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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 Sixth Graduate Research Award Program on Public-Sector Aviation Issues (1991–1992). The program is sponsored by the FAA and administered by TRB; its purpose is to stimulate thought, discussion, and research by those who may become managers and policy makers in aviation. The papers were presented at the 72nd Annual Meeting of TRB in January 1993. The authors, their university affiliations, faculty research advisors, and TRB monitors follow.

John L. Crassidis, a doctoral candidate at the State University of New York at Buffalo, studied robust control techniques applicable to an automatic landing system for commercial aviation. His faculty research advisor was D. Joseph Mook of the Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo. TRB monitors were John Hansman of the Massachusetts Institute of Technology (MIT) and Agam N. Sinha of the MITRE Corporation.

Robert Shumsky, a doctoral candidate at MIT, analyzed the response of U.S. air carriers to the Department of Transportation's on-time disclosure rule. His faculty advisors were Arnold I. Barnett of the Sloan School of Management, MIT, and Amedeo R. Odoni of the Department of Aeronautics and Astronautics, MIT. TRB monitors were Gerald S. McDougall of Wichita State University and Lawrence F. Cunningham of the University of Colorado at Denver.

Tom Svrcek, a Ph.D. candidate at MIT, developed a method for supporting policy-level design decisions relating to airport terminals. His faculty advisor was Amedeo R. Odoni of the Department of Aeronautics and Astronautics, MIT. TRB monitors were J. Bruce McClelland of Dornier Aviation and John W. Fischer of the Congressional Research Service, Library of Congress.

Patrick R. Veillette, a Ph.D. candidate in mechanical engineering at the University of Utah, examined training methods for aircraft stall and spin prevention. His faculty advisor was James K. Strozier of the Department of Mechanical Engineering, University of Utah. TRB monitors were William E. Gehman of the Michigan Aeronautics Commission and Lemoine V. Dickinson Jr. of Failure Analysis Associates.

Joyce Winkler, a candidate for a master's degree in industrial engineering at Rutgers University, developed a model to evaluate collision risk in simultaneous instrument landing system approaches to closely spaced parallel runways. Her faculty advisor was E. A. Elsayed of the Department of Industrial Engineering, Rutgers University. TRB monitors were John E. Lebron of the MITRE Corporation and Robert W. Simpson of MIT.

Robust Control Techniques for a Commercial Autoland System

JOHN L. CRASSIDIS

A robust controller, using H_∞ control design techniques, is developed for a commercial landing system. First, a detailed nonlinear aircraft computer simulation of a commercial aircraft is summarized. The computer simulation, which includes the aircraft flight dynamics, pitch attitude autopilot, and automatic thrust compensator, is presented for a Boeing 737 aircraft. The aircraft simulation is first derived by using a full 6-degree-of-freedom rigid-body model. The model is then increased to include the pitch autopilot and automatic thrust compensator. The control variables for these systems are the elevator, which generally controls pitch angle, and the thrust, which generally controls airspeed. A detailed digital computer simulation allows the replacement of simplified transfer function models for use in an autoland simulation. Therefore, internal states and dynamics associated with the aircraft subsystems can be evaluated. Then, a linear model is used to design a robust controller for the autoland process. The robustness of this controller, with respect to parameter and structural uncertainties, is tested with the aircraft simulation. The design study indicates that this controller dramatically improves the response characteristics and performance of the autoland system.

Commercial and military autoland systems have become more necessary in order to maintain busy flight schedules with safety during poor visibility or bad weather conditions. Today, both military and civil aircraft rely heavily on automatic control systems to provide artificial stabilization, with the use of autopilots to help pilots navigate and land their aircraft in bad weather. Robust control techniques, with respect to aircraft and environmental variations, in the interaction between the aircraft tracking systems and handling qualities are being investigated in the research community. With the aid of flight simulation techniques, emphasis on autoland systems could lead to the reduction of human error during the landing procedure. Therefore, the transfer of simulated robust control techniques to actual landing systems is plausible for both military and civil application in the near future.

The FAA, concerned with aviation safety, has defined specific categories of visual reference conditions with respect to pilot decision height and runway visual range. These considerations provide the basis for aircraft guidance and pilot landing procedures when visibility or weather conditions are extremely degraded (*1*). The use of the instrument landing system enables pilots to land aircraft safely in adverse weather when normal landing procedures using visual reference alone are inadequate. The instrument landing system provides pilots with glide slope information, via a localizer beam, and permits them to guide an aircraft safely through a low-visibility cloud ceiling until they can see the runway. Autoland systems expand the instrument landing system by using an aircraft's autopilot and automatic thrust compensator so that the aircraft is guided all the way to touchdown.

The aircraft's autopilot and automatic thrust compensator are essential components in a commercial autoland system. Primary components of an autoland system include a localizer beam, a glide path coupler, aircraft subsystems, and an automatic flare control system. The localizer beam is used to position the aircraft on a trajectory and intercept the centerline of the runway. The glide path coupler then calculates corrective control commands, which are transmitted to the aircraft's subsystems. The aircraft's autopilot and thrust compensator respond to these flight control commands, which indirectly control the aircraft's position and orientation. Finally, as the aircraft approaches the touchdown point the automatic flare control system is engaged, which enables a decrease in the vertical descent rate in order to allow the aircraft to land safely.

The design methodology of the current autoland system relies on classical control design techniques, such as proportional-integral (PI) control. Other areas of research and interest in the autoland process include fuzzy logic designs (*2*) and microwave landing systems (*3*). Fuzzy logic applications have demonstrated a number of benefits including improved performance, reduced power consumption, and shorter development times. One reason that fuzzy logic controllers have produced these benefits is that they easily embed human-type maneuvers into a mathematically based controller. However, because fuzzy logic depends on categorizing human responses, it may be difficult to create mathematical relations to model pilot handling qualities in an autoland system.

The microwave landing system is capable of determining the position of an aircraft over a large coverage area; therefore, it is less sensitive to surrounding interference during the autoland process. The microwave landing system also allows for increased reliability and maintainability. However, the system requires hardware changes to the current autoland system. The focus in this paper is to investigate the replacement of the current controller in the commercial landing system with a controller that is robust to surrounding interference and structural variations during the landing process. This control design requires only a software change to the current control strategy.

H_∞ methods provide new techniques and perspectives, compared with classical control techniques, in designing control systems. The frequency response characteristics of a plant are shaped according to prespecified performance specifications, in the form of weighting functions. The H_∞ design process is

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chosen because it (a) provides robust stability, (b) achieves performance requirements efficiently, (c) handles both disturbance attenuation and controller saturation problems easily, and (d) works not only on single-input/single-output systems, but also on complex multi-input/multi-output systems. Therefore, frequency response criteria can easily be shaped to desired specifications.

Previously, autoland simulations used a reduced linear model for the aircraft simulation (*4–7*). These models, obtained from experimental flight data, incorporate a transfer function relating the aircraft's attitude response to the transmitted pitch control command. However, the reduced models neglect the dynamic effects of the autopilot and thrust compensator. Of particular interest is the aircraft's response to atmospheric turbulence. With the transfer function model, the aircraft's response to turbulence is solely controlled by the autoland controller. But, in practice, the automatic thrust compensator also minimizes the aircraft's response to turbulence. The transfer function model approach neglects this internal control system.

In this paper, the fundamental elements and feedback control systems of the pitch autopilot and thrust compensator are shown and incorporated into a computer-generated simulation. The simulation is first presented for an open-loop study by a numerical integration scheme of the rigid-body equations of motion (the simulation is shown in the vertical-altitude plane only, although the techniques are easily extended to the horizontal plane). The closed-loop system results are shown, so that the simulation can be analyzed in order to develop a robust control design for the autoland approach simulation. Then a linearized model of the aircraft simulation is used to develop an controller for the autoland system. Finally, performance characteristics of this controller are shown in order to investigate the stability robustness and disturbance sensitivity of the control design.

DESCRIPTION OF SIMULATION

Aircraft Model

The aircraft simulation is derived by using a 12th-order state-space model, based on the 6-degree-of-freedom rigid-body aircraft dynamic equations of motion and the concept of static stability using aircraft forces and moments [see elsewhere for details (*8,9*)]. All computer simulation trajectories are produced for a Boeing 737 aircraft. Experimental (wind tunnel) aerodynamic coefficients are provided by the National Aeronautics and Space Administration (NASA) (*10*). Equation Set 1 summarizes these aircraft equations of motion.

$$\dot{p} = [-(I_{zz} - I_{yy})qr]/I_{xx} + (k_1\beta + k_2p + k_3r + b_1\delta_a + b_2\delta_r)0.5(\overline{V})^2$$

$$\dot{q} = [-(I_{xx} - I_{zz})pr]I_{yy} + (k_4\alpha + k_5q + b_3\delta_e)0.5(\overline{V})^2 + b_4\overline{T}$$

$$\dot{r} = [-(I_{yy} - I_{xx})qr]I_{zz} + (k_6\beta + k_7p + k_8r + b_5\delta_a + b_6\delta_r)0.5(\overline{V})^2$$

$$\dot{\Phi} = p + q\sin\Phi\tan\Theta + r\cos\Phi\tan\Theta$$

$$\dot{\Theta} = q\cos\Phi - r\sin\Theta$$

$$\dot{\Psi} = (q\sin\Phi + r\cos\Phi)/\cos\Theta$$

$$\ddot{x} = [k_{10} + k_{11}\alpha + k_{12}\beta + b_7\delta_a + b_8\delta_r + b_9\delta_e]0.5(\overline{V})^2 + b_{10}\overline{T}$$

$$\ddot{y} = [k_{13} + k_{14}\alpha + k_{15}\beta + b_{11}\delta_a + b_{12}\delta_r + b_{13}\delta_e]0.5(\overline{V})^2 + b_{14}\overline{T}$$

$$\ddot{z} = [k_{16} + k_{17}\alpha + k_{18}\beta + b_{15}\delta_a + b_{16}\delta_r + b_{17}\delta_e]0.5(\overline{V})^2 + b_{18}\overline{T} + g$$

$$\dot{x} = \dot{x}$$

$$\dot{y} = \dot{y}$$

$$\dot{z} = \dot{z} \qquad (1)$$

where

α, β = angle of attack and sideslip angle;
p, q, r = angular velocities;
Φ, Θ, Ψ = roll, pitch, and yaw angles;
δ_e, δ_a, δ_r = elevator, aileron, and rudder angles;
$\overline{V}$, $\overline{T}$ = airspeed and thrust; and
$\ddot{x}$, $\ddot{y}$, $\ddot{z}$ = translational accelerations in an inertial reference frame.

The symbols $k_{i's}$ and $b_{i's}$ represent aircraft forces, moments, and other constants. [See elsewhere for more details (*9*).]

To evaluate the aircraft equations of motion for an actual aircraft trajectory, an open-loop simulation was first conducted using 737 aircraft coefficients. All trajectories are initially started with the aircraft set to trimmed values. For landing, the final approach speed is approximately 240 ft/sec (the trim values for angle of attack and elevator setting are 1.7 and −18 degrees, respectively).

Pitch Autopilot

The basic block diagram for the closed-loop system of the pitch autopilot with attitude feedback is shown in Figure 1. The pitch autopilot operates as follows. A desired pitch command is sent to the aircraft. A pitch angle error signal, representing the difference between the measured pitch angle and the desired pitch angle, is the input to the autopilot controller. The controller commands changes in the elevator setting, relative to a datum (typically, the trim value). The aircraft then responds to the new elevator setting with changes in pitch angle, pitch rate, vertical acceleration, and angle of attack.

Closing the loop using only attitude feedback achieves the desired pitch angle. But, because the aircraft has very little natural damping, the closed-loop response characteristic also has a low damping ratio. The dynamic performance of the aircraft can be severely degraded, even causing the system to become unstable. To achieve significant damping and dynamic performance, a pitch rate feedback is also provided (represented by the inner loop of the block diagram in Figure 1). The control gains used in the simulation are the gains used on an actual 737 autoland system from NASA Langley (*10*). The use of these gains helps to ensure that a proper and practical simulation is derived. Therefore, the simulation can provide a practical means of developing realizable control strategies.

The elevator controller equation in the frequency domain is given by (*10*)

$$\Delta\delta_e = \left[K_{ag}(\Theta - \Theta_c) + \frac{sK_{rg}}{s+1}\dot{\Theta}\right]\left(\frac{1+2s}{2s}\right) \qquad (2)$$

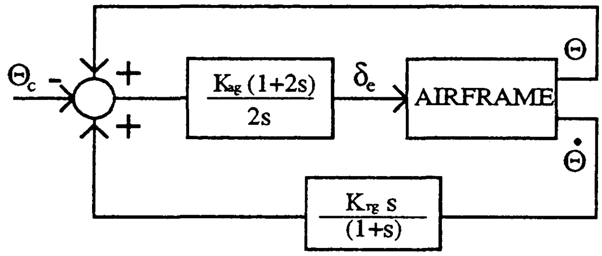

FIGURE 1 Block diagram of pitch autopilot with rate feedback.

where

s = Laplace transform variable,
K_{ag} = attitude gain,
K_{rg} = pitch rate gain, and
Θ_c = input pitch command.

The autopilot simulation is accomplished by converting the aircraft equations of motion (Equation 1) into state-space form and numerically integrating. The autopilot is engaged when the aircraft is trimmed in straight and level flight (Θ_0 = 1.7 degrees). The input to the feedback system is a pitch change command relative to the trim level. The elevator command is also implemented as a relative change from the initial setting:

$$\delta_{enew} = \delta_{etrim} + \Delta\delta_e \tag{3}$$

Simulation results are shown later.

Automatic Thrust Compensator

The autopilot achieves the desired pitch angle, but the inertial flight path angle (γ) must be controlled in order to land the aircraft using the autoland system. One method of achieving a desired flight path angle is to control indirectly the angle of attack to a desired reference point (e.g., the trim value) while also controlling the pitch angle, since the flight path angle represents the difference between the pitch angle and angle of attack. This control is incorporated by maintaining the aircraft's airspeed at a constant level.

The thrust compensator commands thrust changes according to the control law (*10*)

$$\Delta T_c = \left[\left(1 + \frac{K_{com}}{s}\right)\left(\frac{1}{\tau_t s + 1}\right)\left(\frac{1}{\tau_e s + 1}\right)\right]\Delta e \tag{4}$$

where

U_{ref} = reference airspeed of aircraft (usually set to level flight condition),
Δe = detected airspeed error (measured versus commanded),
ΔT_c = change in thrust commanded by autothrottle system,
K_{com} = compensator gain,
K_s = speed feedback gain,
τ_t = throttle servo time constant, and
τ_e = engine lag time constant.

These control gains and time constants used in the simulation are again from the actual 737 autoland system.

Coupling of Autopilot and Thrust Compensator

The combined closed-loop system incorporates the pitch autopilot with pitch rate feedback and the automatic thrust compensator. A pitch command is sent to the pitch autopilot. A pitch angle error signal, representing the difference between the measured and commanded pitch angles, is the input to the controller. The controller, coupled with the pitch rate feedback loop, commands changes in the elevator setting. This command is added to the trim elevator setting. The aircraft then responds to the new elevator setting, producing changes in pitch angle, pitch rate, vertical acceleration, and angle of attack. This part of the closed loop is represented by the pitch displacement autopilot with the feedback loop given by Equation 2. The autopilot also invokes a change in airspeed and angle of attack from the desired values. When this happens, the automatic thrust compensator engages, given by Equation 3, so that the airspeed and angle of attack are controlled. The autopilot and automatic thrust compensator closed-loop operation continues until the flight path angle of the aircraft is changed, which causes a change in aircraft altitude.

Simulation Results

The combined closed-loop response for a 1-degree step pitch command is shown in Figure 2. By incorporating the autopilot loop, the steady-state pitch angle error is near zero. Also, the rise time for the aircraft response is approximately 3 sec. The angle of attack response for this step input is shown in Figure 3. With the autopilot only (dashed line), the combined angle of attack and pitch angle do not enable the control of the inertial flight path angle. The thrust compensator controlled the angle of attack back to the desired trim value (the compensator can control the angle of attack to any desired setting). This combined closed loop now enables the control of the inertial flight path angle to any desired value. Therefore, the autopilot and thrust compensator simulation can be expanded to simulate the autoland process.

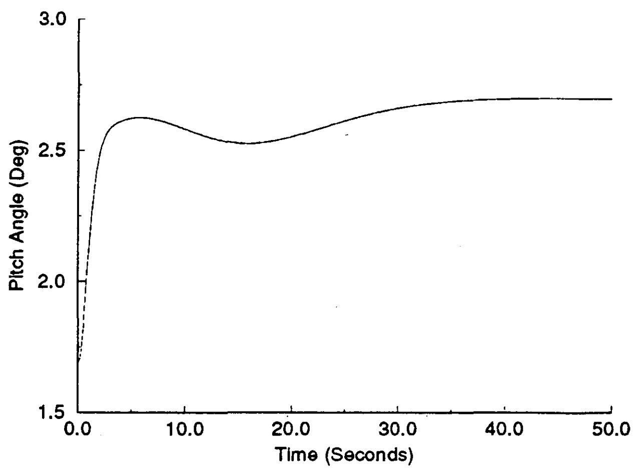

FIGURE 2 Combined closed-loop pitch angle step response.

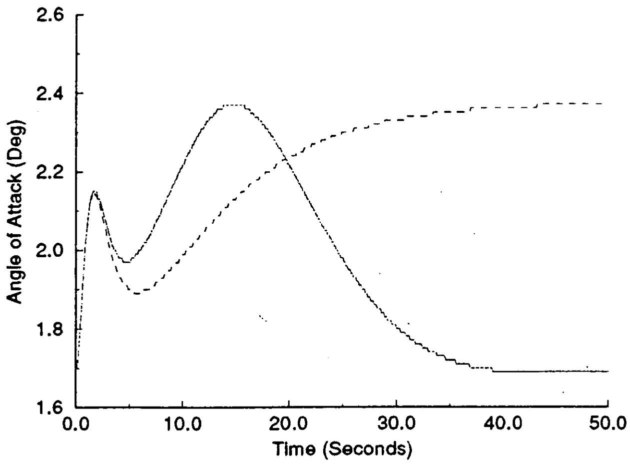

FIGURE 3 Combined closed-loop angle of attack response.

Though the aircraft model is a set of nonlinear differential equations, the response characteristics of the pitch autopilot are linear to the input command signal. This feature is illustrated in the following table, using different magnitudes for the step pitch command:

Step Pitch Command (degrees)	*Rise Time (sec)*	*Settling Time (sec)*
1	3.1	35
4	3.5	34
−3	3.6	34

The vertical acceleration closed-loop response for a 1-degree step pitch command is shown in Figure 4. The initial drop in vertical acceleration is caused by a pitching moment induced when the elevator setting is changed (i.e., a positive pitching moment causes an initial drop in vertical acceleration). The response without the automatic thrust compensator (dashed line) is lightly damped ($\zeta \approx 0.4$). But with the addition of the thrust compensator (solid line), the settling time for the system is faster because of a higher damping ratio ($\zeta \approx 0.6$). This improved acceleration characteristic also provides an increase in stability in the aircraft response to atmospheric disturbances such as turbulence. The thrust history, from the combined closed-loop response, for a step pitch command has a steady

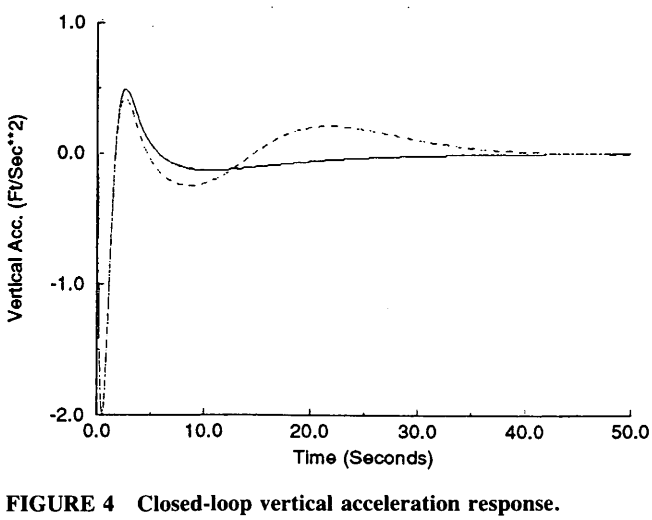

FIGURE 4 Closed-loop vertical acceleration response.

state value of 22,000 lb. Therefore, the thrust increases a net 2,200 lb from the initial level flight thrust setting (19,800 lb). This increase in thrust causes the aircraft to gain altitude. The magnitude of the airspeed response is not significantly changed, which is ideal for the automatic landing process.

ATMOSPHERIC TURBULENCE

The stochastic process of atmospheric turbulence is summarized in this section. Turbulence is a result of instabilities in the velocity field of the atmosphere. The instabilities are caused by such things as solar heating or the earth's rotation; they give rise to gradients in temperature, pressure, and velocity (*9*). Turbulence is random in nature and, in the longitudinal plane, is characterized by horizontal and vertical wind gusts. The horizontal gusts affect the aircraft's altitude by changing the airspeed of the aircraft, which varies the lift on the airplane's wings and causes the aircraft to rise or fall, depending on whether the wind gusts add or subtract from the aircraft's nominal airspeed. Similarly, vertical gusts vary the angle of attack of the aircraft, which also results in a change in the aircraft's altitude.

Because of the complicated and changing nature of turbulence, some simplifying assumptions must be made to develop a model that can be realized mathematically (*11*). First, the turbulence is assumed to be locally isotropic. Isotropy refers to the independence of the statistical properties of the turbulence on the orientation of the coordinate axes. Second, the turbulence is assumed to be homogeneous, implying that all of the statistical properties are the same at each point in the velocity field. A result of these assumptions is that the horizontal and vertical wind velocities will have a small effect on each other, or in mathematical terms, a low cross correlation. Therefore, the aircraft's response to horizontal and vertical wind gusts can be separated individually. Because of the similarity of the two responses, only one of these responses needs to be analyzed. For these reasons, only the effects of the longitudinal wind gusts on the aircraft's vertical velocity are considered as turbulence input.

The aerodynamic forces and moments acting on the aircraft depend on the relative motion of the aircraft to the atmosphere and not on the inertial velocities. Therefore, to account for atmospheric gusts, the forces and moments must be related to the relative motion with respect to the atmosphere. This is accomplished by expressing the velocities used in calculating the aerodynamics in terms of inertial and gust velocities:

$$\Delta u_a = \Delta u - u_g$$
$$\Delta v_a = \Delta v - v_g$$
$$\Delta w_a = \Delta w - w_g \qquad (5)$$

where u_g, v_g, and w_g are gust velocities in the X, Y, and Z directions, and the Δ-quantities are the perturbations in the inertial velocity variables.

Two spectral forms of random continuous turbulence are generally used to model atmospheric turbulence for aircraft response studies. They are the mathematical models named after Von Karman and Dryden, the scientists who first proposed them.

The Von Karman model shows that the power spectral density approaches a constant value asymptotically at low frequencies and decreases asymptotically according to a $-5/3$ power frequency for higher frequencies (*9*). These high frequencies occur in a range called the inertial subrange, in which energy is neither fed into nor dissipated from the turbulence. Mathematically, this relationship can be expressed by

$$\Phi_{u_g}(\Omega) = \sigma_u^2 \frac{2L_u}{\pi} \frac{1}{[1 + (1.339L_u\Omega)^2]^{5/6}}$$

$$\Phi_{v_g}(\Omega) = \sigma_v^2 \frac{2L_v}{\pi} \frac{1 + 8/3(1.339L_v\Omega)^2}{[1 + (1.339L_v\Omega)^2]^{11/6}}$$

$$\Phi_{w_g}(\Omega) = \sigma_w^2 \frac{2L_w}{\pi} \frac{1 + 8/3(1.339L_w\Omega)^2}{[1 + (1.339L_w\Omega)^2]^{11/6}} \tag{6}$$

where

Φ = dimensional power spectrum,
σ = root-mean-square intensity of gust component,
Ω = spatial frequency, and
L = scale of turbulence.

The wavenumber Ω can be converted from a spatial wavelength to a temporal frequency by multiplying the wavenumber by the aircraft's airspeed $\overline{V}$ as follows: $\omega = \Omega\,\overline{V}$.

The scale of turbulence for clean air turbulence is defined as follows (*9*):

$$\text{Above } z = 2{,}500 \text{ ft}, \quad L_{wg} = 2{,}500$$

$$\text{Below } z = 2{,}500 \text{ ft}, \quad L_{wg} = 184(z)^{1/3} \tag{7}$$

For an aircraft landing, the altitude z varies as the aircraft descends. Because of the way in which the power spectral density of the turbulence is defined in the Von Karman model, the corner frequency of the turbulence increases as the aircraft descends. For the turbulence conditions likely to be encountered by the aircraft landing, a range of corner temporal frequencies from 0.5 to 1.0 rad/sec is used. Several data sets of turbulence are used in the simulation in order to investigate the response characteristics of the aircraft.

Robust Control Design

The aircraft simulation can now be used to investigate the feasibility of a robust (H_∞) control design for the automatic landing approach. A block diagram of the glide slope intercept and hold system is shown in Figure 5. The glide slope receiver in the aircraft is designed to sense the angular Γ error relative to the glide slope of the station. This signal is compared to the desired glide slope error Γ_{ref} introduced into the closed-loop system. An error signal is produced that is sent to the controller/coupler. The controller network then generates a pitch command that is transmitted to the aircraft's autopilot and thrust compensator. The aircraft responds to this pitch command as previously described, so that the aircraft's altitude changes with a change in flight path angle. This closed-loop operation continues until the aircraft lands on the landing strip.

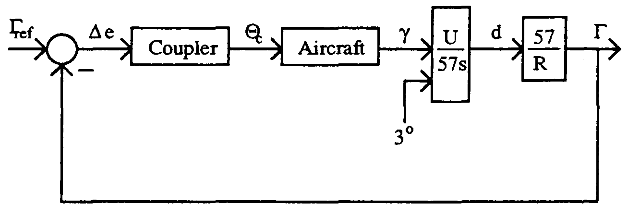

FIGURE 5 Block diagram of autoland system.

The design of robust controllers has been investigated extensively over the past decade (*13–15*). The next step is to develop an H_∞ control design for the coupler while attenuating the turbulence response of the aircraft. The H_∞ criterion is chosen because robust stability in the closed-loop system can be achieved easily by defining performance and robustness specifications in the form of weighting functions. In this manner, frequency response criteria in the autoland system are shaped to desired specifications.

The H_∞ criterion, with controller $K(s)$ and plant $G(s)$, considers the closed-loop system performance on disturbance sensitivity $S(s)$ and stability $[I - S(s)]$ to prespecified weighting functions, denoted as $\gamma W_1^{-1}(j\omega)$ and $W_2(j\omega)$, respectively. The requirements for stability and disturbance attenuation are specified in terms of singular value inequalities (*13*):

$$\overline{\sigma}\,[S(j\omega)] \le |W_1^{-1}\,(j\omega)|$$

$$\overline{\sigma}\,[I - S(j\omega)] \le |W_2(j\omega)| \tag{8}$$

where $\overline{\sigma}$ represents the maximum singular value. These specifications are combined into a single infinity norm:

$$\left\| \begin{matrix} W_1 S \\ W_2(I - S) \end{matrix} \right\|_\infty \le \gamma \tag{9}$$

This equation shapes the frequency loop transfer function $[L(s) = G(s)K(s)]$ by penalizing the sensitivity function $[S = (I + GK)^{-1}]$ to reject the plant disturbances (turbulence), and high frequency $L(s)$ by penalizing the complementary sensitivity function $[T = GK(I + GK)^{-1}]$ to cope with model uncertainties—for example, unmodeled (high-order) dynamics, sensor and actuator dynamics, and so on (*13*). The solution of Equation 9 involves an iteration on the γ term of the specified disturbance weighting function. As γ is increased, the sensitivity function S decreases and the complementary sensitivity function $(I - S)$ approaches the W_2^{-1} weight. Therefore, the function in Equation 9 approaches its zero-decibel limit. The controller solution is determined by a two-Riccati solution (*15*).

Linear Model

The combined computer simulation of the 12th-order aircraft model, pitch attitude autopilot, and thrust compensator results in a complex (high-order) model. A state-space model between the pitch command input and the aircraft flight path angle output can be obtained by linearizing the nonlinear equations of motion and creating closed-loop transfer functions for each feedback loop; however, this involves extensive computational time. To develop a linear model, time-domain techniques are used instead to obtain pole/zero locations of the aircraft, autopilot, and thrust compensator. Therefore, the input/output relationship of the aircraft can accurately be obtained. And time-domain techniques are more realistic, since operational data can be used in the design process.

Several identification techniques have been derived for developing accurate model realizations from time-domain data (*16–18*). The technique used in the aircraft realization is the Eigensystem realization algorithm (ERA) (*18*). The ERA method is chosen because (a) only discrete, time-domain impulse response data are required; (b) the computational requirement is relatively easy; (c) the numerical stability properties have internally balanced realizations; and (d) accurate model representations are possible if the discrete measurements are of low noise in nature. Therefore, a mathematical model of the system is constructed, reproducing the plant's input/output behavior. A complete derivation of the ERA method can be found elsewhere (*18*). This algorithm produced an 18th-order realization of the 737 aircraft and autopilot simulation.

Because of computer software and hardware requirements, the robust control design requires the need for reduced plant models. This need arises because the H_∞ control design results in a controller's having a degree of at least the same order as the plant, that is, 18th-order. Therefore, a model reduction is essential in developing a realizable control strategy. The Schur balanced model reduction technique is used to develop a reduced fifth-order model (*19*). This model is determined as

$$\frac{Z(s)}{\Theta_c(s)} = \frac{0.083s^5 + 0.52s^4 + 1.55s^3 - 0.52s^2 + 0.08s + 0.006}{s(s^4 + 1.06s^3 + 0.75s^2 + 0.0388s + 0.02)} \quad (10)$$

where $Z(s)$ is the altitude of the aircraft. The aircraft model, pitch autopilot, and thrust compensator have a flight path response bandwidth of approximately 1 rad/sec, which is required to achieve good glide slope control for an aircraft under autoland control.

Control Design Results

The robust control design is developed using the reduced-order model given by Equation 10. When the final design is complete, the controller is incorporated into the full aircraft, autopilot, and thrust compensator simulation, given Equations 1 through 4. This adds to the validity for the use of the reduced model in the H_∞ design process.

The complementary sensitivity function is weighted using a first-order weighting function. This weighting function is chosen to achieve the fastest possible response time in the closed-loop system while maintaining the control and actuator limitations in the aircraft response characteristics. The optimal control design achieves a bandwidth specification for the closed-loop system of about 1.8 rad/sec with no overshoot. The sensitivity function is weighted such that the disturbance responses to turbulence are attenuated at least 500:1 with a first-order roll-off of 1 rad/sec. The design specifications obtain the maximum bandwidth response possible, subject to minimizing the sensitivity function. The combination of the sensitivity and complementary sensitivity function responses are also within controller tolerances—that is, ±10 degrees in the pitch command. Stability robustness in the presence of model uncertainties is essential for a modern control design system. In most circumstances, the mathematical model of the plant only approximately represents the behavior of the true system. The difference between the actual system and the mathematical model of the plant arises from parameter variations, unmodeled dynamics, or nonlinearities in the true system. The model error uncertainties are generally represented in terms of both additive and multiplicative uncertainty bounds (*14*). The maximum allowable additive and multiplicative plant perturbations are given by $1/\bar{\sigma}\ [K(I + GK)^{-1}]$ and $1/\bar{\sigma}[GK(I + GK)^{-1}]$, respectively. The minimum additive and multiplicative uncertainty upper bounds for this robust control design are −0.52 and −0.03 decibels, respectively. This means that even if the modeled plant has both −0.52 decibels additive uncertainty and −0.03 decibels multiplicative uncertainty at any frequency, the closed-loop system remains stable. This stability robustness property is one of the advantages of the H_∞ controller.

To demonstrate the stability robustness properties of the H_∞ controller, a comparison is made with respect to a classical control design. The current control design for the autoland land system incorporates a PI control philosophy (*10*). The control gains for the classical PI control strategy are determined from a parameter optimization scheme. The performance criterion for the classical design is evaluated with respect to optimal step response, turbulence attenuation, and controller limitations. The combination of these criteria describes the optimal closed-loop performance.

The cost function chosen for the classical PI control design is based on the integral of the error signal. A quadratic form, the integral-squared error, is used to ensure a well-defined minimum. The step response is used to evaluate the aircraft's response to a step input signal. The step response cost function is chosen as

$$\Upsilon_s = \int_{t_0}^{t_f} t\ [zer^2(t)]dt \quad (11)$$

where *zer* is the error between the desired and actual flight path angles. The turbulence response cost function minimizes the error between the desired and actual altitudes of the aircraft. The desired altitude for the turbulence response is set to zero. This cost function is given as

$$\Upsilon_t = \int_{t_0}^{t_f} [Z^2(t)]dt \quad (12)$$

where Z is the altitude of the aircraft. The final cost function minimizes the control signal level and maintains controller tolerances to within prespecified tolerances. This cost function is given as

$$\Upsilon_c = \int_{t_0}^{t_f} [\Theta_c^2(t)]dt \quad (13)$$

Optimization of any one cost function produces an optimal response for that characteristic but a degradation of other characteristics. Therefore, a combined cost function is used. This cost function is defined as

$$\Upsilon = J_1\Upsilon_s + J_2\Upsilon_t + J_3\Upsilon_c \tag{14}$$

Selection of the weights ($J_1 - J_3$) can be varied in order to trade off individual response characteristics for the classical PI control design.

Optimization Results and Comparison

A turbulence comparison plot of the robust H_∞ control design and the optimized classical PI control design is shown in Figure 6. Clearly, the turbulence response is attenuated to a higher degree with the use of the robust control design. The optimized step response comparison plot is shown in Figure 7. The robust control design has a faster time to peak and no overshoot, whereas the optimized classical control design responds slower and has a slight overshoot. These results clearly show an improvement in system performance when the robust control design is used.

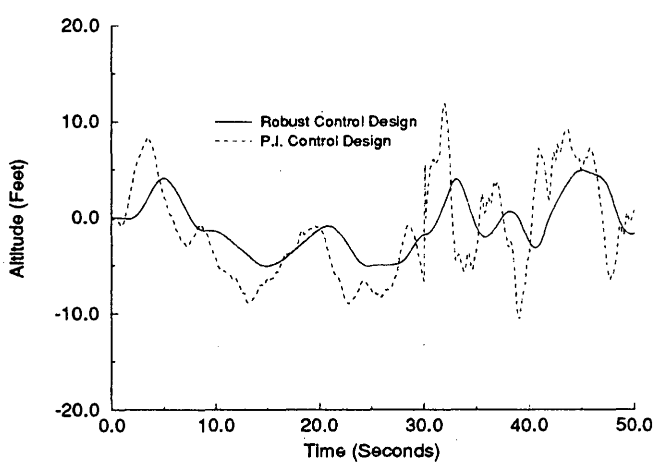

FIGURE 6 Turbulence response comparison.

The robust control design provides better performance characteristics than the "current" classical PI control design. However, the main advantage of the H_∞ control design is the stability robustness in the presence of model uncertainties. To demonstrate this characteristic, a model error is introduced into the aircraft simulation. The model is perturbed by varying all the aircraft stability and control derivatives, given by Equation 1, by a factor of approximately 10 percent. Then both the robust control design and PI control design are compared using the perturbed plant model. Figure 8 shows the step response comparison using the model error plant. The classical PI control design is now unstable, but the robust control design remains stable. Therefore, the H_∞ control design provides a way to guarantee stability in the presence of significant model error and uncertainty.

CONCLUSIONS

In this paper, a detailed simulation of a Boeing 737 aircraft with a pitch autopilot and thrust compensator has been presented. This system was first developed with an open-loop simulation of an aircraft using a 12th-order state-space model. Then a closed-loop simulation was developed for the aircraft under autopilot and thrust compensator control. The autopilot maintains a desired pitch attitude, and the automatic thrust compensator maintains the desired airspeed and angle of attack. The combination of these systems is essential for an automatic flight path control landing.

Next, the turbulence model, used as a disturbance input to the aircraft, was summarized. Therefore, the use of the aircraft simulation and turbulence model enabled the design of a robust H_∞ controller. Combined cost functional results indicate that the robust control design attenuates the turbulence response of the aircraft by a factor nearly two times, as compared with the current controller. The new design was also robust in the presence of model and structural uncertainties.

Finally, the new control design requires only a software modification to the current landing system, so that the controller can easily be implemented onto the actual system. Therefore, an optimal design can be used to simulate an au-

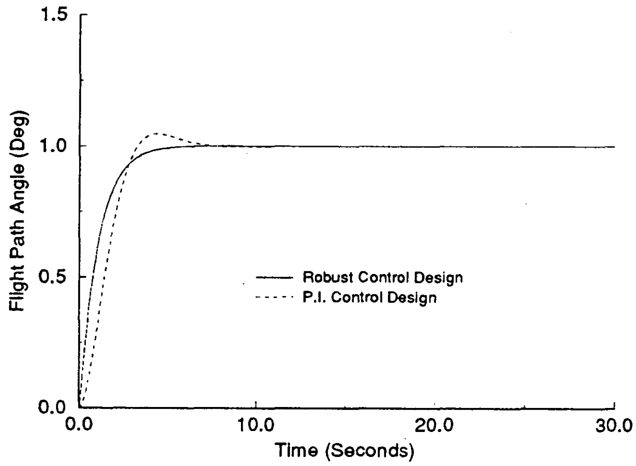

FIGURE 7 Step response comparison.

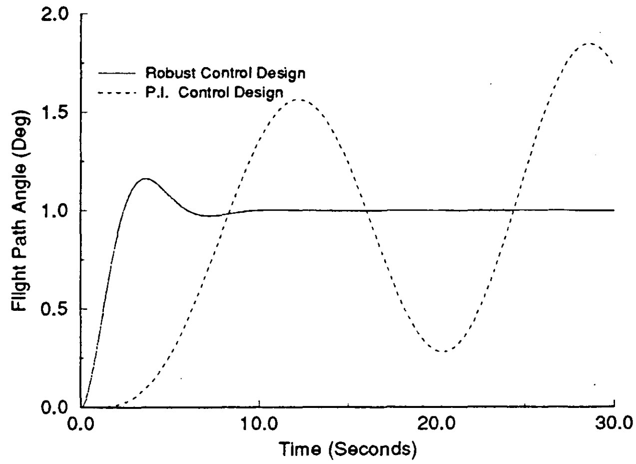

FIGURE 8 Step response comparison with perturbed plant.

tomatic aircraft landing while minimizing the adverse effects of turbulence.

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Response of U.S. Air Carriers to On-Time Disclosure Rule

ROBERT SHUMSKY

The On-Time Disclosure Rule, implemented by the U.S. Department of Transportation in 1987, makes reports of the on-time performance of the major U.S. carriers available to the public. The purpose of the disclosure rule was to create incentives for the carriers to improve their on-time performance by either reducing the amount of time to complete a flight or lengthening the amount of time scheduled for a flight. The evidence shows that although actual flight times have fluctuated, scheduled flight times have increased significantly since 1988. The largest increases occurred just after the disclosure rule went into effect, and a regression analysis shows that since 1988, on-time performance has been a significant factor in the scheduling decisions of many carriers. Then two scheduling strategies are presented that are designed to improve on-time performance. The strategies are implemented, and their performance is compared with the performance of the carriers' schedules. The comparison highlights the challenges that carriers face when designing schedules with the disclosure rule in mind.

According to a U.S. Department of Transportation (DOT) study in 1987, fewer than half the flights operated by the major carriers in and out of eight major hub airports during 1986–1987 arrived on time, where an on-time flight is defined to be an arrival within 15 min of schedule (M. Langelan, DOT, 1987, unpublished data). In response to the 1987 DOT study and many consumer complaints, DOT adopted regulations in 1987 designed to encourage the carriers to improve the percentage of on-time flights. These regulations included the On-Time Disclosure Rule (OTDR) (*1*).

Rather than establish performance goals, the OTDR makes available to the public information about the carriers' on-time performance. The carriers are now required to submit data on their on-time performance to DOT, and DOT publishes cumulative results in the monthly *Air Travel Consumer Report*. The statistics are quoted in the media (*2*), carriers who perform well cite the results in their advertising (*3*,p.15), and the computer reservation systems used by most travel agents display summaries of the statistics. DOT's goal was to allow the marketplace to pressure the carriers to improve their on-time performance. Whether the *Air Travel Consumer Report* contains the most appropriate statistics, and whether consumers make effective use of the information published in the report, has recently been questioned by Cunningham and Brand (*4*) and by consumer advocates (*5*). This paper will focus on the behavior of the carriers under the OTDR.

According to DOT, by March 1988 more than 81 percent of flights flown by the major U.S. carriers were arriving on time, indicating a marked improvement over the results of DOT's 1987 study (*6*). This improvement might be attributable to factors beyond the carriers' control, such as reduced congestion in the national airspace system, but major carriers may have improved their on-time performance by operating their flights in a more timely manner or by changing their posted schedules to more accurately reflect the lengths of their flights. In this paper we investigate whether the carriers implemented these strategies, gauge the success of their efforts, and evaluate the effectiveness of the OTDR itself.

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DATA

Under the OTDR, the major U.S. passenger carriers submit performance data on all domestic flights to DOT. A flight is a scheduled entity that flies regularly between a pair of airports (i.e., USAir Flight 427 from Boston to Washington National). An operation is an instance of a flight on any given day. In the original data, a flight generates between 1 and 31 operations each month. The performance data for each operation include the destination and arrival airport codes, the carrier code, the scheduled departure and arrival times, and the actual departure and arrival times. One month of data contains information on approximately 150,000 operations representing about 14,000 flights. From this information one can calculate the scheduled and actual transit times for each operation. Scheduled transit time is the time from the scheduled departure from the gate to the scheduled arrival at the destination gate; actual transit time is the time from the scheduled departure to the actual arrival. Actual transit time includes time spent holding at the origination gate, taxiing, queueing at the head of the runway, flying to the destination, and taxiing to the destination gate. A flight is on time if its actual transit time is less than 15 min longer than its scheduled transit time. A flight is late if it is not on time.

We obtained DOT data for March of each year from 1988 to 1991. This was more information than could be processed, so we extracted from the 1988 data the operations of a random 5 percent sample of the flights. We then searched the data in subsequent years for flights considered to be equivalent to flights in the 1988 sample.

Specifically, the 1988 sample was selected by sorting all 1988 flights by departure airport code, arrival airport code, and flight number. We then chose every 20th flight that operated at least five times a week. We ignored all Eastern Airlines flights, because Eastern was crippled by a strike during the time covered by our data. This method was simple and easily reproducible, and it resulted in a random sample of 698 flights. The number of flights was large enough to ensure reasonably small standard errors for the estimates that will be described in the next two sections.

We then searched the March 1989, 1990, and 1991 data for flights that were equivalent to flights from the 1988 sample. To match a 1988 flight, a flight in a later year must be operated by the same carrier, flown between the same airports, and scheduled to depart within ½ hr of the original 1988 departure time. For example, Delta's Flight 1719 was scheduled to leave Los Angeles (LAX) for Seattle (SEA) at 6:55 a.m. in 1988. A matching Delta flight was found in 1989 that left LAX for SEA at 6:30 a.m. No matching flights were found in 1990 or 1991, so this flight appears for 2 years in our sample. Of the original sample of 698 flights, 296 appeared in all 4 years. Of these, the schedules of 219 were found in the *Official Airline Guide* for March 1987 (7). We will refer to these 219 flights as the "5-year sample." Because the OTDR was instituted in September 1987, the schedules of the 5-year sample allow the comparison of scheduling practices before and after the passage of the legislation.

TRENDS IN TRANSIT TIMES

Transit Time Changes in 5-Year Sample

Because the 5-year sample contains the same set of flights in every year, the mean scheduled and actual transit times for each year may be compared. The middle line in Figure 1 shows a strong upward trend in scheduled transit times from 1987 to 1991, with the largest increase, one of 4.8 min, occurring between 1987 and 1988, when the OTDR was implemented. Note that only schedule times, and no performance data, were available for 1987. Actual transit times were consistently higher than scheduled transit times throughout the period; the average gap between actual and scheduled times peaked at 11.8 min in 1989. From this observation, one would expect that on-time performance suffered in 1989 and improved as scheduled times lengthened and actual times dropped. The lowest line in Figure 1, which displays the on-time performance of the 5-year sample, confirms this expectation.

To quantify the degree to which the changes in scheduled transit times affected on-time performance, we calculated the fraction of operations that would have arrived on time had the original 1987 schedule not been altered. Figure 2 shows that the fraction of on-time operations would have been 0.5 in 1990, rather than the 0.73 achieved with the schedule changes.

The original sample of 698 flights was a random sample of all 1988 flights, so its characteristics mirror the characteristics of the parent population. Therefore, statistics derived from the original sample will not be biased with respect to the parent population. The same cannot be said about the 5-year sample, because many of its characteristics differ significantly from the original sample, and therefore from the parent population. For example, the original sample and the 5-year sample were significantly different in the percentage of flights allocated to each carrier. TWA flights accounted for 6 percent of the original sample and only 1 percent of the 5-year sample. Other statistically significant differences between the two

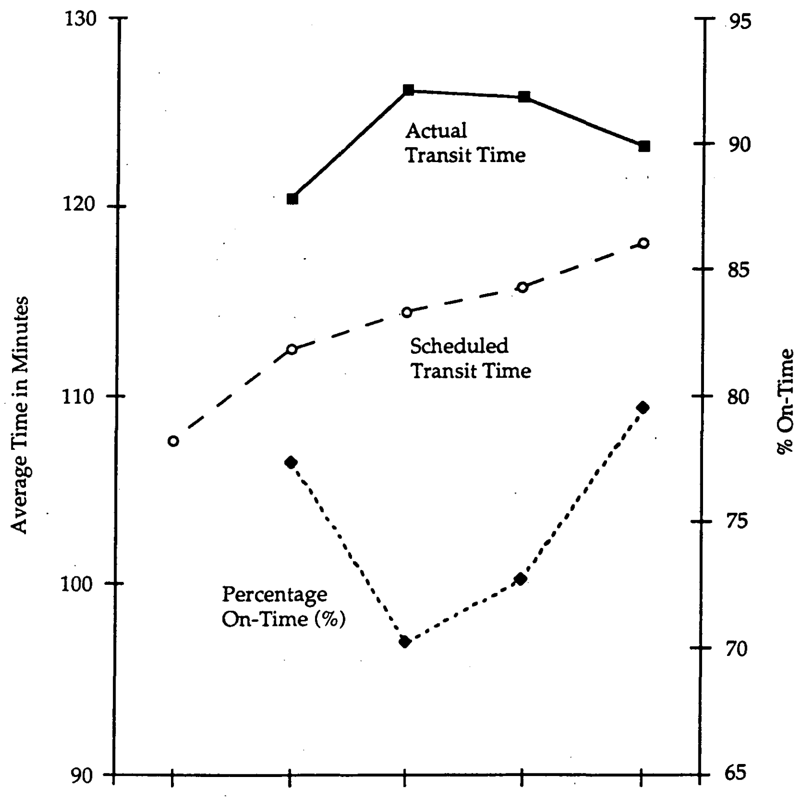

FIGURE 1 Transit times and on-time performance in 5-year sample.

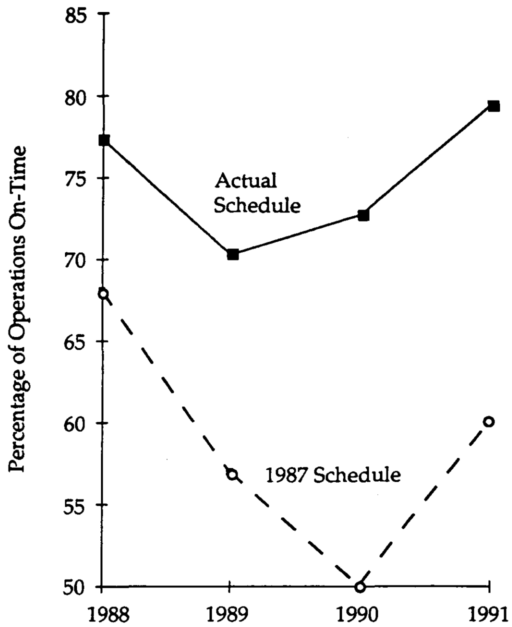

FIGURE 2 Percentage of operations on time under actual and 1987 schedules.

samples included a difference in the types of airports served: the 5-year sample included a higher percentage of flights serving the larger, busier airports.

Transit Time Changes for All Flights

Because the compositions of the 5-year sample and the original random sample have significant differences, we investigated whether the flights left out of the 5-year sample also display increases in scheduled transit times. The subsample of those flights that are not 5-year flights will be called the intermittent sample, because the flights appear intermittently from 1987 to 1991. A reasonable method for measuring schedule changes in 1989, 1990, and 1991 for the intermittent sample is to calculate the mean change in scheduled transit times from the "baseline" transit time established for each flight in 1988. Note that the mean change for 1989 is the mean over a group of flights, which differs from the groups averaged in 1990 and 1991 because some flights "disappear" in 1989 and reappear in 1990 or 1991 and others appear in 1989 but disappear from the sample in a later year. The following table displays these means, as well as the mean change from the 1988 baseline for the 5-year flights and the p-values:

	1988–1989	*1988–1990*	*1988–1991*
5-year sample (min)	2.0	3.3	5.7
Intermittent sample (min)	1.6	3.0	4.2
p-value	0.53	0.71	0.04

These schedule changes were approximately normally distributed, and t-tests were performed on the hypothesis that the means of each of the underlying populations were equal. We have no reason to reject the hypothesis that the mean scheduling increases in 1989 and 1990 were the same in the two samples. Although the difference in 1991 is statistically significant at a .05 level, the table indicates that the scheduled transit times in the intermittent sample have grown at a rate similar to that of the 5-year sample. This implies that the overall trends observed in the 5-year sample may also be observed in the population of flights as a whole.

SCHEDULE CHANGES OF INDIVIDUAL CARRIERS

In the previous section we saw that the carriers as a group have consistently increased the scheduled transit times of flights between 1987 and 1991. The chance to improve on-time performance may motivate carriers to lengthen their scheduled flight times, but other factors restrain the carriers from adding slack. Carriers compete for customers, who prefer short flight times. In addition, contracts for many carriers specify that the flight crew be compensated for each operation on the basis of a maximum of the scheduled and actual transit times. The total time allocated to all flights may be viewed as a scarce resource and the allocation of those minutes among flights as a constrained optimization problem. In this section we investigate how individual carriers solved this problem.

Adjustments in Scheduled Transit Times

Within the 5-year sample, there are large differences between each carrier's schedule adjustments. Table 1 displays the adjustments by year and carrier. The scheduled transit times of American Airlines flights in the 5-year sample increased an average of 17 min between 1987 and 1991, but those of United Airlines increased by an average of just 5 min. American experienced its largest mean increase, of 12 min, in the first year.

It may be that American anticipated or reacted to the OTDR in a more timely manner than its competitors. On the other hand, American's scheduled transit times in 1987 may have been shorter than the transit times of the other carriers, so that American was compelled to add a greater amount of time to its schedule in order to achieve reasonable on-time performance. To evaluate the latter hypothesis, we found the scheduled transit times of the major carriers along 16 popular routes in the March 1987 *Official Airline Guide* (7). On average, American's scheduled times were 7 min shorter than the times of each of the other carriers. Before the OTDR, American underrepresented the transit times of those flights to a greater extent than its competitors.

TABLE 1 Average Change in Scheduled Transit Times by Carrier

	Average Change (min.)				
Year	AA	CO	DL	NW	UA
1987-88	12	5	4	2	1
1988-89	-1	5	4	7	2
1989-90	3	-1	0	1	1
1990-91	3	4	3	-2	1

AA=American, CO=Continental, DL=Delta, NW=Northwest, UA=United

Schedule Changes and On-Time Performance

A carrier's decision to lengthen the scheduled transit time of a particular flight may depend on myriad factors, including competitive pressures, the departure times of connecting flights, and on-time performance history. If on-time performance does enter the decision, we would expect a positive correlation between the fraction of operations that were late in a year and the number of minutes added to that flight's schedule in the next year. Figure 3 displays such a relationship for Continental flights that operated in both 1988 and 1989. Each point represents one such flight, and the point is plotted with the fraction of operations late in 1988 as the abscissa and the subsequent schedule increase as the ordinate. For many of these flights, poor on-time performance led to longer scheduled transit times.

If we assume that the relationship between on-time performance in one year and scheduling adjustments in the next is linear, we may model each carrier's behavior with the following equation:

$$y_i = c + \beta_d x_{di} + \varepsilon_i \qquad (1)$$

where

- y_i = change in minutes of scheduled transit time of Flight i,
- c = change in scheduled transit time applied to all flights,
- β_d = constant for value of (schedule change in minutes)/(percentage late),
- x_{di} = percentage of operations of Flight i late in previous year, and
- ε_i = change in scheduled transit time of Flight i not explained by other variables.

For each carrier we performed a least-squares fit for flights that operated in both 1988 and 1989 in order to obtain the estimates $\hat{c}$ and $\hat{\beta}_d$ that are listed in the first two rows of Table 2. The numbers in parentheses are the standard deviations of the estimates around their true values if we assume normality of the error term ε_i. According to these results, if a Continental flight experienced no late operations in 1988, we would expect its scheduled transit time to decrease by about 4 min in the next year. On the other hand, its schedule would increase by (0.2 min)/(1 percent late), or about 12 sec, for each percentage point of operations late in the previous year.

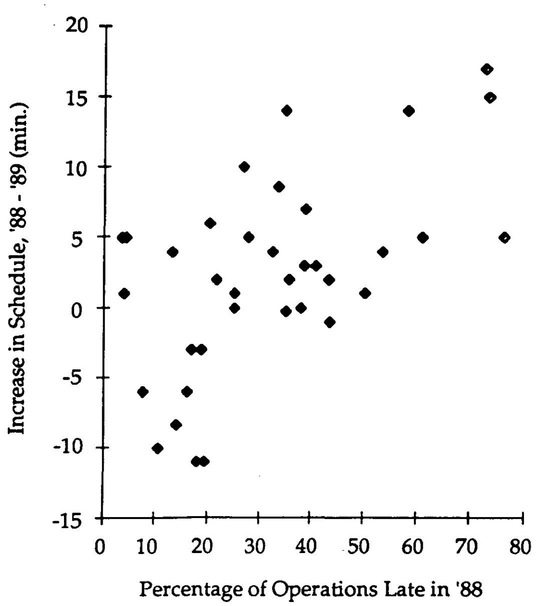

FIGURE 3 Percentage late versus schedule increase for Continental flights.

To test hypotheses about the coefficient estimates in Table 2, we must assume the normality and constant variance of ε_i. We tested these assumptions by examining standard regression diagnostics, such as normal probability plots of the residuals. For all the sample carriers except United, for which there were only 33 sample flights, we found no reason to reject the assumptions. We may therefore construct confidence intervals for our parameters. For example, the true β_d for Continental is within the region $(\hat{\beta}_d - 2\sigma_{\beta_d}, \hat{\beta}_d + 2\sigma_{\beta_d}) = (0.1, 0.3)$ with a probability of approximately 0.95.

Table 2 also contains the R^2-statistic, sometimes called the coefficient of determination. R^2 measures the proportional reduction of the variation in y_i when the model is used. Many of the values in Table 2 are small, indicating that the linear model does not greatly reduce the variation in y_i. This is not unexpected, since it would be difficult to imagine that the carriers rely on a formula such as Equation 1 to construct their schedules.

Despite the low R^2 scores, the estimates of the model parameters allow us to examine the strength of the relationship between on-time performance and the schedule changes for each carrier. In addition, we may use R^2 to test the hypothesis that these two variables are independent. We assume that y_i and x_{di} are jointly normally distributed and test the following hypothesis:

H_0: y_i and x_{di} are independent

H_a: y_i and x_{di} are not independent

If n is the number of flights in our sample and R is the square root of R^2, then under H_0, the statistic

$$t^* = \frac{R\sqrt{n-2}}{\sqrt{1-R^2}} \qquad (2)$$

follows a student-t distribution with $n - 2$ degrees of freedom (*8*). We used t^* to test H_0 for each of the carriers, and the p-values are shown in Table 2. H_0 may be rejected for all airlines except American with a 0.05 level of confidence, and even for American the p-value is only 0.07. Note that this test is equivalent to testing the hypothesis that the constant β_d is equal to 0 for each carrier. Taken together, these results supply strong evidence that the schedule changes are correlated with on-time performance in the previous year.

Schedule Changes and Marginal Gain

Besides the relationship demonstrated in the last section, specific scheduling practices with respect to on-time performance may vary among carriers, so any detailed analysis of these

TABLE 2 Least-Squares Estimates and Diagnostics for Schedule Change Model, 1988–1989

	AA	CO	DL	NW	UA
$\hat{c}(\sigma_c)$	-2 (0.9)	-4 (1.8)	0 (0.9)	4 (1.2)	-1 (1.9)
$\hat{\beta}_d(\sigma_{\beta_d})$	.08 (.05)	.20 (.05)	.14 (.03)	.11 (.04)	.09 (.07)
R^2	0.04	0.33	0.19	0.14	0.08
p-value	0.069	0.001	0.001	0.007	0.041

practices should focus on each carrier as a distinct decision maker. An investigation of the practices at American Airlines may be particularly interesting because American is known for its sophisticated decision-support techniques.

For example, in 1991 American reduced the scheduled transit time of Flight 330 by 4 min from the previous year, even though 69 percent of the operations of this flight were late in 1990. The reason for this decision may be found in the actual transit times of each operation of the flight: 27 percent of the operations arrived more than 35 min after the scheduled arrival time, so a substantial increase in scheduled transit times would not have improved on-time performance. Even if the scheduled transit times had been 10 min shorter, 69 percent of the operations would still have been on time. Using 1990 performance as a guide, American's schedulers may have realized that the gain in on-time performance realized by increasing Flight 330's scheduled transit time was likely to be quite low. To quantify the effect of this factor on American's scheduling decisions, we calculate the marginal gain for a particular flight by finding the percentage of operations that would have been on time had 10 min been added to the schedule, subtracting the percentage that would have been on time had 10 min been subtracted from the schedule, and dividing by 20. In Figure 4, 40 percent of the operations of American's Flight 25 arrived on-time (less than or equal to 14 min after schedule). If the schedule had been 10 min longer, 60 percent would have arrived on-time and if the schedule had been 10 min shorter, 8 percent would have been on-time. The marginal gain, then, is (60 − 8)/20 = 2.6 percent/min.

Again, we will approximate the relationship between performance in one year and schedule changes in the next with a linear function. For this model, American's schedule changes will depend on both on-time performance and marginal gain in the previous year:

$$y_i = c + \beta_d x_{di} + \beta_g x_{gi} + \varepsilon_i \tag{3}$$

where β_g is a constant for the value (schedule change in minutes)/[marginal gain (%)], and x_{gi} is the marginal gain of Flight i in the previous year.

We obtained estimates $\hat{c}$, $\hat{\beta}_d$, and $\hat{\beta}_g$ by performing a least-squares fit on three sets of data: flights operated by American in both 1988 and 1989, in both 1989 and 1990, and in both 1990 and 1991. The results are shown in Table 3, where the numbers in parentheses are the standard deviations of the estimates around the true values if we assume the normality of the error term ε_i. If the marginal gains for two flights in 1988 were 0 percent/20 and 15 percent/20, and if all other factors were equal, we would expect American to increase the scheduled transit time of the second flight by $\hat{\beta}_g$ (15 − 0) = (2.8)(15/20) = 2.1 min more than the first flight.

As we did for our first linear model, we used the R^2-statistic to test whether schedule changes are independent of the other factors in the linear model. Specifically, we test the following hypothesis:

H_0: y_i is independent of x_{di} and x_{gi}

H_a: y_i is not independent of x_{di} and x_{gi}

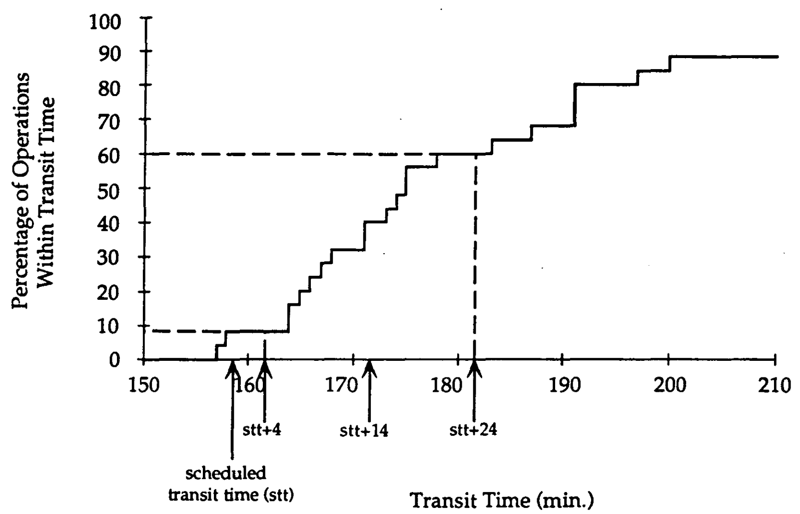

FIGURE 4 Marginal gain of American Flight 25 in 1990.

TABLE 3 Least-Squares Estimates for Schedule Change Model with Marginal Gain

	1988-89	1989-90	1990-91
$\hat{c}(\sigma_c)$	-3.9 (1.0)	-5.4 (2.2)	-0.6 (1.9)
$\hat{\beta}_d(\sigma_{\beta_d})$	0.00 (0.05)	0.11 (0.06)	0.03 (0.05)
$\hat{\beta}_g(\sigma_{\beta_g})$	2.8 (0.8)	3.0 (1.1)	2.3 (1.3)
R^2	0.18	0.20	0.09
p-value	0.0005	0.0008	0.08

When H_0 is true, and when y_i, x_{di}, and x_{gi} are distributed as multivariate normal random variables, then the statistic

$$F^* = \frac{R^2}{1 - R_2}\left(\frac{n - 3}{2}\right) \quad (4)$$

follows an F-distribution with 2 and $n - 3$ degrees of freedom (*8*). Table 3 displays p-values from the tests with this statistic. We may reject the null hypothesis of independence for 2 out of the 3 years with a .05 level of confidence, and the test for the third year obtains a p-value of 0.08.

Note that the inclusion of marginal gain among those factors influencing schedule decisions is an artifice of DOT's definition of being on time as being within 15 min of schedule. If DOT reported the mean number of minutes off schedule for all of a carrier's flights, rather than the percentage more than 15 min late, then any increase in scheduled transit time for any flight would improve the carrier's on-time performance. All flights would have the same marginal gain.

In this analysis we have focused on American and have seen that both the mean and the distribution of actual transit times may influence changes in scheduled transit times. Flights with a large amount of variability in actual transit times or large "right tails" in their histograms offer little marginal gain; these flights require a large investment of schedule minutes to achieve small gains in on-time performance. Carriers whose transit times are extremely variable have a difficult choice: either they implement large increases in scheduled transit times, or they accept relatively poor on-time performance.

APPROACHES FOR SCHEDULING TRANSIT TIMES

In the previous section we saw that the decision to alter a scheduled transit time may depend on the on-time performance of a flight as well as the distribution of the flight's actual transit times. This section explores the opportunities and difficulties that confront the carriers when they rely on past performance to predict future transit times. We examine the effectiveness of the carriers' solutions by comparing their performance with the performance of two strategies of our own design.

Fifty-five of the flights operated by American appear in all 4 years of the sample. The average increase in scheduled transit times for these flights between 1990 and 1991 was 3.4 min, so that American distributed a total of 187 extra min among these flights when it constructed its 1991 schedule. In this section we develop and test two specific strategies for distributing such a budget of extra minutes. To determine the effectiveness of the carriers' scheduling decisions, we test our strategies on the 4-year flights of American, Delta, and United and compare the performance of our strategy with the performance of the carriers.

The first strategy is the simplest possible: take the budget and distribute it uniformly among all flights. For example, to generate American's 1991 schedule for its 4-year flights, we add 3.4 min to the 1990 scheduled transit time of each American flight in the 4-year sample. This strategy is called the uniform strategy.

The second strategy will attempt to allocate the budget in a manner that optimizes the on-time performance of the flights in 1991. An obvious method would be to look ahead at actual 1991 transit times and then design the schedule to capture as many flights as possible within the 15-min on-time limit. However, we would then be using more information than was available to the carriers; they did not know how individual flights would perform in the future when they designed the schedule.

On the other hand, we might use only the actual transit times from 1988 through 1990 to estimate the distributions of 1991 transit times and then use the estimated distributions to design the schedule. We would not allow ourselves to use any 1991 data at all, but this may be too much of a handicap, for the carriers would have had some knowledge of general trends in transit times. For example, the mean actual transit times for all 4-year flights were 121.7, 126.5, 127.4, and 125.2 min in 1988, 1989, 1990, and 1991, respectively. The carriers, by forecasting the economic and political situation, may have been able to anticipate the downward trend for 1991.

Our second strategy, then, compromises between total use and no use of 1991 data by first centering the actual transit times from 1988, 1989, and 1990 by 3.5 min, −1.3 min, and −2.2 min, respectively, so that the aggregate mean for each year is equal to the 1991 mean. We then use these centered 1988–1990 actual transit times to estimate the cumulative distribution function of all actual transit times [for more details on the density estimation procedure, see elsewhere (*9*)]. The distribution functions are used to allocate the budget in a way that maximizes the expected number of on-time operations. We formulate this problem as a mathematical program in the following.

In the formulation, the decision variables are x_i, the proposed changes in scheduled transit times for Flights i, $i = 1 \ldots n$ from the 1990 schedule. The objective function is the sum of the functions $g_i(x_i)$, which are the estimated cumulative distribution functions for the flight's actual transit time, shifted along the horizontal axis so that they are plotted with respect to a change in the 1990 scheduled transit time. In other words, $g_i(x_i)$ represents the expected proportion of operations that would arrive on time if a given change x_i in the schedule were implemented.

The first two constraints in the formulation limit the total number of minutes added to the schedule to the budget of minutes set by the carrier (i.e., 187 min for American's 4-year flights). The last two constraints limit each flight's transit time increase and decrease to 24 and 18 min, respectively.

These constraints match the carriers' own behavior and keep the optimization problem to a manageable size.

Maximize

$$\sum_{i=1}^{n} g_i(x_i) \tag{5}$$

Subject to

$$\sum_{i=1}^{n} x_i \leq B \tag{6}$$

$$B = \sum_{i=1}^{n} t_i \tag{7}$$

$$x_i \leq 24 \text{ for all } i \tag{8}$$

$$x_i \geq -18 \text{ for all } i \tag{9}$$

where

x_i = change in scheduled transit time of Flight i,
$g_i(x_i)$ = expected proportion of operations on time if scheduled transit time were adjusted by x_i, and
t_i = carrier's change in scheduled transit time of Flight i.

To solve this problem, the functions $g_i(x_i)$ were approximated with piecewise linear functions so that a mixed-integer program (MIP) formulation could be used. We will say that schedules generated with this formulation were generated under the MIP strategy.

The 1991 schedules for the 4-year flights of American, United, and Delta were generated under our two strategies. We then examined how each of our strategies would have performed in 1991 year by computing the on-time performance of the flights had the alternative schedules been implemented. The results are given in the following table:

	On-Time Performance (%)		
Schedule Source	*American*	*Delta*	*United*
Uniform strategy	86.5	81.9	62.0
MIP strategy	87.9	83.0	60.9
Carrier	86.4	82.6	62.7

The most surprising result from the table is that the uniform strategy performed as well as the MIP strategy and the carriers' own schedules. The MIP strategy relies on past performance to predict transit times, and its failure stems from the variability in actual transit times from year to year. Even though we centered the data so that the overall mean of the 1991 transit times matched the mean from previous years, the mean transit time for each individual flight in 1991 varied widely from its mean in the past. For example, whereas the actual transit times of Delta Flight 961 averaged 95 min from 1988 to 1990, the transit times in 1991 had a mean of 103 min, a difference of 8 min that the MIP strategy did not anticipate. For all three carriers, these differences were approximately normally distributed and had an overall standard deviation of 8.3 min. However, United Airlines flights varied more widely than the flights of the other two carriers: the variations of United's flights had a standard deviation of 10.9 min. It is not surprising, then, that our MIP strategy performed particularly badly for United.

CONCLUSION

Our analysis of the data gathered under the OTDR demonstrates that between 1987 and 1991 the major carriers increased the scheduled length of their flights by an average of about 10 min, or about 10 percent (see Figure 1). From 1988 to 1991, actual transit times rose and then fell. If the carriers had not lengthened their schedules, the percentage of flights arriving on time would have been as much as 20 points lower (see Figure 2).

Of course, the schedule increases may have occurred in the absence of the OTDR. However, in Figure 1 we see that almost half of the increase occurred between 1987 and 1988, at the time the OTDR was implemented. In addition, our analysis of the behavior of individual carriers showed that many of the schedule increases were correlated with on-time performance as defined by the OTDR. Therefore, it is likely that the OTDR influenced the carriers' scheduling decisions.

Our attempts to create a schedule that was optimal with respect to on-time performance demonstrated that carriers with transit times that vary widely face particular scheduling difficulties. Because past performance may not provide reliable information about the future, only large schedule increases guarantee better on-time performance. The OTDR rewards carriers with stable transit times and carriers with unstable times that can afford to make such large increases.

Excellent on-time performance under the OTDR does not necessarily mean that an airline carries passengers efficiently; it indicates only that passengers arrived according to schedule. Because the primary goal of the OTDR is to protect consumers, we have seen that it has been successful in this respect; it appears to have prevented the carriers from developing two schedules: one that is advertised and one that is flown.

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Policy-Level Decision Support for Airport Passenger Terminal Design

Tom Svrcek

Errors in the initial stages of airport passenger terminal design can be enormously expensive. Thus, providing airport planners with decision support at the policy level can prevent costly errors made on the basis of rules of thumb or "standard" practice. The two traditional approaches for assessing potential terminal performance are inadequate. Detailed, microsimulation programs require large amounts of data and presuppose a strictly defined initial configuration. Analytic formulas, expressing airport performance in terms of one or more decision variables, can be developed and optimized using differential calculus to find the best configuration—unfortunately, this method can oversimplify the problem. A new methodology is presented for providing decision support for assessing airport terminal performance in terms of expected passenger walking distances. It has the advantages of capturing the most important elements of airport operations and being fast and flexible. To achieve such speed, simple mathematical expressions (based on sophisticated analyses) are used that can be computed very quickly so that potential performance can be assessed for a variety of forecasts. Performance can thus be assessed for many possible futures to get an idea of the robustness of a particular configuration, that is, whether it exhibits similar characteristics over a wide range of conditions.

Errors in the initial stages of airport passenger terminal design can be enormously expensive. From a purely economic perspective, preventing avoidable design errors for a single airport passenger terminal can save tens of millions of dollars (*1*). It is believed, for instance, that avoidable design errors at the Air France terminal in Paris (Aerogare 2) resulted in an additional $75 million in expenses. Overdesign of the corridor in the International Terminal Building in Sydney, Australia, unnecessarily increased construction expenditures by an estimated $10 million.

Moreover, inappropriate terminal configuration selection can inconvenience passengers with unnecessarily long walking distances. The linear design of the Dallas–Fort Worth Airport was chosen under the assumption that future passenger traffic would consist largely of originating and terminating passengers. Under such an assumption, a design that provides short distances between ground transportation access and aircraft gates is highly desirable. Traffic patterns changed dramatically after airline deregulation, however, as carriers such as American and Delta Air Lines established large hub-and-spoke operations in Dallas. As a result, much passenger traffic there became transfer traffic, for whom the street-to-gate distance metric is not nearly as important as the average distance between arrival and departure gates. In terms of average gate-to-gate distances, the linear design is inappropriate for large volumes of transfer traffic (*2*).

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To illustrate this point, consider the two curves shown in Figure 1. The lines represent average walking distances for each of two terminal configurations as a function of passenger traffic mix. Note that for low levels of transfer traffic the Dallas configuration performs well, but that as the proportion of transfers increases, walking distances increase steadily. The second line shows the potential performance of some other configuration. As transfer traffic increases, walking distances increase as before, though not nearly as steeply. The second configuration is thus more robust, that is, it performs well over a wide range of circumstances rather than just one.

Basing configuration selection on a single forecast, as is often done, may lead to inflexible selections—ones that are appropriate only for a very limited range of future conditions. Given the enormous uncertainty associated with forecasting conditions 10 to 15 years away, it is crucial to select the most robust design on the basis of a wide range of forecasts. To accomplish such a selection, however, we need to be able to evaluate the potential performance of several different configurations over a variety of conditions.

In short, the process of selecting an initial configuration can benefit greatly from decision-support tools that can assess a priori measures of airport performance such as passenger walking distances. Arriving at an individual estimate, however, is not sufficient. To be effective, the tool must provide performance estimates for a range of future conditions in order to help select a robust design. As shown in Figure 1, the linear configuration performs better over a very restricted range of passenger mix forecasts. But a more complete analysis exposes its inflexibility to the level of transfer traffic.

Computer-based simulation tools are one means of providing decision support for airport terminal design. These programs focus on a detailed minute-by-minute or passenger-by-passenger analysis of a configuration in order to arrive at one or more performance measures. The programs can provide important information for improving designs, but they generally require large amounts of detailed input data that must presuppose a particular initial configuration. Moreover, these microsimulation programs require large setup times for even minor changes to the initial layout, making them cumbersome for performing extensive sensitivity analyses. What results from a series of "design-simulate-redesign" iterations is often an improved layout, though of a very strictly defined initial configuration, with no indication of whether the initial configuration was the most appropriate in the first place.

Other approaches attempt to provide analytic solutions to finding optimal passenger terminal geometries in terms of minimizing performance measures such as passenger walking distances (*3*,*4*). Bandara (*5*) and Bandara, Wirasinghe et al.

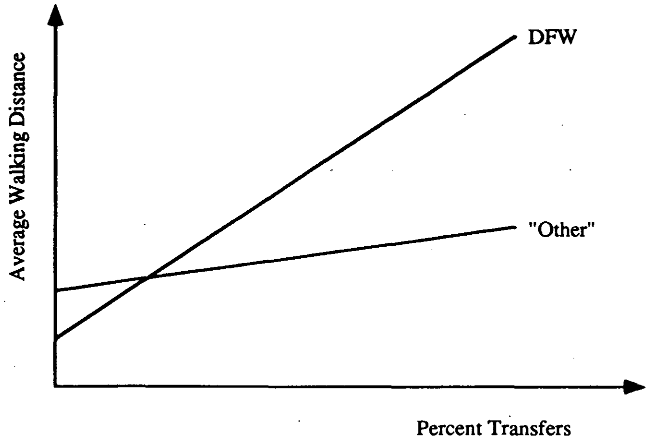


FIGURE 1 Average walking distance (as a function of passenger mix).

(*6–9*) present expressions for expected walking distances in terms of different decision variables for different terminal configuration concepts. Using differential calculus, they find the optimal parameter that minimizes the expected walking distance. Unfortunately, these approaches must make several simplifying assumptions to develop a single expression; examples include universal gate capacity and uniform gate spacing throughout the entire airport, uniform probabilities of arrival and departure at all gates within a terminal, and similarly shaped terminals for a given configuration. Under these assumptions optimal parameters can be determined, and the results from the expressions provide a good first cut for assessing configuration performance. Relaxing assumptions such as universal gate capacity is difficult, however, because of the special structure of the equations.

Absent from the overall terminal design process is a decision-support tool that can quickly evaluate the approximate performance of several very different terminal configurations in order to determine the one most appropriate for a given range of assumptions. Such a tool can be thought of as a front end to more-detailed microsimulations, providing valuable information early on for screening and eliminating inappropriate design alternatives. The remaining alternatives can then be analyzed using a more precise tool, when rapid response times are not as critical and precision becomes important.

This paper describes a new approach for assessing passenger terminal performance during the selection of the initial configuration concept. The method departs from more traditional techniques of discrete-event simulations and analytic formulas, relying instead on the incorporation of the essential elements of airport operations (which affect such performance characteristics as expected walking distances) into a model that can determine performance measures quickly for any given forecast. To achieve such speed, the method uses simple expressions that can be solved on a computer.

With such a fast and flexible tool, we can test the performance of several configurations over a variety of forecasts in the time that it takes to evaluate just one using other methods. The technique reduces the risk associated with making decisions under great uncertainty or with limited evidence. Such high-level decision support during the early phases of terminal design is likely to prevent costly errors that are made because of reliance on intuition and so-called standard practice.

After a brief overview of the quality of service, or performance, of airport terminals, this paper describes the primary types of terminal configurations and the types of passengers who use them. It then presents a model for estimating passenger walking distances and demonstrates how the model can be used to assess configuration robustness. The numerical values used to introduce the methodology are presented only to illustrate the principle of the technique and intentionally are not taken from actual sources, so as to divorce the reader from the notion that the validity of the technique itself somehow depends on specific values of the input data.

AIRPORT PERFORMANCE

The topic of airport performance is one of much study and debate. Lemer provides a comprehensive discussion of the characterization and measurement of performance for airport passenger terminals (*10*). He identifies specific quantifiable measures for assessing airport performance from the perspective of the three principal users of airport services: airport operators, airlines, and passengers. Each group has its own set of often conflicting measures by which to assess airport terminal performance. Thus, it is the task of the airport designer/planner to achieve a balance among the needs of all three groups when designing a passenger terminal.

From the perspective of the airport operator, issues of operational effectiveness, efficiency, and flexibility are of primary importance. Good utilization of gates, labor, and overall space adds to the airport's functionality while keeping operational costs down. Large projects such as airport expansions are often financed through the issue of bonds, and debt coverage is an important financial factor that airport operators also consider when measuring the performance of an airport.

Debt coverage is frequently handled, at least in part, by the airlines that use airport services. Station costs such as terminal and landing fees are important considerations from the perspective of the airlines. Other issues such as operational effectiveness (aircraft turnaround times, baggage transfer reliability, etc.), flexibility, and corporate image are also important, particularly in the United States, where carriers sometimes own their own terminal areas.

From a passenger's perspective, issues of terminal compactness, service area delays, and reliability are among the most important measures of airport performance. Ideally, passengers want to minimize walking distances and waiting times at check-in and baggage claim facilities and never miss a connecting flight. Moreover, they would like good signage and spatial logic to help them get around easily, and they would like the prices at concession areas to be competitive.

Of these measures of performance, policy-level decision makers exert considerable control over passenger walking distances when selecting the initial terminal configuration. Indeed, the physical geometry of a terminal configuration is the largest factor influencing passenger walking distances.

TERMINAL CONFIGURATION TYPES

Airport terminal configurations are as numerous as airports, yet nearly all can be placed in four primary categories based on their underlying philosophies of function: the centralized terminal, the linear (or gate-arrival) terminal, the midfield terminal, and the remote (or transporter) terminal (*11*).

The centralized terminal is characterized by a large common area containing check-in and baggage facilities as well as concession areas and other auxiliary services. Passengers reach departure gates through corridors. If aircraft interfaces (gates) are located along the corridors, the terminal is considered a finger pier [Figure 2(*a*)]. If the aircraft interface is at the end of the corridor, the terminal is considered a satellite [Figure 2(*b*)]. Large airports may comprise several centralized terminal areas with finger piers or satellites extending from each, such as at Chicago O'Hare International Airport.

A more fundamental type of configuration is the linear, or gate-arrival, terminal (Kansas City, new Munich). Represented by one or more simple rectangles [Figure 2(*c*)], the linear configuration provides a more immediate interface between local passengers and aircraft, though it requires the duplication of services (e.g., baggage handling and check-in facilities) for each separate terminal.

An increasingly prevalent configuration is the midfield terminal concept (Atlanta Hartsfield, new Denver), characterized by a centralized terminal and one or more separate concourses connected by an underground people mover or moving walkway [Figure 2(*d*)]. Each of the separate concourses can have aircraft interfaces on virtually all sides, providing good use of terminal space.

The final type of terminal configuration is the remote, or transporter, terminal (Washington Dulles). Passengers board a bus or transporter at a centralized terminal and are taken either directly to their aircraft or to a remote terminal at which the aircraft is parked. The remote terminal can be represented by a simple box, and any of the previous configurations can house remote exit points. The transporter concept is appealing for managing peak traffic because it eliminates fixed structural costs in lieu of smaller variable costs for transporter equipment and labor.

Strict adherence to a particular concept is not required. Indeed, many hybrid terminal configurations embody two or more of the previous concepts. Thus, we can think of a hybrid configuration as a fifth concept.

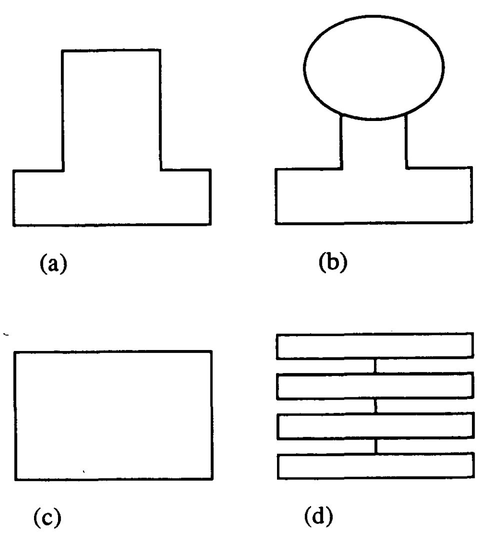


FIGURE 2 Terminal configuration concepts: (*a*) finger pier, (*b*) satellite, (*c*) gate-arrival, and (*d*) midfield.

PASSENGER TYPES

Passengers who either begin or complete their journey at an airport are known as originating or terminating passengers, respectively. Originating passengers are assumed to arrive at the airport entrance nearest to the terminal containing their departure gate. Their required walking distance, therefore, can be modeled as the distance between the terminal entrance and the departure gate. Check-in facilities are generally located somewhere along this path (or nearby), so we make no explicit distinction between the walking distances for passengers who have advance seat assignments and those who must check in. Furthermore, we do not distinguish between walking distances for originating passengers who are carrying luggage and walking distances for those who are not.

Similarly, terminating passengers are assumed to leave the airport through the exit nearest their arrival terminal. Required walking beyond the exit is not necessarily affected by the configuration concept, so it is not considered. Like check-in services, baggage claim services are often located along the path from the arrival gate to the terminal exit, so we do not make a distinction between terminating passengers with and without baggage.

Thus, we model the required walking distances for both originating and terminating passengers as the distance between the departure (arrival) gate and the nearest entrance (exit). Such an approximation helps in performing calculations quickly, though there is also a strong intuitive argument for its use.

Passengers who neither begin nor end their journeys at an airport are considered transfer passengers. Transfer passengers are required to travel some path from their arrival gate to their departure gate. The length and direction of the path depends both on the physical geometry of the terminal and whether the passenger is making a direct or indirect transfer. The more common type of transfer is a direct, or hub, transfer: passengers go directly from their arrival to their departure gates. The required walking distance for a direct transfer is the length of the most direct path between the respective gates, determined by the geometry of the terminal. Indirect, or nonhub, transfers, on the other hand, must include in their path some intermediate service point, which is likely to increase the required walking distance. Most interline connections and international flights with domestic connections can be considered indirect transfers.

ESTIMATING WALKING DISTANCES

We estimate expected walking distances by calculating weighted averages of the absolute distances walked by each of the passenger classifications. Absolute distances are calculated using the right-angle or Manhattan metric and reflect the actual walking distances required of a passenger to get between two locations in the airport, on the basis of terminal geometry. In practice, passengers often divert from the most direct path (to use concession areas, for example). We do not consider such diversions, because they do not reflect the choice of a terminal configuration as much as they do passenger behavior.

For interterminal transitions, we assume each terminal has a waypoint through which passengers must pass when walking between terminals. We can therefore determine all absolute gate-to-gate as well as gate-to-entrance (or exit) distances on the basis of the physical geometry of the terminal configuration. Determining the overall expected walking distance for a particular configuration, however, requires additional information.

The overall expected walking distance is a weighted average of all the individual gate-to-gate and gate-to-entrance/exit distances walked. The frequency that each path is walked depends on the forecast of the passenger mix. Thus, if we anticipate that 60 percent of the traffic will be originating or terminating and 40 percent will be transfers (of which 90 percent are direct and 10 percent are indirect), the expression for the expected overall walking distance is

$$D = 0.60d_{ot} + 0.40(0.90d_{td} + 0.10d_{ti}) \quad (1)$$

where

- D = overall expected walking distance,
- d_{ot} = expected walking distance for originating and terminating passengers,
- d_{td} = expected walking distance for direct transfers, and
- d_{ti} = expected walking distance for indirect transfers.

Each distance term on the right in Expression 1 is a weighted average of walking distances estimated on the basis of other assumptions regarding frequency of use. The rest of the paper describes in detail a conceptual approach used to estimate the distance factors in Expression 1.

Direct Transfer Walking Distances

To illustrate our approach, we begin by developing a model for estimating the expected walking distance for direct transfers, d_{td}, from Expression 1. Consider direct transfers within Terminal 1 of the two-terminal airport configuration shown in Figure 3: passengers arriving at Gate 1 can depart from any one of the three gates, and the absolute distance from Gate 1 to Gate 2 is 30 m and from Gate 1 to Gate 3, 20 m.

If we assume that each gate is equally likely for departure, the expected walking distance for Gate 1 direct transfers, d_{td1}, is

$$d_{td1} = (0.33) \times 0 + (0.33) \times 30 + (0.33) \times 20 = 16.7 \text{ m}$$

Now consider all possible direct transfers, which include those to Terminal 2, a satellite terminal containing two gates (for simplicity) located along the perimeter of the circular aircraft interface.

Gate 1 arrivals may now depart from any one of five gates. We assume (though it is not necessary) that passengers arriving in Terminal 1 are more likely to depart from Terminal 1, reflecting, for instance, the territorial nature of gate occupancy at most U.S. airports. The matrix of transition probabilities (T_{ij}) for passengers arriving at a Terminal i and departing from a Terminal j might look like

To		1	2
From	1	0.80	0.20
	2	0.30	0.70

Note that we have not assumed the matrix to be symmetrical. One explanation may be that, because Terminal 2 contains only two of the five departure gates, it is slightly more likely that Terminal 2 arrivals will need to make an interterminal connection. Maintaining a uniform gate use assumption, the expected walking distance for Gate 1 arrivals becomes

$$d_{td1} = 0.80\ (16.7) + 0.20\ (0.50 \times 240 + 0.50 \times 240)$$
$$= 61.3 \text{ m}$$

The expected walking distance increases considerably because of the 20 percent chance of passengers' having to depart from Terminal 2. Similar analyses can be performed for all five potential arrival gates.

Intelligent Scheduling

Our primary assumption so far has been that gate transitions are uniform, that each gate is equally likely for departure. In reality, airport operators and the airlines exercise much control over flight-to-gate assignments and can reduce transfer walking distances by scheduling arrival gates closer to connecting departure gates (*12,13*). It is reasonable, therefore, to consider that under such "intelligent scheduling" conditions, the probability of departing closer to one's arrival gate is greater than that of departing from far away. We refer to transition probabilities based on flight-to-gate assignments as "gate affinity."

A simple method of capturing such effects of intelligent scheduling is to model the probability of departing from a gate as being inversely proportional to the distance to the arrival gate. This assumption is only one of many possibilities, however. The actual transfer probabilities used can be obtained from more complex analyses involving anticipated flight schedules, or they can simply be estimated and input by the user individually. Appendix A demonstrates how to calculate transition probabilities based on our simple model of intelligent scheduling.

Under the assumption that intraterminal transitions are inversely proportional to distances walked and that interterminal transitions remain uniformly distributed, the transition probabilities for Gate 1 arrivals become

$$t_{11} = 0.32$$
$$t_{12} = 0.19$$
$$t_{13} = 0.29$$
$$t_{14} = 0.10$$
$$t_{15} = 0.10$$

The new direct transfer walking distance estimate becomes

$$d_{td1} = 59.5 \text{ m}$$

Note the reduction from the uniform assumption used before.

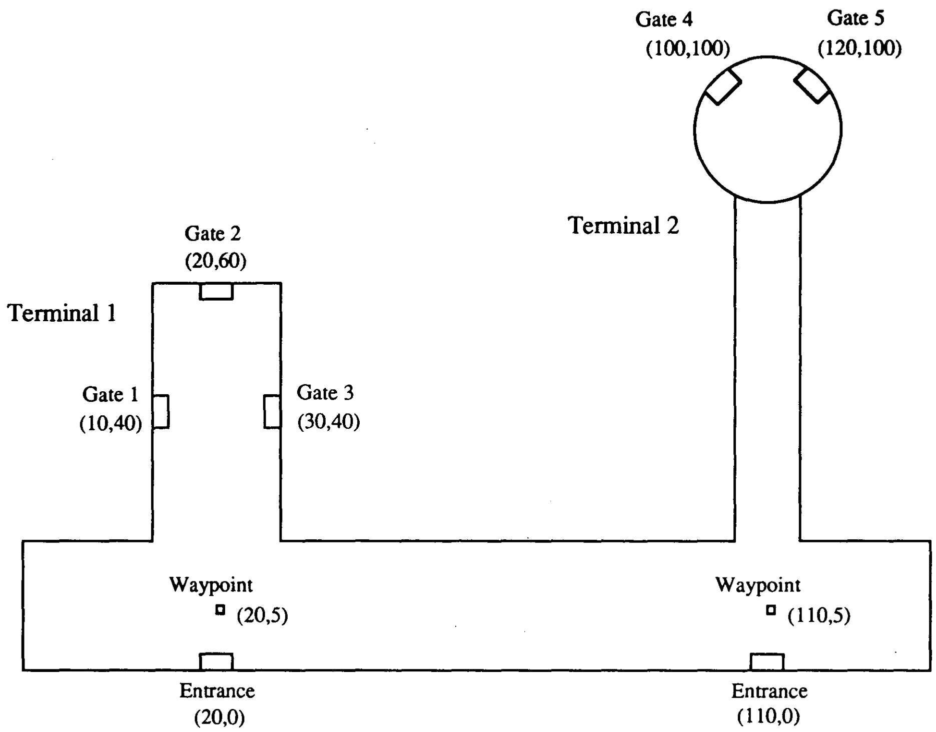


FIGURE 3 Two-terminal airport configuration.

Aircraft Effects

The assumption behind the determination of the transition probabilities calculated thus far has been that each gate handles the same volume of passengers per unit time—that for an airport with n gates, the probability of a random passenger arriving at or departing from any gate is $1/n$. Under such an assumption, differences in gate affinity arise only from the desire of the airport operators or airlines to assign gates for connecting flights closer together.

An important element is missing from such an assumption, though: namely, the capacity of different gates in terms of aircraft use. Different classes of aircraft naturally require different amounts of gate parking space, primarily because of the aircraft's wingspan. Certain gates can handle only small and medium-sized aircraft. Passenger volumes at a gate thus depend on the type and mix of aircraft serviced there throughout the day. We refer to the probability of a passenger's arriving or departing from a gate solely on the basis of the mix of aircraft serviced there as the "demand rate."

The capacity of a gate is often expressed in terms of the largest aircraft that it can service: gates able to accommodate large aircraft, for instance, can also generally accommodate medium-sized and small aircraft. The breakdown of aircraft utilization at a gate is primarily determined by some gate assignment policy—a "Large" gate, for example, may serve 40 percent large aircraft, 50 percent medium-sized aircraft, and only 10 percent small aircraft, whereas a "Medium" gate may service 70 percent medium-sized and 30 percent small aircraft.

Given the gate use by aircraft type, two remaining factors influence the demand rate: the expected number of passengers and the turnaround time for each aircraft type. Aircraft turnaround time is the time required for services such as cleaning and refueling between an arrival and the next departure. In general, larger aircraft may carry more passengers, but they have longer turnaround times. Conversely, smaller aircraft carry fewer passengers but can be turned around more quickly, thus allowing more operations per unit time. The net effect of these two factors on the demand rate can be determined using information about average aircraft use as well as the size and average turnaround times associated with each aircraft type.

Appendix B illustrates how so-called aircraft effects can be used to calculate demand rates. For our example, we use the following data on aircraft size and turnaround times, but the model is entirely general:

Aircraft Type	*Number of Seats*	*Turnaround Time (min)*
Large	400	90
Medium	200	60
Small	150	40

We also assume that the three gates in Terminal 1 are Medium gates and the two gates in Terminal 2 are Large gates, with aircraft utilizations equal to those previously described for Large and Medium gates. From Appendix B, we get the following demand rates:

Gates	*P(Depart)*
1, 2, 3	.19
4, 5	.21

To incorporate demand rates into our original transition probabilities, we weight the two sets of probabilities together. The resulting transition probabilities for Gate 1 arrivals are given in Table 1. The expected walking distance for Gate 1 direct

TABLE 1 Transition Probabilities for Gate 1

T_{ij}	Gate Affinity	Demand Rate	Weighted Transition	Walking Distance (m)
t_{11}	0.32	0.19	0.309	0
t_{12}	0.19	0.19	0.185	30
t_{13}	0.29	0.19	0.278	20
t_{14}	0.10	0.21	0.114	240
t_{15}	0.10	0.21	0.114	240

transfers is the weighted average of the combined transition probabilities and the absolute walking distances, or 65.9 m. On the basis of intelligent scheduling alone, the expected walking distance would be slightly lower, 59.5 m. The increase is due to the higher probability of a passenger's departing from the Large gates in Terminal 2. Similar analyses can be performed for all five gates.

To obtain a single estimate for all direct transfers, we weight the individual direct transfer estimates by the probability of arriving at a given gate. This probability is simply the demand rate based on aircraft effects alone. The implicit assumption is that symmetry exists between departures and arrivals; however, if there is reason to believe that arrival load factors are very different from departure load factors, a similar analysis can be performed to obtain arrival-specific demand rates. We assume symmetry here, and the resulting calculations yield the following:

Gate	*Expected Distance (m)*	*P(Arrival)*
1	65.9	.19
2	71.0	.19
3	65.9	.19
4	73.5	.21
5	73.5	.21

The overall expected walking distance for direct transfer passengers is the weighted average of the individual distances, or 70.2 m.

Other Walking Distances

From this point it is possible to obtain walking distance estimates for originating, terminating, and indirect transfer passengers using similar analyses. The expected originating (terminating) passenger walking distance is the weighted average of the absolute distances walked by such passengers, depending on the probability of departure from (or arrival at) a particular gate. This probability is simply the demand rate based on aircraft effects. Using the demand rates calculated previously, the overall expected walking distance for originating or terminating passengers in the two-terminal airport example is 78.3 m.

Indirect transfers who require intermediate services before departure often must cross greater distances than direct transfers. Given the location of these intermediate service points, we can determine indirect transfer walking distances for all possible gate-to-gate transitions. The overall estimate is the weighted average of all such walking distances.

For our example, we assume services for indirect transfers are located at the waypoint of the respective arrival terminal. Thus, the required walking distance for a Gate 1 arrival departing from Gate 2 is 100 m. Transition probabilities for indirect transfers are calculated similarly to those for direct transfers. Gate-to-gate transition probabilities for indirect transfers are driven almost entirely by interterminal transitions, however, because walking distances to and from intermediate service points are large in relation to gate spacing. Thus, for our example we assume that departure gate affinity for indirect transfers is uniform.

It can be shown that the overall expected walking distance for indirect transfers is 169.3 m. The considerable increase over direct transfer walking distances is explained by the additional walking required for intermediate services.

We now return to Expression 1 and solve for the overall expected walking distance by substituting values calculated previously:

$$D = 0.60(78.3) + 0.40(0.90 \times 70.2 + 0.10 \times 169.3) = 79\,\text{m}$$

Thus, the overall expected walking distance for all traffic weighted by passenger mix is 79 m.

The preceding analysis completes our model for estimating passenger walking distances for a given configuration. But another element of control for airport operators can greatly affect passenger walking distances: namely, dynamic gate selection. The next section details how exploiting demand fluctuations can help reduce walking distances during periods of low demand.

Dynamic Gate Selection

Varying levels of passenger demand place different requirements on an airport and its services throughout the day. Two typical passenger demand profiles faced by airport owners are shown in Figure 4. The first profile is characterized by an almost constant level of demand. The second profile is characterized by distinct peaks in the morning and in the evening. Airport operators facing the second demand profile can exploit such volatility by using only a subset of gates during off-peak periods of demand.

The ability to allocate gate use dynamically on the basis of demand patterns can have significant effects on expected walking distances. By using gates in only one terminal, for instance, direct transfer walking distances are reduced by eliminating lengthy interterminal connections. In Salt Lake City, Delta Air Lines will dynamically reduce gate use along its piers in order to centralize operations and passenger flows during periods of low demand.

Returning to our example, let us assume that during periods of low demand, the airport is used primarily by transfer traffic and that only gates in Terminal 2 are used for arrival and departure operations. To incorporate this new low-demand policy into our expected walking distance model, we perform an independent walking distance analysis as if we were dealing with a new airport consisting only of Terminal 2. We then weight the two overall estimates by the fraction of time that the airport operator uses each configuration to obtain an overall estimate for the given demand profile.

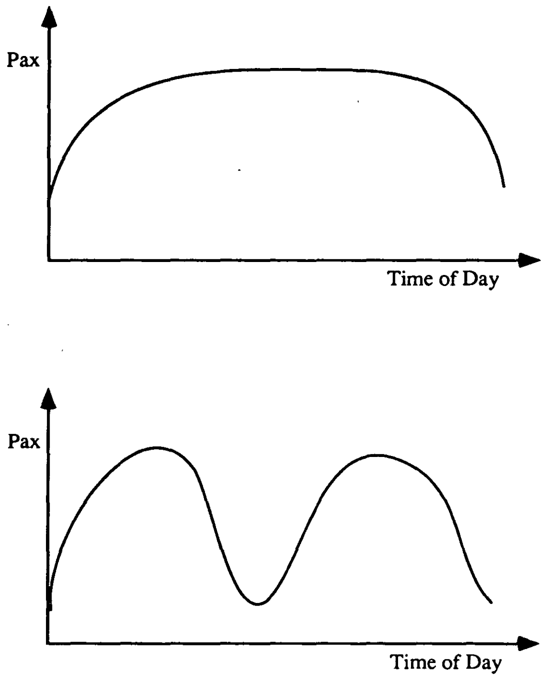


FIGURE 4 Characteristic demand profiles: *top*, constant demand profile; *bottom*, two-peaked demand profile.

Performing a similar walking distance analysis on our Terminal 2 airport yields the following overall walking distance estimates:

Traffic Type	*Passenger Mix*	*Expected Distance (m)*
Originating/terminating	0.30	110.0
Transfer (direct)	0.63	12.0
Transfer (indirect)	0.07	210.0
Overall		55.3

Combining high and low estimates depends on the fraction of time that the airport faces each demand condition. For simplicity, assume that only Terminal 2 is used when the demand level is less than half the highest demand peak, and the full two-terminal configuration is used otherwise. For the demand profile shown in Figure 4 (*top*), this policy translates approximately to a 90/10 demand split. The overall walking distance is thus $(0.90 \times 79.0) + (0.10 \times 55.3) = 76.6$ m.

For the second profile [Figure 4 (*bottom*)], high demand conditions prevail for a smaller fraction of time, so we would expect a greater reduction in walking distances because of our low-demand policy. Indeed, the high/low demand split is approximately 60/40, which translates to an overall expected walking distance of 69.5 m.

To summarize, two factors related to passenger demand profiles influence walking distances. The first is the actual profile of demand, or how much fluctuation exists between high and low demand. The second and perhaps more important factor is the policy used for addressing such volatility. It is the judicious selection of gates used during low demand conditions that reduces walking distances and thus improves performance, not the variability in the demand pattern itself.

SENSITIVITY ANALYSES AND CONFIGURATION ROBUSTNESS

Forecasts are by nature imprecise and often incorrect. Making a decision as important as selecting a terminal configuration on the basis of a single "snapshot" of what might occur can have devastating effects in the face of great uncertainty. More important to decision makers is the robustness of a configuration, a measure of how the configuration will perform over a variety of conditions.

To test configuration robustness for our example, we systematically vary two separate parameters and note their effects on our estimates for expected walking distances. The first parameter is passenger mix, which we vary in terms of the fraction of total traffic made up by transfer passengers. The second parameter is the volatility of the passenger demand profile, which we vary in terms of the fraction of time that the airport faces low demand conditions.

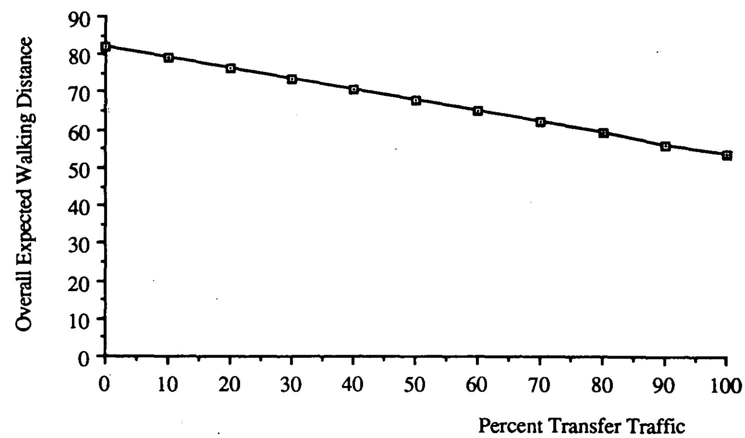
By varying the percentage of transfer traffic, we can determine the sensitivity of our configuration to our original passenger mix assumption. Holding all other parameters constant, we vary the percentage of transfer traffic between 0 and 100 [Figure 5 (*top*)]. Note that as the fraction of transfer traffic increases, the overall expected walking distance decreases, as we would expect given the intermediate values that we calculated for each passenger type.

A similar sensitivity analysis was performed to test configuration robustness to changes in the daily demand profile. Figure 5 (*bottom*) shows the results of varying the fraction of time that the airport faces low demand while holding all other parameters constant. Note that as we increase the fraction of time that the airport faces low demand conditions, the overall expected walking distance decreases, which is precisely the goal of our gate selection policy.

FURTHER RESEARCH AND CONCLUSIONS

This paper has presented a new methodology for estimating passenger walking distances. Unlike other, more traditional models that make restrictive and sometimes inappropriate assumptions, our model allows for a great deal of flexibility and provides the opportunity to assess the effects of not only the physical geometry of a terminal but also the actions of airport operators in a highly dynamic environment. Rather than providing a definitive answer as to the "best" airport configuration for all circumstances (it is unlikely such a configuration exists), the model provides an approach for assessing the robustness of many different designs to determine which configuration is most appropriate in the face of great uncertainty.

The most natural application of our model is as a decision-support tool for airport planners to be used during the earliest stages of the design process. Because the model requires only minimal input, walking distance estimates can be obtained quickly and various sensitivity analyses can be performed to determine the robustness of many candidate designs. Such analyses may help prevent costly design errors that are made early in the planning process. The model can also be used to establish general rules of thumb for initial configuration selection based on forecasts of passenger mix, gate capacity and



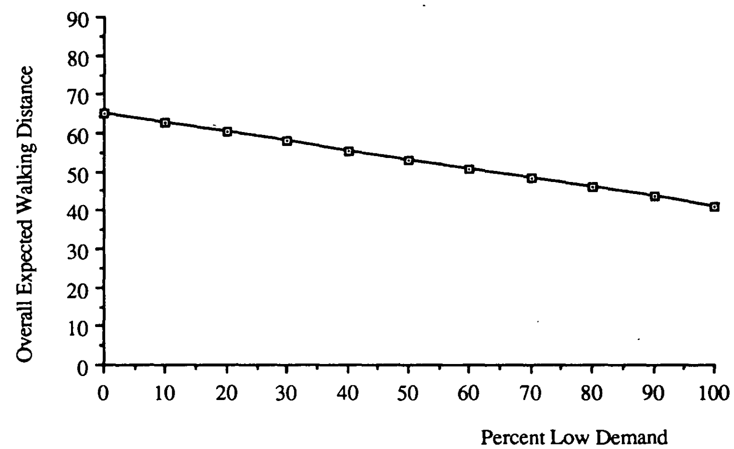


FIGURE 5 Sensitivity analyses and terminal robustness: *top*, robustness to passenger mix; *bottom*, robustness to demand profile volatility.

use, and expected daily demand profiles for future airport construction.

Finally, once an initial configuration is selected, it is possible to test different gate selection policies for handling fluctuations in daily demand. Such sensitivity analyses are not restricted to future airport construction projects. Indeed, many current airports facing high variability in daily demand patterns can benefit greatly from such analyses to decide how best to use existing facilities.

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APPENDIX A
Intelligent Scheduling

To calculate gate affinities on the basis of the assumption that the probability of departure from a gate is inversely proportional to the distance walked, we first need an estimate for through passengers (whose required walking distance is zero). This estimate can be obtained from historical or forecast data. Returning to our example of Gate 1 arrivals connecting within Terminal 1, let us assume that 40 percent of arrivals are through passengers. Thus, the remaining 60 percent of traffic will depart from either Gate 2 or Gate 3.

If transition probabilities are inversely proportional to distance, then the following relation will hold:

$$\frac{d_{12}}{d_{13}} = \frac{t_{13}}{t_{12}}$$

The sum of t_{12} and t_{13} must total the remaining proportion of traffic, which from the preceding is 0.60, or

$$t_{12} + t_{13} = (1 - t_{11})$$

Solving for t_{12} and t_{13} for our example yields

$$t_{12} = \frac{20}{50} * 0.60 = 0.24$$

$$t_{13} = \frac{30}{50} * 0.60 = 0.36$$

In general, for an arrival gate i and a given proportion of through traffic, t_{ii}, the following expressions describe our simple intelligent scheduling model for calculating gate affinities for a terminal with n gates:

$$t_{ij} = \left(1 - \frac{d_{ij}}{d_{\text{tot}i}}\right)(1 - t_{ii})$$

where

t_{ij} = probability that a Gate i arrival departs from Gate j,
d_{ij} = absolute distance from Gate i to Gate j, and
$d_{\text{tot}i} = \sum_{j=1}^{n} d_{ij}$

APPENDIX B
Aircraft Effects

To calculate demand rates on the basis of aircraft effects, consider the following data:

Aircraft Type	*Number of Seats*	*Turnaround Time (min)*
Large	400	90
Medium	200	60
Small	150	40

A gate operating continuously throughout a 12-hr period servicing only large aircraft will thus "witness" 3,200 arrival/departure seats. Similarly, gates servicing only medium-sized or only small aircraft would witness 2,400 or 2,700 seats, respectively. The expected number of passengers witnessed by each gate can be determined by multiplying total seats by the average load factor for each aircraft type. Thus, if large aircraft are generally 67 percent full, our dedicated gate will witness (3,200 × 0.67) or 2,144 passengers. Making a similar load factor assumption for medium-sized and small aircraft yields 1,608 and 1,800 passengers, respectively.

For an individual gate, the expected number of passengers witnessed depends on gate use by aircraft type. Recall our use description of Large and Medium Gates:

Large Gate

Aircraft Type	*Passengers per Day*	*Use*	*Total*
Large	2,144	0.40	858
Medium	1,608	0.50	804
Small	1,800	0.10	181
Total			1,843

Medium Gate

Aircraft Type	*Passengers per Day*	*Use*	*Total*
Medium	1,608	0.70	1,126
Small	1,800	0.30	543
Total			1,669

In our two-terminal airport configuration there are two Large and three Medium gates, for a total of 8,693 passengers witnessed per 12-hr period.

The demand rate is defined as the probability that a passenger will arrive at or depart from a particular gate. This probability is the fraction of total passengers witnessed by a particular gate. Thus, we can determine demand rates for all gates by dividing the number of passengers witnessed by a single gate by the total number of passengers witnessed at the entire airport per time period. Such calculations yield the following:

Gates	*Fraction of Total Pass. Departures*	*Demand Rate*
1, 2, 3	1,669/8,693	0.192
4, 5	1,843/8,693	0.212

Note that since we are dividing one time-dependent figure by another, the actual time period assumed has no effect on the demand rate estimates.

Reexamination of Stall and Spin Prevention Training

PATRICK R. VEILLETTE

Stall and spin accidents continue to cause nearly 25 percent of the fatalities in general aviation each year despite the FAA's emphasis on stall prevention. The effectiveness of past studies, the military's successful approach to stall and spin training, and pilot judgment training are examined; all of these factors may partly explain the relative constancy of the stall and spin accident rates. Recommendations of many past stall and spin studies were examined to determine whether they had been implemented and, if so, whether they had been effective. Second, military flight training programs approach stall and spin prevention very differently and with more successful results. The U.S. Air Force's stall and spin prevention training program is compared with civilian training programs and reveals significant differences in spin training requirements, standardization, pilot knowledge and instructor training and professionalism. Third, pilot judgment has been cited as a causal factor in 95 percent of all stall and spin accidents. Pilot judgment training during private pilot training is also evaluated, and it is found that judgment training has not been incorporated into civilian training syllabi as suggested by previous studies. The investigation determined that the stall and spin problem, rather than being treated as a single issue, really is more symptomatic of several larger issues that must be confronted in general aviation flight safety. Recommendations are made for flight training, flight instructor qualifications, professionalism and skills, pilot knowledge, and aircraft certification; if implemented, these suggestions could reduce the overall accident rate in general aviation.

The most useful purpose of accident investigation is to learn from past mistakes to prevent future accidents. However, the history of stall and spin accidents sounds like a broken record. Spin proficiency was required for private and commercial pilots by Civil Air Regulations (CAR) Part 20 until 1949. Despite the mandatory spin training and demonstration of spin proficiency for certification, spins are listed as the primary cause for 48 percent of the fatal accidents from 1945 to 1948.

In 1949 the Civil Aeronautics Administration reexamined pilot certification and concluded that because an airplane cannot spin unless it has stalled, the accident rate could be reduced by changing the emphasis of training from actual spin recovery to an enhanced stall awareness and recovery (*1*). Spin training was then deleted from the aeronautical skills requirements for private and commercial pilot certificates.

Since 1949 the stall and spin accident rate has been reduced to the point that in recent years, stall and spin accidents account for approximately 12 percent of the flight accidents each year, a statistic that the FAA uses to indicate the success of enhanced stall awareness training (*2*). Despite changes to flight instructor certification and suggested changes to flight training syllabi, efforts to reduce further the accident rate due to stalls and spins have been ineffective. Stall and spin accidents continue to be the cause of 12 percent of the total accidents each year, but in terms of fatalities, spins are consistently the cause of approximately 25 percent of the total fatalities in general aviation (*3*). Among all accident causes, a spin has the greatest potential for fatal injuries—even greater than a midair collision—because of the uncontrolled condition of the aircraft when it hits the ground (*3*).

Perhaps no other topic in general aviation has generated more heated debate than the issue of reinstating mandatory spin training for private pilots. The Experimental Aircraft Association believes that

> better pilots would be produced if there was a return to good solid basics, and that having spin entries and spins explained, demonstrated, and then practiced in the presolo hours adds confidence that reflects in the student's overall flying abilities. The student with spin training will have a better idea of what to do in the case of inadvertent spin entry.

The association adds that too much emphasis is placed on instrument flying, so pilots concentrate inside the cockpit rather than outside the aircraft (*3*). The Air Safety Foundation believes that the current approach, which stresses awareness of aircraft attitude, reliance on indicated airspeed, and use of stall warning devices, does not get the job done (*3*). It should be pointed out that an aircraft can stall at any airspeed, because stall is strictly related to angle of attack and not to airspeed. Therefore, a pilot should not rely on indicated airspeed to prevent a stall. In Crossfield's experience, the pilot who is least likely to be victimized by an inadvertent stall is the one who has developed a sensitive feel for what is happening to the aircraft (*3*). Others counter that 95 percent of all accidental spins occur at low altitudes that leave insufficient time for recovery, and therefore spin training will be of little value. The FAA expresses a concern about the possible increase in training accidents if mandatory spin training were reintroduced (*3*). The president of the National Association of Flight Instructors (*3*) and Tony LeVier, a noted Lockheed test pilot, agree that requiring spin training for a private pilot without corresponding actions to improve the quality of flight instruction would lead to an increase, not a reduction, in stall and spin accidents.

Silver determined that aircraft design changes have been the primary cause of the reduction in stall and spin accidents, not changes in pilot training (*4*). It is also significant to note that, in the instructional category, spin accidents with a certified flight instructor (CFI) on board are three times more

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frequent than in solo student operations where no instructor is present (*4*). Yet another sobering fact is that more than 25 percent of all twin-engine aircraft accidents occur with flight instructors on board, most of those accidents being associated with simulated engine failure demonstrations and practice (*5*).

Many past investigations have addressed general aviation accident statistics. According to the National Plan for Aviation Human Factors, human error has been identified in 88 percent of all general aviation fatal accidents (*6*). The National Transportation Safety Board (NTSB) determined that the pilot was a broad cause/factor in 97 percent of all first type stall and spin accidents (*7*). Hegwood determined that flaws in judgment and decision making were present in 66 percent of general aviation accidents, loss of attention of distraction in 30 percent, and deficiencies in skills and knowledge in 40 percent (*8*).

Campbell asserts that skill and knowledge are necessary for a good pilot but that proper judgment, which leads to correct decisions, is essential (*9*). Good judgment is more difficult to learn than flying skills. During U.S. Air Force (USAF) pilot training, instructors frequently recite, "a superior pilot uses his superior judgment to avoid situations that require superior skills." Many accidents are caused not by a failure of knowledge or skill but by a lack of judgment (*10*), Collins points out that the second leading cause of Piper Cherokee accidents is improper pilot conduct at low altitude, resulting in a stall, despite constant emphasis on stall avoidance training, thus showing a lack of judgment (*11*,p.59).

The FAA's stance on stall and spin training continues to be "avoid, avoid, avoid." The author will not argue with this, but the accident record indicates that this approach has been ineffective in significantly reducing the occurrence of spin accidents during the past 30 years. Accidents are not caused by a single factor; they are the coordinated occurrence of several flawed decisions, performance breakdown, or oversights (*12*). Nance states that "to have any hope of preventing such an error from causing an accident again and again, the REASON the error was made in the first place must be discovered, and the underlying cause of that human failure must be revealed and addressed in future operations" (*13*). Melton asserts that accident investigations of the past has not been effective in preventing human factors accidents (*14*).

In 1972 the NTSB emphasized the need for initiating new and innovative efforts to reduce these types of accidents (*7*). The FAA then undertook a study to determine the most effective training techniques to avoid imminent spins (*15*). However, the FAA's primary changes to spin training have been regulatory in nature. Past experience has shown that stricter regulations will not necessarily reduce accidents (*16*). Melton maintains that education is the most practical method of change available (*14*).

The military services take a different approach. Few pilots are placed at the extremes of aircraft performance as consistently as military pilots. An examination of the military's training objectives and procedures, combined with a relatively long record of accident statistics, renders a number of extremely important lessons. The USAF and Navy would prefer that their pilots avoid spins, but both services attack the spin problem through a standardized program of rigorous and realistic training that teaches spin recognition, recovery, and prevention (*3*).

RESEARCH PROBLEM STATEMENT AND STUDY DESIGN

Previous studies have investigated both the overall general aviation accident and stall and spin records and discovered areas that need improvements (*2–5,7*). This investigation does not seek to reiterate such findings, nor does it seek to determine every single issue that must be resolved to reduce general aviation stall and spin accidents. Instead, the study is designed to complement previous investigations so that a comprehensive approach to solving the stall and spin problem could be found. Accordingly, this investigation sought to determine answers for the following questions:

1. Have recommendations of past stall and spin studies been implemented, and, if so, what has been their effectiveness?
2. What differences between military and civilian flight training could explain their respective stall and spin accident records Which of these differences could be implemented in civilian flight training?
3. What judgment training, both formal and informal, is provided during private pilot training?

Evaluating statistics can be an effective technique in answering some questions, the main effort of this study concentrated on gathering information at the flight-line level to determine more precisely what is happening so that a more accurate assessment could be made to build the necessary curriculum and certification changes.

RESEARCH METHOD

The study consisted of three phases. The first phase addressed the question of whether past recommendations had been implemented and, if so, how effective the changes had been. A search of previous special studies on the stall and spin problem was conducted to compile a list of specific recommended actions (*2–5,7,15*). To determine the procedures currently used in flight training, separate surveys were conducted of pilots, flight schools, and flight instructor recertification clinics. The pilot population was randomly chosen through a distribution of the questionnaire to parked aircraft at two Southern California general aviation airports. Three hundred questionnaires were distributed, and 173 pilots responded. The questionnaire was designed to obtain information about the pilot's training, experience, certificate level, date of certification, and understanding of the stall and spin problem.

The 43 flight schools surveyed were located in selected counties of three widely separated geographical regions: Mississippi/Tennessee, Southern California, and Utah. Chief pilots were interviewed about the training procedures used at the schools, and training course outlines were examined for Federal Aviation Regulation (FAR) Part 141–certified flight schools.

Training course outlines were obtained from nationally advertised refresher clinics for flight instructors to determine the information presented for recertification of flight instructors. Additionally, three courses were monitored.

The information collected from the pilots, flight schools, and refresher clinics was then compared with the recommendations of the special studies. A comparison of the accident statistics of 1967–1969 (*7*) and 1988 (*17*) was also conducted to determine if any significant changes had occurred.

The second phase consisted of a comprehensive study of the USAF's training curriculum, procedures, and instructor qualifications used in the Undergraduate Pilot Training program conducted by Air Training Command (ATC) and comparing them with those used in civilian flight training. Training requirements of the ATC syllabus were compared with both the requirements of FAR Part 61 and the syllabi obtained from flight schools. A survey similar to the aforementioned pilot questionnaire was prepared for CFIs. The survey also sought to determine the instructor's knowledge of aerodynamics relating to stall and spin phenomena, sources of guidance and information, professional activities, career goals, and activity in spin instruction. The surveys were distributed to 59 instructor pilots and 78 student pilots of the 37th Flying Training Squadron at Columbus Air Force Base in August 1985. The same questionnaire was distributed to flight instructors at the flight schools surveyed in the first phase of the study. Many flight instructors operate on a freelance basis, so the surveys were also distributed to flight instructors at seven FAA Accident Prevention Program seminars conducted for flight instructors in Los Angeles and Salt Lake City and at three flight instructor refresher courses. Surveys were also distributed to designated pilot examiners at a regional annual recertification course held in Salt Lake City and at an initial qualification course conducted in Oklahoma City, both in 1992. A total of 513 surveys were collected from the civilian flight instructors, and 28 from designated pilot examiners.

Five aviation professionals (hereinafter referred to as "reviewers") were chosen to grade the survey answers. Answers to each aerodynamic question were scored on a scale of 1 to 5 (1 = unsatisfactory, 2 = marginal, 3 = average, 4 = good, 5 = excellent). A mean score for each question was then computed. All five reviewers were flight instructors (three were military and four held CFI certificates) and had received formal college courses in aerodynamics. Two were accident investigators, two were aviation safety officers, and four had been involved in aeronautical education as either ground school or general aeronautical course instructors. Grading standards were determined mutually by the information in aeronautical research of the National Aeronautics and Space Administration (NASA), journal literature, and *Aerodynamics for Naval Aviators* (18).

The final phase consisted of a separate survey distributed to 126 student and private pilots asking specific questions about formal judgment training during ground and flight training. The survey also asked respondents to remark about informal judgment (both positive and negative) training and experiences during ground and flight training. This phase also examined the syllabi and training course outlines for 11 flight training programs, 9 of which were certified by FAR Part 141.

FINDINGS

Application of Past Recommendations

Past studies have made specific recommendations for changes to stall training, situational judgment and successful prevention techniques, enhancements in aircraft design, and reevaluation of the spin training requirement (*2–5,7,15*). Phase 1 of this investigation centered on determining whether these recommendations had been incorporated and, if so, what their effectiveness had been.

Innovation in Ground and Flight Training Curricula

Private pilots are required to demonstrate competency in stall entry and recovery from various flight attitudes and power combinations. Stalls are taught at high altitude (greater than 1,500 ft above ground level). Unfortunately, during typical training situations the student is keenly aware that the stall is coming and is concentrating on recovery. Realistic stalls occur unexpectedly, near the ground—and while the pilot is concentrating on something else (*11*,p.59). Despite many recommendations suggesting that stall training become more realistic (*3,4,7*), the study found that stall training is still conducted in the same manner. Three specialized aerobatic flight training programs did present stalls in more realistic situations.

Study To Determine Situational Judgment

In response to the recommendations of research conducted by several aviation safety organizations, the FAA initiated the Accident Prevention Program in 1985, which cosponsors a large number of seminars and disseminates material to pilots. To date, about 45 pamphlets addressing different safety issues have been produced and distributed to general aviation pilots through this program. Most of the pamphlets contain detailed information to help pilots learn from past accidents in order to prevent future accidents. Pilots who regularly attend accident prevention seminars speak positively about the value of the seminars and handouts. The program appears to be very effective for the pilots that it reaches. However, the value of the program to pilots who do not participate is doubtful.

Enhancing Airplane Design

The NTSB, General Aviation Manufacturer's Association, and the Society of Experimental Test Pilots believe that FAR Part 23.221 should be reviewed with applying new standards that would allow the designer to concentrate more on preventing the spin rather than on recovering from it. The FAA is considering a redraft and will soon publish a change to this regulation.

Modern aircraft design has been shown to be the most effective approach in reducing the number of stall and spin accidents (*4*), but unfortunately the general aviation manufacturing industry is in a severe slump and fewer than 250 new single-engine aircraft are produced each year (*19*,p.43). Thus, most general aviation pilots will not be able to benefit from this research for many years.

Evaluation of Reinstating Minimum Spin Training

The FAA's chief of flight operations states that any decision to return to spin training must address all issues (*3*). The FAA cites the following issues for its opposition to reinstatement of spin training:

- Possible increased training accidents,
- Many current training aircraft not certified for intentional spins,
- Impact on the increased duration and cost of flight training,
- Economic impact to upgrade the current fleet of trainers, and
- Airspace limitations with urban sprawl and restrictions (federal aviation regulations prohibit aerobatic maneuvers over any congested area of a city, town, or settlement; over an open-air assembly of persons; or within a control zone or federal airway).

The FAA did amend flight instructor applicant training requirements in April 1991 to specifically require spin training and allowed examiners the option of specifically requiring spin demonstration during the practical test.

Spin Training Requirements

The second phase of the study identified significant differences between the FAA's and Air Force's approaches to the stall and spin problem. The Air Force first extensively screens pilot applicants before they are accepted into the Undergraduate Pilot Training program, which is obviously not possible among general aviation pilots. The effect of this screening is not examined in this study; instead, differences in actual training methods are examined.

In the Air Force, spin training has always been a major element in Undergraduate Pilot Training. The primary phase explores the full stall region: recognizing a stall, preventing a spin, recognizing the initiation of incipient spin, and flying the aircraft out. It is a 74-hr program that normally includes 25 intentional spins and 25 spin-prevention maneuvers while exploring the full range of the aircraft envelope. Proficiency is required for student pilots before they solo and checked at mid- and final-phase checkrides.

In contrast, the FAA requires only flight instructor applicants to show a logbook endorsement certifying that the applicant is proficient to teach spins. All other pilot certificate levels are not required to have spin training.

Standardization

Standardization is provided by the ATC headquarters staff of spin examiners who yearly give all T-37 instructor pilots mandatory spin proficiency checkrides. Checkrides, required weekly training, and oral and written exams are all used as tools to ensure standardization of the training objectives, procedures, and course materials throughout the five Air Force training bases.

However, the FAA establishes specific tasks under pilot operations in the practical test standards that must be accomplished for certification. Each area of operation is referenced to a specific handbook for standardization. FAR Part 141–certified flight schools perform yearly checkrides for instructors, but there is very little industry standardization in the area of stalls and spins. Stall procedures varied greatly among the flight schools.

Ground Training and Knowledge

The Air Force has a mandatory course on aerodynamics, of which a 2-hr block is devoted to stall and spin aerodynamics. Additionally, each day student pilots are quizzed orally on various emergency procedures, including stalls and spins, and a mandatory emergency procedures quiz must be completed satisfactorily each week.

Results of the ground school survey determined that the average time spent during civilian ground training courses on stall and spin was less than 30 min. No further training on stall and spin was required in any of the training course outlines inspected in this study. The pilot surveys showed that additional ground training in stall and spin did not occur after the initial ground school course.

The depth of the reference material also differed greatly. The required reading material for the Air Force program was assembled from data at the Air Force Flight Test Center; it explored stall and spin aerodynamics, causes of spins, functions of the controls, effects of improper control movement, and recovery. The T-37 flight manual has a complete section on stall characteristics, spin characteristics for the varying spin modes, the spin envelope, effects of controls, and the proper spin recovery for that aircraft.

The required texts for ground school courses at civilian flight schools devoted an average of 1.6 pages to the discussion of stall and spin and primarily centered on the stall character of an older airfoil design. Pilot operating handbooks for training aircraft contain no information about the spin characteristics of the aircraft. Approximately 97 percent of surveyed pilots and 94 percent of surveyed flight instructors cited popular periodicals as their main sources of information. Both pilots and flight instructors relied heavily on their previous flight instructors for information (85 and 96 percent, respectively.)

As part of this study, more than 250 books, magazine articles, technical papers, research summaries, and conference proceedings pertaining to spins were reviewed. The popular literature reviewed included monthly magazines from the mass media, trade groups, and the FAA dating back more than 30 years. The study found that the popular literature (and several FAA publications) contained very little new material, and what it did contain was repetitive, cursory, incomplete, poorly documented, and of questionable accuracy. In general, the books by Kershner (*20*), Mason (*21*), and Lowery (*22*) were very accurate, readable, and complete.

The study also found that the several excellent FAA publications addressing stall and spin phenomena are not well disseminated. Very few flight instructors were even aware of the Accident Prevention Program handouts, and fewer had copies for their personal libraries and extras for students. Several informative advisory circulars share this fate.

USAF instructor pilots demonstrated good to excellent levels of working knowledge of spins, and USAF student pilots demonstrated overall good levels. Civilian designated pilot examiners, however, demonstrated an overall average level of knowledge (Figure 1). Civilian CFIs and designated pilot

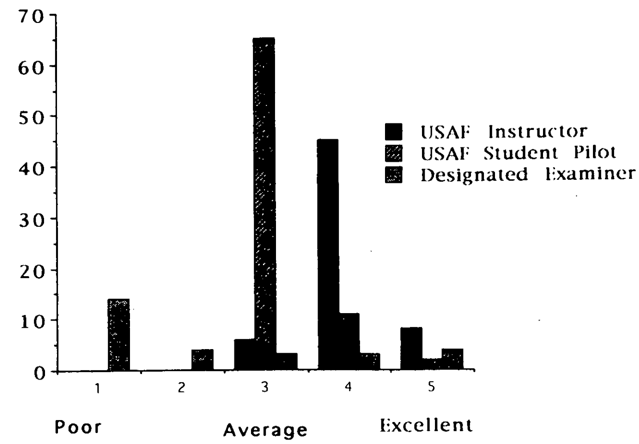

FIGURE 1 Stall and spin knowledge.

examiners demonstrated overall marginal performance levels in the following areas concerning stalls:

- Stall aerodynamics,
- Effects of control deflection on stall,
- Airfoil stall development,
- Planform effects on stall development,
- Spanwise flow effects,
- Stall warning signs on aircraft and the effects on aircraft motion,
- Secondary effects of flight controls, and
- Roll control at high angles of attack.

As for spins, civilian flight instructors and designated pilot examiners demonstrated overall unsatisfactory performance in the following areas:

- Pro- and antispin forces;
- Autorotational and stabilized spin motion;
- Effects of various variables on spins (e.g., location, mass distribution, pitch, direction, mass imbalances, power);
- Spin phases, phase differences on recovery, and spin modes;
- Effects of the controls on spin motion and recovery; and
- Common student recovery errors and the effects on aircraft motion.

The FAA modified stall and spin training regulations on April 15, 1991. Yet more than a year later, 97 percent of surveyed flight instructors—including all 35 survey participants who had been certified since the training amendment—were not aware of these changes to the regulations, nor were they aware of the FAA's excellent advisory circular giving guidance on ground and flight training. The performance of this recently certified group on the survey was as poor as the rest.

Another interesting point occurred during the analysis of survey results. Flight instructors who stated that their aviation goal was to attain an airline cockpit position performed at poor and marginal levels, whereas the few surveyed flight instructors who stated other long-term goals in aviation performed at an overall good level (Figure 2).

Instructor Training and Quality Assurance

ATC introduced instructor spin qualification and standardization in 1962 to ensure that all instructors were well versed in all aspects of spinning. Instructor spin training is conducted by certified spin examiners. Extensive academic training is based on manuals and work performed at the USAF Flight Test Center to ensure rigorous quality standards. Flight instructor training is conducted with an emphasis on conditions leading to inadvertent spins, spin performance, proper instructional techniques, student error analysis, spinning in various modes, and the effects of controls.

Ninety-eight percent of the responding civilian flight instructors stated that their spin training consisted of no ground training and just two spins (one in each direction) before they were endorsed as being proficient to teach spins. Ninety-five percent of the respondents did not receive training that emphasized conditions leading to inadvertent spins, spin aerodynamics, common student errors, and the effects of the controls in a spin.

Proficiency Demonstrations and Reviews

All T-37 pilots are scheduled for annual spin seminars conducted by spin examiners, and all USAF pilots undergo fre-

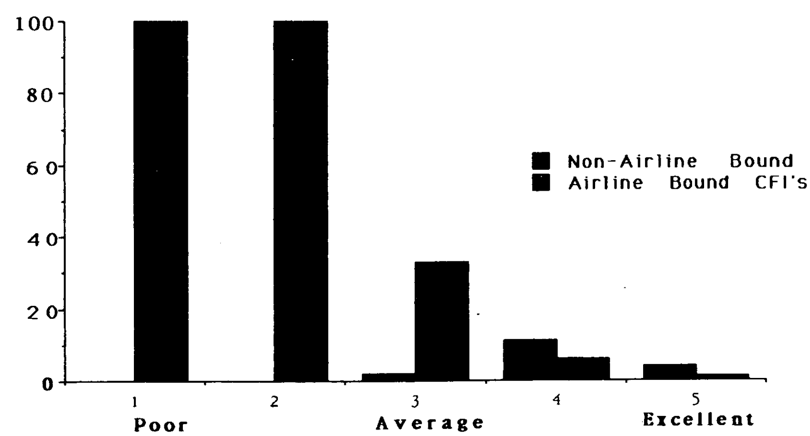

FIGURE 2 Stall and spin knowledge of flight instructors.

quent periodic evaluations (an average of five evaluations each year.)

FAR Part 61 requires all certified pilots to undergo a biennial flight review every 24 calendar months. Yet, despite this regulatory requirement, 20 percent of all accidents occurred within a month of biennial flight review (*5*). Pilots responded that very few proficiency maneuvers were required during their last biennial flight review.

Once a civilian flight instructor is certified, there is no mandatory requirement that the flight instructor be evaluated in flight ever again. The flight instructor can renew a certificate by attending a flight instructor refresher course.

Instructor Professionalism

Perhaps more disturbing were findings that a professional standard has not been well established and promulgated in civilian flight instruction. The following facts about the professional activities of flight instructors were determined from the survey:

- Three percent attended advanced training clinics and seminars;
- Two and a half percent were involved in formal training to upgrade knowledge;
- Less than 1 percent read advanced training materials;
- Ninety-seven percent relied on mass popular literature for information;
- Four percent were aware of advances in flight sciences, research efforts, and technology;
- Twelve percent were active in professional associations and pilot groups;
- Thirteen percent maintained a limited professional reference library; and
- Ninety-four percent were unaware of NTSB/NASA accident reviews for lessons learned from past accidents.

It should also be noted that flight instructing is frequently used as a strategy for obtaining a more permanent position. Among flight instructor respondents, 97 percent claimed that their goal is to upgrade to a commercial or corporate flight crew member position as soon as practical.

Additional Items

This study also found that not a single civilian flight instructor had a prespin checklist of critical items before spin practice. Previous flight test investigations have shown that items such as fuel loads, fuel balance, aircraft weight and balance limits, control alignment, and systems operating procedures are critical factors that must be checked before spinning an aircraft (*23*). Ninety-eight percent were largely unable to describe a set of procedures or steps they would undertake to determine whether an individual aircraft was safe to spin. Ninety-four percent did not understand the limitations of aircraft spin requirements in the certification process and did not know where to obtain information on recommended spin entry techniques and spin motions of the aircraft.

The survey also found that 96 percent of multiengine flight instructors showed poor understanding of multiengine aerodynamics, particularly with regard to simulated engine failure practice, and a lack of awareness of critical warnings published in aircraft flight manuals and safety newsletters by aircraft manufacturers.

Judgment Training

The training course outlines for the surveyed flight schools did not incorporate any formal judgment training into ground or flight training curriculums.

All 126 respondents replied that ground and flight training courses taken between autumn 1989 and spring 1992 contained no formal judgment training. Ninety-three respondents related incidents in which judgment was taught unintentionally during flight training. Twelve of these respondents recounted incidents that taught good judgment, of which five occurred during dual flight instruction. Eighty-two respondents related experiences during dual flight instruction that taught poor judgment.

CONCLUSIONS AND RECOMMENDATIONS

There is no single solution to this complex issue. It involves much more than flight instruction. The subject of stall and spin improvement by including spin training in the flight training syllabus cannot be treated alone. The pilot as a final product must be the goal. The FAA has regulatory control over flight safety but cannot do it alone.

This study determined that recent regulatory changes and all other past FAA efforts have not translated into effective changes in flight and ground training. Rather than a mere change in regulations, a combination of approaches must be considered and effectively implemented at the flight-line level to include changes to flight training, increased flight instructor qualifications, higher professionalism and skills, effective dissemination of information to line pilots and instructors, and more spin-resistant aircraft. The recommendations of this paper, if implemented, could reduce the overall accident rate in general aviation, not just the stall and spin numbers.

Flight Training

Some spin training could help to prevent accidents, but the training needs are far broader than the demonstration of spin entry and recovery techniques. Consideration must be given to enhancing the quality of ground and flight training on the following topics:

- Pilot proficiency and ability to handle distractions,
- Planning,
- Judgment,
- Coordination exercises,
- Learning to read the subtle signs of an aircraft,
- Visual illusions,
- Wind effects,

- Lessons from the past,
- Traffic pattern operations conducive to stall and spin accidents,
- Reeducation in dangers of low-level flight, and
- Aircraft motion at high angles of attack.

The biennial flight review should be used more effectively to update pilots and enhance pilot proficiency. The FAA has published guidelines and regulatory changes to upgrade the performance of a biennial flight review. The FAA and several trade groups have disseminated excellent materials to aid flight instructors in making biennial flight review more effective, but the material has not been used widely. A concerted effort must be made to enforce this important requirement.

The FAA has produced several manuals on judgment training. This study found that these resources had not been incorporated into ground or flight training syllabi, nor had judgment training been specified formally as an objective in any course. A method of incorporating judgment training into both ground and flight syllabi and flight instructor methodology must be investigated.

Flight Instructor Training, Certification, and Professionalism

Flight instructors form the backbone and the first line in quality assurance of the general aviation pilot's knowledge, judgment, and proficiency. Yet, this survey determined that the main motivation of flight instruction is to build experience for obtaining an airline pilot position, with the result that devotion to flight instruction professionalism is questionable. More time must be spent with CFIs to ensure that they correct the deficiencies mentioned in this paper. Flight instructors must be totally dedicated to making objective assessments of matters involving aircraft performance and pilot training.

Common sense would require instructor spin proficiency because not all students will adequately handle incipient spin recovery during their training cycles. Flight instructors should feel fully at home, be excellently qualified, and have every aspect of spins under their control to teach it. The Society of Experimental Test Pilots, although it generally avoids making public judgments, endorses at the very least instructor spin recovery proficiency as a requirement for a flight instructor certificate (*3*). At present, flight instructors are required to demonstrate spin proficiency, but this study has shown that pilot examiners are largely unqualified to make this determination and previous flight instructor training has been received from inadequately trained instructors. Unless the suggestions for upgraded instructor and examiner qualifications and testing are incorporated, the regulations amended in 1991 and the recommendations of this study will be relatively ineffective.

The government and industry, including the trade associations, need to set a professional standard for flight instruction. Standards, requirements, and conduct required of professionals should be addressed by a cooperative effort to upgrade the level of flight instruction. Before professional licensing, these requirements should be met.

This investigation determined the following deficiencies in professional standards:

1. Continuing education at advanced levels;
2. Participating in flight safety and aeronautics conferences and seminars;
3. Keeping current with the latest research findings and techniques;
4. Updating knowledge and skills through advanced professional training;
5. Participating in professional organizations; and
6. Maintaining and reading a professional library of classic texts, professional peer-reviewed periodical literature, research studies, and accident prevention materials.

It is unlikely that significant improvement in flight instructor professional standards will occur on a volunteer basis as long as flight instruction is the main track for civilians hoping to build experience for airline pilot positions. It is unfortunately left to the professional licensing body to enhance instructor professionalism.

Flight instructors must incorporate more judgment training and lessons learned from the past into ground and flight training. Most survey respondents replied that flight instructor actions actually left more impressions on the development of judgment than formal lectures, so flight instructors must become more aware of their role in judgment training. This point is worth investigation to explore its potential further.

Knowledge and Dissemination of Information

This study strongly suggests that a comprehensive text and videotape should be published to address the areas of deficient pilot knowledge of stall and spin aerodynamics and to serve as a standardized source of factual information intended for use by pilots. Included in the book and videotape would be the previously listed areas of deficient knowledge, common stall and spin accidents, prespin checklists, training maneuvers that would enhance "stick and rudder" skills, determination of an individual aircraft's suitability for spinning, lessons learned from the past, and a historical perspective.

The combined textbook and videotape could set a precedent of accuracy, standardization, cost-effectiveness, and completeness. The FAA could stipulate that flight instructors, safety inspectors, and designated pilot examiners satisfactorily complete a test on this topic before their next renewal, thus ensuring that the material will be disseminated within 2 yr.

The FAA has recognized special situations in which flight instructors are required to be additionally rated, such as instrument and multiengine flight instruction. Given the unique body of knowledge and expertise required for spins and aerobatics, the number of instructional stall and spin accidents with flight instructors, and the overall lack of stall and spin knowledge within the flight instructor corps, this study suggests that consideration be given to a special certification procedure to license designated examiners and instructors who are truly qualified to give spin instruction and checkrides. This corps of instructors and examiners could then provide better spin instruction and better quality assurance.

Like the Air Force has, we must learn from flight tests what airplanes will do in common pilot input error situations. The information should be communicated to the pilot in terms of perception (aircraft buffet, control lack of effectiveness), not just in terms of the airplane performance. Each training aircraft should experience an empirical test determination of its spin characteristics, similar to the Cessna Aircraft Corporation's tests of its training series (*23*). Testing should be followed by suitable recommendations, or notation, in all operator's manuals, and pilots and flight instructors should be qualified to interpret them.

The FAA's Accident Prevention Program should be used to an even fuller extent as a medium for disseminating information. A cooperative effort between industry, trade groups, pilot associations, and local flight standards offices has been effective in providing continuing education to the general aviation pilot. This approach further serves an important role in maintaining a positive working relationship between pilots and the FAA.

This study determined that the vast majority of pilots obtain flight information from popular periodical literature. It is realized that journalists will not consent to review of their works, but they must realize their effect on pilot knowledge. It would be helpful for authors to follow the standards expected in writing, that of citing references, giving credit to original works, and conducting some in-depth research rather than merely quoting or copying older articles. This study also suggests that a system of peer review be established to boost accuracy.

Aircraft Design

In the future, the FAA and manufacturers must realize a pilot's limitations in being able to perceive, decide, and respond effectively if he has not been exposed to the incipient spin environment under controlled training conditions. Aircraft must be designed to minimize the surprise and rapidity with which an aircraft departs from controlled flight in typical operational environments.

Unfortunately, because of economic factors, the restricted number of single-engine aircraft produced today means that the lessons from NASA's stall and spin research will not be available to the general aviation pilot for a long time.

SUGGESTED FURTHER RESEARCH

Aviation authorities such as LeVier, Crossfield, and Mason have suggested that general aviation pilots obtain a limited amount of aerobatic training to improve fundamental pilot skills (*3*). The argument certainly has merit and deserves to be studied.

Many aviation authorities still insist that spin training be reinstated (*3*). The military's results show the worth of actual spin training. A controlled long-term study of civilian pilots using different training methods should be undertaken to determine the effectiveness in preventing spin accidents and, perhaps more important, producing better overall pilot skills.

With pilot activity declining because of the high cost of aircraft rental, the effect on a pilot's ability to maintain flying skills must be questioned. Not only is proficiency affected by currency of experience, but judgment skills are also developed and maintained through regular experience. The effectiveness of developing lower-cost alternatives and their effects on flight activity and pilot proficiency and judgment should be studied. This will aid the FAA and industry in guiding future aircraft production and regulatory policies in order to help pilots fly more and maintain and build better flying skills.

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Development of Risk Models for Simultaneous Instrument Landing System Approaches to Closely Spaced Parallel Runways

JOYCE WINKLER

The potential for safely reducing the runway separation standard for simultaneous instrument landing system (ILS) approaches is demonstrated; the standard is based on the current surveillance system. A general autoregression model that generates realistic and stabilized final approach flight tracks is developed. The model is then used in a simulation of simultaneous ILS approaches during which the aircraft deviate normally about the ILS (Simulation 1), to study the probabilities of violating the no-transgression zone and causing false alarms (the probability that radar displays the aircraft in the no-transgression zone when it actually is in the normal operating zone). Simulation 2, which is similar to Simulation 1, considers a worst-case scenario of simultaneous ILS approaches during which one aircraft blunders and determines the probability of collision. Simulation 1 and 2 results indicate that the minimum runway separation that maintains the probabilities of false alarm and collision for the current runway separation and surveillance system is 3,700 ft, when used with radar having an update interval of 2.4 sec and an accuracy of 1 milliradian.

Air travel delays resulting from limited airport capacity are a significant problem for the FAA and the airline industry. Airport capacity is greatly reduced during instrument meteorological conditions (IMC), which are typically conditions with a measured or estimated ceiling less than 1,000 ft or visibility less than 3 mi; during IMC the number of arrivals that can be accepted is well below that attained during visual meteorological conditions.

To increase the capacity of existing airports, the FAA allows simultaneous, independent instrument landing system (ILS) approaches (each approach has its own ILS equipment) to closely spaced parallel runways, which will be referred to as "parallel approaches." However, current FAA regulations stipulate that there must be at least 4,300 ft between runway centerlines for these approaches to occur under IMC with current surveillance systems, which include radar with an azimuthal accuracy of about 5 milliradians (mr), an update interval of 4.8 sec, and Automated Radar Terminal System (ARTS) displays (*1*). The regulation restricts arrival capacity not only at airports with parallel runways separated by less than 4,300 ft but also at airports that do not have the additional space needed to add a usable runway parallel to an existing one. The FAA is interested in decreasing the spacing regulation to help increase the capacity of airports during IMC.

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TECHNICAL AND PROCEDURAL BACKGROUND

Requirements for the authorized use of parallel approaches in addition to the 4,300-ft centerline spacing are as follows (*2*):

1. ILS, radar, and two-way radio communications;
2. Aircraft separated by a minimum of 1,000 ft vertically or 3.0 nautical-mi (nmi) longitudinally on radar until established on their respective localizer courses;
3. Two monitor controllers to ensure lateral separation between aircraft and to intercede in the event of an aircraft blunder; and
4. A 2,000-ft-wide no-transgression zone (NTZ) centered between the two extended runway centerlines.

The ILS is a combination of independent transmitters that provide navigational guidance for aircraft executing an instrument flight rules (IFR) approach. One such transmitter is the localizer, which radiates a horizontal, 3- to 6-degree fan-shaped beam that provides lateral guidance for aircraft on final approach to a distance of 18 nmi from the runway. Another transmitter is the glide slope, which provides a vertically oriented, 1.4-degree fan-shaped beam that provides altitude guidance. The composite beam resulting from these transmitters defines a precise approach course for arriving aircraft.

The approach course runs along the imaginary line (the extended runway centerline) projecting upward from the end of the aircraft's assigned runway (the runway threshold) at approximately a 3-degree angle relative to the ground. Each runway has an approach course with an independent ILS. ILS approach procedures require that arriving aircraft be established on the localizer (flying within the localizer course) before intersecting the outer marker, which is approximately 5 nmi from the runway threshold. For parallel approaches, this distance is typically extended to 10 nmi or more (*3*).

During parallel approaches, two aircraft turn onto their respective approaches at different altitudes. The aircraft are required to maintain at least 1,000 ft of vertical separation until both are established on the localizer. At this point, vertical separation may be lost. Thus, after stabilization, the aircraft are proximate in the vertical direction of flight. The aircraft may also be proximate in the longitudinal direction of flight. Therefore, for stabilized parallel approaches, lateral deviation of the aircraft from their respective ILSs must be controlled to ensure safe approaches.

Aircraft normally deviate from the ILS as a result of the angular spread of the localizer beam and the increase in the signal noise from the beam as it is radiated from the transmitter (*4*). The magnitude of an aircraft's lateral deviation from the ILS decreases as the distance from the runway threshold decreases. Aircraft might also blunder, or abnormally deviate from the ILS, because of pilot error or equipment failure.

Parallel approaches require two monitor controllers, who are used to ensure lateral separation between aircraft on adjacent runways. The monitor controllers are located at the same ARTS display and are responsible for keeping their aircraft within the normal operating zone (NOZ) on the proper side of the NTZ. Figure 1 illustrates the positioning of the NOZs and the NTZ between extended runway centerlines.

Most of the time, the ILS receivers and aircraft navigation systems are accurate enough to guide the aircraft directly down the path of the extended runway centerline without significant lateral deviation to either side. However, in the event that an aircraft is observed on a track that would violate the NTZ, the monitor controller in charge of that runway is required to advise the pilot to turn left (or right) and return to localizer course (*5*). When an aircraft is observed to be blundering and violating the NTZ in a manner that could jeopardize an aircraft on the adjacent approach, the monitor controller of the endangered aircraft orders the aircraft's pilot to execute an evasive maneuver, which is a combination turn-and-climb maneuver away from the adjacent runway. The other monitor controller should continue to attempt to have the pilot of the blundering aircraft correct the errant course.

The endangered aircraft is vectored off the ILS course instead of the blundering aircraft for two principle reasons: (a) the pilot of the blundering aircraft has demonstrated an inability to navigate or control the aircraft adequately, and (b) doing so increases the airspace between the two conflicting aircraft (*5*). If the monitor controller of the blundering aircraft is unable to correct its course, then it is handed off to be resequenced into the traffic pattern.

RESEARCH OBJECTIVES

The objective of this research is to demonstrate the potential for safely reducing the runway separation standard for parallel approaches, which is based on current surveillance system configurations. A mathematical model developed to represent the flight track of an aircraft stabilized on the ILS is used in

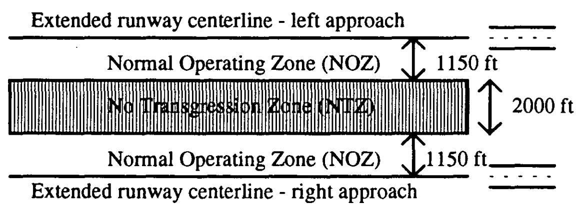

FIGURE 1 Illustration of parallel approaches: NOZ and NTZ width based on 4,300-ft spacing regulation.

the simulation of parallel approaches, during which both aircraft deviate normally from their respective ILSs. The simulation is run for various distances between parallel runway centerlines. This distance is referred to as "runway separation." For each runway separation considered, we determine the probability of an actual NTZ violation and of a false alarm for several combinations of radar accuracies and update intervals; a false alarm is defined as the probability that the radar displays the aircraft in the NTZ when it is actually in the NOZ. The mathematical model is used in another simulation of parallel approaches, during which a standardized aircraft blunder (abnormal lateral deviation) is introduced. The simulation is also run for different runway separations, radar accuracies, and update intervals; the probability of collision (the probability that the smallest distance between two aircraft during parallel approaches is less than or equal to 500 ft) is determined for each runway separation. The results from the 4,300-ft runway separation regulation with current system configurations are compared with those from smaller runway separations with different system configurations. Conclusions are drawn about the possible reduction of the current runway separation regulation.

LITERATURE REVIEW

Research on the risk analysis of parallel approaches that is related to this work can be grouped into two categories: (a) data collection and analysis studies and (b) parametric blunder resolution models (*6*). For both categories, we limit our discussion to the most recent and most relevant studies.

Data Collection and Analysis Studies

Data from direct observation of aircraft executing IFR approaches are collected and analyzed to determine the risk involved in parallel approaches. The resulting data are compiled to generate statistics for the lateral ILS deviation of the aircraft such as the mean, standard deviation, and percentage containment (the percentage of aircraft that fly within the respective NOZs).

In early 1989, under the objective of decreasing the spacing regulation, Thomas and Timoteo conducted a study at O'Hare International Airport in Chicago during which ILS flight tracks were collected, written to a data base, and analyzed (*3*). The analysis consisted of considering the flight tracks in three different views depending on the definition chosen for ILS localizer acquisition. Each successive view removed slightly more data from the approach's localizer acquisition phase. View 1 included some turn-on and all initial overshoot. (Turn-on is defined as the aircraft's turn onto the extended runway centerline in order to begin the final approach. The aircraft may overshoot the extended runway centerline when turning onto it and then must turn back toward it, hence the oscillations during final approach.) View 2 included either a small amount of initial overshoot or, if there was no initial overshoot, a small amount of turn-on. View 3 contained only the View 2 tracks with initial localizer stability points of 10.5 mi or more from touchdown. The analysis showed that after stabilization on the localizer (View 2), the lateral ILS deviation decreased with the range from runway threshold. The data generally suggested that the current ILS navigational performance of a typical mix of aircraft types at a large airport could support a decreased runway separation over what is currently permissible during IMC.

Parametric Blunder Resolution Models

Parametric blunder resolution models are for parallel approaches during which at least one aircraft abnormally deviates from the ILS. They are used to determine if a standardized worst-case blunder situation can be resolved safely. A standardized worst-case blunder is described by the maneuver in which an aircraft makes an unusually sharp 30-degree turn off its assigned ILS, toward the aircraft on the adjacent ILS. This turn is defined as the worst conceivable excursion from an assigned course that an aircraft could experience, because of pilot error or equipment failure. Although there is no documented instance of an actual blunder of this magnitude, this modeling approach for evaluating safety risk has become generally accepted by researchers and the FAA.

To resolve the blunder situation, an evasive maneuver is executed by the endangered aircraft. This conservatively assumes that the blundering aircraft has lost either communications or control and the monitor controller's attempts to correct the errant course are unsuccessful. The situation is considered resolved when the endangered aircraft, after receiving instructions from the monitor controller, achieves a heading parallel to that of the blundering aircraft. The miss distance is defined as the smallest lateral or slant distance between the aircraft that are conducting parallel approaches.

Altschuler developed a model to determine the risk of collision for simultaneous ILS approaches (*6*). Altschuler used analytical models and fast-time simulation to determine the probability of collision. The model was based on the assumption that the lateral ILS deviation can be modeled using a Gaussian distribution with a mean of zero and a constant standard deviation. It also used estimates of significant parameter distributions, such as the controller-to-pilot communication delay and the pilot/aircraft response delay.

Hollister developed the Blunder Risk Model for Lincoln Laboratory; the model is a Monte Carlo simulation of the events and aircraft positions during a worst-case blunder situation (*7,8*). The model was designed to assist in the evaluation of Precision Runway Monitor (PRM) radars and displays. The per-blunder failure (collision) rate was calculated on the basis of the number of approaches during which the miss distance was less than 500 ft. It is important to note that the results of this simulation were based on PRM aircraft tracking and alert generation algorithms. It could not be used in its present form to model the current surveillance system. In addition, raw data distributions were used to estimate controller response and communication delay times.

The Blunder Resolution Performance Model (BRPM) was a Monte Carlo simulation model developed by MITRE Corporation (*9*). It was intended to assist the FAA in the development of national standards for multiple parallel approaches. The BRPM was a Lotus 1-2-3 spreadsheet that represented a single blunder scenario and operated under the following assumptions:

1. There is no glide slope error.
2. Course deviations have a Gaussian distribution with a zero mean and a standard deviation proportional to the distance from the runway threshold.
3. The statistical distributions for controller and pilot delay times are known and statistically independent of one another.

The BRPM is similar to Hollister's model and can be used to model both current and PRM surveillance systems. BRPM determines the minimum slant range and horizontal range for each iteration and statistically analyzes the results after all iterations have been completed.

Summary

Data collection and analysis studies are advantageous because there is little need for simplifying assumptions. Accordingly, results based on collected data traditionally have been more convincing to policy makers. However, to obtain a statistic such as the probability of NTZ penetration, enormous amounts of data are needed. In addition, sensitivity analyses are difficult to perform. This research develops a mathematical model based on the Chicago data (*3*) that is capable of generating thousands of realistic, stabilized flight tracks. The model will be used in determining the probability of NTZ penetration and the corresponding probability of a false alarm for various runway spacings.

The main advantage of parametric blunder resolution models is that they support parametric analysis of controllable design parameters and allow for sensitivity analysis of competing systems. However, it is very difficult to estimate some parameters accurately because such data are not readily available. This research develops a simulation model similar to those of Hollister and MITRE that is used to model the current surveillance system. It is different from the previous models because probability distributions that describe actual data are used to generate delay times. In addition, an evasive maneuver model is used to generate the path of the endangered plane. This gives control over parameters such as the velocity of the endangered plane and the turn rate that it uses in its evasive maneuver. The model will be discussed in the following sections.

MATHEMATICAL MODEL DEVELOPMENT

This research uses the Chicago View 2 data in the development of a mathematical model that represents the approach path of an airplane flying the ILS after it is stabilized on the localizer. View 2 data are used because, according to Thomas and Timoteo, View 2 gives the best estimate of how the general population of simultaneous ILS approaches at Chicago navigate the ILS (*3*). After extensive review of the actual stabilized flight tracks, it is determined that representing all of the tracks with a single model would be difficult. Further review of the data indicates that many flight tracks share similar characteristics with respect to shape and can be categorized into the following families:

Family	*Track*
1	Asymptotic approach to centerline
2	Asymptotic approach to shifted centerline
3	Multiple deviations around centerline
4	Multiple deviations around shifted centerline
5	Multiple deviations around radial centerline

Figure 2 illustrates a sample flight track for each family.

Categorizing the flight tracks into the five families facilitates the mathematical model development because of the common characteristics within each family. Flight tracks of 1,377 airplanes are visually inspected and assigned a family number and a value for the centerline shift when applicable. Shift values range between -200 and 250 ft. A positive shift value indicates that the approach is shifted to the right of the extended runway centerline, and a negative shift value indicates that the approach is shifted to the left. A positive shift value is depicted in Figure 2 for Families 2 and 4. The probability distribution of the categorization is as follows:

Family	*Probability*
1	0.0261
2	0.0232
3	0.3501
4	0.4989
5	0.1017

Families 1 and 2 represent a small proportion of the total flight tracks. Most flight tracks fall into Families 3 and 4. Therefore, the mathematical model is developed to represent specifically Families 3 and 4 and is modified to represent Families 1, 2, and 5.

An autoregression model is developed that is a general case of control theory's second-order damping model. It is a position-dependent model (the current position can only be determined if the previous two positions are known) that includes a parameter β and an error term, which is normally distributed with a mean of zero and a standard deviation of σ. The model is explained as follows: let y_t be the aircraft's location at time t; the flight track is assumed to be represented by a cosine curve.

$$y_t = \cos(t) \tag{1}$$

Assume β to be a small time increment. Then y_{t-1} is the location of the plane at time $t - 1$, and y_{t-2} is the location of the plane at time $t - 2$. It follows that

$$y_{t-1} = \cos(t - \beta) \tag{2}$$

$$y_{t-2} = \cos(t - 2\beta) \tag{3}$$

After substituting trigonometric expansions and simplification:

$$y_t = \frac{1}{1 + \beta^2}(2y_{t-1} - y_{t-2}) + \varepsilon \tag{4}$$

$$\varepsilon \sim N(0, \sigma)$$

The $1/(1 + \beta^2)$ term is responsible for the rate of damping (the rate at which the amplitude of the deviations decreases with time). As β becomes larger, the approach to the centerline becomes steeper, the amplitude of the deviations around the centerline becomes smaller, and the flight track stabilizes sooner.

Further examination of the autoregression model reveals that it can be used to represent flight tracks in Families 1 and 2 as well as Families 3 and 4 with a change in the range of the parameter β. However, Family 5 can be represented only when a radial term is added to the autoregression model:

$$y_t = \frac{1}{1 + \beta^2}(2y_{t-1} - y_{t-2}) + \varepsilon + \Delta \tag{5}$$

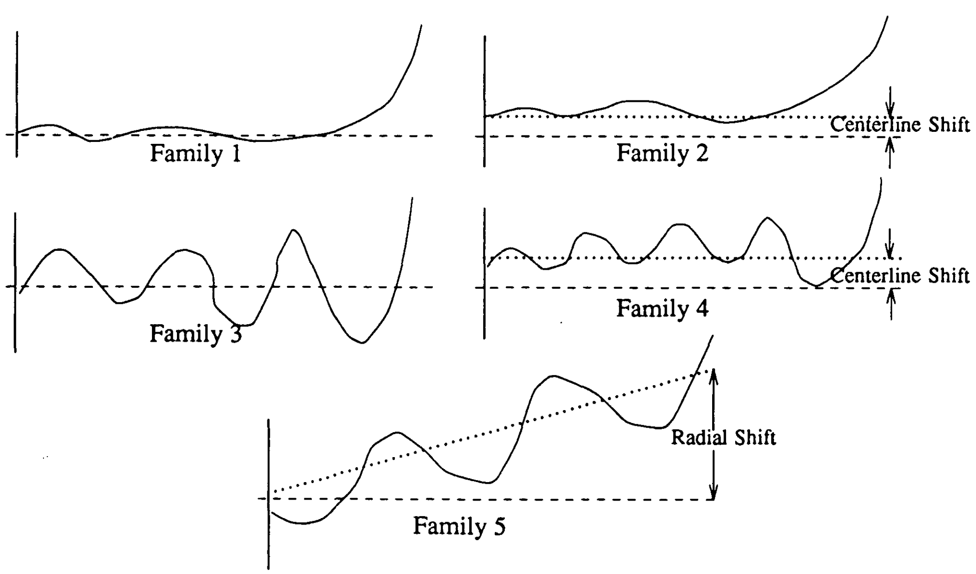

FIGURE 2 Example plots of flight tracks for each family.

where Δ is the vertical component of the radial shift that decreases with the range from the runway threshold. The radial shift can be calculated as follows:

$$\Delta = x \tan(\phi) \quad (6)$$

where ϕ is the radial shift angle and x is the airplane's range from the runway threshold.

The autoregression model is based on the following simplifying assumptions:

1. The shapes of the actual, stabilized ILS flight tracks used in generating the model are representative of all possible flight track shapes.
2. All possible combinations of visibility and ceilings, as well as crosswind and shear conditions, are represented in the actual data on which the model is based.
3. The aircraft types included in the data are representative of all aircraft.

At this point, a computer program is written to determine the extent to which the autoregression model represents the flight tracks in all five families. The program reads an actual flight track from a data file and generates many simulated flight tracks that have all possible parameter value combinations chosen from a wide range of β- and σ-values. These initial ranges of β and σ are determined empirically by comparing model behavior with flight track behavior. A simulated flight track has the same length as the corresponding actual track and is composed of a series of lateral positions that are generated by the autoregression model every 0.45 nmi along the final approach. The simulated track's lateral positions are compared to those of the corresponding actual track every 0.45 nmi. The sum of squared errors between the simulated and actual lateral positions is calculated, and it is decided whether the autoregression model can be used to represent the actual flight track using the following criterion: the autoregression model adequately represents an actual flight track when, for at least one of the simulated flight tracks, 70 percent of the simulated lateral positions are within 150 ft of the actual lateral positions.

If the actual track is adequately represented by the autoregression model, the parameters of the simulated flight track with the smallest sum of squared errors are considered to represent optimally that actual track.

The program is run using 1,377 actual flight tracks. Results indicate that the autoregression model adequately represents 1,203 of 1,377 actual flight tracks, or 87.36 percent. The optimal parameters of each family's actual tracks are developed into probability distributions for use in the simulations. The range of σ is the same for each family, $0.004 \leq \sigma \leq 0.008$. The ranges of β are as follows:

- Families 1 and 2: $2.0 \leq \beta \leq 4.0$
- Families 3 and 4: $0.5 \leq \beta \leq 1.4$
- Family 5: $0.5 \leq \beta \leq 1.0$

The range of ϕ for the Family 5 model is $0.20 \leq \phi \leq 0.30$. Because of statistical similarities between the β and σ probability distributions of Families 1 and 2, they are combined. The same occurs for the probability distributions of Families 3 and 4.

The family probability distribution, autoregression model, and its parameter distributions for each family, along with other distributions for the shift values and the initial two lateral locations, are used to generate stabilized flight tracks for the simulation models explained in the following.

SIMULATION 1: RISK MODEL FOR NORMAL ILS DEVIATION

Simulation 1 generates the probability of NTZ violation and the probability of false alarm for different combinations of runway separation, radar update intervals, and radar accuracies.

Methodology

Simulation 1 generates parallel approaches during which aircraft normally deviate about the ILS. An experiment is run for a given set of variables; it consists of 5,000 trials of parallel approaches. In each trial, two stabilized flight tracks are generated randomly by the autoregression model and are superimposed on final approach paths. After a random delay time to the first radar update, which is less than or equal to the radar update interval, an amount of radar error is generated randomly and added to the actual lateral location to give the radar lateral location. Next, the actual and radar lateral locations of both aircraft are checked to determine if an actual or radar NTZ violation occurs. If neither occurs, the program waits until the next radar update, again adds radar accuracy to the actual lateral location and checks the actual and radar lateral locations of both aircraft. If the actual or radar (or both) indicates NTZ violation, the trial is stopped momentarily and statistics for the number of false alarms and actual NTZ violations are updated. The trial is then continued in the same manner to collect only actual NTZ violation data. The trial ends after both aircraft have reach their respective runway thresholds and the probabilities of NTZ violation and false alarm are computed.

Variables

1. Runway separation: Values between 3,400 and 4,300 ft, inclusive, are considered. The 4,300-ft distance represents the U.S. national standard with current surveillance systems. Runway separations of less than 3,400 ft are not considered because a recent FAA regulation specifies that parallel approaches are allowed when runway separation is at least 3,400 ft and the PRM surveillance system is in use (7). Therefore, it is unrealistic to consider the current surveillance system with runway separations of less than 3,400 ft.
2. Radar update interval: Values of 1, 2.4, and 4.8 sec are considered on the basis of the current surveillance system and other available technologies (7).
3. Radar accuracy: Values between 1 and 5 mr, inclusive, are considered.

4. Stabilization range: The stabilization range for the aircraft on the right approach is 12.5 nmi. The range for the aircraft on the left approach is generated randomly to be within 1.5 nmi of the aircraft on the right approach (*7,8*).

5. Velocity: The velocity (measured in knots) of each plane is generated randomly in the following manner:

velocity = 129.3 + (R × 64.9)

where R is uniform = (0,1) and 129.3 knots/194.2 knots represents the minimum/maximum airspeed attained by aircraft on final approach, as studied by the FAA's Aviation Standards (*8,10,11*).

6. Random number stream seeds: Each experiment uses three random number streams.

Assumptions

Simulation 1 operates under the following assumptions:

1. The moment that the monitor controller perceives an aircraft (its radar lateral location) to be within the NTZ, he or she instructs the plane on the adjacent approach to execute an evasive maneuver.
2. All movements by both aircraft take place in the assigned glide slope.
3. Radar error is normally distributed with a mean of zero and a standard deviation equal to the radar accuracy (1 − 5 mr).
4. Radar range error is negligible.
5. The width of the NTZ is 2,000 ft.
6. The width of the NOZ is equal for each plane and is calculated as (runway spacing − 2,000)/2.
7. The autoregression model generates realistic, stabilized flight tracks for a typical mix of today's aircraft.

Simulation 1 Results

For each runway separation considered, 18 experiments are run, each having a unique combination of random number stream seeds. An update interval of 4.8 sec is studied with radar accuracies of 3, 4, and 5 mr. These combinations reflect parameter values of current surveillance systems (*1,6*). In addition, more recent technologies have the following radar update interval and accuracy values: 4.8 sec/2 mr, 2.4 sec/1 mr, and 1.0 sec/1 mr (*7*). These combinations are also considered in the analysis.

Results from the NTZ violation analysis provide the probability of an aircraft's entering the NTZ during its approach to either of the parallel runways. Results from the false alarm analysis give the probability of an aircraft's, on either approach, being displayed within the NTZ when its actual location is in the NOZ. Table 1 gives the average results of the experiments.

The analysis may be considered a worst case with respect to both the probabilities of NTZ violation and of a false alarm because controller intervention is assumed to occur only after the aircraft is displayed by the radar to be violating the NTZ. If the controller intervenes when it appears that the aircraft is heading toward the NTZ, to turn the aircraft back toward its ILS, some NTZ violations and false alarms may be prevented.

From Table 1, as expected, the probability of NTZ violation increases as the runway separation decreases. In addition, the marginal increase in the probability of NTZ violation is greater for smaller runway separations. If the runway separation regulation can be decreased only when the current probability of NTZ violation is maintained (0.0057, or 1 in 175 approaches during which NTZ violation occurs), clearly the accuracy of aircraft ILS navigation must be improved.

The false alarm probabilities are plotted in Figure 3. For each update interval/accuracy combination, the probability of a false alarm increases as runway separation decreases. And like the probability of NTZ violation, the marginal increase in the probability of a false alarm is greater for smaller runway separations. The radar update interval/accuracy combination that shows the worst performance is 4.8 sec/5 mr; that which shows the best performance is 2.4 sec/1 mr. Although the 1.0 sec/1 mr combination has the same radar accuracy as the 2.4 sec/1 mr combination, it results in a greater probability of false alarm for every runway separation because there are approximately 2.5 more radar updates.

These results suggest that the current probability of a false alarm is between the two bounds of 0.0065 and 0.0357. If the lower bound (0.0065, or 1 false alarm in 153 approaches) is the probability that must be maintained when considering the reduction of the 4,300-ft runway separation regulation, fea-

TABLE 1 Simulation 1: Probabilities of NTZ Violation and False Alarm

Runway Separation (feet)	Probability of NTZ Violation	Radar Update (seconds) / Radar Accuracy (milliradians)					
		4.8 sec				2.4 sec	1.0 sec
		2 mr	3 mr	4 mr	5 mr	1 mr	1 mr
4300	0.0057	0.0026	0.0065	0.0140	0.0357	0.0012	0.0032
4200	0.0076	0.0030	0.0084	0.0189	0.0432	0.0018	0.0034
4100	0.0090	0.0034	0.0088	0.0247	0.0599	0.0017	0.0043
4000	0.0112	0.0042	0.0121	0.0322	0.0803	0.0022	0.0062
3900	0.0135	0.0050	0.0146	0.0413	0.1020	0.0027	0.0069
3800	0.0166	0.0073	0.0195	0.0535	0.1326	0.0027	0.0076
3700	0.0196	0.0077	0.0280	0.0708	0.1691	0.0035	0.0102
3600	0.0234	0.0139	0.0376	0.0977	0.2243	0.0046	0.0113
3500	0.0274	0.0185	0.0506	0.1303	0.2768	0.0082	0.0165
3400	0.0333	0.0244	0.0686	0.1768	0.3438	0.0108	0.0212

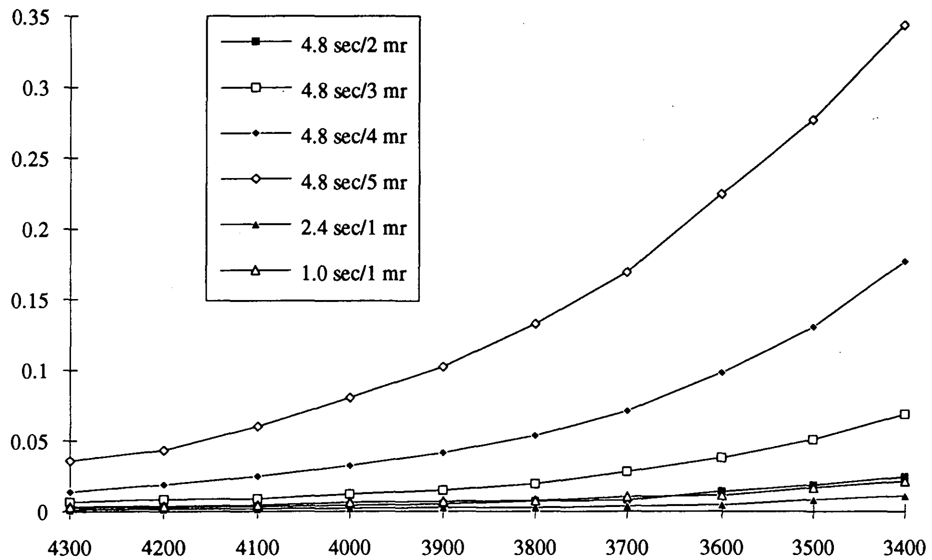

FIGURE 3 Plots of probability of false alarm versus runway separation for various combinations of radar accuracy and update.

sible alternatives, based on the results in Table 1, are given in Table 2.

SIMULATION 2: RISK (AIRCRAFT BLUNDER) MODEL FOR ABNORMAL ILS DEVIATION

Simulation 2 is a model for parallel approaches in which a standardized worst case blunder is introduced, as shown in Figure 4. This model is used to generate the probability of collision given a standardized worst case blunder, for various combinations of runway separation, radar update interval, and accuracy.

Simulation 2 Methodology

This simulation is similar to Simulation 1, but at a randomly determined range along the final approach, one aircraft makes an unusually sharp turn off its assigned ILS, endangering the

TABLE 2 Alternatives for Runway Separation Regulation Based on Probability of False Alarm

Runway Separation (ft)	Update Interval/ Accuracy	Probability of False Alarm
4,000	1.0 sec/1 mr	0.0062 (1 FA/161 approaches)
3,900	4.8 sec/2 mr	0.0050 (1 FA/200 approaches)
3,600	2.4 sec/1 mr	0.0046 (1 FA/217 approaches)

NOTE: FA = false alarm

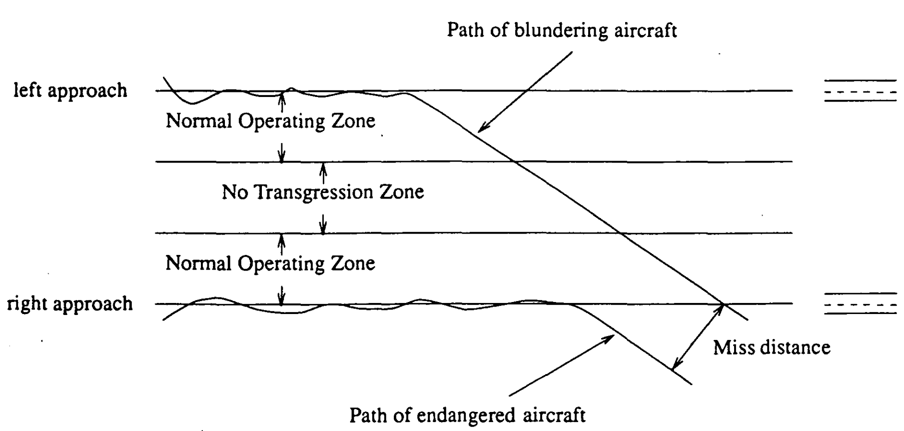

FIGURE 4 Illustration of standardized worst-case blunder.

aircraft on the adjacent approach. An experiment consists of 5,000 trials of parallel approaches and is run for a given set of variables, the same as defined for Simulation 1 in addition to those defined in the following. The blundering aircraft travels at a constant speed along an approach track randomly generated by the autoregression model. When it reaches the blunder range, it begins its blunder maneuver and turns toward the adjacent approach, with its turn rate accelerating until the desired rate is obtained. The blundering aircraft continues to turn at this rate until it reaches the blunder angle. It continues to fly at this heading for the rest of the trial. At the same time, the endangered plane flies at a constant speed along its approach track, which is also determined randomly by the autoregression model. Before the endangered aircraft can begin its evasive maneuver, a series of time delays must take place: detection delay, possible blocked frequency delay and communication/start turn delay. After the delays, the endangered aircraft turns in the same manner as described for the blundering aircraft, until it achieves a heading parallel to that of the blundering aircraft. The miss distance, or the smallest distance between the aircraft, is calculated every second after the blunder maneuver is initiated. The trial is terminated after both aircraft have flown at the same blunder heading for 5 sec. The minimum miss distance for each trial is recorded. If the minimum miss distance is less than 500 ft, a collision is assumed to occur. After the desired number of simulation trials are completed, the probability of collision is calculated as the number of collisions divided by the total number of trials.

Variables

1. Blundering aircraft: It is randomly determined before the start of each parallel approach whether the blundering aircraft is on the left or on the right approach.
2. Blunder range: The blunder range is generated randomly and varies between 5 and 12 nmi.
3. Turn rate acceleration: The acceleration is 1 degree per second^2.
4. Turn rate: The rate is 3 degrees per second.
5. Blunder angle: The angle is 30 degrees.
6. Detection delay: This delay is the time lapse from the start of the blunder to the first time the blundering aircraft is displayed by the radar to be in the NTZ. This variable is dependent on the radar update interval and accuracy.
7. Blocked frequency blocking delay: This delay occurs if the controller's frequency is blocked by noncontroller transmissions when he/she attempts to issue an evasive command to the endangered aircraft, with a probability of 0.0675 (*7*). This delay is the time that the controller must wait before he/she is able to access the frequency. Raw data for this delay have been obtained from Lincoln Laboratories, and can be represented with a Weibull distribution.
8. Communication/start turn delay: This delay begins with the time the controller begins to issue the evasive command and ends with the time that the endangered aircraft begins its evasive maneuver. Statistics on this delay are obtained from the FAA's Aviation Standards (*14,15*). The communication/start turn delay is estimated to follow a Weibull distribution.

Assumptions

Simulation 2 operates under the same assumptions as Simulation 1 along with the following:

1. The course of the blundering aircraft is a linear path toward the adjacent runway at a constant blunder angle with respect to the assigned approach (*1,6*).
2. The pilot of the blundering aircraft is either unaware of the significant course deviation or unable to effect a correction (*1,6*). Any attempt by the pilot or monitor controller to correct this course will prove futile.

Simulation 2 Results

As with Simulation 1, 18 experiments are run for each runway separation using a unique combination of random number stream seeds. The same radar update interval/accuracy combinations used for Simulation 1 are considered in this analysis.

The results from Simulation 2 provide the probability of collision given a standardized blunder executed by an aircraft on either of the two final approaches. The average results of the experiments are given in Table 3.

The probabilities of collision are plotted in Figure 5. As expected, the probability of collision, for all combinations of radar update/accuracy, generally increases as the runway separation decreases. The update interval/accuracy combination that shows the best performance is 1.0 sec/1 mr, and that which shows the worst performance is 4.8 sec/5 mr. These results are consistent because with a smaller radar update interval, the aircraft locations are more frequently updated. This allows the controller to detect an aircraft that is violating the NTZ sooner and to issue evasive maneuver instructions immediately to the aircraft on the adjacent approach, generally resulting in a larger miss distance and therefore fewer collisions.

From Table 3, for a 4,300-ft runway separation, the probability of collision, given a worst-case blunder, is between the bounds of 0.0025 and 0.0028. If the lower bound (0.0025), which equates to 1 collision in 400 standardized worst-case blunders, must be maintained when considering a reduction in the runway spacing regulation, feasible alternatives are shown in Table 4.

TABLE 3 Simulation 2: Probability of Collision

Runway Separation (feet)	Radar Update (seconds) / Radar Accuracy (milliradians)					
	4.8 sec				2.4 sec	1.0 sec
	2 mr	3 mr	4 mr	5 mr	1 mr	1 mr
4300	0.0019	0.0025	0.0027	0.0028	0.0001	0.0000
4200	0.0024	0.0028	0.0033	0.0030	0.0001	0.0001
4100	0.0035	0.0030	0.0031	0.0037	0.0005	0.0003
4000	0.0042	0.0031	0.0047	0.0051	0.0007	0.0003
3900	0.0045	0.0056	0.0051	0.0067	0.0011	0.0002
3800	0.0059	0.0069	0.0065	0.0065	0.0015	0.0006
3700	0.0075	0.0087	0.0075	0.0082	0.0024	0.0008
3600	0.0081	0.0093	0.0107	0.0100	0.0036	0.0015
3500	0.0091	0.0095	0.0125	0.0111	0.0046	0.0016
3400	0.0111	0.0119	0.0140	0.0120	0.0053	0.0021

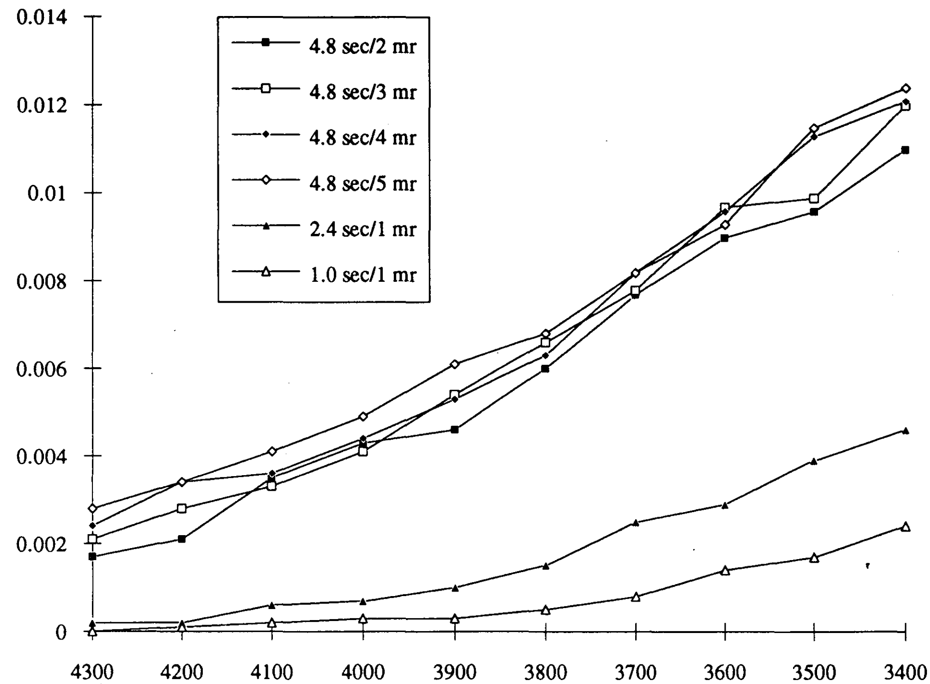

FIGURE 5 Plots of probability of collision versus runway separation for various combinations of radar accuracy and update.

TABLE 4 Alternatives for Runway Separation Regulation Based on Probability of Collision

Runway Separation (ft)	Update Interval/ Accuracy	Probability of Collision
4,200	4.8 sec/2 mr	0.0024 (1 COL/416 WCB)
3,700	2.4 sec/1 mr	0.0024 (1 COL/416 WCB)
3,400	1.0 sec/1 mr	0.0021 (1 COL/467 WCB)

NOTE: COL = collision, WCB = worst-case blunder

TABLE 5 Current Regulation Compared with Suggested Regulation

	Runway Separation (ft)	P(NTZ)	P(FA)	P(COL/WCB)
Current standards	4,300	0.0057	0.0065	0.0025
Research results	3,700	0.0196	0.0035	0.0024

CONCLUSIONS

This research is intended to aid the FAA in its decision to reduce the parallel approach runway spacing regulation for current surveillance system configurations. Simulations are developed to quantify the probabilities of NTZ violation, false alarm, and collision given a standardized worst-case blunder, for different runway separations and combinations of radar update interval and accuracy. Simulation results for current surveillance system configurations are considered to be the level that must be maintained when a reduction in the standard is being considered.

When considering the probability of NTZ violation and the results of this research, which are based on the assumption that the monitor controller intervenes only after a NTZ violation occurs, reducing the separation regulation is possible only if aircraft ILS navigational accuracy is improved. In addition, the increased navigational accuracy, when combined with a reduced runway separation, must result in a P(NTZ) of at most 0.0057 (result for 4,300-ft runway separation). If this assumption is relaxed and an accurate controller response algorithm is developed in which controllers intervene to change the course of an aircraft when it appears to be on a path that will violate the NTZ, more realistic statistics about NTZ violation can be collected. These statistics may support a decrease in the separation regulation.

The current probability of false alarm, as calculated by Simulation 1, is equal to 0.0065. The minimum runway separation that maintains this, with a P(FA) equal to 0.0046, is 3,600 ft, when combined with a radar update interval of 2.4 sec and accuracy of 1 mr. From Simulation 2, the current probability of collision given a worst-case blunder is equal to

0.0025. The minimum runway separation that maintains this, with a P(COL/WCB) equal to 0.0021, is 3,400 ft, when combined with a radar update interval of 1.0 sec and accuracy of 1 mr. However, both the P(FA) and P(COL/WCB) must be maintained to consider a decrease in the runway separation regulation. From Tables 1 and 3, the smallest runway separation that maintains both probabilities, with a P(FA) of 0.0035 and a P(COL/WCB) of 0.0024, is 3,700 ft, when using a radar with an update interval of 2.4 sec and accuracy of 1 mr. These results are summarized in Table 5.

When examining the results, it is important to remember that P(NTZ) is based on a radar update of 4.8 sec and an accuracy of 3 mr. When the update interval is reduced, the monitor controllers have better control over the locations of the aircraft because of the increase in radar updates. For this reason, it is most likely that the P(NTZ) will be smaller for the runway separation of 3,700 ft. This research suggests that, with an improved surveillance system that has a radar update interval of 2.4 sec and accuracy of 1 mr, the runway separation regulation can be reduced to 3,700 ft, if the reduced update interval results in a P(NTZ) less than or equal to 0.0057. However, the accuracy of the risk quantifications remains untested because of the lack of available empirical data. In addition, the risk quantifications are based on many conservative assumptions and are probably conservative themselves.

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