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Development, design, and flight test evaluation of a continuous descent approach procedure for nighttime operation at Louisville International Airport

prepared by
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Report of the PARTNER Continuous Descent Approach Development Team

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Development, Design, and Flight Test Evaluation of a Continuous Descent Approach Procedure for Nighttime Operation at Louisville International Airport

Report of the PARTNER CDA Development Team

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Abstract

The design and flight test of a Continuous Descent Approach (CDA) procedure for regular nighttime operation at Louisville International Airport are described in this report. Results of the analyses of aircraft and FMS performance indicate that this procedure is operationally feasible and that aircraft may be vectored and spaced at intermediate altitudes where aircraft are outside the terminal area without compromising the separation between aircraft on final approach. Results of the analyses of economic and environmental benefits indicate that the CDA provides significant time, fuel burn, emissions and noise impact reductions.

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Nomenclature

ACARS	Aircraft Communication Addressing and Reporting System
AGL	Above Ground Level
ARIES	Airborne Research Integrated Experiments System
ARTS	Automated Radar Terminal System
ATC	Air Traffic Control
AWLEE	waypoint corresponding to 37° 59' 6N 85° 40' 36W
B&K	Brüel & Kjær
BLGRS	waypoint corresponding to 38° 20' 55N 85° 48' 21W
CAL_f	final microphone calibration levels
CAL_i	initial microphone calibration levels
CDA	Continuous Descent Approach
CDU	Control Display Unit
CHERI	waypoint corresponding to 38° 13' 49N 86° 30' 54W
CHRCL	waypoint corresponding to 38° 16' 29N 85° 46' 47W
CO	carbon monoxide
CRDNL	waypoint corresponding to 38° 3' 55N 85° 42' 18W
DAT	Digital Audio Tape
DBA	decibels adjusted
df	degrees of freedom
DNL	Day Night Average Noise Level
EADI	Electronic Attitude Director Indicator
ENL	waypoint corresponding to 38° 25' 12N 89° 9' 32W
FAF	Final Approach Fix
FDR	Flight Data Recorder
FLCH	Flight level Change
FLPxx	Flap Waypoint
FMS	Flight Management System(s)
FMS-PIP	Flight Management System(s) – Product Improvement Package
HC	hydrocarbons
IAF	Initial Approach Fix
ICAO	International Civil Aviation Organization
IFD	Integration Flight Deck
IIU	Louisville VORTAC
ILS	Instrument Landing System
INM	Integrated Noise Model
INTxx	Intercept Waypoint
IRU	Inertial Reference Unit
KSDF	Louisville International Airport-Standiford Field
L&D	Larson and Davis
Leq	Equivalent Noise Levels
LNAV	Lateral Navigation
LNG	Low Noise Guidance
LTO	landing and takeoff
MAIZE	waypoint corresponding to 38° 28' 28N 86° 0' 57W
MCP	Mode Control Panel
MIT	Massachusetts Institute of Technology
MSL	Mean Sea Level
N1 speed	engine fan speed power setting

NASA	National Aeronautics and Space Administration
ND	Navigation Display
NOAA	National Oceanic and Atmospheric Administration
Nox	Nitrogen Oxide(s)
NPD	Noise-Power-Distance
NTSC	National Transportation Systems Center
PARTNER	Partnership for Air Transportation Noise and Emissions Reduction
PENTO	waypoint corresponding to 38° 19' 43N 87° 17' 17W
PW	Pratt and Whitney
PXV	waypoint corresponding to 37° 55' 42N 87° 45' 45W
R-3704	Fort Knox restricted area
RAA	Regional Airline Association
RNAV	Area Navigation
RR	Rolls Royce
SACKO	waypoint corresponding to 38° 15' 27N 86° 43' 32W
SAE	society of automotive engineers
SEL	sound exposure levels
STD	standard
T/D	Thrust-to-drag ratio
THR-HOLD	autothrottle hold
TOD	top-of-descent
TRACON	Terminal Radar Approach Control
TRNxx	Turn Waypoint
UPS	Company formerly known as “United Parcel Service”
UTC	Co-ordinated Universal Time, formerly Greenwich Mean Time
VNAV	Vertical Navigation
VNAV-PTH	Vertical Navigation Path
VNAV-SPD	Vertical Navigation Speed
VORTAC	Very high frequency Omnidirectional Range station and/or TACtical air navigation
WOODY:	waypoint corresponding to 38° 23' 42N 85° 51' 48W
ZARDA:	waypoint corresponding to 38° 22' 38N 88° 12' 23W

1 Introduction

The environmental impact of aircraft operations has been an impediment to the expansion of airports in the US. Past work has shown that significant reductions in noise and emissions can be achieved through changes in aircraft operations that are enabled by advanced flight management systems.

From the perspective of arrivals, operational changes include, but are not limited to, keeping arriving aircraft at their cruise altitude for longer than during conventional approaches and then having them make a continuous descent to the runway at idle or near idle thrust with no level flight segments. Procedures with these features are commonly referred to as continuous descent approach (CDA) procedures.

1.1 Background and Motivation

In 2002, Clarke et al. designed and flight-tested a CDA procedure for UPS-operated Boeing B767-300 aircraft at the end of the nightly UPS arrival bank at Louisville International Airport (KSDF) [Clarke et al. 2004]. For background information on KSDF, including a description of the nighttime operation of UPS at KSDF, the noise sensitive areas surrounding KSDF, and the objectives of the main system stakeholders (i.e., the community, the air traffic controllers, and the pilots), the reader is referred to [Clarke et al. 2004].

The CDA 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. This noise reduction is significant given that a 3-dB difference represents a twofold 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.

Although operational changes were limited to the Terminal Radar Approach control (TRACON) surrounding KSDF, the CDA procedure was also shown to reduce the flight time in the terminal area of the Boeing B767-300 aircraft used in the test by up to 100 seconds relative to the nominal approach procedure, and the corresponding fuel burn by up to 500 pounds [Clarke et al. 2004]. In a subsequent analysis by Lee, the CDA procedure was shown to reduce the NO_x produced below 3,000 ft by approximately 30% [Lee 2005].

Several issues surrounding the widespread implementation of CDA procedures were also identified during the 2002 flight test. For example, analysis of aircraft performance data revealed that pilot delay, in combination with auto-throttle and flight management system (FMS) logic could result in deviations from the desired trajectory. However, all the issues that were identified could be resolved through procedural changes, and without changes to the FMS.

The researchers concluded that CDA procedures could be developed for permanent use at night and that further work should be initiated towards that end.

1.2 Research Objective

To further the development and implementation of CDA procedures, the Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) undertook the development of a CDA procedure that could be used every night by UPS aircraft destined to runways 17R or 35L at KSDF from origins in the Western United States. The procedure features a continuous descent with the power set at or near idle from cruise altitude (well outside the TRACON) to the runway. A flight test was conducted to demonstrate the consistency of the procedure; to measure the reductions in noise, emissions, fuel burn and time; and to obtain the data necessary for approval to use the procedure on a regular basis.

The development process followed the systems design methodology outlined in [Clarke et al. 2004] using the following goals and functional requirements that were synthesized from these goals.

1.2.1 Goals

- Develop a CDA procedure for UPS aircraft destined to runways 17R or 35L from West coast origins.

- Ensure that the procedure can be performed within the current air traffic control system and with current cockpit technology.

- Conduct flight test to evaluate the feasibility and benefits of the procedure in terms of the following measures: operator acceptance/workload, aircraft/FMS performance, flight time, fuel consumption, emissions, and noise impact.

- Obtain sufficient data (from airborne and ground systems) to prove the feasibility of implementation.

- Make recommendations for future procedure development and widespread implementation of CDA

1.2.2 Functional Requirements

- Applicable to UPS-operated, FMS-equipped B757-200 and B767-300 aircraft arriving KSDF from the West coast and landing on either runway 17R or 35L descending continuously with thrust set to at or near idle from cruise altitude to touchdown

- Operated without violating the required aircraft separation minima, without disrupting other traffic in and surrounding KSDF, within the terms outlined in the current/proposed letters of agreements among ATC centers and TRACONs, within the capability of the participating aircraft, within the capability of the operators, with sufficient safety and efficiency in all weather conditions and traffic situations.

- Minimize the workload on operators and the flight time, fuel consumption, emissions and noise impact of the landing.

- Minimize the adverse effects (e.g., thrust transients, level flights, excessive usage of spoilers) of weather, pilot delay, and limitations of the FMS.

1.3 Structure of Report

The details of the procedure development process are presented in this report, along with the results of the flight test and the ensuing analyses. The structure of the report is as follows. In section 2, the procedure development process and resulting procedure are discussed in detail. In section 3, and overview of the flight test and data available from the flight test are presented. In section 4, the analysis of the pilot acceptance/workload is presented. In section 5, the analysis of the FMS performance is presented. In section 6, the analysis of the aircraft performance is presented. In section 7, the analysis of the flight time and fuel consumption is presented. In section 8, the analysis of the emissions is presented. In section 9, the analysis of the noise impact is presented. In section 10, the analysis of aircraft separation is presented. In section 11, a brief summary of the results and findings is provided.

2 Procedure Design and Development

The process of developing the CDA procedure consisted of 1) designing a baseline procedure using high-fidelity simulators; 2) refining the baseline procedure through further simulator studies and beta-test flights conducted by UPS management pilots; 3) conducting a Monte-Carlo analysis to determine the appropriate initial separation between aircraft to ensure safe operation.

2.1 Preliminary Design

The procedure used in the 2002 flight test (which was designed for aircraft destined to runway 17R) provided the basis for several new procedures that met the functional requirements. The new procedures were developed by evaluating the effects on aircraft performance and environmental impacts of modifications to the horizontal, vertical and speed profiles (defined using waypoints with speed and altitude constraints) under different wind conditions; while simultaneously constraining the procedure to meet basic operational requirements (e.g., the flap schedule doesn’t violate the placard and minimum maneuvering speeds, and provides adequate deceleration). An arrival chart and crew procedures were also developed.

The first step in the design process was to develop candidate routings for landings to the North (to runway 35L) and to the South (to runway 17R). Arrivals from the West currently utilize the CHERI TWO arrival (See Figure 2-1) which places aircraft on a direct heading from the CHERI waypoint to the Louisville VORTAC (IIU). At some point along this direct routing, depending on the traffic levels, the TRACON controller begins to issue altitude, heading and speed clearances to vector aircraft to runway 17R (See Figure 2-2) or runway 35L (See Figure 2-3).

FMS arrivals require a continuous lateral path from cruise to the point where the aircraft is established on the final approach glide slope. During the 2002 flight test, an FMS RNAV route was designed for approaches to runway 17R. The first segment of the routing was from the waypoint CHERI (the existing TRACON entry fix for aircraft arriving from the West) to a new waypoint WOODY that was placed outside the Initial Approach Fix (IAF) for the ILS approach to runway 17R. This new waypoint provided a 30-degree intercept angle to the ILS localizer at the IAF waypoint (BLGRS).

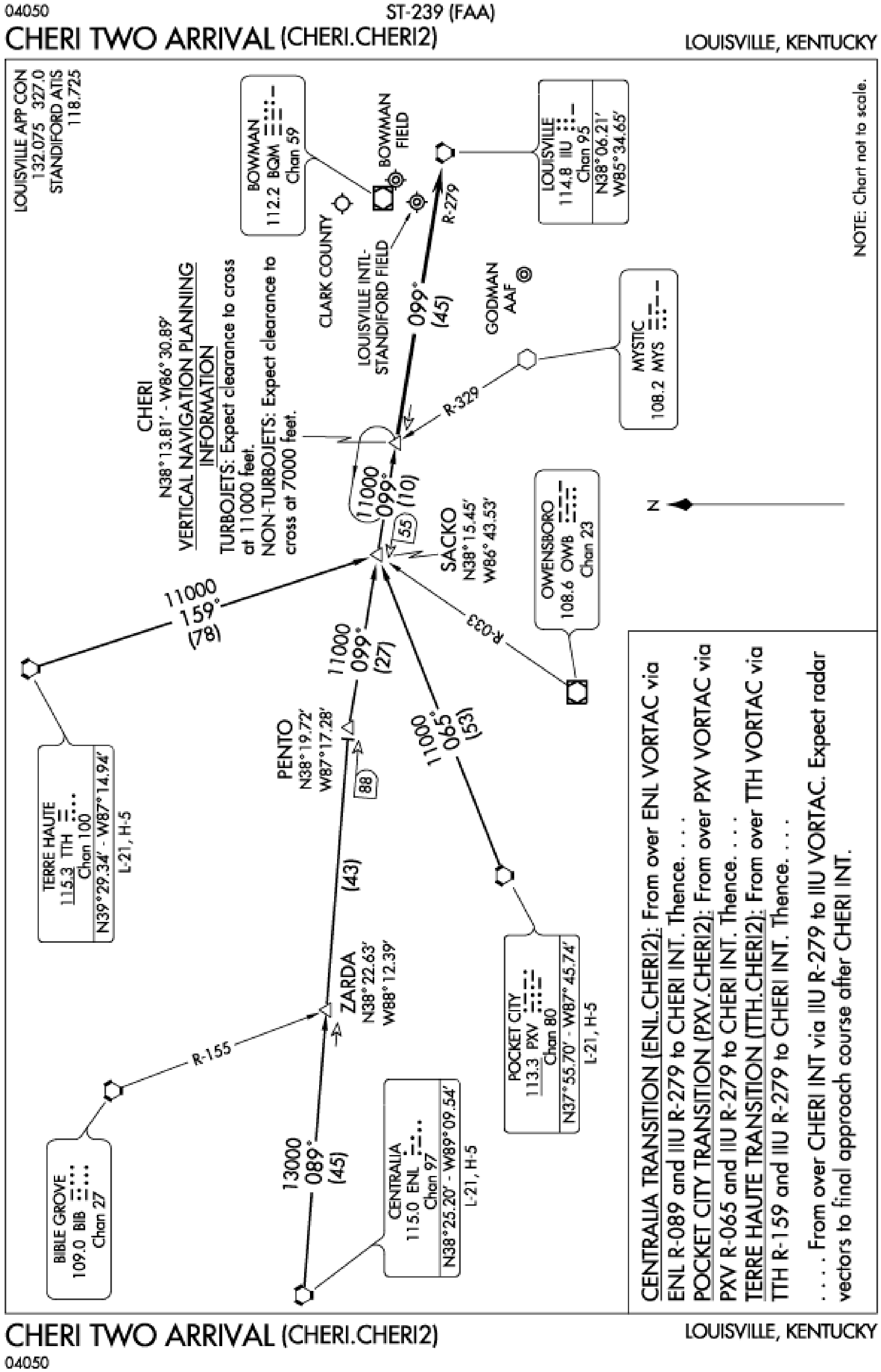


Figure 2-1: Current CHERI TWO arrival into Louisville

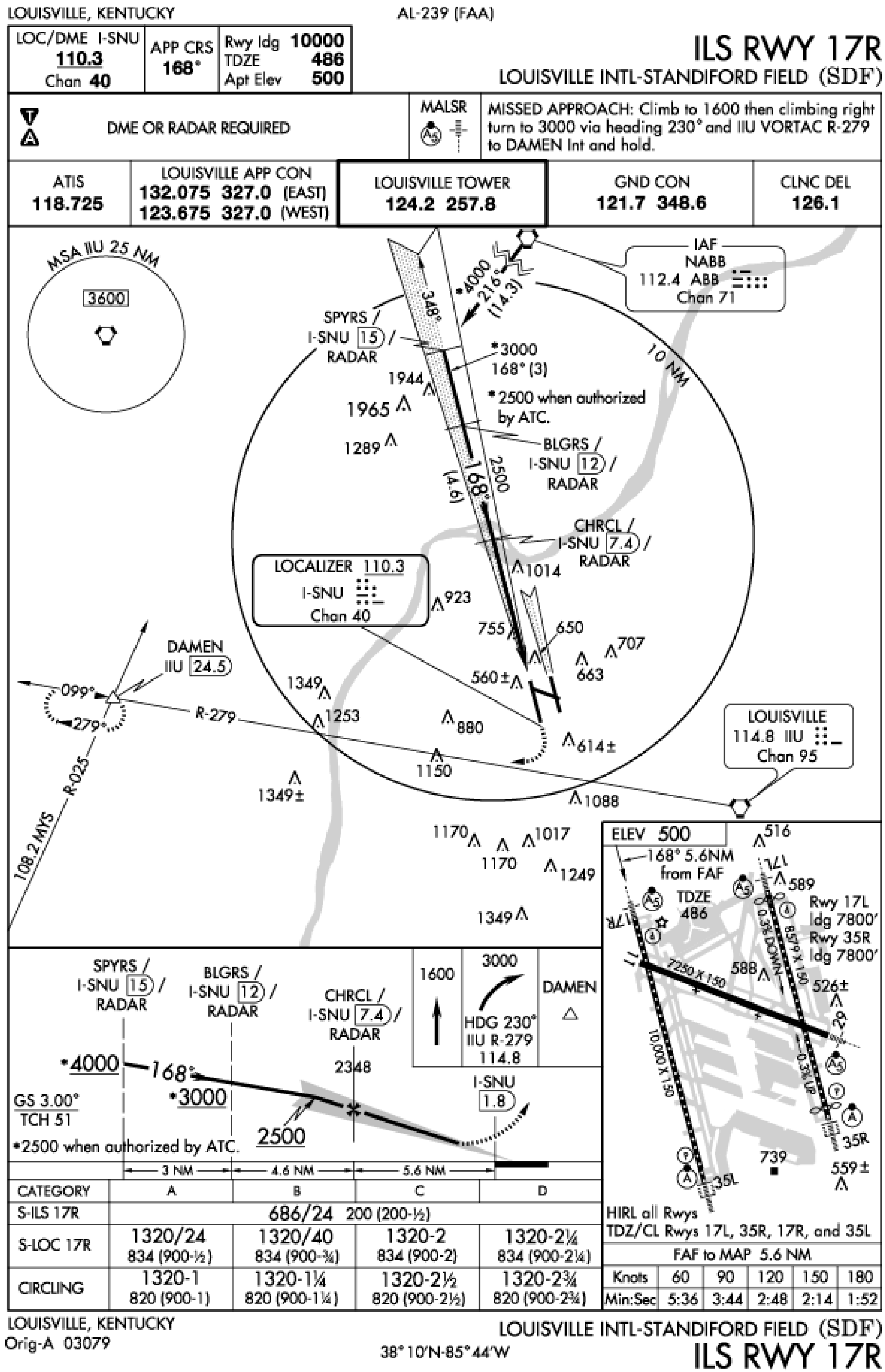


Figure 2-2: ILS approach to runway 17R.

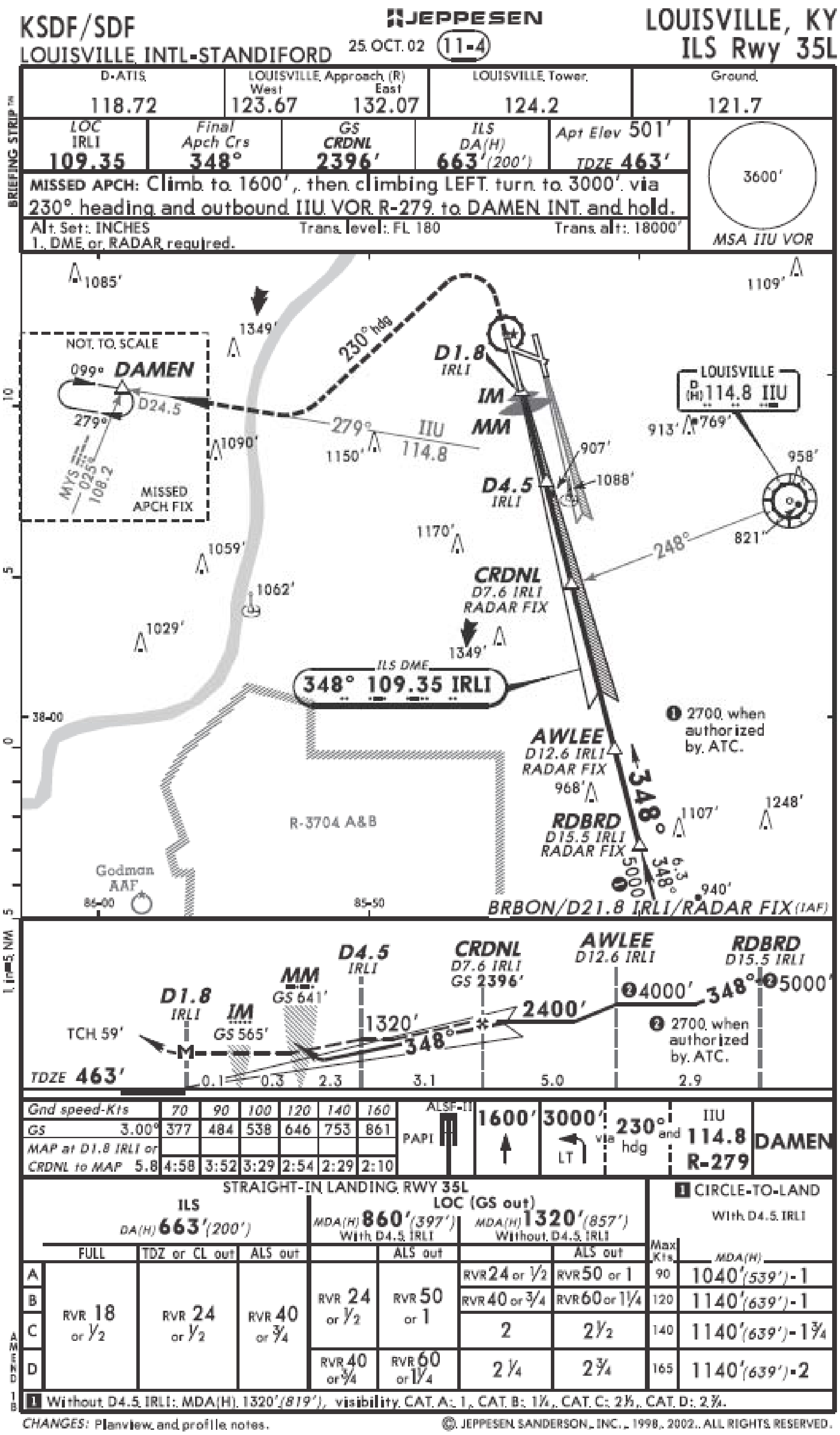


Figure 2-3: ILS approach to runway 35L with R-3704 restricted area

While this routing worked well, the path distance from CHERI to the runway was longer than a typical vectored approach, where aircraft would in a large percentage of the cases fly directly toward BLGRS with a final vector to intercept the localizer between BLGRS and CHRCL. Thus, a revised routing, consisting of a single leg between CHERI and BLGRS, was selected as the candidate RNAV route for the CDA to 17R.

The FMS routing to runway 35L proved more difficult to design. The Fort Knox restricted area (R-3704) is located just to the left of the inbound course to 35L, as shown in Figure 2-4. Aircraft arriving from the West must be kept clear of this area as they are being vectored by ATC onto the 35L localizer. An RNAV route from CHERI to the AWLEE fix, with a 90-degree turn at AWLEE, would encroach on the restricted area. An alternate path, using the northeast corner of the protected area and a waypoint positioned between AWLEE and CRDNL on the 35L approach, was selected for the 35L RNAV routing.

A similar geometry was designed for the routing to 17R to provide consistency in the routings and procedures for both 17R and 35L arrivals. A waypoint was created prior to BLGRS with a turn to a waypoint on the final approach course that is between BLGRS and CHRCL. The resulting geometry is also shown in Figure 2-4.

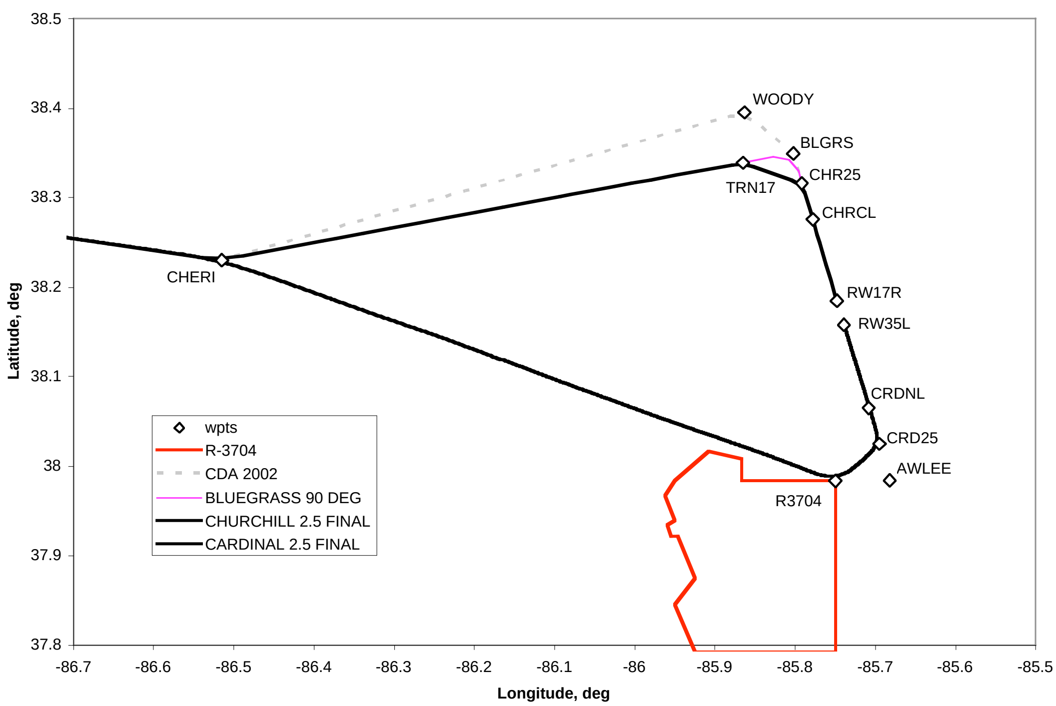


Figure 2-4: Lateral routing alternatives

With the lateral routings defined, the next step was to define the vertical trajectory. As the name implies, the CDA is characterized by a continuously descending vertical trajectory. The performance-based Flight Management Systems on the UPS B757-200 and B767-300 aircraft are well suited for building and flying such a trajectory. Given a continuous lateral path, the FMS will build a vertical path, starting from the end of the route working backwards to the airplane location at cruise altitude. The FMS will attempt to build idle descent segments whenever possible, however, insertion of crossing conditions will force the FMS to use non-idle path segments as needed to meet the constraints. The internal logic used for the construction of descent segments is dependent on the type and software version of the FMS. The UPS aircraft targeted for the CDA procedures consisted of a mix of B757-200 aircraft with an older ‘200K’ FMS, and B767-300 aircraft with a newer ‘Pegasus’ FMS. Although they are fundamentally the same, the minor differences between these systems presented additional challenges in designing the VNAV procedures. However, those challenges were not significant enough to warrant further exposition.

The primary method to control the vertical trajectory using VNAV is to place altitude and airspeed crossing constraints at the waypoints along the route. As a minimum, the final waypoint of the trajectory must have a fixed altitude and airspeed target. The desired end condition for the CDA profiles in this test is a location on final approach suitable for capture of the ILS localizer and glide slope. The natural point for this would be the Final Approach Fix (FAF) for the runway. The altitude target for this waypoint would be the altitude of the glide slope at that location. Airspeed would be a typical initial approach speed for jet transport aircraft. The navigation database in the FMS has pre-stored ILS approach entries that contain the waypoints on the approach with associated crossing altitudes and speeds. Because normal flight procedures include loading the appropriate FMS ILS approach, the ILS-specified crossing conditions at the FAF were used as the end point for the CDA.

The arrival options were evaluated through simulation studies in the NASA Langley Integration Flight Deck (IFD) cockpit simulator. This simulator, illustrated in Figure 2-5, is a high-fidelity cockpit simulator of the NASA ARIES B757-200 research aircraft. The B757-200 simulator at NASA Langley has an interim version of the FMS, referred to as the ‘Product Improvement Package’ or ‘FMS-PIP’. The key features of the simulator include full six degree of freedom equations of motion, complete avionics hardware including Mode Control Panel (MCP), Electronic Attitude Director Indicator (EADI), Navigation Display (ND), and dual Control Display Units (CDU) connected to the FMC-PIP (see Figure 2-6 for a depiction of the EADI and ND).

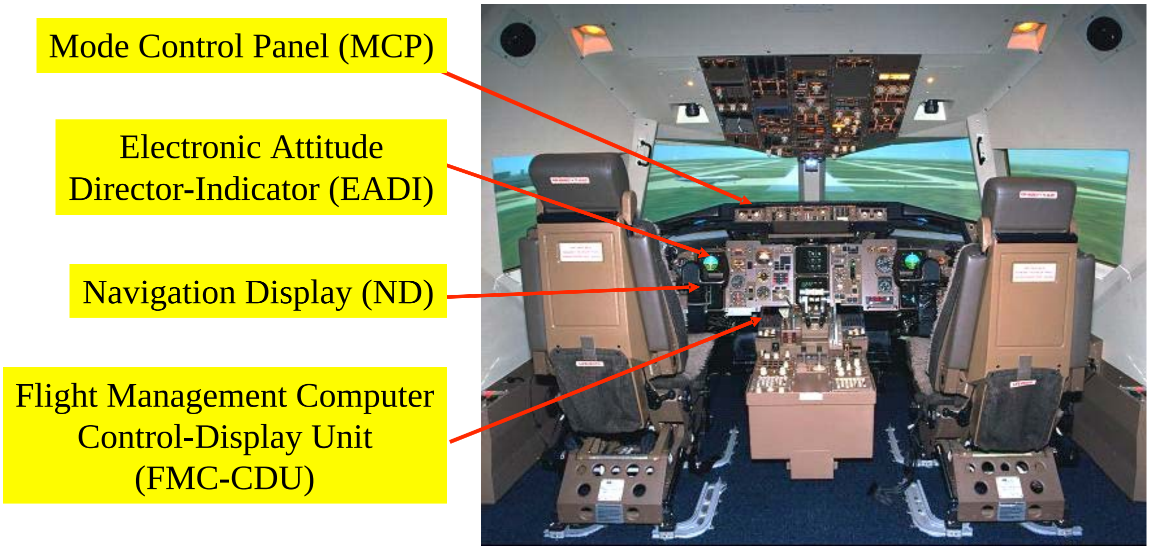


Figure 2-5: B757-200 integration flight deck simulator at NASA Langley

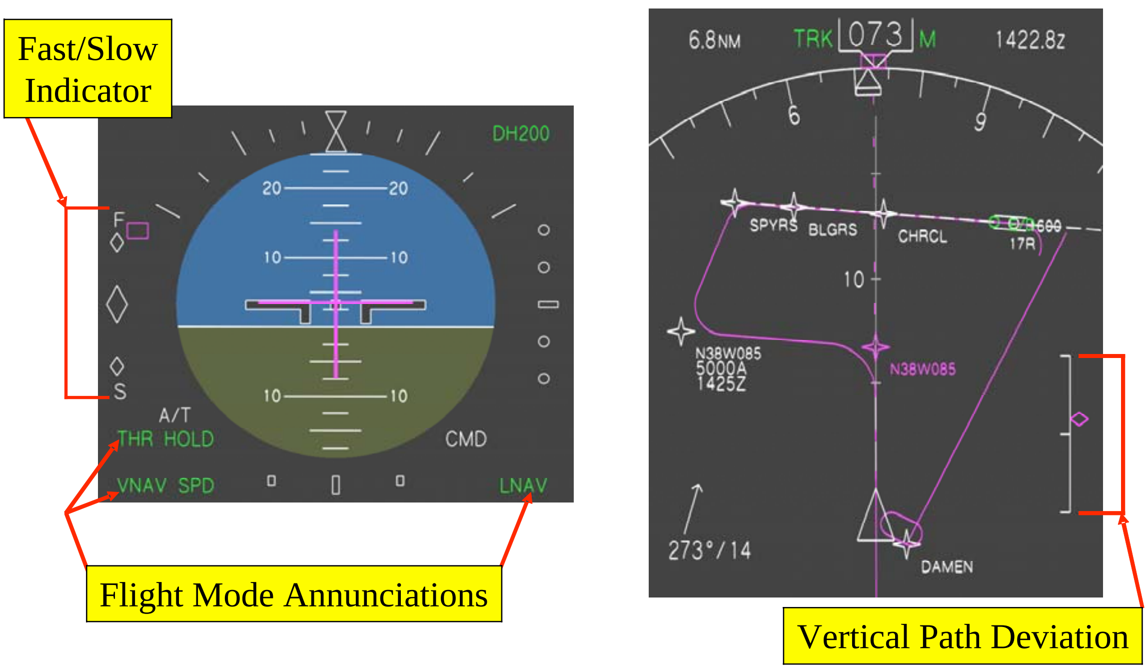


Figure 2-6: Standard displays in B757-200 simulator at NASA Langley

A test matrix of possible crossing restrictions along the routing to 17R was developed to test VNAV performance. These options are listed in Table 2-1.

Table 2-1: Candidate waypoint constraints

Name	Waypoints	Restrictions	Comments
CHRCL	CHERI	---/-----	Default conditions for FMS
	BLGRS	---/-----	FMS slows to 240 at 10000í
	CHRCL	170/2350	Idle thrust to CHRCL
BLGRS	CHERI	---/-----	Glide slope intercept at BLGRS
	BLGRS	190/3750	FMS slows to 240 at 10000’
	CHRCL	170/2350	Idle thrust to BLGRS
CHERI	CHERI	240/11000	2 deg descent from CHERI to BLGRS
	BLGRS	190/3750	Provides consistent slow down to 240
	CHRCL	170/2350	Thrust needed after CHERI
CHERI+10	CHERI	---/-----	3 deg descent from CHERI+10 to BLGRS
	CHERI+10	240/11000	Provides consistent slow down to 240
	BLGRS	190/3750	Near-idle thrust to BLGRS
	CHRCL	170/2350	

Some results from the simulation tests using the waypoint constraint conditions listed in Table 2-1 are shown in Figure 2-7. As can be seen, all of the altitude profiles exhibited the desired continuous descent characteristics. The CHRCL and BLGRS test conditions provided an idle descent with a deceleration leg just prior to the first constrained waypoint. The CHERI condition added the typical crossing constraints of 11000 feet and 240 knots at CHERI. This resulted in a non-idle descent after CHERI. Moving the 11000/240 constraint 10 miles inside of CHERI provided a near-idle descent all the way to BLGRS. The addition of the constraints at CHERI or CHERI+10, however, resulted in the loss of the deceleration segment prior to the next waypoint with a crossing speed constraint. As a result, the airplane could not achieve the crossing speed constraint at BLGRS or CHRCL without deployment of speed brake. This situation was deemed unacceptable for normal operations.

A second series of simulations was performed to evaluate the need for a restriction prior to the glide slope intercept location. For these tests, the 35L arrivals were flown using the routing shown in Figure 2-4. The runs were performed with and without an at-or-above altitude restriction of 4000 feet (4000A) at the R3704 waypoint. The resulting vertical trajectories are shown in Figure 2-8. Both trajectories were easily flown, with minimal throttle activity, and without the need for speed brake even with significant tailwinds.

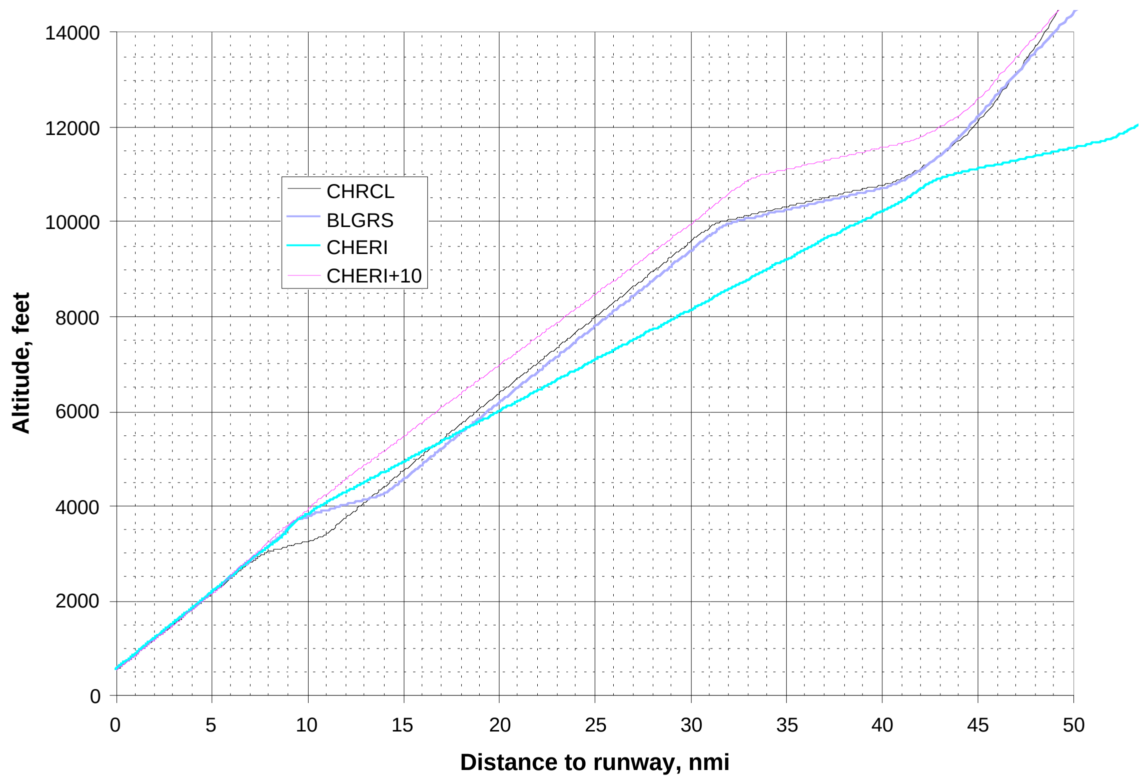


Figure 2-7: Comparison of altitude profiles

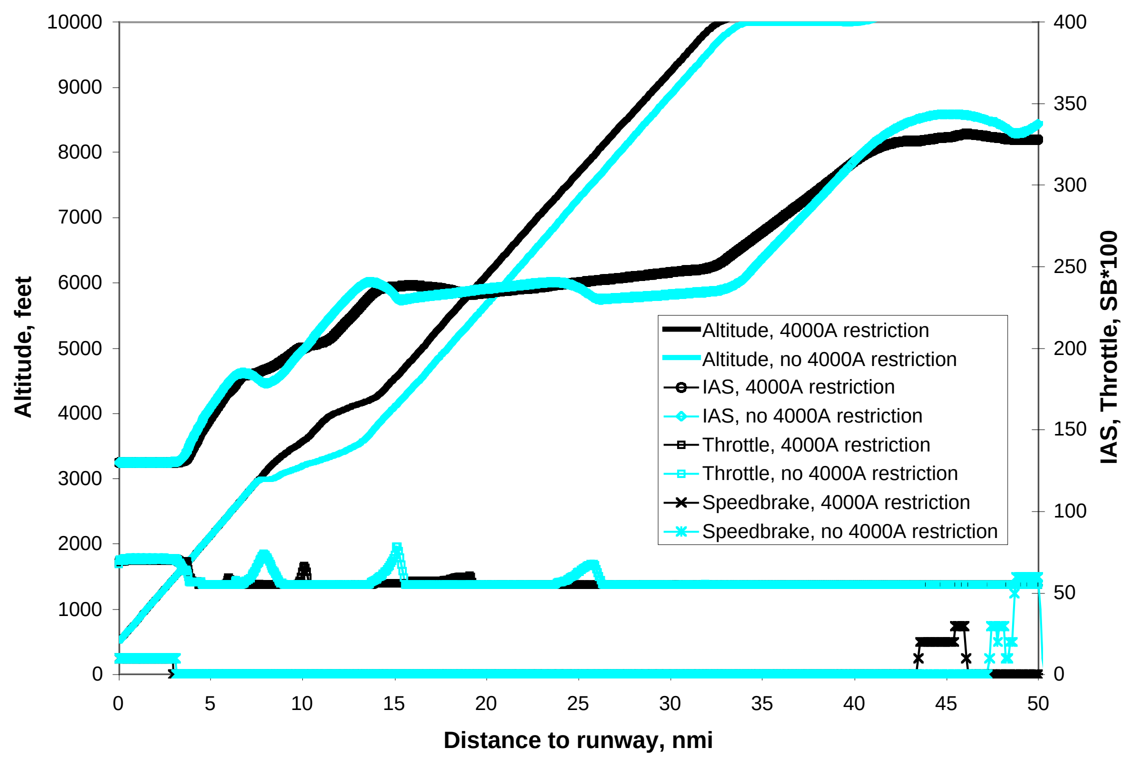


Figure 2-8: Trajectory comparison for 35L

The trajectory data were processed using an experimental version of the FAA Integrated Noise Model (INM) computer program to estimate the noise under the flight path. This version of the INM used configuration and speed specific noise-power-distance (NPD) curves to determine noise levels on the ground. The results are shown in Figure 2-9. Based on the simulation results, the noise benefits of including the 4000A constraint were deemed significant.

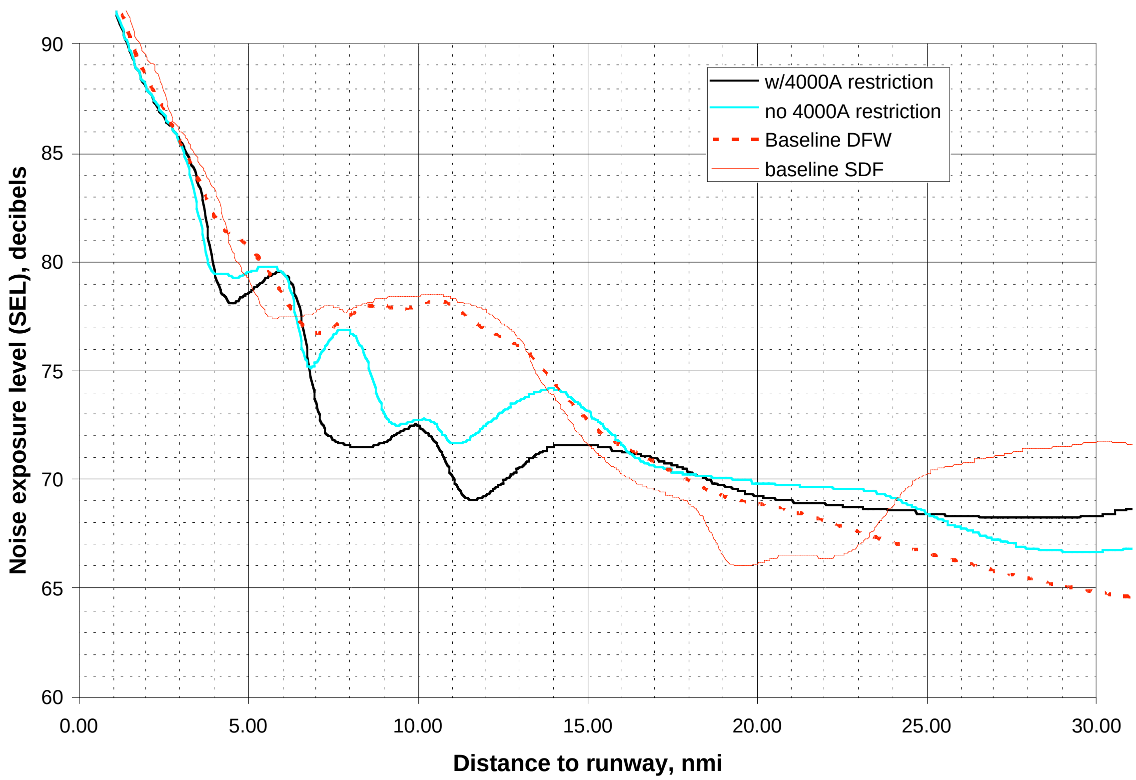


Figure 2-9: Predicted noise levels for 35L

The results of simulation testing at Langley lead to the design of a preliminary arrival chart for refinement by UPS. The preliminary arrival chart is shown in Figure 2-10. As can be seen, the waypoint restrictions that proved most useful in achieving the desired trajectory are an integral part of the procedure.

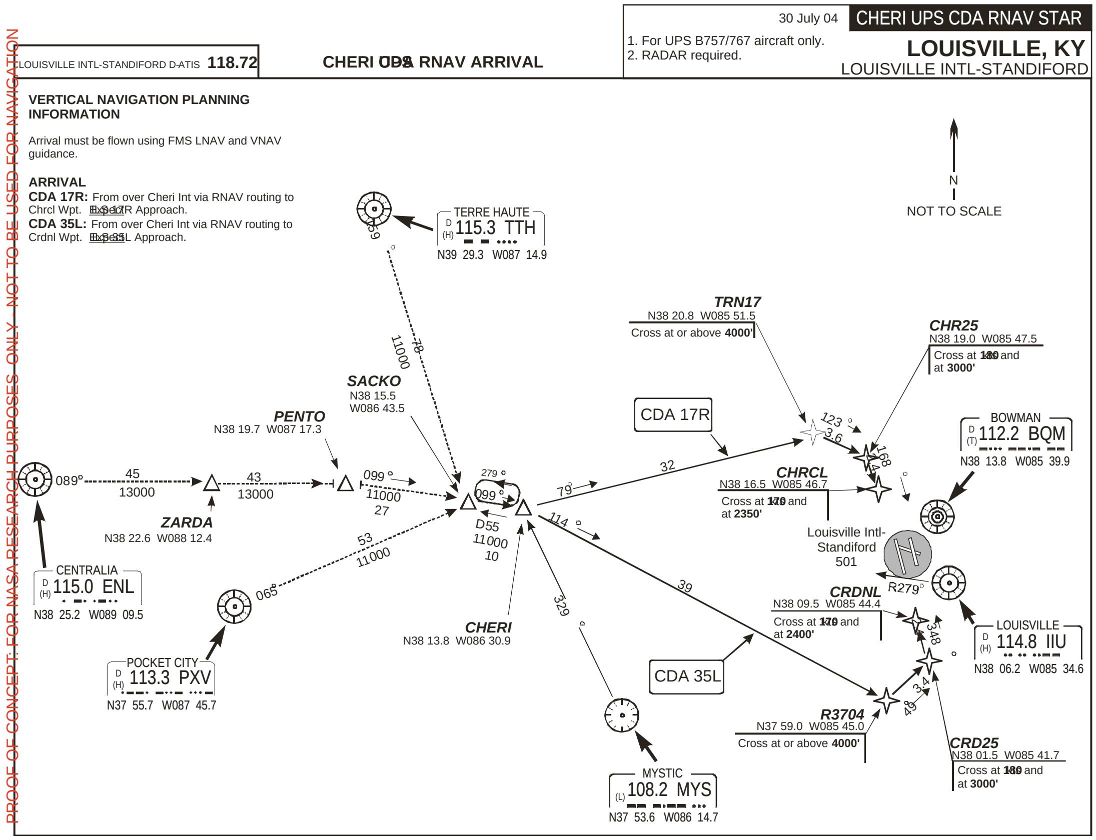


Figure 2-10: Preliminary arrival chart

Preliminary pilot procedures were also developed. These procedures are described below in the format in which they were given to the UPS pilots who would further refine them using the B757-200 and B767-300 simulators at UPS and limited beta-flight tests.

Speed transition at 10,000 ft:

- For FMS to remain in ‘VNAV PTH’, pilots must ensure that speed is below 250 knots before the aircraft descents through 10,000 ft.

- If FMS goes into ‘VNAV SPD’ and speed is greater than 250 knots, pilots must apply speed brakes until FMS is back into ‘VNAV PTH’.

10,000 ft. to start of speed reduction:

- Modes should be ‘VNAV PTH’ and ‘THR HOLD’.

- Pilots should add the minimum thrust and/or drag necessary to maintain speed within 5 knots of the VNAV speed target.

Flap extension:

- FLAP 1 at 10 knots before FLAP 0 maneuver speed.

- FLAP 5 prior to 4000A restriction.

Gear Extension:

- Pilots should extend gear at least 1 mile prior to CHRCL.

2.2 Final Design

Over forty hours of simulation studies were conducted in high-fidelity full-motion B757-200 simulators and a fixed-base B767-300 simulator at the UPS Flight Training Center. The simulation studies provided most of the data required to define the final speed and altitude constraints at the waypoints and to ensure that the procedure was compatible with both aircraft types and different FMS systems over the predicted ranges of landing weights and wind conditions. Additionally, three beta-test flights were performed to validate the CDA prior to the formal two-week test period.

In the simulator, both aircraft were able to perform the procedure over a wide range of wind conditions with limited speed brake use and very little workload increase for the pilot. To keep the noise profile as low as possible, the procedure was initially designed for a 3-degree descent from a waypoint at

4000 ft MSL to touchdown, with no speed constraints until it was necessary to begin the re-configuration of the aircraft for landing. It had been determined from simulations at NASA Langley that the flaps had to be set to Flaps 5 prior to the 3-degree descent segment for the aircraft to slow further during the descent. Thus, the first speed constraint was placed at the waypoint approximately 2.5 to 3 miles prior to the final approach fix. Further, during the simulations at UPS, it was determined that the aircraft had to be slightly below the ILS glide slope to ensure ILS glide slope capture. Thus, the altitude of the waypoint prior to the final approach fix was set to the typical minimum vectoring altitude of 3000 feet. The location of the waypoint was then adjusted to anchor this altitude slightly below the glide slope. The crossing altitude of the turn waypoint was then lowered to account for the changes to the intercept waypoint. The altitude constraint at this waypoint was changed from 4000 ft MSL to an at-or-above restriction of 3800 feet MSL to ensure electronic glide slope intercept.

The standard UPS technique for ILS operations is to select the approach mode once the flight has been cleared for the ILS approach. In some cases, this clearance is not received until the aircraft is nearing or already in the localizer coverage area. However, at this angle and distance from the runway, the turn guidance provided by the localizer was insufficient and would result in overshooting of the extended runway centerline. Thus, it was deemed important that the approach mode be selected prior to entering the ILS localizer coverage area so that the LNAV mode could lead the turn based on ground speed and amount of turn.

Several wind profiles that are representative of the actual wind conditions were used in the simulator. The mean wind was used as the basis for procedure development, but simulation runs were also conducted with the 2-sigma wind profiles (strong headwinds and tailwinds) to ensure that the deviation from the nominal performance was not significant in terms of the change in the deceleration that occurs. However, the simulators were limited in their ability to simulate actual wind patterns from cruise altitude down to 1500 feet AGL. This led to some modifications of the altitude constraints after the procedure was flown in the actual aircraft (during the beta-test flights).

The beta-test flights revealed that speed brake usage would be greater than had been observed in the simulator. Although speed brake usage could be reduced by entering––at up to four different altitudes––the forecast winds into the FMS, the speed brake usage was well within the range observed in typical operations. In addition, UPS does not normally require flight crews to enter the forecast winds in the FMS. For these two reasons, the entry of forecast winds was not initially part of the CDA procedure.

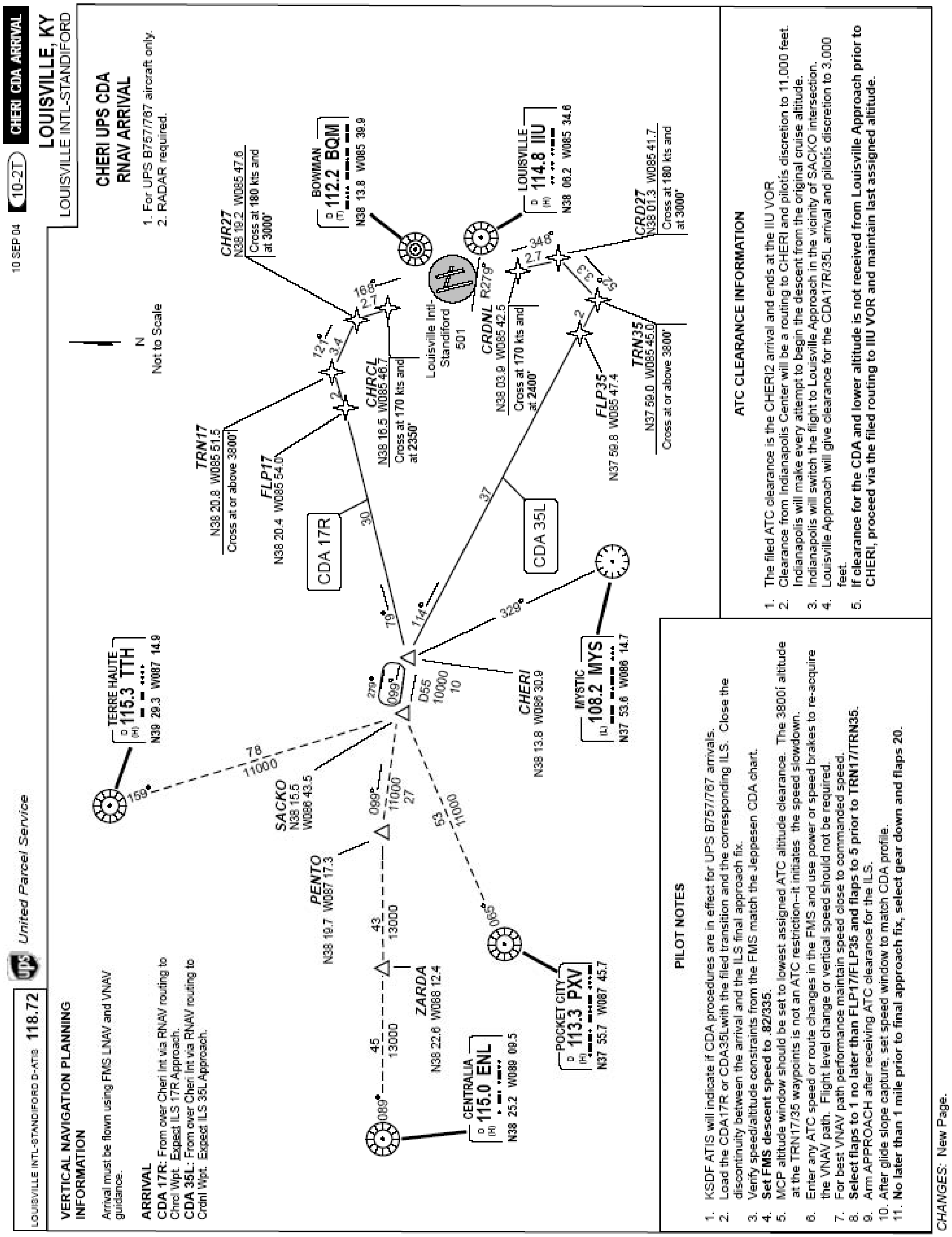


Figure 2-11: Refined arrival chart

The arrival chart went through several iterations during the UPS simulator studies and beta-test flights. First among these were the changes in the location of and constraints at the different waypoints (mentioned above). Additionally, significant pilot notes were included in the arrival chart. The purpose of these ‘atypical’ notes was to provide pilots with the details of the CDA procedure in a condensed version for easy reference.

The pilot procedures were also refined based on the revised FMS procedure. The pilot procedures, integrated into the arrival chart shown in Figure 2-11, include details of the decision-making process and steps for executing the procedure. In addition, pilots were also provided with a general information bulletin describing the general ATC procedures and aircraft related procedures for the B757-200 and B767-300 fleet.

The procedures were designed to standardize descent speeds prior to 10000 feet MSL, provide information on FMS and auto flight programming and operations, standardize aircraft configuration locations, and provide ATC clearance information and terminology. The descent speed was pre-determined to help make the spacing interval between aircraft as predictable as possible during the descent. FMS and auto flight procedures were provided to standardize lateral and vertical programming and operations. This was also necessary for spacing interval performance. The configuration procedures were designed to achieve the desired speeds for the 3-degree descent and to meet the stabilized approach criteria.

UPS requires its pilots to meet the stabilized approach criteria prior to 1,000 ft. AGL. To maintain the proper speed profile, the bulletin recommended aircraft configuration changes at specific points, or gates, along the lateral route. These gates were defined on the CDA procedure as waypoints. Waypoints, typically, had other purposes such as speed and/or altitude constraints and/or lateral course changes. One waypoint, the flap waypoint (FLP17/35), was added specifically as a visual cue for the pilot to begin to configure to Flaps 1. Previously, this gate was specified at a fixed distance (2 nm) from the turn waypoint (TRN17/TRN35). Without the flap waypoint crews would have to reference distance information from the turn waypoint to make this initial configuration change. The addition of the flap waypoint was used to reduce the workload and ensure that the pilot remain on the proper speed profile.

This idea combined the concepts of two independent research programs. MIT researchers were experimenting with a series of pre-computed gates displayed on a chart as a feedback mechanism to follow the recommended speed profile of a procedure. While, researchers at NASA Langley were developing a Low Noise Guidance (LNG) tool that through advanced algorithms provided pilots with visual cues on their navigation displays, such as T/D and flap and gear to precisely fly an optimized CDA. A gate, the flap waypoint, displayed on the navigation display was a logical compromise using current day flight management systems.

UPS flight crews will normally use VNAV until 10000 feet MSL whenever possible. The information concerning configuration and FMS modes was provided in the procedures because flight crews do not normally use the VNAV mode below 10,000 feet. The reason for this is that in normal, non-CDA, operations, the flight crew does not usually know the lateral track that ATC will use to vector the aircraft to the final approach. As a result, the flight crew will descend in modes that use idle thrust to the cleared altitude and then level off and power up until the next descent is given.

Finally, the ATC clearance terminology and timing of the clearances was developed with the participating FAA facilities. These were included in the procedures bulletin and as part of the pilot notes on the Jeppesen arrival chart.

2.3 Separation Analysis

The separation analysis was performed using a Monte-Carlo simulation tool that was specially developed for evaluating the performance of aircraft performing a specified procedure under different operating condition, and for predicting the required initial separation for noise abatement procedures such as the procedure tested at KSDF. The tool may be used to quickly simulate aircraft operations is a wide range of operating conditions, namely combinations of aircraft configurations, procedure design parameters, pilot response and weather.

2.3.1 Components of the Monte-Carlo Simulation Tool

The Fast-Time Aircraft Simulator

The central piece of the Monte Carlo simulation tool is a fast-time aircraft simulator. The dynamics of the aircraft are determined using a point-mass model based on non-steady-state equations of motion and is thus more accurate in simulating the wind effects than a normal point-mass model based on steady-state equations of motion. The model for each aircraft type was developed using aircraft performance engineering data including aerodynamic data and installed engine data provided by Boeing (the manufacturer).

In the simulator, the three-axis control and power setting control are assumed to be performed by the autopilot and auto-throttle respectively. The autopilot has a lateral channel and a vertical channel; each channel is modeled as a second order linear controller. The auto-throttle is also modeled as a second order linear controller, with the response of the engines modeled as a first order delay. Altitude error, speed error and cross track error are fed as inputs to the autopilot and auto-throttle so that they can control the aircraft. Depending on flight conditions, the autopilot together with auto-throttle can operate in several different modes. All the control modes relevant to performing approach procedures are modeled. With these modes, the aircraft can be directed to hold a given altitude and speed, or to hold a given speed and flight path angle; or to follow a given vertical flight path defined by altitude, speed, and preferred power setting.

The simulator also has an FMS module. The FMS module models the basic RNAV functionalities found onboard modern commercial aircraft. Before the execution of the procedure, the FMS module builds the lateral flight path (LNAV path) based on the location of the given waypoints and the vertical flight path (VNAV path) based on the given altitude/speed constraints at the waypoints in the same way a actual FMS would. The lateral turn anticipation is computed from projected aircraft speed at the turn. The vertical flight path is computed through backward integration of the aircraft dynamics from the last altitude/speed constraint to cruise altitude. If proper altitude/speed constraints are given, an idle VNAV path can be built from cruise to final approach fix. During the execution of the procedure, the FMS module continuously monitors the states of the aircraft and compares them with the computed LNAV and VNAV flight paths. It selects the proper modes for, and feeds altitude, speed and cross track into the autopilot and auto-throttle so that the aircraft will follow the computed flight paths.

Pilot Response Model

While the aircraft is guided by the FMS and controlled by the autopilot and auto-throttle, the pilot assumes the responsibility of controlling the extension of flaps and landing gear and speed brakes, just as in the real world. In the Monte-Carlo simulation tool, the behavior of the pilot is modeled as a delay relative to the flap/gear schedule. That is, a specific flap schedule is first determined using the information available in aircraft operation manuals such as reference [UPS 2004] that provides the speeds at which the flap and gear should be extended (the flap/gear schedule) as a function of aircraft weight. Then, the time that the pilot extends the flaps and gear during a particular simulation run is the time that the specified speed is achieve plus an offset taken from the distribution on Figure 2-12, which was developed by Ho and Clarke [Ho et al. 2003].

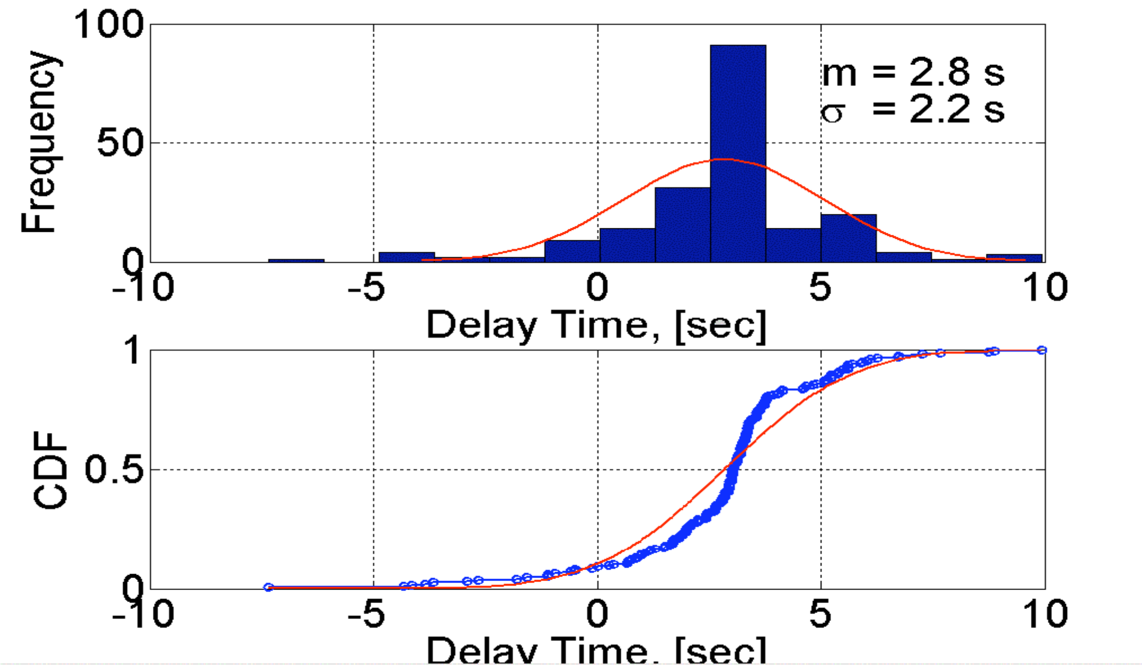


Figure 2-12: Delay in pilot response

Wind Model

Wind is the most significant factor affecting aircraft trajectories. In this research, wind conditions are modeled using both long-term statistical expectations (such as two-sigma wind and mean wind) to reflect the magnitude of the wind that an aircraft would expect to experience during its descent to the runway, and short-term statistical variations to reflect wind changes between flights arriving in quick succession.

ACARS data that has been archived by the National Oceanic and Atmospheric Administration (NOAA) is used to develop the wind model. The model is built as a Monte-Carlo simulation itself so that the wind profile will be different for each simulation run. The long-term statistical wind profiles for KSDF are shown in Figure 2-13. These wind profiles were obtained from ACARS reports of flights arriving from the West during the five-hour period on each day around the time the flight test was to be conducted. Comparison with existing wind databases confirmed that the wind profiles that are shown in the figure more closely depict what would be experienced by CDA flights during the flight test.

An example of the typical variation in wind magnitude between flights is shown in Figure 2-14. In the simulation, the wind change is decomposed into the East and North wind components.

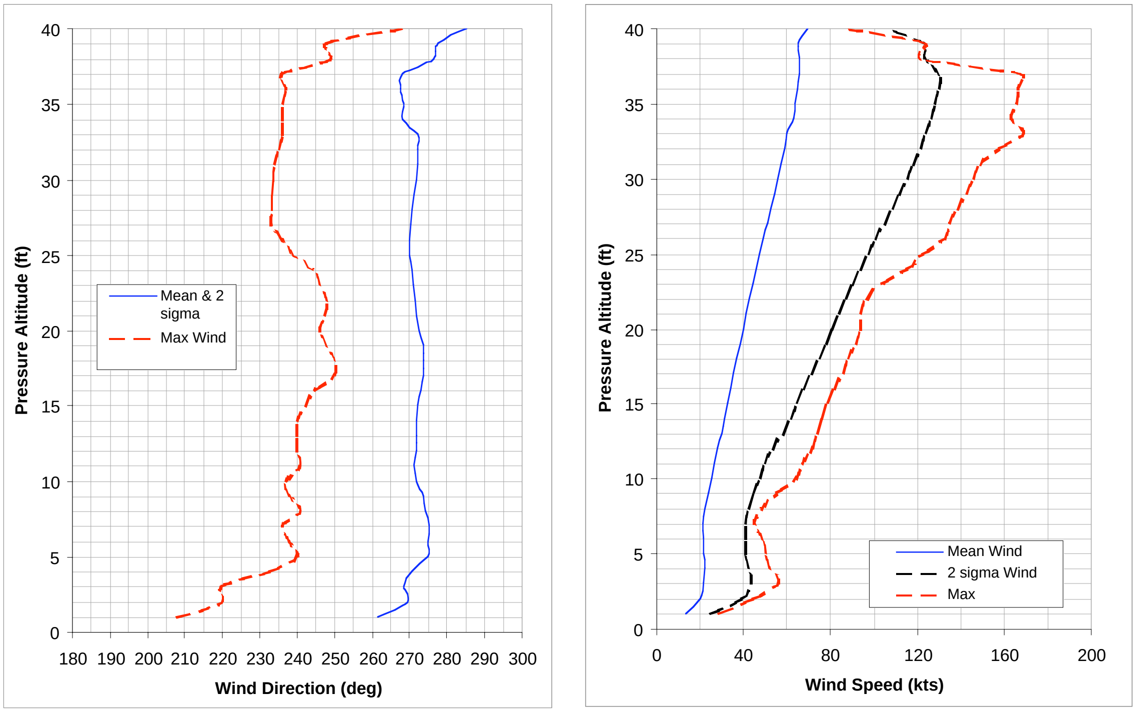


Figure 2-13: Mean and 2σ wind profile for aircraft from the West

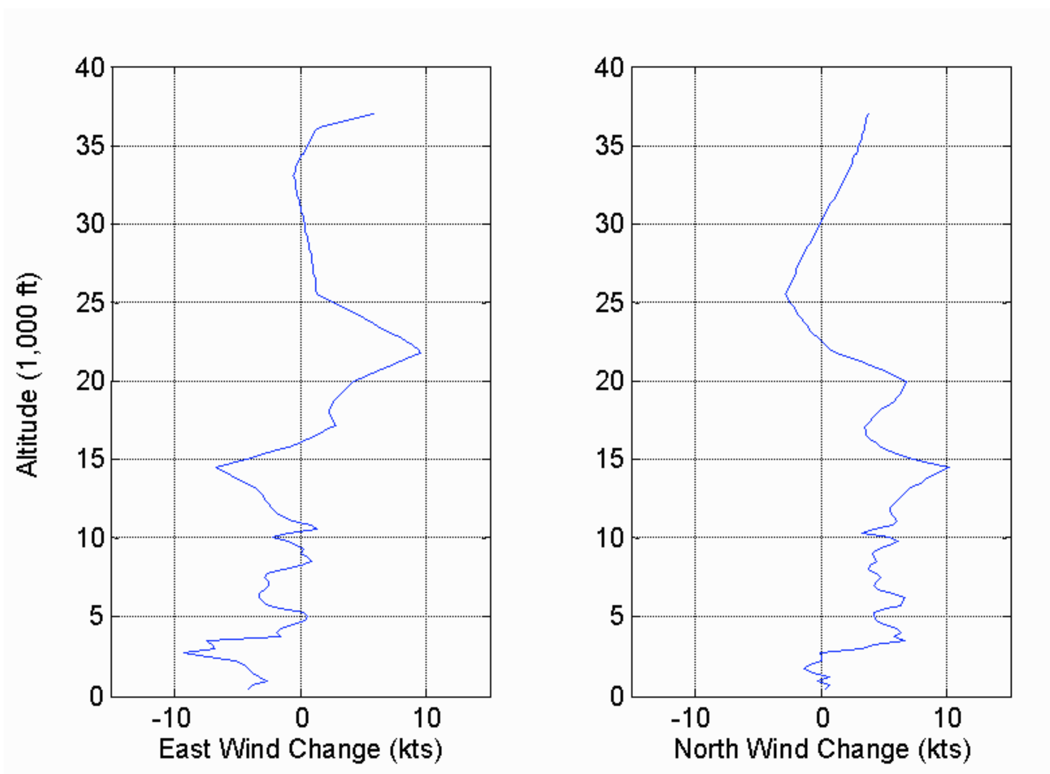
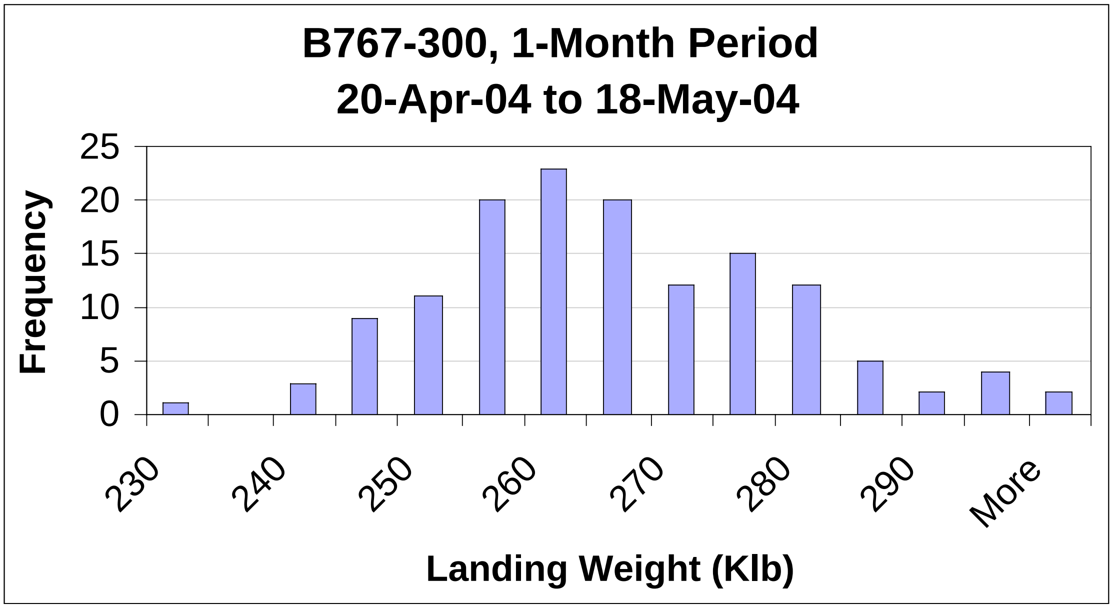


Figure 2-14: Variation in North and East wind between aircraft pairs

Aircraft Weight Model

Weight is also another important factor in the performance of aircraft. Thus, one month of aircraft landing weight data was used to develop distributions describing the landing weight of UPS B757-200 and B767-300 arriving from the same origins as targeted for the test. These distributions are shown below in Figure 2-15.



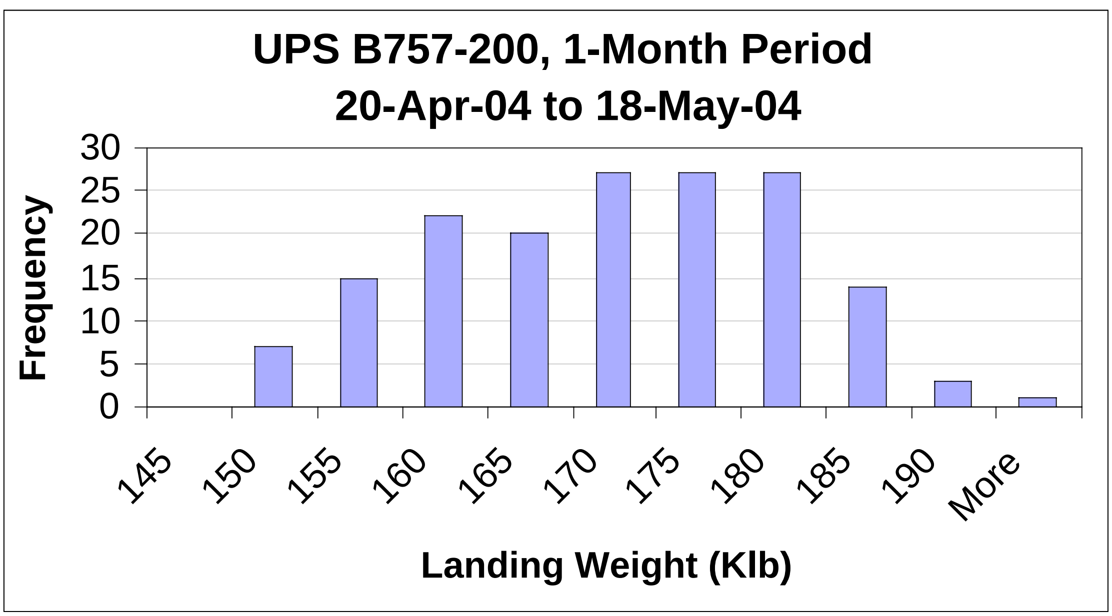


Figure 2-15: Historical weight distributions for UPS B757-200 and B767-300

2.3.2 The Simulation Environment

The pilot response model, wind model, aircraft weight model were coupled with the aircraft simulator to form an integrated Monte-Carlo simulation tool, as illustrated in Figure 2-16.

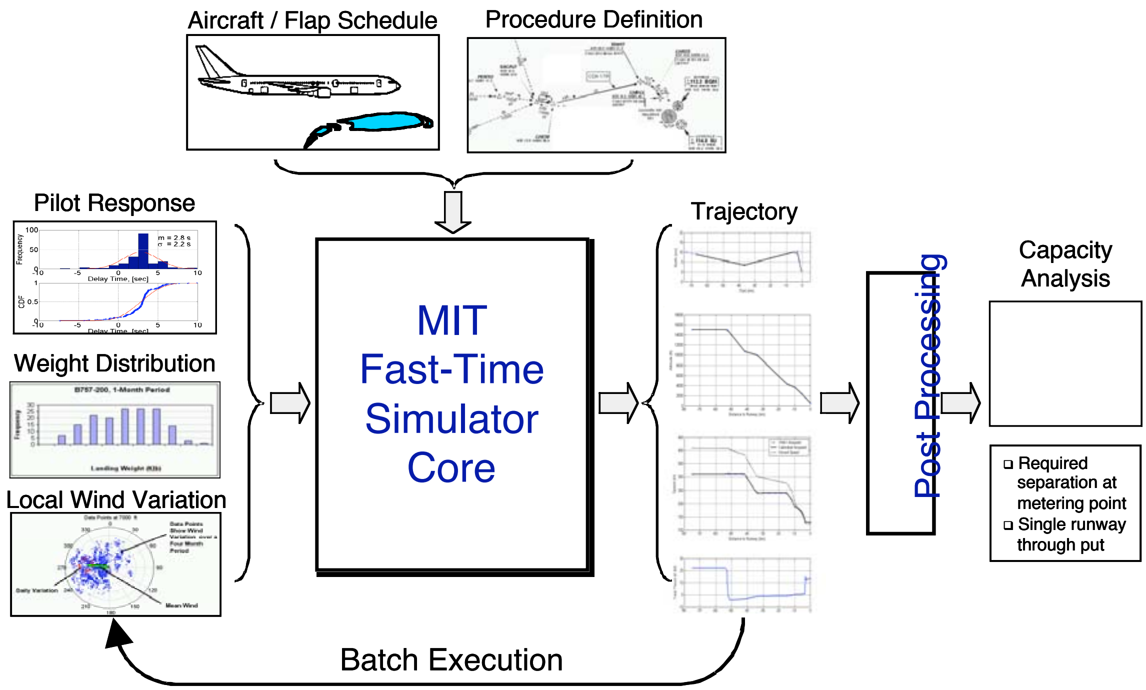


Figure 2-16: Schematic of Monte-Carlo simulation tool

Using this Monte Carlo simulation tool, the approach procedure was simulated hundreds of times for each type under different wind and weight conditions to generate an ensemble of possible aircraft trajectories.

2.3.3 Methodology for Separation Analysis

The methodology for determining the separation between successive aircraft is depicted in Figure 2-17. As shown in the figure, the performance of aircraft is in general such that the uncertainty in the future position of each aircraft grows monotonically with time [Ren et al. 2003]. Thus, a pair of aircraft with a specified initial separation at a metering point will have a range of possible separation values when the first aircraft is at the runway threshold, where the extent of this range is a function of the initial separation at the intermediate metering point and the rate at which the future position of each aircraft grows with time.

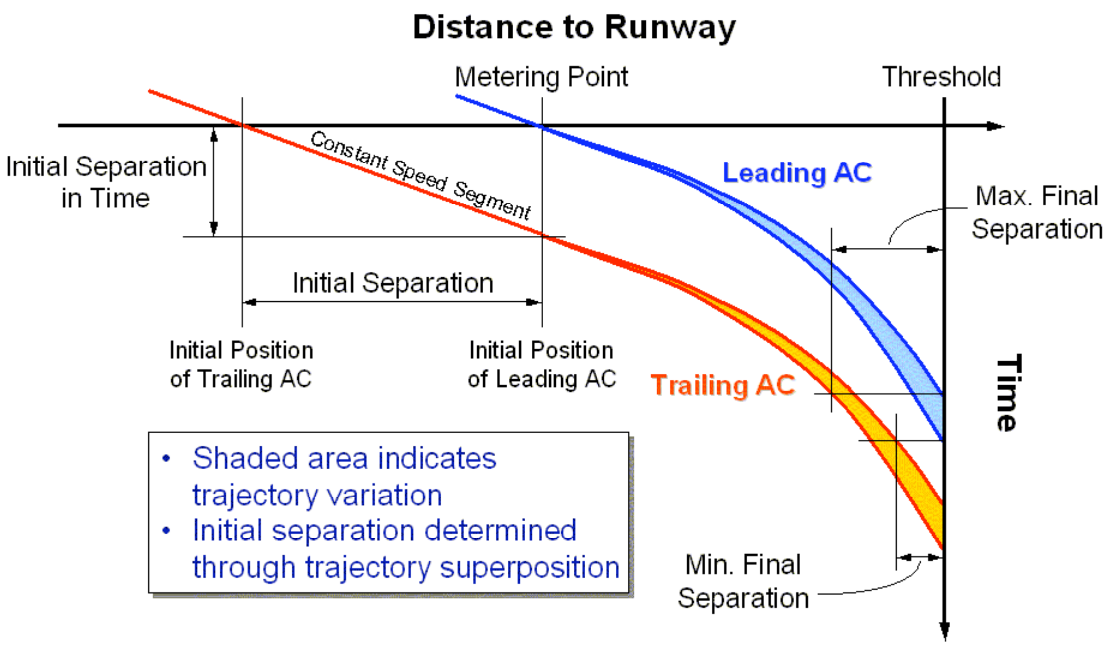


Figure 2-17: Methodology for Separation Analysis

In the methodology, it is assumed that the future position of one aircraft is independent of the future position of the other aircraft. While it is true that the pilots in the trail aircraft might modify their behavior in terms of flap and gear extension if the lead aircraft is decelerating more quickly or more slowly than they expect, in the vast majority of cases they will operate their aircraft according to the schedule that is prescribed for the weight of their own aircraft and thus independent of what is happening to the lead aircraft. Additionally, the assumption of independence of aircraft provides some measure of conservatism in the separation values that are calculated.

The probability distribution for the future position of the first aircraft is determined by repeatedly simulating the trajectory of the specified aircraft type of the first aircraft in a specified wind profile--for example the average wind profile at the airport in question--each time selecting values for the weight and pilot behavior from distributions that describe how they vary. The probability distribution for the future position of the second aircraft is determined by repeatedly simulating the trajectory of the specified aircraft type of the second aircraft in a series of wind profiles that are short-term variations about the specified wind profile for the first aircraft while also selecting values for the weight and pilot behavior from distributions that describe how they vary.

For a given initial separation and a given time in the future, the distribution for the position of the first aircraft is convolved with the distribution for the position of the second aircraft to determine the range of separations that would be expected at that time in the future. By simple changing the initial separation and repeating the convolution––changing the initial separation is equivalent on a graph to sliding the set of trajectories of one aircraft relative to the other––it is thus possible to determine the initial separation that provides the desired confidence that the minimum separation between aircraft types is not violated.

2.3.4 Results of Separation Analysis

The performance of B757-200 and B767-300 aircraft was simulated under the range of wind conditions and aircraft weights that were expected during the flight test. It was determined that a separation of 15 nautical miles at the waypoint SACKO would guarantee separation in a very high percentage of the possible aircraft pairings that would result if aircraft were arriving in a random order and that separation would be assured by the ability of controllers to project whether a violation was likely to occur and respond by vectoring aircraft or sending aircraft to the parallel runway.

3 Flight Test

The flight demonstration test began on Tuesday, 14 September and ended on Saturday, 25 September 2004. The test aircraft were all scheduled to arrive within the one hour period between UTC 5:30 (1:30 AM local day light savings time) and UTC 6:30 (2:30 AM local day light savings time) each morning.

The initial plan called for 12 CDA flights on Tuesdays through Fridays, and 14 CDA flights on Saturdays. However, due to changes in aircraft assignments (where B757-200 or B767-300 replaced A300, or vice versa) and the desire to participate by the crew of an initially unscheduled aircraft, a total of 126 flights were finally scheduled to perform the CDA. Among those 126 flights, 125 aircraft performed a CDA and 1 aircraft performed a visual approach because of issues with its navigation database.

All the flights on 16 and 24 September and one flight on 23 September flew the CDA to runway 17R; the remainder of the flights flew the CDA to runway 35L. The numbers of CDA flown by each aircraft type to each runway are summarized in Table 3-1. Some of the flights that flew the CDA to runway 35L actually landed on runway 35R as directed by ATC to assure separation. The need for these landings on runway 35R will be explained later.

Table 3-1: Breakdown of CDA flights

		September										
		14	15	16	17	18	21	22	23	24	25	
Runway	Aircraft											Total
35L	B757-200	6	7		5	8	6	7	7		8	54
	B767-300	6	5		6	6	6	6	5		6	46
17R	B757-200			6						6		12
	B767-300			6					1	6		13
Total		12	12	12	11	14	12	13	13	12	14	125

3.1 Pilot Surveys

At the completion of each flight, pilots were given a survey to complete. The survey contained questions regarding the adequacy of the information in the Bulletin as it pertained to flying the arrival, the benefits of pilot notes on the arrival chart, the accuracy of the altitude and speed constraints in the FMS database, the ATC clearance pilots received, the similarities and differences between the procedure as described and the actual flight, and the workload. Pilots were also asked to provide general comments on the procedure. In the interest of time (pilots are often fatigued at the completion of their flight), the survey was designed to have a forced-response (i.e., yes or no) format. The strong benefit of this format was that it forced the subjects to give definite answers regarding the CDA charts and accompanying pilot information.

3.2 Radar Data

Automated Radar Terminal System (ARTS) data for the two-week test period were retrieved from the UPS surface management system. These data provided flight identification, aircraft position, altitude, and ground speed at a rate of once every 4 to 10 seconds. An example of the radar data is shown in section 1.1 of the appendix. On each day, the data covered a time span of about 3 hours around the scheduled CDA arrival time except on 25 September when only 2 hours of data were available. The data covered a spatial area of 55 nm from the airport. All UPS flights arriving during the 3-hour period were included. Although there were occasional flights from other operators during this time of the day, their numbers were minimal; and they seldom came from the west where the CDA flights arrived.

3.3 Flight Recorder Data

Flight recorder data was retrieved from 61 flights during the two-week flight test period. An example of the raw flight recorder data is shown in section 1.2 of the appendix. Of the 61 flights, one flight was not a CDA flight, and a second flight was the aircraft that flew a visual approach. Thus, flight recorder data was only available for 59 CDA flights. The breakdown of flight recorder data for CDA flights is shown in Table 3-2 in terms of the aircraft type and the runway to which the aircraft is destined. As mentioned earlier, flights that are categorized as being destined for either ‘35L’ or ‘17R’, aircraft may have actually landed on runway 35R or runway 17L respectively if instructed to do so by ATC.

Table 3-2: Breakdown of flight recorder data for CDA flights

		September										
		14	15	16	17	18	21	22	23	24	25	
Runway	A/C											Total
35L	B757-200	1	3		1	5	5	3	4		6	28
	B767-300	4	2		3	3	2	4	2		3	23
17R	B757-200			2								2
	B767-300			1					1	4		6
Total		5	5	3	4	8	7	7	7	4	9	59

To compare the performance of CDA flights with conventional flights, flight recorder data were also retrieved from 99 conventional flights. Four of these flights were on 8 September, which was before the flight test period. The remaining flights occurred during the three-week period immediately following the flight test period. As with the CDA flights, flight recorder data were only available for a subset of the conventional flights that occurred during that period. Of the 99 flights, data from one flight on 1 October was not used in the analysis because that aircraft flew a unique lateral path, making the comparison difficult. The breakdown of flight recorder data for conventional flights is shown in Table 3-3 in terms of the aircraft type and the runway to which the aircraft is destined.

Table 3-3: Breakdown of flight recorder data for conventional flights

		September				October												
		8	28	29	30	1	2	5	6	7	8	9	12	13	14	15	16	
Runway	Aircraft																	Total
35L	B757-200	1	2	1	3	1		5	3	4		5	5		3			33
	B767-300	3	3	2	2	2		4	2	1		5	4		4			32
17R	B757-200						5				5			2		2	5	19
	B767-300						4				1			4		3	2	14
Total		4	5	3	5	3	9	9	5	5	6	10	9	6	7	5	7	98

3.4 Noise Monitor Data

Prior to the test, twelve locations were selected for noise measurements. Six were North of the airport in Floyds Knobs, Indiana and six were South of the airport in Shepherdsville, Kentucky (see Figure 3-1). The criteria used to evaluate potential noise measurement sites included proximity to the flight path and a clear sound propagation path while an aircraft is approaching, above, and flying away from the measurement location. Other factors considered in the selection process included operator security, accessibility, and remoteness so as to be away from any obvious noise sources such as roadways and machinery, which could potentially contribute to the background noise and thus contaminate the aircraft noise measurements.

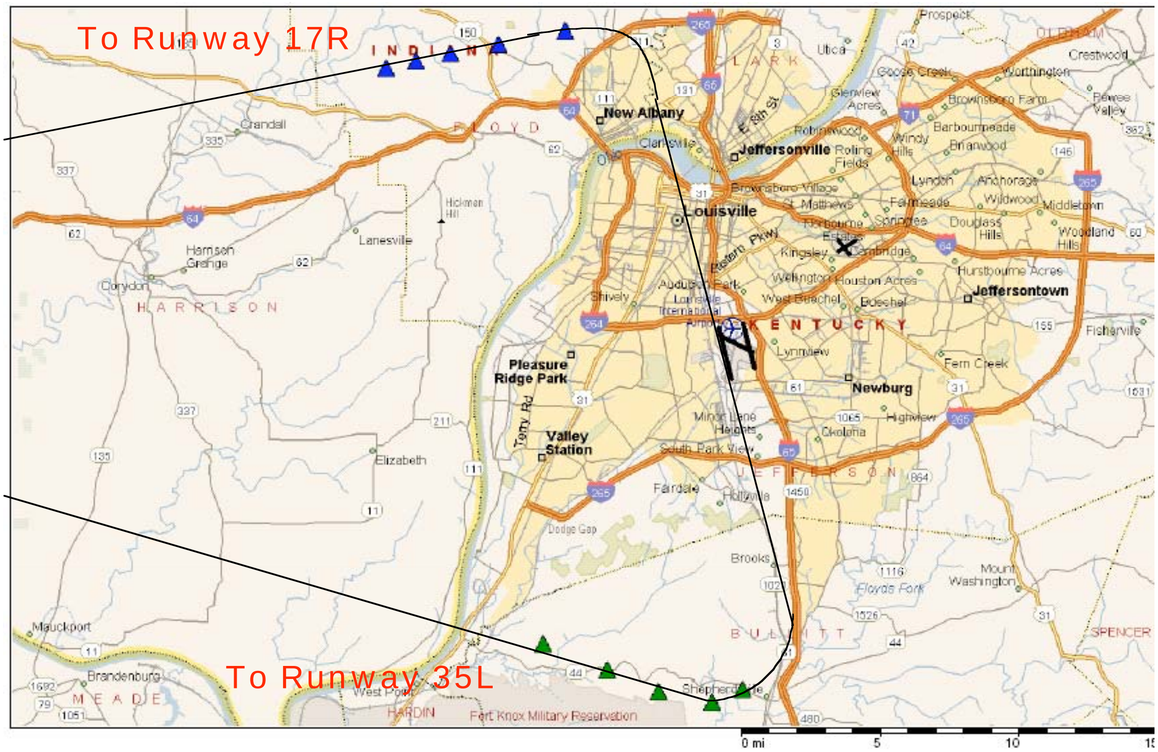
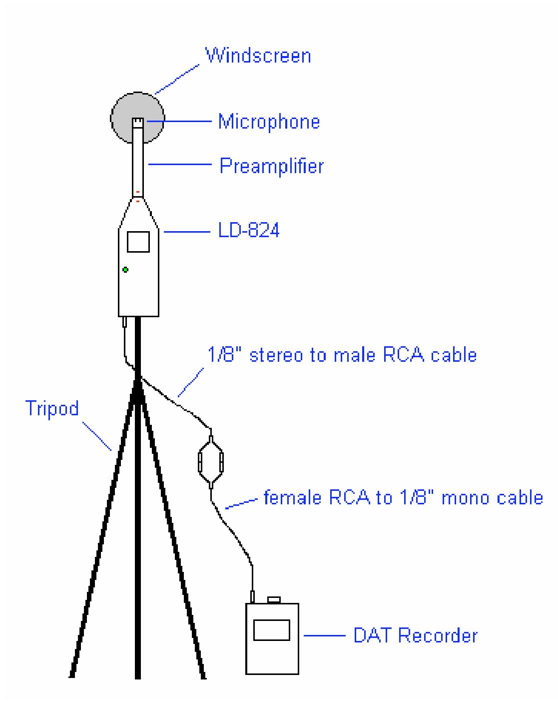


Figure 3-1: Noise measurement sites

3.4.1 Noise Monitoring Equipment

Portable Larson Davis (L&D) 824 sound level monitors were used at each site with an L&D 812 connected to a digital audio tape (DAT) recorder as a spare. Additional data was collected with supplemental acoustic measurement equipment including a binaural manikin and DAT recording equipment provided by NASA, two portable sound level monitors provided by the RAA, and a portable B&K sound level meter provided by Boeing. This supplemental equipment was located close to the L&D 824 monitors for most of the test period, although some were moved between sites on different nights. The L&D 824s were programmed to record measured A-weighted sound pressure levels with slow response at each of the microphone positions. They were mounted on a tripod that was adjusted to a microphone height of 1.5 m (5 ft). A diagram and photo of the L&D 824 test setup are shown in Figure 3-2. Although each monitoring location was situated differently relative to the flight path, all microphones were positioned to point straight up, so that their diaphragms were parallel to the ground. This was done for consistency.



Overall acoustic instrumentation setup	North site 4 - typical site, and equipment setup

Figure 3-2: Noise Monitor Equipment test setup

Care was also taken to ensure that the observer / operator was far enough away from the microphone while recording so as not to adversely influence the measurements with personal noise. Equivalent noise levels (Leq) and un-weighted frequency spectral data (1/3 octave data) were recorded at 1-second intervals. This data was collected for the entire two- to three-hour measurement period, starting at approximately midnight each night, to minimize operator interaction. Individual events were later correlated with flight tracking data by time stamping the recorded noise data with the logged recording start times and then matching this time stamped data to flight time / aircraft position data collected by the RAA for all SDF traffic. This was performed during post-processing. Each L&D 824 monitor was downloaded to a PC the next day using the L&D-824 utility software (Version 3.12) and CBL006 interface cable to serial port.

3.4.2 Noise Monitoring Procedure

Each night a sub-set of the research team (students from MIT and Purdue, as well as engineers from Boeing, NASA and Volpe NTSC) were on hand to setup, calibrate, record, and then take down the measurement equipment. Aside from operating the instruments they also performed other tasks such as synchronizing digital watches, logging recording start and stop times, logging the approximate time of closet approach between aircraft and the observer, noting extraneous noise events, and making general weather observations.

3.4.3 Noise Measurements

In total there were 622 noise measurements of 123 flights recorded at 6 separate sites on 9 of the 10 test days. On 7 days the test equipment were taken to the sites to the South of the airport to measure the noise from aircraft performing the CDA to runway 35L. The runway that is used is primarily a function of the prevailing winds at the airport and the airport is said to be operating in ‘north flow’ when aircraft are landing on runways 35L and 35R, and in ‘south flow’ when aircraft are landing on runways 17L and 17R. The airport is in north flow approximately 80% of the time. On three nights the noise equipment was taken to the sites to the North of the airport because the airport was projected to be in south flow. However, because of a sudden and significant change in the wind conditions on the night of 17 September, operations at the airport changed from south flow to north flow after the noise team had setup the measurement equipment at the sites to the North of the airport (for south flow measurements). At that time it was too late to move the equipment to the sites to the South of the airport.

4 Analysis of Pilot Ratings

4.1 CDA Bulleting Information

As shown in Figure 4-1, most pilots felt that the CDA bulletin provided enough information for them to fly the procedure. Two pilots commented that the information was ‘overkill’.

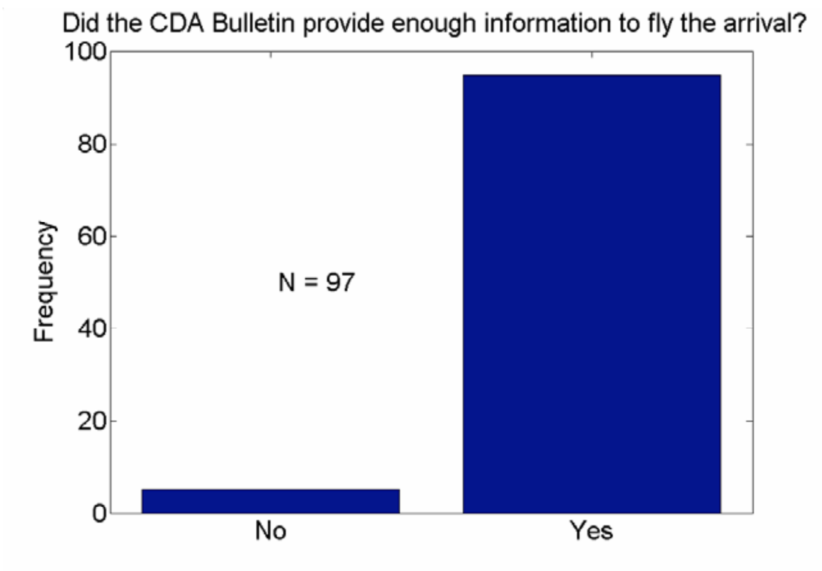


Figure 4-1: Pilot response to question on CDA bulletin

4.2 Pilot Notes on CDA Chart

As shown in Figure 4-2, most pilots felt that the pilot notes on the arrival chart were beneficial. Within this group, two pilots mentioned that there were too many notes. One pilot in the group that responded with a ‘No’ commented that the letter ‘A’ was missing in the altitude constraint 3800A at the TRN17 waypoint.

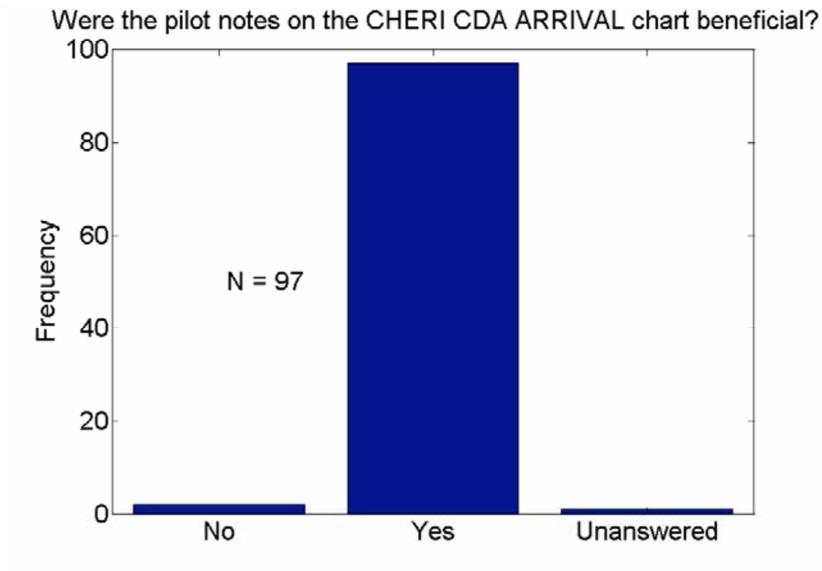


Figure 4-2: Pilot response to question on pilot notes

4.3 Constraints in FMS Database

As shown in Figure 4-3, the altitude and speed constraints were correctly loaded into the FMS database in two third of all the flights. On the other hand, due to the discussed FMS data-loading problem, in one third of all the flights, thirty-three pilots reported that missing, incorrect, or out-of-place information was observed in the latitude, longitude, course/distance, and speed/altitude constraints. Ten pilots felt that it was undesirable to manually enter the data.

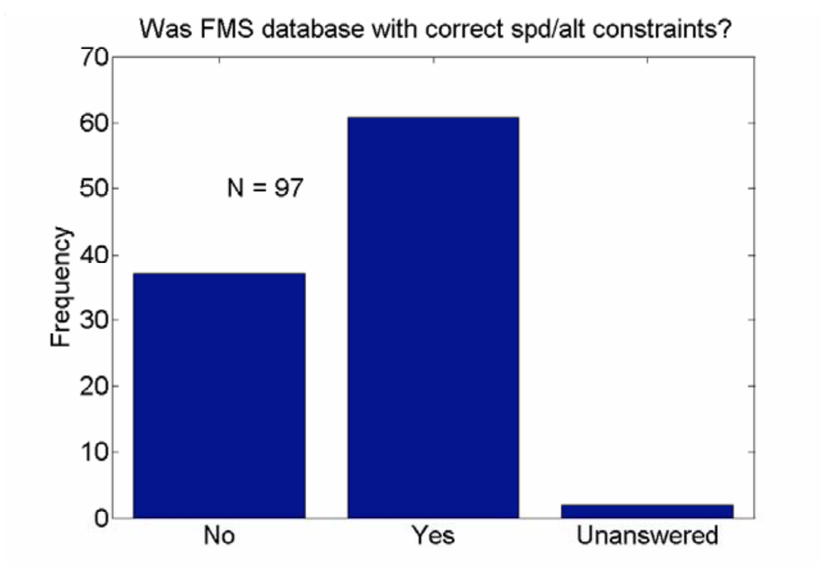


Figure 4-3: Pilot response to question on constraints in FMS database

4.4 ATC Clearance

Most pilots reported that the ATC clearance was received as outlined in the Bulletin. As shown in Figure 4-4, of the group that responded with a ‘Yes’, one pilot indicated that ATC required him to descend early and at a slower pace than the profile, and another pilot indicated that the clearance came at the last moment. Of the group that responded with a ‘No’, five pilots reported some variations from the outlined bulleting, including a refilling from PXV to ZARDA; a runway change from 17R to 35L; and the imposition of an at-or-below altitude restriction at Indianapolis Center which required the use of the flight level change (FLCH) mode to rejoin the path.

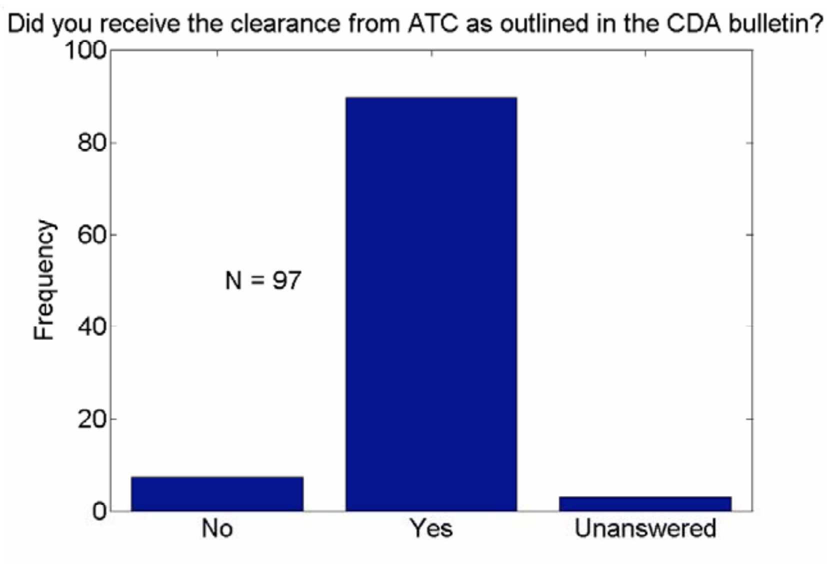


Figure 4-4: Pilot response to question on ATC clearance

4.5 Comparison of Procedure and Actual Flight

As shown in Figure 4-5, most pilots thought the aircraft flew the procedure as expected. Of the group responded ‘yes’, six indicated that speed brake extension was required to stay on speed and vertical path, and two reported that the recommended flap schedule was insufficient to cope with aircraft separation closure that led to runway changes. Of the group responded ‘no’, fifteen indicated that the deceleration was insufficient (due to tailwind and ATC commands), and that speed brake extension was required to recover or stay on speed and vertical path; one pilot reported that the runway change command occurred after the descent had started caused the aircraft to reduce speed early and led to early extension of flap 15; one pilot reported that the aircraft was on speed but did not capture the glide slope and had to stay high until touchdown; one pilot reported that his aircraft was high and fast at waypoints FLP35 and TRN35. Of the eight pilots who chose not to answer the question, one felt that the speed brake would always be required.

Figure 4-5: Pilot response to question on procedure v. actual flight

4.6 Workload

Because the questionnaire on the workload that pilots experienced while flying the procedure was open-ended, the answers were collated and grouped into four categories: 1) easy to normal; 2) slightly high; 3) high; 4) no comment. These categories were chosen based on the interpretation of the answers with specific words such as easy, normal, slightly high, or high. As shown in Figure 4-6, a majority of the pilots indicated that the workload was normal to slightly high, and that the procedure was well designed, simple and easy to fly. Of the pilots who reported a high workload: five said that the head-down time was high because they spend more time monitoring the profile and using the speed brake than listening to the radio and monitoring other airplane parameters or performance; one pilot said the high workload was due to the runway change; three said that slower leading aircraft or faster trailing aircraft increased their efforts in maintaining the separation; ten said the manual entry of the FMS data increased their workload; and one commented that the lack of training made it difficult for him to fly the procedure.

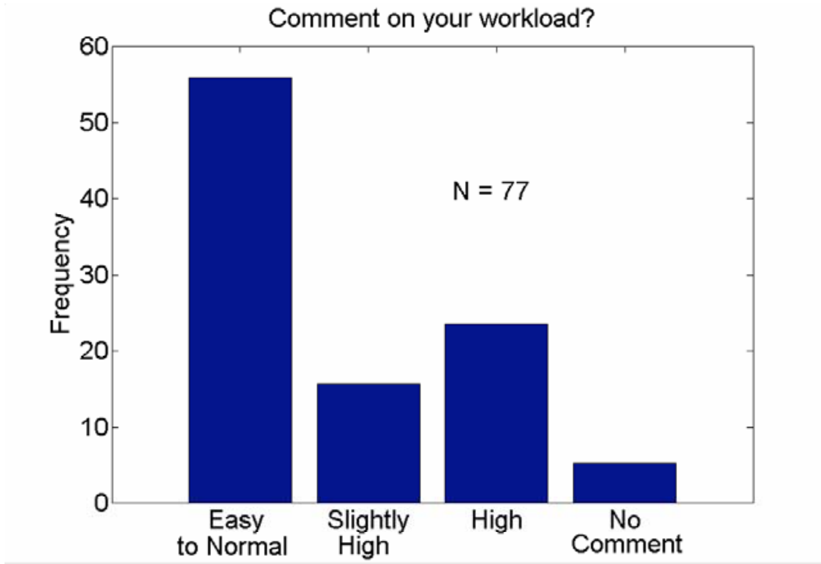


Figure 4-6: Pilot response to question on workload

4.7 General Comments

The general pilot acceptance of the procedure was overwhelmingly positive. Ninety-two of the ninety-five pilots who answered this question commented that based on their performance, the procedure would work well in practice. Typical comments include 'Excellent/great procedure', 'should do this every night', 'Low workload', and 'would like to try procedure again.' Three pilots commented that the workload was too high to adhere to the speed/altitude constraints and that the procedure would not work in practice.

Despite the high acceptance of the procedure, there were many suggestions for improving the procedure. The suggestions include correcting the incorrect/missing information in the FMS database, modifying procedure and flap schedule to provide adequate deceleration in tailwinds, avoiding the operation of the speed near the placard speed limits, refining the bulletin/checklist to include information such as speed/altitude constraints, and inputting winds into the FMS.

5 Analysis of FMS performance

The flight recorder data were analyzed to determine FMS usage and performance during the flight tests. A data reduction program was written to read the raw data files from the FDR and extract pertinent airplane state and FMS status information. Of particular interest were the FMS VNAV usage and control modes during the arrival, the adherence to the programmed FMS vertical trajectory, and the thrust and speed brake control activity during the descent.

The analysis of the flight recorder data was complicated by the uncertainty of the route and crossing restrictions programmed into the aircraft FMS. Numerous pilots reported having the waypoint crossing restrictions cleared after they loaded the CDA Arrival and ILS Approach into their route. Subsequent investigation revealed that the if the Approach was loaded after the Arrival, and if the Approach had any crossing restrictions higher than the crossing restrictions on the Arrival, the Arrival crossing restrictions would be automatically cleared. For the 35L arrivals, the crossing restriction of 4000 feet at the AWLEE waypoint on the ILS approach would result in the CDA35L crossing constraints at TRN35 and INT35 being removed. The pilots would then need to manually re-enter the constraints to match the arrival chart. In some cases the pilots reported on the post-flight questionnaire that they re-entered the constraints. However, it was not known whether all pilots re-entered the constraints when faced with this problem.

The FDR data and pilot questionnaires were reviewed to determine the flights that completed the CDA arrival with the crossing constraints properly entered. Of the 61 FDR flights during the test period, a total of 44 were deemed suitable for analysis, as shown in Table 5-1. Of the 17 unsuitable flights, 3 did not fly the CDA all the way to the waypoint where the aircraft intercepts the glideslope, 5 had invalid data on some of the data channels needed in the analysis, and 9 of the flights had obvious errors in the vertical crossing constraints.

Table 5-1: Flights during test period that were suitable for FMS analysis

Aircraft	B757-200		B767-300		All
Runway	17R	35L	17R	35L	All
Non-CDA	0	2	0	1	3
Invalid data channels	1	4	0	0	5
Improper constraints	0	5	0	4	9
Suitable for analysis	1	18	6	19	44
Total	2	29	6	24	61

5.1 VNAV usage

VNAV usage was indicated in the FDR data by discrete bits showing the status of the VNAV PATH and VNAV SPD guidance modes of the FMS. When either of these bits are set true, the airplane flight guidance is being driven by the FMS VNAV signals. In VNAV PATH, the pitch guidance will direct the airplane to follow the FMS predicted vertical path with auto throttle used to control speed. In VNAV SPD, the pitch guidance will direct the airplane to follow the target airspeed with auto throttle set to idle (for descent segments). The CDA arrivals were designed to keep the airplane in VNAV PATH from top of descent to capture of the ILS glideslope on final approach. Reversion to VNAV SPD will occur if the airplane is unable to follow the vertical path and remain within an internally defined speed tolerance about the target airspeed. VNAV SPD can also occur if the pilot uses the mode control panel to change the target airspeed, referred to as speed intervention.

For accurate and efficient flying of the CDA trajectories, it is desirable to remain in VNAV PATH throughout the descent. Of particular interest is the flight segment between the CHERI waypoint and glideslope intercept waypoint (INT17R or INT35L on the chart). This is the critical region where the airplane is flying within Louisville approach airspace and is descending to altitudes low enough for noise generated by the airplane to be heard on the ground. Statistics were gathered on the amount of time VNAV was used during this critical flight segment as well as the amount of time VNAV PATH was the guidance mode. VNAV usage within the terminal area for the airplanes with suitable FDR data is summarized in Table 5-2.

Table 5-2: VNAV usage within the terminal area

Aircraft	B757-200		B767-300		All
Runway	17R	35L	17R	35L	All
Time in VNAV (%)	100.0	97.0	96.2	95.7	96.4
Time in VNAV PATH (%)	100.0	87.5	95.8	84.3	87.7

As seen in the table, VNAV was used a remarkable 96% of the time within the terminal area, prior to glideslope capture. Nearly 88% of this time was in the preferred VNAV PATH mode.

5.2 Trajectory adherence

The FDR data did not contain the FMS vertical path error. This is an internal FMS parameter used by the FMS guidance control laws and displayed to the pilot as a vertical deviation indication on the Navigation Display and text read out on the CDU. With 88% of the airplanes remaining in VNAV PATH throughout the terminal area descent, vertical deviation can be assumed to be quite small. A measure of the trajectory variation between airplanes can be obtained by examining the altitudes and speeds at the key waypoints on the arrival. A summary of the crossing conditions at these key waypoint is given in Table 5-3.

As seen in the table, the aircraft were able to consistently meet the altitude and speed constraints at the bottom of the trajectory. Altitude and speed variations were significant at the CHERI waypoint however this was expected due to weight, wind, and initial descent speed variation between airplanes. A more detailed discussion of airplane performance issues is presented in the next section of this report.

Table 5-3: Crossing conditions at key waypoints

Aircraft				B757-200		B767-300		All
Runway				17R	35L	17R	35L	All
Waypoint	Constraint	Value	Observed					
CHERI	Altitude	--	Average	10872	14324	10647	13082	13214
			Std dev	--	1715	132	1006	1763
			Maximum	10872	16683	10776	14280	16683
			Minimum	10872	10872	10398	10719	10398
	CAS	--	Average	326	333	292	338	328
			Std dev	--	11	29	18	23
			Maximum	326	339	316	350	350
			Minimum	326	292	242	268	242
FLPxx	Altitude	--	Average	4029	4142	4007	3969	4043
			Std dev	--	419	7	67	271
			Maximum	4029	5717	4018	4020	5717
			Minimum	4029	3982	3999	3805	3805
	CAS	--	Average	224	215	228	217	218
			Std dev	--	16	12	8	13
			Maximum	224	232	244	231	244
			Minimum	224	182	216	197	182
TRNxx	Altitude	3800A	Average	3835	3916	3813	3839	3865
			Std dev	--	286	17	22	180
			Maximum	3835	5012	3844	3876	5012
			Minimum	3835	3805	3795	3802	3795
	CAS	--	Average	202	192	206	191	194
			Std dev	--	13	14	9	12
			Maximum	202	209	223	205	223
			Minimum	202	163	194	178	163
INTxx	Altitude	3000	Average	3039	3069	3021	3105	3077
			Std dev	--	46	9	56	55
			Maximum	3039	3186	3033	3195	3195
			Minimum	3039	3006	3005	3004	3004
	CAS	180	Average	182	182	187	179	181
			Std dev	--	12	11	3	9
			Maximum	182	203	201	185	203
			Minimum	182	154	178	172	154

5.3 Usage of speed brake

A major concern in the design of the CDA procedures was the amount of speed brake required to fly the idle-thrust descents computed by the FMS. Without a level, constant speed segment at the bottom of descent, differences in actual airplane performance compared to the FMS performance models, as well as unpredicted tail winds encountered in flight, can result in predicted trajectories that cannot be flown without the addition of extra drag from the speed brakes. The FDR data provided a record of actual speed brake and thrust usage during the descent. A summary of the average speed brake (in percent of full speed brake) and engine power setting (N1 speed) during the descent from CHERI to the glideslope intercept is provided in Table 5-4.

Table 5-4: Speed brake and thrust usage within the terminal area

Aircraft	B757-200		B767-300		All
Runway	17R	35L	17R	35L	All
Average speed brake (%)	16.0	19.2	8.9	18.3	17.4
Average engine N1 (%)	29.4	32.3	33.7	35.1	33.6

The engine setting was very close to idle, as expected. Actual throttle position was not available in the FDR data set for these flights; however, engine N1 settings of about 30% are typical for flight idle. Speed brake usage was seen to be significantly greater than expected, especially for the arrival to runway 35L. During simulation tests, little if any speed brake was required, even with significant tail winds. During the test, nearly every flight showed some speed brake activity. A small percentage of this speed brake activity was not needed, as extra thrust was sometimes added when excessive speed brake was used. In general, however, the speed brake was required to achieve the desired Final Approach Fix crossing conditions.

6 Analysis of Aircraft Performance

An analysis of the aircraft performance of four flights––two performing a CDA and two performing a conventional approach––is presented in this section to help explain the sources of the flight time, fuel burn, emissions and noise that will be presented in the subsequent sections of this report. However, before the comparison between the flights is presented, it is necessary to explain how the data was processed to remove artifacts of the flight data recorder, and how two along track distances were computed to better illustrate the differences between the flights.

6.1 Data Processing

FDR data were preprocessed before they were used for further analysis. Altitude data contained in the data set included both pressure altitude and radio altitude. The pressure altitude below 18,000 ft was corrected to present altitude above mean sea level. The altitude correction was obtained for each flight by comparing the value of pressure altitude, the value of radio altitude, and field elevation, all at the threshold of the actual runway used. This correction was done in such a way that the correction at ground level was 100% of the correction, no correction at 18,000 ft, and linearly interpolated in between.

The FDR system on several older UPS Boeing 757-200 aircraft used Inertial Reference Unit (IRU) as position data source for current aircraft position rather than GPS as used by all other B757-200 and B767-300 aircraft in the UPS fleet. The latitude and longitude fields in the FDR data from those B757-200 aircraft were often shifted from actual position. The shifted latitude and longitude were corrected through comparing the FDR position with corresponding expected position at two points, one at a waypoint on the CDA arrival, another one at the airport surface. The raw data and the corrected flight path of one flight on 15 September are shown in Figure 6-1 to illustrate this effect.

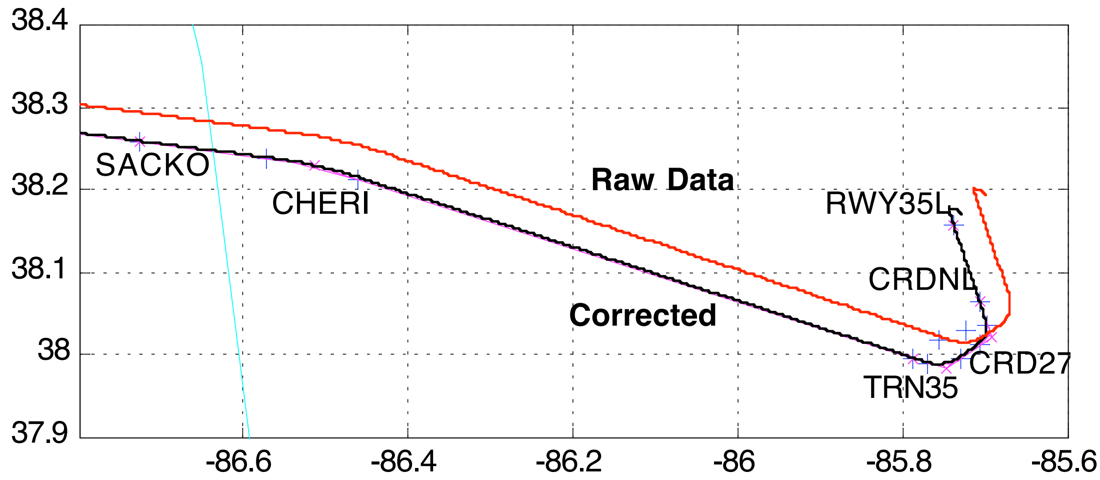


Figure 6-1: Latitude/longitude correction

6.2 'Computed' Along Track Distances Used in this Section

Two different along track distances were also computed and added to the processed FDR data. The first 'computed' distance was the distance along a nominal flight path. This distance was computed by first projecting the current aircraft position onto the nominal flight path, then computing the distance of the projected point to the runway threshold along the nominal flight path. In this section, this distance is referred to as the distance to the runway threshold. The second 'computed' distance was the distance flown by the aircraft. This distance was computed by integrating the distance between the position data points. In this section, this distance is referred to as the distance flown.

The rationale for computing these two distances is as follows. If two aircraft were at the same location, their distance to runway would be the same whether the aircraft was vectored or not. Thus, the distance to the runway is a good indicator of the progress that an aircraft is making during the approach. On the other hand, if two aircraft were at the same location, their distance flown would be different if one aircraft was vectored, or both were vectored (but not in the same way). Thus, distance flown is an indicator of the difference between aircraft trajectories due to vectoring.

6.3 Comparison of Sample CDA with Conventional Approach Trajectories

A CDA to runway 35L on 15 September––performed by a B757-200––and a CDA to runway 35L on 22 September––performed by a B767-300––were selected to represent the best CDA performance by the two aircraft types. A conventional approach (abbreviated as STD) to runway 35L on 28 September––performed by a B757-200––and a conventional approach to runway 35L on 8 September––performed by a B767-300––were selected to represent typical conventional flights. Sample raw data for the CDA and conventional approach trajectories are shown in sections 1.3 and 1.4 of the appendix, respectively. The two conventional flights were selected because they were in the midst of the laterally vectored approaches that compose the majority of conventional flights. Occasionally, when the traffic was light and the weather condition was good, the controller might clear a flight for visual approach. In such a case, the flight would not be heavily vectored thus would have a ground track close to a CDA, but the vertical profile and speed profile would still be different from that of a CDA. CDA and conventional approaches to runway 17R were similar to the ones to runway 35L in terms of generic procedure characteristics. In the analysis below, distance to runway was computed based on the CDA flight path.

6.3.1 Differences in Ground Track

The ground tracks of the four flights are shown in Figure 6-2. As shown, the ground tracks of the two CDA flights were right on top of each other. In fact all the un-interrupted CDA flights for the same procedure had the same ground track. Within the terminal area, the ground tracks of the two conventional or STD flights were very different from each other due to vectoring by ATC. The standard vectoring techniques were developed to control the separation between successive aircraft and to maximize traffic through put. However, the lateral vectoring increased the distance flown and time spent by the aircraft within the terminal area. In the vectored conventional approaches, aircraft spread noise to a larger area of communities.

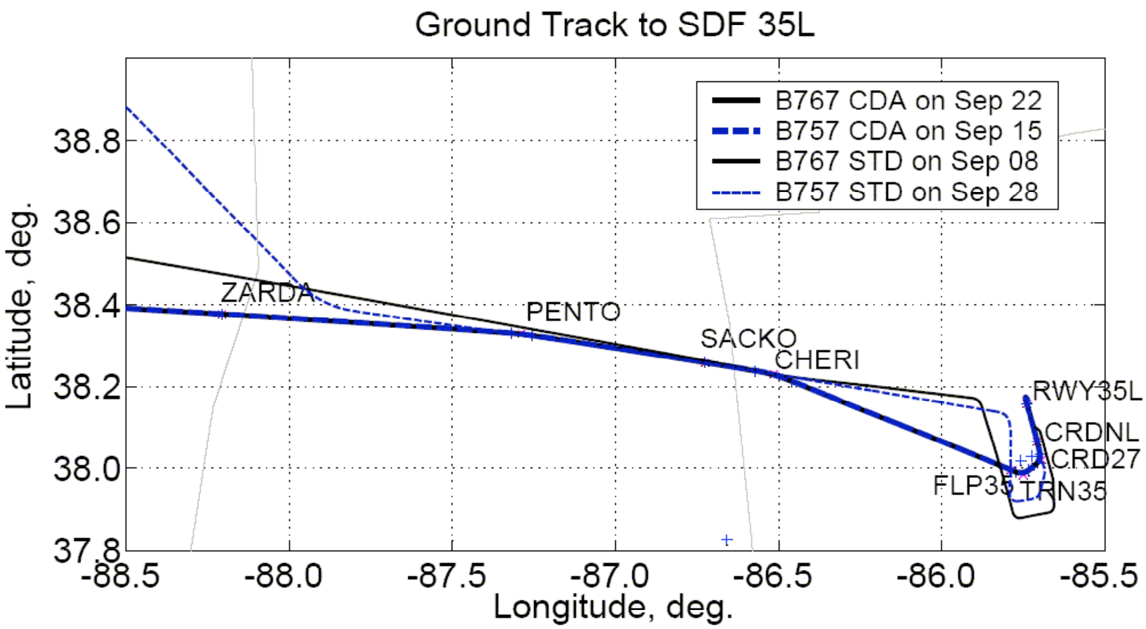


Figure 6-2: Ground track

6.3.2 Differences in Altitude Profile

The altitude of the four flights is shown in Figure 6-3 versus distance flown. Below the speed transition altitude (10,000 ft), the vertical profile of the B767-300 and the B757-200 performing the CDA were similar. In contrast, the two conventional approaches were different from each other. As shown, the two aircraft that performed the conventional approach descended sooner and thus flew lower over the community. The figure clearly shows the conventional flights performed step down descents. There were several level segments, measuring up to 10 nm in length. On the other hand, the CDA flights performed continuous descent. The shallower segments end at 10,000 ft and 4,000 ft were devised to slow down the aircraft with power set to idle. Between 15 and 20 nm away from the runway, CDA flights were up to 1,500 ft higher. This is one of the reasons why CDA has a lower noise impact than conventional approaches. As shown in the figure, above the speed transition altitude, there were apparent differences between the two CDA vertical profiles. This was due to the aircraft weight, wind conditions, and the difference between the aerodynamics characteristics of the two aircraft types.

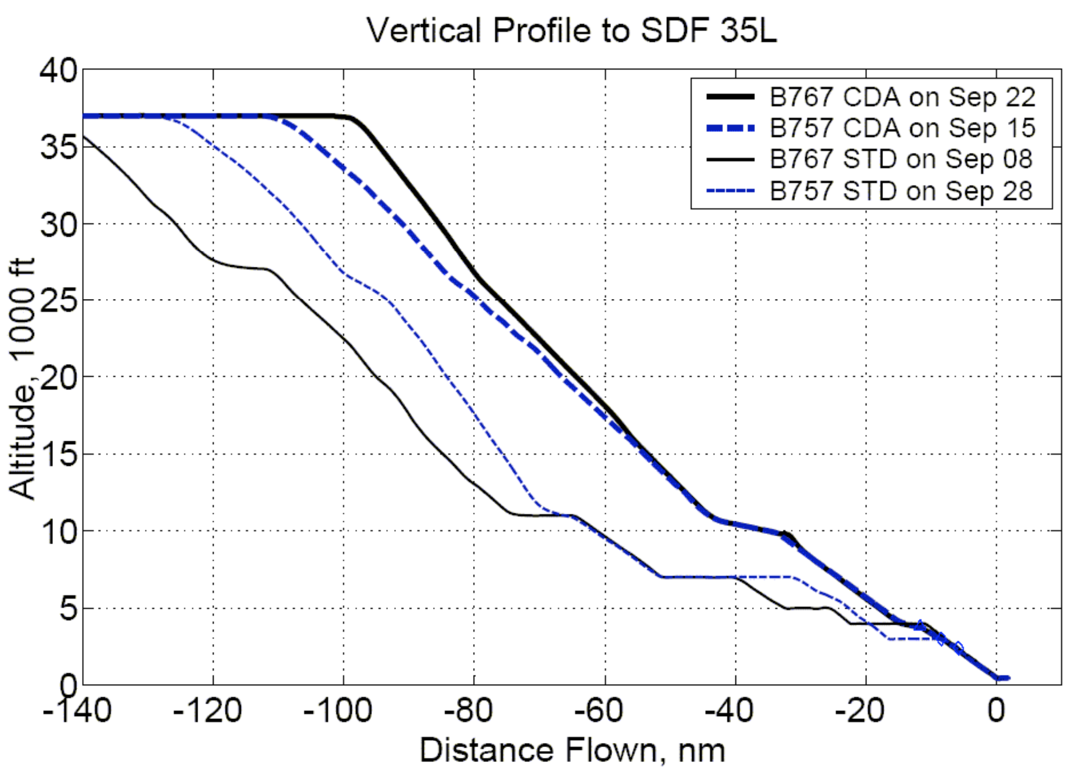


Figure 6-3: Altitude v. distance to runway

6.3.3 Differences in Fan Speed

CDA flights also had lower source noise. The corrected fan speed (average for both engines) of the four flights is shown in Figure 6-4 versus distance to runway. It can be seen from the figure that the engines were operating at nearly idle all the way from top of decent (TOD) until the aircraft captured ILS glide slope during the CDA. In comparison, the conventional approaches had extended engine spool ups mainly due to the long level segments. Thus, the engine noise was louder during the conventional approaches. This also indicated CDA approaches consumed less fuel than the conventional approaches. Fuel consumption will be discussed in further details later.

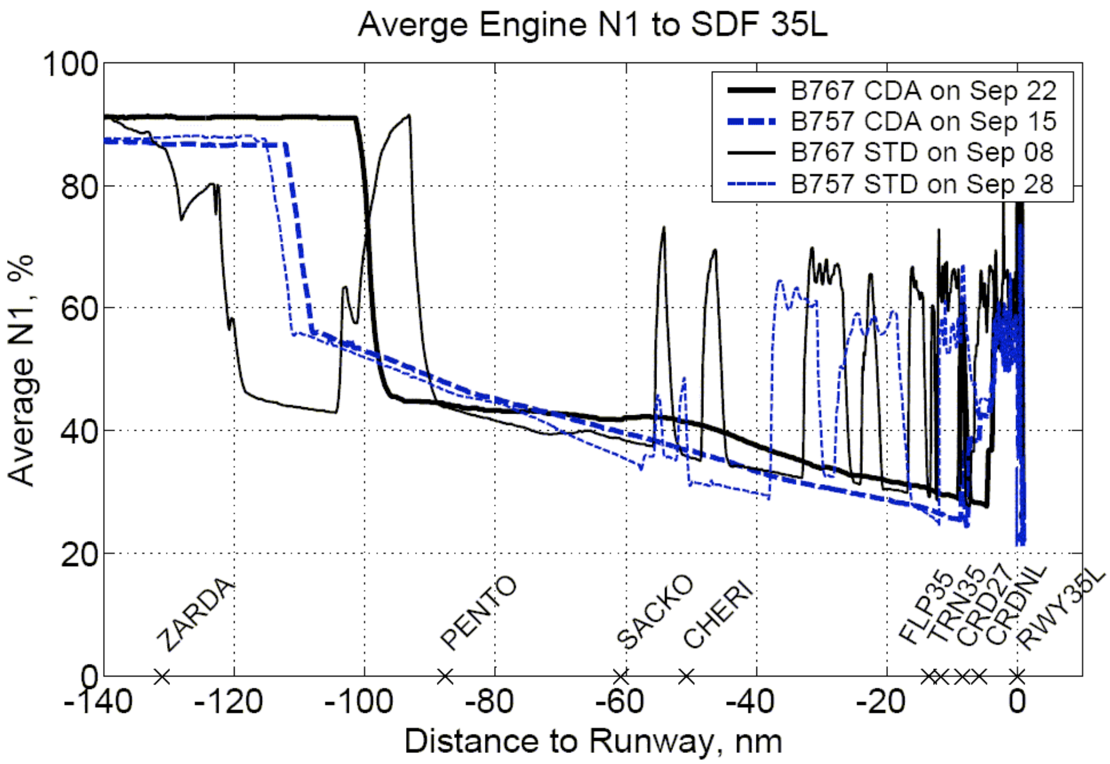


Figure 6-4: Corrected fan speed v. distance to runway

6.3.4 Differences in Flap Extension

The other major source noise component is airframe noise, which is a function of aircraft configuration--flap and landing gear position. The flap position of the four flights is shown in Figure 6-5 versus distance to runway. As the figure shows, the flap was extended to higher flap settings at a later time during the CDA relative to the conventional approaches, resulting in lower aerodynamic drag and lower airframe noise.

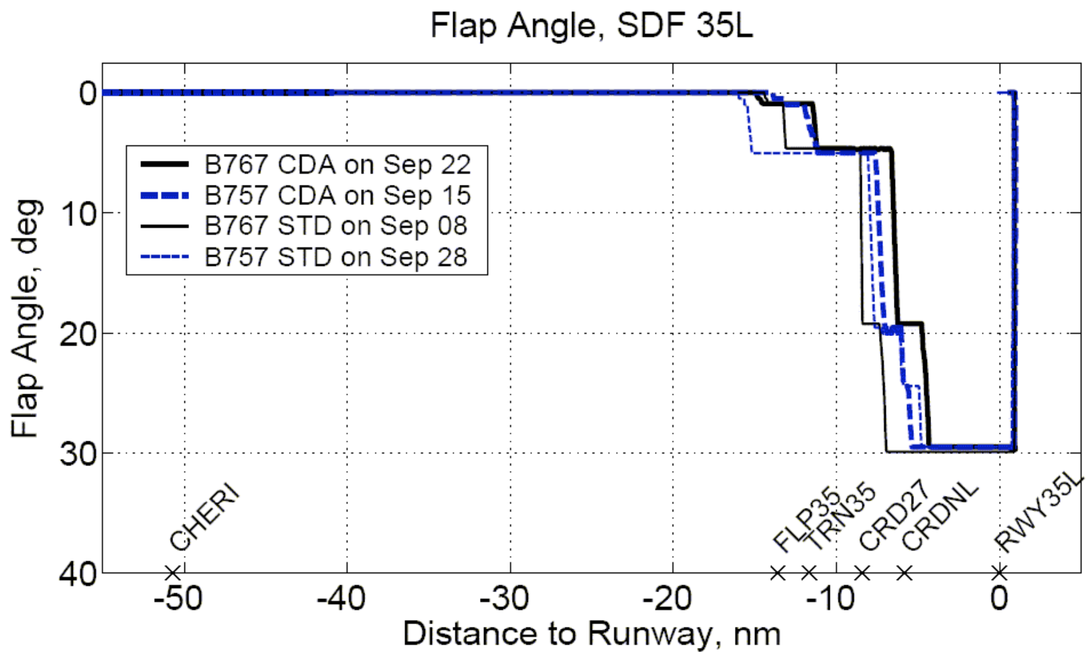


Figure 6-5: Flap position v. distance to runway

6.3.5 Differences in Speed Brake Usage and Speed Profile

The speed brake usage of the four flights is shown in Figure 6-6 versus distance to runway. Speed brake was used extensively by the two conventional flights during their descent to the speed transition altitude. This was necessary to slow the aircraft during the descent. As also shown in the figure, the two conventional flights used slower descents speeds than the CDA flights. Speed brakes were not used by the two conventional flights below the speed transition altitude because during that time the conventional flights were performing a step down descent and therefore needed no additional drag.

The two CDA flights used speed brakes briefly while above the speed transition altitude, however most of their speed brake usage occurred below the speed transition altitude. As shown in the figure, the B767-300 performing the CDA on 22 September used more speed brakes than the B757-200 performing the CDA on 15

September. There are two possible reasons for this greater use of speed brakes by the B767-300. First, the flight crew may not have entered forecast winds in the FMS, thus leaving the FMS to compute the VNAV descent path assuming calm conditions when in fact the aircraft was descending with a tail wind. Second, the forecasted tail winds entered into the FMS were lower than the actual tail winds experienced by the aircraft, thus requiring more speed brake usage to dissipate energy and thereby stay on the computed path. It was not possible to verify whether forecast winds were entered in the FMS for the B767-300 performing the CDA on 22 September.

Regardless, speed brake usage at low altitude increases airframe noise and should thus be minimized. Additionally, speed brake usage at any point during the descent means that the descent could have been started earlier thus reducing fuel-burn as the aircraft would have been at idle for longer.

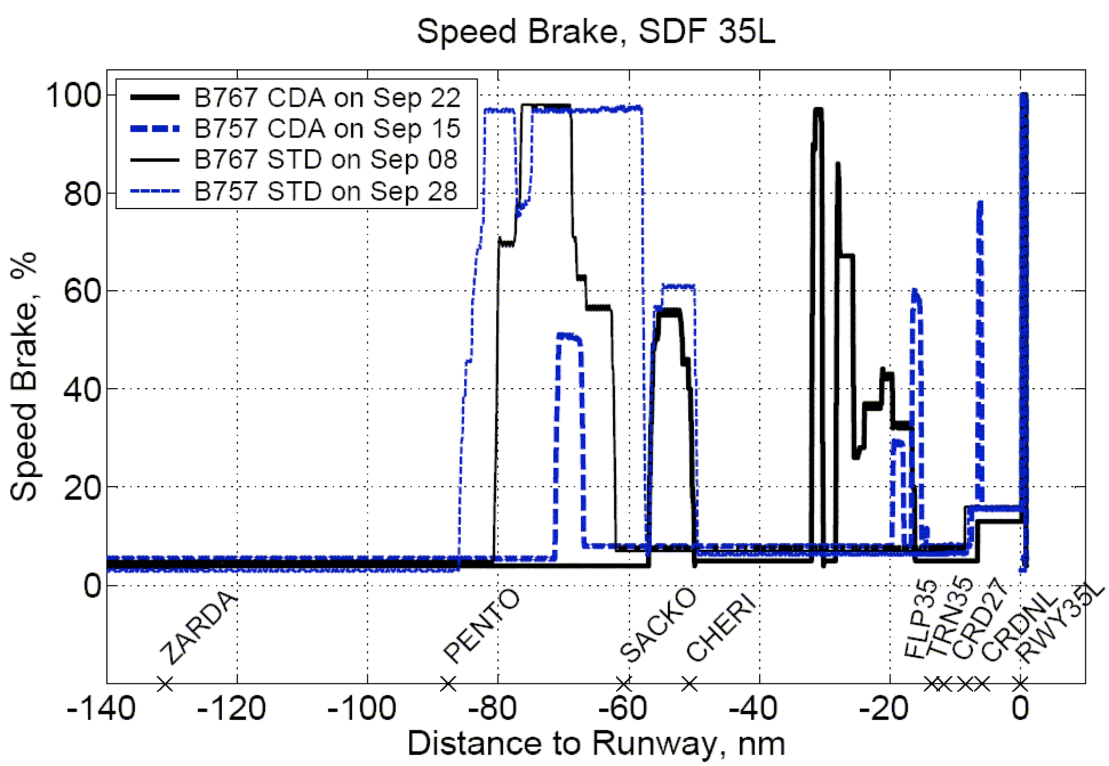


Figure 6-6: Speed brake usage v. distance to runway

As shown in Figure 6-7, in addition to the speed difference above speed transition altitude, the two conventional flights performed segmented constant speed approaches in the terminal area. While the CDA flights kept speed high until near the waypoint FLP35, then started continuous deceleration until reaching the appropriate final approach speeds thus staying in the lowest drag state for as long as possible.

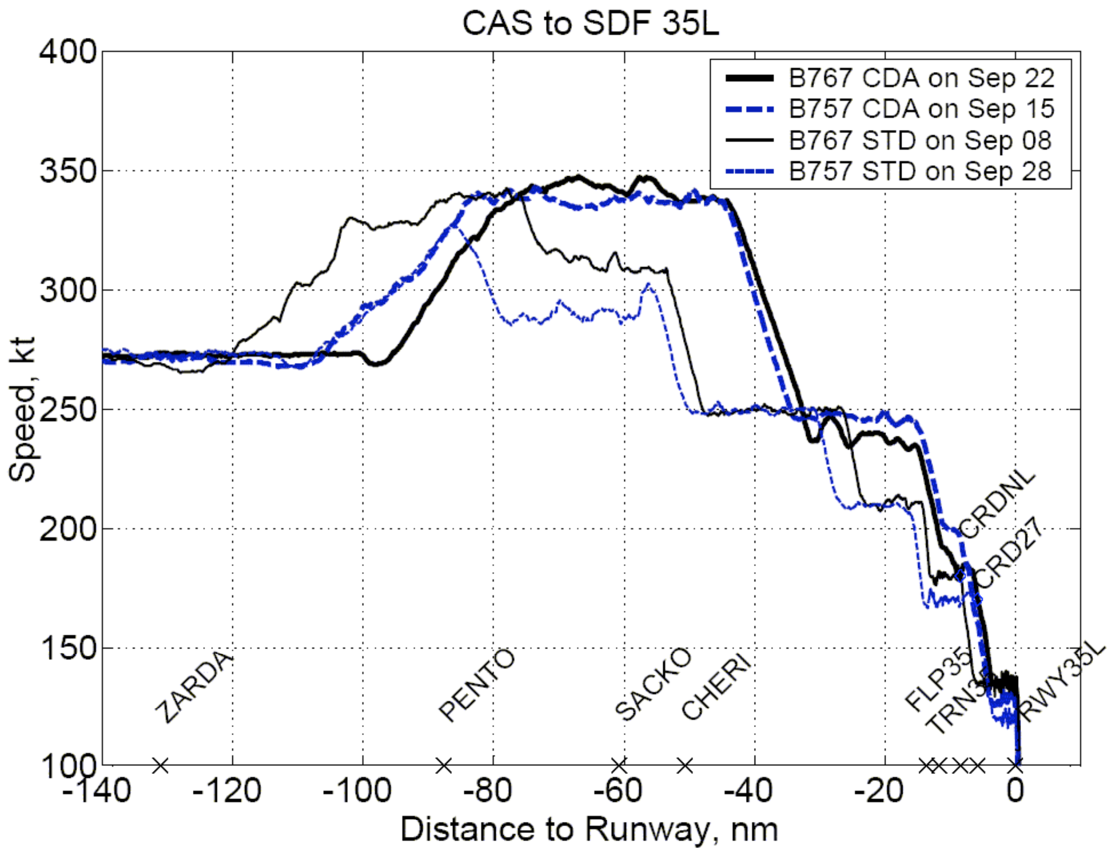


Figure 6-7: Calibrated speed v. distance to runway

6.3.6 Differences in Flight Time

In addition to noise reductions, CDA also saves flight time and fuel. The time for the four flights in question to fly a specified distance to the runway is shown in Figure 6-8 versus distance to runway. The overall time savings shown in the figure were over 450 sec, or over 7.5 min. This is significant savings especially for UPS. It means more time for package sorting. This savings were due to both a higher speed and the elimination of vectoring in the terminal area. As also shown in the figure, most of savings in time were achieved within the terminal area, i.e. after the aircraft had passed the waypoint CHERI.

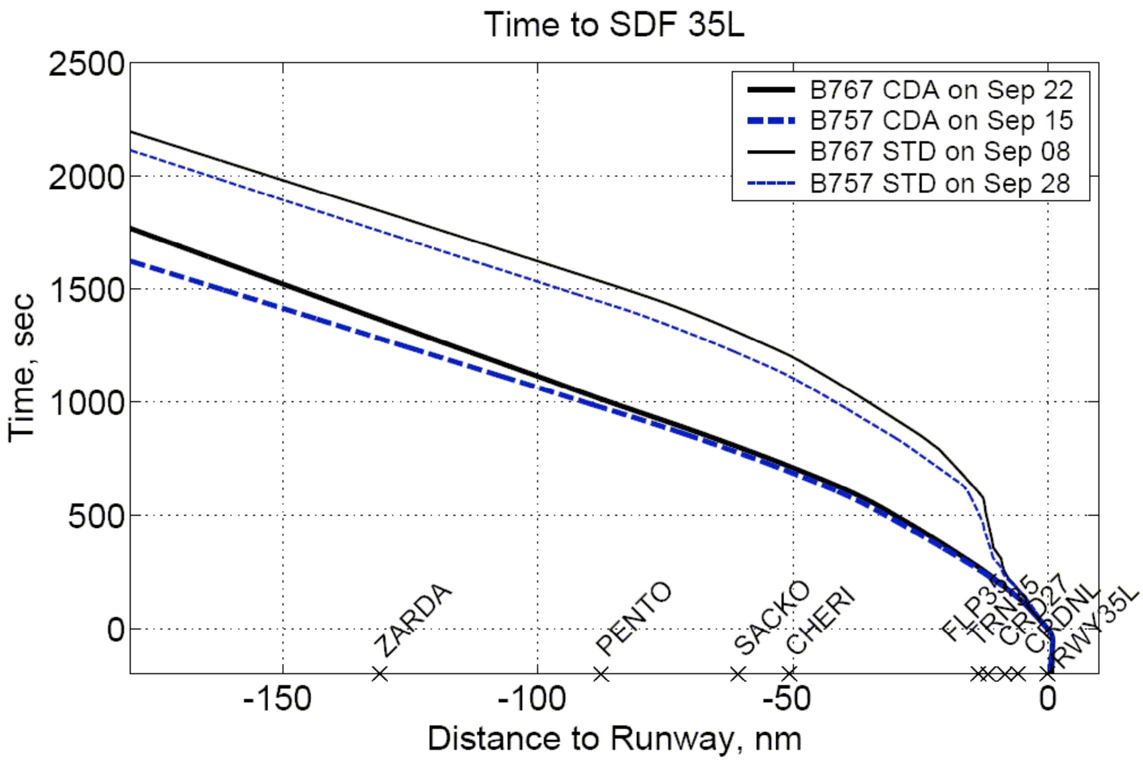


Figure 6-8: Time to fly v. distance to runway

6.3.7 Differences in Fuel Consumption

Fuel consumption during the four flights from a specified distance to runway is shown in Figure 6-9 versus distance to runway. For the two flights with B757-200 aircraft, the CDA approach on 15 September consumed approximately 900 lb less fuel than the conventional approach on 28 September. For the two flights with B767-300 aircraft, the CDA approach on 22 September consumed approximately 1,500 lb less fuel than the conventional approach on 8 September. The conventional approaches burnt more fuel mainly because of the higher engine thrust required by the level flight segments, and the longer flight time due to lateral vectoring. As with the time to fly a specified distance, similar to the time to fly, most of savings in fuel were achieved within the terminal area.

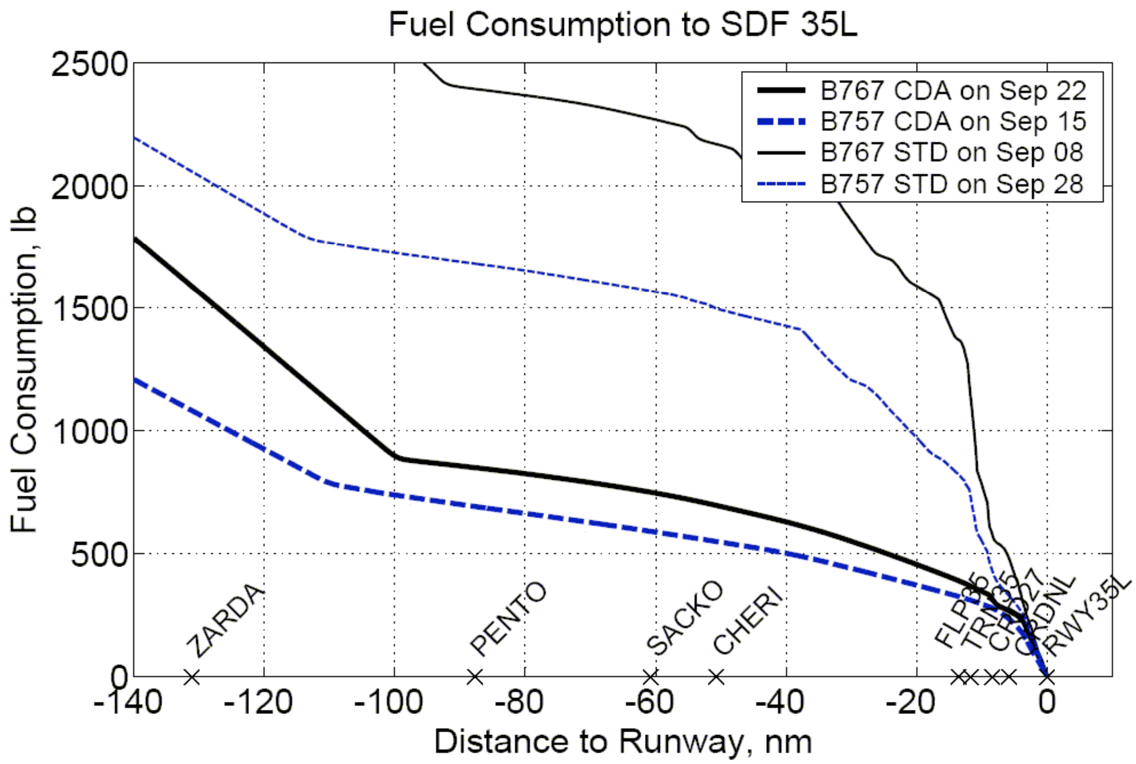


Figure 6-9: Fuel consumed v. distance to runway

6.4 Summary

The comparisons presented above are between specific flights on different days. There is no doubt that many factors such as weather, aircraft weight, equipage difference between the same aircraft type played a rule in the actual numbers. However, the analysis does reveal the characteristic differences between CDA approaches and conventional approaches. The sources of noise abatement benefits and time and fuel savings are also discussed. In the next section, analysis will be performed over all the flights for which data were available to provide statistics on the flight time and fuel consumptions savings.

7 Analysis of Flight Time and Fuel Consumption

In this section, flight time and fuel consumption are reported from the point along the trajectory of each aircraft that is at a distance that is equivalent to a straight-line distance of 180 nautical miles from the center of the airport. As will be discussed in subsections 7.1 and 7.2, the ‘equivalent’ or ‘normalized’ distance to the airport is determined by first adjusting the trajectory to account for the effects of test artifacts and wind, and then projecting the trajectory onto a ‘nominal’ direct path to the center of the airport. Note that there is one nominal direct path to the airport for each entry fix. It is also important to note that the distance of 180 nautical miles is far enough away from the airport that all aircraft will be at their cruise altitude and all vectoring to ‘condition’ the stream of aircraft performing the CDA will be included.

After the removal of trajectories that was deemed unacceptable for analysis (see discussion in section 5) the resulting dataset for aircraft performing CDA included trajectories for: zero B757-200 and 2 B767-300 aircraft performing CDA to runway 17R; 28 B757-200 and 23 B767-300 aircraft performing CDA to runway 35L. Given the scarcity of data for aircraft performing CDA to runway 17R, only the trajectories for aircraft performing CDA to runway 35L were analyzed. These trajectories were then compared to the 33 B757-200 and 32 B767-300 approaches to runway 35L that are listed in Table 2-1. The results of that comparison are presented here.

7.1 Accounting for the Effects of Test Artifacts and Wind

Before computing the normalized distance to the airport, it was first necessary to determine how to accounting for the effects of test artifacts and wind.

7.1.1 Accounting for the Effects of Test Artifacts

All the aircraft performing the CDA were required to follow a single CDA routing as opposed to flying to the nearest terminal area entry fix and then directly to the airport. A single CDA routing was deemed necessary for the sake of simplicity and to create sufficient traffic volume to ensure the statistical validity of the analyses to be performed. In regular operation it is expected that there would be a CDA routing via each entry fix and that aircraft would simply use the CDA routing via the nearest terminal area entry fix. Thus, the extra distance that some CDA aircraft had to fly is solely an artifact of the testing procedure and must therefore be properly accounted for.

This test artifact is accounted for by developing nominal routings to the airport via each entry fix so that the distance to the runway is a function of the fix that is used to enter the terminal area rather than the straight-line distance between the current position and the center of the airport. For example, an aircraft that is at a straight-line distance of 250 nautical miles from the center of the airport will have different distances to the airport depending on the entry fix that it used. The greater the distance to an entry fix the greater the distance to the airport. Thus, aircraft will not be penalized for being forced to fly through a fix that is not the nearest entry fix.

7.1.2 Accounting for the Effect of Wind

For aircraft following a prescribed routing, the along track component of the wind has a direct impact on the ground speed and thus the distance traveled by an aircraft in a given time period. Additionally, the cross track component of the wind has an indirect effect on the ground speed because the heading of the aircraft must be adjusted to counter the drift that would be induced by the crosswind if the heading were left unchanged. Therefore, the distance that an aircraft travels along the prescribed routing is a function of the wind field through which is travels on a particular day.

The effect of wind was removed from all the trajectories that were analyzed by calculating the distance that the aircraft would have traveled in a scenario where there is no wind. That is, for each segment in a given trajectory, the distance traveled in the corresponding time increment was adjusted based on the local wind conditions at that location (in three dimensions) and that time. The effects of the crosswind and the headwind/tailwind were removed simultaneously by subtracting the wind components from the translational movement of the aircraft.

7.2 Normalized Distance to the Airport

Before describing how the distance to the airport was calculated, it is instructive to describe the nominal CDA and conventional routings upon which the computation is based.

7.2.1 Nominal CDA Routing

The nominal CDA routing is defined by the sequence of four straight-line segments between ENL and CHERI––the sequence being ENL to ZARDA to PENTO to SACKO to CHERI––and thereafter successive straight-line segments to the turn waypoint, intercept waypoint and threshold of the designated runway. During the flight test, air traffic controllers were instructed to merge the aircraft performing the CDA onto the nominal CDA ground track at

ENL, ZARDA or CHERI depending on traffic volume. Thus, the distance to the airport via the nominal CDA routing is not the straight-line distance between the current position of the aircraft and the center of the airport. Rather, it is the straight-line distance between the current position of the aircraft and the point where the aircraft merges onto the nominal CDA routing plus the distance from the merge point to the threshold of the designated runway along the nominal CDA routing.

7.2.2 Nominal Conventional Routings

Although the majority of aircraft performing the conventional approach entered the terminal area via CHERI, a few aircraft entered the terminal area via MAIZE, which is a waypoint to the Northwest of the waypoint CHRCL. Thus, it was necessary to develop nominal conventional routings for aircraft entering the terminal area via CHERI, and for aircraft entering the terminal area via MAIZE.

Aircraft entering the terminal area via CHERI follow the prescribed arrival procedure to CHERI (this is the CHERI TWO arrival used as the basis for the CDA routing) and then, when there was no vectoring due to traffic volume, fly directly from CHERI to the final approach fix and threshold of the appropriate runway. Because the CDA routing shares common waypoints with the CHERI TWO arrival, the initial part of the nominal conventional routing is defined by the same sequence of four straight-line segments between ENL and CHERI but thereafter by straight-line segments to the final approach fix and threshold of the designated runway. Thus, the distance to the airport via the nominal conventional routing through CHERI is the straight-line distance between the current position of the aircraft and the point where the aircraft merges onto the routing plus the distance from the merge point to the threshold of the designated runway along the routing.

Aircraft entering the terminal area via MAIZE follow the prescribed arrival procedure (or a direct routing) to MAIZE. Then, aircraft destined for runways 17L and 17R would, when there was no vectoring due to traffic volume, fly directly to the final approach fix and threshold of the appropriate runway. However, aircraft destined for runways 35L and 35R would, when there was no vectoring due to traffic volume, fly directly from MAIZE to a point abeam the appropriate final approach fix, then along the ‘base leg’ to the final approach fix, and thereafter to the threshold. Whatever the details of the particular routing, the distance to the airport via the nominal conventional routing through MAIZE is the straight-line distance between the current position of the aircraft and the point where the aircraft merges onto the routing plus the distance from the merge point to the threshold of the designated runway along the routing.

7.2.3 Computing the Distance to the Airport

As you will note from the descriptions above, all aircraft entering the terminal area via CHERI use components of the existing CHERI TWO arrival procedure during the transition to the entry fix. Thus, during this phase of the arrival, the distance that the aircraft must travel to get to the airport is simply the distance along the routing. The same would be true is an CDA routing had been developed for arrivals through MAIZE.

However, before joining these common routing segments, there are significant differences between the trajectories of the aircraft. Similarly, there are also significant differences between the CDA and conventional routings within the terminal area. Thus, there is a need for a common definition of distance when the aircraft are not on these common routing segments.

With these observations and objectives in mind, the following definitions for the distance to the airport were developed. For aircraft outside the terminal area, the distance to the airport it is the straight-line distance to the point where the aircraft merges onto the common routing segments plus the distance along the common routing segments to the appropriate entry fix (either CHERI or MAIZE) plus the straight-line distance from the entry fix to the center of the airport. For aircraft inside the terminal area, the distance to the airport it is simply the straight-line distance to the center of the airport.

7.3 Analysis of Flight Time

The time to fly the last 180 nautical miles to the airport is shown in Figure 7-1. As shown in the figure, the average flight time for B757-200 aircraft performing the CDA is 1,808 seconds while the average flight time for B757-200 aircraft performing the conventional approach is 1,926 seconds, representing a reduction in flight time of 118 seconds. The average flight time for B767-300 aircraft performing the CDA is 1,797 seconds while the average flight time for B767-300 aircraft performing the conventional approach is 1,944 seconds, representing a reduction in flight time of 147 seconds. A two-sample t-Test assuming unequal variances [Box et al. 1978] was performed on the data for the aircraft performing a CDA and the data for the aircraft performing a conventional approach. For a confidence level of 0.05, the one tail t-Test gives ($df = 46$, $t\text{-Stat} = 4.47$, $p = 0.000025$) and ($df = 36$, $t\text{-Stat} = 4.87$, $p = 0.000011$) for the B757-200 and B767-300 respectively, indicating that the reductions in flight times are statistically significant ($p \ll 0.05$).

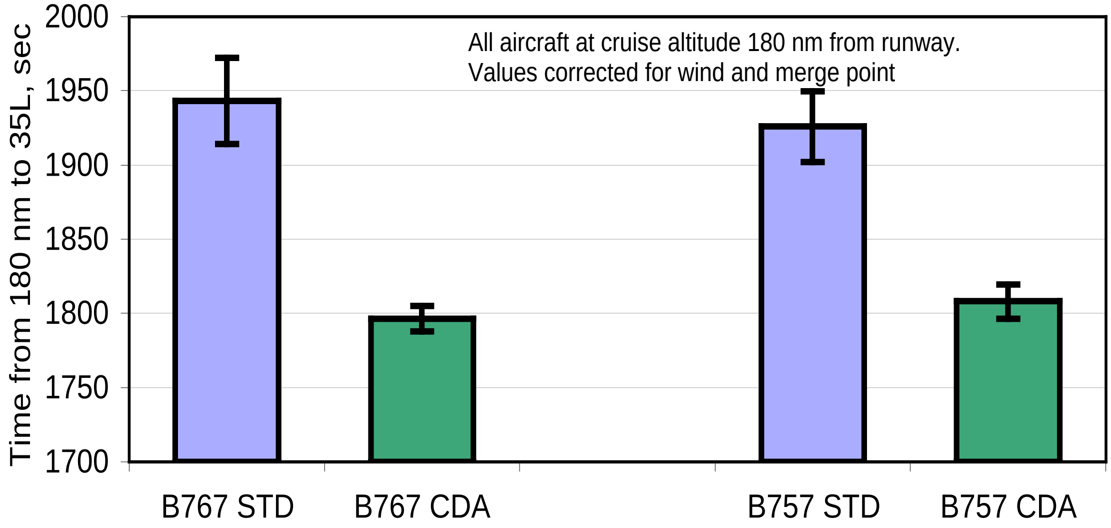


Figure 7-1: Time to fly last 180 nautical miles to runway 35L

The majority of the flight time reduction is achieved in the terminal area. This is to be expected given the significant reduction in vectoring at the lower speeds that are typical within the terminal area.

7.4 Analysis of Fuel Consumption

The fuel consumed over last 180 nautical miles to runway 35L is shown in Figure 7-2. As shown in the figure, the average amount of fuel consumed by B757-200 aircraft performing the CDA is approximately 2,308 pounds while the average amount of fuel consumed by B757-200 aircraft performing the conventional approach is approximately 2,426 pounds, representing a reduction in fuel consumption of approximately 118 pounds. The average amount of fuel consumed by B767-300 aircraft performing the CDA is approximately 2,937 pounds while the average amount of fuel consumed by B767-300 aircraft performing the conventional approach is approximately 3,301 pounds, representing a reduction in fuel consumption of approximately 364 pounds. A two-sample t-Test assuming unequal variances was again performed on the data for the aircraft performing a CDA and the data for the aircraft performing a conventional approach. For a confidence level of 0.05 the one tail t-Test gives (df = 57, t-Stat = 1.45, p = 0.076) and (df = 47, t-Stat = 4.12, p = 0.000076) for the B757-200 and B767-300 respectively. These results indicate that the reduction in fuel consumption for B767-300 aircraft is statistically significant, while the reduction in fuel consumption B757-200 aircraft is not statistically significant. The later is due to the relatively large performance variations in the UPS B757-200 fleet.

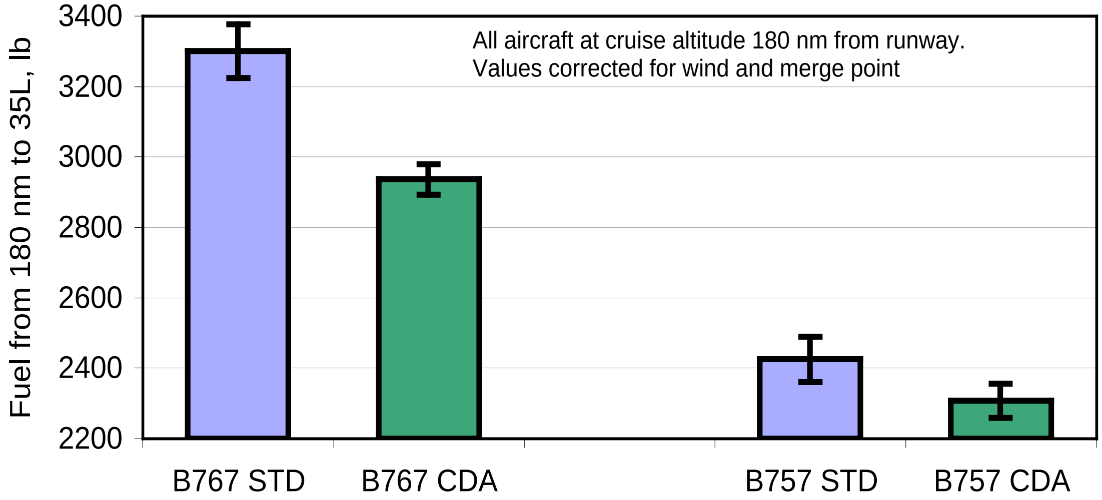


Figure 7-2: Fuel Consumed over last 180 nautical miles to runway 35L

As in the case of flight time, the majority of this reduction in fuel consumption is achieved in the terminal area. This is to be expected given the significant reduction in vectoring at the lower speeds and lower altitudes within the terminal area.

8 Analysis of Emissions

The focus of the emissions analysis was the emissions produced in the boundary (mixing) layer during the approach/landing phase. Typically this is the region within 3,000 ft of the airport altitude. This region is an important one in which to determine emissions because the emissions that are produced up to a height of 3,000 ft above ground level may play a role in local air quality. Hence the assumption in all Landing and Take-Off (LTO) cycle calculations for the corresponding ICAO emissions standard is that the mixing layer extends from the ground to 3,000 ft above ground level. Thus, it is very appropriate that the difference in the emissions produced by aircraft performing the CDA and aircraft performing the conventional approach be determined for this region.

To that end, the available flight recorder data from several cases(see Table 3-2 and 3-3) was used to estimate the NOX, CO, and HC produced by the B757-200 and B767-300 aircraft performing the CDA and the conventional approach. The first step toward calculating emissions, however, was to extract fuel flow and flight condition data from the flight data recorder which has an update rate of once per second for the entire flight. The parameters extracted were time, pressure altitude, calibrated airspeed, static air temperature and fuel flow rate for each engine as listed in Table 8-1.

time, sec	Press Alt, ft	Static Air Temp, deg C	CAS, kts	Eng 1 Fuel flow, lb/hr	Eng 2 Fuel Flow, lbs/hr
12562	3037	21.8	180	2879	2815
12563	3018	21.8	180.5	2687	2623
12564	2997	21.8	180.5	2496	2431
12565	2976	21.8	181	2336	2240
12566	2957	21.8	181	2144	2080
12567	2939	22	181	2016	1920
12568	2921	22	181	1888	1792
12569	2904	22	181.5	1792	1696
12570	2886	22	181.5	1664	1568

Table 8-1 Sample flight data input for emission calculations

The fuel flows for both engines were averaged together for each data point. As there was no relative humidity recorded during the conditions, 60% relative humidity was assumed. The numbers of datapoints were reduced to include only the data for the descent and arrival flight segment that fell between a pressure altitude of 3,000 ft and where the aircraft crossed the runway threshold. The total emissions expelled during this segment of flight were then calculated then using the Boeing Fuel Flow Method 2.

Method2 allows one to take the reported sea level static emissions index vs. fuel flow characteristic and both interpolate power setting and correlate to other flight conditions. For details on the method see NASA CR-4700, “Scheduled Civil Aircraft Emissions Inventories for 1992: Database Development and

Analysis", April 1996. The CDA procedure, while starting at top of descent, has its largest impact on emissions once one reaches the baseline flight conditions where typically the engine throttles are moved off of idle and other airplane attitude and flap/slat/gear configurations are changed. This is commonly referred to as the approach/landing phase of the flight. The differences in calculated emissions between the baseline and CDA procedures during the descent phase from cruise altitude up until this point are small, on the order of 3 percent. Note, these calculations compared data as flown and did not take into account, differences in wind conditions and flight plans. As the descent phase showed little sensitivity to the procedure chosen, the focus of this study concentrated on the emissions occurring in the boundary (mixing) layer during the approach/landing phase. Typically this is the region below 3000' above airport altitude. This is also the assumed mixing layer altitude for the ICAO emissions standards Landing and Takeoff (LTO) cycle. For this reason it is more appropriate to compare the difference in emissions between the CDA procedure and current procedures at altitudes below 3000'.

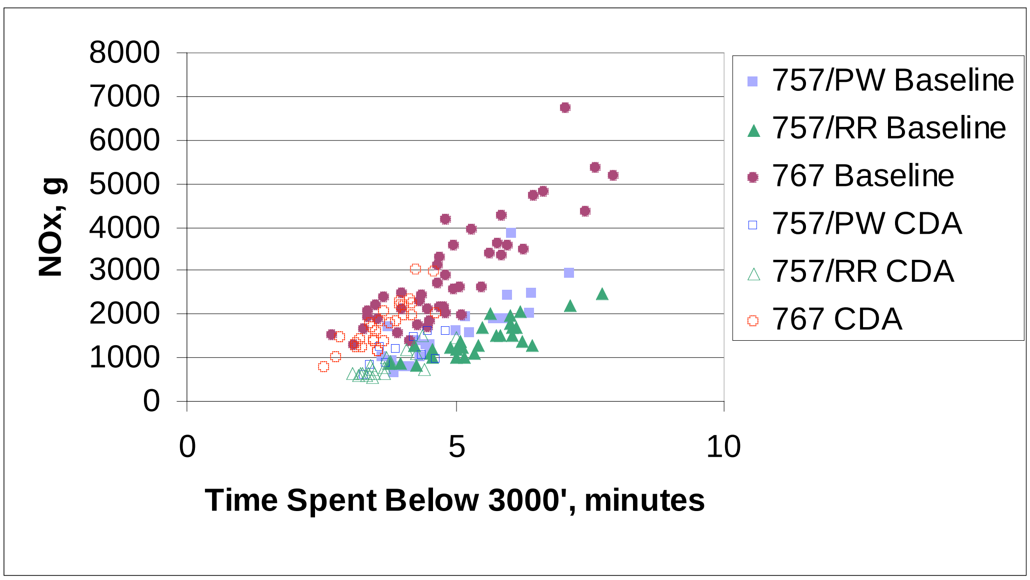


Figure 8-1a NOx produced by the B757-200 and B767-300 aircraft vs. time

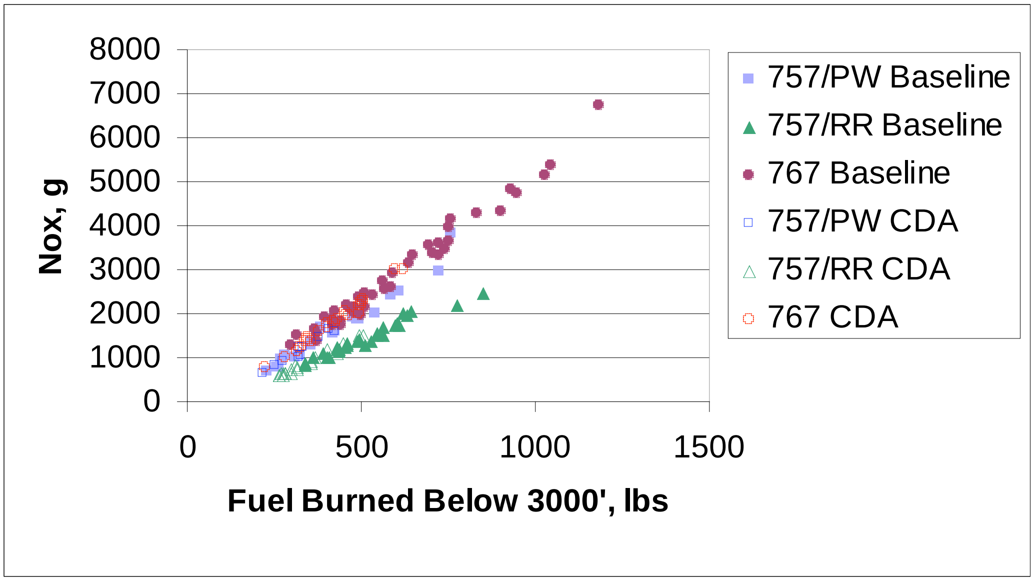


Figure 8-1b NOx produced by the B757-200 and B767-300 aircraft vs. fuel burned

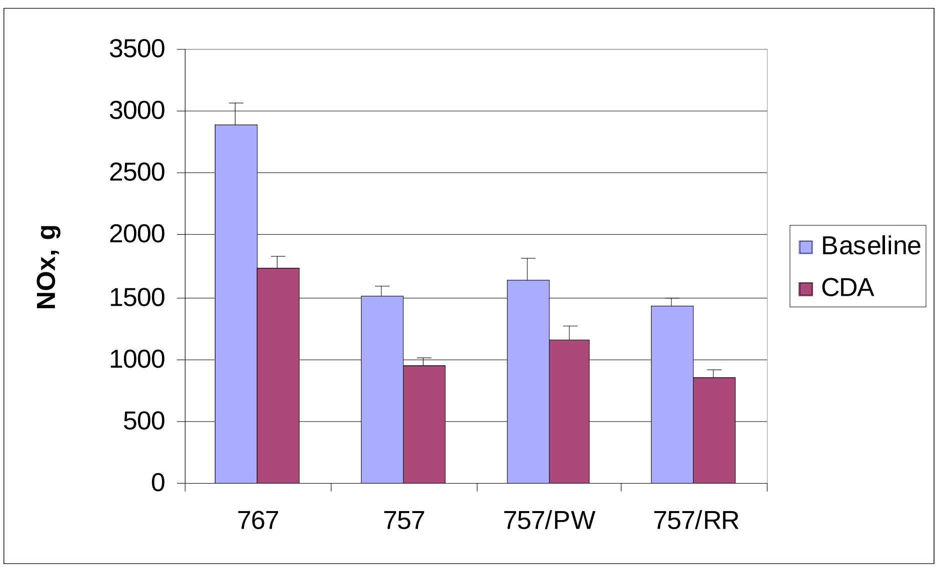


Figure 8-1c Average NOX produced by the B757-200 and B767-300 aircraft

The NOx produced by the B757-200 and B767-300 aircraft performing the CDA and the conventional approach are shown in Figure 8-1a and 8-1b versus time and fuel burned respectively. It is noted that combined 757 emission results are shown as well as a separation by Pratt and Whitney (PW) and Rolls Royce (RR) engine types. During the CDA testing aircraft spent less time and burned less fuel resulting in lower NOX production than during the baseline weeks. As shown in Figure 8-1c, the average NOx produced by the B757-200 is reduced by 37.0%, from 1510g to 951g. The corresponding reduction for the B767-300 is 39.9%, from 2882g to 1732g. These significant reductions in NOx were not surprising as they are very much in line with those reported by Lee [Lee 2005].

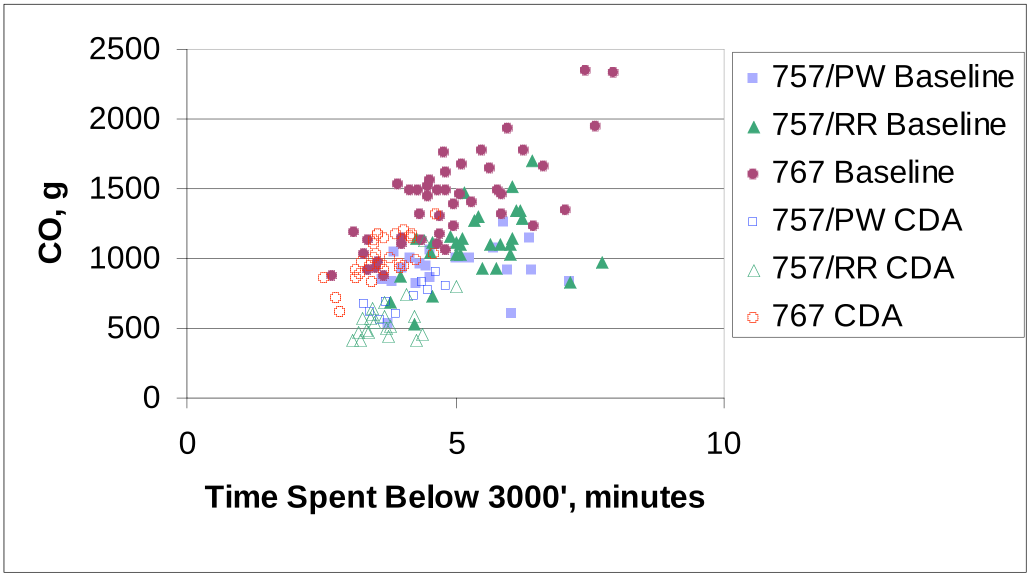


Figure 8-2a CO produced by the B757-200 and B767-300 aircraft vs. time

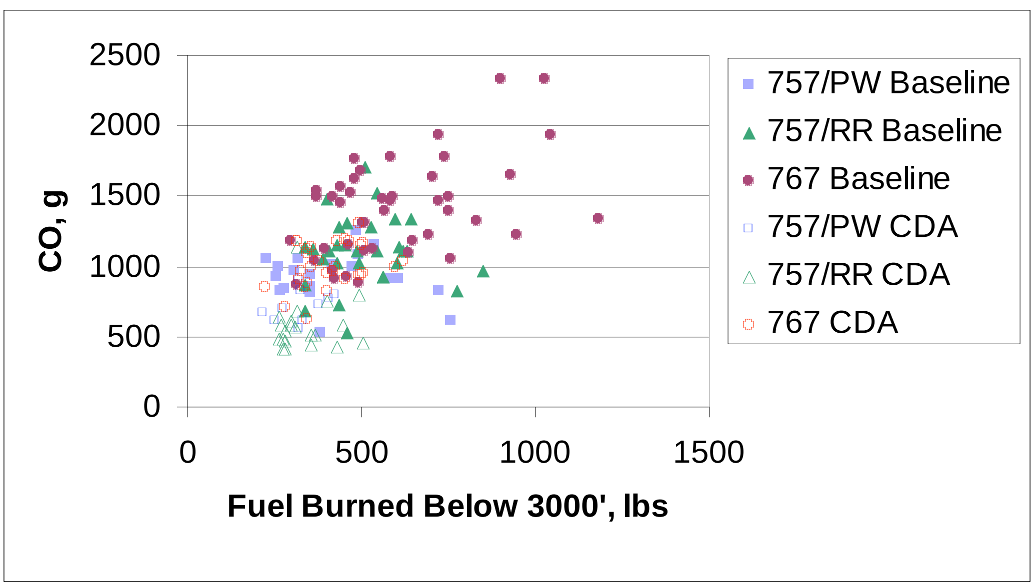


Figure 8-2b CO produced by the B757-200 and B767-300 aircraft vs. fuel burned

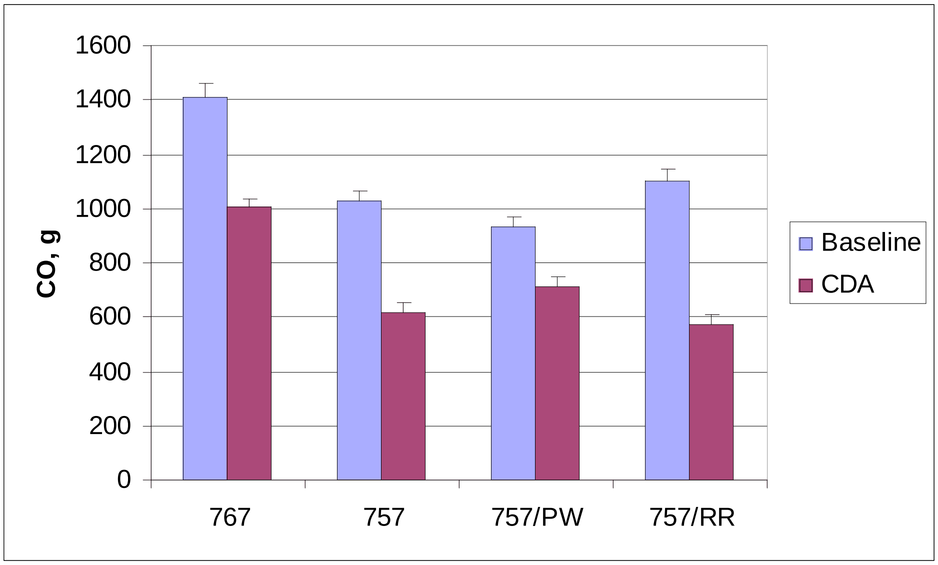


Figure 8-2c Average CO produced by the B757-200 and B767-300 aircraft

The CO produced by the B757-200 and B767-300 aircraft performing the CDA and the conventional approach is shown in Figure 8-2a and 8-2b versus time and fuel burned respectively. As shown in Figure 8-2c, the average CO produced by the B757-200 is reduced by 39.9%, from 1030g to 620g. The corresponding reduction for the B767-300 is 28.5%, from 1408g to 1007g. These significant reductions in CO were somewhat surprising given the very slight increase in CO reported by Lee for the CDA relative to the conventional approach [Lee 2005]. However, the comparison by Lee was conducted for two aircraft following the same routing. As was seen in Figure 6-2 and
Figure 10-1, conventional aircraft are typical vectored significantly distances at low altitude thus spending greater time below the mixing height of 3,000ft AGL. Further analysis confirmed that the greater time that the aircraft is spending below the mixing height is overwhelming the slight decrease in the CO emission rate that occurs at the higher throttle settings that are typical of the conventional approach.

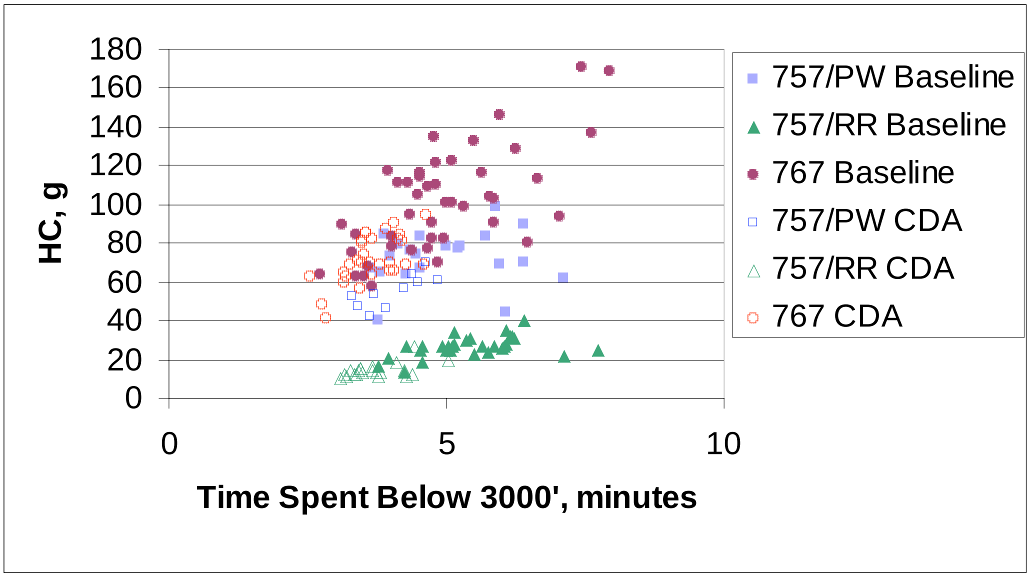


Figure 8-3a HC produced by the B757-200 and B767-300 aircraft vs. time

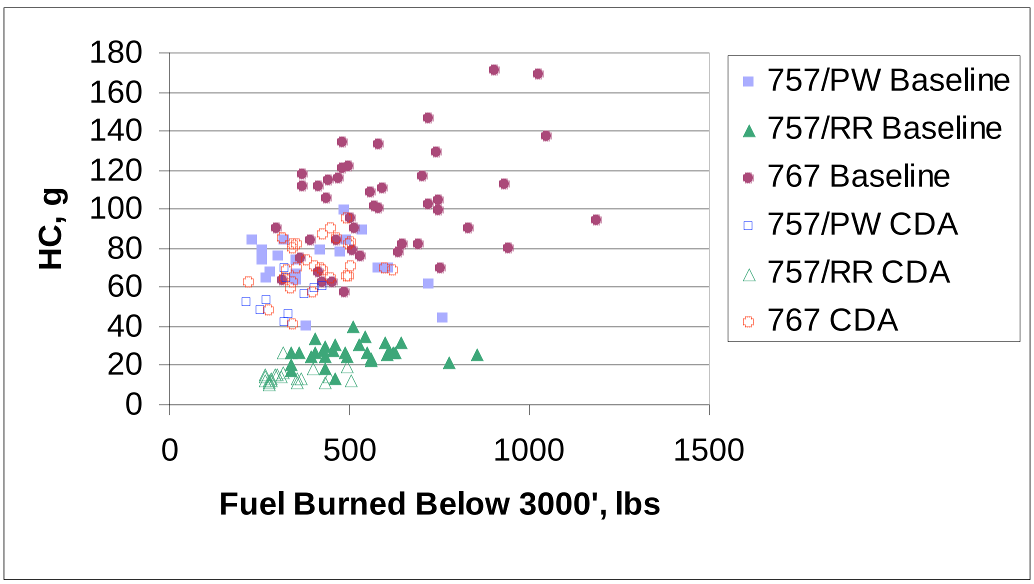


Figure 8-3b HC produced by the B757-200 and B767-300 aircraft vs. fuel burned

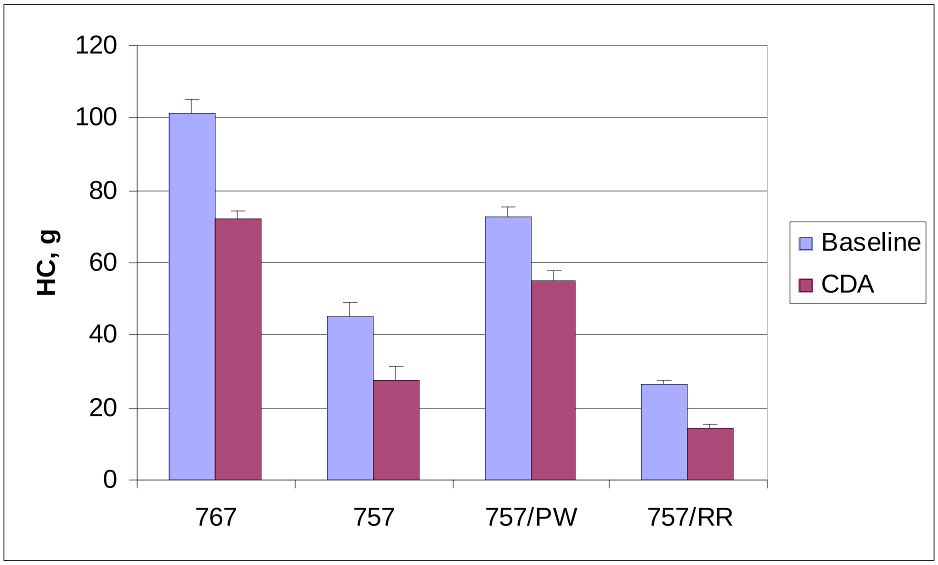


Figure 8-3c Average HC produced by the B757-200 and B767-300 aircraft

The HC produced by the B757-200 and B767-300 aircraft performing the CDA and the conventional approach is shown in Figure 8-3a and 8-3b versus time and fuel burned respectively. In Figure 8-1c, the average HC produced by the B757-200 is reduced by 29.0%, from 45g to 27g. The corresponding reduction for the B767-300 is 39.2%, from 101g to 72g. As was the case for CO, the greater time that the aircraft spends below the mixing height is overwhelming the slight decrease in the HC emission rate that occurs at the higher throttle settings that are typical of the conventional approach.

9 Analysis of Noise Impact

9.1 Event Correlation

The elevation and distance along the CDA ground track for each noise measurement site is listed in Table 9-1. Also listed is the average difference between the time that the aircraft passed through a one-mile wide gate that is centered on the measurement site and parallel to the nominal ground track and the time that each aircraft was logged by the observer as being overhead the measurement site. The ‘gate times’ were determined using the AIRSCENE software program––owned and operated by the Louisville Regional Airport Authority (RAA)––that correlates tracking data obtained via a multi-sensor tracking system to the measurement locations. The ‘log times’ were recorded by the observers at all the sites, which were located between 11 and 17 nautical miles from the airport. As shown in the table, the difference between the gate and log time varied from approximately +58 seconds at site #6––where a positive difference indicates that the log time is prior to the gate time––to approximately -6 second at site #1.

Table 9-1: Site locations

Sites North of the airport (for flights destined to runway 17R)			
Site#	Elevation (ft)	Track Distance (nm)	Gate Time - Log Time (seconds)
1	865	12.4139	10.5
2	946	12.4637	38.6
3	715	15.3243	32.7
4	820	16.0459	48.8
5	675	16.6954	46.7
6	753	17.3571	58.1
Sites South of the airport (for flights destined to runway 35L)			
Site#	Elevation (ft)	Track Distance (nm)	Gate Time - Log Time (seconds)
1	468	11.9364	-5.8
2	428	12.0563	23.2
3	496	13.5982	26.9
4	813	14.3365	29.0
5	795	14.8768	35.9
6	453	16.5348	45.6

9.2 Ambient Conditions and Measurement Calibration

Ambient noise levels at the measurement locations were typically between 36 and 50 dBA (see Table 9-2). Because the measurement equipment had to be close to the flight track some of the selected sites were in less than ideal locations. Thus, a few of the sites were located in residential areas with paved streets and standard lot sizes (a somewhat high density of buildings) while others were in more rural settings on open grass fields. Nightly temperatures during the tests were between 60 and 70 degrees F. There was no rain or precipitation to speak of and wind conditions at the measurement sites were generally calm.

Table 9-2: Ambient noise at all site between 1:09:00AM and 1:10:59 AM

Sites South of the airport (for flights destined to runway 35L)						
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Sep 16th	48.84	N/A	49.99	45.72	46.03	46.25
Sep 24th	46.66	42.64	N/A	40.1	40.71	42.58
Average	47.75	42.64	49.99	42.91	43.37	44.42
Sites South of the airport (for flights destined to runway 35L)						
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Sep 14th	48.81	47.1	51.19	46.71	47.33	53.78
Sep 15th	48.42	50.04	49.31	49.38	49.6	43.9
Sep 17th	N/A	N/A	N/A	N/A	N/A	N/A
Sep 18th	41.14	40.34	43.18	43	N/A	38.19
Sep 21st	38.48	36.42	39.73	41.93	42.19	37.12
Sep 22nd	43.6	42.41	44.15	46.54	N/A	38.99
Sep 23rd	41.61	40.08	46.95	48.26	46.63	41.46
Sep 25th	49.56	50.93	50.07	40.31	45.32	47.01
Average	44.52	43.90	46.37	45.16	46.21	42.92

The LD-824s were calibrated before and after each measurement period of approximately two hours in duration. The initial (CAL_i) and final (CAL_f) calibration levels were recorded as part of the time history data. During each calibration, the calibrator was placed on the microphone for at least 30 seconds. If it was determined that a drift had occurred during the measurement period, the calibration levels were used to adjustment the data. A drift was determined to have occurred if the initial and final calibration levels differed by more than 1 dB––the differences between CAL_i and CAL_f are listed in see Table 9-3. In this one case, the signals were adjusted by arithmetically adding the CAL_{adj} described in Equation 9-1.

$$CAL_{adj} = [(CAL_i - CAL_f) / 2]$$

Equation 9-1: Calibration Correction

Table 9-3: Differences between initial and final calibrations (db)

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
14 September	0.00	0.00	0.10	0.20	0.12	1.30
15 September	0.10	0.10	0.09	0.32	0.10	0.10
16 September	0.10	N/A	0.20	0.16	0.00	0.30
18 September	0.00	0.20	0.40	0.16	N/A	0.10
21 September	0.00	0.00	0.08	0.15	0.00	0.10
22 September	0.00	0.10	0.10	0.06	N/A	0.10
23 September	0.10	0.14	0.09	0.04	0.12	0.10
24 September	0.08	0.08	N/A	0.40	0.14	0.10
25 September	0.00	0.10	0.20	0.05	0.04	0.10

9.3 Noise Data Reduction

After the noise events were correlated to aircraft flights and the appropriate adjustments were made to the time histories, the time histories were screened to determine the maximum A-weighted noise level for each noise event. The SEL for each event was also calculated using, when possible, the conventional method of logarithmic summation of recorded noise levels between the two instances, before and after the peak level that are 10 dB lower than the peak level (see Equation 9-2). Sound Exposure Level (SEL) is an L_{eq} normalized to 1 second. It can be used to compare the energy of noise events that have different time durations.

$$SEL = 10\log_{10}\left[\sum_{t1}^{t2} 10^{spl/10}\right] = 10\log_{10}\left[\frac{1}{t_2 - t_1}\sum_{t1}^{t2} 10^{spl/10}\right] + 10\log_{10}[t_2 - t_1]$$

Equation 9-2: Sound exposure level calculation

While most of the aircraft noise measurements were of excellent quality with peak levels well above the ambient, it was not possible to determine the ‘10dB down points’ for some noise events because either the peak level of an event was not much higher than the ambient noise level or two events occurred in quick succession. Of the 93 such noise events (14.6% of total number of aircraft noise events) where it was not possible to calculate a standard SEL, the majority of cases (63 cases) were due to aircraft arriving within two minutes of each other (57 cases) or so close to each other that the peaks were virtually indistinguishable (6 cases). In these cases the process to calculate SEL was modified by lowering the down dB requirement until SEL values could be calculated. The specifics of the cases where this non-standard SEL calculation was required are shown in Table 9-4.

Table 9-4: Number of SEL calculations v. dB down point

Down Point	Number of Events
-10dB	546
-9dB	47
-8dB	23
-7dB	7
-6dB	9
-5dB	3
-4dB	4
Total	639

Additionally, there were times when other noise sources such as barking dogs masked the aircraft noise. One such example is shown in Figure 9-1. On this occasion, a group of territorial dogs belonging to a neighbor contaminated a number of the measurements at site #5 on the first night of testing; however, a talk with the owner resolved this issue for the remainder of the test period. A few measurement opportunities were also lost due to equipment problems and calibration errors, late recording starts, and early recording stops. The latter was attributed to an occasional aircraft arriving earlier or later than expected. Some measurements overlapped each other due to short separation times between flights. A few measurements were corrupted by sound from other aircraft in the area that were not descending into Louisville. The observers noted these events when they occurred.

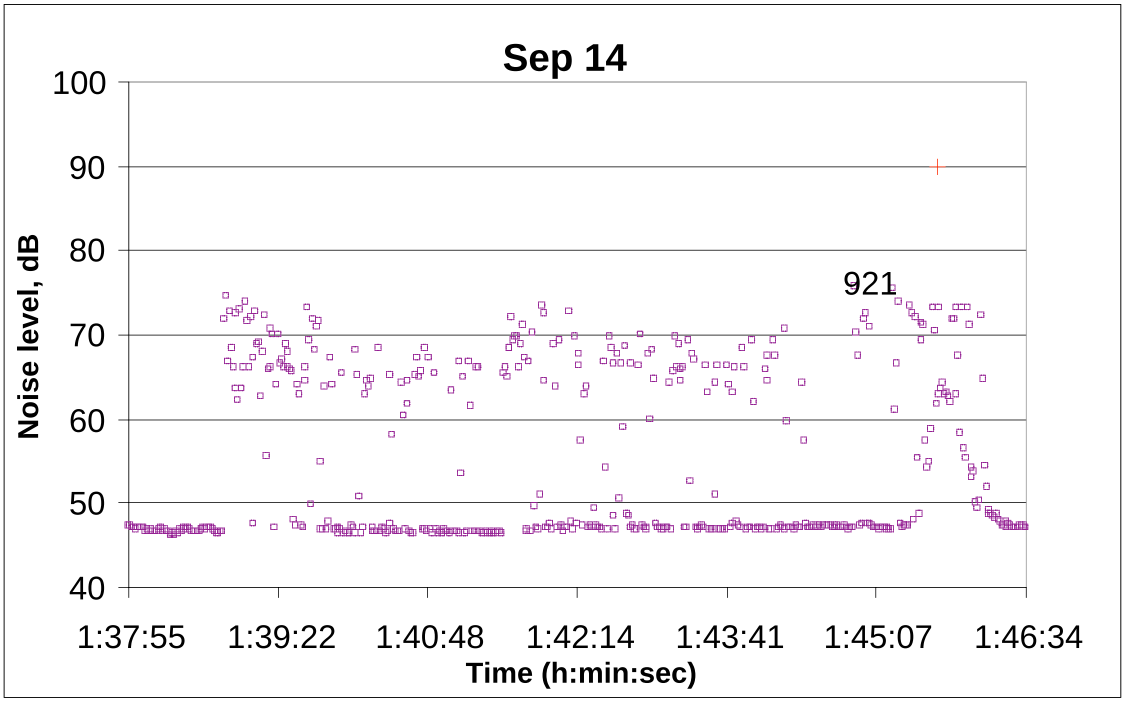


Figure 9-1: Aircraft noise measurement contaminated with dog barks

9.4 Results of Noise Data Analysis

The average peak noise levels at the 6 measurement sites to the South of the airport are shown in Figure 9-2 for all aircraft that performed the CDA on 25 September. For the B757-200 aircraft, the average peak noise level ranged between 56.5 and 61.4 dBA, with a standard error of up to up to 1.7 dBA. For the B767-300 aircraft, the average peak noise level ranged between 61.8 and 67.8 dBA with a standard error of up to 3.5 dBA. The corresponding sound exposure levels are shown in Figure 9-3. For the B757-200 aircraft, the average SEL ranged between 69 to 72.6 dBA, with a standard error of up to up to 0.8 dBA. For the B767-300 aircraft, the average SEL ranged between 73.6 and 76.8 dBA with a standard error of up to 2.5 dBA. As expected, the values for both noise measures decrease with increasing distance from the runway (increasing site number) except from site 2 to site 3 in the case of the peak noise level and from site 3 to site 4 in the case of the SEL. These anomalies in the trend are due to both source directivity and duration issues at site 2–-the aircraft were the midst of their turn onto the final approach course when they were passing that site–-and the location of site 3–-which is further to the side of the ground track than any other measurement site and thus has a greater slant range than a corresponding site under the flight track. Additionally, some of the variations in the noise levels are due to flap changes, engine thrust transients, and/or difference in site elevations.

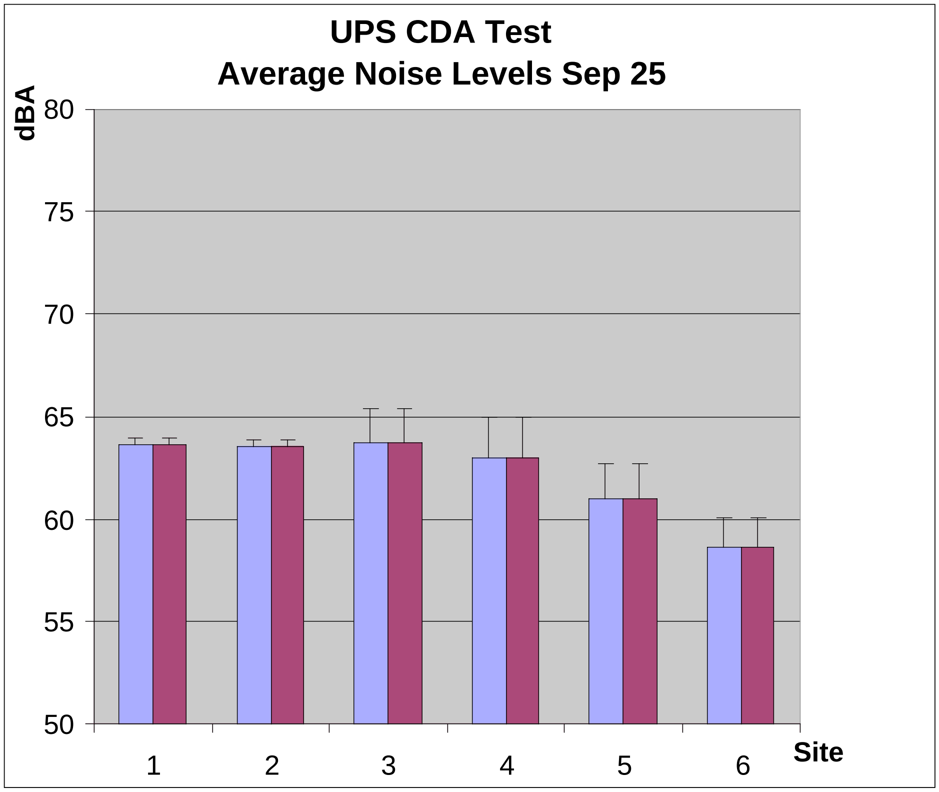


Figure 9-2: Peak noise levels on 25 Sep at South sites

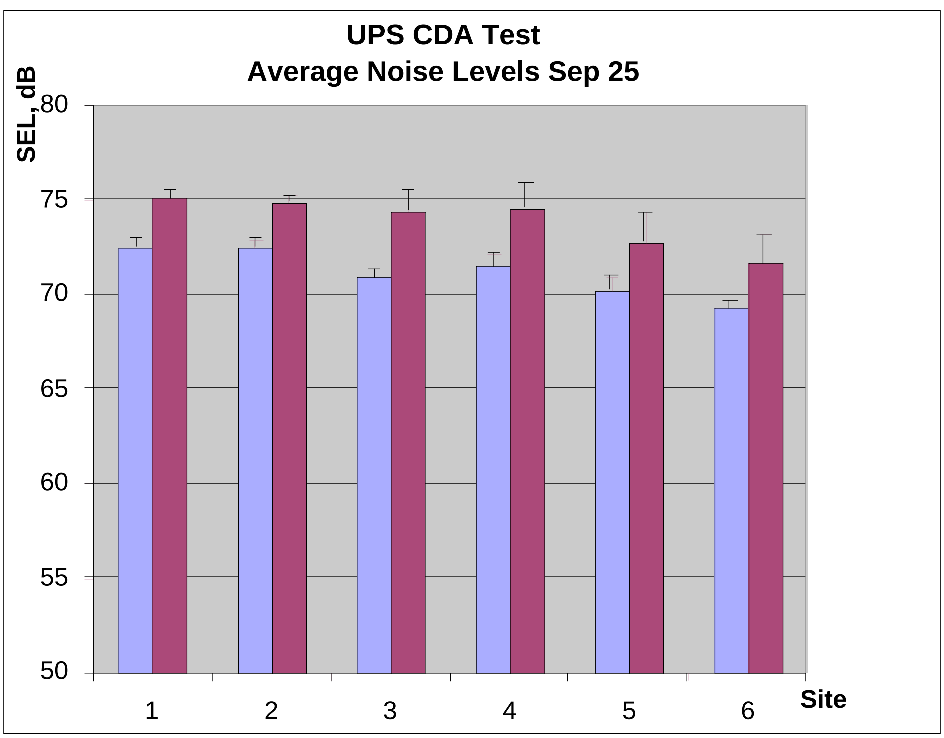


Figure 9-3: Sound exposure levels on 25 Sep at South sites

Similar trends were observed at the sites to the South of the airport on other days and at the sites to the North of the airport on the two days that measurements were taken at those sites. The overall dependence of noise level for both aircraft types on distance to the runway threshold (and thus altitude) is shown in Figure 9-4. As shown in the figure, the SEL changes by approximately 5dB over a distance of approximately 5nm and a corresponding altitude change of approximately 2,000ft.

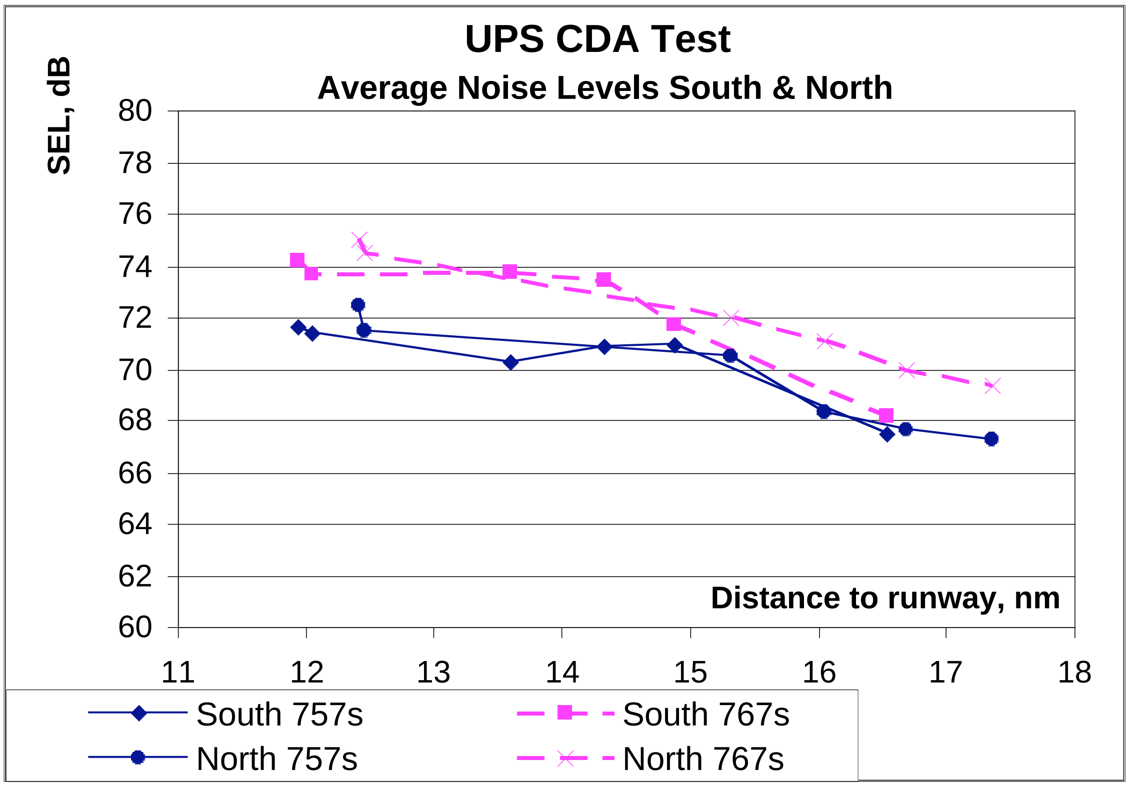


Figure 9-4: SEL v. distance to the runway

A complete comparison of the noise from aircraft performing the CDA to aircraft performing the conventional approach would require a back-to-back comparison of the two procedures such as in the flight test conducted in 2002. However, the test conditions were not optimized for such back-to-back noise measurements because, as you may recall, the objective of the test was to show operational suitability of the CDA and to enable comparison of operations when there is an entire sequence of CDA flights to operations when aircraft use conventional procedures. Thus, none of the aircraft performing the conventional approach were required to follow the CDA routing. Rather, all the flight recorder data that was retrieved (see Table 3-2 and Table 3-3 for details) were used in the Integrated Noise Model (INM) to make a CDA to conventional approach comparison in terms of the size of the resulting noise contours.

The accuracy of these predictions was evaluated by comparing the peak noise level and SEL measurements that were measured during the test period to predictions of the noise levels at the measurement sites that were derived using INM (with the flight recorder data as input). The comparison of the measured to the predicted peak noise levels for all flights over the South sites is shown in Figure 9-5. The small differences and variations that are shown are to be expected given the difference between the atmospheric condition during the test period and the atmospheric condition during certification, the difference between the atmospheric condition during the test period and the SAE standard day––the noise-power-distance curves in INM are based on certification data corrected to the SAE standard day––and the aforementioned variations in the noise levels due to flap changes and engine thrust transients.

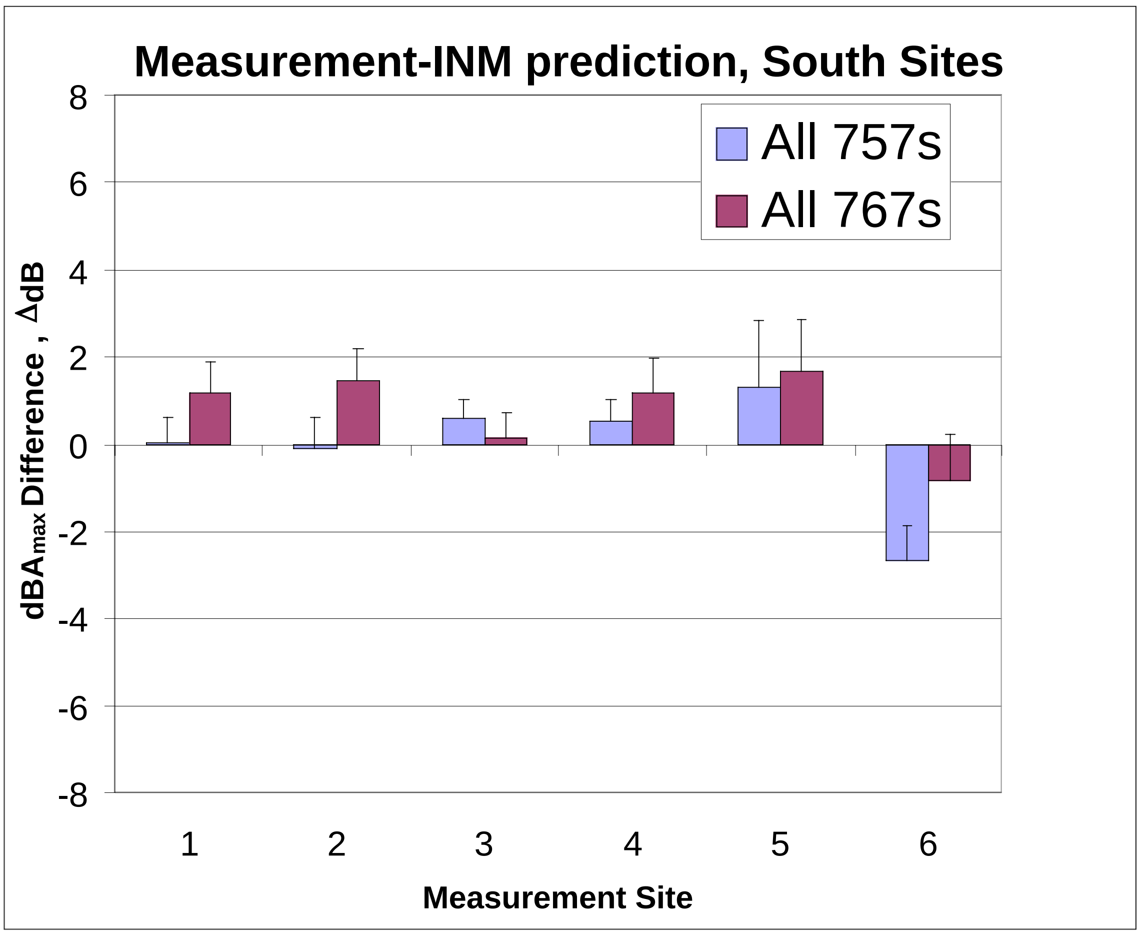


Figure 9-5: Evaluation of noise prediction accuracy

Single event noise contours were calculated for all the aircraft for which there was flight recorder data. The average sizes of the 60dBA peak noise contours are shown in Figure 9-6 for both the CDA and the conventional approach. The results are broken down by aircraft type: 757-200 and 767-300. Because UPS operates B757-200 with two different engine types, the results for the B757-200 are further broken down into results for the B757-200 with Pratt and Whitney engines, and results for the B757-200 with Rolls-Royce engines. UPS has only one engine type on the B767-300. As shown in the figure, the size of the conventional contour is in all cases larger than the size of the CDA contour.

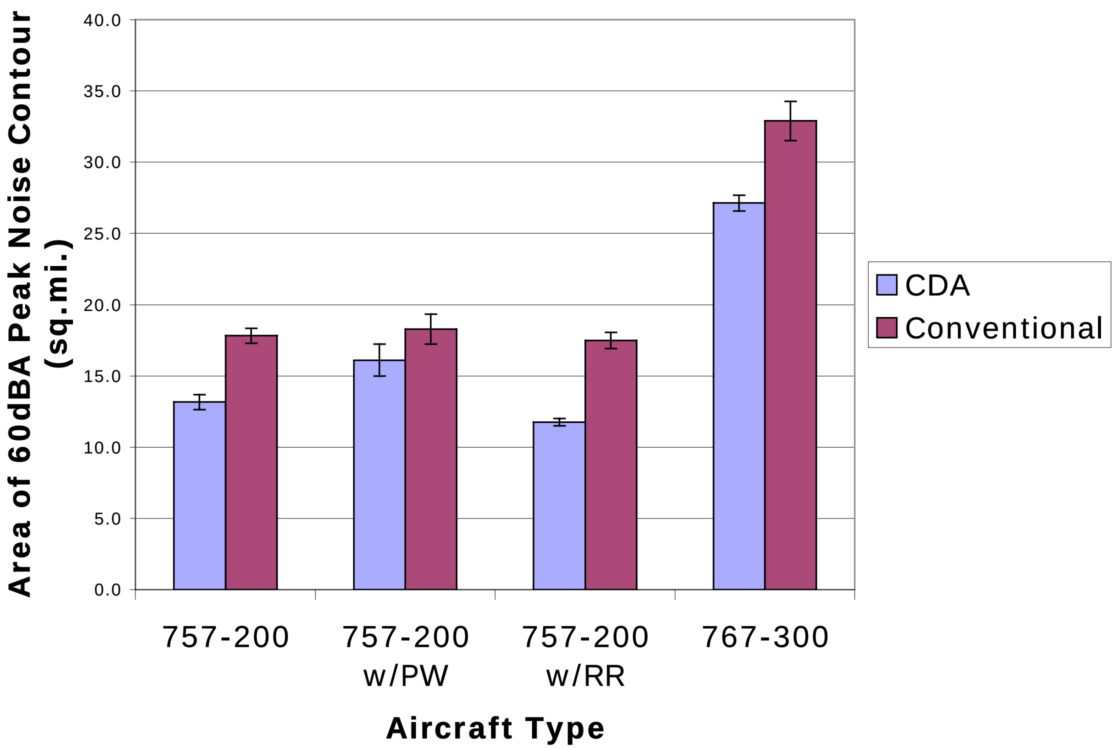


Figure 9-6: Size of 60dBA contours for CDA and conventional approach

For the B757-200, the average size of the 60dBA contour is reduced from 17.8 to 13.2 sq. mi., a reduction of 26%. However, this reduction is not the same for both aircraft types. For the case of the B757-200 powered by Pratt and Whitney engines, the average size of the 60dBA contour is reduced from 18.3 to 16.1 sq. mi., a reduction of 12%; while for the B757-200 powered by Rolls-Royce engines, the size of the 60dBA contour is reduced from 17.5 to 11.8 sq. mi., a reduction of 33%. For the B767-300, the size of the 60dBA contour is reduced from 32.9 to 27.1 sq. mi., a reduction of 17%. The reduction in the size of the 60dBA contour is statistically significant in all cases except the case for the B757-200 with Pratt and Whitney engines.

Cumulative noise impact contours are shown in Figure 9-8 for 16 flights that would land when aircraft are performing a CDA during a representative two-hour period between 1 AM and 3 AM. Two-hour day-night equivalent noise level contours are depicted for 7 B757-200 and 9 767-300 aircraft, the average mix of these aircraft types that was observed during the testing period. The trajectories for the aircraft were selected at random from the flight recorder data retrieved during the first week of the test period: 14 September to 18 September. Of note are the virtually indistinguishable ground tracks and the very narrow noise contours, indicating how well the LNAV function of the FMS performs in terms of keeping aircraft on their prescribed routing.

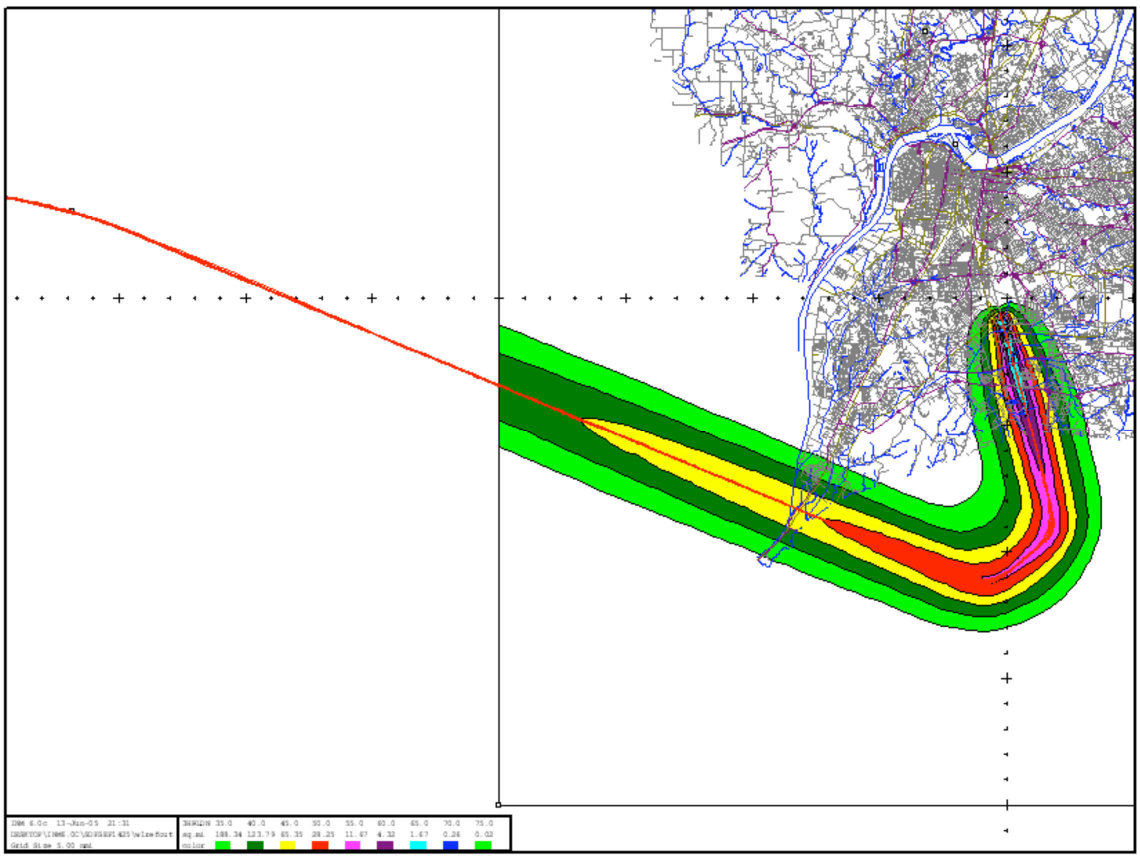


Figure 9-8 Representative cumulative noise contours for CDA

Cumulative noise contours are shown in Figure 9-9 for 16 flights that would land when conventional approaches are being performed during the same representative two-hour period between 1 AM and 3 AM as in the case before. Two-hour day-night equivalent noise level contours are depicted for 7 B757-200 and 9 767-300 aircraft. The trajectories for the aircraft were selected at random from the flight recorder data retrieved during the first week after the test period: 28 September to 2 October. As seen from the contours, many of the flights were vectored directly to the outer marker while others were vectored to the classic downwind-base-final leg sequence. When this greater lateral expanse of the noise contours is combined with the higher single event noise levels of conventional approaches, the net results is greater noise impact in the terminal area. A comparison of the contours revealed that the size of the 55 Leq contour is 14.2 sq. mi. during the representative conventional night versus 11.7 sq. mi. during the representative CDA night, a reduction of 18% with the introduction of CDA.

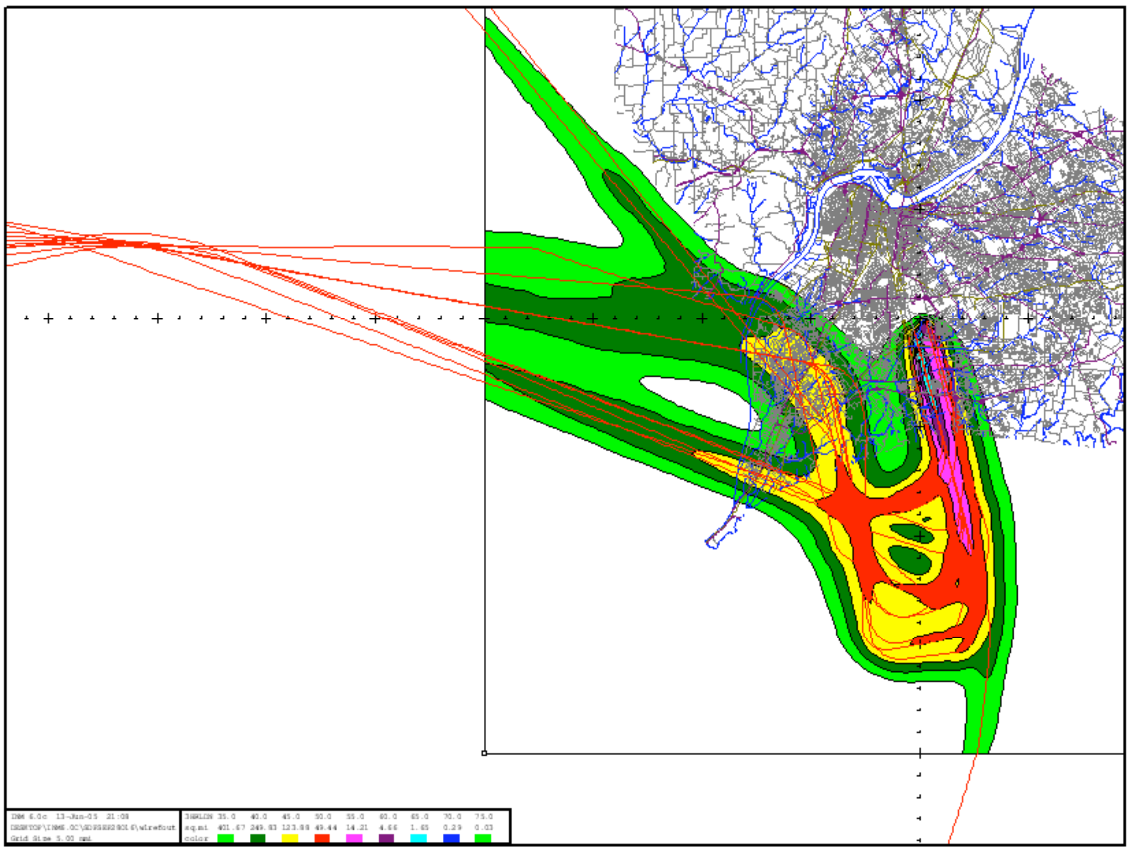


Figure 9-9: Representative cumulative noise contours for conventional approach

10 Separation Analysis

10.1 Data Processing and Reduction

The ARTS data provided a good basis for separation analysis in the terminal area. In the data retrieved from the UPS surface management system, aircraft position was represented as latitude and longitude. Upon closer inspection it was determined that magnetic variation was not corrected by the system when ARTS X-Y coordinates were converted into latitude and longitude. This was corrected by converting the latitude and longitude into bearing and range relative to the reference point at the airport, rotating counterclockwise by 3 deg, then converting back to latitude and longitude. The corrected ground tracks closely matched the waypoints on CDA arrivals.

The ground tracks for all flights from the West are shown in Figure 10-1. The solid thin (black) tracks were CDA flights; the dashed (red) tracks were non-CDA flights, and the thick (blue) tracks were CDA flights vectored for separation during the flight test. The data for 8 ‘CDA flights’ on 25 September were missing or incomplete. Data for 1 flight on 23 September was also missing because it was delayed by more than an hour. Flight recorder data for 6 of those 9 flights were available and thus were used in place of the ARTS data. ‘Non-CDA flights’ that arrived from the west during the test period were also included in the analysis to provide a complete view of the scenario.

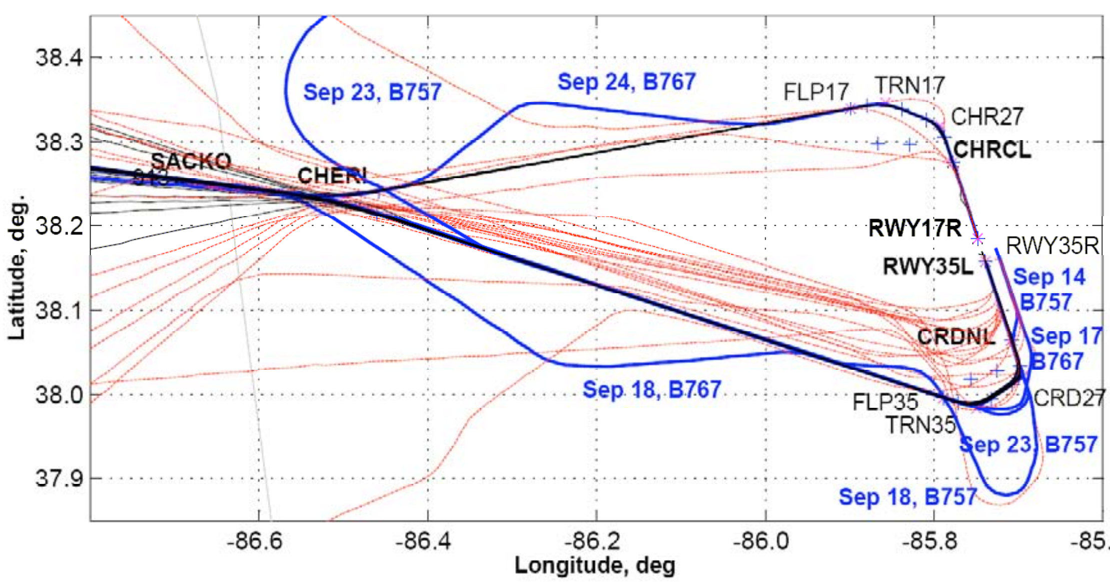


Figure 10-1: Flight Test Ground Tracks

The aircraft types in the dataset include the A300, B747, B757-200, B767-300 and DC8. These include B757-200 and B767-300 that were participating in the flight test and those that were not but arrived from the west during the testing period. Except for the B757-200, all aircraft were in the heavy weight class.

10.2 Observed Separations between Aircraft

An analysis was conducted of the distribution of the separation at SACKO between 105 pairs of aircraft destined to runway 35L and 26 pairs of aircraft destined to runway 17R during the test period. The values for separation were measured when the lead aircraft in each pair was at SACKO. Recall that SACKO was the intermediate metering point selected for the CDA flight test, and that controllers were asked to maintain a separation of 15 nautical miles up to that point.

10.2.1 Aircraft with separation greater than 15 nm

The vast majority of the aircraft pairs, all except 13, were separated by more than 15 nm. None of the aircraft pairs with separation greater than 15 nm, except in one case where the controller interjected a non-CDA aircraft from another direction between two CDA aircraft that had a large separation, had to be vectored during the approach. These results indicate the superb performance of the Monte-Carlo analysis in determining the initial separation.

10.2.2 Aircraft with separation less than 15 nm

A total of 13 aircraft pairs had a longitudinal separation of less than 15 nm when the lead aircraft was at SACKO. However, in 4 of those 13 cases, either a) the lead aircraft was performing a CDA while the trailing aircraft was not even on the CDA routing as it was performing a conventional approach––2 cases; b) both aircraft were on the CDA routing but the lead aircraft was performing a CDA while the trailing aircraft was performing a conventional approach––1 case; or c) both aircraft were on the CDA routing but the lead aircraft was performing a conventional approach while the trailing aircraft was performing a CDA––1 case.

Although these 4 cases are not indicative of the inter-CDA arrival separation, they are included here for completeness and to highlight that the controller was able to vector them as usual within the stream of CDA aircraft to achieve wake turbulence separation. This is or particular note in 3 of the 4 case where the non-CDA aircraft were either A300s or DC8s and therefore did not have the FMS capabilities of the B757-200 or B767-300. In the fourth case (case where the non-CDA aircraft was a B757-200, the pilot did enter the correct waypoint locations but the speed profile was not as described in procedure indicating that there were some issues with the entry of the constraints at these waypoints.

In another 4 of those 13 cases, cases where both aircraft were performing a CDA, the aircraft were able to complete their approach without requiring any action on the part of air traffic controllers. In fact, in 2 of these 4 cases a B757-200 was trailing a B767-300. This indicates that indeed the choice of a 15 nm initial separation was a conservative one as the B757-200 typically has a higher average speed during the approach than the B767-300.

In the remaining 5 of those 13 cases, the trailing aircraft had to be vectored for separation. Two had to be side stepped to runway 35R, 2 flew an extended base leg and the one aircraft destined to runway 17R was vectored at CHERI. It is important at this juncture to note that 3 of these 5 cases are attributable to the introduction of a non-CDA aircraft and are therefore not attributable to any failure on the part of a CDA aircraft. In fact, **only the remaining 2 cases** were due to aircraft that had problems maintaining the desired speed profile, indicating that there were some issues with the entry of the constraints at the waypoints. This however is understandable given the database issues during the first few days of the flight test.

11 Summary

A brief summary of the results is presented below. Note that only the main points of each set of analyses are listed.

Analysis of the pilot surveys revealed the following:

- Ninety-two of the ninety-five pilots who answered this question commented that based on their performance, the procedure would work well in practice.

Analysis of the FMS performance of the aircraft revealed the following:

- VNAV was used a remarkable 96% of the time within the terminal area, prior to glideslope capture.

- The aircraft were able to consistently meet the altitude and speed constraints at the bottom of the trajectory.

- Speed brake usage was seen to be significantly greater than expected, however a small percentage of this speed brake activity was not needed, as extra thrust was sometimes added when excessive speed brake was used.

Analysis of the flight time of the B757-200 and B767-300 aircraft revealed the following:

- The average time to fly the last 180 nautical miles to runway 35L is reduced by 118 and 147 seconds, respectively.

Analysis of the fuel consumed by the B757-200 and B767-300 aircraft revealed the following:

- The average fuel consumed over last 180 nautical miles to runway 35L is reduced by 118 and 364 pounds, respectively.

Analysis of the emissions produced by the B757-200 and B767-300 aircraft revealed the following:

- The average NO_x produced is reduced by 37.0% and 39.9%, respectively.

- The average CO produced is reduced by 39.9% and 28.5%, respectively.

- The average HC produced is reduced by 29.0% and 39.2%, respectively.

Analysis of the noise impact of the B757-200 and B767-300 aircraft revealed the following:

- For B757-200 powered by Pratt and Whitney engines, the average size of the 60dBA peak noise level contour is reduced by 12%

- For B757-200 powered by Rolls-Royce engines, the size of the 60dBA contour is reduced by 33%.

- For B767-300, the size of the 60dBA contour is reduced by 17%.

- The size of the 55 Leq contour during a representative conventional two-hour period between 1 AM and 3 AM is reduced by 18%.

Analysis of the separation between aircraft revealed the following:

- None of the aircraft pairs with separation greater than 15 nm had to be vectored during the approach, except in one case where the controller interjected a non-CDA aircraft.

- Only 2 cases when the aircraft were vectored were due to aircraft having problems maintaining the desired speed profile, indicating that there were some issues with the entry of the constraints at the waypoints.

12 References

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A.1 Appendix – Sample Flight Test Data

Representative samples of tabulated Radar data and FDR data are presented below to facilitate future experimental and modeling activities.

A.1.1 Radar Data

Automated Radar Terminal System (ARTS) data retrieved from the UPS surface management system were used in the analysis. A typical record of corrected Radar data is shown below:

```
945,09/22/2004,06:08:38,22118,-86.8746077039951,38.2780524314948,24241,460.686,102.429,0
```

In the above sample record, data fields are comma separated. The data fields, from right to left, are defined as follows.

UPS Flight Number
UTC Date, mm/dd/yyyy
UTC Time, hh:mm:ss
UTC Second, counting from zero hours of the day
Longitude, deg
Latitude, deg
Altitude, ft
Ground speed, kt
True heading, deg
Ascent Rate, ft/min

A.1.2 FDR Data

FDR data retrieved from UPS aircraft were used in the analysis. FDR data were first preprocessed to include data fields that are necessary to the analysis. A typical record of such preprocessed FDR data Radar data is shown below:

```
5,51,48,-1873,-192.504,-192.726,-89.4975,38.4841,-89.4975,38.4841,107.9,1,37008,36992,37008,5500,
272.5,0.836,430,91.2,91.3,91.1,9886,2220.4,2263.9,2978.95,3438,23234,11517,11717,0,263360,0,0,4,
1,0,1.4,0,0.042,-0.005,-51.8,143.09,68,1,1,1,0,1,0,
```

In the above sample record, data fields are also comma separated. The data fields, from right to left (wrapped to the second and third lines), are defined as follows:

UTC time, hr
UTC time, min
UTC time, sec
Time to runway threshold, sec
Along track distance to runway threshold, nm
Distance flown to runway threshold, nm
Corrected longitude (B757-200 older aircraft only, otherwise same as longitude), deg

Corrected latitude (B757-200 older aircraft only, otherwise same as longitude), deg
Longitude (raw data), deg
Latitude (raw data), deg
Magnetic heading, deg
Air/Ground flag, 0 – air; 1 - ground
Corrected altitude (corrected from pressure altitude to represent true altitude), ft
MCP selected altitude, ft
Pressure altitude, ft
Radio altimeter altitude, ft
Computed calibrated speed, kt
Mach number
Ground speed, kt
Average N1, %
N11C, %
N12C, %
Fuel flow, lb/hr
FF1C, kg/hr
FF2C, kg/hr
Fuel burn to runway threshold, integrated value, lb
Fuel burn to runway threshold, direct reading, lb
Fuel quantity, lb
FUEL_QTY1, lb
FUEL_QTY2, lb
FUEL_QTY3, lb
Gross weight, lb
Flap handle position, deg
Flap angle, deg
Speed brake, %
Landing gear lever, 0 - down; 1 - up
Landing gear lockdown, 0 - up; 1 - down
Pitch angle, deg
Roll angle, deg
Longitudinal acceleration, g
Lateral acceleration, g
Static air temperature, °C
Wind direction, deg
Wind speed, kt
Autothrottle engaged, 0 – not engaged; 1 - engaged
LNAV mode
VNAV mode
VALT OPER
VPATH OPER
VSPD OPER