where

PV = present value,
A = annuity, and
i = discount rate.

This is the same as a traditional present value formula with the value of n set at infinity (∞):

$$PV = A * \{[1 - 1/(1 + i)^n]/i\} \tag{2}$$

where

PV = present value,
A = annuity,
i = the discount rate, and
n = years.

The largest portion of the investment is tied up in the land itself, but at the end of the lease, the land and the buildings on it revert back to the airport. This portion of the investment is not lost over time and indeed may have appreciated in value. The land is still there, and the airport still owns it.

In this present value equation, A equals \$160,000, the amount received per year in revenues from leased property, and i the discount rate set at 0.12, considered a normal rate of return on investment if the money for infrastructure improvements was used for other investments. The present value of the industrial development at the Reading airport is about \$1.33 million, or about 2.8 times the cost of the infrastructure improvements.

There are other benefits that have yet to be realized at the Reading Municipal Airport. First, there is room for more tenants in the industrial park, and if more firms locate there, more rent will be collected, increasing the present value of the development. Second, vast benefits accrue to the community from this development. Since the development took place, 1,500 new jobs have been created at the Reading airport, with an annual combined income of \$30 million. For this the city of Reading paid about \$300,000 in Community Development Block Grant funds and the school tax abatement program. These benefits accrue to the community directly, but if \$30 million in income is being generated at the airport, it makes sense intuitively that some of that money is coming back to the airport indirectly.

The investment in an industrial park was a good one in the case of the Reading airport. The benefits to the airport authority are 2.8 times greater than the costs, and there is room for expansion in the industrial park, which could offset even more of those costs. The public benefits are great and accrue to the municipality on a larger scale than those enjoyed by the airport authority.

Procedural

The case study airports are all different in the way that they have been developed and in the type of development that each airport has attracted. Reading, although it has other types of tenants, is primarily oriented toward light industry and manufacturing. Scottsdale, however, is moving away from industry and toward large campus developments with mixed land uses accommodating primarily corporate offices, research and development firms, and resort activities. DFW has developed very slowly, and will probably continue to do so until the area's economy turns around. Even though these developments are widely varied in their composition and origin, they have some factors in common that are essential to this type of development.

First, when a development of this type is begun, goals and objectives to guide the development process must be clearly defined. In the case of Reading, the goal of the airport authority was to turn the rundown Army barracks into a modern industrial park, adding to the airport's revenue base. In Scottsdale, the goal of the city's economic development department and airport management is economic development for the community through innovative zoning of the airpark. The city of Scottsdale is zoning the development in the airpark in a way that maximizes the economic benefit to the community through tax revenues and jobs created. In addition, the airport is experiencing a growth in operations per year and an expansion of the terminal that might not have happened if the development of the airpark had been tailored differently. The goal of the DFW properties and facilities management department was to develop DFW's excess lands to bring more revenue into the airport.

Second, representatives of all three airports say that it is vitally important to zone with compatible land uses around the airport. This can be accomplished with the help of a Part 150 Noise Compatibility Study, or through the master planning process. The Part 150 study, although not required for small general aviation airports, may be a good base to start with for an airport that is developing excess lands. The study will show not only how the airport will affect residential areas around it, but how noise might affect tenants in the development. This helps to identify potential conflicts so the airport can deal with them in the planning stage, rather than having to react to a bad situation later on. If an airport is developing excess lands and is competing for business with a neighboring airport, bringing the other municipality into the planning process at the earliest possible time is essential to ensure that the surrounding area is zoned with compatible land uses regardless of municipal boundaries. This type of cooperation in the planning stage will benefit both municipalities.

Third, there was strong local support for development of the Scottsdale and Reading airports. Both communities won support for the development around their airports by being completely open and honest, and holding public meetings on any specific development issues and proposals. Another

important factor is that in each of these communities, the development in no way conflicts with long-term community goals, and indeed facilitates attainment of these goals. In Scottsdale, the airpark is strongly supported by members of the community, partly because of the attention that the Scottsdale planning department has paid to it. The airpark is a very attractive part of the city and the major employment center for Scottsdale.

Reading's airport development also enjoys support from the community because of the jobs and economic base that it has brought to the city. Reading's airport authority worked closely with the community when the airport was developing its industrial park: money was borrowed from local banks, community development funds were received, the school tax abatement program was put together, and the Reading Chamber of Commerce was involved in getting the FTZ designation. In November 1989, Scottsdale voted on a bond issue to finance ground transportation improvements for the airpark. The issue was expected to pass. Without the strong support of the community these necessary funds could not be acquired.

Fourth, the Reading and Scottsdale airports had focused administrations. All administrative staff played an important role in making each development a success. It is vital that new staff come in with good ideas, have a good track record in their field, and be open to new ideas that can improve the airport.

These four qualities—clearly defined goals and objectives, a good master plan that zones with compatible land uses, community support, and a sound airport administration—are essential for nonaviation development to take root at an airport. There is no way to make a how-to guide to airport development. Each airport is individual and has different conditions surrounding it. These four qualities must be present, however, to accomplish something as administratively complex as nonaviation development.

CONCLUSIONS

Development of nonaviation-use lands at airports can be a good source of revenue. The potential is there for a good portion of an airport's operating and debt service costs to be covered by revenues from leased property. This has been demonstrated by numerous airports: Reading receives one-third of its operation revenue from leaseholds; Fort Lauderdale Executive Airport receives approximately one-half of its operating revenue from leaseholds; El Paso International, perhaps the best-known airport for development of this type, receives one-fourth of its operating revenues from nonaviation land use leaseholds. It is important, however, for an airport to assess the situation carefully before any development investments are made.

If the potential for increased funding is there, why has there not been greater use of this financing mechanism? There are several reasons for this. First, not all airports have excess lands. Scottsdale Municipal Airport did not have excess lands but still managed to use the airport and zoning to maximize benefits to the community, the airport, and the tenants in the airpark. This type of development might be useful for an airport with privately owned lands around it.

Second, an airport may have excess lands, but they may be earmarked for future airport development. If so, and development rather than expansion seems prudent, the FAR Part 155 application may change that designation. The airport master plan has to be amended, and this amendment with a justification for the change has to be sent to FAA for approval. In order for the amendment to be approved, FAA must be satisfied that such an amendment would enhance future aviation needs at the airport. The airport administration must not be short-sighted in this venture. If the land may be needed at a later date for aviation purposes, FAA will not change the land's designation back again.

Development of excess lands can help to accomplish several public policy goals. The primary goal that can be achieved is making public airports more self-supporting. If extra dollars are coming into the system, other dollars will be available for capital improvements, as well as infrastructure expansion, congestion reduction, and air travel safety improvements. Another important policy goal that can be achieved with industrial development of excess lands is noise mitigation. It is common sense to zone land uses around an airport that are not as noise sensitive as others; however, this is not always done. Development of excess lands puts that land to work for the airport and ensures that it will not be developed in a manner that is incompatible with the levels of noise around the airport.

FAA should issue a policy statement that mandates that all airports with excess lands investigate the prospects for nonaviation land use development on their grounds. This should be made a funding requirement for inclusion of an airport in the National Plan of Integrated Airport Systems. If larger airports with excess lands do not tap this source of revenue, the small airports, like Iowa City Municipal, essentially are subsidizing the larger airports through FAA grant money. If larger airports were developing their excess lands and generating revenue from them, this revenue could replace FAA grant money, which could then be distributed to airports with a greater need for funding.

FAA also should look into changing its funding formulas. There are airports that are making relatively large profits from nonaviation development, yet are still eligible for capital improvement grants based on project priority. If airports have money or assets in a capital account or land banking like Fort Lauderdale Executive, they should be considered assets to be used for capital improvement projects, making these airports eligible for fewer funds and extending scarce resources.

This type of development has not been widely publicized. Airport officials need to be made aware of the potential that nonaviation development has for a wide variety of situations. If it is not publicized as a potentially lucrative funding mechanism, it will not be used.

With the need to expand and upgrade the infrastructure, airports are looking for every source of revenue to help. A seminar conducted by AAAE describes this type of development and shares ideas on how to do more with it. Two airport magazines, *Airport Services Management* and *Air and Space Technology*, have printed articles about nonaviation development, describing it as a good source of revenue for some airports. More needs to be published about this type of development, because the possiblities are many and the revenues that can be generated are much needed.

Finally, more research should be done on the topic to learn more about the process by which these developments are started, and the effects they have on a community. There are

many other ways to approach this topic, and other areas to learn, such as marketing a facility once the plans are made, and the effects these developments have on a community in terms of economic development, jobs, property values, tax assessments, and so forth. This will accomplish two things: (a) enrich the working knowledge of airport development, and (b) bring the topic to the forefront for greater exposure to airport administrators looking for ways to finance airport activities.

ACKNOWLEDGMENTS

The author would like to thank the following people and organizations: FAA for sponsoring the Graduate Research Award Program; TRB monitors Mike Moffet and John Fischer; TRB program coordinators Tom Burnard and Larry Jenney; and Robert Nash Parker and faculty advisor John Fuller at the University of Iowa. Most of all, the author wishes to thank his wife Kathy, who put up with all the long days that turned into long nights, and his son Donald Charles III for being a constant source of pride when the going got rough.

REFERENCES

1. Embry-Riddle Aeronautical University. *Developing Airport Revenue From Non-Aeronautical Use Land.* FAA, U.S. Department of Transportation, 1989.
2. Federal Aviation Regulation A150.101 Part B—Noise Exposure Map Development, Noise Contours and Land Uses. FAA, U.S. Department of Transportation, 1984.
3. L. Susskind and J. Cruikshank. *Breaking the Impasse: Consensual Approaches to Resolving Public Disputes.* Basic Books, Inc., New York, N.Y. 1987.

General Aviation Safety: Where Can Safety Improvements Be Made?

DONNA MCLEAN

In an attempt to improve general aviation safety, the causes of the 9,245 general aviation accidents that occurred from 1983 to 1986 are analyzed and summarized. During this period, general aviation accidents were responsible for 8 of every 10 aviation-related deaths. The leading causes of general aviation accidents over the 4-year period are identified, and apparent trends are noted. Although the safety record of general aviation improved from 1983 to 1986, the circumstances in general aviation in which safety improvements are most urgent are identified. The leading cause of general aviation accidents is pilot error, but specific causes of accidents include failure to conduct preflight procedures properly, inadequate flying skills, and poor in-flight procedures or in-flight judgment.

General aviation is civil aviation under the *Code of Federal Regulations* (14 CFR 91) and includes business flying, recreational flying, instructional flying, agricultural applications, and a host of other flying activities. Although the media and the public focus on jet aviation, most aviation is general aviation. In 1986 general aviation logged four of every five civil aviation flight hours and accounted for 9 of every 10 U.S. civil operations (*1*).

The majority of aviation fatalities and accidents occur in general aviation. From 1980 to 1985, general aviation accidents accounted for 8 of every 10 fatalities in U.S. civil operations (*2*). Between 1980 and 1985, general aviation aircraft were involved in 9 of every 10 accidents (*3*). Although general aviation comprises the majority of civil aviation operations and accidents, it is often overlooked by Congress, the press, and the public when the safety of the national airspace system is discussed. (One may speculate that the focus on jet aviation safety results from the large number of people who fly in jets, the catastrophic nature of jet aviation accidents, and the amount of media coverage.)

In this analysis, each general aviation accident that occurred in the United States between 1983 and 1986 was reviewed individually and categorized by accident cause. The accidents then were summarized by cause to examine recurrent patterns.

OVERALL GENERAL AVIATION ACCIDENT TRENDS

Between 1983 and 1986, there were 9,245 general aviation accidents in the United States. In this analysis, general aviation accidents that occurred in Alaska are reviewed separately from those in the remaining 49 states. This distinction is made because of the possibility that Alaskan weather results in a different mix of accidents. Thus, in the discussion of overall accident trends, the data include only 49 states.

As shown in Table 1, a downward trend in the total number of general aviation accidents occurred between 1983 and 1986, both in absolute numbers and in the accident rate per 100,000 flight hours. Table 2 provides the distribution of accidents over the 4-year period by the causal categories used in this analysis. During this period, the frequency of aviation accidents by cause appears nearly constant. The three most common accident categories—Pilot Error, Equipment Failure, and Environment—maintain a consistent ranking over the 4 years. The consistency of general aviation accident causes may be seen as an indication of the use of a consistent methodology to categorize the accidents.

As Table 2 indicates, pilot error clearly prevails as the leading accident cause, with an average 64 percent of the accidents. On average during the 4-year period, pilot error

TABLE 1 GENERAL AVIATION ACCIDENT TRENDS: ALL ACCIDENTS

	1983	1984	1985	1986	Total
Total number of accidents	2,511	2,116	2,047	1,952	8,626
Accident rate per 100,000 flight hours	10.64	8.72	8.57	8.10	9.00
Annual flight hours (*8*)					
General aviation (hr 000s)	28,879	29,629	28,552	28,718	115,778
Executive (91d) (hr 000s)	4,473	4,422	3,868	3,424	16,187
Alaska (%)	3.3	3.8	3.3	4.7	
GA adjusted[a] (hr 000s)	23,601	24,261	23,882	24,102	95,847

[a]GA adjusted is the general aviation flight hours minus the Executive 91d flight hours and the FAA estimate of the percentage of Alaskan general aviation flight hours.

TABLE 2 FREQUENCY OF ALL ACCIDENTS

	Percentage by Year				
Accident Category	1983	1984	1985	1986	Total
Equipment Failure	16.3	16.4	23	19	18.5
Environment	7.3	7.5	9.8	8.2	8.1
Pilot Error	69.4	66.8	56.4	63.1	64.2
ATC	0.1	0.1	0.1	0.3	0.2
Ground Crew Error	0.4	0.7	0.5	0.1	0.4
Other Aircraft	2.1	2.6	2.8	2.7	2.5
Other	4.4	6	7.3	6.6	6

School of Public and Environmental Affairs, Room 430, Indiana University, Bloomington, Ind. 47405. Current affiliation: Office of Management and Budget, 725 17th Street, N.W., Washington, D.C. 20503.

accounted for 6 of every 10 accidents. This statistic should be compared with pilot error accidents of domestic jet carriers, which account for only 2 of every 10 accidents between 1979 and 1985 (*4*).

The second and third leading general aviation accident categories—Equipment Failure and Environment—account for an average of 19 and 8 percent of the accidents, respectively. Although Equipment Failure is the second leading accident category, it accounts for only 2 of every 10 accidents. Environment, which includes weather-related accidents, accounts for less than 1 of every 10 accidents.

The remaining four categories account for only 9 percent of the accidents. Midair collisions and on-ground collisions included under the category of Other Aircraft were responsible for 2.5 percent of the accidents. The Air Traffic Control (ATC) and Ground Crew Error categories account for less than 1 percent of the accidents. The miscellaneous accidents falling under Other include 6 percent of the total accidents for the 4-year period.

To understand fully the significance of the statistics in Table 1, a discussion of the methodology that includes the accident category definitions follows. The accident categories must be understood to avoid a misinterpretation of the data.

METHODOLOGY

The National Transportation Safety Board (NTSB) conducts or supervises investigations of all U.S. aviation accidents. NTSB collects and compiles accident information such as the type of aircraft flown, the number of occupants, and the weather conditions at the time of the accident. This analysis uses the NTSB accident data from the 9,245 general aviation accidents that occurred in the United States between 1983 and 1986.

Only accidents involving fixed-wing aircraft operating under 14 CFR 91 as a general aviation operation are included. Aircraft such as helicopters, ultralights, balloons, and gliders are excluded. Because of their exceptional safety record, large and turbine-powered multiengined airplanes operating under 14 CFR 91(d) are also excluded. The analysis includes all U.S. general aviation operations.

Aviation accidents are often viewed as a chain of events that ends in an accident. An example might be an equipment failure that led to a total loss of power and ended in an accident in which the pilot unsuccessfully executed an emergency landing in windy conditions. There are three events, or factors, contributing to the accident: the equipment failure, the pilot's inability to execute an emergency landing, and the weather conditions. Identifying the cause of this accident may be approached in three different ways: by using the initial factor, the final factor, or all factors. This research uses the initial factor to identify the accident cause. In the above example, the initial factor would be equipment failure.

Using the initial factor, however, is not an attempt to deny that accidents are the result of the contribution of a number of interrelated causes. By using the initial factor, the research identifies the first link in the chain of events, and therefore will target those factors that most frequently initiate aviation accidents.

This analysis included the most recent and complete general aviation accident data available, which were compiled in 1986. Because of the detail in the data, there is a delay of over 2 years in data availability. The applicability of the analysis depends on the assumption that today's accident trends resemble those of 1983 to 1986. The general consistency in the causes of aviation accidents suggests that the overall pattern seen from 1983 to 1986 will match that of today.

The analysis only includes 4 years of data, simply because of the large number of accident reports. Over 2,000 general aviation accidents occurred each year. The time-consuming process of reading and categorizing the NTSB data limited the number of years included in the analysis. In addition, changes in the data format for previous years would make comparing years difficult.

The initial factor contributing to the accident was identified for each general aviation accident that occurred from 1983 through 1986. The accident was placed in one of seven categories, each of which is divided into subcategories to gather additional insight on the causes of general aviation accidents. The categories and subcategories are as follows:

1. Pilot Error
   a. Flying Skills
   b. In-Flight Procedures/Judgment
   c. Preflight Procedures/Judgment
   d. Fuel Management
   e. Student Pilot
   f. Home-Built Aircraft
   g. Alcohol/Drug Use
2. Equipment Failure
   a. Engine
   b. Instruments/Electrical
   c. Landing Gear/Tires
   d. Structure
   e. Home-Built
   f. Other
3. Environment
   a. Weather
   b. Wind Gusts
   c. Wind on Landing/Takeoff
   d. Improper Briefing
   e. Animals
4. Air Traffic
   a. En Route
   b. Terminal
   c. Ground
5. Ground Crew Error
6. Other Aircraft
   a. Midair Collision
   b. On-Ground Collision
   c. Evasive Action
7. Other
   a. Aircraft Not Recovered
   b. Apparent Drug Transport
   c. Cause Ambiguous

Before the data are reviewed, the guidelines for the categories and the subcategories will be discussed.

Pilot Error

As mentioned earlier, the leading factor contributing to general aviation accidents is pilot error. The seven subcategories

chosen for Pilot Error differentiate among accidents caused by poor judgment, accidents caused by inadequate flying skills, and accidents involving specific circumstances. The subcategories Preflight Procedures/Judgment and In-Flight Procedures/Judgment encompass accidents in which the pilot failed to execute sound judgment or follow expected procedures. Accidents placed in the Flying Skills subcategory are a result of poor flying ability. Separate subcategories for accidents involving alcohol or drug use, student pilots, and home-built aircraft are also included. The distinctions among the Pilot Error subcategories are more subtle than those of the other subcategories and therefore, to ensure clarity, will be discussed in greater detail along with the research results.

Equipment Failure

The Equipment Failure category includes all accidents in which the failure of the aircraft's equipment triggered the accident. Equipment failure was the second leading cause of general aviation accidents between 1983 and 1986, accounting for 18.5 percent of all accidents. To distinguish among the types of equipment failure accidents, the category contains six subcategories: Engine, Instruments/Electrical, Landing Gear/Tires, Structure, Home-Built, and Other.

The Engine subcategory includes accidents that occurred because of the failure of the internal engine parts, the carburetors, the magnetos, the exhaust system, the propellers, or fuel contaminates other than those detectable during the preflight check, for example, water. This subcategory also includes situations in which a pilot or witness claimed that engine failure initiated the accident and the postaccident investigation failed to determine another likely cause. In this situation, however, if the engine operated without difficulty during the postcrash investigation, the accident was categorized under Cause Ambiguous.

The Instruments/Electrical subcategory includes accidents that resulted from malfunctions in the aircraft's instruments or any electrical failure other than a magneto failure. An inaccurate fuel gauge, however, is not considered an instrument or electrical failure. Because of the inherent inaccuracy of fuel gauges, instructors urge pilots to mistrust fuel gauge readings. Instructors request that pilots calculate fuel consumption rates before and during flight. Thus, running out of fuel becomes a Pilot Error accident.

The subcategory of Landing Gear/Tires includes accidents in which the structural or mechanical failure of the landing equipment led to the accident. For instance, in Oklahoma in 1986 an aircraft flipped over during the landing roll after the left brake locked. The accident is classified under Landing Gear/Tires because postaccident investigation revealed that the brake shoe return spring failed.

The Structure subcategory includes failure of wings, flight control surfaces, or other structural components of the aircraft. The Home-Built subcategory contains all home-built aircraft accidents in which equipment failure initiated the accident. A separate subcategory exists for home-built aircraft because they are often considered experimental. Experimental aircraft are subject to airworthiness regulations, which differ from those observed by other aircraft when operating under 14 CFR 91. The Other subcategory includes all accidents resulting from faulty equipment that was excluded from previous subcategories, for example, seats.

Environment

Environmental factors were the third leading cause of general aviation accidents, containing 8 percent of all accidents that occurred between 1983 and 1986. The five Environment subcategories are Weather, Wind Gusts, Wind on Landing/Takeoff, Improper Briefing, and Animals.

The Weather subcategory covers accidents resulting from adverse meteorological conditions, such as in-flight thunderstorm turbulence and icing, and slippery runways. However, if a pilot failed to obtain a weather briefing before the flight and an accident resulted because of adverse weather, the accident falls under Pilot Error—Preflight Procedures/Judgment, not Weather.

Wind-gust accidents result from strong winds during taxiing, landing roll, or takeoff roll. An example of a wind-gust accident occurred in October 1984 in Oklahoma. As the pilot taxied from the active runway, the aircraft overturned because of strong, gusting winds. The subcategory Wind on Landing/Takeoff includes accidents caused by strong winds just before runway contact or immediately after take-off.

Weather-related accidents in which pilots obtained an incorrect weather briefing are categorized under improper briefing. The Animal subcategory includes accidents caused by striking an animal in-flight or while on the ground. Accidents resulting from evasive action taken to avoid animals also qualify for this category. For example, in December 1984, in an attempt to avoid four deer running across the runway, a Texas pilot landed his aircraft to the left of the runway, causing the landing gear to collapse.

Air Traffic Control

Any accident resulting from air traffic controller mismanagement is included under the ATC category. The three subcategories for ATC accidents are En Route, Terminal, and Ground. The accident falls under the Ground subcategory if the aircraft was misguided by a controller operating from the airport tower. Terminal accidents occur if the controller was located in the terminal radar approach control facility, which means that the controller was responsible for airborne aircraft immediately surrounding the airport. The En Route subcategory involves accidents precipitated by a controller at an air route traffic control center while the aircraft was en route.

Ground Crew Error

Situations in which actions of individuals on the ground lead to accidents fall under the Ground Crew Error category. For instance, if a maintenance vehicle hit the wing of an aircraft, causing damage, it would be a Ground Crew Error accident.

Other Aircraft

Midair collisions and on-ground collisions are included in this category. A midair collision occurs when two planes collide

while one or both of the planes are airborne. For instance, in Indiana in October 1985, a pilot landed his Cessna 150 on top of a Cessna 152. Although the Cessna 152 was taxiing on the ground, a midair collision occurred because the Cessna 150 was airborne. An on-ground accident occurs when neither aircraft is airborne. The third subcategory, Evasive Action, is used when damage to an aircraft occurs as a result of attempting to avoid a midair or on-ground collision.

Other

The Other category includes miscellaneous accident subcategories such as Aircraft Not Recovered and Apparent Drug Transport. The subcategory of Cause Ambiguous covers the largest number of accidents in the Other category. An example of a Cause Ambiguous accident occurred in 1983: the pilot could not recall the events leading to the accident, there were no witnesses, and the aircraft was destroyed.

CAUSES OF GENERAL AVIATION ACCIDENTS

General aviation accidents are concentrated in the categories of Pilot Error and Equipment Failure: 83 percent of all U.S. general aviation accidents that occurred between 1983 and 1986 were due to these factors. The categories Environment, ATC, Ground Crew Error, Other Aircraft, and Other were responsible for 17 percent of the general aviation accidents and for 25 percent of the fatalities.

Pilot Error

Pilot error was cited as the cause of 5,542 general aviation accidents from 1983 to 1986. The seven subcategories of pilot error were listed earlier.

The data in Table 3 illustrate that accidents in the Flying Skills subcategory occurred most frequently, followed by accidents in the In-Flight Procedures/Judgment and Preflight Procedures/Judgment subcategories. Because pilot error causes 64 percent of all general aviation accidents, each subcategory of Pilot Error will be addressed.

The Flying Skills subcategory includes accidents in which the pilot was unable to maintain control of the aircraft. Stalling the aircraft, landing hard or long, and taxiing into stationary objects fall in this accident category. The Flying Skills category attempts to isolate accidents in which the pilot's ability to fly the aircraft was insufficient. Over the 4-year period, 1,750 accidents of this type occurred; however, only 11 percent of those accidents were fatal.

TABLE 3 FREQUENCY OF PILOT ERROR ACCIDENTS: 1983–1986

Accident Subcategory	Percentage by Severity		
	Fatal	Nonfatal	Total
Flying Skills	11.4	22.4	20.3
In-flight Procedures/Judgment	17.7	10.5	11.9
Preflight Procedures/Judgment	19.9	9.9	11.8
Fuel Management	2.7	8.6	7.4
Student Pilot	3.4	11	9.5
Home-built Aircraft	2.7	1.4	1.7
Alcohol/Drug Use	6.2	0.5	1.6
Total	64	64.3	64.2

The large number of accidents due to insufficient flying skills may suggest a need for additional initial and recurrent pilot training. In June 1985, the Federal Aviation Administrator expressed his concern regarding the large number of pilot-induced accidents. To emphasize the importance of fundamental flight skills, the administrator initiated a 3-year program in January 1986—Back-to-Basics.

The first priority of the Back-to-Basics program was take-offs and landings. Between January and March 1986, FAA and independent aviation organizations sponsored local seminars and clinics on improving pilot take-off and landing skills. FAA does not know the number of pilots who participated in the first quarter of 1986; however, during the 3-year life of the program, over one million pilots attended Back-to-Basics seminars.

Improving a pilot's ability to negotiate take-offs and landings focuses on those skills involved in the Flying Skills accident category. If the seminars produced safety improvements, a decrease in the number of accidents caused by insufficient flying skills might have resulted. Typically, all general aviation accidents increase during the summer. The number of accidents in the Flying Skills subcategory in 1986 did not vary from this typical pattern.

Although the data do not show a reduction in the number of such accidents, the Back-to-Basics program on take-offs and landings was not necessarily unsuccessful. To measure its success accurately, the accident record of individuals participating in the program would have to be reviewed. Perhaps the program successfully reached a limited number of pilots, which was not revealed by the aggregate accident data. The data may also indicate that those who most need accident prevention training do not participate in voluntary programs. Perhaps the Back-to-Basics program should have been mandatory or targeted at pilots who needed recurrent training to decrease the overall number of accidents in the Flying Skills subcategory. Without detailed data on the participants, however, these questions cannot be answered.

In-Flight Procedures/Judgment and Preflight Procedures/Judgment are the next two leading Pilot Error subcategories. The In-Flight Procedures/Judgment subcategory includes accidents resulting from mental errors that led to incorrect procedures or judgment errors that caused the aircraft to be in unnecessarily hazardous situations. Mental errors include failing to complete the landing checklist, unintentional gear-up landing, improper flap settings for flight or landing, and failure to maintain proper fuel mixture. Judgment errors include recreational flying at low altitudes (buzzing, spotting animals, hitting power lines) and choosing to land in uncertain terrain (roads, pastures, and the like) during nonemergency situations.

Preflight Procedures/Judgment errors include failing to perform expected preflight duties and failing to use appropriate judgment before the flight. Preflight errors include failure to obtain a weather briefing, failure to complete the preflight checklist, and failure to detect water in the fuel tank.

As shown in Table 3, these two subcategories account for 37.6 percent of the fatal accidents caused by pilot error. The fact that the Preflight Procedures/Judgment subcategory con-

tains the largest percentage of fatal pilot error accidents is surprising. Logically, accidents in this subcategory should be the easiest to avoid because the initial accident factor occurs before departure. A tragic example of such an accident occurred in 1984 when the pilot took off with approximately 170 lb over the maximum allowable gross weight and five passengers on board. The pilot flew into known moderate icing conditions in an aircraft unequipped to operate under such conditions. Shortly after take-off, the plane was sighted falling out of an overcast sky with a failed wing. All six occupants died.

As with the Preflight Procedures/Judgment subcategory, accidents in the Fuel Management subcategory should be avoidable. However, over the 4-year period, 640 general aviation aircraft were involved in accidents stemming from lack of fuel. In many cases fuel was available on the aircraft, but the pilot failed to switch fuel tanks. For instance, in 1985 an aircraft was substantially damaged after the pilot made a forced landing because of a complete loss of power. The investigators found the fuel selector positioned on the right tank, which was empty. The left tank contained 20 gal of fuel.

Although an apparent solution to avoid some accidents due to lack of fuel would be an aircraft designed with one fuel tank, low-wing aircraft do not lend themselves to a balanced single-tank fuel system (*7*). It appears that pilots must know the fuel consumption rate of their aircraft, be aware of the preflight fuel quantity in each tank, and be attentive to the timing of fuel-tank switching. These factors should be stressed during training.

The Alcohol/Drug subcategory includes all accidents in which the pilot was under the influence of alcohol or drugs. This subcategory included less than 1 percent of all nonfatal accidents and 16 percent of all fatal accidents over the 4 years. According to the data, an accident involving a pilot who is under the influence of alcohol or drugs will most probably be fatal. However, it may also be that the number of nonfatal alcohol- or drug-related accidents is under-reported. Because investigations may not occur immediately following an accident, pilots may successfully conceal the involvement of alcohol or drugs. The data may therefore underestimate the number of such accidents that are not fatal.

The remaining two subcategories under pilot error are Student Pilot and Home-Built, isolating accidents in which student pilots or home-built aircraft were involved. Over the 4-year period, both subcategories fluctuated and showed no definite increasing or decreasing trend.

Equipment Failure

Equipment failure accounts for 11.6 percent of the fatal accidents and 20.4 percent of the nonfatal accidents that occurred between 1983 and 1986. As shown in Table 4, the accident rates per 100,000 hr for equipment failure during the 4 years fluctuate. All of the subcategories in Equipment Failure follow the same trend, decreasing from 1983 to 1984, increasing in 1985, and decreasing slightly in 1986.

Equipment failures also increase in the summer and decrease in the winter (see Figure 1). This trend is probably due to an increase in flight hours during the summer. However, this is only a speculation, because hours flown are reported annually, not monthly.

As shown in Figure 1, the number of accidents due to equipment failures usually increases significantly during July

TABLE 4 EQUIPMENT FAILURE ACCIDENTS

	Rate per 100,000 Flight Hours				
All Accidents	1983 ($N=409$)	1984 ($N=348$)	1985 ($N=471$)	1986 ($N=371$)	Total ($N=1,599$)
Fatal	0.23	0.14	0.23	0.21	0.20
Nonfatal	1.50	1.29	1.74	1.33	1.47
Total	1.73	1.43	1.97	1.54	1.67

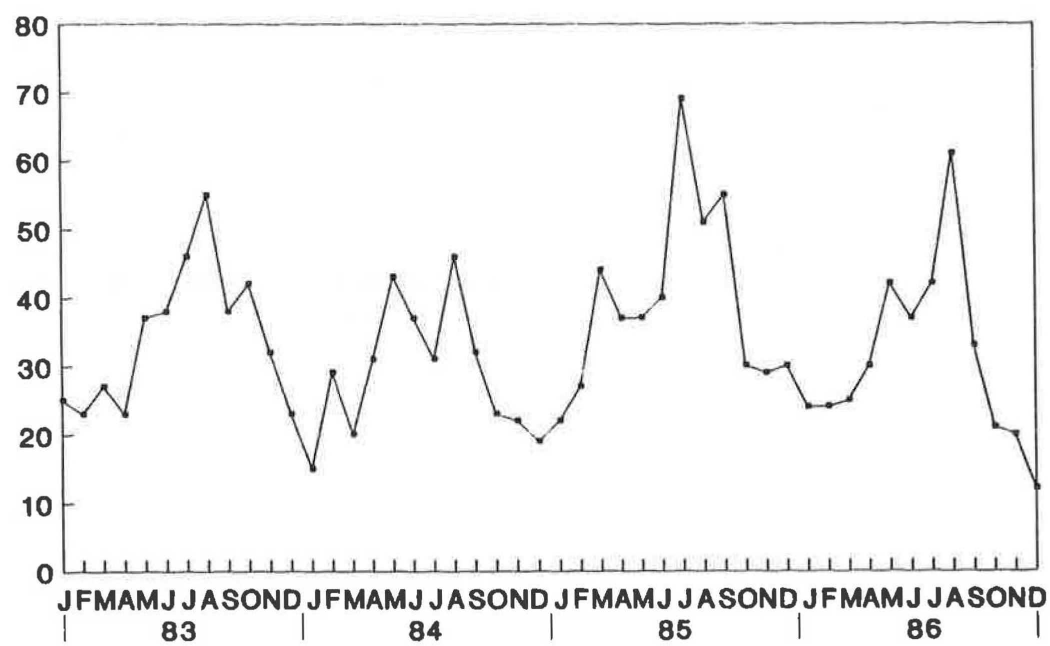


FIGURE 1 Number of equipment failures by month.

and August. However, the number of such accidents in the summer of 1984 is conspicuously low. The accident rate per 100,000 flight hours for equipment failure is also the lowest in 1984, at 1.4. There is no definitive explanation for this decrease; however, it did coincide with an FAA-initiated program, the General Aviation Safety Audit (GASA).

On June 20, 1984, the U.S. Secretary of Transportation requested that the FAA conduct an audit with the goal of (5) "promot(ing) continued safety in the operation and maintenance of aircraft used in the general aviation and commercial environment." GASA included inspections of repair facilities and mechanics with inspection authorization. During the 12-month audit, FAA inspected over 85 percent of the non-certificated maintenance facilities that service single- and multiengine aircraft.

A decreasing trend in accidents due to equipment failure began as early as January 1984, which suggests that the publicity surrounding the initiation of the audit may have caused mechanics and maintenance facilities to operate more cautiously. Detailed information on the aircraft affected by GASA is not available, and thus, proving a causal relationship between GASA and the decline in accidents is impossible. The accident trend, however, is encouraging and suggests that the FAA program possibly improved aviation safety.

If a connection could be established between the timing of GASA and the decreasing number of equipment failure accidents, it might indicate that FAA's announcement of a concern regarding a safety issue, in this case general aviation maintenance facilities, is effective in improving the safety record. If GASA actually caused the reduction of equipment failure accidents in 1984, the program apparently did not provide permanent improvements. The largest number of equipment failure accidents in any single month during the 4-year period occurred 1 year after the initiation of the program.

The short-lived reduction in equipment failure accidents suggests that FAA's maintenance inspections are effective only shortly before and during the inspections, and have little long-term consequence. The lack of detailed data on the aircraft affected by GASA, however, decreases the reliability of this conclusion. If FAA adopts another program to improve general aviation maintenance, the agency should make an effort to collect and examine accident data before, during, and after program implementation. Without detailed data on aircraft that are and are not involved, FAA cannot evaluate the success of the safety program.

Environment

If a decrease occurred in the number of Environment accidents, it might suggest an improvement in weather forecasts or an improvement in pilot judgment. The 4 years of accident rates per 100,000 hr in Table 5, however, show no trends.

TABLE 5 ENVIRONMENT ACCIDENTS

	Rate per 100,000 Flight Hours				
Accident Subcategory	1983	1984	1985	1986	Total
Weather	0.24	0.18	0.20	0.23	0.21
Wind Gusts	0.12	0.15	0.21	0.19	0.17
Wind on Landing/Takeoff	0.36	0.27	0.33	0.17	0.28
Improper Briefing	0.01	0.00	0.01	0.01	0.01
Animals	0.05	0.05	0.09	0.06	0.06
Total	0.77	0.65	0.84	0.67	0.73

Air Traffic Control and Other Aircraft

ATC induced only 13 general aviation accidents during the 4-year period (see Table 6). Few ATC-induced accidents are expected, because most general aviation flights are conducted under Visual Flight Rules (VFR) and operate from airports that do not depend on air traffic controllers to manage traffic.

TABLE 6 NUMBER OF AIR TRAFFIC CONTROL ACCIDENTS

Accident Subcategory	1983	1984	1985	1986	Total
En route	1	1	0	1	3
Terminal	1	1	0	2	4
Ground	1	1	2	2	6
Total	3	3	2	5	13

VFR flights depend on the "see and avoid" concept, which means that the responsibility for aircraft separation falls on the pilot. However, the "see and avoid" concept occasionally fails. During the 4-year period, 218 general aviation aircraft were involved in accidents caused by the inability to "see and avoid." The data in Table 7 show a relatively constant number of total aircraft involved in accidents with other aircraft over the 4-year period. However, the number of aircraft involved in midair collisions appears to be rising.

Between 1983 and 1986, 148 general aviation aircraft were involved in midair collisions, with 101 fatalities. The accident rate per 100,000 flight hours rose from 0.093 in 1983 to 0.195 in 1986. The majority of general aviation midair collisions occurred while in the landing or take-off phase, during the day, and under clear (or VFR) meteorological conditions. Fifty-one percent of general aviation midair collisions occurred during take-off or landing, and 29 percent occurred en route. The remaining 19.5 percent occurred while the aircraft were either preparing to land or had recently left the airport and were no closer than ½ mi from the airport. Only two midair collisions involved a general aviation and a commercial aircraft.

The location of midair collisions in the United States seems to vary from year to year, with the exception of one state. Over the 4-year period, 21 midair collisions occurred in California. As shown in Table 8, the rate of aircraft involved in midair collisions per 100,000 flight hours in California is substantially higher than the average rate for the United States. The majority of the midair collisions in California occurred near Los Angeles or San Francisco, where the airspace is highly congested.

TABLE 7 NUMBER OF OTHER AIRCRAFT ACCIDENTS

Accident Subcategory	1983	1984	1985	1986	Total
Midair Collision	22	36	43	47	148
On-Ground Collision	26	14	10	6	56
Evasive Action	5	4	5	0	14
Total	53	54	58	53	218

TABLE 8 MIDAIR COLLISION ACCIDENTS

State or Region	Rate per 100,000 Flight Hours 1983	1984	1985	1986	Total
California	0.164	0.273	0.333	0.304	0.268
Eastern Region	0.116	0	0.033	0.227	0.098
New England Region	0	0.351	0	0.254	0.164
Total	0.093	0.148	0.180	0.195	0.154

Table 8 gives the midair collision rates per 100,000 flight hours for the Eastern Region (Virginia, West Virginia, Maryland, Delaware, New Jersey, Pennsylvania, and New York) and the New England Region (Rhode Island, Connecticut, Massachusetts, Vermont, New Hampshire, and Maine). Although East Coast airspace is also congested, the accident rates in these two regions are not consistently above the national average.

Alaska General Aviation Accidents

As mentioned previously, the Alaskan general aviation accident record was separated from those of the remaining 49 states because of the hypothesis that the severe weather conditions and terrain would create different accident trends. In addition, Alaska is unique because aviation may often be the only transportation option.

Predictably, Alaskan general aviation suffers a high occurrence of accidents and a high distribution of fatal and weather-related accidents. Alaskan general aviation accidents occurred at an average rate of 16.5 per 100,000 flight hours between 1983 and 1986, whereas the rate for the remaining 49 states was only 9.0. Fatal accidents make up a small percentage of the total accidents—only 12 percent compared with 19.5 percent in the remaining 49 states.

Weather-related accidents occurred more frequently in Alaska than in the remaining 49 states, accounting for 5.5 percent of all accidents, compared with 2.4 percent in the remaining 49 states. The subcategory Wind on Landing/Takeoff included a larger percentage of Alaskan accidents (6.8), whereas remaining 49 states accounted for 3.1 percent of the total accidents in this subcategory.

Although the Environment category accounts for 14 percent of the Alaskan accidents, Pilot Error is the most common category of accidents in both Alaska and the remaining 49 states (see Table 9). The percentage of Pilot Error accidents in Alaska and that in the remaining 49 states are similar; however, the distribution of Pilot Error accidents is slightly different. Preflight Procedures/Judgment accounts for 19.9 percent of the fatal accidents in the remaining 49 states, but only 8.1 percent in Alaska. Alcohol/Drugs accounts for 16.2 percent of the fatal accidents in Alaska, but only 6.2 percent in the remaining 49 states.

Although the environment in which general aviation operates in Alaska differs from that in the remaining 49 states, the most common cause of accidents—pilot error—is shared. As suggested in the discussion of pilot error, additional pilot training might be warranted. The most common subcategory under Pilot Error in Alaska and the remaining 49 states is Flying Skills. Again, this suggests that the effectiveness of initial and recurrent training in the physical control of the aircraft might be evaluated.

TABLE 9 FREQUENCY OF ALL ACCIDENTS: ALASKA VERSUS REMAINING U.S. STATES

Accident Category	Alaska (%)	United States (%)
Pilot Error	66.2	64.2
Equipment Failure	9.5	18.5
Environment	14.2	8.1
ATC	0.5	0.2
Ground Crew Error	0	0.4
Other Aircraft	2.4	2.5
Other	7.1	6

COMPARING AVIATION SECTORS

Accident rates for U.S. air carrier operations are lower than those for general aviation. During 1983, aircraft operating under 14 CFR 121, 125, and 127, which include large commercial air carriers and helicopters used as scheduled air carriers, had an accident rate of 0.06 per 100,000 flight hours (*6*). In contrast, general aviation's accident rate per 100,000 flight hours was 10.64. The fact that general aviation includes new pilots with limited experience might explain the difference in accident rates. An individual can get a private pilot's license to fly a general aviation aircraft after a total of 40 hr of flight time (Federal Aviation Regulation 61.109). In contrast, jet carrier airline pilots hold Air Transport Pilot licenses, which require a minimum of 1,500 hr of flight time (Federal Aviation Regulation 61.155).

Because of the variety of pilot experience between aviation sectors, a higher percentage of accidents caused by pilot error in general aviation would be expected. As shown in Table 10, which includes data from the Aviation Safety Commission report, this speculation is correct (*4*). The research in the Aviation Safety Commission report includes all the NTSB accident briefs for jet carriers and commuters. All accidents were categorized by the initial contributing factor that led to the accident. The categories of Pilot Error and Equipment Failure used by the Aviation Safety Commission are identical to those defined in this general aviation research. Note, however, that the Aviation Safety Commission report provides the average distribution of accidents by cause for 1979 through 1985.

Table 10 reveals that pilot error is the leading cause of general aviation accidents at 64 percent, but accounts for only

TABLE 10 FREQUENCY OF SELECTED ACCIDENTS BY AVIATION SECTOR

Accident Category	Percentage by Sector: General Aviation[a]	Scheduled Jet Carriers[b]	Scheduled Commuters[c]
Pilot Error	64.2	9	27
Equipment Failure	18.5	19	39
Seat Belts	0	28	1

[a]CFR Part 91, 1983–1986.
[b]CFR Part 121, 1979–1985 (*4*)
[c]CFR Part 135, 1979–1985 (*4*)

9 percent of jet carrier accidents. Pilot error accidents for scheduled commuter flights, in contrast, account for 28 percent of the total number of accidents. Failure of passengers to wear seat belts is the most frequent cause of jet carrier accidents. Because an aviation accident includes events ending in serious personal injury, not wearing a seat belt after the pilot has requested that the passengers return to their seats and fasten their safety belts may result in personal injury and be reported to NTSB as an accident.

The different distributions of accident causes for the aviation sectors may also be a function of the types of flights conducted. General aviation flights are typically much shorter than the average jet carrier flight. Shorter flights mean additional takeoffs and landings. Because many pilot error accidents occur during these flight phases, a higher accident rate per 100,000 flight hours for general aviation pilot error accidents might be expected.

RECOMMENDATIONS

Identifying the causes of general aviation accidents is not equivalent to identifying where FAA should concentrate safety programs. The primary causes of general aviation accidents may suggest logical areas for safety improvements, but the information on the FAA aviation safety programs is inadequate to evaluate the success of current or past programs. The recommendations, therefore, include suggestions that FAA carefully evaluate current safety programs and consider focusing additional safety efforts in areas where accidents have frequently occurred in the past.

The safety programs Back-to-Basics and GASA are examples of efforts in which program evaluation could have enlightened the agency on the effectiveness of their safety programs. The Back-to-Basics program included training in pilot decision making. Research published before the program suggested that pilot judgment training improved pilots' decision-making efforts (*7*). Nevertheless, FAA failed to collect detailed information on the program participants, which would have allowed an evaluation of the training program's effectiveness.

The accident data suggest that the GASA program briefly reduced accidents due to equipment failure. Although this is inconclusive, the findings suggest that FAA's maintenance audits enhanced safety. Again, the findings were inconclusive because of the lack of information on the participants. In the case of Back-to-Basics and GASA, if FAA had recorded who participated in the program and surveyed their accident records before and after participation, the effects of the program could have been evaluated. Without program evaluation, an agency cannot determine whether a program should continue to receive support.

FAA should begin evaluation of those programs that target the leading causes of accidents—particularly fatal accidents. The four subcategories containing the largest percent of fatal accidents are Preflight Procedures/Judgment, with 19.9 percent; In-Flight Procedures/Judgment, with 17.7 percent; Cause Ambiguous, with 11.6 percent; and Flying Skills, with 11.4 percent. Nonfatal accidents are also concentrated in these categories.

FAA should also use the leading causes of general aviation accidents identified in this study to design effective safety programs. Designing appropriate safety programs in the future, however, depends on FAA's ability to identify factors most frequently contributing to accidents. To achieve this, FAA and NTSB should coordinate efforts to improve access to NTSB data. The published NTSB data are not always aggregated and presented in a helpful way to shape policies and programs.

FAA has recently formed a new general aviation office, one of the goals of which is to focus on safety. This office should consider working with NTSB to access the general aviation accident data base and use the information to improve safety. An annual assessment of the initial factors contributing to general aviation accidents would help FAA design the most beneficial safety programs.

ACKNOWLEDGMENTS

The author would like to thank TRB and FAA for their support; Clinton V. Oster, Jr., for his invaluable help and guidance; and Vicki L. Golich, Dennis W. Mewshaw, and C. Kurt Zorn for their constructive criticism.

REFERENCES

1. *General Aviation Activity and Avionics Survey: Annual Summary Report 1986 Data*. Report FAA-MS-87-5, DOT-TSC-FAA-87-5. FAA, U.S. Department of Transportation, Dec. 1987.
2. *Annual Review of Aircraft Accident Data: U.S. General Aviation*. Bureau of Safety Programs, National Transportation Safety Board, Washington, D.C., 1978–1985.
3. *Statistical Handbook of Aviation, Calendar Year 1985*. FAA, U.S. Department of Transportation, 1986.
4. *Aviation Safety Commission, Volume II: Staff Background Papers*. Aviation Safety Commission, Washington, D.C., April 1988.
5. *General Aviation Safety Audit*. FAA, U.S. Department of Transportation, April 1986.
6. *Annual Review of Aircraft Accident Data: U.S. Air Carrier Operations*. NTSB, Bureau of Safety Programs, Washington, D.C., 1985.
7. G. Bush and A. Diehl. An Investigation of the Effectiveness of Pilot Judgment Training, *Human Factors*, Vol. 26, No. 5, 1984, p. 557.
8. *General Aviation Activity and Avionics Survey: Annual Summary Report 1985 Data*. Report FAA-MS-86-5 DOT-TSC-FAA-87-2. FAA, U.S. Department of Transportation, Jan. 1987.

Opinions expressed in this paper are the author's and should not be interpreted to reflect the position of the U.S. Department of Transportation.

Cockpit-Crew Crisis Decision Making

MAUREEN A. PETTITT

The purpose of the present research was to examine pilots' perceptions of crisis and their attitudes toward the decision-making processes used in crises. A scenario and a 19-item questionnaire were used to determine the perception of crisis, the sense of urgency in the situation, and the rigidity of response. The pilots' ratings of the situation as a crisis were positively correlated with their ratings of the characteristics usually attributed to crises. Overall, perception of the situation as a crisis was high, but response rigidity was low. However, pilots who had a high sense of urgency also tended to have higher response rigidity scores. This group differed significantly from pilots who exhibited a low-urgency–low-rigidity pattern. Rigidity scores also differed significantly between the high-urgency–low-urgency groups when crisis perception was high. Lower urgency scores always yielded lower response rigidity scores. The study suggested that a potentially optimal decision pattern in crisis, one more situationally responsive, may be high crisis perception, low sense of urgency, and low response rigidity. Pilots who had formal Cockpit Resources Management training and pilots of two-crew-member aircraft both exhibited this pattern.

The aviation community has long realized that the effective performance of cockpit crews is essential to aviation system safety. Research in the area of flight crew performance conducted in the United States dates back to World War I (*1*). Early experiments—and the bulk of the research conducted during the following six decades—focused primarily on skills acquisition and retention, perceptual requirements, and physical stress. Much less attention was given to the psychosocial aspects of the cockpit environment. Air transport accident analyses and related research during the past decade have, however, produced convincing evidence that pilot training and evaluation systems must address the crucial dimension of crew interaction and decision making in the cockpit (*2–5*).

In response to these findings, several airlines have initiated training programs to encourage effective Cockpit Resources Management (CRM). The history of CRM as a concept and as a training program is well documented in the proceedings of two workshops sponsored by NASA-Ames Research Center in 1979 (*6*) and 1986 (*7*). The proceedings provide general guidelines for program content and instructional strategies. Although CRM programs vary, they are essentially designed to educate pilots about the importance to safe flight operations of interpersonal relations, communication skills, synergistic activity, and participatory decision making.

Subsequent evaluative research has supported the notion that CRM training can improve cockpit performance and suggests that performance-related attitudes are significant predictors of crew coordination in line operations (*8*). However, this research also indicates that crew members lack awareness of the deleterious effects of stress and have unrealistic attitudes about their personal vulnerability to stress (*9*). Some researchers caution that during a crisis the crew is likely to revert to prior well-learned behavior rather than the concepts espoused by CRM (*10*).

Claremont Graduate School, 1615 S. Grand Avenue, Glendora, Calif. 91740.

Despite the increased attention to crew interaction, coordination, and decision making, it is clear that further research is requisite to improve present pilot training programs. This viewpoint was emphasized in a recent report by the congressional Office of Technology Assessment (*11*). The authors concluded that long-term improvements in aviation safety will come primarily from human factors solutions, particularly those that encourage the development of explicit training procedures for upgrading crew coordination and decision making.

In the broadest sense, the purpose of the present research was to examine pilots' attitudes toward cockpit crises and the processes and procedures used in making decisions in crises. The study also provided baseline data on specific concepts associated with cockpit crew performance and crisis decision making that can be utilized in future development and modification of pilot training programs. In addition, the findings may be applied to other small, task-oriented groups faced with crisis decision making, especially groups operating in a complex, technical environment.

LITERATURE REVIEW

Implicit in an event labeled as crisis are real or perceived levels of threat, uncertainty, tension, information inadequacy, and time pressure or urgency (*12–16*). The literature regarding group-level processes suggests that strategies utilized or developed to resolve crises can be affected by a multiplicity of variables: the nature of the threat (*16*), psychological and physiological conditions within the individual (*17*), task/role structure and demands (*18*), and interpersonal relationships and interaction (*19*). These group-level effects will be discussed in more detail following a brief discussion of decision-making theory.

Decision-Making Theory

Following decades of research into the decision-making process, theorists have been able to describe a semistructured framework for making decisions. They speculate that the decision maker partially or completely proceeds through several steps before reaching a decisional choice (*20–22*). These steps include problem definition or diagnosis, generation of alternative courses of action, evaluation of alternatives, and implementation of the chosen alternative.

Beyond this general framework for decision making, the literature also provides some insight into decision making in

situations characterized by stress, conflict, and uncertainty. Janis and Mann (*22*) have described the successful decision maker under such circumstances as being discriminating in the search for and evaluation of information, thorough in the search for and appraisal of alternatives, confident that a better solution can be found in the time available, and disposed toward contingency planning.

Less successful decision strategies are characterized by (a) a tendency to use a small number of rules of thumb, or heuristics, in making decisions; (b) failure to consider all the possible decision and outcome options; (c) inconsistency in dealing with risks; and (d) inappropriate levels of confidence in one's own decision. It has also been asserted that experts are as likely to make decisions on impulse as on careful analysis (*23*).

Group-Level Process Effects

The theory and research relevant to group-level processes in crisis conditions suggest that the decisional process may be affected by several highly interrelated factors, including leadership, control structures, information search and exchange patterns, and the search for and evaluation of alternative solutions.

The role of the leader in a crisis situation is the subject of competing viewpoints. One proposition is that the group looks to the leader to supply the structure (or anchor) lacking in a crisis and to provide the expertness for coping with the demands of the situation (*24*). Alternatively, it has been hypothesized that experience and judgment may be less useful because of the unique, nonroutine nature of crisis (*15*) and that the motivation to resolve the crisis quickly reduces the importance of traditional roles (*25*).

Further, there appears to be little consensus as to which leader orientation—task or relational—is more effective in crises. One study suggests that effective leaders have a high task orientation, several power bases, and an autocratic decision style (*26*). Other writers have argued that the effective leader shifts from an initially relational orientation to a task orientation as the crisis proceeds toward resolution (*19*).

The disposition of authority and communication structures in crises is no clearer than that of leadership. Researchers have observed that standard operating procedures may be suspended or ignored (*27*) and task assignments reallocated (*15*). Although these tendencies would suggest a loosening of the structure, other writers have reported that the outcome is more likely to be the centralization of authority and communication (*16,28*). There is agreement, however, that centralization of authority and communication commonly leads to role or information overload (*14*), accompanied by the loss or distortion of information (*29*).

The criticality of information exchange to successful crisis resolution was recognized in early research by Torrance (*24*), and the continued search for information is an antecedent condition for successful decision making in the model developed by Janis and Mann (*22*). However, decision makers have been observed to handle information in a less-than-optimal manner in crises—to restrict information, to be indiscriminately open to all information, and to disregard or ignore information that does not support the preferred alternative (*16,22*).

The literature also suggests that fewer alternatives are likely to be considered in a crisis (*14,15*). Such a situation may result from an incomplete search pattern (*16,22*), the centralization of authority or communications, or both (*12,16,28*), the overreliance on previous experience (*14*) or heuristics (*23*), strong leadership (*24*), or the belief that there is not enough time to engage in the search for or evaluation of alternatives (*22*).

COCKPIT ENVIRONMENT

Aircraft operation is primarily a technical task that consists of multiple subtasks. In airline operations these tasks can be quite complex, requiring high levels of information processing, response rates, and subtask coordination. However, a majority of tasks are programmable and can be routinized, as shown by the increasing automation of cockpit functions. Although the effects of automation on crew behavior and system safety are not yet known, preliminary research suggests that cockpit automation may relocate, not eliminate, human error (*30*).

The cockpit "culture" is determined by rather formalized task and role structures, which are in turn legitimated, and often prescribed, by organizational policies and federal regulations. These structures are further reinforced through training, experience, and group norms. Flight crew performance evaluation and norms have traditionally emphasized individualism, mastery of technical skills, and an attitude that loosely translates as "the captain is always right."

Although crises in the cockpit occur in a complex environment, the standardized training procedures, formalized roles, and routinized tasks characteristic of air transport operations would, at first glance, seemingly contribute to successful crisis resolution. However, the history of commercial airlines is marred with numerous accounts of mismanaged crises. Those who support CRM programs hope to improve the accident record by addressing the issues of crew coordination and decision making (*2,7*).

RESEARCH DESCRIPTION AND METHODOLOGY

Research Objectives

The purpose of the study was to examine pilots' perceptions of cockpit crisis and their attitudes toward decision making in such situations. The hypotheses and variables of interest were derived from the literature and from the results of a preliminary study conducted to explore crisis decision making in air transport operations.

The first hypothesis states that the higher the perception of crisis, the higher the ratings of the crisis characteristics. That is, a positive linear relationship is expected between the pilots' ratings of the scenario as a crisis and their ratings of the characteristics of crises—threat, limited availability of decision-relevant information, uncertainty, and tension—specific to the scenario.

It was also anticipated that the combined effects of pilot training, the hierarchical structure of the cockpit, and the very

nature of crisis itself would promote mechanistic, relatively rigid responses to crises. Thus, the second hypothesis states that the higher the rating of the situation as a crisis, the higher the level of response rigidity. For the purposes of the present research, response rigidity includes decision process rigidity (reluctance to engage in participatory decision making), role rigidity (role differentiation, centralization of authority, and reliance on the captain's authority and capabilities), and procedural rigidity (adherence to flight manual operating procedures and company policy).

Following preliminary analysis of the data, a third concept related to the crisis-rigidity hypothesis developed. The decision maker's belief that there is time to search for and evaluate alternatives has been posited as an antecedent condition for optimal decision making in crises (*22*). A high sense of urgency, on the other hand, evokes the dysfunctional coping pattern referred to as hypervigilance. It was hypothesized that a high sense of urgency would result in high response rigidity.

In addition to testing the hypotheses stated above, another objective of the present research was to examine differences in pilots' perceptions and attitudes based on background variables such as flight position, type of aircraft flown, flight time, and age of pilot. A comprehensive background information sheet was developed to provide the data for making these comparisons. Of particular interest are differences in attitudes toward crises and decision making among pilots based on their exposure to CRM training.

Pretest

As a first step, a preliminary study was conducted to assess pilot attitudes toward cockpit crisis and decision making across a broad range of variables drawn from the literature. The pretest instruments, a scenario and questionnaire, were developed with the assistance of airline personnel involved in CRM training programs. The scenario, which follows, includes several factors associated with mismanaged critical situations in air transport operations.

The crew is en route from Cancun to Houston Intercontinental in a Boeing 727 when a crossfeed valve failure renders the fuel in tank No. 2 unusable. Although the weather is deteriorating, the captain favors pushing on to Houston. The second officer has apprised the captain of the fuel situation—if they are forced to make a missed approach at Houston because of the inclement weather, they do not have enough fuel to reach their alternative airport. The first officer has stated that he thinks they should divert to New Orleans, which is closer and where the weather is better. The captain, however, is certain that they can make it into Houston. At this point, the scenario ends. The complete scenario can be found in the Appendix to this paper.

The scenario and survey instruments were pretested during personal interviews with 24 airline pilots to ensure that they understood both the scenario and questionnaire regardless of their flight experience or airline affiliation. Pilots were asked to read the scenario and then to respond to seven open-ended questions and to complete a closed-ended questionnaire. The background information sheet was also completed for each subject.

Data analysis indicated that pilots differed in their perception of crisis and the decision-making process in the scenario depending on their flight position and the aircraft they had flown. The pretest sample included only a few pilots who had not attended some type of CRM training program, so it was not possible to make comparisons with respect to this factor.

Measurement of the Research Variables

The concept of crisis was measured in two ways. The perception of crisis was determined by asking pilots to respond to the statement "At the point where the scenario ends, this crew is in a crisis situation" (Question 1, Part 1) on a Likert-type scale numbered 1 (strongly agree) through 7 (strongly disagree). In Part 2 of the questionnaire pilots were asked to rate five characteristics of the scenario on a Likert-type scale numbered 1 (low) to 9 (high). The second measure of crisis is a combination of the mean ratings of four crisis characteristics—level of threat to the safety of the flight, level of situational uncertainty, availability of decision-relevant information, and the level of tension.

The perception of urgency was measured by combining the responses to Questions 3, 7, and 10 in Part 1 and Question 4 (level of time pressure) in Part 2 of the questionnaire.

Response rigidity, as previously stated, is characterized by the restriction of participation and adherence to or reliance on authority and procedures. In Part 1 of the questionnaire, a response in the "agree" end of the scale to Questions 4, 6, 9, 12, and 13 indicates response rigidity, as does a "disagree" response to Questions 2, 5, 11, and 14.

Survey Distribution

Based on feedback from the pretest subjects and an analysis of the results, both the scenario and questionnaire were modified to clarify ambiguities. The survey materials included a cover letter, a background information sheet, and the revised 6-page scenario and 19-item questionnaire.

The chief pilots from three Los Angeles-based airlines were contacted. They reviewed the survey instruments and agreed to distribute the materials to each of their line pilots after the anonymity of the airlines and their pilots was assured. Six hundred sixty survey packets with a prepaid return envelope attached were distributed among the three airlines.

RESULTS

One hundred eighty-five usable surveys were returned, a 28 percent return rate. Table 1 presents descriptive information on the pilots who responded to the survey. As the table suggests, a relatively broad cross section of the pilot population is represented.

Responses to Questionnaire

The responses to Part 1 of the questionnaire are presented in Table 2, responses to Part 2 in Table 3. Each table indicates the mean and standard deviation for each question in the

TABLE 1 DESCRIPTIVE INFORMATION ON RESPONDENTS

Variable	Response Number	Response % of Total
Current Position		
Captain	85	46.0
First Officer	62	33.5
Second Officer	38	20.5
Years in Current Position		
0 - 3 Years	69	37.3
3.1 - 10 Years	60	32.4
10.1 - 20 Years	31	16.8
20.1 - 25 Years	24	13.0
Missing	1	.5
Current Aircraft		
Three Crewmember	149	80.5
Two Crewmember	34	18.4
Missing	2	1.1
Years in Current Aircraft		
0 - 1 Year	42	22.7
1.1 - 4 Years	84	45.5
4.1 - 10 Years	47	25.4
10.1 - 20 Years	11	5.9
Missing	1	.5
Total Flight Time		
Less Than 7000 Hours	67	36.2
7001 - 14000 Hours	64	34.6
14001 - 29000 Hours	54	29.2
Years With Current Airline		
0 - 10 Years	64	34.6
10.1 - 20 Years	33	17.8
20.1 - 35 Years	88	47.6
Age		
20 - 29 Years	11	5.9
30 - 39 Years	59	31.9
40 - 49 Years	54	29.2
50 - 59 Years	61	33.0
Duties Other Than Line Pilot		
No	166	89.7
Yes	19	10.3
Formal CRM Training		
No	124	67.0
Yes	61	33.0

TABLE 2 RESPONSES TO PART I OF QUESTIONNAIRE

Question	Mean	SD
1. At the point where the scenario ends, this crew is in a crisis situation.	2.23	1.47
2. This crew's decision making would be more effective if the Captain encouraged the other crewmembers to participate more in the decision process.	1.96	1.18
3. The crew in this scenario has time to try and find a better alternative course of action.	3.28	1.98
4. In this scenario, effective resolution of the problem is primarily dependent upon the Captain's flying skills.	5.30	1.77
5. A better decision could be reached if all crewmembers agree on a course of action.	2.60	1.66
6. Since the Captain wants to go to IAH, now is not the time for the other crewmembers to come up with creative alternatives.	5.79	1.79
7. At this point, it is more important for the crew in this scenario to make a decision than to search for new, alternative courses of action.	3.79	2.03
8. The crew in the scenario has all the information needed to make a good decision.	3.30	1.94
9. The Captain should be making a decision based on his experience rather than the opinions of the other crewmembers.	5.35	1.50
10. The crew in this scenario might make a better decision if they took the time to reevaluate the positive and negative consequences of all the alternatives before making a final decision.	2.42	1.58

TABLE 2 *(continued)*

Question	Mean	SD
11. If the other crewmembers feel that the Captain has made a bad decision, they should question the Captain's decision.	1.63	1.02
12. A better decision would be made if this crew paid more attention to following operating procedures than debating which course of action to take.	4.30	1.76
13. If a crewmember suggests an alternative course of action not covered by standard operating procedures, it should not be given serious consideration.	5.54	1.68
14. Since the First Officer has suggested an alternative different from the one suggested by the Captain, the Second Officer should verbally support whomever he thinks is right.	2.19	1.63

Note. Responses were on a scale from 1 (strongly agree) to 7 (strongly disagree).

TABLE 3 RESPONSES TO PART II OF QUESTIONNAIRE

Crisis Characteristic	Mean	SD
1. Level of threat to the safety of the flight	6.65	1.79
2. Level of uncertainty in the situation	6.43	1.78
3. Level of time pressure	6.44	1.74
4. Availability of information needed to make a decision	6.60	1.93
5. Level of tension	6.83	1.47

Note. Responses were on a scale from 1 (low) to 9 (high).

survey. Table 4 presents a summary of significant differences in responses to the questionnaire between selected subgroups based on background variables. The null hypothesis that there were no differences between these groups was tested with *t*-tests for independent samples.

Fewer captains disagreed with the statement that "the captain should be making a decision based on his experience rather than the opinions of other crew members" than did first and second officers. Pilots with formal CRM training and pilots who fly in a two-person cockpit both tend toward participatory decision making (Questions 2 and 5). Although pilots who fly in two-person-crew aircraft perceived higher levels of threat and uncertainty in the scenario than those in three-person crews, they believed that the crew should be more participatory in their decision making and that there was more time available for the evaluation of alternative courses of action (Question 10).

In addition to being more participatory, those who had formal CRM training were significantly more likely to indicate that they believed that the crew might not have all the decision-relevant information needed (Question 8) and that they should search for alternative courses of action despite the captain's preference to proceed to Intercontinental (Questions 6 and 7) than were those pilots who had no formal CRM training.

Results Pertaining to the Hypotheses

Responses to the statement that the crew in the scenario is in a crisis situation (Question 1) ranged from high agreement (1) to high disagreement (7); however, 90.8 percent of the respondents indicated some level of agreement. The mean was 2.27. The combined-mean rating of the four crisis characteristics ranged from 2.25 (low) to 7.5 (high). The mean was 5.8.

Pearson's correlation coefficient was used to test the hypothesis that the perception of crisis and the ratings of the crisis characteristics were positively correlated. The correlation was .36 (p = .000). Thus, the first hypothesis appears to be true: the higher the perception of crisis, the higher the rating of the crisis characteristics. However, the relationship was not as strong as anticipated.

The concept of response rigidity was derived by combining the means of Questions 2, 4–9, and 11–14 in Part 1 after recoding Questions 4, 6, 9, 12, and 13 to obtain consistent directionality. The rigidity scores ranged from a low of 1.25 to a high of 7.5. The mean rigidity score was 4.08. Both crisis measures were used separately to test the second hypothesis using Pearson's correlation coefficient. The correlation between Question 1 and the rigidity variable was −.30 (p = .000), indicating a linear relationship in a direction opposite to that

TABLE 4 SIGNIFICANT DIFFERENCES IN RESPONSES BY GROUPS (*t*-TESTS)[a]

Question	Mean		df	t
	Current Position			
	Captain	First/Second		
Q9	5.00	5.65	182	2.98
	Aircraft Flown			
	2-Crewmember	3-Crewmember		
Q2	1.59	2.06	181	2.31
Q5	2.09	2.70	181	1.98
Q10	2.00	2.52	181	1.72
Threat	7.21	6.52	181	2.03
Uncertainty	7.06	6.31	181	2.27
	Formal CRM Training			
	No	Yes		
Q2	2.10	1.69	183	2.73
Q5	2.78	2.23	183	2.33
Q6	5.58	6.21	183	2.58
Q7	3.59	4.25	181	2.09
Q8	3.09	3.75	183	2.21

[a] All differences are significant at the .05 level.

predicted by the hypothesis. The correlation between the ratings of crisis characteristics and the rigidity variable was low, −.18, but significant (p = .001) and similarly indicates a relationship opposite to the hypothesis. The results suggest that the higher the perception of crisis, the lower the response rigiditv

It was also hypothesized that a high sense of urgency would result in a high rigidity score. The correlation was .23—again, a signficant (p = .002) but relatively weak relationship. However, the relationship was in the direction hypothesized. A higher sense of urgency resulted in a higher rigidity score.

In order to further explore the relationship among the crisis characteristics, urgency, and rigidity variables, the responses were transformed to a percentage score to compensate for differences between the scales used in Parts 1 and 2 of the questionnaire. The mean percentage score for the crisis characteristic variable was 64.75; for the urgency variable, it was 53.20; and 35.02 was the mean percentage score for rigidity. The crisis characteristic variable was used as the measure of crisis perception because it is considered to be a more comprehensive measure of crisis.

Table 5 shows, as previously noted, that crisis and rigidity are negatively related (high-low, low-high), but the rigidity scores are not significantly different as a result of a high or low perception of crisis. Urgency and rigidity are, however, positively related (low-low, high-high), and pilots with a low sense of urgency have significantly lower rigidity scores (t = 2.88; p = .004).

The last section of Table 5 shows the interrelationship among the three variables. Respondents who rated the situation as more urgent also had higher rigidity scores, regardless of the perception of crisis. However, rigidity scores differed significantly as a result of urgency only when the perception of crisis was high (t = 2.74; p = .007).

Table 6 shows the differences based on aircraft flown and CRM training in relation to the hypotheses. (No significant differences were found between groups based on flight position with respect to the variables central to the hypotheses.) T-tests for independent samples showed that pilots who flew in two-person cockpits had a significantly higher perception of crisis than their counterparts in three-person crews (t = 2.68; p = .009) as well as a lower sense of urgency and lower rigidity.

Pilots who had no formal CRM training indicated a lower rating of the crisis characteristics, but had higher urgency and rigidity scores than those pilots who had attended a formal CRM program. They differed significantly on the urgency variable (t = 2.16; p = .032) and on the rigidity variable (t = 2.06; p = .026).

CONCLUSION

Overall, pilots perceived that the crew in the scenario was in a crisis situation and, as hypothesized, this perception positively correlated with their ratings of the crisis characteristics.

TABLE 5 COMPARISONS AMONG CRISIS CHARACTERISTICS, URGENCY, AND RIGIDITY VARIABLES

Variables						
Crisis	n	Urgency	n	Rigidity (%)	t	p
High	97			34.3	1.03	.305
Low	87			35.8		
		High	87	37.3	2.88	.004
		Low	95	33.0		
High	97	High	44	37.5	2.74	.007
		Low	53	31.7		
Low	85	High	43	37.2	1.17	.244
		Low	42	34.8		

TABLE 6 COMPARISION OF PERCENTAGE SCORES IN CRISIS CHARACTERISTICS, URGENCY, AND RIGIDITY VARIABLES BY AIRCRAFT FLOWN AND CRM

Group	n	Crisis	Urgency	Rigidity
		Variable		
Current Aircraft[a]				
2-Person Crew	34	68.6	49.8	33.1
3-Person Crew	149	64.1	53.8	35.4
Cockpit Resources Management[b]				
No Formal	124	64.5	54.9	36.0
Formal	61	65.6	49.4	32.9

[a] Significant differences were found between two-person and three-person cockpit crews on Crisis (t=2.68; p=.009).

[b] Groups differ significantly on Urgency (t=2.16; p=.032) and on Rigidity (t=2.06; p=.026).

An unexpected finding was that a higher perception of crisis resulted in a lower rigidity score. The high-crisis–low-rigidity relationship was opposite to that hypothesized, and, further, pilots had overall surprisingly low rigidity scores.

The hypothesis that a high sense of urgency would evoke high response rigidity was supported by the data. Rigidity scores were higher when urgency was high, regardless of the perception of crisis. It appears that flexible, participatory decision making is more a function of low urgency than high crisis perception. Interestingly, pilots with a high perception of crisis had significantly lower mean rigidity scores when urgency was also low.

It is possible that a high perception of crisis is indicative of high arousal. If so, the high-crisis–low-urgency–low-rigidity pattern may represent an optimal approach to crisis decision making. In other words, the decision maker perceives the situation as a crisis and consequently is motivated to act. But the low sense of urgency (the belief that there is sufficient time to search for and evaluate alternative courses of action) allows for more flexibility with respect to participation, roles, and procedures.

This high-crisis–low-urgency–low-rigidity pattern was exhibited by both CRM-trained pilots and pilots of two-crew member aircraft. The similarities between these two groups are probably due to the fact that 29 of the 34 members of two-crew-member cockpits had attended formal CRM training programs. In any case, the results of the study support the notion that CRM training does, in fact, encourage more situationally responsive decision patterns.

ACKNOWLEDGMENTS

The author would like to acknowledge FAA as the sponsor of the Graduate Research Award Program, which made possible the timely completion of this research. The author also would like to thank TRB monitors William Edmunds of the Air Line Pilots Association and Richard Pain of TRB for their helpful suggestions, and E. Thomas Burnard, program coordinator at TRB, for his support.

The invaluable assistance and patience of faculty advisors Charles Kerchner of the Claremont Graduate School and Harvey Wichman of Claremont McKenna College are gratefully acknowledged.

Special thanks go to Robert Treakle and Frank Tullo for their insights into the airline cockpit and for their constant support and encouraging words.

APPENDIX
Crisis Scenario

On January 6, 1989 at 19:00Z Flight 451, a Boeing 727-200, departed Cancun bound for Houston's Intercontinental Airport. The flight was dispatched with 32,500 lb of fuel on board as follows:

En route	1:49	17,500
Alternate (DFW)	:42	7,000
Reserve	:45	6,000
Contingency	:15	2,000
	3:31	32,500

All three fuel tanks were fueled evenly at 10,834 lb each. There were 151 passengers on board and a crew of 7. The takeoff gross weight was calculated at 167,500 lb, with a planned landing weight at IAH of 150,000 lb.

The flight was cleared via the standard Center-stored route of CUN J-52 ELGAR A-766 GLS DIRECT IAH. The computer flight plan indicated that the Equal Time Point was 51 min into the flight with a 9,500 lb fuel burn.

That day a stationary front was lying along the Texas Gulf Coast swinging northward over the Texas/Louisiana border, bringing widespread low stratus, drizzle, and fog to the region. The crew received the following weather briefing:

CUN FT 061111	250 SCT. 12Z 80 SCT C250 BKN. 20Z 30 SCT C80 BKN 250 BKN 0415. 05Z VFR.
CZM FT 061111	250 SCT. 12Z 70 SCT C250 BKN. 20Z 30 SCT C70 BKN 250 BKN 0510. 05Z VFR.
MID FT 061111	CLR. 14Z 50 SCT C100 BKN. 18Z C50 OVC 0915. 00Z C10 OVC 3R 0915. 05Z MVFR CIG VIS R.
IAH FT 061212	C2 X 1L-F. 14Z C5 BKN 8 OVC 2L 3215. 18Z C10 OVC 2RF 3210 OCNL C2 X 1/2RF. 00Z C4 OVC 1 L-F 3410. 06Z LIFR CIG LF.
HOU FT 061212	C2 X 1L-F. 14Z C5 BKN 8 OVC 2L 3215. 18Z C10 OVC 2RF 3210 OCNL C2 X1/2 RF. 00Z C4 OVC 1 L-F 3410. 06Z LIFR CIG LF.
DFW FT 061212	C10 OVC 3L 0110. 15Z C10 BKN 25 OVC. 18Z 30 SCT C100 BKN 0110. 21Z 100 SCT 0310. 06Z VFR NO CIG.
CRP FT 061212	C3 OVC 1 LF. 14Z C2 X 1/2 L-F. 16Z C4 OVC 1 R-F 0310. 20Z C2 X 1/2LF. 06Z LIFR CIG LF.
SAT FT 061212	C5 OVC 1 LF 2RF 3010. 15Z C5 BKN 8 OVC 2R-F 3015. 21Z C2 X 1/2 LF. 06Z IFR CIG.
MSY FT 061313	C8 OVC 2RF 0610. 15Z 8 SCT C20 OVC 0615. 20Z C20 BKN 0710. 07Z VFR.
IAH SA 1650	M9 OVC 3R 113/65/62/3009/986
HOU SA 1645	E10 OVC 2RF 113/64/61/3110/986
SAT SA 1650	E6 BKN 10 OVC 2R 132/69/60/2915/992
CRP SA 1650	M4 OVC 1 R-F 113/64/61/0310/986
DFW SA 1645	M10 BKN 6 132/70/55/0105/992
MSY SA 1655	M15 OVC 3L 114/68/60/0609/987

The flight departed Cancun at 19:04Z with an undetected inoperative number 2 crossfeed valve. The valve failed in the closed position.

19:58

Second Officer: Number 2 is spooling down.
Captain: Turn on the ignition.
Second Officer: It's on. No help.
Captain: All right, get out the book and try a relight.

20:01

Second Officer: It says airspeed and N1-N2 relationship within appropriate envelope. Should be 24 and 31—looks good. Nacelle anti-ice off, fire handle push in. Don, is the fire handle in?
Captain: Yeah, it's in. Just get the checklist done. The airspeed is bleeding; we can't stay at this altitude. John, get me lower.
First Officer: Merida Center, 451 needs lower.

20:02

Merida: 451, say again.
First Officer: 451 has lost an engine. We need a lower altitude.
Merida: Stand by.

20:03

Merida: 451, descend, maintain FL310.
First Officer: 310. 451.
Second Officer: Don, it won't relight.
Captain: What do you mean, it won't relight? You got the fuel pumps on?
Second Officer: Yes, sir.
Captain: You fly this thing. I'll get it started. Give me that book.

20:05

Captain: You're right. It's not going to run. What altitude can we maintain?
Second Officer: The book says 20 max at 157.

20:06

First Officer: Shouldn't we run the engine failure checklist?
Captain: Yeah, let's get that done.
Second Officer: Throttle closed . . . start lever cutoff . . . essential power check . . . electrical load check . . . I'll finish up the secondary items.

20:08

Captain: Request FL200.
First Officer: Merida Center, 451 would like FL200.
Merida: 451, descend and maintain FL200. Report reaching.
First Officer: 451, roger.

20:10

Second Officer: Engine failure checklist is complete.

20:12

Merida: 451, say your Nuley estimate.
First Officer: I forgot to report Nuley.
Center, 451. Stand by.
We must've crossed it at about 02. What's our true airspeed now? About 380?
Captain: 360.

20:14

First Officer: 451 passed Nuley 20:02, descending to FL200. Estimating Barow at 20:29. Earns is next.
Merida: 451, roger. Say your altitude.
First Officer: Leaving FL270.
Merida: 451, roger. Contact Houston Center on 132.65.
First Officer: 132.65. 451.

20:15

Captain: When you check in ask for the IAH weather.
First Officer: Houston Center, 451 descending to FL200.

20:16

First Officer: Houston Center, 451.
I'll go back to Merida.
Captain: Don't bother. We'll pick 'em up in a few minutes. We're still a ways out.

20:21

Captain: Dale, try to get that fuel in balance, will ya. Burn out of the center tank.

Second Officer: I am. Something's wrong here, Don. I've been crossfeeding for about 15 minutes.
Captain: Looks right. Try cycling the crossfeed valve.
First Officer: What's going on?
Captain: Aw, the fuel's all screwed up.

20:23

Second Officer: I'm not getting an in-transit light.
Captain: Check the breaker.

20:25

Second Officer: It's still not working.
Captain: Are you sure you checked the right breaker? Which one did you cycle?
Second Officer: This one—the manifold valve.

20:29

First Officer: Well, the fuel in that tank is going to be unusable.
Captain: Yeah. Give Houston another call.
First Officer: Houston Center, 451.
Houston: 451, Houston Center. Go ahead.
First Officer: 451, FL200.

20:30

Houston: 451, squawk 2641 and indent.
First Officer: 2641.

20:32

Houston: 451, radar contact 10 north of the Barow intersection. Cleared direct Scholes, direct IAH.
Captain: Get the IAH weather.
First Officer: Direct Scholes, direct IAH. What's the IAH weather?
Houston: Stand by.

20:35

Houston: 451. The IAH weather at 19:50Z, 500 overcast, visibility 1, temperature 64, dewpoint 62, wind 300 at 4, altimeter 29.85.
First Officer: Thanks.

20:40

Second Officer: I've got the latest weather for IAH and MSY. IAH's now 200 overcast, visibility 1/4, rvr on 8 is 1800 variable 2400. MSY is 800 overcast, visibility 1 mile.
Captain: Well, Houston's above minimums. What's the current weather at DFW?
Second Officer: I can't get an update for DFW. Anyway, according to this chart, if we can't use the fuel in the number 2 tank, we won't have enough to make the alternate.
First Officer: What?

20:41

Second Officer: If we miss the approach at IAH, we won't have enough fuel to make it to DFW. The fuel in tank 2 is unusable.
First Officer: How much fuel do we have now?
Second Officer: 8,700 usable. How far is it to MSY?

20:43

First Officer: It's about 215 to MSY and 335 to DFW.

20:45

Second Officer: If we divert now, we'd land at MSY with 3,700 and DFW with about 1,000.
Captain: Oh, we'll make it into IAH o.k. I've made it in there in worse conditions than this.

20:46

First Officer: Don, I think we should go to MSY. We have a real fuel problem here and the weather in IAH is getting worse.
Captain: We're scheduled into IAH—we'll make it.

REFERENCES

1. J. M. Koonce. A Brief History of Aviation Psychology. *Human Factors*, Vol. 26, 1984, pp. 499–508.
2. H. C. Foushee. Dyads and Triads at 35,000 Feet. *American Psychologist*, Vol. 39, 1984, pp. 885–893.
3. H. P. Ruffell Smith. *A Simulator Study of the Interaction of Pilot Workload with Errors, Vigilance and Decisions*. NASA Report TM-78482. NASA-Ames Research Center, Moffett Field, Calif., Jan. 1979.
4. R. L. Sears. *A New Look at Accident Contributions and the Implications of Operational and Training Procedures*. Boeing Commercial Aircraft Company, Seattle, Wash., 1986.
5. J. L. Wheale. An Analysis of Crew Coordination Problems in Commercial Transport Aircraft. *International Journal of Aviation Safety*, Vol. 2, 1984, pp. 83–89.
6. G. E. Cooper, M. D. White, and J. K. Lauber, eds. *Resource Management on the Flight Deck: Proceedings of a NASA/Industry Workshop*. NASA CP-2120. NASA-Ames Research Center, Moffett Field, Calif., 1979.
7. H. W. Orlady and H. C. Foushee, eds. *Cockpit Resources Management Training: Proceedings of the NASA/MAC Workshop*, NASA CP-2455. NASA-Ames Research Center, Moffett Field, Calif., 1987.
8. R. L. Helmreich, H. C. Foushee, R. Benson, and R. Russini. Cockpit Managment Attitudes: Exploring the Attitude-Performance Linkage. *Aviation, Space and Environmental Medicine*, Vol. 57, 1986, pp. 1198–2000.
9. R. L. Helmreich. Cockpit Management Attitudes. *Human Factors*, Vol. 26, 1984, pp. 583–89.
10. J. R. Hackman. Group Level Issues in the Design and Training of Cockpit Crews. In *Cockpit Resource Management Training: Proceedings of the NASA/MAC Workshop* (H. W. Orlady and H. C. Foushee, eds.), NASA CP-2455. NASA-Ames Research Center, Moffett Field, Calif., 1987, pp. 23–39.
11. *Safe Skies for Tomorrow: Aviation Safety in a Competitive Environment*. Office of Technology Assessment, OTA-SET-381. Washington, D.C., July 1988.
12. R. S. Billings, T. W. Milburn, and M. L. Schaalman. Crisis Perception: A Theoretical and Empirical Analysis. *Administrative Science Quarterly*, Vol. 25, 1980, pp. 300–15.
13. C. F. Hermann. *Crisis in Foreign Policy*. Bobbs-Merrill, Indianapolis, Ind. 1969.
14. T. W. Milburn. The Management of Crisis. In *International Crisis: Insights from Human Behavioral Research*. (C. F. Hermann, ed.), The Free Press, New York, N.Y., 1972, pp. 257–277.
15. J. A. Robinson. Crisis: An Appraisal of Concepts and Theories. In *International Crisis: Insights from Human Behavioral Research*. (C. F. Hermann, ed.), The Free Press, New York, N.Y., 1972, pp. 18–35.
16. B. M. Straw, L. E. Sanderlands, and J. E. Dutton. Threat-Rigidity Effects in Organizational Behavior: A Multi-Level Analysis. *Administrative Science Quarterly*, Vol. 26, 1981, pp. 640–657.
17. T. C. Wiegele. Decision Making in an International Crisis: Some Biological Factors. *International Studies Quarterly*, Vol. 17, 1973, pp. 295–336.
18. J. E. McGrath. Stress and Behavior in Organizations. In *Handbook of Industrial and Organizational Psychology*, (M. D. Dunnette, ed.), Rand-McNally, Chicago, Ill., 1976, pp. 1351–1395.

19. S. Fink, J. Beak, and K. Taddeo. Organizational Crisis and Change. *Journal of Applied Behavioral Science*, Vol. 7, 1971, pp. 15–37.
20. L. R. Hoffman. Improving the Problem-Solving Process in Managerial Groups. In *Improving Group Decision Making in Organizations: Approaches from Theory and Research*. (R. A. Guzzo, ed.), Academic Press, Orlando, Fla., 1982, pp. 95–126.
21. H. A. Simon. *The New Science of Management Decision*, rev. ed. Prentice-Hall, Englewood Cliffs, N.J., 1977.
22. I. L. Janis and L. Mann. *Decision Making: A Psychological Analysis of Conflict, Choice, and Commitment*. The Free Press, New York, N.Y., 1977.
23. D. C. Nagel. Human Error in Aviation Operations. In *Human Factors in Aviation*. (E. L. Weiner and D. C. Nagel, eds.), Academic Press, San Diego, Calif., 1988, pp. 263–303.
24. E. P. Torrance. A Theory of Leadership and Interpersonal Behavior Under Stress. In *Leadership and Interpersonal Behavior*. (L. Petrullo and B. M. Bass, eds.), Holt, Rinehart & Winston, New York, N.Y., 1961, pp. 100–117.
25. L. Berkowitz. Sharing Leadership in Small, Decision-Making Groups. In *Small Groups: Studies in Social Interaction*, (A. P. Hare, E. F. Borgatta and R. F. Bales, eds.), Knopf, New York, N.Y., 1966, pp. 675–687.
26. M. Mulder, J. R. Ritsema, and R. deJong. An Organization in Crisis and Non-Crisis Situations. *Human Relations*, Vol. 24, 1971, pp. 19–41.
27. C. T. Kerchner and J. H. Schuster. The Uses of Crisis: Taking the Tide at the Flood. *The Review of Higher Education*, Vol. 5, 1982, pp. 121–141.
28. J. E. Dutton. The Processing of Crisis and Non-Crisis Strategic Issues. *Journal of Management Studies*, Vol. 23, 1986, pp. 501–517.
29. C. Smart and I. Vertinsky. Designs for Crisis Decision Units. *Administrative Science Quarterly*, Vol. 22, 1977, pp. 640–57.
30. E. L. Weiner. Cockpit Automation. In *Human Factors in Aviation*. (E. L. Weiner and D. C. Nagel, eds.), Academic Press, San Diego, Calif., 1988, pp. 433–461.

Robust Tracking and Control Strategies for Automatic Landing Systems

MICHAEL J. ROEMER

An automatic landing system (ALS) for aircraft is discussed and analyzed to emphasize possible procedures for enhancing the performance of aircraft tracking and control strategies. Techniques such as control/filter variable optimization and noise filtering are introduced as incentives for the development of an ALS for commercial aircraft. The robust nature (less sensitive to noise and disturbance) of the tracking and control algorithms is advantageous for adverse weather conditions and noise-corrupted radar measurements. Improvements attributed to these tracking and control concepts are demonstrated on a closed-loop computer simulation of an aircraft under automatic control. Robust automatic landing systems utilizing these strategies will prove to be essential in the design of aircraft control systems proposed for accurate terminal-area automatic landings.

Consider an automatic landing system (ALS) for commercial aircraft that would allow for safer and more efficient airspace management or an advanced guidance and control scheme for military combat aircraft that would permit leaving the pilot home under extremely hazardous situations. Are these aviation goals for automatic control possible? Definitely, considering the projected advances in computer technologies that will shape the automated control industry of the future. Full integration of the many aspects of aircraft control, in particular those associated with robust (less sensitive to noise and disturbance) tracking and control methodologies, is a first step to reaching these goals.

The Microwave Landing System (MLS) is the new international standard landing aid planned to replace the current Instrument Landing System (ILS) as early as 1995. The MLS will be capable of determining the position of an aircraft in three-dimensional space over a large coverage area, and it is less sensitive to surrounding interference than the ILS. Some of the operational benefits of the MLS include (a) use of curve/segmented approaches, (b) use of back azimuth guidance, (c) use of higher glide slopes/reduced siting problems, (d) relief of frequency congestion, and (e) increased reliability and maintainability (*1,2*). The MLS, however, is an advanced guidance system in which no direct, automatic control of the aircraft is performed. The focus of this paper is the development and simulation of some robust features associated with ALSs that could contribute to the evolution of a future ALS for commercial aircraft.

There are many unanswered questions about the technical feasibility of an ALS for civilian aircraft. The current ALSs used by naval aircraft carriers utilize ground-based, lock-on-type radar, whereas current civilian technology includes MLS and satellite procedures. The main difference is that MLS and satellite technologies are not fast enough for the required frequency of position updates needed for automatic control in the current system. The author does not propose to overcome the inertia of the current civilian technology. However, possible alternatives include (a) developing a separate, ground-based ALS to supplement MLS technologies, (b) using accurate estimation techniques that predict aircraft position between radar measurements, and (c) waiting for the advances in computer technologies so that the required position updates can be obtained. Regardless of the alternative, the future development of an ALS for commercial aircraft must remain an option for aviation policy makers.

Assuming that the option for civilian ALSs is feasible, the performance of the tracking and control strategies of a ground-based ALS are investigated. A computer simulation that accurately represents an operating ALS is necessary for testing possible improvement techniques. The essential computer simulation blocks contained in an ALS are the tracking filter, the controller, and the aircraft model. These simulation blocks are introduced, analyzed, and then combined in a closed-loop simulation to model an aircraft under a particular ALS control. This closed-loop performance is carefully analyzed in the frequency and time domains and compared with actual measurements taken during a test flight to ensure compatibility. Once the basic ALS background is established, some possible areas of improvement are examined. An area of particular interest, highlighted in a later section, is the ALS's noise rejection capabilities.

To decrease the noise sensitivity of a generalized ALS, a filtering technique utilizing both measurement data and modeled aircraft dynamics is introduced. The proposed filter blends information obtained by radar measurements with aircraft model estimates to produce a less noise-sensitive pitch command, which in turn is sent to the aircraft to control it. The proposed noise rejection filter equations are explained in detail later. After the filter is included in the computer simulation, a complete frequency and time domain analysis is performed and compared with the simulation without the filter. The filter produces the desired reduction in noise sensitivity. However, this desirable reduction is obtained at the cost of an undesirable increase of the turbulence response of the aircraft.

To address the concern of an increased turbulence response, the author approached the problem using optimization techniques. The optimization problem consists of the minimization of a cost function related to (a) the turbulence response of an aircraft and (b) the unit step response of the aircraft. The optimization of the cost function is with respect to the control gains as well as the tracking filter gains. After cal-

Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo, Buffalo, N.Y. 14260.

culation of the optimal control and filter gains for a particular weighting, the complete ALS simulation is tested to ensure an improved solution.

GENERALIZED ALS

First, the procedures and equations necessary for the construction of an ALS computer simulation are discussed. For the purpose of organization, the simulation can be classified into three parts: aircraft model, tracking filter, and controller.

Aircraft Model

Creating a concise mathematical model of the dynamics of an aircraft for computer simulation is not a trivial procedure. The sophistication levels can range from a coupled 12th-order state-space representation of the familiar equations of motion to a simple transfer function model utilizing an integration procedure. For the purposes of evaluating tracking filter performance and control schemes in a closed-loop ALS simulation, a relatively small-order model is sufficient. The underlying procedure used in the construction of the aircraft model is to match the dynamic response characteristics of actual aircraft data measured through flight testing (*3*). The measurements come from an F-4 fighter plane and consist of frequency domain data for a transfer function relating altitude to pitch command. For a commercial aircraft, the mathematically modeled differences would consist of slower time constants (denominator) and a larger overall gain (numerator). The F-4 was used in the modeling process because of the availability of the data for comparison purposes. For simplification reasons, the aircraft model transfer function used in the generalized ALS computer simulation is as follows:

$$\frac{Z(s)}{\Theta_c(s)} = \frac{G}{s(1 + t_1 s)(1 + t_2 s)} \tag{1}$$

where

$Z(s)$ = aircraft altitude,
$\Theta_c(s)$ = pitch command signal,
G = constant gain, and
t_1, t_2 = time constants.

This simplified aircraft transfer function is a single-input, single-output (SISO) relationship. The input signal is the pitch command calculated by the controller, and the output signal is the aircraft altitude. The obvious question that arises is, what happens to the other aircraft states that are in theory coupled with the pitch command signal to control the aircraft? The answer is found by decoupling the equations of motion. Decoupling the states associated with the control of aircraft is a common practice often performed in industry to simplify the design criteria and retain robust stability. In this case, the aircraft model only gives information about the aircraft altitude. However, if information about the lateral position of the aircraft is desired, a more advanced transfer function matrix could be substituted. This was not considered here because a simplified aircraft model was desired.

The aircraft model's transfer function consists of a second-order pole with time constans of $t_1 = 1.0$ and $t_2 = 1.4$ sec multiplied by an integrator with constant gain of $G = 5.0$. However, to more practically represent the motions of an aircraft, turbulence must be added to the transfer function. The block diagram of the transfer function with this addition is shown in Figure 1.

The integrator acts to produce the elevation changes in the aircraft, whereas the two poles approximate the cut-off frequencies associated with elementary aircraft motions. The aircraft transfer function was digitally simulated using a fourth-order Runge-Kutta numerical integration technique. The output states represent close approximations of the aircraft altitude and its first and second derivatives. This transfer function is a good imitation to measured data obtained during an aircraft test flight (*3*).

Tracking Filter

A state estimation filter that aids in aircraft tracking is examined in this section. Assuming that the aircraft's position is the only radar measurement currently available, aircraft tracking would be performed by processing noisy position measurements only. A great deal of effort has been concentrated on producing suboptimal filters with reduced computational requirements (*4–9*). This type of filter is used for examining the noise sensitivity of the generalized ALS discussed in this paper. With this in mind, a basic α-β-γ filter is designed as part of the ALS computer simulation to assist in estimating the prominent states of the aircraft.

Similar to most digital filters, the output of the α-β-γ filter is based on a weighted average between a current measurement and an estimated prediction. The estimated prediction is calculated using previous output measurements. For the ALS under investigation, the digital filter precedes the standard control algorithms. Derivative (D) and double derivative (DD) control is necessary to obtain useful velocity and accel-

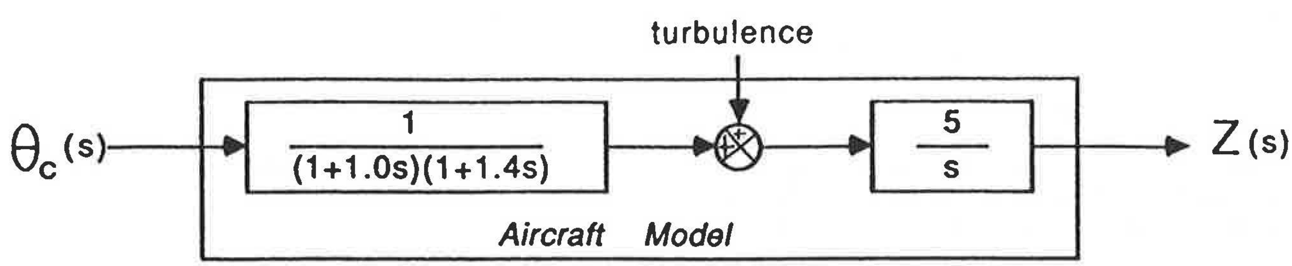


FIGURE 1 Aircraft transfer function block diagram.

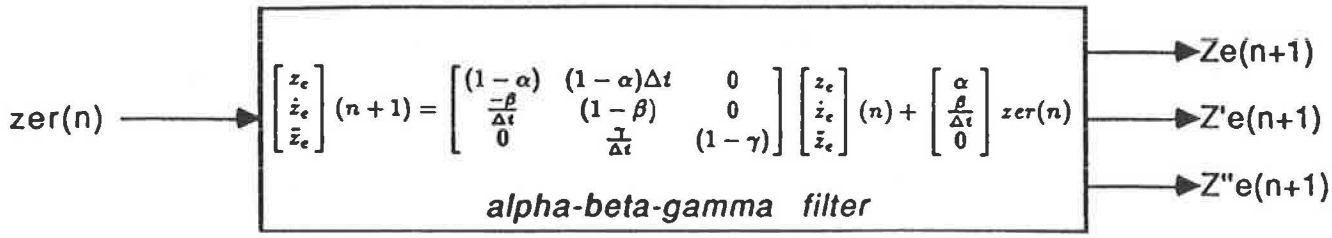


FIGURE 2 Tracking filter block diagram.

eration error estimates. This technique of filtering the error signal of the position measurement is illustrated in Figure 2. The position error signal is the difference between the command trajectory and the actual aircraft position obtained by radar.

The α-β-γ filter equations are derived in the following manner. First, a predicted error signal $z_e^p(n)$ is derived using a discrete time, truncated Taylor series:

$$z_e^p(n) = z_e(n-1) + \Delta t \dot{z}_e(n-1) \quad (2)$$

where n and $n - 1$ are the current and previous discrete times.

Utilizing the filtering idea of a weighted average, the predicted error signal $z_e^p(n)$ and the current position error measurement signal $zer(n)$ are combined in the following manner to produce the output signal $z_e(n)$.

$$z_e(n) = (1 - \alpha) z_e^p(n) + \alpha zer(n) \quad (3)$$

where α is the weighting gain for position error measurement.

In similar fashion, the first derivative of the filtered error signal is calculated by combining the previous velocity estimate with a numerical estimate of the derivative. The equation used in its calculation is the following:

$$\dot{z}_e(n) = (1 - \beta)\dot{z}_e(n-1) + \beta\left[\frac{zer(n) - z_e(n-1)}{\Delta t}\right] \quad (4)$$

where β is the weighting gain for the velocity error estimate.

The acceleration section of the α-β-γ filter is separated into two equations. The first equation serves as an intermediate step to the calculation of the second derivative of the filtered error signal. This equation is written as follows:

$$\ddot{z}'_e(n) = (1 - \gamma)\ddot{z}_e(n-1) + \frac{\gamma}{\Delta t}\left[\dot{z}_e(n) - \dot{z}_e(n-1)\right] \quad (5)$$

where γ is the weighting gain for the acceleration error estimate.

The second derivative of the filtered error signal is then calculated using the previous equation, and is shown below:

$$\ddot{z}_e(n) = \ddot{z}_e(n-1) + \gamma[\ddot{z}'_e(n) - \ddot{z}'_e(n-1)] \quad (6)$$

A performance evaluation of the α-β-γ filter equations was conducted. The analysis can be broken down into two sections. First, a gaussian distributed random signal with mean ($\mu \approx 0.0$) and variance ($\sigma^2 \approx 1.0$) was used to test the transient and steady-state responses of the filter. The values of μ and σ were chosen to represent a possible error signal between the desired and actual aircraft measurements. Next, two sine waves with frequencies of 4.0 and 0.8 rad/sec were used as inputs to check the phase lag in the filter. It was concluded that if there was a significant transient input to the filter, the filter would adjust to it within 1 sec (*3*).

Controller

A commonly implemented control strategy often utilizes proportional (P), integral (I), derivative (D), and second derivative (DD) control methodologies. This type of controller was chosen so that the best possible combination of classical control techniques could be implemented. Also, additional filtering is often desirable at the output of such conventional control algorithms. For instance, a simple first-order low-pass filter could be used to protect against severely changing control signals. This robust filter-controller algorithm is designed to withstand the most intense turbulence and to eliminate the possibility that the controller might produce a control signal that forces the plane to become unstable.

The PIDDD controller equations implemented in the general ALS computer simulation are formulated in the following manner. First, the equations are illustrated in block diagram form (Figure 3) and then written in a discrete time format.

The discrete time integral action is derived by summing a weighted average of the previous integral signal with a numerical integration approximation. This equivalence is shown below:

$$\Theta_{INT}(n) = \Theta_{INT}(n-1) + \frac{K_0}{K_I}\left[\frac{z_e(n) + z_e(n-1)}{2}\right]\Delta t \quad (7)$$

where $\Theta_{INT}(n)$ is the integral control action.

This result is then used along with the filtered error signal and its derivatives to produce the following control signal:

$$\Theta'_c(n) = K_0[K_P z_e(n) + K_D \dot{z}_e(n) + K_{DD}\ddot{z}_e(n)] + \Theta_{INT}(n) \quad (8)$$

where

K_0 = encompassing gain constant,
K_P = proportional control gain,
K_I = integral control gain,
K_D = derivative control gain, and
K_{DD} = double derivative control gain.

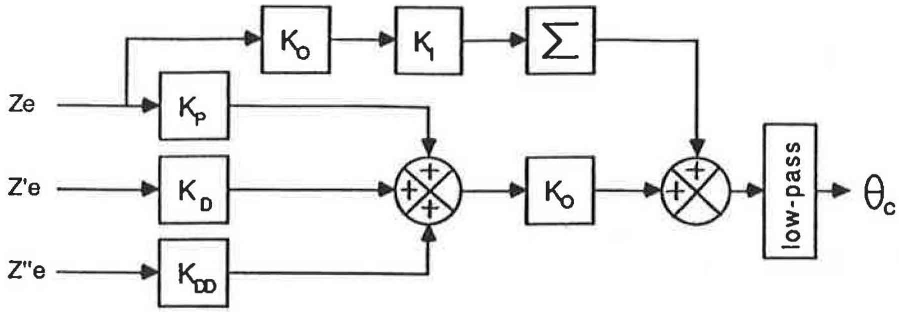


FIGURE 3 PIDDD controller block diagram.

The calculated $\Theta'_c(n)$ control signal is then used as an input to the low-pass filter to produce the actual control signal $\Theta_c(n)$,

$$\Theta_c(n) = \Theta_c(n-1) + \alpha_p[\Theta'_c(n) - \Theta_c(n-1)] \quad (9)$$

where α_p is the $(\Delta t)\omega_c$, and ω_c is the break point frequency.

CLOSED-LOOP COMPUTER SIMULATION

Attention is now focused on the closed-loop integration of the simulation blocks discussed in the previous section. The blocks of a general ALS model are arranged into the closed-loop configuration shown in Figure 4.

This closed-loop ALS is designed to control the vertical position of an approaching aircraft until it lands safely. The position error signal characterized by the aircraft's vertical position is the input to the filter. The output contains estimates of the aircraft's altitude error and its first and second derivatives. The output error estimates of the α-β-γ filter are used as inputs to a PIDDD controller scheme. The controller is responsible for producing an unpolished pitch command signal that, in refined form, will be communicated to the aircraft to produce a desired vertical position. Finally, the current position of the aircraft is tracked by the radar system and fed back to the ALS to begin the cyclic process again. This closed-loop signal processing continues until the aircraft has landed.

Frequency and time domain analysis was employed to fully investigate the compatibility of the general ALS's computer simulation with practical operating conditions. First, a frequency domain approach is used to compare the resulting computer simulation with actual test flight data, followed by an examination of the time domain step response to ensure proper closed-loop behavior. Then, simulated noise and turbulence are added to the simulation to examine noise sensitivity and turbulence response.

Frequency Domain Characteristics

An excellent means of confirming whether the closed-loop simulation is operating properly is to compare it with some actual test flight measurments. Through the use of a Nichol's chart, an available set of open-loop frequency test flight data is transformed into a closed-loop Bode plot. Next, the closed-loop simulation is subjected to sinusoids of several different frequencies in order to construct the computer-simulated Bode plot. The results of the simulated frequency domain analysis are plotted together with the test flight data to ensure compatibility. These plots appear in Figures 5 and 6.

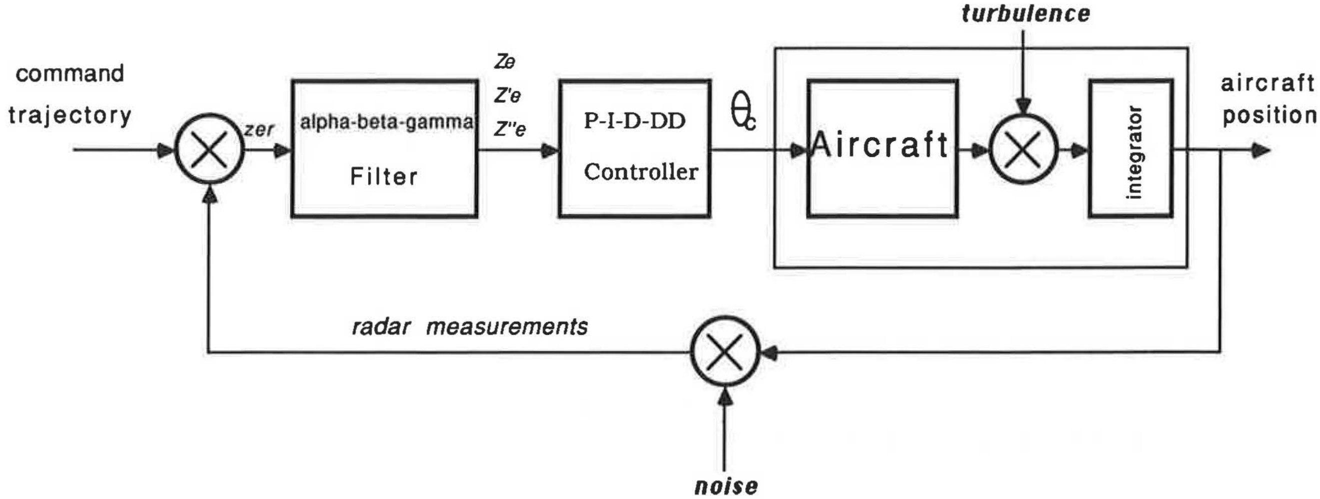


FIGURE 4 Automatic landing system block diagram.

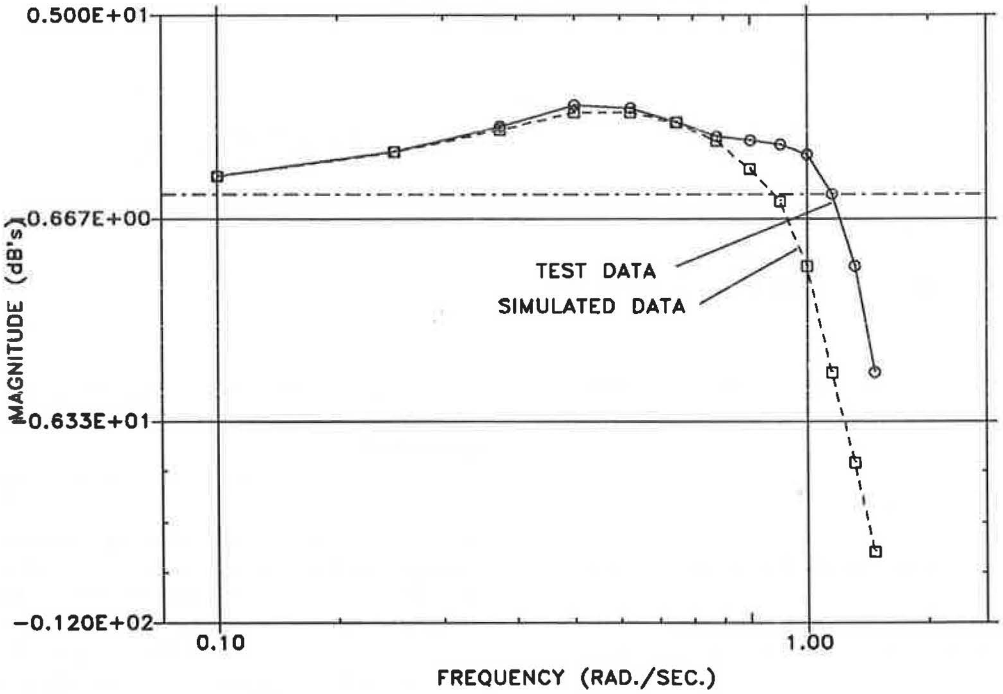


FIGURE 5 Magnitude Bode plot comparison.

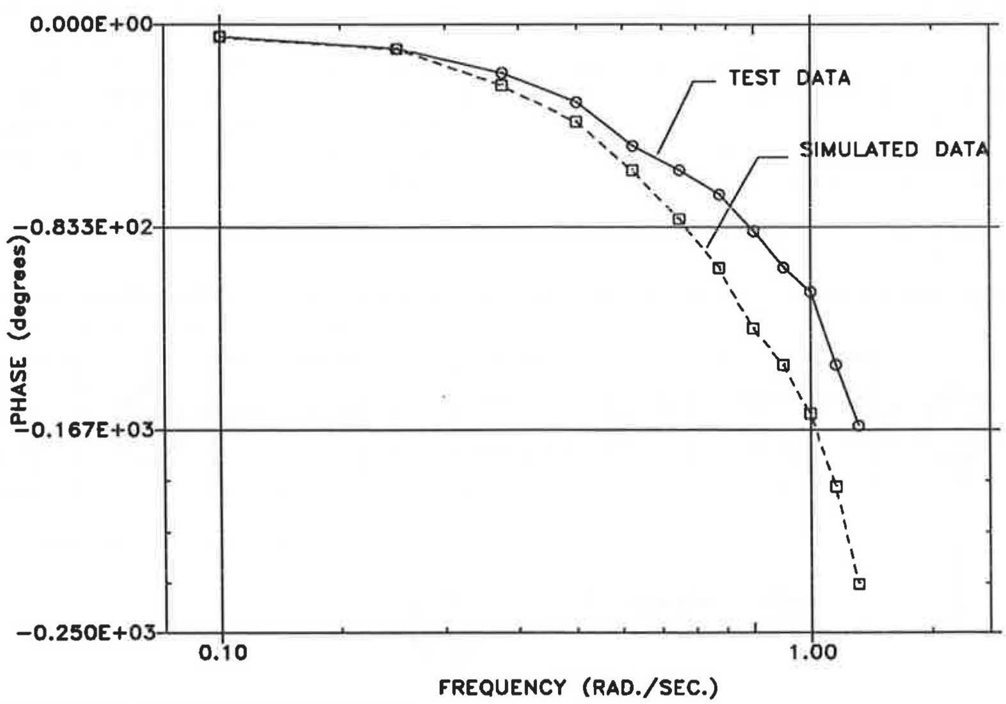


FIGURE 6 Phase Bode plot comparison.

Time Domain Considerations

Time domain analysis, in particular the step and turbulence responses, is a widely used graphic tool for designing various types of aircraft controllers. Design characteristics associated with the step response, such as rise time, overshoot, and settling time, are often considered the most significant results when the performance of a control system is rated. Moreover, obtaining a minimal turbulence response with respect to a given trajectory is often desirable when the turbulence response of an aircraft is examined. Examining the step response of the ALS simulation reveals an overshoot of 5.0 percent, a rise time of 5 sec, and a settling time (±5 percent of steady-state value) of 20 sec. This step response incorporates a fine balance between the integral and derivative control gains that controllers of all robust landing systems must acquire. The gains must be structured enough to keep an airplane from suffering rapidly changing motions and flexible enough to allow for a quick response time.

To better represent the practical operation of the ALS, simulated radar noise and turbulence are introduced into the closed-loop simulation. As shown in Figure 4, the turbulence is added directly to the aircraft transfer function, whereas the noise is added to the position measurements of the aircraft. Turbulence is normally a result of air temperature instabilities and adverse weather conditions. Noise can include such complex ingredients as electromagnetic interference (EMI) from the radar system or any combination of measurement uncertainties. Therefore, the ability of a landing system to maintain tight control in the presence of noise and turbulence is of primary importance.

Althogh exact models predicting the nature and magnitude of the noise and turbulence present in the ALS are not obtainable, experimentally tested approximations used by the U.S. Navy are employed. First, an approximation of the noise that corrupts the position measurements of the radar tracking device is discussed. Normally, the most troublesome noise a landing system encounters is that in which the frequency content of the noise is located in the system's normal operating frequency bandwidth. Therefore, simply using a sine wave with a frequency near that of the system's operating frequency is assumed to be sufficient. The simulated ALS's frequency bandwidth ranges from approximately 0.1 rad/sec to 5 rad/sec. Next, a digital representation of turbulence is approximated by low-pass filtering a gaussian distributed random signal with zero mean. For this approximation, a commonly used cut-off frequency for the filter is 0.30 rad/sec. This is consistent with actual aircraft data (*3*).

The turbulence response of an aircraft can be defined as the relative position of the aircraft when the command (reference) signal is zero and only outside disturbances (noise and turbulence) affect the system. The generalized ALS, without noise rejection capabilities, has the turbulence response and corresponding error signal shown in Figure 7. Examining the turbulence response reveals that the error signal (which is directly related to the control signal) contains a high degree of noise. Therefore, the problem with the ALS is its inability to reduce the amount of noise present in the error (or control) signal while preserving the closed-loop response of the aircraft. Next, a method is presented for improving the noise rejection capabilities of the ALS.

CLOSED-LOOP SIMULATION WITH NOISE REJECTION FILTER

This section is concerned with the design of a noise rejection filter and its resulting effects on the closed-loop response of

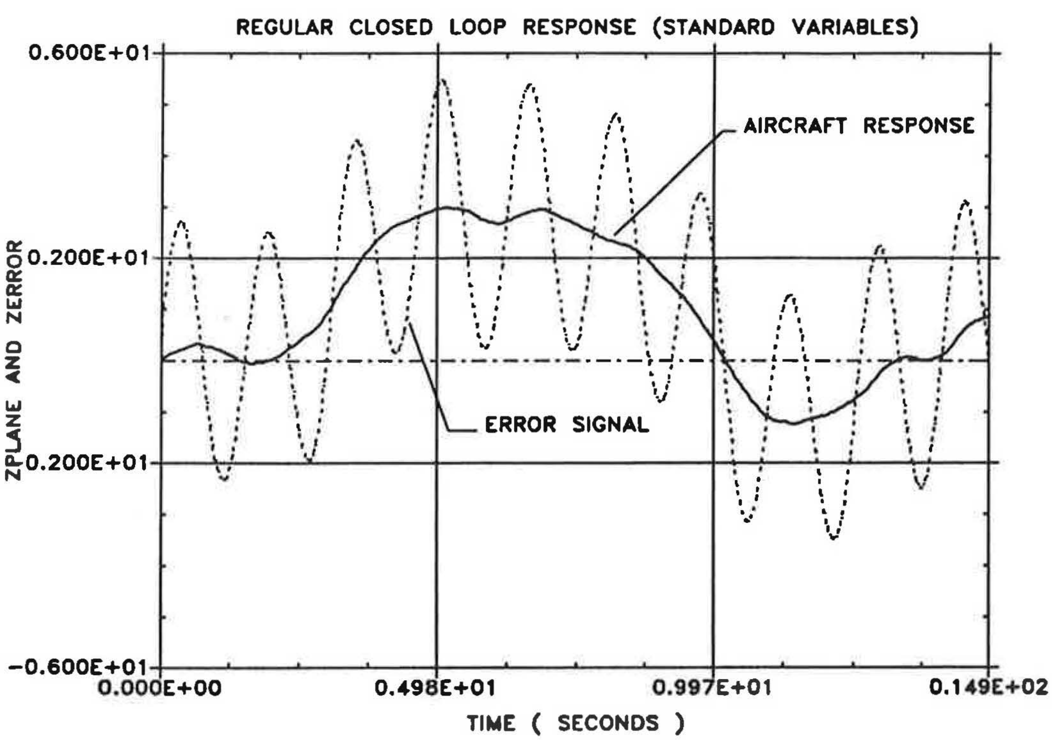


FIGURE 7 Turbulence response of ALS closed-loop simulation.

the ALS. First, a derivation of the theory involved in the development of the filter is examined. Next, frequency and time domain analysis of the total closed-loop response is used to investigate the critical characteristics of the landing system (with and without the noise rejection filter). Finally, some conclusions are drawn from the effects of the noise rejection filter on the ALS.

Noise Rejection Filter

The primary incentive for developing a noise rejection filter as part of the ALS is to reduce the amount of noise present in the control signal sent to the aircraft. This success will "smooth the bumps" in the control signal, and therefore produce more stable motions for the aircraft's response. Ideally, the effects of all radar noise should be minimized and the motion caused by turbulence should continue to be limited (preservation of the turbulence response).

The proposed noise rejection filter blends the combination of radar positional measurements with model estimates of the aircraft's velocity and acceleration to produce an error signal that is less sensitive to radar noise. The aircraft model estimates are produced from the numerical integration of the model previously developed. A transfer function representation of the proposed noise rejection filter is given as

$$Y(s) = \frac{X(s)}{s^2 + 2\zeta\omega s + \omega^2} + \frac{\Phi\hat{\dot{x}} + \Psi\hat{\ddot{x}}}{s^2 + 2\zeta\omega s + \omega^2} \quad (10)$$

where

$Y(s)$ = filter output,
$X(s)$ = measured position data,
$\hat{\dot{x}}$ = velocity estimate from aircraft model,
$\hat{\ddot{x}}$ = acceleration estimate from aircraft model, and
$\Phi, \Psi, \zeta, \omega$ = variable gains of the filter.

The corresponding time domain equivalent, which is the basis of the discrete-time simulation, can be described by the following equation:

$$y(t) = \int_0^t \int_0^t \omega^2[x(\tau) - y(\tau)]d\tau - \int_0^t 2\zeta\omega y(\tau)d\tau + \int_0^t \int_0^t \Phi\omega^2\hat{\dot{x}}(\tau)d\tau + \int_0^t \int_0^t \Psi\omega^2\hat{\ddot{x}}(\tau)d\tau \quad (11)$$

One of the underlying themes of this filter design is to assume that the equivalences $\hat{\dot{x}} \equiv s$ and $\hat{\ddot{x}} \equiv s^2$ are approximately true. Employing these assumptions and matching the numerator with the denominator, the relationships $\Phi = 2\zeta/\omega$ and $\Psi = 1/\omega^2$ are obtained. Therefore, it can easily be verified that the magnitude response of the filter should be close to unity while a blend of aircraft dynamics and measurements is performed.

The implementation of the filter's equations can be described in the following manner. First, the control signal that is sent to the aircraft is sampled at an arbitrary rate and used as input to the aircraft model. The model will in turn produce estimates of the velocity and acceleration of the aircraft. Next, the estimates and position measurements are blended to produce an error signal that is less sensitive to noise in the measurements. Therefore, the improved error signal will create a "smoother" control signal, which will in turn yield a more stable aircraft motion. The actual position of the noise filter with respect to the regular closed-loop system is shown in the block diagram in Figure 8. Because of the position of the filter, it is commonly referred to in the control literature as a model-following filter.

The parameters Φ, Ψ, ζ, and ω of the noise filter were chosen to minimize the amount of noise present in the control signal and allow the motion of the aircraft due to turbulence to pass through. Examining the parameters, the transfer function will produce a gross effect equivalent to 1 for the magnitude response of the filter. However, simultaneously these

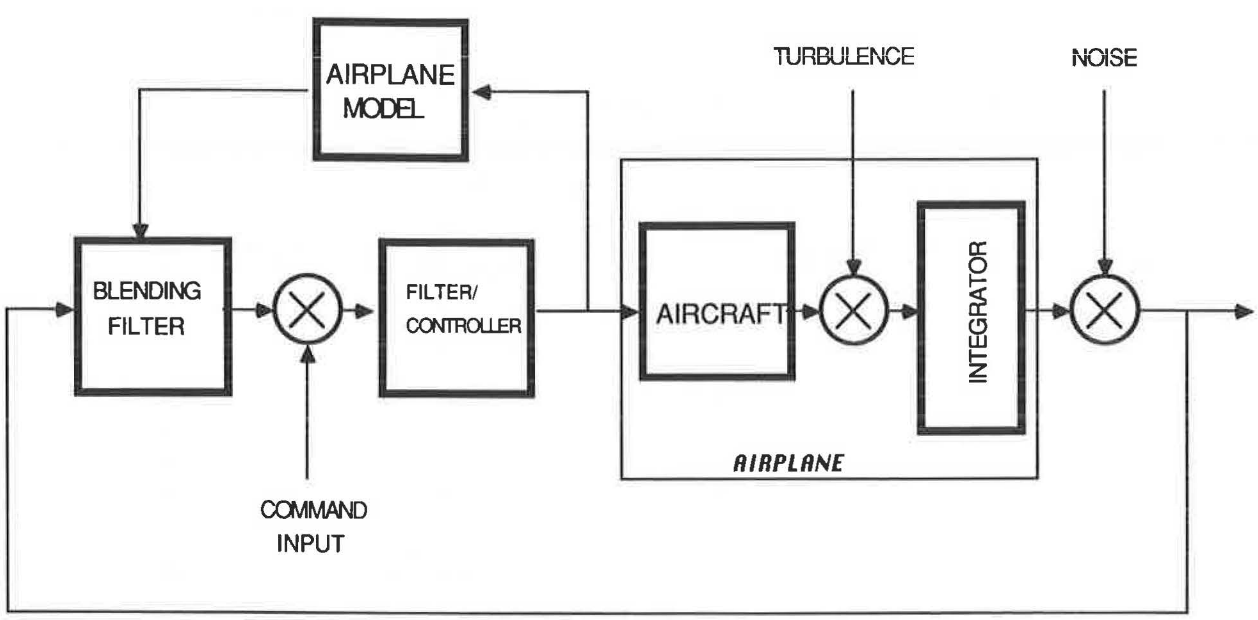


FIGURE 8 Closed-loop block diagram with noise filter.

parameters directly affect the measurement or estimate present in the blended error signal. For example, if ω equals 0.10, the modeled aircraft dynamics become the dominant factor in the blended error signal. However, for a value of ω equal to 10.0 the emphasis is placed on the position measurements.

It is equally important to choose these parameters in order to obey the classical control laws of a second-order system. For example, the denominator of the transfer function (called the characteristic equation) should produce roots (poles) that yield a proper damping ratio and natural frequency consistent with a stable system. Thus, choosing to model a system with ω equal to 1 rad/sec and a damping ratio of 0.7 produces the parameters $\Phi = 1.4$ and $\Psi = 1.0$. These are the parameters used in the simulation of the ALS.

An example of the noise rejection capabilities of the proposed filter is shown in Figures 9 and 10. First, using only noise as the input disturbance, a command signal of zero was directed to the aircraft. A plot of the input noise, control signal, and aircraft response for the case of no noise rejection filter is given in Figure 9. Under identical conditions, the simulation including the noise rejection filter was tested, and the resulting plot is given in Figure 10. The disturbance response of the aircraft utilizing this noise rejection (model-following) filter is obviously much less than that with no filter. These results illustrate the advantage for employing this filter in the basic ALS.

Filter Analysis

The generation of frequency domain Bode plots for the closed-loop system with a noise rejection filter was conducted in a manner similar to that described earlier. Sinusoids of several different frequencies with a magnitude of 1 were used as inputs to the discrete time simulation. Then the steady-state output was observed to determine the magnitude and phase changes in the signal. A summary of the closed-loop characteristics obtained from the Bode plots of both simulations is given in Table 1. It is apparent that there is a small increase in the magnitude response for the simulation with the noise filter.

To further examine the properties of this closed-loop simulation with a noise rejection filter, an investigation of the time domain characteristics is conducted. The time domain step response properties of both simulations are given in Table 2. Similar to the frequency domain results, the characteristics are almost identical except for the percentage of maximum overshoot. This supports an inclination that an increased aircraft response exists when the noise rejection filter is employed.

Judging from the relative increases in the response of the aircraft from the previous frequency and time domain analysis, one might predict that the turbulence response of the aircraft is also magnified. The turbulence response, using the identical noise and turbulence disturbance inputs, is in fact increased by almost a factor of 2. However, the great reduction of noise sensitivity in the control signal due to this filtering must not be forgotten. The graph of the turbulence response with the noise rejection filter is shown in Figure 11.

It can be deduced, by comparing Figures 7 and 11, that despite the successful reduction of the noise sensitivity of the control signal, the noise filter did not preserve the motion of the aircraft due to turbulence. Therefore, the question of how to decrease this turbulence response and simultaneously reject the noise using the proposed filter must be addressed. A simple solution to the problem might be to eliminate the use of the filter and try something different. However, because of the excellent noise rejection capabilities of the filter, an alternative solution would be more advantageous. One pos-

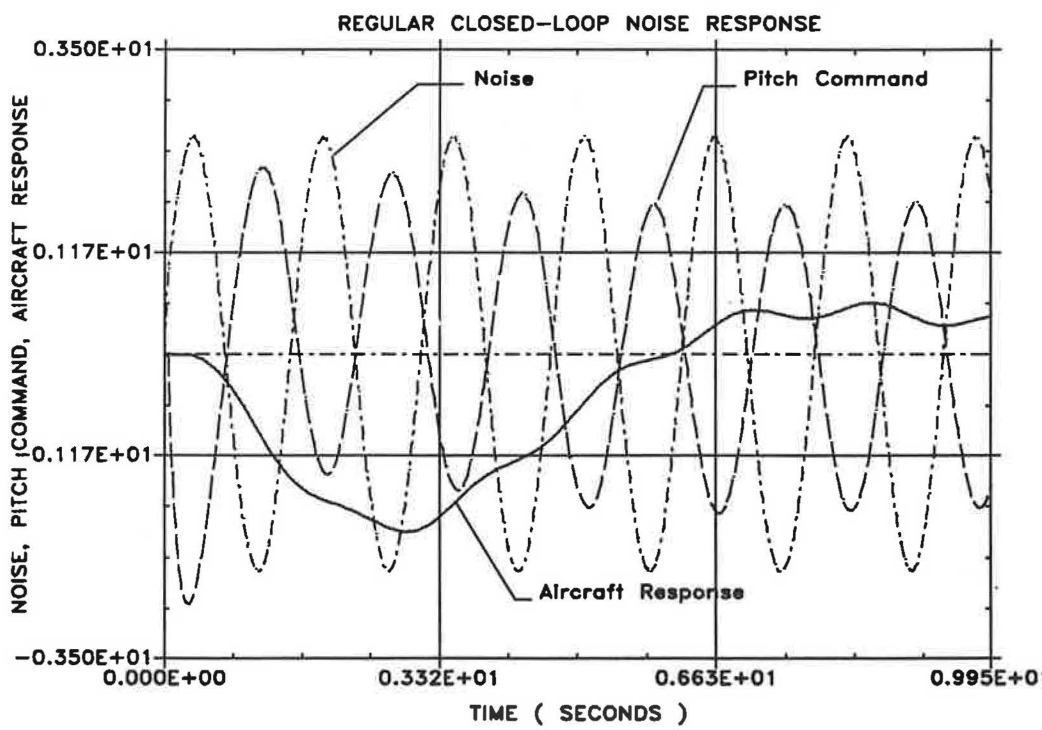


FIGURE 9 Disturbance response without noise filter.

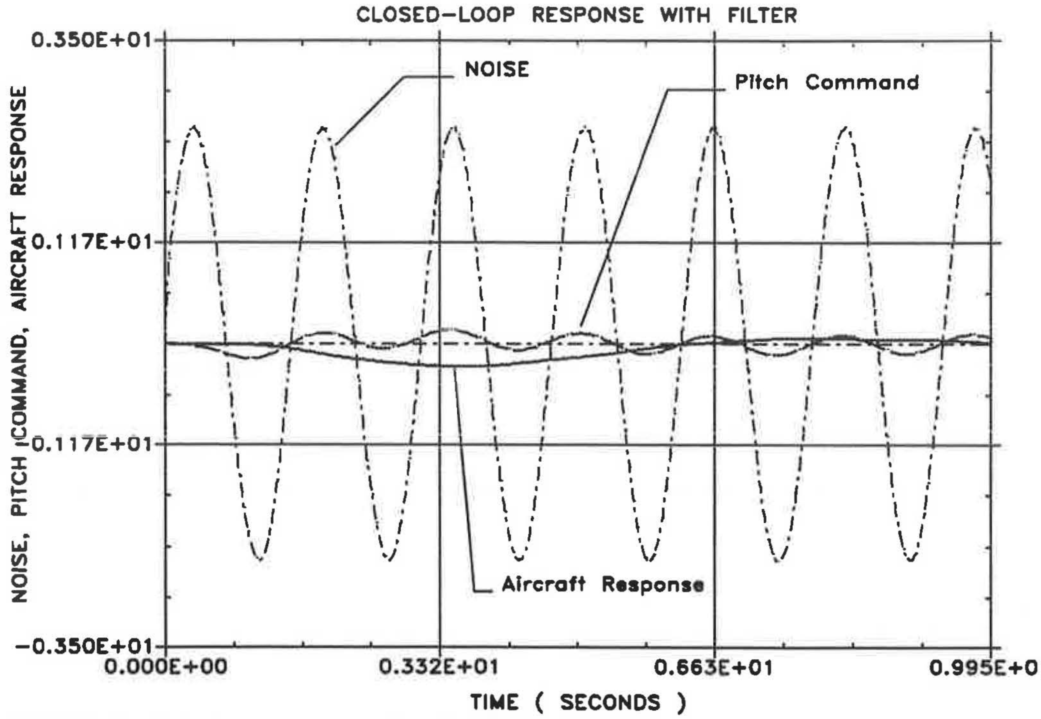


FIGURE 10 Disturbance response with noise filter.

TABLE 1 SUMMARY OF CLOSED-LOOP CHARACTERISTICS OF BODE PLOTS

	Regular Simulation	Noise Filter Simulation
Gain Margin	4.2 dB	4.3 dB
Phase Margin	40 degrees	45 degrees
Bandwidth	1.1 rad/sec	1.2 rad/sec
Maximum Gain	2.5 dB	3.0 dB

TABLE 2 TIME DOMAIN STEP RESPONSE PROPERTIES

	Regular Simulation	Noise Filter Simulation
Overshoot	5.0	8.0
Rise Time	5.0 sec	5.0 sec
Settling Time	20.0 sec	25.0 sec

sible solution, discussed in detail in the following section, is to alter the control loop gains of the PIDDD controller to produce a reduced turbulence response. The gains in the α-β-γ filter can also be changed to provoke similar results. However, one must be careful when altering gains to ensure stable closed-loop behavior.

CONTROL VARIABLE OPTIMIZATION

A proposed technique that allows for the use of the noise rejection filter by reducing the system's turbulence response is an optimization technique that treats the turbulence response of the aircraft as a cost function (performance index) and the controller gains as the variables to be optimized. A gradient direction extremization algorithm is used to formulate the optimization program that calculates the optimal control gains for the landing system. Also, a variety of three-dimensional optimization surfaces that correspond with the cost functions and two independent control variables are constructed to ensure proper operation of the optimization programs. As a result, the turbulence response of the aircraft is examined (employing the optimized control variables) to reveal the improved results when the noise rejection filter is used.

Optimization of Turbulence Response

One of the most straightforward numerical techniques used for optimization with respect to a given cost function is the

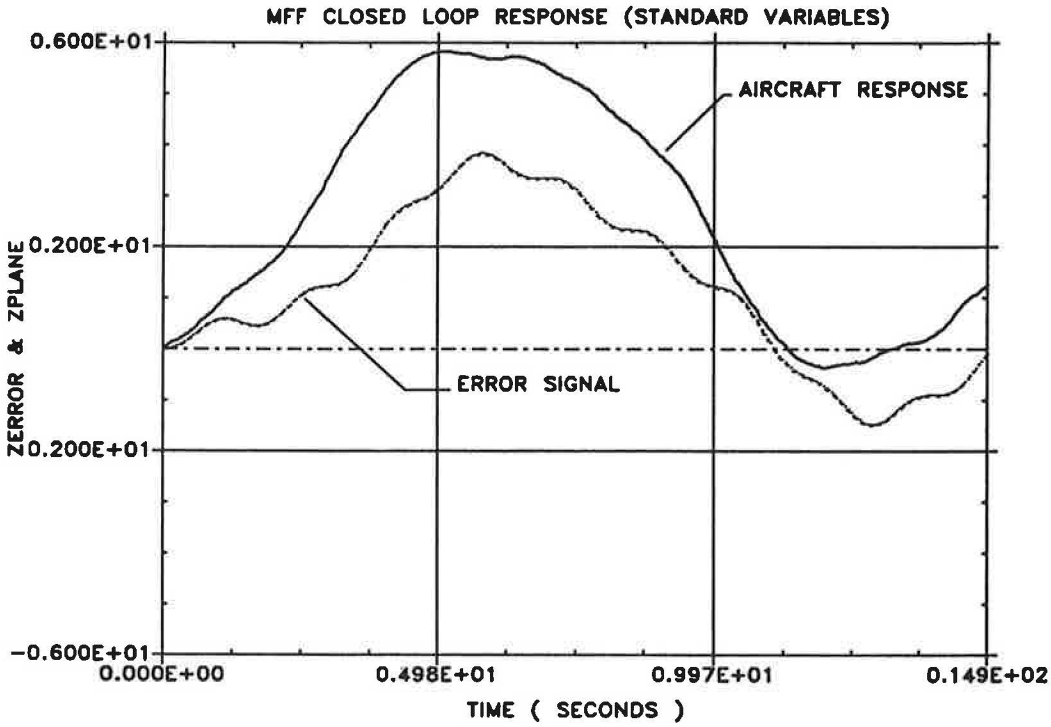


FIGURE 11 Turbulence response with noise filter.

gradient method or method of steepest descent (ascent) (*4*). This method of parameter optimization consists of several consecutive one-dimensional searches of an extremum of a function with respect to a specific cost function. More specifically, the numerical technique moves iteratively in the direction of the gradient, which points locally to the direction of steepest decline (incline) of the respective cost function. A detailed description of the optimization procedure as well as an optimal control representation are given by Bhagavan and Polge (*5*).

The direct application of the gradient direction algorithms for functional extremization varies extensively from problem to problem. For example, the minimization of the turbulence response of an aircraft with respect to its control variables is very unstable in many circumstances. Some of these circumstances include the choice of step size, the time interval used when determining the numerical gradient, and the initial starting guess of the control gains. However, after proper determination of the correct combination of these parameters, the optimization methods converge rather nicely on a minimum.

The cost function is calculated at every iteration to ensure that it is being minimized. The cost function used to describe the turbulence response is illustrated in the following equation. The quadratic form is used to ensure a "well-defined" minimum and also to offset the positive and negative portions of the response.

$$\Phi(x, t) = \int_{t_0}^{t_f} x(t)^T x(t) dt \qquad (12)$$

where $x(t)$ is the position of the aircraft.

This type of cost function, as related to the simulation program, provides for a good convergence rate in the control gains. Other, more complicated cost functions did not produce such stable results.

After implementation of the gradient method optimization program, the results can be summarized in the following manner. First, the optimization program was employed in the ALS computer simulation without the noise filter. Specifically, the two cases considered were (a) minimization of Φ with respect to the derivative and integral gains, and (b) minimization of Φ with respect to the filter gains α, β. Next, the optimization program was used in the ALS computer simulation with the noise rejection filter. The same two cases were considered as in the case without the filter. Illustrations of the optimization surfaces associated with the noise filter closed-loop simulation are given in Figures 12 and 13. The height of the three-dimensional optimization surfaces represents the value of the cost function for the pair of particular independent variables chosen. The two pairs investigated in this paper are integral and derivative controller gains and α and β filter gains.

These particular gains were chosen as optimization variables because the given cost function exhibited high sensitivity to them. For example, varying the double-derivative gain did not affect the magnitude of the cost function to any significant degree. However, the integral and derivative gains affected the cost function very much. For the case including the noise rejection filter, the value of the cost functional for the original gains was 401.4, whereas the optimal gains produced a cost function of 210.7. Therefore, the optimal gains reduced the cost function by approximately 50 percent.

When the α and β filter gains were optimized, the control gains were set to the values optimized. Note that after initial improvements caused by the control gains, additional improvements caused by α and β are minimal.

The minimized turbulence response of the aircraft due to the use of the optimized control and filter gains is now exam-

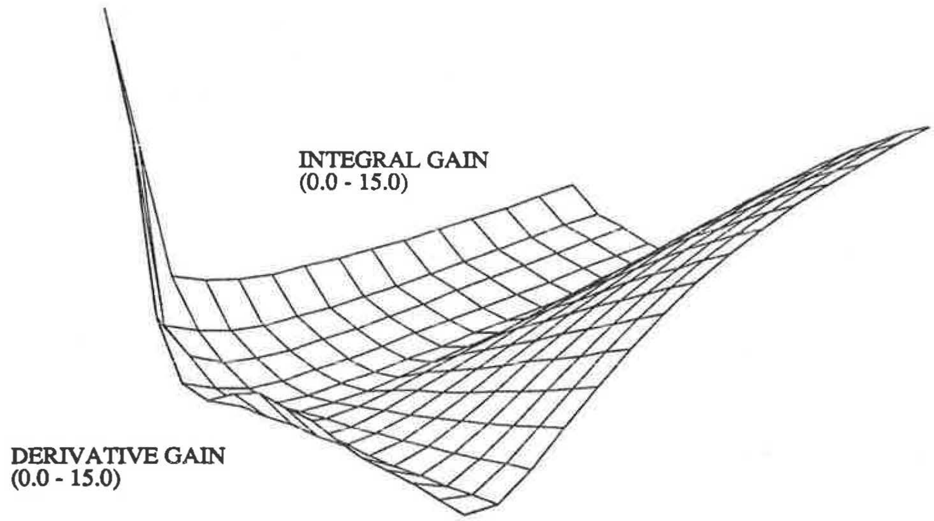


FIGURE 12 Optimization surface for K_I and K_D.

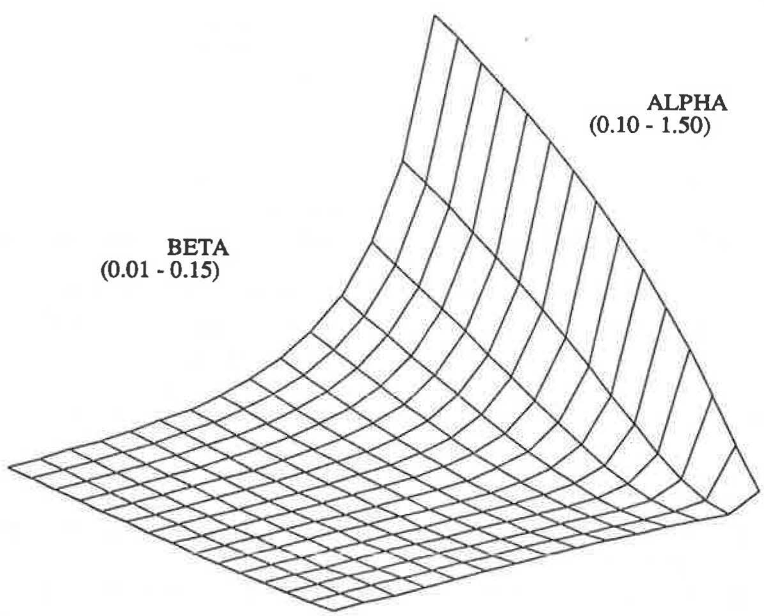


FIGURE 13 Optimization surface for α and β.

ined (Figure 14). In particular, does the implementation of the optimized control and filter gains succeed in improving the turbulence response of the aircraft while continuing to reject noise? The answer to this question is yes. The degree to which the turbulence response is minimized is best described by the figures of the turbulence response of the noise filter system utilizing the original and optimal gains. Note the reduction in both the noise contained in the error signal as compared with the case without the noise filter and also the basic aircraft response.

These results are fine if only the turbulence response is considered. However, this particular change in control/filter gains produces a more oscillatory response for the case of no turbulence. The next section addresses the problem of increased oscillations by optimizing the step response.

Optimization of Step Response

In the previous section, the optimization procedure consisted of minimizing a cost function related to the aircraft's turbulence response with respect to some control variables. However, by simply minimizing a cost function representative of only the turbulence response, the closed-loop characteristics of the ALS can easily be degraded. Therefore, attention is focused on obtaining an optimal step response so that these

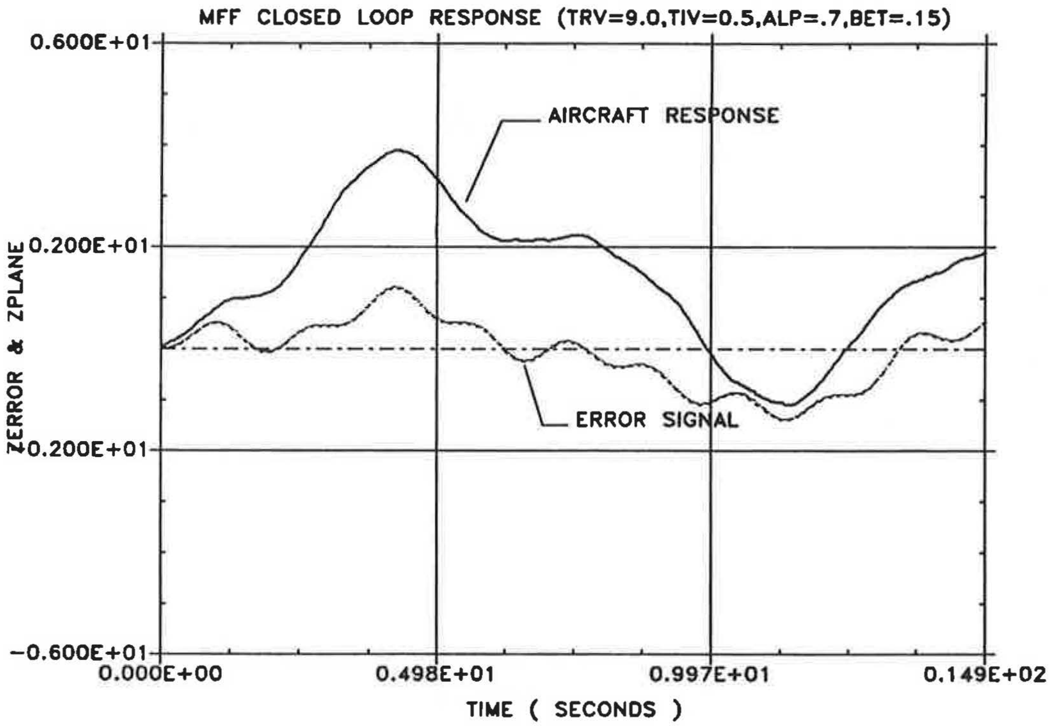


FIGURE 14 Turbulence response for optimal control gains.

TABLE 3 DERIVATIVE AND INTEGRAL GAINS OF OPTIMAL STEP RESPONSE

	Regular Simulation	Noise Filter Simulation
Derivative Gain	1.45	1.32
Integral Gain	16.75	29.52

closed-loop properties are conserved. To obtain an optimal step response, one must produce a fast response time, a low overshoot, and a reasonable settling time. A cost function that takes into account all of the stated requirements for an optimal step response is illustrated below:

$$\Phi(x,t) = \int_{t_0}^{t_f} [1.0 - x(t)]^T[1.0 - x(t)]dt \tag{13}$$

Implementing this cost function in place of the minimal turbulence response cost function will yield the proper control variables for an optimal step response. For the ALS simulations with and without the noise filter the derivative and integral gains of the optimal step response are given in Table 3. The step response with the noise filter is plotted for the original and optimal gains (Figure 15) to illustrate the significant improvements.

Combined Cost Function

Optimizing a cost function that is solely representitive of one particular response often degrades other critical characteristics related to the performance of the ALS. Therefore, the obvious solution is to develop a more encompassing cost function that considers both the turbulence response and the closed-loop characteristics. Because of the two separate parts that would make up such a cost function, each part must be properly weighted to obtain a desired optimal response. The choice of this weighting is left to the discretion of the user. Some examples are given that express the basic ideas of a combined cost function. The first cost function represents the minimization of the turbulence response, and the second represents the best possible step response. To aid in explaining the results more clearly, two tables are formulated. The first table, Table 4, gives the basic results of the uncombined cost functions. Each set of gains from the individual cost functions is then evaluated for the turbulence response and step response. Table 5 combines the preferable qualities from both cost functions and then examines their respective turbulence and step responses. The two gains examined for all cases are derivative and integral control gains. On close examination of the various plots, it can be seen that cases 4 and 7 have good results for both sets of criteria.

CONCLUSIONS

Projected advances in computer technologies coupled with control, filtering, and optimization techniques similar to those

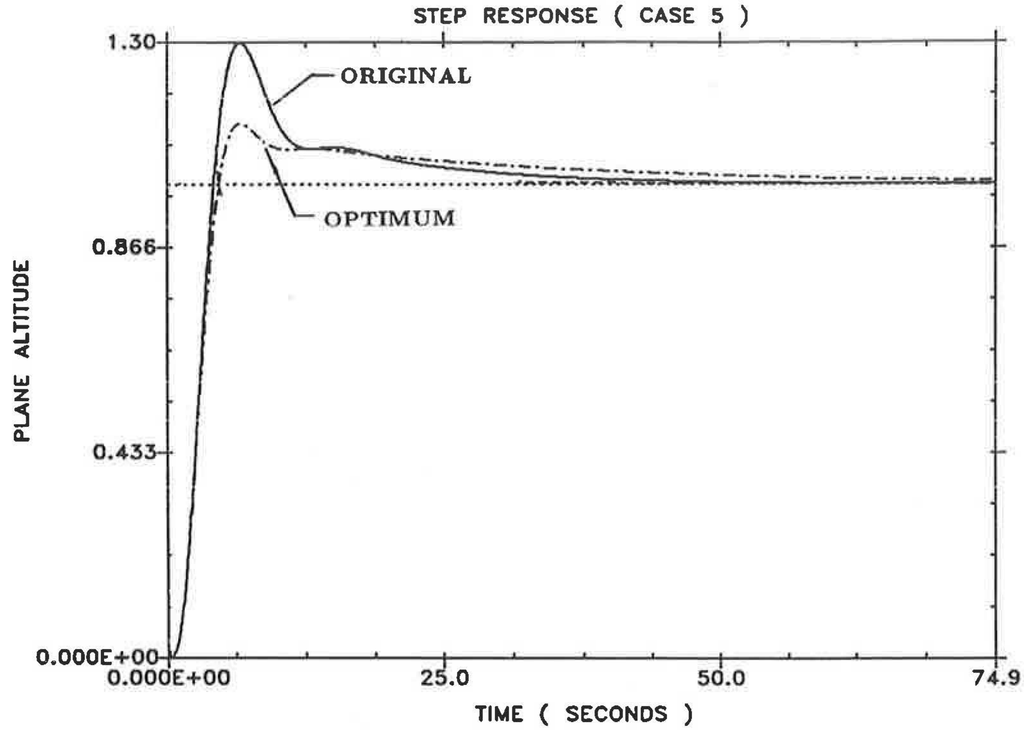


FIGURE 15 **Step response comparison for original and optimal gains.**

TABLE 4 RESULTS OF UNCOMBINED COST FUNCTIONS

	Gain Type	Gain Values	Turbulence Response	Step Response
Case 1	original gains	derivative = 1.0, integral = 15.0	very poor	good
Case 2	minimum turbulence response gains	derivative = 9.24, integral = 0.91	very good	very poor
Case 3	minimum step response gains	derivative = 1.32, integral = 29.52	very poor	very good

TABLE 5 RESULTS OF COMBINED COST FUNCTIONS

	Gain Values	Turbulence Response	Step Response
Case 4	derivative = 4.0, integral = 21.0	good	good
Case 5	derivative = 2.0, integral = 5.0	poor	very poor
Case 6	derivative = 8.0, integral = 25.0	good	poor
Case 7	derivative = 3.0, integral = 10.0	good	good
Case 8	derivative = 7.0, integral = 10.0	good	poor

presented here will become significant in the design of future ALSs for commercial aircraft. An ALS was simulated and analyzed so that improved performance with respect to radar tracking and control could be evaluated. Using a simplified model with robust tracking and control strategies, the noise sensitivity of the closed-loop simulation was examined. A noise rejection filter was introduced that produced excellent noise rejection abilities, but at the cost of an increased turbulence response of the aircraft. To address this dilemma, an optimization program was developed that minimized the turbulence response of the aircraft with repsect to some of the control and filter variables of the ALS. This optimization produced the optimal control and filter gains of the ALS with respect to a cost function related to the turbulence and step responses. Employing these optimal gains in the ALS control and filter algorithms produced improved results for the goal of rejecting radar noise while preserving a normal turbulence response.

ACKNOWLEDGMENTS

This paper was written for the Graduate Research Award Program on Public-Sector Aviation Issues sponsored by FAA and administered by TRB.

The author would like to thank D. Joseph Mook, assistant professor of mechanical engineering, State University of New York at Buffalo; E. Thomas Burnard and Larry Jenney of TRB; Greig W. Harvey, assistant professor of civil engineering, Stanford University; and Agam N. Sinha, head, transportation and data systems, MITRE Corporation, for their support, help, and encouragement throughout this project.

REFERENCES

1. A. N. Sinha. The Realization of Microwave Landing System Benefits. Presented at the PLANS 1988 Conference, Orlando, Fla, 1988.
2. J. N. Barrer and A. N. Sinha. An Operational Perspective of Potential Benefits of Microwave Landing Systems. *Proc. 31st Annual Meeting of the Air Traffic Control Association*, Arlington, Va., 1986.
3. M. J. Roemer. An Automatic Carrier Landing System Simulation/Realization with Control Variable Optimization. Master's thesis. University of Buffalo, N.Y. Feb. 1989.
4. D. Andrisani, F. P. Kuhl, and D. Gleason. A Nonlinear Tracker Using Attitude Measurements. *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-22, No. 5, Sept. 1986, pp. 574–580.
5. B. K. Bhagavan and R. J. Polge. Performance of the g-h Filter for Tracking Maneuvering Targets. *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-10, No. 6, Nov. 1974, pp. 721–727.
6. R. J. Fitzgerald. Simple Tracking Filters: Steady State Filtering and Smoothing Performance. *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-16, No. 3, Nov. 1980, pp. 860–864.
7. A. Gelb, ed. *Applied Optimal Estimation*. MIT Press, Cambridge, Mass., 1984.
8. F. L. Lewis. *Optimal Estimation*. Wiley-Interscience, New York, 1986.
9. J. B. Pearson. Kalman Filter Applications In Airborne Radar Tracking. *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-10, No. 3, May 1974, pp. 685–691.
10. R. J. Fitzgerald. Simple Tracking Filters: Closed Form Solutions. *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-17, No. 6, Nov. 1981, pp. 781–785.
11. A. P. Sage and C. C. White. *Optimum Systems Control*, Prentice Hall, Inc., Englewood Cliffs, N.J., 1977.
12. J. P. Schwieterman. Airline Routes and Metropolitan Areas: Changing Access to Non-stop Service Under Deregulation. In *Transportation Research Record 1161*, TRB, National Research Council, Washington, D.C., 1988, pp. 1–13.
13. I. H. Shyu. Performance Analysis of Several Aircraft Tracking Filters. Master's thesis. University of Buffalo, N.Y. Aug. 1988.
14. R. A. Singer. Estimating Optimal Tracking Filter Performance for Maneuvering Targets. *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-6, No. 4, July 1970, pp. 432–439.
15. C. T. Villarreal. Uses and Misuses of Risk Metrics in Air Transportation. In *Transportation Research Record 1161*, TRB, National Research Council, Washington, D.C., 1988, pp. 31–42.

Empirical Analysis of Runway Occupancy with Applications to Exit Taxiway Location and Automated Exit Guidance

TERRY A. RUHL

Airfield delay has a substantial economic impact on the users and suppliers of air transportation in the United States. A possible cost-effective measure to enhance runway capacity is to reduce the headway between aircraft arrivals and departures. Previous studies indicate that this alteration in operational procedure may increase runway capacity between 15 and 40 percent. Such a reduction in aircraft headway, however, implies that runway occupancy may become a constraint. Existing jet aircraft runway occupancy is addressed. Using data obtained from videotaped aircraft arrivals at four major airports in the western United States, factors that contribute most to arrival runway occupancy are analyzed. In particular, observed differences caused by airport-, aircraft-, and airline-related factors are identified. A model based on typical time-velocity relationships is developed, and the applications of such a model are presented. Using the model, two feasible alternatives are identified for a potential decrease in runway occupancy, which could then provide a possible increase in airfield capacity. Those alternatives are the improvement of exit taxiway placement and the introduction of Integrated Landing Management systems to match aircraft headways with existing runway occupancy times. Such a motivational system would be provided by the use of a real-time automated exit guidance system not only to assist in enhancing runway capacity but to communicate to the flight crew the optimum airfield routing scheme. The most serious impacts of such a system are those that deal with safety, which are beyond the scope of this paper. It is recommended that further research address the issues of airfield automation, primarily in relation to safety.

The ability to expand capacity at U.S. airports is of primary concern to the aviation industry. In particular, the potential for more efficient utilization of existing airport facilities is the most cost-effective procedure of upgrading airfield capacity. Airport delays are not all caused by runway occupancy and its related impacts. Nevertheless, Gosling et al. (*1*) estimate that approximately $75 million per year (1981 dollars) can be saved in aircraft operating costs by reducing runway occupancy, with even larger savings possible in the future. Although runway occupancy is currently not a constraint, further increases in runway capacity implied by changes in operational procedures require reducing the headway between aircraft. Therefore, runway occupancy may become a critical factor. To better understand the potential for reducing runway occupancy time, a field study was performed by videotaping arriving aircraft operations at four major airports in the western United States. The components of the landing sequence were analyzed on the basis of aircraft type (which is significant, especially because of the recent introductions of various Stage III aircraft) to statistically determine differences between airport-, aircraft-, and airline-related factors and to determine the parameter distributions.

The scope of this paper is to provide some insight into the possibilities of studying changes within the arrival process by developing a landing process model, sampling the various parameter distributions within the model, and illustrating how such a model can be applied toward improved exit taxiway location and innovations such as real-time deceleration guidance. With an improved knowledge of the aircraft arrival process, the potential exists for more effective airfield designs, thereby making capacity enhancement alternatives possible for the future.

BACKGROUND

Various studies concerning runway occupancy have produced similar results. In 1978, Koenig (*2*) analyzed observations collected in 1972 and 1973 and concluded that the dominant factor influencing a carrier's exit selection was its terminal gate location. Other controlling factors identified were incoming traffic density, flight crew performance, airline procedure, and passenger comfort. Significant differences were found between carriers motivated and not motivated by operational factors to exit early. It was estimated that feasible exits currently exist, although they are highly underutilized because of the availability of more favorable exits in terms of gate location. Also, it was estimated that further reductions in runway occupancy of between 2 and 14 sec could be anticipated if motivational factors were better incorporated.

In a study conducted in 1979, Jackson and Moy (*3*) verified Koenig's findings. They found that airline gate location had the most influence on runway occupancy. Thus it appeared, given certain conditions, that measures did exist to enhance runway capacity by employing motivational factors to decrease runway occupancy time. In addition, Jackson and Moy concluded that Instrument Flight Rule conditions actually led to a decrease in runway occupancy time because of an increase in operational awareness. This finding, however, was contrary to the conclusions reached in a later study by Steuart and Gray (*4*), which showed that runway occupancy times actually increase during poor weather conditions because of lower exit acceptance speeds and less braking adjustment to meet a particular exit.

Department of Civil Engineering, University of California, Berkeley, Calif. 94720. Current affiliation: Burns & McDonnell Engineering Co., 4800 East 63rd Street, Kansas City, Mo. 64141-0173.

One of the key variables involved in reducing runway occupancy time is the placement of exit taxiways. Methods for determing the location of exit taxiways (particularly high-speed taxiways) during saturation conditions were first developed around 1959. Two early studies by Horonjeff et al. (*5*, *6*) employed analytical models whereby optimal runway exit locations were determined from the standpoint of minimizing runway occupancy and wave-off probabilities. Later, in 1974, Daellenbach and Joline used dynamic programming concepts to optimize the placement of exit taxiways. Daellenbach's solution (*7*) determined exit locations using any joint probability distribution function of deceleration distances and times and any number of exits, which minimized the expected probability of a wave-off. Joline (*8*), using empirical exit distributions measured for the aircraft mix at O'Hare International Airport, developed an objective function to locate exit taxiways by minimizing runway occupancy time given capital investment constraints.

With the various methods of determining exit taxiway locations, empirical observations suggest that many aircraft use high-speed exits at approximately 20 to 40 mph below their design speeds (*9*, *10*). In separate studies, completed at different airport locations, Akinyemi and Braaksma (*9*), FAA (*10*), and Hosang (*11*) concluded that, among other reasons, high-speed exits were underutilized because of the desire to avoid unnecessary risk or passenger discomfort, the locaton of other exits in better proximity to the terminal building, and the incompatibility between aircraft performance with exit locations and geometric designs. FAA (*10*) analyzed existing runway occupancy statistics and concurrently developed design criteria and requirements for the redesign of high-speed exits. The results led FAA (*12*) to publish suggested exit taxiway locations for an "average" aircraft mix. Similar design specifications are provided by the International Civil Aviation Organization (ICAO) *Aerodrome Design Manual* (*13*).

Even today, there still appears to be a disparity in runway occupancy times among the various aircraft types. Of the methods used to determine exit taxiway locations, none rely on the individual parameters of the various aircraft types, nor are they based on any criterion for passenger comfort. The previous models are formulated on generalized relationships between landing distances and occupancy times and, in certain instances, the probability of a wave-off. If operational procedures are altered to increase capacity such that the landing sequence becomes critical, more detailed information will be necessary to assimilate the possibilities of obtaining such increases in capacity.

MODEL OF THE LANDING SEQUENCE

The runway occupancy model is based on the ability to use Monte Carlo simulation to generate aircraft arrivals that would reflect the input parameter distributions of the design aircraft, or those in use at the airport in question. The model is employed to analyze any changes in the parameter distributions or, in the case of exit taxiway locations, to determine the probability that an aircraft is able to accept an exit at any given location along the runway. Such cumulative acceptance curves may be estimated by trial runs of a given number of simulated aircraft arrivals. The percentage of aircraft accepting those exits can then be determined for any number of different exit taxiway locations by repeating the simulation for each exit location.

Input variables may be represented by random numbers with known means and variances that reflect the influences of environmental and airport conditions, as well as pilot technique. The general outline of the model is founded on basic kinematic equations that are developed in several discrete components, similar to those presented by Coggins (*14*). In order to distinguish between phases, time-velocity diagrams and a simplified profile view of typical aircraft arrivals are shown in Figure 1.

Initially, the aircraft passes the runway threshold at a height H_T ($t = 0$) and travels approximately at a constant velocity (V_T) until the flare maneuver, at which time the aircraft begins an in-air deceleration. This deceleration may take place at the runway threshold as well. Given the height at which the in-air deceleration is initiated, H_F, the approximate glide slope of the aircraft, S (feet/foot), and the wind speed component parallel to the moving aircraft, V_W (ft/sec) [(+) = headwind, (−) = tailwind], the time and distance to flare may be estimated by

$$T_F = \frac{S\,(H_T - H_F)}{(V_T - V_W)} \tag{1}$$

$$D_F = S\,(H_T - H_F) \approx 19\,(H_T - H_F) \quad \text{for a 3-degree glide slope} \tag{2}$$

After initiating the flare maneuver, the aircraft begins its in-air deceleration, a_{Air}, until the point of main gear touchdown. The touchdown airspeed of the aircraft, V_{TD}, is not an independent variable. It is dependent on the airspeed at threshold. Thus, by describing the relationship between the touchdown speed and the speed at the runway threshold [$V_{TD} = f(V_T)$] the time and distance to main gear touchdown may be estimated by

$$T_{TD} = \frac{(V_{TD} - V_T)}{a_{\text{Air}}} + T_F \qquad (V_F = V_T) \tag{3}$$

$$D_{TD} = V_T\,(T_{TD} - T_F) + \tfrac{1}{2}\,a_{\text{Air}}\,(T_{TD} - T_F)^2 + D_F \tag{4}$$

The sequence continues as the aircraft rotates to nose gear touchdown where it experiences a slight roll deceleration (a_{Roll}) due to the resistance gained by the surface friction between the pavement and the aircraft's main landing gear. The roll deceleration appears to be slightly larger than the in-air deceleration as the resistance gained by surface friction overcomes the resistance lost by the aerodynamic drag of the flare maneuver. Given this deceleration and the difference in time for the aircraft to rotate from main gear down until nose gear down ($T_{NG} - T_{TD}$) the airspeed (V_{NG}) and distance (D_{NG}) at nose gear touchdown may be found from

$$V_{NG} = (T_{NG} - T_{TD})\,a_{\text{Roll}} + V_{TD} \tag{5}$$

$$D_{NG} = V_{TD}\,(T_{NG} - T_{TD}) + \tfrac{1}{2}\,a_{\text{Roll}}\,(T_{NG} - T_{TD})^2 + D_{TD} \tag{6}$$

Immediately after touchdown, the deceleration rate reaches a maximum with the occurrence of reverse thrust and braking.

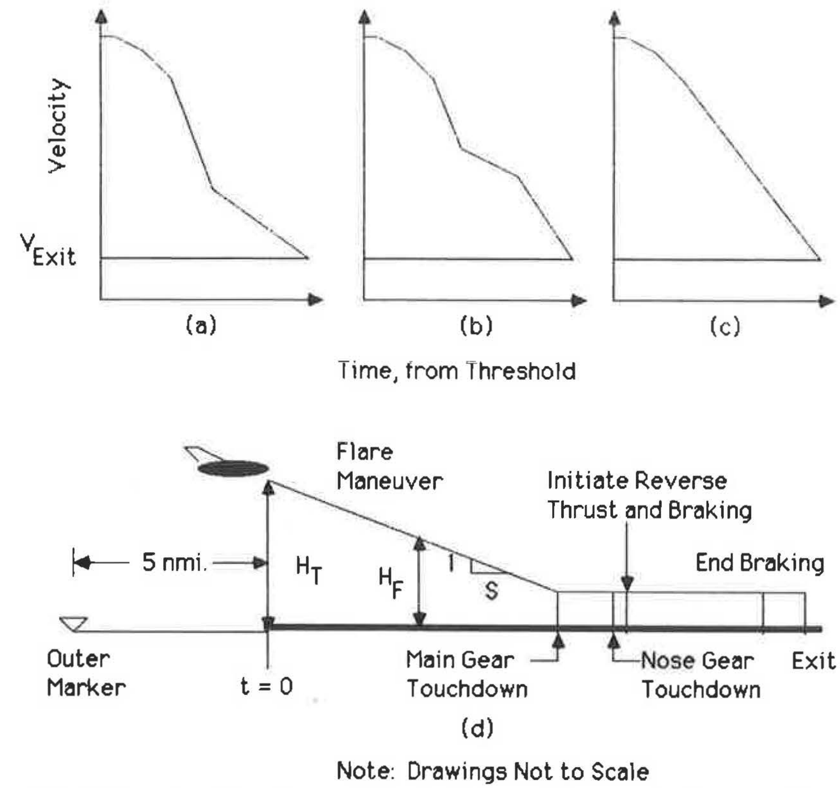


FIGURE 1 Aircraft landing sequence: (a,b) typical time-velocity diagrams; (c) model time-velocity diagram; (d) simplified profile view.

Depending on the exit location, aircraft speed is then adjusted to a safe handling speed for that exit. This can occur in two ways. First, the pilot may adjust deceleration to a lower rate so that the aircraft is at a safe acceptance speed by the time the exit is reached (Figure 1a). Second, the pilot may coast on the runway and engage in several distinct deceleration patterns (Figure 1b). An average braking deceleration rate will be used in this paper (Figure 1c). If this average deceleration rate allows the simulated aircraft to accept the exit or to stop before reaching the exit, it will be assumed that the pilot adjusted (decreased) the deceleration rate to meet the exit acceptance speed. This would be reflected in an average deceleration rate lower than the initial rate generated in the Monte Carlo simulation.

Once the aircraft begins braking deceleration, it traverses the runway until it comes to a point where a decision is made whether to accept a given exit and to turn off the runway. This decision point is assumed to be at the intersection of the exit taxiway centerline and the runway centerline. Therefore, knowing the average braking deceleration rate (a_{Brake}), the velocity (V'_x) at any point x, measured in feet from the runway threshold, can be determined from

$$V'_x = [V'^2_{NG} + 2a_{\text{Brake}}(x - D_{NG})]^{1/2} \tag{7}$$

for which the prime denotes groundspeed. Comparing V'_x with the exit acceptance velocity (V'_E), the velocity at which a safe exit maneuver may be initiated, it can be determined whether an aircraft will accept a given exit placed at a distance x from the runway threshold. The time and distance to the exit are calculated by

$$T_E = \frac{(V'_E - V'_{NG})}{a_{\text{Brake}}} + T_{NG} \tag{8}$$

$$D_E = \frac{V'^2_E - V'^2_{NG})}{2a_{\text{Brake}}} + D_{NG} \tag{9}$$

If no information is known concerning runway friction factors and gradients, which are effective when estimating stopping distances under inclement weather conditions and for abnormal runway grades, Equation 9 may be rewritten as

$$D_E = \frac{(V'_E - V'_{NG})^2}{(2\,g)\,(f + G)} + D_{NG} \tag{10}$$

where

g = acceleration of gravity (32.2 ft/sec^2),
f = coefficient of friction between the tires and the runway surface, and
G = grade of the runway over which the aircraft is traveling [(+) = upgrade, (−) = downgrade].

The final segment of the landing process involves the time an aircraft takes to clear the runway from the time it initiates its turn off the runway. This increment is a function of the exit type. Using the exit acceptance speed, the time to clear the runway can be found by dividing the arc length traversed by the exit acceptance speed. This value is only an approximation because a slight deceleration will still be taking place

during the actual turning movement. In fact, for its design criteria of high-speed exit taxiways, the ICAO *Aerodrome Design Manual* (*13*) provides estimated deceleration rates of 0.76 m/sec^2 (2.49 ft/sec^2) along the turnoff curve and 1.52 m/sec^2 (4.99 ft/sec^2) along the straight section of the exit taxiway. A simpler assumption would be to add a constant additional time increment. Analysis of data obtained within this study indicates that an average value for the clearance time of an aircraft at right-angle exits is approximately 12 sec. Shorter clearances would be expected for high-speed exits. Horonjeff and McKelvey (*15*) suggest an aggregate value of 10 sec as a good estimate of the time for an aircraft to clear the runway from the beginning of its turn into the exit taxiway.

PARAMETER DISTRIBUTIONS

Field Study

In order to determine the input parameter distributions as well as the influence of various airport-, aircraft-, and airline-related factors, including environmental conditions and pilot technique, a field study was performed. It involved simultaneously videotaping arriving aircraft, recording approach speeds from the ARTS III BRITE radar display, and recording tower-to-aircraft communication at the following four airports: Metropolitan Oakland International Airport (OAK), Phoenix Sky Harbor International Airport (PHX), San Francisco International Airport (SFO), and San Jose International Airport (SJC).

At each airport, standard videotaping equipment was used to film as many air carrier jet aircraft as possible during a 2-hr time frame that was prearranged with the FAA. Aircraft were filmed from the control tower and were followed throughout the landing sequence as they appeared approximately 1 mi out from the runway threshold. The aircraft were then followed through touchdown, braking, and exiting until at least the tail of the aircraft had crossed the runway edge striping as it proceeded onto the exit taxiway. While the aircraft was being videotaped, its approach speed at each mile from the runway threshold, beginning at the outer marker (5 nautical mi out), was recorded from the BRITE radar display. Concurrently, tower-to-aircraft communication was recorded to obtain existing wind information and any special instructions given to and among the pilots. In addition, weather information was obtained from the Automated Terminal Information System.

A complete analysis of the landing sequence was conducted for 180 aircraft. This included the aircraft type (B727, MD80, etc.), airline, flight number, runway, airport, date, approximate time, weather conditions, groundspeed at 5 mi out (outer marker), distances and times to touchdown, height at threshold, runway occupancy time, and any special instructions given to a pilot. In addition, the velocity at threshold was estimated by fitting a smooth curve to a plot of velocity versus position from the runway threshold, using the information obtained from the BRITE radar screen. In all, 20 hr of videotaping was produced, with the traffic density during the 2 hr of filming varying considerably between airports. An additional 100 arrivals were analyzed by recording aircraft type, airline, exit location, runway occupancy time, and the radio transmission between the pilots and the control tower. These observations were incomplete because of the inability to reference positions in the video image for certain situations (crossing threshold, touchdown, etc.).

Once the aircraft was viewed over the runway, time and distance information was recorded with the aid of a stopwatch contained within the video image and an aerial photograph of the airfield surface. The height of the aircraft at threshold (referenced from the bottom of the nose gear) could be estimated to the nearest 5 ft by using video-enhancing computer software and proportioning known heights of the aircraft from the bottom of its nose gear to the top of the cabin with the respective heights in the video image.

Distance references were made from touchdown markings as well as centerline striping and any other distinct objects that could be witnessed in the image. Times to touchdown (both main gear and nose gear) were recorded to the nearest second and referenced from the time the aircraft crossed the runway threshold. Distances (to both main gear and nose gear touchdown) were also referenced from the runway threshold using the aircraft's nose gear position and recorded to the nearest 100 ft. In an attempt to verify position and threshold velocity estimations, the average speed from threshold to main gear touchdown and from threshold to nose gear touchdown was recorded for each arrival. (All recorded speeds were estimated to the nearest 5 knots.)

For most observations, speed estimations, such as those at touchdown and at other points along the runway, could not be obtained until the aircraft was close enough to the camera location because of the inability to distinguish known lengths and corresponding times at locations further away. However, using an average of the speeds from threshold to main gear touchdown and threshold to nose gear touchdown along with their corresponding positions, an average braking deceleration rate was estimated from touchdown to exit. It is emphasized that this is only an approximation because at certain times, especially during the initiation of reverse thrust and braking, actual deceleration rates may be higher. A summary of the previously described information, segregated by aircraft type, is presented in Table 1.

Once the aircraft began to turn off the runway, its velocity at the decision point was determined by measuring the time that the aircraft nose gear traversed the final runway centerline hash mark of known length. Information by aircraft type for each exit is presented in Table 2. On the average, for both high-speed and right-angle exits, the average exit speed for heavy aircraft is approximately 7 knots less than that for large aircraft. Standard deviations of the various exit speeds are approximately 5 knots. Table 2 also indicates that the high-speed exits at Oakland appear to be entered at velocities closer to their design speed, because of their location and spiral (or transitional) design. In addition, the right-angle taxiways at Phoenix show relatively high speeds. For the most part, aircraft at Phoenix were able to "cut the corner" and not make as sharp a right turn as necessary at San Francisco because of the airfield pavement layout. Also, note that San Francisco exit taxiway J has the same average exit speed as exit taxiway T because of the difference in the aircraft mix using the exits. Both taxiways are high-speed designs, but taxiway T has a more gradual radius change and thus a higher design speed. In fact, the design speed of 60 knots is nearly

TABLE 1 EMPIRICALLY MEASURED PARAMETER DISTRIBUTIONS BY AIRCRAFT TYPE

Aircraft Type and Statistical Category	Airspeed @ Threshold (knots)	Height @ Threshold (feet)	Distance to MG Down (feet)	Time to MG Down (seconds)	Distance to NG Down (feet)	MG to NG Rotation (seconds)	Avg. Brake Deceleration (ft/sec/sec)
BAe146							
Average	117	52	1980	11.3	2660	4.4	3.91
Standard Deviation	10.66	12.49	600	3.17	652	1.84	1.14
Range	105-140	30-70	800-3200	5-17	1700-3900	2-8	1.7-3.9
Num. of Observations	15	15	15	15	15	15	15
B727							
Average	130	49	1870	9.2	3060	6.6	5.23
Standard Deviation	11	7.36	534	2.30	731	2.90	2.14
Range	105-145	35-70	1100-2900	5-14	1400-4500	3-12	1.3-10.1
Num. of Observations	27	25	25	25	25	25	24
B737							
Average	136	48	1810	8.5	2490	3.4	5.71
Standard Deviation	10.51	9.48	386	1.88	414	1.39	1.17
Range	135-165	25-65	1100-2800	5-13	1500-3600	1-7	3.3-9.9
Num. of Observations	68	68	68	68	68	68	68
B757							
Average	129	54	2260	11.1	3000	3.9	5.76
Standard Deviation	10.18	6.07	443	2.12	455	1.95	0.52
Range	115-145	45-60	1400-2600	7-13	2300-3700	1-7	5.0-6.4
Num. of Observations	7	7	7	7	7	7	7
B767							
Average	128	56	2360	11.6	3290	4.9	5.34
Standard Deviation	7.20	10.11	652	3.26	991	2.02	1.28
Range	115-140	45-70	1500-3400	7-16	2200-5500	3-10	2.5-7.4
Num. of Observations	11	11	11	11	11	11	11
MD80							
Average	134	54	1950	9.3	2650	3.5	5.49
Standard Deviation	12.75	9.90	457	2.11	505	1.48	1.31
Range	105-160	35-70	1300-3100	6-14	1800-4000	1-8	1.7-8.7
Num. of Observations	28	26	26	26	26	26	26
All Heavies (B747, L1011, DC8, DC10)							
Average	141	64	2530	11.2	3970	5.9	5.91
Standard Deviation	7.19	10.46	828	3.53	1161	3.04	1.34
Range	130-155	45-80	1300-4400	5-19	2300-6000	1-11	3.9-7.7
Num. of Observations	14	14	14	14	14	14	14

20 knots greater than the speed at which pilots are willing to begin to negotiate a turn onto the exit taxiway.

Air traffic controller guidance was recorded and the runway occupancy time was determined as the time during which the aircraft began to cross the runway threshold until the tail of the aircraft had cleared the runway. Those runway occupancy times measured at the various airports for aircraft that were motivated to exit, either by terminal gate location or by air traffic controller guidance, as well as those that were not motivated are presented in Table 3. Comparison with other published studies indicates relative similarity in runway occupancy times even though some of the earlier studies are analyses of aircraft landings conducted 10 to 20 years ago. Thus, major changes in runway occupancy times have not occurred with the introduction of various Stage III aircraft. More important, note the wide range of runway occupancy times for motivated carriers.

Review of Other Data Sources

In order to provide a realistic and accurate model of the landing process, it is necessary to know the distributions of the various parameters involved, and as previously noted, it was not possible to obtain all the necessary information from the videotaped arrivals. Therefore, various other sources were consulted.

First, the height at flare, which could not be distinctly observed in the video image, was presented in a study by Schoen et al. (*17*) based on observations of various turbojet aircraft in a study by Geoffrian and Kibardin (*18*) published much earlier, in 1962. The average height at which the flare maneuver took place was estimated to be 32 ft with a standard deviation of 15 ft above the runway surface. From the flare maneuver to touchdown, it is also necessary to project the in-air deceleration rate, which could vary quite significantly

TABLE 2 EXIT SPEED ANALYSIS FOR ALL AIRCRAFT TYPES

Airport - Runway	*Exit	Avg. Exit Speed (kn)	% Large	% Heavy
OAK - 29	6 (H)	50	100	0
	7 (H)	45	100	0
PHX - 8R	C5 (R)	29	100	0
	C6 (R)	35	100	0
	C7 (R)	29	100	0
	C8 (R)	28	0	100
	All (R)	32	96	4
SFO - 28L	D (R)	28	75	25
	E (H)	35	75	25
	J (H)	43	86	14
	K (R)	29	43	57
SFO - 28R	D (R)	22	0	100
	E (H)	33	87	13
	K (R)	28	40	60
	T (H)	43	21	79

* - Letters in parentheses denote High-speed (H), or Right-angle (R) exits.

Average Exit Speeds (knots)

		Right Angle	High Speed
Aircraft	Large	32	46
Type:	Heavy	25	39

TABLE 3 RUNWAY OCCUPANCY TIME SUMMARY

Airport - Runway	Aircraft Class	Num. of Observations	Range (seconds)	Average ROT (seconds)	Previous Studies: Avg. ROT (seconds)
Motivated Carriers:					
PHX - 8R	Large	54	41-62	49.7	---
OAK- 29	Large	20	32-57	44.5	---
SJC - 30L	Large	10	36-56	45.3	51.3 (16)
SFO - 28L	Large	37	37-68	47.3	49.1 (2)
SFO - 28R	Large	52	42-68	52.0	46.3 (2)
SFO - 28R	Heavy	13	47-77	54.6	56.0 (2)
All Observations:					
SFO - 28L	Large	53	37-83	54.3	
SFO - 28L	Heavy	12	35-82	64.0	
SFO - 28R	Large	82	42-77	54.3	
SFO- 28R	Heavy	27	47-92	63.1	

Dashes indicate that previous runway occupancy studies were not available.

across aircraft types because of the disparity among the existing aerodynamic designs. Not much data is currently available concerning aircraft in-air deceleration rates, yet Horonjeff and McKelvey (*15*) project an aggregate average in-air deceleration of 2.5 ft/sec^2, and from a recent draft report on runway friction tests by Yager et al. (*19*), decleration rates of 2.2 ft/sec^2 and 1.7 ft/sec^2 were observed for the B737-100 and B727-100 aircraft, respectively. Unfortunately, no information concerning the actual distributions of these deceleration rates is readily available.

Various sources were also consulted for information concerning the relationship between the speed at threshold and the corresponding speed at touchdown. Horonjeff and McKelvey (*15*) provide information that speeds at touchdown are on the order of 5 to 8 knots less than the speed across threshold. In addition, Yager et al (*19*) displayed time-velocity relationships in which the groundspeed difference between threshold and touchdown for the B737-100 was 8.5 knots ($V_{TD} = 0.93V_T$) and 5 knots ($V_{TD} = 0.97V_T$) for the B727-100. Similarly, B727-200 simulator data, obtained from the National Aeronautics and Space Administration Ames Research Center, showed that the airspeed at touchdown was approximately 97 percent of the airspeed at threshold. Finally, Schoen et al. (*17*) presented results as given in the earlier study (*18*) that, on the average, touchdown speeds were approximately 8.63 knots less than the corresponding speed at threshold ($V_{TD} = 0.935V_T$) with a standard deviation of 5.07 knots ($0.038V_T$).

As mentioned earlier, once the aircraft touches down, it begins to exhibit a slightly greater deceleration rate. From a study by Yager et al. (*19*), the average roll deceleration for

the B727-100 was calculated to be about 2.4 ft/sec², which is approximately 40 percent higher than the in-air deceleration rate. Also, it is believed that differences in roll deceleration rates vary depending more on the weight of the aircraft than on the individual aerodynamic design. No other published values for roll deceleration rates have been found. However, because the in-air and roll deceleration rates account for only a small portion of the overall deceleration rate, their estimates are not as important as the average braking deceleration rates.

Braking rates are obviously dependent on the relationship between the aircraft touchdown point and the available locations of exit taxiways in relation to the terminal building. Maximum braking rates can approach between 10 and 16 ft/sec² (*19*) depending on surface friction and the braking maneuver (automatic or manual) performed. More important, it is necessary to determine the comfort threshold for aircraft passengers because such a value is necessary when determining realistic exit taxiway locations. Whereas few studies have investigated comfortable rates for aircraft occupants, automobile occupants appear to have a comfort threshold of 8 ft/sec² (*20*). Although conditions could not be controlled in the field study so as to determine an exact value, Figure 2 indicates that 8 ft/sec² appears to be the maximum rate at which aircraft deceleration takes place. In some instances, for those touchdown points that are less than 2,000 ft from the exit accepted, pilots were willing to reach a maximum of 10 ft/sec². In addition, of the three aircraft witnessed to have deceleration rates over 9 ft/sec² two of them were cargo carriers. This seems to imply that the human comfort threshold for aircraft deceleration rates is near 8 ft/sec² as well, but as mentioned earlier, these average values somewhat underestimate the instantaneous decelerations taking place.

Besides the criterion for comfort, surface conditions play an important role in the ability of an aircraft to decelerate to a safe exit speed. Approximate values for the coefficient of friction (f) between the tires and the runway surface have been noted in previous research. Specifically, Schoen et al. (*17*) estimated the following available ground coefficients of friction: dry pavement, 0.8; wet pavement, 0.4; packed snow, 0.2; and ice, 0.1. These values suggest that considerably longer runway occupancy times can be expected in inclement weather.

STATISTICAL ANALYSIS

To determine the parameter distributions and to distinguish possible differences between certain external factors, various statistical analyses were performed on the data obtained from the field study. Statistics for those parameters measured in the field study are given in Tables 1 through 3. In addition, using a one-way analysis of variance (ANOVA), parameters were tested to differ among airports, aircraft types, and airlines at a 0.05 level of significance. Higher-level ANOVA tests were not used because it was observed that all airlines did not use all airports nor did airlines always use the same aircraft type at each airport.

Investigation of the data by aircraft type indicated that environmental conditions seemed to have little impact on the individual parameters. Because all the operations were witnessed under Visual Flight Rules (VFR) conditions, this is not surprising, yet even the Phoenix observations, which include somewhat different environmental conditions, were not statistically significantly different from the Bay Area observations. The temperatures ranged from 60°F at Oakland to 82° at Phoenix (95° temperatures occurred at San Jose, but only during 10 observations). Pressures ranged from 29.81 in. of mercury at Phoenix, to 30.34 in. at San Francisco. These variations are within 2 percent of standard pressure and 4.5 percent of standard temperature conditions.

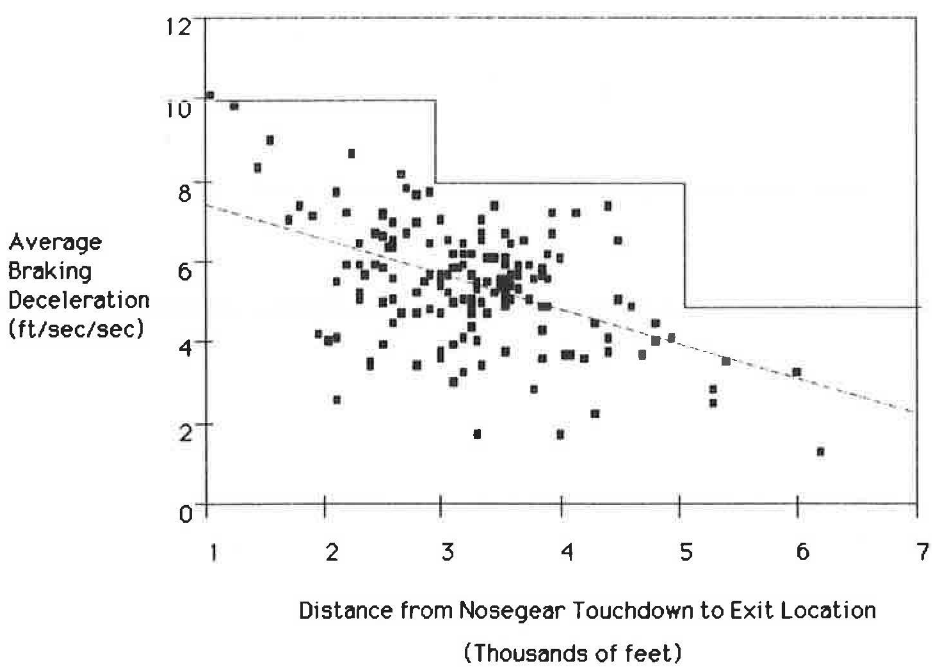


FIGURE 2 Relationship between average braking rate and touchdown location.

Interairport Differences

Intuitively, the configuration of the runway and taxiway system as well as the placement of exit taxiways has a large impact on runway occupancy. This analysis, however, investigated specific aspects within the landing sequence, as well as the overall result that makes one airport significantly different from another.

For all the types of air carrier aircraft flying into San Jose International, significant differences in the height at threshold, distance and time to main gear touchdown, and thus distance and time to nose gear touchdown resulted. This is due to the displaced threshold design used by arriving aircraft at San Jose. For example, the aggregate average height at threshold at the three remaining airports was nearly 50 ft, whereas for those aircraft sampled at San Jose the average height was 24 ft, with a range of 10 to 35 ft. Furthermore, lower height-at-threshold values propagated to lower touchdown distances and times. (For this reason, data obtained from San Jose were removed from the aggregated aircraft type parameter distributions given in Table 1.)

It should be evident from Table 2 that the high-speed exit taxiways in place at Metropolitan Oakland International Airport are utilized closest to their potential. This observation, matched with the fact that all airlines are motivated to exit early because of their terminal location, yields the lowest runway occupancy minimum and average time values. With only two exits in place, this seems to be an economical optimum in terms of construction cost as well as the availability to increase capacity. However, it should be noted that exit taxiway placement and its relationship to the terminal location significantly affect the taxiing times for aircraft. Thus, depending on the incoming traffic density, the ultimate solution to the placement of exit taxiways may not be found using a simulation concerned with the arrival sequence alone, but incorporated within network optimizations that are found in other simulation and optimization programs. Programs that deal with optimizations during saturation conditions are described in a recent article in *Airport Forum* (*21*) and in existing FAA simulations (*22*). In addition, Tosić et al. (*23*) present an optimization to locate exit taxiways such that the cost of taxiing to the terminal building is minimized. Such an optimization is relevant during periods of low incoming traffic density.

Interaircraft Differences

Several ANOVA tests were performed on heavy aircraft to determine whether the parameters of individual aircraft types were sufficiently similar to group them under one classification. Results indicated that heavy aircraft were statistically similar, with the exception of the B767. More specifically, the airspeeds at threshold values expected for the B767 were significantly lower than those for other heavy aircraft (F-ratio = 13.89, Probe > F = 0.00). Lower values for this parameter propagated into lower comparable values for some of the other parameters. Table 1, however, indicates that not all of the parameters show significant differences. For example, the times to touchdown among all heavy aircraft are quite similar.

Similarities were also noted in the parameter values given in Table 1 between the B757 and the B767. This is expected, because the design and operating characteristics of the two aircraft are very similar. Even though they may be classified differently (the weight of the B757 is just under the minimum for classification as a heavy aircraft, and the B767 is just over the weight separation), they operate in a very similar manner. In many respects, including airspeed at threshold, the two aircraft operate more like large aircraft, yet their exiting and turning capabilities are similar to those of heavy aircraft.

Analyses of runway occupancy times for large aircraft across all exits illustrated a significant difference between individual aircraft types (F = 2.95, Prob > F = 0.01. However, when B757 aircraft were omitted from this classification, the differences in runway occupancy times became insignificant (F = 1.35, Prob > F = 0.25). This indicates the similarity between runway occupancy times among large aircraft, with the exception of the B757. Moreover, after the BAe146 is omitted, the F-ratio drops even further to 0.80 with a probability of 0.49. However, when differences in exit distances, aggregated among all airports are analyzed, there is relatively little difference between large aircraft types (F = 0.77, Prob > F = 0.58). Without the B757, the F-ratio and corresponding probability remain fairly constant (F = 0.79, Prob > F = 0.53). Furthermore, without the BAe146, the F-ratio change is again insignificant (F = 0.73, Prob > F = 0.54). Therefore, the exit distances for large aircraft are relatively similar, but the runway occupancy times vary, chiefly because of the BAe146 and the B757.

It is postulated that even though the BAe146 is able to make the same exits as its larger counterparts, the aircraft is typically slower across threshold, and even slower in comparison with other large aircraft immediately after touchdown. In addition, even though there is no significant difference in average braking deceleration between large and heavy aircraft, there is a significant difference among individual aircraft types (F = 2.64, Prob > F = 0.01). When the BAe146 are removed from this aggregation, the F-ratio drops to 0.73 with a probability of 0.67. Most likely this is not because of the braking characteristics of the aircraft itself, but because the lower arrival speed of the BAe146 forces it to taxi for some time on the runway before reaching a suitable exit.

The B757 differences are believed to be the result of other factors. The B757 exhibits deceleration and speed characteristics similar to those of other large aircraft. However, it is believed that because of the large amount of torque built up at the nose gear during exiting maneuvers, the aircraft has a slower exit acceptance velocity than other large aircraft and, in turn, takes longer to exit the runway after reaching the exit decision point.

Interairline Differences

Strong differences in parameter means between airlines and airports resulted within the B737 aircraft classification. Analyses of distances and times to touchdown indicated significant differences between airports; however, this difference was isolated to the differences in only one airline at one airport. Also, significant differences in the height at threshold resulted between airlines. Again, this was attributed to one airline.

Similar differences occurred for other aircraft types as well. For instance, the height at threshold for the MD80s showed a significant difference among airlines ($F = 3.07$, Prob > $F = 0.04$). Omitting the data for one airline (for which there were only two observations) and rerunning the ANOVA test, it was determined that no significant difference resulted between airlines ($F = 1.64$, Prob > $F = 0.20$). Also, because the distance to touchdown was significantly higher because of one airline, the same procedure was repeated with the BAe146 observations, and no significant difference resulted.

Thus in all of the witnessed deviations, one airline could be singled out for the observed differences. In some instances this is probably due to the relatively few observations made of that airline. In other cases, many observations were made and so company procedure may play some part in the observed differences. In consideration of the observations made and the large number of airlines witnessed, differences attributed to one airline do not suggest a strong influence in airline operational procedure, at least up to the point of touchdown. However, it has been well documented in past studies (*2, 3*) that overall runway occupancy is very much dependent on airline operational procedure.

The data analyzed in this study support the same conclusion. Results of the ANOVA test for differences among airline landing distances for all large aircraft are as follows:

	Airport			
	SFO	*PHX*	*OAK*	*SJC*
F Ratio	9.66	1.46	1.69	0.00
Prob > *F*	0.00	0.21	0.20	1.00

San Francisco is the only airport that shows a significant difference among the airlines. This is because at the other airports, pilots are motivated to exit by the proximity of the terminal. By observing the relationship between the airline gate locations and the position of the exit taxiways, it can be seen that the results are consistent with the hypothesis that gate location is a primary motivational factor. The overwhelming majority of airlines is motivated to exit early at the other airports because gate location is displaced further the longer the aircraft is on the runway. San Francisco provides the only opportunity for certain carriers to taxi longer on the runway in order to be closer to the airline's gate location.

Because the landing sequence, for the most part, is independent of airline operating procedure up to the point of touchdown, differences in landing distance should be a result of differences among deceleration rates. In fact, average braking deceleration rates were found to differ significantly among airlines for certain aircraft types.

Distribution Modeling

Data obtained from the field study were also investigated to determine the type of distribution shown by the given parameters. Because of the limited number of observations, however, it was difficult to determine the exact distribution by aircraft type. When the various aggregated parameter histograms are observed, the distributions in Table 1 appear to be normal. After data obtained from the earlier study of turbojet aircraft were analyzed (*18*), it was discovered by Schoen et al. (*17*) that many of the parameters in the landing sequence followed a Pearson Type III distribution. The lack of available data segregated by aircraft type and obtained from field studies, especially recent studies, has prevented definite descriptions of the input parameter distributions themselves.

Parameter Interrelationships

Because of the independent nature of random number generation, it is necessary to determine possible correlations between the generated parameters. Some relationships are obvious and are accounted for in the mathematics of the model. For example, there is an obvious correlation between the time to touchdown and the height and speed at threshold. Such relationships are explicitly developed in the mathematical algorithm presented earlier.

As showed in Figure 2, a significant relationship did exist between the average braking deceleration and the remaining distance between nose gear touchdown and the exit chosen. This relationship arises from adjustment of aircraft speeds by air traffic controllers to maintain proper separations on final approach. Although other dependencies, such as the aircraft approach speed and the existing traffic density, are known to occur, they are difficult to measure.

For two reasons, another correlation was expected to exist between the height and airspeed at threshold. First, as witnessed in Table 1, heavy aircraft tend to have higher speeds and higher heights at threshold, whereas large aircraft have lower speeds and lower heights. Second, because an aircraft on final approach has a high speed, the pilot's instinct would be to decelerate by decreasing the aircraft's rate of descent, providing for a higher height at threshold. However, after a linear regression analysis was performed, no definite relationship could be explained. The first hypothesis was tested by analyzing all observations, and a correlation coefficient of +0.09 was determined. Even though some positive correlation was found, it was not enough to explicitly explain the relationship. Testing of the second hypothesis was performed by analyzing one given aircraft type (B737 aircraft at Phoenix), and a correlation coefficient of +0.17 was found. Again, no definite relationship could be determined. In both instances, however, the differences could be explained by the individual aircraft weights. Although this parameter has a definite impact on both the height and airspeed at threshold, it was not measured or accounted for in the field study.

RUNWAY OCCUPANCY AND AIRFIELD CAPACITY

To measure the potential increases in airport capacity, Lebron (*24*), using the FAA *Airfield Capacity Model* (with defined airfield configurations and aircraft mixes), evaluated various capacity enhancement schemes to determine their effect. The study concluded that capacity could be increased between 33 and 100 percent by the addition of new runways or multiple approach paths. Also, it was found that reductions in separation criteria could provide an increase in capacity between 15 and 25 percent, and reduced variability in interarrival times and reduced runway occupancy time could produce an increase in capacity between 16 and 18 percent.

Because there may be many constraints on physical expansion, that is, additional runways, of existing airport facilities, alterations in current operational procedures may be a beneficial means for increasing runway capacity. Although the subject of multiple approach path concepts is beyond the scope of this paper, the reduction in separation standards is directly related to runway occupancy.

The capacity C of a runway can be defined as the inverse reciprocal of the weighted headway (h) between aircraft operations, or

$$C = \frac{1}{h} \tag{11}$$

Simply stated, if separation standards are reduced, the corresponding headway between aircraft is reduced and capacity is increased. If a runway consisting of 100 percent arrivals is analyzed, the capacity can be rewritten as

$$C = \frac{1}{h} = \frac{v}{s} \tag{12}$$

where v is the aircraft approach speed and s is the distance separation between aircraft arrivals. This equation indicates that other alternatives are available to increase capacity by changing operational procedures. In a paper fully devoted to those procedures, Kanafani (*25*) proposes that aircraft may increase their approach speeds to increase runway capacity. However, as approach speeds increase, so will the corresponding runway occupancy times, and increases in capacity will eventually be limited. A more promising innovation to increase capacity would be to relax existing fixed-distance separations and base aircraft separations on headways by adjusting approach speeds, distance separations, or both (*25*). In addition, to obtain the maximum capacity potential available under the current criterion of restricting the runway surface to one aircraft at a time, these headways may be matched with existing runway occupancy times and any necessary safety buffers. This principle extends to mixed operations as well.

Because time is the key element in the response to unforeseen circumstances, it would be possible, theoretically, to negotiate safety issues with headway control rather than distance control. Of course, such a procedure must be researched from a safety standpoint. Moreover, safety concerns should extend beyond collision risk analysis; the impact on air traffic controllers and pilots must be rigorously analyzed as well. In addition, other problems may exist with a reduction in arrival spacing and must be addressed in a comprehensive research effort. These problems include Instrument Landing System signal interference, beacon system garbling, and potential conflict caused by missed approaches (*26*).

APPLICATIONS

In order to achieve any of the potential capacity previously identified, measures should be deployed to decrease the runway occupancy time mean and variance. By applying the runway occupancy model, exit taxiway locations could be analyzed in terms of minimizing runway occupancy time for a given mix of aircraft. Also, the model could be applied within an automated environment by providing real-time deceleration guidance or within a larger Integrated Landing Management (ILM) system to sequence aircraft operations with existing runway occupancy times. As stated earlier, this provides the maximum potential capacity gain from any change in operational procedure.

Exit Taxiway Location

A practical application of the runway occupancy model would be to estimate, for a given exit taxiway located any distance from the runway threshold, the probability that a given aircraft type (B727, MD80, and so forth) is able to accept that exit. By repeating the process at various locations from the runway threshold and for each aircraft type, the exit acceptance cumulative distribution function could be determined. The results are then weighted by the aircraft mix, and final design recommendations can be made after factors such as benefits and costs have been included.

As a test, the statistical parameters of the B737 aircraft typically in operation at Phoenix Sky Harbor were used as inputs to the model: an average braking deceleration rate of 6.5 ft/sec^2 (standard deviation of 1 ft/sec^2) and an average exit acceptance velocity of 30 knots (standard deviation of 5 knots). A comparison of the actual exit selection distribution and runway occupancy time (ROT) distribution with those predicted by the model is shown in Figure 3. The actual distribution was based on approximately 50 arrivals, whereas the model is based on a significantly higher number of arrivals (values were averaged on the basis of separate runs of 100 aircraft per run). The two graphs are very similar, with greater deviations occurring at the extremes. These deviations in the exit acceptance distribution could be attributed to the lack of knowledge of the exact parameter distributions, possible undiscovered interrelationships between the generated parameters, or braking adjustments made by the pilot to meet an exit in better proximity to the aircraft's terminal gate location. The differences between the actual and modeled runway occupancy times at locations further from the runway threshold are because of the omission of exit taxiways other than the one being analyzed. If the model simulated multiple exits, certain aircraft would have been able to exit earlier, reducing taxi time and thereby lowering the average runway occupancy time. Because space restrictions limit further discussion of the exit taxiway location analysis, including the adaptations to multiple exit locations, the reader should consult a paper by Gosling and Ruhl (*27*), which is fully devoted to the subject.

In addition, Phoenix Sky Harbor's Runway 8R is unique because all exit taxiways are right-angle exits, and high-speed exits are prevented because of the taxiway system design. However, by using the model, the impact of an added high-speed exit can illustrate the runway occupancy time savings possible. If a 60-knot high-speed exit taxiway were added, preliminary results suggest that the 50 percent acceptance distance would be reduced to 5,000 ft with an average runway occupancy time of 41 sec, a 20 percent time savings. Even though the above situation shows a possible improvement at Phoenix Sky Harbor, the same adjustments may not have similar impacts elsewhere.

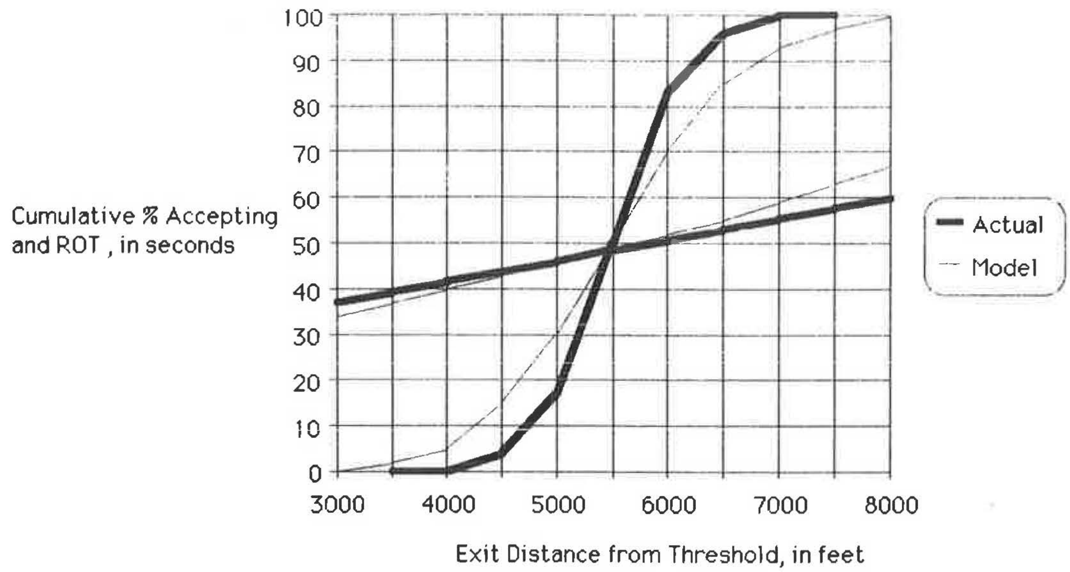


FIGURE 3 Phoenix 8R exit taxiway location case study (all B737 aircraft)

Automated Exit Guidance

Further capacity enhancements, in terms of the aircraft arrival sequence, have been proposed by Gosling et al. (*1*). In this respect, automating the landing process would give the pilot a visual target, with the use of new or existing centerline lighting systems and sophisticated on-line analyses, to select an exit as well as to determine the optimum profile guidance for an arriving aircraft depending on existing environmental conditions and traffic density. Once data on current airport conditions and individual aircraft characteristics are obtained, the model could estimate the optimum exit taxiway location. With the use of existing radar and additional sensors located within the runway pavement, real-time updates could be used to reaffirm predicted variables, thus providing more accurate information to the pilot in communicating the optimum deceleration path. This system may lower actual occupancy times by forcing an aircraft to choose a feasible eixt that may be otherwise bypassed for nonsafety-related conditions. As discussed earlier, aircraft could be separated on the basis of headway and sequenced according to their landing characteristics, thereby increasing capacity by as much as 40 percent, as predicted by Gosling et al. (*1*). Such a sytem is referred to as an ILM.

The basic configuration of the automated exit guidance system is given in Figure 4. The approach is to again use the runway occupancy model, but instead of a Monte Carlo simulation, the input variables may be represented by the expected values of those parameters. Then, with feasible limits on deceleration rates, a target location may be defined to assist in reducing runway occupancy. Feasible limits include those rates that are safe and acceptable to the pilot and passengers.

The process begins when the aircraft is located at the outer marker where input parameters concerning aircraft type, approach speed, and environmental conditions at the airport are input into the system. The velocity and height at threshold are initially estimated, and the model is used to predict landing distances and occupancy times. Once the aircraft is over the runway, sensors in the pavement can update any information concerning position and speed, and the target location may be continually updated. Detectors on the exit taxiways can provide exit clearance to the pilot and then clear the system for the next arrival.

Ideally, information concerning each individual flight (aircraft type, environmental conditions, etc.) would be used to predict the stall speed of the aircraft. Then the speed at threshold may be estimated according to the standard

$$V_T = 1.3V_S \tag{13}$$

The aircraft's stall speed is based on its landing weight. Such a variable is difficult to estimate, but by using simplifying assumptions concerning average load factors or by representing the landing weight as 85 percent of the maximum landing weight for the individual aircraft type (*13*), reasonable estimates for the airspeed at threshold may be calculated. The same logic may also be applied to predict the average threshold speeds for the various aircraft types in the exit taxiway location analysis.

Another procedure to predict the speed at threshold is an estimation based on the aircraft's approach speed at the outer marker. This procedure requires additional information concerning the air deceleration from the outer marker to threshold, which should be distinguished from the in-air deceleration initiated during the flare maneuver. Average air deceleration rates from the outer marker (5 nautical mi from the runway threshold) to the threshold have been calculated for each observation made during the field study. From such information, it appears that the BAe146 yields higher average deceleration rates compared with all the other observations. The BAe146 observations have been removed from the data file in order to obtain a general regression model, which appears in Figure 5, for all aircraft. Note that the model has very significant *t*-statistics and *F*-ratios along with a correlation coefficient of +0.93.

Thus, if a given radar source (possibly the same system that produces the BRITE radar display) can read the airspeed at 5 mi out, and given information concerning existing environ-

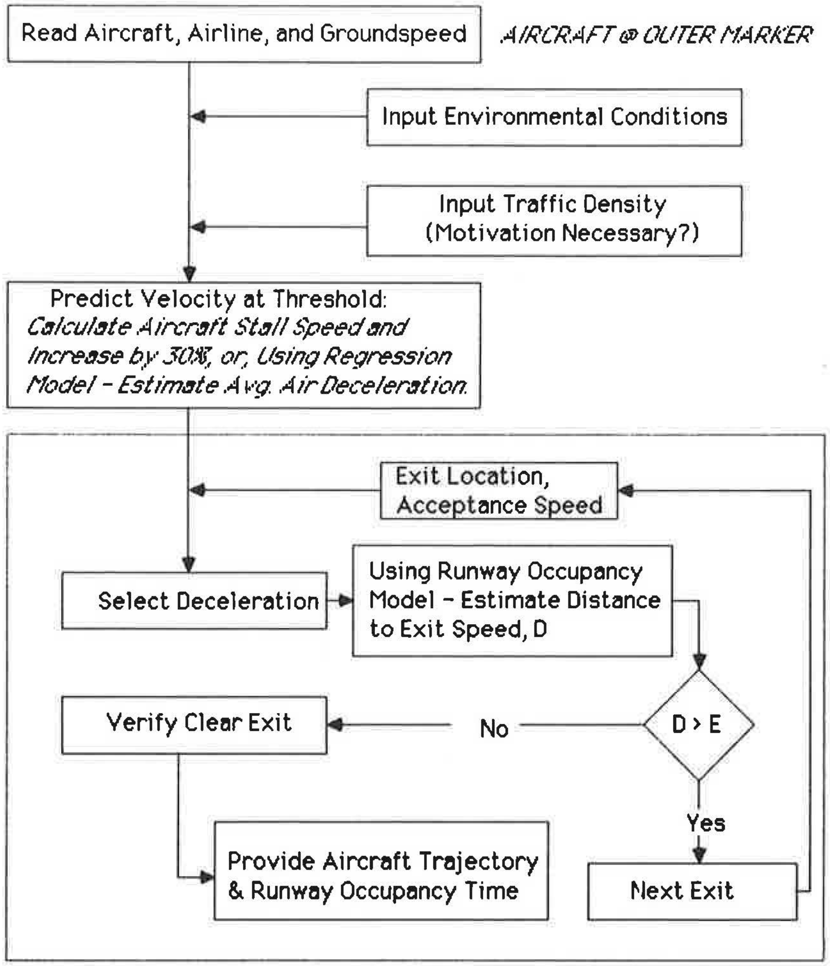


FIGURE 4 Automated exit guidance control logic.

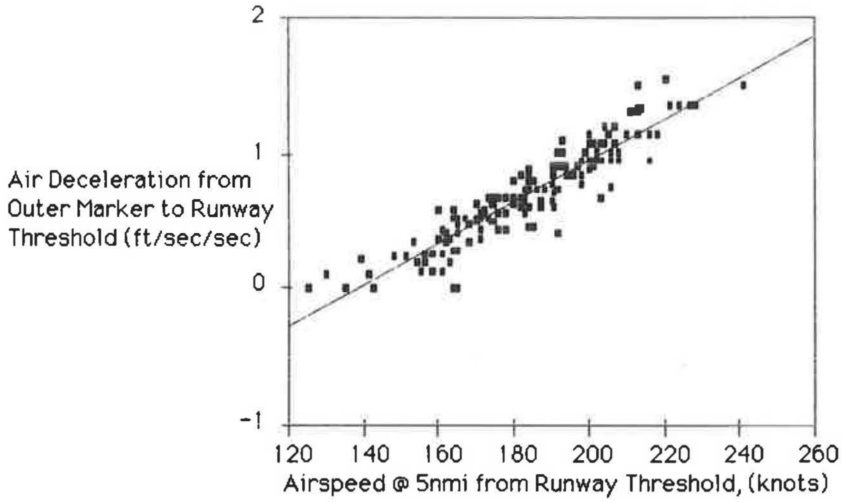
mental conditions, the velocity at threshold can be predicted. Again, this value could be confirmed at a later time using sensors and detectors within the runway surface. Additional information concerning the airline gate location and traffic density (motivation versus nonmotivation) can further adjust the model to all the aircraft to exit at the optimum location.

Such a system would benefit air traffic controllers by relieving them of the duty to provide certain ground control tasks that can be performed by automation. Also, by incorporating real-time deceleration guidance within the larger ILM framework of controlling separations by headways and sequencing arrivals and departures according to their runway occupancy times, significant increases in capacity may be achieved.

CONCLUSIONS AND RECOMMENDATIONS

The potential to increase existing airfield capacity does exist, with substantial gains largely developed by the addition of new runways and multiple approach path concepts. Capacity increases from 15 to 40 percent may be expected with more efficient use of existing high-speed exit taxiways, a reduction in runway occupancy time mean and variance, and a change in operational procedure from rather arbitrarily defined distance separation standards to aircraft separations based on headways. However, a substantial research effort is necessary before deploying any system based on headways, particularly an ILM system, in order to address various safety implications.

The model developed in this paper may prove to be beneficial to future airfield analyses because changes due to differences in the operational parameters among individual aircraft types may be taken into account. More important, the model applies to all types of aircraft (including those not accounted for in this study) given that the necessary operational parameters are available. These parameters may be found in aircraft informational manuals, aircraft simulator data, or data contained in this paper and in the literature cited. Statistical analyses produced in this paper show that if data are not readily available for individual aircraft types, the categories of large and heavy aircraft may be used to simplify the analysis, except in the case of B757 and B767 aircraft. Because the operational similarities of these aircraft combine the traits of both large and heavy aircraft, they should be provided their own classification. More data (most efficiently determined from aircraft simulator runs) are necessary to analyze the operational performance of the various aircraft types (specifically the BAe146) with regard to their in-air deceleration and roll deceleration rates. Moreover, further research is necessary to fully understand the parameter differences that occur during poor weather conditions because this is a time during which capacity is most strained.



Variable Name	Coefficient	Std. Err. Estimate	t Statistic	Prob > t
Constant	-2.1157	0.0905	-23.39	0.000
Air. @ 5 nm	0.0153	0.0005	31.43	0.000

Source	Sum of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Prob>F
Model	16.3839	1	16.3839	988.02	0.000
Error	2.7030	163	0.0166		
Total	19.08688	164	0.8584		

Coefficient of Determination (R^2)	0.86
Coefficient of Correlation (R)	0.93

FIGURE 5 Automated exit guidance air deceleration model.

Exit taxiways may be located such that runway occupancy or operational cost is minimized, depending on the airfield in question. However, even if exit taxiways are placed to minimize runway occupancy, overall system capacity may be limited because of conflicts among the runway, taxiway, and terminal location network. The mathematical model presented in this paper may be used independently, or it may be used in conjunction with any of the previously described models to optimize exit taxiway placement because those models require aircraft exit selection distributions as input (with or without considering runway occupancy time). This applies to those models that are concerned with demand rates above, or below, saturation conditions.

Finally, the introduction of an automated exit guidance system may have a substantial impact on creating more unused capacity by motivating carriers to use exit taxiways that may be bypassed for reasons others then safety. Moreover, such a system may be used for interarrival separation based on aircraft headways to achieve even larger capacity gains. The automated exit guidance system may benefit controllers by relieving them of certain ground control responsibilities, and it will assist pilots by offering landside guidance that could be extended beyond the exit taxiway to provide a networkwide, system-optimal positioning system.

ACKNOWLEDGMENT

The research contained in this paper was supported by a grant provided by the FAA and administered by TRB as part of the Graduate Research Award Program on Public-Sector Aviation Issues. The author would like to thank E. Thomas Burnard, Larry L. Jenney, Ronald W. Pulling, and Francis X. McKelvey for their assistance in monitoring the project and providing helpful critiques. Also, special thanks are expressed to Adib Kanafani at the University of California, Berkeley, for providing his precious time and leadership as faculty research advisor.

The author is especially indebted to Geoffrey D. Gosling at the Institute of Transportation Studies for his continuous assistance and effort on this and other research projects. The foundation of the model developed in this paper was initiated by the author and Gosling to be applied to an actual airport design.

Also, many thanks to Tim Heier and Kazuya Kawamura for their assistance in the field study and data reduction tasks and to Matt Naclerio for reviewing drafts of the paper. Special thanks are also extended to the following courteous and helpful FAA control tower personnel: Ben Kennedy, Mary Goshern, and Ron Johnston, Oakland tower; Don Green and Lanny

McCaslin, Phoenix tower; Ed Lewis and Hugh Peterson, San Francisco tower; and Al Reidle, San Jose tower.

REFERENCES

1. G. D. Gosling, A. Kanafani, and S. L. M. Hockaday. *Measures to Increase Airfield Capacity by Changing Aircraft Runway Occupancy Characteristics*. Report UCB-ITS-RR-81-7. Institute of Transportation Studies, University of California, Berkeley, Dec. 1981.
2. S. E. Koenig. *Analysis of the Runway Occupancy Times at Major Airports*. Report FAA-EM-78-9. FAA, U.S. Department of Transportation, May 1978.
3. T. J. Jackson and E. P. Moy. *An Analysis of Runway Occupancy Time for Large Aircraft at San Francisco International Airport*. Report UCB-ITS-GR-79-3. Institute of Transportation Studies, University of Californa, Berkeley, 1979.
4. G. N. Steuart and A. R. Gray. *The Effect of Weather on Airport Runway Operation*. Joint Program in Transportation, University of Toronto, April 1981.
5. R. Horonjeff, R. C. Grassi, R. R. Read, and G. Ahlborn. *A Mathematical Model for Locating Exit Taxiways*. Special Report 37. Institute of Transportation and Traffic Engineering, University of California, Berkeley, Dec. 1959.
6. R. Horonjeff, R. R. Read, and G. Ahlborn, *Exit Taxiway Locations*. Special Report 40. Institute of Transportation and Traffic Engineering, University of California, Berkeley, Sept. 1960.
7. H. G. Daellenbach. Dynamic Programming Model for Optimal Location of Runway Exits. *Transportation Research*, Vol. 8, 1974, pp. 225–232.
8. E. S. Joline. Optimization of Runway Exit Configurations. *Transportation Engineering Journal*, ASCE, Vol. 100, No. TE1, Feb. 1974, pp. 85–102.
9. E. O. Akinyemi and J. P. Braaksma. *Effectiveness of High Speed Exit Taxiways*. Department of Civil Engineering, Carleton University, Ottawa, April 1979.
10. FAA. *High Speed Exit Taxiways*. Report FAA-RD-81-16. Systems Research and Development Service, U.S. Department of Transportation, Feb. 1981.
11. V. A. Hosang. *An Analysis of High-Speed Exit Utilization on Runway 26L at Denver Stapleton International Airport*. Howard Needles Tammen and Bergendoff, New York, N.Y., Feb. 1975.
12. FAA. *Airport Design Standards—Transport Airports*. Advisory Circular 150/5300-12. U.S. Department of Transportation, Aug. 1982.
13. International Civil Aviation Organization. *Aerodrome Design Manual (Doc 9157-AN/901), Part 2, Taxiways, Aprons, and Holding Bays*. Montreal, 1983.
14. M. H. Coggins. *The Airport Capacity Increasing Potential of Angled Runway Designs*. Society of Automotive Engineers Technical Paper 780567, Presented at 1978 Air Transportation Meeting, Boston, Mass., May 1–4, 1978.
15. R. Horonjeff and F. X. McKelvey. *Planning and Design of Airports*, 3rd ed. McGraw-Hill, New York, N.Y. 1983, 616 pp.
16. D. F. Morse. *Analysis of the Common Approach Path and Runway Occupancy Times for the Aircraft Mix at San Jose Municipal Airport*. Report UCB-ITS-GR-80-6. Institute of Transportation Studies, University of California, Berkeley, Aug. 1980.
17. M. L. Schoen, J. E. Hosford, J. M. Graham, Jr., O. W. Preston, R. S. Frankel, and J. B. Erickson. *Aircraft and Avionics Related Research Required to Develop an Effective High-Speed Runway Exit System*. NASA Contractor Report 159075. Douglas Aircraft Company, Long Beach, Calif. June 1979.
18. D. R. Geoffrian and V. M. Kibardin. *Statistical Presentation of Operational Landing Parameters for Transport Jet Airplanes*. FAA Flight Standards Release 470. U.S. Department of Transportation, Aug. 8, 1962.
19. T. J. Yager, W. A. Vogler, and P. Baldasare. *An Evaluation of Two Transport Aircraft and Several Ground Test Vehicle Friction Measurements Obtained on Various Runway Surface Types and Conditions*. Summary of Test Results from Joint FAA/NASA Runway Friction Program, Draft Report, June 1989.
20. W. S. Homburger. *Transportation and Traffic Engineering Handbook*, 2nd ed. Prentice-Hall, Englewood Cliffs, N.J., 1982, p. 169.
21. M. Janić and T. Jovanović, A Capacity Model of the Airport Airside System. *Airport Forum*, No. 1, Feb. 1989, pp. 54–56.
22. FAA. *Airfield Delay Simulation Model (ADSIM) User's Guide*. Report DOT/FAA/PM-84/2. FAA Technical Center, U.S. Department of Transportation, Atlantic City Airport, N.J., June 1984.
23. V. Tosić, D. Teodorović, and O. Babić. Optimum Runway Exit Location. *Transportation Planning and Technology*. Vol. 10, 1985, pp. 135–145.
24. J. E. Lebron. *Estimates of Potential Increases in Airport Capacity Through ATC System Improvements in the Airport and Terminal Areas*. Report FAA-DL5-87-1. FAA, U.S. Department of Transportation, Oct. 1987.
25. A. Kanafani. Operational Procedures to Increase Runway Capacity. *Transportation Engineering Journal*, ASCE, Vol. 109, No. 3, May 1983, pp. 414–424.
26. W. J. Swedish. *Evaluation of the Potential for Reduced Longitudinal Spacing on Final Approach*. Report FAA-EM-79-7. FAA, U.S. Department of Transportation, Aug. 1979.
27. G. D. Gosling and T. A. Ruhl. *Exit Taxiway Location: A Monte Carlo Simulation Model*. Working Paper, Institute of Transportation Studies, University of California, Berkeley, Nov. 1989.