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Continuous Descent Approach: Design and Flight Test for Louisville International Airport

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A design methodology based on the principles of system analysis was used to design a noise abatement approach procedure for Louisville International Airport. In a flight demonstration test, the procedure was shown to reduce the A-weighted peak noise level at seven locations along the flight path by 3.9 to 6.5 dBA, and to reduce the fuel consumed during approach by 400 to 500 lb (181 to 227 kg). The noise reduction is significant given that a 3-dB difference represents a 50% reduction in acoustic energy and is noticeable to the human ear, and the 7% reduction in the size of the 50 day night average noise level (DNL) contour that would result if all aircraft were to perform the procedure. The fuel saving is also significant, given the financial benefit to airlines and the accompanying reduction in gaseous and particulate emissions. Although the analysis of aircraft performance data showed how pilot delay, in combination with auto-throttle and flight management system logic, can result in deviations from the desired trajectory, the results confirm that near-term implementation of this advanced noise abatement procedure is possible. The results also provide ample motivation for proposed pilot cueing solutions and low-noise guidance features in flight management systems.

I. Introduction

COMMUNITY concerns about aircraft noise are currently constraining the growth of aviation. Because of the increasingly active legal opposition to airport expansion by residents in impacted communities, many runway expansion projects have either been delayed or abandoned. The net effect is that fewer than five additional runways have been built at the 30 busiest airports in the United States within the past 10 years,[1] resulting in greater delays and congestion at major airports.[2] Because airports are the nodes of the air transportation system, capacity limitations at the busiest nodes will limit the capacity of the entire system.

A number of measures have been adopted to address the issue of aircraft noise. These measures include phasing out noisier aircraft[3] and introducing aircraft with quieter engine technology[4]; enforcing nighttime curfews on the operation of all or only certain aircraft; and insulating (or purchasing and then demolishing) homes that are severely impacted by aircraft noise.[5] Although these measures have reduced the impact of aircraft noise, they have not reduced the opposition to airport expansion. Given the relatively wide implementation of the measures just described and the potential capacity crisis in the national and international airspace system, there is a critical need for new solutions.

One promising approach to the reduction of the impact of noise in communities near airports is to change the way aircraft are operated when they are in the vicinity of airports. These modified flight procedures, commonly referred to as noise abatement procedures, have been shown in simulation and analysis and, through limited implementation, to provide significant noise reduction.[6–9] However, widespread implementation of these procedures has been limited by the capabilities of both air traffic controllers and air traffic control (ATC) automation.[10–12] For example, because it is difficult to predict the future position of an aircraft when its speed varies significantly, air traffic controllers typically instruct all aircraft to fly a staged approach, where at each stage the aircraft maintain a common altitude and speed. Whereas this greatly reduces the complexity of the tasks the controllers must perform, it also limits the options available to procedure designers.

In an effort to further the development of noise abatement procedures, a research team, led by the Massachusetts Institute of Technology (MIT) with members from The Boeing Company, the Federal Aviation Administration (FAA), NASA, the Regional Airport Authority (RAA) of Louisville and Jefferson County, and United Parcel Service (UPS), designed a continuous descent approach (CDA), in which aircraft descend and decelerate continuously without reverting to level flight, for runway 17R at Louisville International Airport (KSDF). The team also conducted a flight demonstration test at KSDF to evaluate the operational characteristics and demonstrate

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the noise-reducing potential of this advanced noise abatement procedure.

In this paper, the design methodology, the experimental design, and the results of this flight demonstration test are presented. The paper is structured as follows. Background information about KSDF and the affected community of Floyds Knobs, Indiana, is presented in Sec. II. The design methodology is presented in Sec. III. The development of the noise abatement procedure is described in Sec. IV. The flight demonstration test is described in Sec. V. The noise results and analysis are presented in Sec. VI, and the aircraft performance results and analysis are presented in Sec. VII. A summary and conclusions are presented in Sec. VIII.

II. Background

KSDF is the major hub of operations for UPS, a large overnight package delivery and air cargo carrier. Because overnight package delivery requests are typically generated near or at the end of the business day with the intention that each package arrive at its destination at the beginning of the next business day, most UPS flight operations occur in the late evening or at night. In fact, FAA flight operations logs indicate that, on a typical weeknight, over 90 large jet aircraft land at KSDF between 1000 and 0200 hrs, the period during the day when residents in communities near the airport are most sensitive to noise. As a result, UPS is often cited by residents in communities near the airport as impacting negatively on their quality of life.

This is especially true in communities such as Floyds Knobs, Indiana (North of the Ohio River from Louisville, Kentucky) where the average terrain elevation is over 850 ft higher than the field elevation at KSDF (Fig. 1). Floyds Knobs is directly under the flight path of aircraft that are landing toward the South following the standard approach procedure for Runway 17R. In this procedure, aircraft descend to an altitude that is 3000 ft above the elevation at KSDF (less than 2150 ft above the terrain elevation in Floyds Knobs) well before reaching the airport and maintain this altitude as they turn (passing directly over Floyds Knobs) onto the final approach course (where they are in line with the runway). The net effect of the level flight turn and the altitude difference between Floyds Knobs and KSDF is that the noise levels in homes in this area are higher than if the homes were at the same elevation as the airport.

III. Design Methodology

Clarke[6] identified and demonstrated the noise reducing potential of advanced noise abatement procedures using a methodology based on the principles of system analysis. One of the key features of this methodology is that it incorporates all of the factors that must be considered when a noise abatement procedure is designed for a single aircraft. When efficient trade studies are enabled between the relevant factors (including noise), the methodology provides a framework for multiobjective optimization with noise as a key factor. The tool underpinning this methodology is NOISIM. This tool combines a flight simulator, a noise model, and a geographic information system to create a rapid prototyping environment in which the user can simulate an aircraft's operation in existing and potential guidance and navigation environments, while simultaneously evaluating the aircraft's noise impact. The factors considered in NOISIM include aircraft performance and trajectory; noise generated by the aircraft; population distribution and density; flight safety and pilot acceptance; guidance and navigation requirements; and local atmospheric conditions. Traditionally, these factors have been considered either independently or in subsets. NOISIM provides a mechanism to incorporate and evaluate these factors simultaneously. To understand why the simultaneous consideration of all factors is beneficial to the design of noise abatement procedures, it is important to understand the process of design in general.

At the most fundamental level, the process of design is a search through the design space for, at first, a feasible and then, ideally, an optimal solution (or pareto-optimal solution when there is more than one objective).[13] It is logical then to expect that an examination of the properties of numerical searches will offer insights into the process of design. In a numerical search, iterations provide information about the topology. For example, in a gradient-based search, this information is in the form of the partial derivative of the objective function with respect to each independent variable. This information is then used in subsequent iterations to determine the best direction in which to move to reach the optimum solution. One very common approach is to move in the direction of the steepest gradient (the direction in which the change in objective function value is greatest). The utility (the solution time and the accuracy of the resulting solution) of gradient-based search methods is limited by the accuracy of the estimates of the gradient. If one or more of

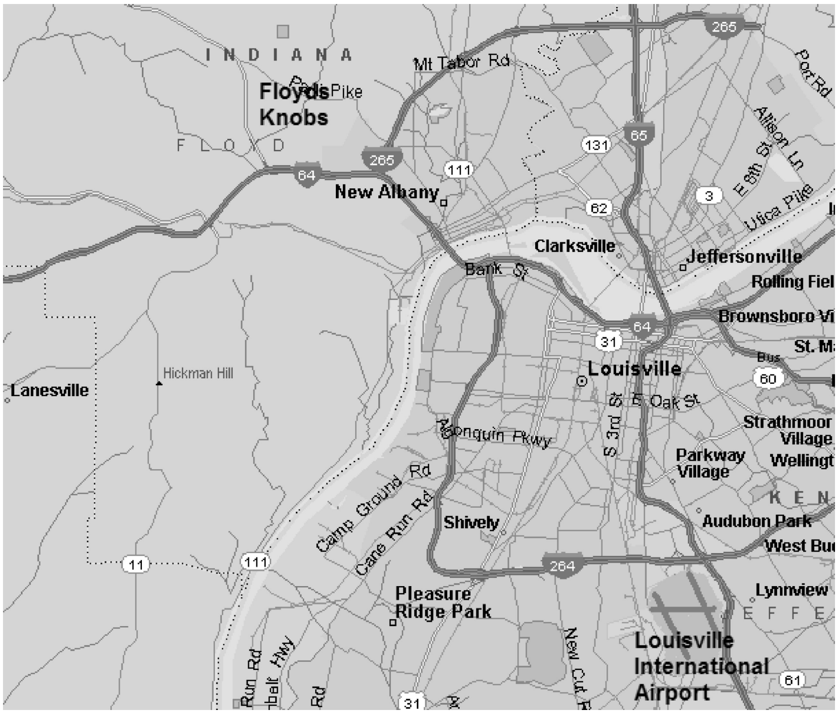

Fig. 1 Map of Louisville area showing the airport and Floyds Knobs.

the estimates are inaccurate, solution time will increase, and the accuracy of the resulting solution might be poor (especially with respect to the factors that are poorly characterized). Thus, it is critical to have accurate (or at least comparable) estimates for all factors either through higher fidelity analytical and/or simulation models.

Similarly, design iterations provide vital information about the topology of the design space. By evaluation of the performance of the latest design through analysis and/or simulation, the designer learns about the likely changes in performance that would result from changes in design parameters or the design itself. In other words, design iterations provide the gradient of the design objective with respect to design parameters and design options (the different concepts that could satisfy the objective). Using this information, the designer can determine if and how the desired goal can be met by changing the design parameters of the current option, and, if the current option cannot meet the objective, which option is the most appropriate alternative. However, as in the case of a numerical search, the utility of the search is limited by the accuracy of the estimates of the gradients. Thus, it is critical during the design process to consider and model all factors with sufficient fidelity to support the required trade studies between them. NOISIM proved to be a very useful mechanism for the trade studies required in the design of a noise abatement procedure.

As an example of its utility, NOISIM was used to develop a noise abatement approach procedure for Runway 13L at John F. Kennedy Airport in New York City. The situation at that airport is such that aircraft performing the traditional instrument landing system (ILS) approach to Runway 13L have a significant noise impact on the communities under their flight path. A 3-deg decelerating approach with a single turn at an altitude of 2000 ft was developed to reduce the noise impact in these communities. This approach has a very similar ground track to the ILS approach, but the aircraft is in an idle descent throughout the approach with no level segments at constant speed. Simulation results showed that, if implemented, the number of people impacted by peak noise greater than 60 dBA (where dbA refers to A-weighted peak noise level) would be reduced from 252,734 to 79,851, a 68% reduction. Subsequently, the methodology and its variants[9,11,12] have been used throughout the world to develop flight procedures that minimize both noise and emissions.

However, because NOISIM does not presently consider the impact that a procedure has on the ability of air traffic controllers to manage streams of aircraft, it cannot be used to determine the workload and the situation awareness of controllers in environments where aircraft are unpredictable. A complete evaluation of these factors would require a real-time pilot- and controller-in-the-loop simulation evaluation. Given the high number of iterations typically associated with the design of a flight procedure, this approach was neither feasible nor affordable for this study.

Fortunately, because the design process does not place limits on the source of the information that is used in design iterations, this information may be obtained through expert knowledge and experience. Thus, an integrated team was formed with subject matter experts from MIT, The Boeing Company, the FAA, NASA, the RAA of Louisville and Jefferson County, and UPS.

IV. Procedure Development

The CDA procedure was developed in two distinct phases: preliminary design and simulation sessions. In the preliminary design, the objectives and constraints of the community, pilots, and air traffic controllers were synthesized into a baseline procedure. In the simulation sessions, the parameters for the baseline procedure were verified, and a pilot procedure that was robust to wind variations was developed. These two phases are described in more detail hereafter.

A. Preliminary Design

During the preliminary design, community, pilot, and air traffic controller requirements were synthesized into a baseline procedure. These requirements are presented hereafter, followed by a description of the rationale used to determine the appropriate test aircraft and the parameters that define the procedure: the lateral position of the aircraft as a function of time (ground track), the altitude as a function of time (vertical profile), and the speed as a function of time (speed profile).

The community desires a procedure in which the aircraft thrust is kept as low as possible for as long as possible (especially over noise-sensitive locations); and the aircraft is kept as high as possible for as long as possible. These considerations point to a procedure where the aircraft descends at idle or low thrust to the runway at the steepest angle at which it can decelerate to its final approach speed. Because of practical considerations related to aircraft design and wake vortices,[14–16] this angle must be between 2 and 3 deg. if all aircraft are to perform such a procedure. The procedure must also be designed so that there are no transients in thrust over noise-sensitive locations.

Pilots desire a procedure in which the aircraft is capable of staying on the desired vertical and lateral flight path in the presence of wind, the flap and gear schedules have sufficient safety margins, the deceleration rates are not too high, the number of step-downs in speed is minimized to reduce pilot workload, and the changes in the configuration of onboard systems are minimized for implementation feasibility. These considerations suggest a procedure where the most advanced flight management system is employed to help the pilot reduce workload and stay on the intended flight path while extending the flaps and gear and achieving the required deceleration rate within an acceptable margin of safety.

Air traffic controllers desire a procedure in which they can use the speed of the aircraft as a surrogate for distance. That is, to separate and sequence aircraft, controllers frequently place a series of aircraft at the same speed with the desired separation during the initial segments of the approach. From that point onward, they keep the aircraft at the commanded speed and fine tune the separation with vector commands to assure that the desired separation is being maintained. This practice requires constant-speed segments during the descent with speed changes that occur over short periods of time. These considerations point to a procedure where the angle of descent is high enough that the aircraft is able to maintain a constant speed while at idle or very low thrust; but low enough that the aircraft decelerates quickly to a new equilibrium speed due to the drag induced by a shallower flight-path angle and/or the extension of flaps and gear.

1. *Test Aircraft*

The Boeing 767-300 aircraft equipped with the Pegasus flight management system (FMS) was selected as the test aircraft for two reasons. First, a number of such aircraft were at the tail end of the UPS arrival bank where the traffic levels were relative low. The low traffic levels eased the controllers' separation surveillance effort and limited the interaction of the test aircraft with other UPS aircraft. This helped controllers ensure that the test aircraft would fly the planned route without interrupting the nominal traffic flow. Second, the Pegasus FMS is the most advanced FMS in the UPS fleet.

2. *Ground Track*

The ground track was designed to minimize flight time and ensure that aircraft could turn safely onto the final approach course given their guidance and navigation system constraints. At Louisville, aircraft from the west typically enter the TRACON at the waypoint CHERI (Fig. 2) and are vectored by air traffic control to runway 17R via the waypoints SPYRS, BLGRS, and CHRCL. These three waypoints are all located along the extended centerline of runway 17R, and are 13.2, 10.2, and 5.6 n mile away from the runway threshold, respectively. Because the turn onto the final approach course would be too tight if the aircraft flew directly from CHERI to SPYRS, the waypoint WOODI (located 4 n mile northwest of BLGRS) was added to ensure that the turn onto the final approach course was no larger than 30 deg. Two additional waypoints, BOBBE and JIMME, were added for speed and altitude control. The resulting ground track from CHERI through BOBBE, JIMME, WOODI, BLGRS, CHRCL and 17R is shown in Fig. 2.

3. *Vertical Profile*

A two-segment CDA with a constant flight path angle (FPA) initial segment and a 3-deg ILS glide slope second segment was

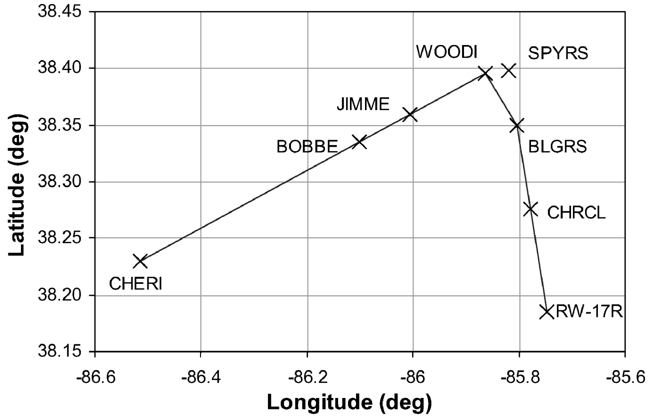

Fig. 2 Waypoint locations for flight track.

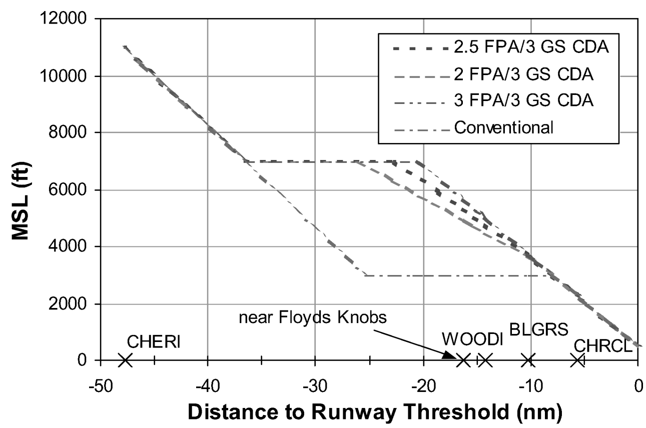

Fig. 3 Altitude profiles examined.

developed. The constant FPA during the initial segment provides pilots and controllers with more predictable aircraft performance. Figure 3 shows the altitude profile for the three FPAs: −2, −2.5, and −3 deg that were considered. As shown in Fig. 3, the larger FPA leads to higher altitudes at a given distance from the threshold and a starting point that is closer to the runway threshold. The altitude profile for a conventional step-down approach, with the aircraft descending from 11,000 to 3000 ft, followed by a level-flight segment before intercepting the 3-deg ILS glide slope, is also shown. In the vicinity of Floyds Knobs, the two-segment paths are approximately 2000–2500 ft higher than the conventional step-down approach. This difference in altitude is one of two reasons why aircraft performing the CDA are quieter than aircraft performing the conventional approach.

The second reason is that the noise on the ground also depends on engine thrust. The engine thrust required to achieve a specified descent rate is related to drag (which, in turn, is governed by aircraft configuration and airspeed), aircraft mass, and the rate of deceleration. If there is no wind, the energy equation for a point mass is

$$Wh + \frac{1}{2}\left(\frac{W}{g}\right)V_g^2 = \int (T - D)^* V_g \, \mathrm{d}t \tag{1}$$

where W is the weight, h is the altitude, g is the gravitational constant, V_g is the ground speed, T is the thrust, D is the drag, and t is time.

By the use of the time derivative and under the assumption that W stays constant with time gives

$$\frac{\mathrm{d}h}{\mathrm{d}t} + \left(\frac{V_g}{g}\right)^* \frac{\mathrm{d}(V_g)}{\mathrm{d}t} = (T - D)^* \frac{V_g}{W} \tag{2}$$

The assumption of constant W is valid given the finding from the flight data recorder that the fuel that is burnt during the approach

Table 1 Predicted A-weighted peak noise level at WOODI [∼820 ft mean sea level (MSL)]

Vertical profile	Peak dBA
3 FPA/3 GS	61.1
2.5 FPA/3 GS	61.9
2 FPA/3GS	62.9
Level flight at 3000-ft MSL and 180-kn CAS	69.9

is only 0.4% of the total aircraft weight. Furthermore, under the assumption that the lift L is approximately equal to W, Eq. (2) can be rewritten as

$$\tan\gamma + \left(\frac{1}{g}\right)^* \frac{\mathrm{d}(V_g)}{\mathrm{d}t} \sim \left(\frac{T}{W}\right) - \frac{C_d}{C_l} \tag{3}$$

where γ is the FPA and C_d and C_l are the drag and lift coefficients, respectively.

The foregoing equation was used to estimate the required thrust for a B767 descending at a 2, 2.5 or 3 deg, respectively, under the assumption that the aircraft was flying at a constant speed of 180 kn over the noise-sensitive areas of Floyds Knobs, WOODI, and BLGRS. The ground noise level at WOODI was then estimated with existing noise-power-distance data. The results are listed in Table 1, along with the estimated noise level for the conventional approach. As expected, the conventional approach was the loudest approach, whereas the three-degree approach was the quietest approach. As shown, all three CDA procedures achieved significant, but comparable, noise reduction, that is, greater than 7 dBA relative to the conventional approach. The choice of FPA was, therefore, not a binding constraint.

The potential for noise reduction of each descent must be balanced with its deceleration rate, especially during the initial portion of the descent. A comparison among these FPA revealed that a 2-deg descent, although not the best in terms of noise, provided the most aggressive deceleration during the initial segment and, thus, the greatest margin in terms of ensuring that the aircraft would be able to decelerate fully before reaching the noise-sensitive area. Given the relatively small difference in noise impact between the three FPAs considered, the 2-deg descent option was selected. This step-down speed profile also happens to be easier to control with the FMS.

4. *Speed Profile*

Although it would be desirable for the aircraft to decelerate at idle thrust over the noise-sensitive area, the difficulty with a perfectly timed deceleration is that the noise measured on the ground is very sensitive to pilot performance (or lack thereof) and autothrottle thrust transients (sudden changes in thrust when the aircraft reaches its desired speed). To prevent changes in thrust from occurring over the noise-sensitive area, the procedure was designed so that the aircraft would maintain constant speed at higher altitudes, decelerate before reaching the noise-sensitive area, and then maintain a constant speed over the noise-sensitive area.

5. *Baseline Procedure*

Figure 4 shows the altitude and speed profiles for a B767-300 performing the baseline 2-deg FPA/3-deg GS approach. Altitude values are shown on the left vertical axis and calibrated airspeed (CAS) values are shown on the right vertical axis. The constant speed of approximately 180 kn near WOODI and BLGRS is intended to avoid thrust transients over the noise-sensitive area. The points at which flap transitions occur are indicated on the CAS profile. Note that, because analysis showed that the procedure could be initiated at a higher altitude with no aircraft performance penalty or additional workload for controllers, the level flight segment at 7000 ft, shown in Fig. 3 was eliminated and the 2-deg flight path was extended to CHERI (where it coincided with the normal altitude of 11,000 ft at that waypoint). Also note that the speed profile chosen satisfies the

Table 2 Speed and altitude constraints for VNAV (slow descent)

Waypoint	Speed constraint	Altitude constraint
CHERI	At 240 kn	At 11,000 ft
BOBBE	At 205 kn	At 7,000 ft
JIMME	At 180 kn	At or above 5,000 ft
WOODI	No constraint	No constraint
BLGRS	At 180 kn	At or above 3,000 ft
CHRCL	No constraint	At 2,350 ft

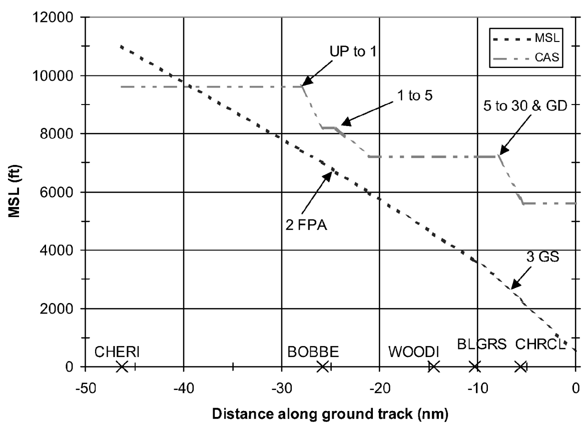

Fig. 4 Profiles for baseline procedure.

speed restrictions imposed by the Federal Aviation Regulations: less than 250 kn below 10,000 ft and less than 200 kn near the airport.

B. Simulator Sessions

The goals of the simulator sessions were to 1) determine the FMS parameters of the baseline procedure, 2) establish pilot procedures for both the CDA baseline procedure and the conventional approach procedure, 3) verify that the CDA procedure was robust to wind variations. The sessions were conducted in the 757/767 Engineering Simulator at Boeing Commercial Airplanes.

1. Speed and Altitude Constraints

Three variants of the CDA procedure were developed: slow, medium, and fast. In all three procedures, aircraft have the same initial conditions when they enter the TRACON and the same final approach speed. However, as their names suggest, the slow CDA corresponds to the procedure with the slowest average speed and the fast CDA corresponds to the procedure with the highest average speed. The procedures were all implemented with speed and altitude constraints at the six waypoints depicted in Fig. 2: CHERI, BOOBE, JIMME, WOODI, BLGRS, and CHRCL. As mentioned in Secs. IV.A.3 and IV.A.4, the desired vertical and speed profiles were achieved with speed and altitude constraints at these six waypoints. BOBBE is the point along the −2-deg FPA initial segment at an altitude of 7000 ft. This waypoint is approximately 26 n mile from the threshold of runway 17R. JIMME was added to ensure that the deceleration to 180 kn would be completed before the noise-sensitive area. This waypoint is located on the straight line between CHERI and WOODI and is 7 n mile before WOODI. There were no speed or altitude constraints at WOODI. The specific speed and altitude constraints are described hereafter.

The speed and altitude constraints for the slow CDA are listed in Table 2. As shown in Table 2, the aircraft slowed to 205 kn at BOBBE and then slowed to 180 kn at JIMME. This procedure corresponds most closely to the baseline procedure from the preliminary design phase in that the speed is constant over the noise-sensitive area near WOODI. The speed and altitude constraints for the medium CDA are listed in Table 3. As shown in Table 3, the aircraft was allowed to fly at its initial TRACON speed of 240 kn for longer than in the slow CDA, slowing to 205 kn at JIMME (vs at BOBBE in the slow CDA) and then only slowing to 180 kn at BLGRS (vs at JIMME in

Table 3 Speed and altitude constraints for VNAV (medium descent)

Waypoint	Speed constraint	Altitude constraint
CHERI	At 240 kn	At 11,000 ft
BOBBE	No constraint	No constraint
JIMME	At 205 kn	At or above 5,000 ft
WOODI	No constraint	No constraint
BLGRS	At 180 kn	At or above 3,000 ft
CHRCL	No constraint	At 2,350 ft

Table 4 Speed and altitude constraints for VNAV (fast descent)

Waypoint	Speed constraint	Altitude constraint
CHERI	At 240 kn	At 11,000 ft
BOBBE	No constraint	No constraint
JIMME	No constraint	At or above 5,000 ft
WOODI	No constraint	No constraint
BLGRS	At 180 kn	At or above 3,000 ft
CHRCL	No constraint	At 2,350 ft

the slow CDA). The speed and altitude constraints for the fast CDA are listed in Table 4. As shown in Table 4, the aircraft is allowed to fly at its initial TRACON speed of 240 kn until it was turning onto the final approach course, slowing from 240 kn to 180 kn at BLGRS.

2. Pilot Procedure

Pilot procedures were developed based on the speed and altitude constraints determined in Sec. IV.B.1. The CDA pilot procedure used both the lateral navigation (LNAV) and vertical navigation (VNAV) modes of the FMS. The conventional approach pilot procedure used the LNAV and either the vertical speed mode or the flight level change mode to follow ATC commands. The pilot procedures for the conventional approach and the slow CDA are described hereafter.

The conventional approach pilot procedure is as follows:

1) Select the "NOISE 1" arrival to 17R ILS before CHERI and close any route discontinuities between CHERI and CHRCL.

2) Use LNAV to fly the "NOISE 1" arrival routing.

3) Follow ATC descent clearances as normal.

4) Select "LOC" or "APP," as appropriate when cleared for the ILS 17R.

5) Fly a normal ILS approach to landing.

The slow CDA pilot procedure is as follows:

1) Select the "NOISE 1" arrival to 17R ILS before CHERI and close any route discontinuities between CHERI and CHRCL.

2) Select 240 KCAS when aircraft levels at CHERI.

3) Select 3000 ft in the mode control panel (MCP) and ensure that LNAV and VNAV are engaged when KSDF approach issues the clearance for the "NOISE 1" arrival and descent to 3000 ft MSL.

4) Select flap 1 as speed decays to 230 knots in calibrated airspeed (KCAS).

5) Select flap 5 when the aircraft reaches 180 KCAS (or at the flap 5 maneuvering speed if landing weight is greater than 300,000 lb).

6) Arm the approach when ATC clears the flight for the ILS 17R (after passing WOODI).

7) Maintain 180 KCAS to CHRCL unless ATC advises otherwise.

8) Fly a normal ILS approach to landing from CHRCL.

3. Robustness to Winds

The robustness of the procedure was evaluated by the use of values for the wind speed and direction for the planned test period, from the Boeing Global Weather database. Four different wind profiles were derived from the weather database: 1) no wind, 2) mean wind (with average wind speed), 3) two-sigma wind (average wind speed plus two times standard deviation in wind speed), and 4) head wind. The mean, two-sigma, and head wind profiles consisted of three constant wind speed and direction segments: from 11,000 to 7000 ft, from 7000 to 5000 ft, and below 5000 ft. The details of the wind speed

Table 5 Wind profiles used in simulator sessions

Altitude range	Mean wind, speed/heading	Two-sigma wind, speed/heading	Head wind, speed/heading
11,000 to 7,000 ft	16 kt/270°	40 kt/270°	16 kt/270°
7,000 to 5,000 ft	12 kt/269°	36 kt/269°	12 kt/269°
5,000 ft and below	9 kt/268°	30 kt/268°	15 kt/90°

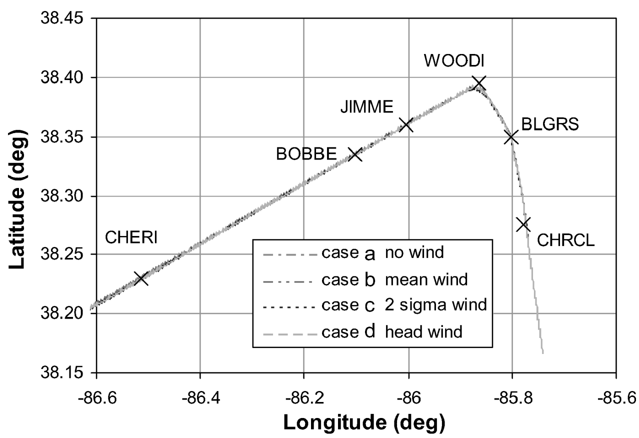

Fig. 5 Ground track for different wind conditions (simulator data).

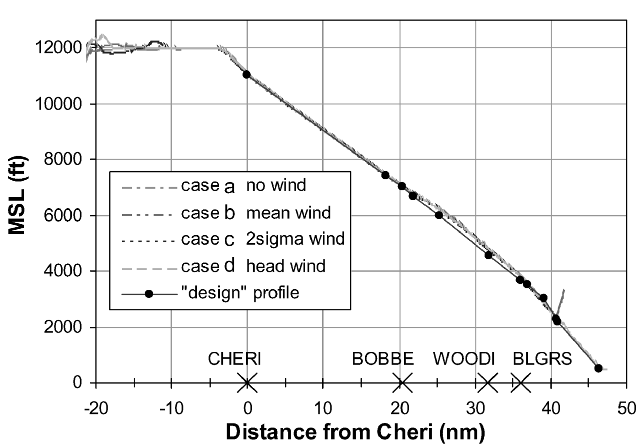

Fig. 6 Altitude vs distance from CHERI for different wind conditions.

and direction are listed in Table 5. The head wind profile had the same wind speed and direction as the mean wind profiles above 5000 ft; but below 5000 ft, the head wind profile had a 10-kn head wind along the track from WOODI to BLGRS and a 14-kn head wind from BLGRS to the threshold.

Figure 5 shows the ground tracks from the simulation. As Fig. 5 shows, the ground tracks are virtually indistinguishable, except for the slight variations at the turn near WOODI. However, these variations are relatively small. This indicated that the LNAV function provides very consistent performance and that the test aircraft would be able to follow the planned ground track for a wide range of wind conditions.

Figure 6 shows the altitude above MSL vs distance from CHERI for all four cases simulated. The design profile is the vertical profile shown in Fig. 4. For all simulator sessions, the LNAV and VNAV functions were engaged 5 to 10 n mile before. CHERI, at 12,000-ft altitude and 240-kn CAS. As shown in Fig. 6, the aircraft started the descent approximately 2 n mile before CHERI at 12,000 ft and followed the design profile throughout the descent with only small deviations (less than 250 ft) for a very short duration between BOBBE and WOODI.

Figure 7 shows plots of the CAS vs distance. The results show that, whereas the speed profiles followed the design speed profile very well, their deceleration was more gradual than the deceleration from

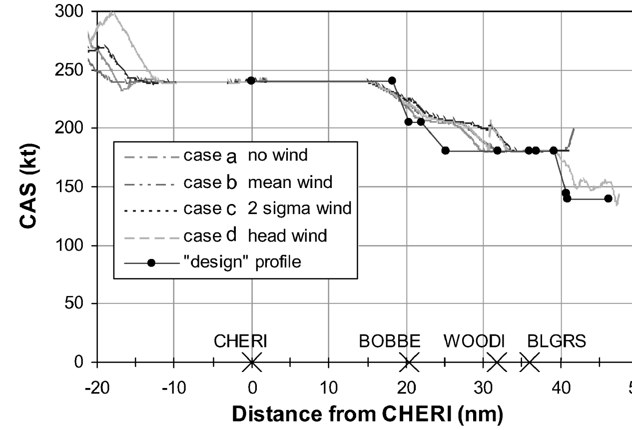

Fig. 7 CAS vs distance from CHERI for different wind conditions.

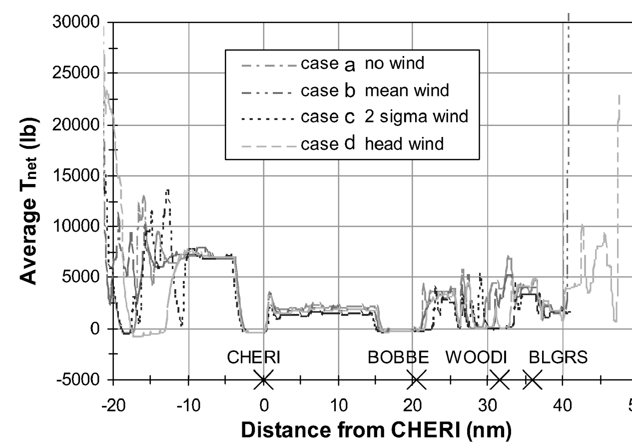

Fig. 8 Engine thrust vs distance from CHERI for different wind conditions.

240 kn to 205 kn of the design profile. Additionally, there were rapid changes in the CAS profile at specific points. The reasons are as follows: The slight increases in the CAS at 20 n mile and 31 n mile from CHERI were caused by the sudden change in the wind profile at 7000 and 5000 ft, respectively. The more significant change in the CAS for the head wind case at 30 n mile from CHERI was caused by the sudden change from a tail wind to a head wind at 5000 ft. Except for the first two-sigma wind case, all other cases showed very similar CAS profiles with the speed reducing to 180 kn at WOODI. For the first two-sigma wind case, the CAS remained at 200 kn at WOODI. It was believed that this was caused by the late extension of flap 5 (2 to 3 n mile) relative to the other cases. Also note that, except for the head wind case and the second two-sigma wind case, the simulation was discontinued after the aircraft intercepted the glide slope.

Figure 8 shows plots of the average thrust per engine-distance. The results show that the thrust was low (less than 2500 lb per engine) between CHERI and the start of deceleration from 240 kn and idle thrust during the deceleration from 240 to 205 kn. For the entire descent from CHERI until the ILS glide slope intercept near BLGRS, the thrust was typically well below 5000 lb per engine. This low level of engine thrust was consistent with the analysis conducted during preliminary design and had no significant effect on the noise on the ground.

V. Flight Demonstration Test

The flight demonstration test occurred during the two-week period from Monday, 28 October to Saturday, 9 November 2002. For safety reasons, the test was not performed on nights when the ceiling and visibility did not allow for visual clearances. Thus, no tests were conducted on 30 October and 2 November.

A. Experimental Protocol

Before departing from the West Coast for KSDF, the pilots of four to five 767 aircraft were given the pilot procedures summarized in Sec. IV.B.2, informed that their aircraft might be selected for the noise study, and told that the selected aircraft would be notified through the Aircraft Communications and Recording System (ACARS) to either use the conventional approach pilot procedure or the CDA pilot procedure. They were also told that if the procedure was not in the navigation database, they should manually program the FMS with the given waypoints. If the weather was satisfactory, two aircraft were selected for the test based on the estimated time of arrival after all of the aircraft were airborne.

The two test aircraft were typically separated by more than 20 min as they entered the KSDF airspace. Once inside the KSDF airspace, feeder controllers cleared the test aircraft for their respective arrival procedures. CDA aircraft were cleared for descent to 3000 ft, whereas conventional test aircraft were cleared to their normal altitudes at the discretion of the controllers. On leaving the feeder sector, the feeder controllers handed the test aircraft to the final approach controllers, who cleared the test aircraft for landing. When the weather permitted, controllers directed the two test aircraft to runway 17R and all other aircraft to runway 35R (in the opposite direction on the runway parallel to runway 17R). This maneuver is referred to as contraflow. By avoidance of the noise-sensitive areas, contraflow also ensured that the noise from nontest aircraft would not contaminate the noise measurements. On days when the wind conditions did not permit contraflow, the controllers instructed the two test aircraft to report when passing BOBBE, JIMME, and WOODI, so that their noise signatures could be clearly identified from the ground.

The noise measurement teams set up and took down the noise measurement equipment each night. Recording commenced after the test aircraft received their clearance for the NOISE 1 arrival (with pilot–controller communications monitored) and before they approached the measurement area. After the aircraft had passed over the measurement site and the noise had returned to ambient levels, the recording was terminated.

B. Noise Measurement Locations

Figure 9 shows the measurement sites along with the planned ground track of the test aircraft. The measurement locations were selected to ensure that noise recordings would be of the highest quality. All seven sites had flat terrain, an unobstructed view of the flight path, and were remote from other potential noise sources such as roadways and machinery. Sites P1, P2, and P3 were staffed by Boeing and MIT. Sites N1, N2, N3, and N4 were staffed by NASA. As shown, the measurement sites were either under or immediately adjacent to the ground track. Sites N1 and N4 were located under the flight path. Sites P1, P2, and P3 were placed on either side of the turn at WOODI. Sites N2 and N3 were placed to measure noise levels outside and inside of the turn. All seven locations were between 14 and 18 n mile from the airport.

C. Noise Measurement Equipment

The test equipment at each site consisted of a digital audiotape recorder and two Bruel and Kjaer Type 4192 one-half-in. 4-ft pole-mounted microphones spaced 10 ft apart. To minimize directivity effects, the microphones were positioned at a grazing incidence angle and installed 1.2 m above the local ground plane. The microphones were calibrated before and after the test.

VI. Noise Results and Analysis

A. Noise Data Processing and Reduction

Table 6 summarizes the availability of the noise data. In Table 6, A denotes the days at each site for which data are available and NA denotes the days for which data are not available. On 29 October, 31 October, and 9 November, a number of data recorders malfunctioned. On 9 November, there were pilot errors, navigation database error, and strong temperature inversion.

The data for each event were postprocessed into $\frac{1}{3}$-octave band sound pressure level (SPL) time histories. Figure 10 shows examples of the resulting time history: A-weighted peak noise level time histories for the two microphones at site N1 for the flights on the morning of 31 October. A 60-s time interval is shown starting at a common reference time of 300 s. This reference time corresponds to 0153:14 for the CDA procedure and 0201:47 for the conventional procedure. As shown, the peak noise during the CDA was 5 dBA lower than the peak noise during the conventional approach. Similar noise reductions were observed for other sites and days. This is supported by the analysis in the next section. For reference, a 3-dB difference represents a 50% reduction in acoustic energy and is noticeably different to the average human ear, whereas a reduction of 10 dB for example, would be perceived as a 50% reduction in noise.

Table 6 Availability of noise data[a]

Date	N4	P1	N3	N2	P2	P3	N1
29 Oct.	NA	A	NA	A	A	NA	A
31 Oct.	NA	A	NA	A	A	A	A
1 Nov.	A	A	A	A	A	A	A
5 Nov.	A	A	A	A	A	A	A
6 Nov.	A	A	A	A	A	A	A
7 Nov.	A	A	A	A	A	A	A
8 Nov.	NA	NA	NA	NA	NA	NA	NA
9 Nov.	A	A	NA	A	A	A	A

[a]A, available and NA, not available.

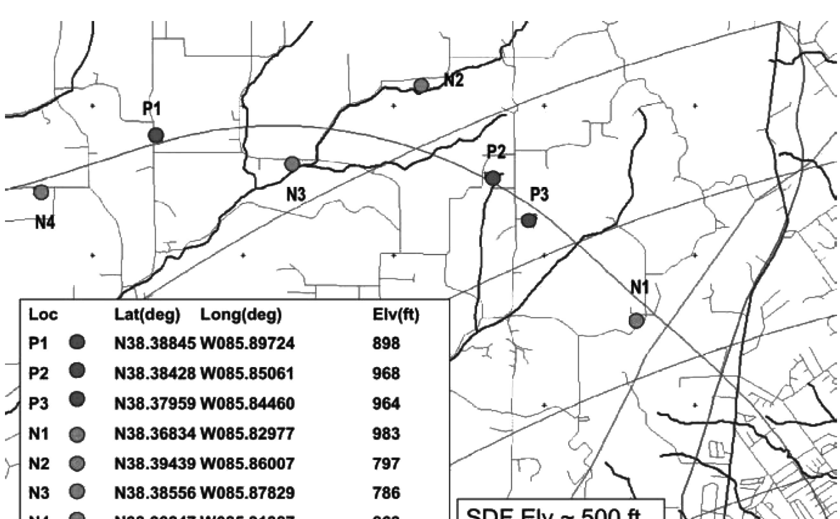

Fig. 9 Location of measurement sites (P1–P3 and N1–N4) in Floyds Knobs, Indiana.

Table 7 Two-factor ANOVA table

Variable	N4	P1	N3	N2	P2	P3	N1
			CDA vs conventional				
Df	1,4	1,5	1,3	1,5	1,5	1,5	1,5
F	4.70	9.87	10.90	5.68	19.13	19.36	8.57
P	0.096	0.026	0.046	0.063	0.007	0.007	0.033
			Different test days				
Df	4,4	5,5	3,3	5,5	5,5	5,5	5,5
F	0.24	0.97	1.29	0.64	2.09	1.14	0.38
P	0.902	0.515	0.420	0.680	0.219	0.446	0.846

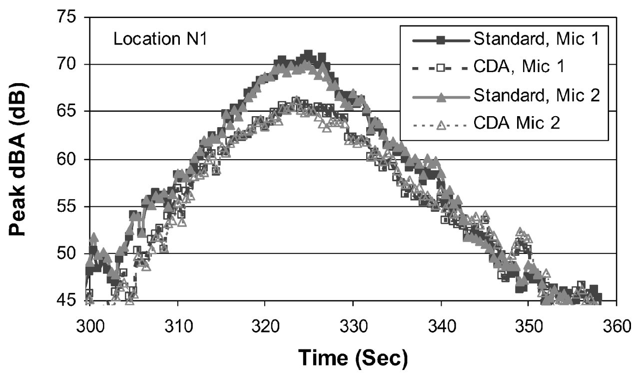

Fig. 10 Time histories of noise at site N1.

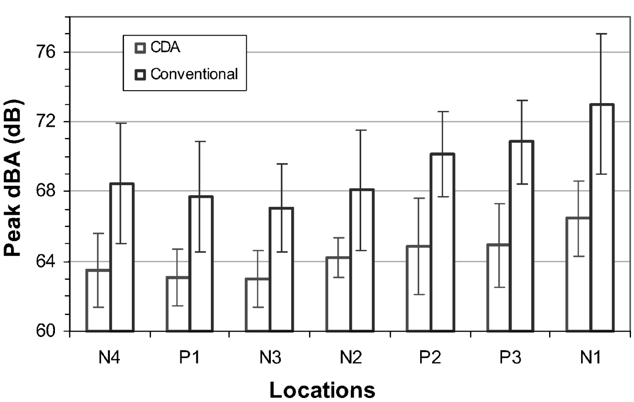

Fig. 11 Statistics of the noise observed at Floyds Knobs, Indiana.

B. Noise Data Analysis

At each measurement site the A-weighted peak noise levels for a given event, as measured by the two microphones, were averaged. This average noise level was then reported as the peak noise level for that event. As was the case at site N1 on 31 October (Fig. 10), there was very good agreement between microphones; thus, no significant error was introduced by the use of the average. Figure 11 shows the mean values of the peak dBA levels for the CDA approach and the conventional approach at each site. In Fig. 11, the measurement sites are listed in descending order of their distance from the runway threshold. The error bars represent the standard deviations of the peak noise levels. It can be seen from Fig. 11 that, at most measurement sites, the standard deviation of the peak dBA for the CDA was much lower than the corresponding standard deviation for the conventional approach. This result is not surprising, given that the CDA was designed to have little variation in aircraft performance and, thus, noise impact, whereas the conventional approach was more susceptible to variations in controller technique. The average noise reduction at the seven measurement sites was between 3.9 and 6.5 dBA.

A two-factor analysis of variance (ANOVA) was performed to determine whether the noise reduction observed at each site was statistically significant and to determine whether there were any statistically significant differences across test days. Table 7 shows the results of the ANOVA. As shown in Table 7, the reduction in peak dBA was statistically significant at five of the seven measurement sites. A difference is considered statistically significant when the value of P is less than -0.05. The fact that two of the seven sites failed the test for statistical significance was unexpected given the consistent trend in the noise reduction across all measurements sites (as can be seen in Fig. 11) and the finding that there were no statistically significant different differences across test days. One possible explanation is that the ANOVA assumption that the variance of all samples is equal is invalid because the noise level for the conventional approach has a significantly larger variation.

Table 8 Two-sample *t*-test assuming unequal variances, CDA vs conventional

Variable	N4	P1	N3	N2	P2	P3	N1
Df	7	7	8	6	10	10	8
T	2.75	3.17	3.10	2.63	3.52	4.26	3.53
P	0.014	0.008	0.007	0.020	0.003	0.001	0.004

Table 9 KSDF average daily airport operations 2 June 1999–12 June 1999

Aircraft	Day arrivals	Night arrivals	Day departures	Night departures
737-700	19.2	15.5	18.6	11.2
727-100	17.1	13.7	16.5	10.0
737-200	14.9	12.0	14.4	8.7
757-200	12.8	10.3	12.4	7.5
767-300	9.6	7.7	9.3	5.6
DC8	8.5	6.9	8.3	5.0
747	6.4	5.2	6.2	3.7
737-300	5.3	4.3	5.2	3.1
Lear	4.3	3.4	4.1	2.5
C130	4.3	3.4	4.1	2.5
MD80	4.3	3.4	4.1	2.5
SF340	2.1	1.7	2.1	1.2

To account for this, a two-sample t-test was performed on the data at each site. This test, which does not require the variances to be equal, involves a one-factor variance analysis similar to the ANOVA.[17] The factor considered in this test was the approach (CDA vs conventional approach). In this test, data for the CDA approach and data for the conventional approach were considered to be samples from two distinct groups, each with a different variance (or error). The results of the one-tail test are shown in Table 8. As shown by the very low values of P (less than 0.05), the noise reduction was statistically significant at all measurement sites.

C. Implications

The results in the preceding section suggest that adoption of the CDA for daily operation will reduce noise in communities surrounding airports. Additionally, the distances where these reductions were measured also suggest that much of the benefit will accrue in communities that are further from airports than those typically considered, that is, beyond the 65 DNL noise contour.

To determine the reduction in noise impact that would occur if all aircraft arriving at KSDF were required to fly the CDA, the cumulative noise impact with the current procedure and with the CDA procedure was determined with the FAA's Integrated Noise Model (INM) version 6.0c. The type and number of aircraft operations used in the INM were derived from actual runway use data collected during the noise monitoring program conducted in 1999 (Ref. 18). The breakdown of daytime and nighttime departures and arrivals are listed in Table 9 by aircraft type. The runway use in terms of percentage of the total operations, averaged over the 11 days of the noise monitoring program, is shown in Table 10. Note that some noisier aircraft types were replaced with certified stage 3 aircraft types to better reflect the current and future fleet mix. The departure and arrival ground tracks used in the INM correspond to those shown in the noise contour plots of the Part 150 study conducted in 2001 (Ref. 19). All operations for a particular runway were split evenly between two to four ground tracks for commercial aircraft operations. General aviation operations were also included.

The resulting changes may be seen by comparison of the noise contours in Fig. 12 (the noise contours when all aircraft perform the conventional approach and the noise contours when all aircraft perform the CDA). As shown in Fig. 12, the noise benefits are felt most in areas immediately to the north of the airport, between the runways and the Ohio River. (See also Fig. 1.) These areas include many noise-sensitive facilities, such as the University of Louisville, preschools, schools, religious facilities, and historic districts.[19] Historically, these areas have been the origin of numerous noise complaints due to arrival and landing aircraft on runways 17R/L. Table 11 shows that when the CDA approach was used instead of the conventional ILS approach, the total number of people impacted by noise between 50 and 60 DNL levels was reduced by 12,165.

Table 11 also shows that adoption of the CDA reduces the noise contour area by an average of 7% for DNL levels between 50 and 60 dB. Although this analysis was tailored specifically for Louisville Airport operation and Louisville population distribution, the reduction in the area exposed to noise suggests that in more densely populated cities such as New York or San Francisco, the reduction in the number of people impacted by noise would be greater.

VII. Aircraft Performance Results and Analysis

A. Data Processing and Reduction

Aircraft performance data for four test flights were retrieved from the flight data recording system of the corresponding aircraft at the first maintenance event after the flight test. Because of coordination issues within UPS, no flight performance data were retrieved from the other aircraft. Data were retrieved for the CDA on 29 and 31 October, and the conventional approach on 5 and 7 November. Although it is unfortunate that the full data set was not available, the data that were available helped to verify the sources of the noise benefits of the CDA and to illustrate how existing FMS VNAV and auto-throttle logic (in instances where pilots are slow in extending flaps) can negatively impact performance. For ease of exposition, only the data for the CDA on 31 October and the conventional approach on 5 November are shown.

B. Data Analysis

1. Sources of CDA Noise Benefits

Figure 13 shows the altitude vs distance for the CDA on 31 October and the conventional approach on 5 November. As shown, the aircraft that performed the conventional approach descended sooner and, thus, flew lower over the community. In fact, the aircraft that performed the CDA was approximately 1500 ft higher in the noise-sensitive area near WOODI. As was discussed in Sec. IV.A this is one of two reasons why the conventional approach is noisier than the CDA.

The other reason is that the source itself (the aircraft) was quieter. Figure 14 shows the corrected revolutions per minute (RPM) (average for both engines) vs distance. It can be seen from Fig. 14 that between WOODI and BLGRS, the engines were operating at a higher RPM during the conventional approach relative to the CDA.

Table 11 Comparison of noise impact at KSDF for conventional approach and CDA

	All conventional approach		All CDA	
DNL	Population	Square miles	Population	Square miles
50	229592	91.73	219789	86.89
55	115691	43.89	113329	41.07
60	44085	21.34	44014	19.58
65	8079	9.30	8743	8.57
70	103	3.69	103	3.47
75	0	1.40	0	1.40
80	0	0.52	0	0.51
85	0	0.16	0	0.15

Table 10 Louisville average runway use 2 June 1999–12 June 1999

Arrival/Departure type	Total operations	17L	17R	35L	35R	11	29
Day arrivals	106.7	83.6%	8.8%	4.1%	3.3%	0.1%	0.1%
Night arrivals	85.9	35.2%	4.6%	32.8%	27.0%	0.0%	0.4%
Day departures	103.2	52.5%	38.8%	2.8%	5.8%	0.0%	0.1%
Night departures	62.2	47.9%	41.8%	5.0%	5.3%	0.0%	0.0%

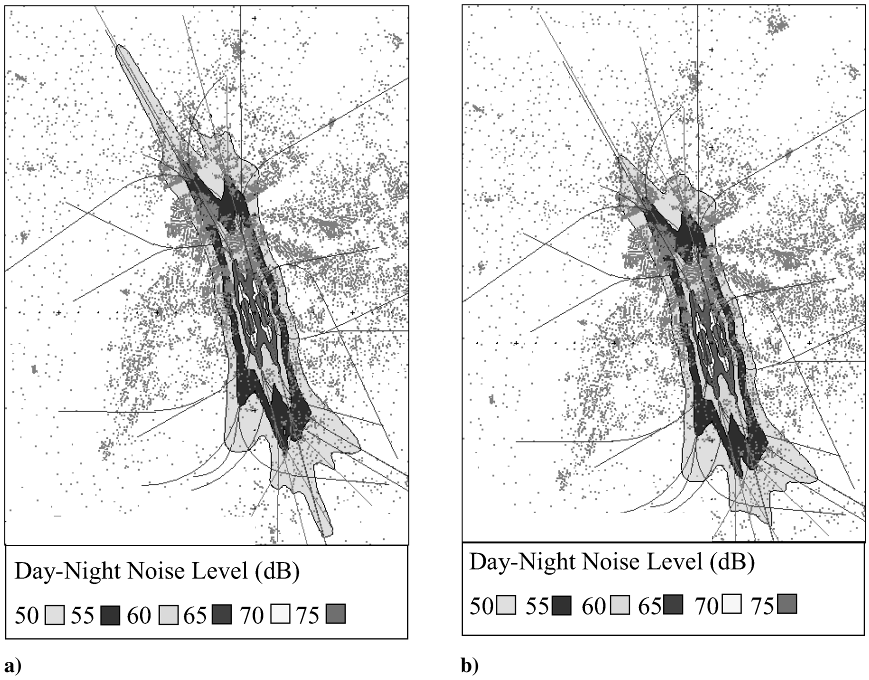

Fig. 12 Noise contours with a) conventional approach and b) CDA at KSDF.

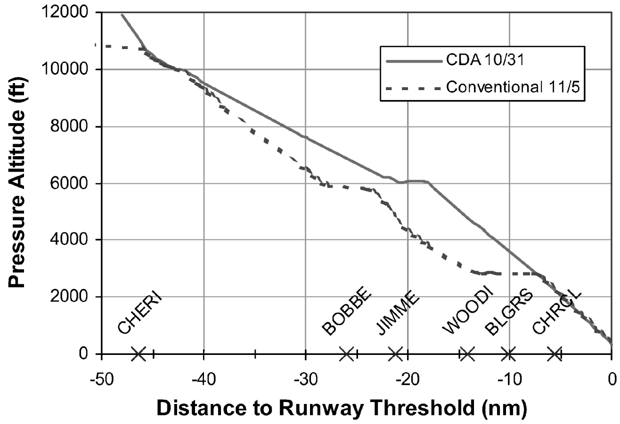

Fig. 13 Altitude vs distance to threshold.

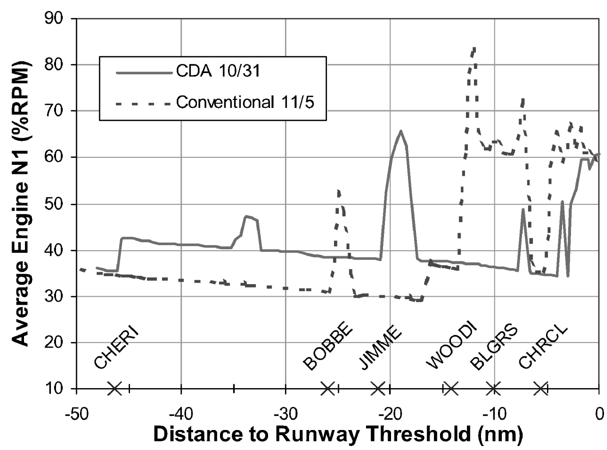

Fig. 14 Corrected RPM vs distance to threshold.

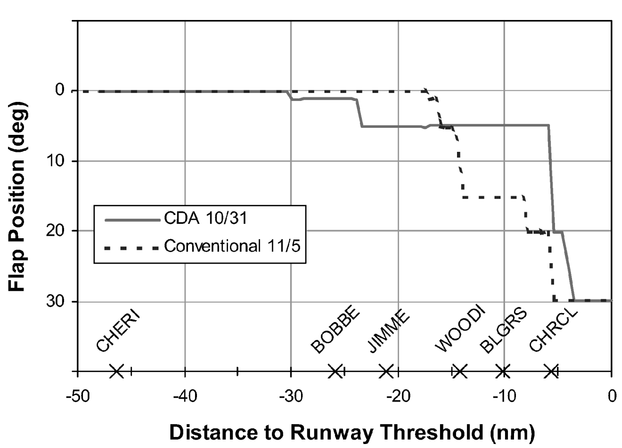

Fig. 15 Flap vs distance to runway threshold.

Whereas it is also true that the thrust is higher for the CDA between CHERI and JIMME, that difference is small, when compared to the difference between WOODI and CHRLC, in terms of both thrust and the noise produced. Thus, the engine noise was louder during the conventional approach. This was also the reason why the CDA approach consumed less fuel than the conventional approach. Analysis of the flight recorder data revealed that the aircraft that flew the CDA consumed 400–500 lb of fuel less than the aircraft that flew the standard approach. This finding was further supported by an analysis of RPM data (with the appropriate conversion to fuel flow) from the simulator sessions.

The other major source noise component is airframe noise. Figure 15 shows the flap position vs distance to runway threshold. As Fig. 15 shows, the flap was extended to higher flap settings at a later time, delayed during the CDA relative to the conventional approach, resulting in lower aerodynamic drag and lower airframe noise. While the aircraft was over the noise-sensitive area, the flap setting during the CDA was 5 deg. The corresponding flap setting during the conventional approach was 15 deg, a significant difference in terms of drag.

2. *Limitation of FMS VNAV and auto-throttle logic*

As can be seen in Fig. 16a, the aircraft performing the CDA had four distinct thrust transients (significant but short duration increases in thrust) and a level-flight segment between JIMME and WOODI. To understand how and why these occurred, the altitude, speed, and

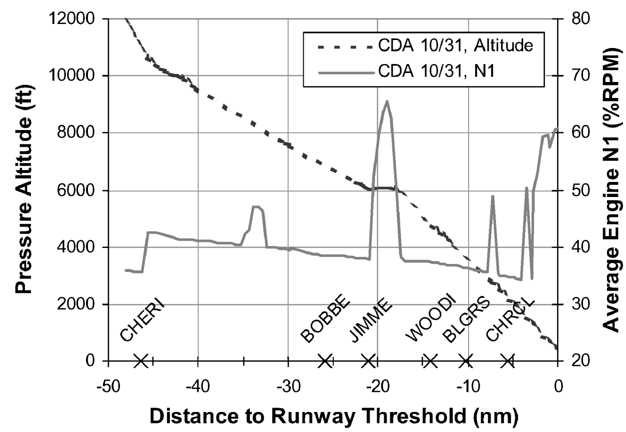

Fig. 16a CDA altitude and average engine N1 vs distance to runway threshold.

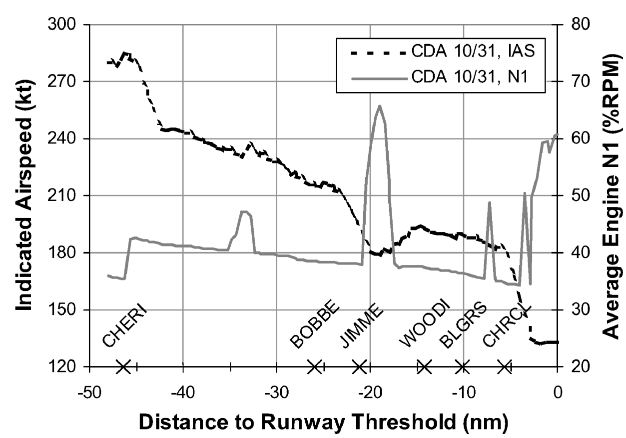

Fig. 16b CDA indicated airspeed and average engine N1 vs distance to runway threshold.

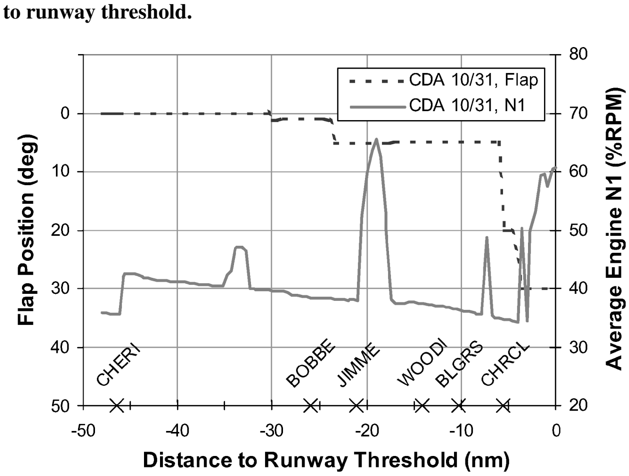

Fig. 16c CDA average engine N1 and flap vs distance to runway threshold.

configuration profiles were examined chronologically to determine how the VNAV and auto-throttle managed the control functions of the aircraft to satisfy the speed and altitude constraints of the CDA procedure.

As shown in Fig. 16a, the aircraft descended from its cruise altitude (not shown) to the first altitude constraint at CHERI (11,000 ft) at idle power. Although VNAV typically computes an idle descent path from the cruise altitude to the first waypoint with an altitude constraint,[20] the relatively high descent rate may have been the result of an unaccounted for tailwind, the aircraft being handed over from the center to the TRACON at a higher than normal altitude, or the pilot being late in initiating the procedure. Whatever the cause, the aircraft met the altitude constraint at CHERI, but the speed constraint of 240 kn was reached sometime after the aircraft had passed CHERI (Fig. 16b). This result was not surprising given that, in the existing VNAV logic, the altitude constraint is always given preference over the speed constraint.[20] That is, when both constraints cannot be met, VNAV will sacrifice the speed constraint to meet the altitude constraint, provided that speed limitations such as the maximum allowable speed or stall speed are not violated.

On reaching CHERI, VNAV slowed the rate of descent to reduce the speed to 240 kn and increased the thrust to a thrust level (which was noticeably higher than idle thrust but still relatively low overall) that it believed would enable a steady deceleration to the speed and altitude constraints at BOBBE (205 kn, 7000 ft). However, as can be seen in Fig. 16b, a thrust transient occurred when the aircraft reached 230 kn. One likely explanation for this transient is that the auto-throttle, predicting that the aircraft would decelerate below the minimum maneuver speed for the clean configuration and knowing that the flap had not yet been extended to flap 1, increased the thrust to prevent the aircraft from decelerating further. This hypothesis is consistent with the following facts: 1) The aircraft was 10 kn below the maximum allowable speed in the flap 1 configuration. 2) The maneuver speed in the clean configuration for the 767-300 at the recorded weight of 253,000 lb is 210 kn (Ref. 21). 3) No thrust transient occurred when the speed returned to 230 kn for a second time (after the flap had been extended to the flap 5 configuration).

Unfortunately, the auto-throttle provided too much thrust, resulting in an increase in the speed of the aircraft. In response to this increase in speed, VNAV slowed the rate of descent to arrest the acceleration and to provide sufficient time to compute the thrust and FPA required to make a steady deceleration to the speed and altitude target at BOBBE. As was the case before CHERI, VNAV gave preference to the altitude constraint, and, thus, the aircraft was at a higher than desired speed when it passed above BOBBE.

On reaching BOBBE, VNAV then computed the thrust and FPA to meet the speed constraints at JIMME and BLGRS and the altitude constraint at CHRCL. Note that the altitude constraints at JIMME and BLRGS where the aircraft only had to be at or above specified altitudes) were not binding because there were many possible flight paths that crossed these locations above the altitudes that were specified. As a result, VNAV was free to choose a flight path to satisfy the speed constraint at JIMME. As shown in Fig. 16b, the aircraft did indeed meet the speed constraint of 180 kn at JIMME, at which point the auto-throttle responded by increasing the thrust to prevent the speed from decreasing any further. As was seen earlier, the thrust supplied was disproportionate to the increase in drag because the aircraft actually started ot accelerate. The response of VNAV, as shown in Fig. 16a, was to slow the rate of descent, resulting in the level flight segment. This level flight segment arrested the acceleration, but, during that time, the aircraft had flown sufficiently far that it was not possible to decelerate to meet the speed constraint of 180 kn at BLGRS. In fact, the speed at BLGRS was approximately 190 kn, which implied that the VNAV failed to meet the speed constraint by 10 kn.

Figure 16b also shows that a third, brief thrust transient occurred just before the aircraft reaches BLGRS and 180 kn for the second time. There are two likely explanations for this thrust transient. First, the thrust transient was needed to maintain the speed at 180 kn until the aircraft reached CHRCL. Second, as was the case for the first thrust transient, the auto-throttle commanded an increase in thrust to prevent the speed from dropping below the flap 5 minimum maneuver speed of 170 kn (Ref. 21).

The fourth thrust transient occurred during the transition from flap 20 to 30. It appears that the auto-throttle increased the thrust in anticipation that the aircraft would be at its final approach speed when the flap extension was completed, but then had to reduce the thrust to enable further deceleration once it became clear that the aircraft was 20 kn above the desired speed.

C. Implications

Just as the results in Sec. VII.B illustrate the utility of the FMS VNAV and the auto-throttle in executing the CDA, they also illustrate how pilot delay, FMS VNAV logic, and auto-throttle logic, individually or collectively, produce undesirable behavior.

First, when the pilot is late in initiating the procedure, the aircraft will descend to meet the altitude constraint at the first waypoint and then slow its rate of descent after it has passed the waypoint to decelerate to the desired speed. The reason for this is that VNAV gives preference to the altitude constraint over the speed constraint when both constraints cannot be satisfied. Thus, instead of achieving the desired constant FPA descent, the aircraft will actually perform a staged descent, albeit with very short (near level flight) segments.

Second, when the pilot is late in extending the flap or the aircraft reaches a speed target, the auto-throttle provides more thrust than is required to simply prevent the aircraft from decelerating further. This results from the difficulty in controlling a system (such as the turbofan engine) with significant inertia and time lags during spool up and spool down. Thus, the aircraft will begin to accelerate.

Third, VNAV responds to excessive thrust transients by slowing the rate of descent to arrest the resulting acceleration. If the thrust transient is very large (as was the case during the CDA described in the preceding section) VNAV will create a level flight segment. Once this maneuver occurs, the aircraft will then be above the desired flight path. In cases where there are both speed and altitude constraints at the next waypoint, the aircraft then has to descend rapidly to meet the altitude target, thus increasing the speed and requiring an additional shallower flight segment to arrest the acceleration. If the subsequent waypoint also has both speed and altitude constraints, the sequence of events is repeated (albeit without thrust transients and, therefore, at lower amplitude).

The preceding discussion suggests that efforts should be made, individually and collectively, to 1) reduce pilot delay, 2) create CDA procedures that are robust to pilot delay, and 3) modify the logic of FMS VNAV, the auto-throttle, and mode control panel modes such as the FPA mode so that their responses are in line with the overall objective.

One possible solution to mitigate the effect of pilot delay is to provide pilots with cues to help them initiate the procedure and extend the flaps and gear in a timely manner. Determination of the appropriate cues and automation is a topic of on-going research. Researchers at National Aerospace Laboratory have proposed that a flap/gear cue be displayed in the speed tape of the flight director.[12] The cue looks like a speed bug, and its position (on the speed tape) provides the speed at which the pilot should extend the flaps and gear. In this approach, the pilot simply executes the procedure by following the cue. If there is a delay in the pilot response, then the onboard algorithm/automation recomputes the new position of the cue. This strategy of exercising closed-loop control on the speed to correct pilot variability ensures that the aircraft meets speed and altitude targets independent of pilot performance for earlier targets.

Researchers at NASA Langley Research Center have proposed the use of an energy indicator in conjunction with a flap/gear annunciation (calculated before the start of the descent) to help pilots determine when to extend the flap.[22] The energy indicator is displayed in the flight director between the low-energy bar and the high-energy bar. The annunciation is represented by characters such as “FL 1” (for flap 1), “G/D” (for gear down), or “TOD” (for top of descent) and is displayed on the top of the trajectory in the navigation/map display. In this approach, the pilot executes the procedure by initiating the procedure or extending the flaps and gear as suggested by the annunciations. In addition, the pilot uses the energy indicator to make decisions such as extending the speed brake when the energy is too high or delaying a flap extension when the energy is too low. The energy indicator can also work in a closed-loop fashion if the onboard automation/algorithm recomputes and updates the flap and gear annunciations along the descent.

Researchers at MIT have proposed that the pilot use a series of gates (or checkpoints) where the gates are discrete points along the desired speed profile. Each gate consists of an altitude and a speed. The pilot would also be provided with a flap schedule (precomputed before the start of the descent based on a nominal trajectory) that allows the aircraft to achieve the target. The gates serve as a feedback mechanism to help the aircraft follow the desired speed profile. Specifically, each time the aircraft crosses a gate, the pilot determines the deviation in the aircraft speed from the gate's speed, and, based on this deviation, the pilot makes small adjustments to the flap schedule so that the aircraft can meet the next gate and eventually the target. For example, when a gate is crossed and the aircraft speed is a few knots faster than desired, the pilot would extend the next flap a bit earlier than suggested, or, conversely, when the speed is a few knots lower than desired, the pilot would delay extending the next flap. This approach leverages on the pilot's experience and familiarity with the aircraft dynamics to make small adjustments to the flap schedule and, hence, does not require onboard automation/ algorithm.

However, delay in the pilot response is inevitable during the course of an approach. Thus, the CDA procedure must be designed to be robust to pilot delay. In this flight demonstration test, the CDA procedure (in terms of the desired constant FPAs) was somewhat robust to pilot variability because the at or above altitude constraints at JIMME and BLGRS provided VNAV with the flexibility required to determine the altitudes at the speed constraints, thereby preventing the level flight segments that would have occurred had a binding altitude constraint been placed at these waypoints. Despite this preemption in avoiding thrust transients, the specified constant speed segment of 180 kn between JIMME and BLGRS induced a thrust transient because the auto-throttle must supply thrust to maintain the speed. The thrust transient, in turn, caused VNAV to create a level flight segment to arrest the acceleration due to the thrust transient. This observation suggests that, in the future design of the CDA procedure, the point where the constant speed segment starts should be placed at a high altitude (further away from noise-sensitive locations), or the constant speed segment should be removed altogether and replaced with speed constraints along the descent.

Further improvement in the performance of the CDA can be attained by modification of the auto-throttle logic. This is supported by the fact that the thrust transients and the resulting acceleration and level flight segment observed in the flight demonstration test occurred because the auto-throttle supplied disproportionate thrust. Better auto-throttle logic requires improved modeling of the nonlinear dynamics of the gas-turbine engine spool-up and spool-down. An enhancement in the modeling would enable graceful and proportionate changes in the thrust in response to the circumstances faced during a typical descent.

Finally, the procedure can be flown by the use of the FPA mode of the MCP. The existing FPA mode operates in an open-loop fashion in that it maintains the aircraft FPA relative to the wind rather than to the ground. If the functionality of this mode were expanded so that the FPA was ground-referenced (as is the case when the aircraft is following the ILS glide slope) then the flight path would be constant regardless of winds. The global positioning system can be utilized to provide the information on the position of the aircraft to the FMS. This information would enable the FMS to plan a constant FPA from the top of descent to the threshold and execute the descent without reverting to level flight. To meet speed constraints and accommodate pilot variability, the intent information of the CDA procedure can be integrated into VNAV and auto-throttle computation so that the auto-throttle can better anticipate when the minimum and maximum allowable speed in each flap setting would be reached and, thereby, exercise graceful controls of the thrust.

VIII. Conclusions

The national airspace system is complex. Thus, solutions to specific problems must be developed within the context of the entire system. To that end, a design methodology based on the principles of system analysis was introduced to account for all of the factors relevant to the design of a noise abatement approach procedure for KSDF. In this design methodology (an extension of the framework introduced by Clarke[6]), analytical- and simulation-based evaluations and the expertise and processes of an integrated design team were used in a structured search of the design space to determine a feasible solution. The result was a CDA procedure for KSDF.

The utility of this procedure was evaluated through a flight demonstration test where the noise impact of the CDA and the conventional approach were measured at seven different locations in Floyds Knobs, Indiana. The results proved that the CDA provides consistent noise reduction. There were statistically significant differences at all seven measurement sites between the CDA and the conventional approach over the testing period. In fact, the observed reductions of between 3.9 and 6.5 dBA are very significant given the fact that a 3-dBA difference represents a 50% reduction in acoustic energy and is noticeable to the human ear. Given the subsequent analysis showing that the 50 DNL contour would shrink by 7% if all aircraft were to perform the CDA, it is clear that adoption of the CDA at major airports would provide much needed relief for residents in communities near airports.

The flight demonstration test also proved useful in identifying how pilot delay, FMS VNAV logic, and auto-throttle logic, individually or collectively, create undesirable behavior. Specifically, analysis of aircraft flight recorder data showed how these factors created a number of thrust transients and a significant, unplanned level flight segment. The analysis provided insights into the design of the FMS VNAV logic and auto-throttle logic, thereby providing a basis for changes that could make their responses more in line with the overall objective of a smooth, continuous descent, and confirmed that a number of solutions that have been proposed, for example, providing pilots with cues for flap and gear extension, will be very helpful in preventing undesirable behavior.

The results clearly indicate that the design methodology, the design tools, and current flight management systems are sufficiently advanced that near-term procedures could be developed for all terminal areas. Given the high cost to certify and upgrade FMSs, this is a critical enabling observation. However, one of the key issues preventing widespread implementation of these procedures is the inability of air traffic controllers to predict the future trajectory of aircraft with enough accuracy and confidence that they would use these procedures during periods of high-density traffic. At the most basic level, controllers use speed as a surrogate for distance. That is, to separate and sequence aircraft, controllers frequently place a series of aircraft at the same speed with the desired separation during the initial segments of the approach. From that point onward, they keep the aircraft at the commanded speed and use the time interval between successive crossings of target waypoints to confirm that the desired separation is being maintained. This suggests that an appropriate solution for the system would be to provide a tool that will translate the predicted trajectory of each aircraft into a form that controllers can easily monitor and use to predict future separation.

Given public concern about aircraft noise and the projected growth in air traffic, it is critical that further research be done to develop the controller tools and the modifications to FMSs, that will enable widespread implementation of these procedures.

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STOL PROGENITORS: THE TECHNOLOGY PATH TO A LARGE STOL AIRCRAFT AND THE C-17

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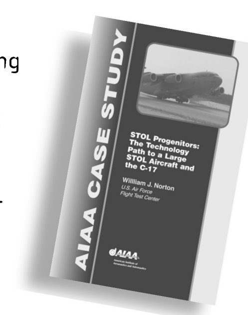

This case study presents the history and technical achievements in developing the Boeing C-17, the largest STOL transport aircraft. It examines STOL technology and predecessor aircraft, but focuses on the United States Air Force's Advanced Medium STOL Transport (AMST) program and its YC-14 and YC-15 demonstrators.

The book describes every step of the process including the needs requirements, technological approaches, design and operation implications, proposals and winning designs, alterations, innovations, cost constraints, construction, and flight testing. STOL aircraft that flew before and after the C-17 are also discussed to illustrate the continuing evolution of the technology.

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