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Energy Navigation: Simulation Evaluation and Benefit Analysis

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Contents

Abbreviations and Symbols

ADRS	Air Data Radar Simulation
AGL	Above Ground Level
ASDO	Airspace Super Density Operations
ASTOR	Aircraft Simulator for Traffic Operations Research
ATC	Air Traffic Control
ATL	Atlanta Hartsfield-Jackson International Airport
ATOL	Air Traffic Operations Laboratory
ATOS	Air Traffic Operations Simulation
CAS	Calibrated Airspeed
CDA	Continuous Descent Arrival
CDU	Control Display Unit
EFIS	Electronic Flight Information System
ENAV	Energy Navigation
FAF	Final Approach Fix
FMB	Flight Manual Bulletin
FMC	Flight Management Computer
FMS	Flight Management System
IAF	Initial Approach Fix
ILS	Instrument Landing System
INM	Integrated Noise Model
JPDO	Joint Planning and Development Office
LNAV	Lateral Navigation
LNFP	Low Noise Flight Procedures
LNG	Low Noise Guidance

MCP	Mode Control Panel
MSL	Mean Sea Level
NAS	National Airspace System
ND	Navigation Display
NextGen	Next Generation Air Transportation System
nm	nautical miles
NWS	National Weather Service
OPD	Optimized Profile Descent
PFD	Primary Flight Display
PM	Pilot Model
QAT	Quiet Aircraft Technology project
RFD	Research Flight Deck
RNAV	Area Navigation
RPFMS	Research Prototype Flight Management System
RUC	Rapid Update Cycle
SDF	Louisville-Standiford International Airport
SEL	Sound Exposure Level
STAR	Standard Terminal Arrival Route
TBO	Trajectory Based Operations
VNAV	Vertical Navigation
Vref	Reference Speed

Abstract

This paper presents results from two simulation studies investigating the use of advanced flight-deck-based energy navigation (ENAV) and conventional transport-category vertical navigation (VNAV) for conducting a descent through a busy terminal area, using Continuous Descent Arrival (CDA) procedures. This research was part of the Low Noise Flight Procedures (LNFP) element within the Quiet Aircraft Technology (QAT) Project, and the subsequent Airspace Super Density Operations (ASDO) research focus area of the Airspace Project. A piloted simulation study addressed development of flight guidance, and supporting pilot and Air Traffic Control (ATC) procedures for high density terminal operations. The procedures and charts were designed to be easy to understand, and to make it easy for the crew to make changes via the Flight Management Computer Control-Display Unit (FMC-CDU) to accommodate changes from ATC. The test runs were intended to represent situations typical of what exists in many of today's terminal areas, including interruptions to the descent in the form of clearances issued by ATC. A subsequent non-piloted simulation study provided extended benefits analysis for situations not tested in the piloted study.

The results showed that the pilots were able to conduct the descents with both forms of guidance, even when interrupted by ATC with instructions that took the aircraft off of the programmed path, laterally, vertically or both. The uninterrupted descent resulted in the most optimal profile, which translated to the lowest perceived noise levels and lowest amount of fuel burned. These benefits were reduced in the VNAV cases as the interruptions from ATC increased, but remained more consistent in the ENAV cases. The workload associated with conducting the descents were rated comparably for the two forms of guidance. Pilots were able to conduct the descents with a minimum amount of time allowed for studying the instructions and charts they were given, and expressed a strong preference for displaying the ENAV energy guidance on the Primary Flight Display. The extended benefits analysis identified the final approach region as the primary location for ENAV benefits, with limited improvements seen in the enroute descent region.

Introduction

The noise generated by aircraft during departure and arrival flight operations continues to be a significant problem at most major airports in the United States. Complaints from the communities surrounding these airports often result in restrictions to the number and type of operations that can be conducted in the surrounding areas. They also result in significant delays to construction of new runways and extension of existing runways. These restrictions in turn limit the capacity of the airport and can result in economic hardship for the airport, airlines, and communities served by the airport.

Improvements to the design of jet engines over the past several decades have reduced jet engine noise and greatly reduced the noise footprint of individual aircraft. However, the increasing number of flights and the expansion of population in the vicinity of airports have prompted renewed interest in methods for noise abatement. Procedural solutions to the noise problem, which involve changing the way pilots operate their aircraft to minimize the perceived noise on the ground below, have been investigated for a number of years, and several promising techniques have been developed. The primary advantage of procedural solutions is that benefits can be achieved without making design changes to the aircraft engines or airframe. The major challenges involved with the use of operational noise abatement procedures include development of acceptable pilot procedures, development of flight guidance techniques, and development of acceptable procedures for Air Traffic Control (ATC).

This paper presents results of two studies that were conducted as part of NASA's Quiet Aircraft Technology (QAT) and NextGen Airspace Projects. The primary goal of the QAT Project was to identify technology which can be applied to aircraft and to flight operations that will reduce the community noise generated by aircraft. The objective was to reduce noise by 10 dB, with flight operations contributing 2 dB to the total noise reduction. The element within the QAT Project that addressed the operational issues was called Low Noise Flight Procedures (LNFP), and included the development of flight guidance, and supporting pilot and ATC procedures for low noise operations. The NASA NextGen Airspace Project conducts fundamental research supporting development of the Joint Planning and Development Office (JPDO) Next Generation Air Transportation System (NextGen). A key research focus area within the Airspace Project involves Airspace Super Density Operations (ASDO) at the major airport terminals. The efficiency and noise characteristics of arrivals and departures within the airport terminal airspace are primary concerns of ASDO.

The studies described in this paper involved the development and testing of operational procedures for conducting continuous descent arrivals using a flight deck tool that computes and displays energy cues for pilots to use to fly the most optimal descent for the given conditions. Descents conducted with the use of this energy guidance are compared with those conducted using conventional aircraft guidance.

Background

RNAV Arrival Procedures

The Continuous Descent Arrival (CDA) has been identified as a beneficial method for operationally reducing community noise near airports. As the name implies, a CDA optimally consists of an uninterrupted descent through the terminal area for an arriving aircraft, without any level altitude segments. The CDA is designed to minimize level flight at low altitudes, which produces more noise than descending segments, due to the higher thrust setting required to maintain level flight. Also, the CDA design keeps the aircraft higher throughout most of the descent through the terminal area, which allows for increased noise attenuation (see Figure 1). The higher altitude, lower thrust characteristics of CDAs also contribute to potentially significant fuel savings.

Considerable research and operational testing of CDA procedures has been conducted over the past decade [1-3]. Several airports, such as Heathrow in London and Schiphol in Amsterdam, have operational CDA procedures that are used mainly during night-time low traffic-density operations. Area navigation (RNAV) arrival procedures with CDA characteristics (called Optimized Profile Descents, or OPD) are being designed and tested at several airports in the United States. The FAA NextGen Implementation Plan includes RNAV with OPD as a key element of Trajectory Based Operations (TBO) in the future National Airspace System (NAS).

There are major obstacles, however, that limit the ability to use CDAs on a regular basis, especially during high traffic-density periods.

One is the lack of flight guidance to properly manage thrust and drag when interrupted by ATC for spacing with other aircraft while flying a near-idle CDA. Another obstacle is the lack of operational techniques that can integrate current ATC procedures with CDA and OPD procedures. This is particularly important during high traffic density operations, when controllers rely on the ability to issue speed and routing changes for maintaining aircraft separation and spacing.

These studies address both the flight guidance issues as well as procedures needed to conduct CDA descents. The following two sections expand on the issues of Flight Management Systems and Air Traffic Control, as they relate to the CDA procedures.

Flight Management Systems and RNAV Procedures

Since the early 1980s, standard avionics on commercial transport aircraft have included systems for managing various aspects of the flight trajectory. A modern Flight Management System (FMS) allows pilots to plan the trajectory for an entire flight, and includes Vertical Navigation (VNAV) functions that can compute a performance-based vertical trajectory for the aircraft. The VNAV function also provides flight guidance to follow the computed trajectory, and thus could be used to follow a CDA trajectory. Reference 4 includes a report on a study where CDA procedures were demonstrated, using commercial FMS VNAV functions to conduct the descent. Limitations in both the basic functionality of VNAV as well as in pilot understanding of VNAV guidance, however, have prevented widespread adoption of VNAV-based CDA procedures for operational use. Three main limitations associated with use of existing VNAV for CDA procedures are:

- The lack of a standard pre-defined lateral path that is continuous from top of descent to the runway, and can be used as the basis for a CDA trajectory,

- The lack of flexibility in operation of the VNAV function, that does not allow pilots to easily make speed changes during the descent, while maintaining the CDA vertical trajectory, and

- The lack of consistent operation between different versions of VNAV as implemented for different aircraft.

These VNAV limitations could make it difficult, if not impossible, for aircraft to conduct CDAs in busy terminal areas, where controllers typically rely on tactical procedures to space traffic. The first item above can be addressed by the design of RNAV arrival procedures. Many new RNAV arrivals are being designed to have ending locations that coincide with the Initial Approach Fixes (IAF) of the final approach procedures. This allows a continuous lateral path on which a CDA can be overlaid. The second item can be addressed through pilot/controller techniques, such as those developed for this study, and expanded pilot training using existing VNAV functionality. The third item requires adoption of new performance standards for FMS VNAV to ensure consistent interoperability between different systems. Enhanced guidance modes, such as the Energy Navigation (ENAV) concept described in this paper, can assist in alleviating the limitations of VNAV and provide consistent performance with minimal pilot training.

Traffic Control and RNAV Procedures

CDA procedures using VNAV can be readily implemented in the terminal area for single aircraft operations. However, multiple aircraft following CDA procedures for landing at the same or parallel runways present a significant challenge for ATC. Typically, terminal area air traffic controllers (approach controllers) will utilize vectoring techniques in order to sequence arriving aircraft for landing, and to provide adequate lateral and vertical separation between aircraft. This requires controllers to make tactical changes to the aircraft heading and airspeed, in addition to using staggered altitude profiles, to facilitate a safe and orderly flow of traffic to the runways. The fixed lateral routing needed for

CDA descents is seldom used for busy terminal areas. On arrival segments that have defined lateral routing, controllers typically use speed control to achieve and maintain desired spacing intervals between aircraft. Aircraft flying continuous descent procedures have higher energy than those flying current-day procedures, mostly because of their higher altitude throughout the arrival. It may not be possible for an aircraft to dissipate this higher energy if the flying distance is shortened, thus making it difficult to comply with vectors that shorten the aircraft's flight path.

To effectively utilize FMS-based CDA procedures while also maintaining separation in a high traffic density terminal area, controllers must be able to specify changes in the lateral path, airspeed, and altitude of all aircraft. To be usable, CDA procedures must be flexible enough to accommodate these tactical clearances. Procedures for this experiment were developed to take these considerations into account.

Energy Navigation Concept

The ENAV concept combines dynamic, energy-based reference trajectory generation with real-time flight guidance and energy-based auto throttle commands. Originally developed at NASA Langley as a low-altitude terminal area tool during the QAT Project in the early 2000s, the concept has been expanded to include full arrival operations in support of the NASA NextGen Airspace Systems Program.

Low Noise Guidance Flight Deck Tool

The original Low Noise Guidance (LNG) concept was developed specifically to reduce community noise and engine emissions during terminal arrival situations. A prototype LNG flight deck tool was developed to construct high energy, low thrust arrival trajectories under the dynamic conditions of high density terminal arrival situations [4]. Depiction of energy state relative to the reference trajectory and display of the location of events needed to manage the energy of the aircraft (flap and landing gear deployment) were key elements of LNG.

The primary challenge in developing LNG was the dynamic nature of real-world terminal arrival situations and the need for continuous adjustment to the reference trajectory based on speed, altitude and lateral path changes from ATC as well as fluctuating atmospheric conditions encountered during flight. To accommodate these dynamic conditions, the state of the aircraft relative to the reference trajectory, the current atmospheric winds and temperatures, as well as the pilot selected target speed and altitude limits were continuously monitored by the LNG algorithm. A new reference trajectory was generated when any of these parameters exceeded tolerances from the expected or modeled conditions. Normal flight plan changes, such as cost index, routing, cruise altitude and desired speed schedules, were handled by standard VNAV with the resulting trajectory becoming the new basic trajectory for LNG.

Expanded Energy Guidance Tool

Following completion of the piloted simulation described in this report, the LNG tool was expanded to support the extended cruise to landing operations envisioned for the NextGen ASDO concepts. Additional logic was added to the LNG tool in order to handle the optimized descents from cruise altitude as well as arbitrary altitude and airspeed crossing constraints at waypoints along the arrival. During this time period, NASA was also supporting government, industry and academia efforts at developing and testing CDA operations and dedicated RNAV arrival procedures with Optimized Profile Descents [3]. Lessons learned in these tests were incorporated in the new ENAV algorithm and research Flight Management System used for NASA testing.

ENAV Software

The original LNG and extended ENAV software were designed to operate as complete and stand-alone flight guidance modules. A single procedure call to the software provided all inputs required by the guidance and returned all necessary guidance signals needed for both flight displays and the airplane auto-flight systems. Details of the ENAV software are contained in Appendix A.

Related studies

The experiments documented in this report make use of the LNG and ENAV flight deck tools. It is useful to recall a previous study, which examined the use of an early version of this energy-based guidance to maintain the ideal CDA profile. This study provided researchers with an initial look at the benefit of and pilot acceptability issues associated with ENAV for conducting CDA operations.

The study [4] paired individual subject pilots (acting as the flying pilot) with a researcher (acting as the non-flying pilot). Because this pairing did not truly represent an airline crew, a full set of crew procedures was not developed or evaluated. However, a charted procedure was developed and used, and the pilots were given a set of crew procedures that described how the LNG algorithm could be used to conduct the CDA descent.

The LNG algorithm was designed and tested as a VNAV sub-mode, in a simulated subsonic jet transport aircraft with advanced all-electronic displays. The subject pilots in this experiment were able to use the LNG guidance to effectively conduct low-noise arrivals, with no major problems conducting the descent profiles as outlined in the procedures they were given. This included the test runs where they were required to make route and speed changes. Compared to the baseline runs, noise under the flight path was reduced by at least 2 decibels at distances from 3 nm out to 17.5 nm from the runway, with peak reductions of 8.5 decibels at about 10.5 nm. Fuel consumption was also reduced by about 17% for the LNG conditions compared to baseline runs for the same flight distance.

A standard CDA procedure, in which the pilots used charted altitude crossing conditions with extended glideslope on final approach (a CDA using conventional guidance), also proved effective in reducing noise and fuel consumption. Without the benefit of continuous VNAV guidance, however, the pilots were not able to consistently achieve continuous descents. The level-altitude segments prior to glideslope intercept resulted in additional required thrust, and subsequently reduced the potential noise benefit. Peak noise reductions of 6.5 decibels and fuel savings of about 8% were achieved with the standard CDA procedure compared to the baseline runs.

A subsequent study [5] addressed the issue of conducting CDAs using only conventional guidance technology (VNAV). Although the CDA profile cannot be maintained exactly using only conventional VNAV, the profile can be approximated, and could still provide a significant noise advantage over current-day procedures. In recent years there has been much interest in the development of flexible CDA procedures that could be used in terminal areas with moderately heavy traffic levels. The degree to which a CDA profile can be maintained is dependent partially on how well the charted procedures are designed, and partially on how much ATC lets the aircraft stay on the profile. The charted and crew procedures used for this experiment were developed with these factors in mind.

Results from the experiment indicated that, with appropriate charts and crew procedures, CDA descents could be flown with VNAV guidance and provide fuel savings and noise reduction benefits over current-day operations, even when interrupted by ATC with instructions that took the aircraft off of the VNAV path, laterally, vertically or both. The uninterrupted descent resulted in the most optimal profile, which translated to the lowest perceived noise levels and lowest amount of fuel burned. The potential fuel savings could be significant, on the order of 10% to 20% less fuel used in the descent segment. These benefits were reduced as the interruptions from ATC increased and took the aircraft off its optimal descent path, but all the CDA runs were quieter and more fuel efficient than those with current-day (non-CDA) procedures. The workload and pilot acceptability associated with conducting the descents were rated comparable to current-day procedures.

At the conclusion of the test runs, pilots were introduced to the concept of energy-based guidance for conducting CDA descents. Reactions were very positive from the subject pilots, with all of them indicating this type of guidance could make CDA descents much easier to conduct, with the only cause for concern being to ensure that the aircraft speed was above the flap extension speed prior to reaching the flap extension point that is generated and displayed on the ND by the low-noise algorithm.

The experiments described in this document continue the work from these two previous studies, incorporating updated versions of charts, training, and crew procedures, along with the latest modifications to the LNG and ENAV algorithms. The studies assessed the effectiveness and potential benefits of both conventional VNAV and advanced energy guidance technologies for conducting CDA procedures.

Experiment Descriptions

This report presents the results of two separate but related experiments conducted by the same research team. The first was a piloted simulation experiment conducted in 2005 as part of the NASA QAT Project. The second was a non-piloted batch simulation of the extended ENAV concept conducted in 2010 as part of the NASA NextGen Airspace Systems Program. Although separated by several years, the studies are linked and focused on different aspects of the same concept.

Objectives and Approach

The piloted simulation experiment described in this report was the culmination of a series of experiments evaluating low noise flight guidance and procedures, focused primarily on qualitative pilot assessment (references 4 and 5). The batch simulation experiment was designed to provide a more quantitative assessment of the ENAV guidance concept. The following sections detail the specific objectives and approach taken for each experiment.

Piloted Simulation Experiment

The main objective of the piloted simulation experiment was to assess the effectiveness of using LNG, in comparison with conventional VNAV, for conducting CDA procedures. Secondary experiment objectives were to identify strengths, weaknesses, and potential sources of confusion in using the LNG tool and CDA procedures.

The first objective, assessing the effectiveness of LNG and VNAV for conducting CDAs, required both objective and subjective data to determine whether or not the pilots could conduct a descent using the CDA procedures with acceptable levels of perceived workload. The effectiveness of the guidance would be determined by reduction of perceived noise levels and fuel use. Subjective data from subject pilots would give supporting data on workload and acceptability of the guidance and CDA procedures.

The second objective, identification of strengths, weaknesses, and potential sources of confusion, is important to the development of clear and concise CDA and LNG procedures, since the CDA differs from current-day procedures in subtle but important aspects. The primary source of data for determining this was from pilot comments and observations of how the crews conducted the descent.

To achieve these experiment objectives, a series of four simulator test runs was developed, based on a scenario that consisted of a descent and approach into a moderately busy terminal area, Louisville-Standiford International Airport (SDF). Each of the test runs used for this study had slight variations that represented situations typical of what an aircraft might encounter in that environment. The subject pilots were given instructions and information on how to conduct the CDA descent. Following practice time in the simulator, the pilots completed the test runs, during which objective and subjective data were recorded.

Benefits Analysis Batch Study

The primary objective of the batch study was to further evaluate the benefits and efficiency gains of ENAV compared to conventional VNAV during high-density terminal arrival operations. These benefits were measured in terms of fuel burn and community noise levels. Secondary objectives were to evaluate operational enhancements afforded by ENAV, including reduced dispersion of final approach stabilization altitude, elimination of high-energy landing conditions, and potential reduction in missed-approach conditions.

To accomplish the batch study, results of the piloted simulation were evaluated and a model of pilot behavior was developed. Details of the pilot model development are included in the Experiment Design section of this report. This pilot model allowed operation of the simulated airplane without the need for pilot test subjects. Test conditions were then designed to exercise ENAV and VNAV under a variety of arrival conditions. The Louisville scenarios developed for the piloted simulation tests were used to validate the behavior of the airplane simulation model, pilot model and FMS logic used by the batch airplane simulation. Additional Louisville scenarios were then tested to explore wind conditions and ATC speed changes not included in the piloted simulation. Finally, more extensive arrival situations were tested using a simulated Atlanta Hartsfield-Jackson International airport (ATL) terminal environment. The Atlanta scenarios involved full arrivals from high-altitude cruise to landing using an RNAV/OPD arrival developed for a companion study conducted at NASA Ames to explore Controller Managed Spacing research topics. The RNAV procedure represents a state of the art current-day (circa 2008) procedure designed to take maximum advantage of FMS capabilities while observing the airspace restrictions of the high-density Atlanta environment. The batch study was conducted several years after the conclusion of the piloted simulation study and utilized an enhanced ENAV algorithm designed to accommodate full descent from cruise altitude with arbitrary altitude and speed constraints at waypoints on the arrival.

Simulation Facilities

The two studies utilized different research facilities to accomplish the research objectives. The piloted simulation experiment was conducted in a high-fidelity cockpit simulator in order to properly assess flight crew workload and procedures. The batch simulation experiment was conducted using multiple simultaneous airplane simulations without the need for a full flight deck environment.

Piloted Flight Simulator

The facility used for the piloted simulation study was the NASA Langley Research Center Research Flight Deck (RFD) simulator (Figure 2). The RFD simulator cockpit is an engineering cab designed to represent the conventional flight deck of an advanced current-day commercial airplane. The simulation model used in the RFD consisted of full six degree of freedom equations of motion with high-fidelity aerodynamic and propulsion models of a current twin-engine jet transport aircraft. The cab is populated with flight instrumentation, including the overhead subsystems panels, center-aisle throttle quadrant, and full Electronic Flight Instrumentation System (EFIS) displays. The Primary Flight Display (PFD), Navigation Display (ND), and Engine Indicating and Crew Alerting System (EICAS) displays were representative of current display formats used in modern Boeing-style aircraft. The flight management computer was a Honeywell FMC-PIP used in Boeing 757/767 airplanes. The Mode Control Panel (MCP) was also from the Boeing 757 airplane. The cockpit contains a “Panorama” visual out-the-window display system. This system provides a 200 degree by 40 degree visual out-the-window display to add realism to piloted experiments.

During these simulation tests, cockpit

modifications included a non-standard control panel for the ND, and format modifications to the baseline ND and PFD. The non-standard ND control panel was located on the aisle stand just aft of the throttles. A description of the ND and PFD is contained in the Flight Manual Bulletin in Appendix B.

Air Traffic Operations Laboratory

The benefits analysis batch study utilized the NASA Air Traffic Operations Laboratory (ATOL) running multiple airplane simulations communicating via data-link with scripted ATC commands. Pilot modeling was used to operate the airplane simulations and human intervention was not required during the experiment data runs. A description of the basic design and capabilities of this simulation is provided in [6].

Aircraft Model. The aircraft model used in the batch study was the Aircraft Simulator for Traffic Operations Research (ASTOR). This is a medium-fidelity simulation of a modern jet transport aircraft utilizing the same core Six Degree-Of-Freedom simulation model as used in the piloted simulation cab described previously. The aerodynamic and engine models, however, were simplified using trimmed drag polars and tables of steady-state engine parameters similar to those used by flight management systems for trajectory predictions.

Flight Management System. The Research Prototype Flight Management System (RPFMS) used by the ASTORs was designed and developed by NASA to provide a research platform for studying FMS-related air traffic management topics. The core trajectory prediction and guidance algorithms evolved from the flight guidance software of the NASA Transport Systems Research Vehicle [7] and a PC-based simulation [8]. The trajectory prediction and VNAV guidance logic has been modified to replicate the behavior of the commercial FMS in the piloted simulation cab during the descent flight phase.

Pilot Modeling. The Pilot Model (PM) used by the ASTORs was designed to follow rules to support batch mode activities without human interactions. The PM has a class structure which consists of Sensors, Rules, and Actions objects. These objects are developed to sense flight conditions, recognize alerts and advisories, generate needed actions, and execute these actions, respectively, to maintain normal flight operations. The specific PM rules and actions used in this study are described in the Experiment Design section of this report.

RNAV Procedures and Charts

Charted RNAV arrival procedures were developed for each of the simulation studies described in this report.

Louisville Arrival

The charted arrival used for the piloted simulation study was called the SILENT CDA RNAV Arrival (Figure 3), and was based on the then existing CHERI Two Standard Terminal Arrival (STAR) into Louisville. The CHERI Two Arrival brings aircraft arriving from the West on a direct course to the IIU VOR, which is a radio navigational aid located southeast of the airport. Normally, aircraft landing to the South are vectored towards the airport, onto a right downwind or base leg. The SILENT CDA RNAV STAR included transitions for arrivals from the South (New Hope, EWO), West (CHERI), and North (DANNY).

Crossing restrictions of 13,000 ft and 240 knots were applied at CHERI and DANNY for handoff from Enroute Center airspace. The next hard altitude restriction was applied at CHRCL, the Final Approach Fix (FAF) for runway 17R. A speed restriction of 190 knots was applied at the SILNT waypoint to force aircraft to slow and deploy initial approach flaps in preparation for intercept of the final approach leg at SPYRS. An altitude restriction of at or above 6,000 feet at SILNT was used to avoid low altitude segments prior to final approach. SPYRS, BLGRS and CHRCL were also waypoints on the Instrument Landing System (ILS) 17R Approach, and the

FMS would link the Arrival and Approach into a continuous path when both were selected by the flight crew.

Atlanta Arrivals

The benefits analysis batch study extended the evaluation of ENAV to the more complex, high density terminal environments being tested in the NASA NextGen ASDO research focus area. A primary terminal of interest in ASDO is the Atlanta Metroplex. A recent simulation study of Controller Managed Spacing concepts developed candidate RNAV arrival procedures into Atlanta. These arrival procedures provided East and West arrivals merging to a common runway with altitude and speed crossing constraints at waypoints that are consistent with current-day Atlanta airspace design. The crossing constraints permitted an idle descent from cruise into the terminal area, followed by partial power continuous descent segments to final approach. These arrivals proved acceptable to air traffic controllers during human-in-the-loop testing, and represent the current state of the art in RNAV procedure design. Figure 4 illustrates these RNAV arrivals. The altitude and speed crossing restrictions for these arrivals are shown in Table 1.

The crossing restrictions at NOFIV from the West and BYRDS from the East provided the bottom of descent anchors for the idle descents from cruise. The routes merged at HAVAD, indicated by the shaded section of the table, and followed a fairly rigid vertical profile to final approach. A custom waypoint, named ELLLE, was inserted on final approach to allow a 90 degree turn from base to final. All other waypoints were taken from existing arrival and approach procedures at Atlanta.

The initial condition points, IC_SFO and IC_ORF, provided a common route distance of 150 nm for the West and East arrivals. These points represented the initial cruise locations of the aircraft flying the arrivals and were not part of the RNAV Arrival procedures. The aircraft would initialize at these locations and proceed direct to the first waypoint on the Arrival (CALCO or ODF).

ATC Environment

The two experiments required different levels of ATC simulation. The piloted study required live interaction with an air traffic controller to provide a realistic environment and proper communication workload. The non-piloted batch simulation needed a way of mimicking ATC speed clearances without human interaction. The following sections describe the methods used to accomplish these ATC requirements.

Piloted Simulation Study

A PC-based Air Traffic Control simulation was used to help provide realism to the subject pilots’ experience in the simulator. The simulation used was called the Multi-Aircraft Control System (MACS), a program developed in-house at NASA Ames Research Center for internal NASA use. An air traffic controller operating the MACS controller station watched the ground tracks of all the simulated air traffic (including the subject crew’s aircraft) on a PC display. All other air traffic (excepting the subject crew’s aircraft) were pre-recorded and played back during the runs. An example of the controller display is shown in figure 5.

Communications between the other aircraft and the controller were scripted and recorded on a desktop computer as audio files that could be played back at the appropriate times by the controller. The recorded communications were all natural voice using standard terminology. The controller communications were recorded by the controllers participating in the study. Communications from other aircraft were recorded by a variety of other people with piloting backgrounds. The controller also had scripts for the communications with the subject pilots, but had some flexibility for real-time requests or questions from the pilots. The subject pilots were able to hear all the pre-recorded communications, but talked directly with the controller, enabling him to issue clearances and vectors to them in real-time and adjust as needed for each particular situation. Position data for the other aircraft were also transmitted to the simulator, so the subject pilots could see them as traffic targets on their ND.

Benefits Analysis Batch Study

The benefits analysis batch study was designed to run without human pilots, and there was no need to include an ATC simulation. There was, however, the need to provide speed changes to the aircraft at specific locations along the arrival in order to mimic ATC speed clearances. This was accomplished by using the data link capability in ATOL along with custom pilot model rules. A series of free text data link messages would be sent to the aircraft with a distance to FAF and a commanded calibrated airspeed. The pilot model software would store these clearances, and then open the MCP speed window and dial the appropriate speed at the designated distance to FAF. This provided a repeatable way of mimicking a controller-instructed speed change at a specific location on the arrival. The pilot model would then close the MCP speed window just prior to the FAF to allow the airplane to decelerate and deploy flaps and gear for landing using the programmed FMS schedule.

Experiment Design

This section describes the test conditions and primary test variables for each experiment.

Piloted Simulation Test Conditions

Four different CDA test conditions were developed for this experiment: a nominal condition, where the CDA was flown without interruptions from ATC and three variations with different interruptions to the nominal path. Two versions of each of the four scenarios were developed: one arriving at the waypoint DANNY (north of the airport), and the other arriving at the waypoint CHERI (west of the airport). The four test conditions are described in this section, and are referred to with the following shorthand notation: a) *Nominal* for the uninterrupted CDA; b) *Slow* for the condition where the descent was interrupted with speed reductions from ATC; c) *Vector* for the condition where the descent was interrupted with an off-route vector in addition to the speed reductions; and d) *Stress* for the descent that was shortened significantly towards the end of the run. Examples of lateral paths for the four different run conditions are shown in Figure 6.

Nominal. The simplest CDA test run was an uninterrupted descent, flown with no changes to the charted procedure. After being cleared for the CDA, no further instructions from ATC (other than frequency changes) were issued until the approach clearance was issued on the base leg. The resulting descent would be near-optimal CDA. When flown properly, the vertical profile for this run had no level segments.

Slow. The second CDA test run began the same as a *Nominal* CDA descent, but was interrupted by ATC with speed changes that required the crew to come off of the optimal descent profile to some extent. A speed reduction from 240 knots to 210 knots was issued just after passing the CHERI or DANNY waypoint. A second speed change to 180 knots was issued just prior to the SILNT waypoint. Since the uninterrupted CDA was designed with faster speeds at near idle thrust, it was expected that this test run would result in a descent that was less optimal.

Vector. The Vector test run began the same as the *Nominal* and *Slow* CDA runs, but included more interruptions from ATC. In this run, the aircraft was taken off the CDA with a vector to the West just after the speed reduction to 210 knots as shown by Vector Routes in Figure 6. The resulting lateral path was not as direct as in the *Nominal* or *Slow* runs. The vertical trajectory did not require any level segments if properly flown, but had two segments that were very shallow. It was expected that this test run would result in a descent that was less optimal than either the *Nominal* or *Slow* test runs.

Stress. The fourth CDA test run began the same as the *Nominal* CDA test run, but was interrupted by ATC on the base leg with a heading vector that shortened the path distance (as shown in figure 6). It was expected that this test run would result in a high energy state and force timely pilot action to recover the vertical profile. The intent of this condition was to stress both the vertical guidance as well as pilot workload.

All piloted simulation runs were conducted using a nominal, vertically-varying wind field representative of typical winds in the Louisville area (Table 3). The same winds were used in all piloted simulation runs.

Batch Simulation Test Conditions

The fuel and noise benefits observed in the piloted simulation study were obtained using a single aircraft type, flown at the same weight, using the same atmospheric conditions along the same routes. The same speed restrictions and controller vectors were also issued to the flight crews at common locations on the route. These parameters were held constant in order to isolate the effects of flight crew performance. The batch study, however, exercised some of these previously controlled variables as independent variables with pilot performance and actions held constant.

The batch simulation was designed as an observational experiment rather than a randomized, Monte-Carlo style test. The values for the independent variables were chosen to cover the full operational range expected to be encountered in order to excite and/or uncover deficiencies or strengths in the ENAV guidance. A randomized design, while permitting more rigorous statistical analysis, would not ensure the full range of conditions would be exercised.

Aircraft Weight. The landing weight of an aircraft has a direct and proportional affect on the flap deployment and final approach speeds for the same aircraft type. The heavier the aircraft, the higher the speeds will be for flap deployment and for landing. A speed restriction at a waypoint or an ATC-instructed speed reduction may require different flap settings depending on the current aircraft weight. This change in flap setting will result in different drag and deceleration characteristics and different thrust requirements along a common vertical path. The fuel usage of a particular aircraft will therefore be dependent on weight. The Louisville scenarios used 17 weights providing a one knot difference in approach speed between each weight covering the entire weight range of the airplane. For the Atlanta scenarios, four weights were chosen that evenly covered the approach speed variation of the airplane.

Wind Conditions. Another major independent variable in the benefits study was atmospheric winds aloft. The nominal vertical wind profile shown in Table 2 was used as the baseline winds for the Louisville scenarios. Two additional wind profiles were tested, using double or half the wind magnitudes specified at the altitudes of Table 2. The wind directions remained the same for all three wind profiles.

The wind conditions for the Atlanta scenarios used a different approach. The historic data for winds aloft for every day over a two year period were collected from archived NOAA data from 2008 and 2009. The wind profiles were extracted from the Rapid Update Cycle (RUC) 20 km grid data for the location corresponding to the Peachtree National Weather Service (NWS) site (location shown in Figure 4). This location is used by the NWS to launch Radiosonde weather balloons on a twice daily basis. The extracted RUC data was found to be a good match to the balloon data and provided a complete altitude profile for use in the simulation. A profile of wind speed and direction versus pressure altitude was created using each pressure point in the RUC data for the time corresponding to the morning balloon launch. The profiles were then analyzed to determine the general characteristics of the wind, and the suitability of the profile for use in the experiment. The following were the characteristics deemed significant:

- Easterly winds at 1,000 ft pressure altitude (headwind component near touchdown).

- Easterly winds at 3,000 ft pressure altitude (headwind component near final approach fix).

- Northerly winds at 5,000 ft pressure altitude (crosswind component near final approach intercept).

The wind profiles were grouped according to these characteristics using the criteria in Table 3.

Individual wind profiles for each of the available 679 days were created for testing in the batch simulation. In addition, average profiles were created for the *All*, *Headwind*, *Tailwind*, *Southerly Crosswind* and *Northerly Crosswind* data shown in Table 3. Plots of the resulting averaged profiles are shown in Figure 7.

The final independent variable in the benefits analysis batch study was speed changes issued to the aircraft. Tactical speed changes, typically required for spacing and separation from other aircraft, interrupt the descent of an aircraft and force the FMS guidance to adapt to the new speed. Flight crews were instructed to respond to tactical speed interruptions using the speed window on the aircraft MCP. Conventional VNAV will revert to a mode called “Speed Intervention” in order to honor the speed entered by the flight crew in the MCP. Depending on where during the descent this speed is entered, the VNAV system will use different control strategies to manage the speed. The system used in the NASA simulator, a commercial FMS unit, would normally use pitch control to fly the speed and require pilot intervention with thrust and/or drag to follow the aircraft vertical path. Once the aircraft was on the approach portion of the route (inside the initial approach fix), the VNAV system reverted to flying the vertical path with pitch and would use thrust to manage the speed. The location of the tactical speed interruption can thus have an effect on the efficiency of the flight. The magnitude of the speed change can also affect the need for early (or late) deployment of aircraft flaps. Both the magnitude and location of tactical speed changes were varied in the benefits analysis batch study.

Piloted Simulation Crew Procedures

Procedures for the crew to use as a guideline in conducting the CDA descent were included in a Flight Manual Bulletin (FMB). The FMB described the RNAV CDA procedure and included instructions for pilots on how to manage their speed, altitude, and lateral route while conducting the CDA (see Appendix B). A subsection of the FMB provided specific instructions on how to use LNG to conduct the CDA procedure. For all test runs, the pilots were instructed to maintain their normal operating procedures as much as possible, except for the instructions in the FMB that were specific to conducting the CDA and using LNG.

The pilots were instructed to remain in VNAV and Lateral Navigation (LNAV) as much as possible. This included the times when ATC issued changes in lateral route or speed. The speed changes were to be made using the SPEED INTERVENE function, thereby allowing the aircraft to remain in VNAV guidance. Off-route vectors could be executed using Heading mode, but LNAV was to be engaged as soon as possible after being vectored back on course. Pilots were cautioned that using SPEED INTERVENE would affect how well the aircraft maintained the vertical path, and they needed to be aware of their position relative to the vertical path. This meant that pilots needed to maintain awareness of the aircraft flight modes as much as possible.

Batch Simulation Pilot Modeling

The batch simulation used pilot modeling based on rules developed from the crew procedures of the piloted simulation and observed behavior of the flight crews from that study. Table 4 summarizes the pilot actions that were modeled in the batch simulations.

Flap extension was based on current flap position, current airspeed, target airspeed and distance to the Final Approach Fix (FAF), as shown in table 5. The pilot model would always extend flaps to the next setting when the airspeed approached a prescribed minimum tolerance value above the minimum speed allowed for the current flap setting. For current flaps of 0, 1 and 20, this minimum tolerance value was 5 knots. For flaps 15 and 25, the pilots tended to deploy flaps earlier, and the tolerances were set to 12 and 14 knots, respectively. The need for additional deceleration on final approach required pilot model criteria for flap deployment at 0, 1 and 5 degrees based on distance to FAF and speed above the target speed.

Deployment of landing gear was based on criteria developed for the flight tests of CDA procedures conducted at Louisville, as described in reference 3. Normal criteria, based on intercepting the ILS glideslope, were not applicable to descents that followed the glideslope for a considerable distance. Instead, the distance to FAF was used as a guide for deployment of landing gear. The value found acceptable during CDA flight trials was deployment of gear at one nautical mile before the FAF. This criterion was used for the pilot model in the batch simulation. The pilots in the piloted simulation study were told to deploy gear prior to the FAF without a numerical value provided.

Piloted Simulation Test Matrix

Since workload and acceptability results were primary metrics for the piloted simulation, it was important that the crews be paired from the same company and aircraft type, to maintain continuity in their normal operating procedures. It was recognized that this constraint would limit the time that the subject pilots from each crew could both be expected to be available to participate in the test. It was also considered necessary to complete the test within a period of approximately nine hours, to minimize any negative effects due to fatigue from an excessively long day. To meet these constraints, the test was structured such that each crew could complete their run matrix in one 9-hour day. This made it difficult to completely counterbalance the test matrix by the control variables (run condition, pilot flying, type of guidance used), as this would have produced too many runs for the intended time frame of one 9-hour day per crew.

Another experiment design concern that arose was that it was unrealistic to expect the pilots to be able to switch between guidance modes (LNG vs. VNAV) from one run to the next, without any adverse effects on their performance. This back-and-forth switching could potentially happen from one run to the next if the conditions were either counterbalanced or randomized. However, some level of counterbalancing was considered necessary. To address the guidance switching issue, it was decided that the run conditions for each crew needed to be grouped by type of guidance used (that is, all the LNG runs together, and all the VNAV runs together); every crew would complete two sets of runs, one each with the two types of guidance.

If each pilot was allowed to fly one run as Flying Pilot (FP) and one as Non-Flying Pilot (NFP), the number of runs required was sixteen (4 conditions times 2 guidance modes times 2 pilots). This was more than it was felt could be accomplished in one 9-hour day. Since normally either pilot would fly any given arrival, the two pilots were considered equivalent from the standpoint of performance (noise, fuel, trajectory flown) results. This allowed the number of runs per crew to be divided in half, resulting in eight runs, which could easily be completed in one day, However, if both pilots flew some of the conditions as FP and some as NFP they could both provide ratings on workload and acceptability, which could all be combined for analysis, essentially doubling the pool of subjective data obtained.

A final issue of concern was the fact that conducting eight runs based on the same initial conditions might soon result in boredom, since they would know what to expect at the start of each run. To help mitigate boredom that might result from conducting the same approach so many times in a row, the arrival transitions were designed to initiate from two different directions, which were considered equivalent in terms of the CDA condition that was being investigated.

The resulting combinations of guidance, arrival transition, and flying pilot, and numbering scheme used to identify each of the conditions is shown in Table 6. For example, conditions 1 and 2 are both VNAV *Nominal* runs, but one is flown by the Captain and one by the First Officer, and one initiates on the DANNY Transition and one on the CHERI Transition. These two conditions are considered equivalent, and both represent the VNAV *Nominal* condition.

Each crew flew half of conditions 1-12, and either 13a and 14a, or 13b and 14b, for a total of eight test runs. The runs were selected such that for every crew, approximately half the runs were flown by each pilot. Because the guidance conditions were grouped together, this variable was balanced from one crew to the next, so that half the crews flew the VNAV group first, followed by the LNG group, and the other half flew the LNG group first, followed by the VNAV group. Within each of these groups, the four runs were randomized. Table 7 shows the order in which the test runs were conducted.

Subject Pilots

Twenty-four subject pilots were used for this study and were recruited as crews of two (one Captain and one First Officer), both from the same airline. All the subject pilots were required to be currently flying Boeing-style EFIS-equipped aircraft, such as B747-400 or B777, to minimize the amount of training time needed for this study. The resulting eight crews were each assigned a day to participate in the study. A single day was required for training and completion of the test matrix of runs.

Generally, the subject pilots recruited for this experiment had a great deal of experience. The subject crews represented four different airlines. The mean total flying hours for the pilots was over 10,000 hours, with a low of 3,300 hours and a high of over 20,000 hours. Most of the subject pilots had greater than 1,000 hours in either the B747-400 or B777 type aircraft. Also, when they participated in the study most had more than 100 flying hours in the previous 90 days (only four indicated they had fewer than 100 flying hours in the previous 90 days).

Batch Simulation Test Matrix

The benefits analysis batch simulation focused on the effects of aircraft weight, atmospheric wind, and simulated ATC-required speed variations during the arrival. The *Nominal* and *Slow* CDA procedures from the piloted simulation study were replicated in the batch simulation in order to compare and validate the batch simulation with the piloted simulation. The same routes were then flown with variations in aircraft weight, various wind conditions, and changes in the location and magnitude of ATC-directed speed changes. The Atlanta routes were flown using the same pilot procedures as developed for the Louisville scenarios, except using the Atlanta RNAV arrivals.

The test matrix for the Louisville scenarios is shown in Table 8. Each guidance mode (ENAV and VNAV) was flown on each route using 3 wind conditions, 7 combinations of speed schedules, and 17 different weights for a total of 1428 individual runs. The shaded values in the table indicate the test conditions used in the piloted simulation. The magnitude of the nominal winds was halved and doubled to examine the effect of winds on the guidance. The ATC speeds represented the range of speed variations that could be expected from ATC-directed speed changes along the route. Nominal speed was the uninterrupted case where the airplane flew charted speeds as programmed in the FMS. The remaining speeds were the ATC-directed speed changes issued at the same locations on the routes as used in the piloted simulation. Each speed combination represented an operationally realistic situation, covering the speed range available for jet transport operations. Finally, 17 weights were chosen to provide a complete range of final approach reference speeds (V_{ref}) for the simulated airplane type. Each weight value was chosen to provide a one knot change in V_{ref}.

The test matrix for the Atlanta scenarios was designed to exercise ENAV in a wide variety of realistic atmospheric wind conditions with aircraft weights and ATC speed conditions spanning the full capability of the aircraft. The test matrix was divided into two main sections. The first section was designed to explore the impact of recorded wind variations on the guidance for uninterrupted arrivals using charted speeds and altitude restrictions as programmed for the RNAV arrivals in the FMS. For these scenarios, the archived winds from the Peachtree weather station location for every day in 2008 and 2009 were used. The only days not used were those with tailwinds on final approach of greater than 10 knots. The resulting matrix consisted of 679 individual wind scenarios. For each wind scenario, 16 aircraft were flown, distributed between guidance mode, arrival route, and weights, as shown in Table 9. This resulted in a total of 10,864 individual runs.

The second section of the Atlanta evaluation was designed to explore the impact of speed interruptions during the arrival, as might occur from ATC speed changes for traffic spacing. Table 10 shows the test matrix variables used for this evaluation.

Three nominal locations were chosen where speed changes would typically be issued by ATC. These locations were further modified by shifting them early or late by 2 nm, resulting in three sets of speed change locations. Six combinations of speed change values were then defined that would bracket the available speed capability of the aircraft. The winds used in these scenarios were the averages for the headwind, tailwind, southerly crosswind, and northerly crosswind, as described in the section on wind conditions. The resulting test matrix, including two guidance modes along two arrival routes, was 1152 runs.

Data collection

The effectiveness of ENAV and VNAV in the piloted simulation experiment was determined by whether or not its use resulted in a decrease in noise and fuel use. Acceptability and workload associated with the guidance and CDA procedures were assessed from questionnaire data, as another measure of effectiveness. Identification of strengths, weaknesses, and potential sources of confusion was determined partially from results of how well the pilots were able to follow the procedure, and partially from the pilots' questionnaires.

Objective data

The main parameters used for determining the effectiveness of the guidance and CDA procedures from the recorded simulator data were altitude, airspeed, latitude/longitude, throttle activity, and fuel use. Many of these parameters were used for computing noise exposure levels using software programs developed external to NASA. Other parameters of interest were the operating modes (VNAV PATH, VNAV SPD, LNAV), and use of flaps, speed brakes, and landing gear.

Subjective data

Data such as workload and acceptability ratings are considered subjective, because they represent the pilots' opinions, rather than direct measurements of physical (or simulated) quantities. Subjective data collected for the piloted simulation experiment included workload ratings and structured questionnaires, which solicited ratings of acceptability, clarity, and ease of use, and open-ended questions and comments.

The workload ratings were obtained by means of a Bedford scale [5]. This is a 10-point scale adapted from the Modified Cooper-Harper scale commonly used in flight testing for rating aircraft handling qualities.

Some of the questions asked the pilots to provide a numbered rating used a 7-point scale, with the mid-point representing the neutral point. Some of the questions required a "Yes" or "No" answer, and others asked for comments or other explanations. Most of the questions on the final questionnaire were also given to the pilots in a pre-test questionnaire before conducting the test runs in the simulator. When the pilots were given the pre-test questionnaire, they were not told that they would be seeing the questions again after the test runs were completed, thus enabling researchers to obtain "before and after" responses to many of the questions.

Prior to beginning the initial briefing on the study, the pilots were given a test of their knowledge of certain VNAV modes. The nine questions on the test were intended to provide the researchers with some indication of the pilots' level of understanding of VNAV modes that they had developed from their previous flying and simulator experiences. The pilots were not told in advance that they would be given this test, nor were the results discussed with them. Questionnaires are included in Appendix C.

Results and Discussion

Two separate but related simulation experiments were conducted in 2005 and then 2010 in order to evaluate the effectiveness, pilot workload, and potential benefits of an energy management flight guidance concept. The analysis of the results from these experiments is divided into two major sections. The first section presents results from the piloted simulation experiment. The second presents the results of the non-piloted batch experiment.

Piloted Simulation Study

The two main indicators of the effectiveness of the flight guidance are whether it resulted in a reduced level of perceived noise level under the flight path, and whether it resulted in reduced fuel use. The vertical guidance mode (VNAV or LNG) affected the vertical profile flown by the aircraft and, in turn, the noise and fuel usage. The following sections examine the effect of guidance mode on the vertical profile followed by the effects on noise and fuel.

For data analysis and reporting purposes, the run conditions are referred to as *Nominal* (uninterrupted CDA), *Slow* (runs where the descent speed was reduced), *Vector* (runs where the aircraft was temporarily taken off the LNAV path), and *Stress* (runs where the lateral path was substantially shortened just prior to turning base leg). This terminology is used for the remainder of this report.

Vertical Profile

The CDA design of the RNAV arrivals was intended to provide a continuously descending flight path requiring low thrust levels. The guidance mode affects the actual trajectory flown. Figures 8 through 11 show the altitude and airspeed profiles for each of the test conditions. As expected, there was little difference in the profiles for the *Nominal* condition. The *Slow* and *Vector* runs, however, exhibit an overall higher altitude profile for LNG while retaining the same speed profile. This higher profile, coupled with dynamic gear and flap deployment, provides the noise and fuel benefits for LNG.

Noise

Perceived noise level was determined using the FAA Integrated Noise Model (INM) program with proprietary noise data tables from the Boeing Company, as described in [4]. Aircraft trajectories and parameters such as thrust level from the simulation were provided as inputs to the INM program, along with environmental factors (airport elevation, atmospheric pressure and temperature). The INM program then computed the Sound Exposure Level (SEL) at location points defined every 250 feet along the flight path, which were further reduced to obtain the average noise level for the range (along-track) between 3 nm and 15 nm. This is the region where there is the greatest need for reduction in noise levels. This also coincides with the data obtained in [5] for the identical simulated aircraft following typical baseline vectored routes into Louisville. Table 11 shows these results in tabular form for the different run conditions compared to the baseline data from reference [5].

The reduction in noise using VNAV compared to the baseline data was substantial in all cases. The data from the VNAV runs for the case of a near-optimal CDA descent (as represented by the *Nominal* condition), produced a reduction in the perceived noise levels of 4 decibels compared to baseline data. LNG runs resulted in an additional 1 decibel beyond what could be accomplished with VNAV only. The noise reduction obtained by using LNG remained relatively constant for the *Slow* and *Vector* conditions, while the benefit from VNAV guidance was reduced. This is indicative of the fact that the use of LNG allows the crew to maintain a more optimal descent when interrupted with additional speed or altitude constraints. The majority of the noise benefit, however, comes from the CDA design and not the guidance.

Fuel Use

Fuel use was compared among the four different run conditions, and between VNAV and LNG runs. Since all runs for the same test conditions were repeated from the same initial conditions for both VNAV and LNG, a direct comparison of fuel usage could be made.

Table 12 shows a comparison of the fuel use between VNAV and LNG runs, as well as the percent reduction these numbers represent for the LNG conditions. Generally speaking, for any given condition (*Nominal*, etc.), the percent reduction in fuel use by using LNG versus VNAV is less than 10 percent. In the *Nominal* conditions the fuel difference is especially small. This result was expected, as it represents a near-optimal CDA (the aircraft was able to conduct an uninterrupted CDA descent), and there would not be a significant advantage to using LNG over VNAV. In the *Slow* and *Stress* conditions, the required speed changes (and path changes in the *Stress* condition) caused more fluctuations in the speed and altitude when VNAV was used, whereas LNG was able to re-compute a new optimal trajectory that accommodated the changes. The limited number of data points and lack of variation in aircraft type, weight, winds or ATC speed changes prevent any definitive conclusions on fuel benefits afforded by LNG. These limitations are addressed in the batch simulation benefits analysis section of this report.

Since this experiment did not include a baseline descent (i.e., a descent with current-day procedures), the results from reference [5] were used to illustrate the reduction in fuel use due to the CDA procedures as well as the vertical guidance mode. This previous study is very comparable to the current study in that it used procedures very similar to those used in the current study, and was conducted in the same simulator, under similar conditions and pilot training. The RNAV STAR used in that study was different than the one used in this study; however, the baseline procedures were representative of controller vectoring and could be used for comparison with the RNAV procedures in this study. As was done in the prior study, the fuel data were examined along a common path distance. This allowed comparison of the fuel benefits afforded by the CDA vertical profile used in this study against the fuel used for non-CDA vertical descent procedures from the prior study.

Table 13 shows the percent reduction in fuel use from the reference 5 baseline condition, separately for VNAV and LNG runs. Each condition was adjusted to a common range of 82.6 nm, the minimum distance needed to include the Top Of Descent for each simulation run. These fuel numbers thus represent the fuel difference due to the vertical profile flown for each test condition. In Figure 12, the fuel numbers are presented normalized by the path distance (fuel used per nm), as another way to illustrate the differences among the different conditions and between VNAV and LNG runs.

These results showed that use of LNG to conduct the CDAs resulted in a greater reduction of fuel used over that seen with VNAV use. As with the noise level, the differences were not as great for the *Nominal* condition, which represented the closest to an optimal CDA descent. As the aircraft was taken off the optimal descent, however, the differences are more obvious. In the *Slow*, *Vector*, and *Stress* conditions, the percent fuel reduction was about twice as much when LNG was used versus when VNAV was used. These differences illustrate the advantage that can be gained by using LNG, which continually updates the aircraft's descent, taking into account any required changes to the trajectory, to re-compute a new optimal descent trajectory.

The fuel data presented in Table 13 and Figure 12 do not include the fuel benefit afforded by shortening path distance by using the RNAV CDA STAR. This benefit can be quite substantial, and is discussed in more detail in reference [5].

Workload

Perceived workload ratings were collected from the subject pilots at several points during each run. These ratings were based on the Bedford scale (Figure 13), which asks pilots to rate their spare capacity (i.e., their ability to complete other tasks after having completed the primary task of flying the descent). The pilots were asked to provide a rating at three points during the run (Figure 14): A) during the descent from 18,000 ft, B) on base leg (two miles after crossing the waypoint SILNT), and C) on final (two miles after crossing the waypoint BLGRS). During the *Stress* conditions, the lateral path did not take the aircraft over SILNT, but rather cut short the path and went direct to BLGRS. Because of this shortcut, the second workload rating (after SILNT) was skipped for these runs.

Results of the pilot ratings are summarized in Table 14, and shown graphically in Figure 15. Overall, the ratings were low on the scale (below 3.5), indicating that the pilots felt the workload levels were at a very acceptable level. According to the scale, a rating of 3 indicates "enough spare capacity for all desirable additional tasks". Each pair of data sets (VNAV vs. LNG at each condition and evaluation point) was compared with a Mann-Whitney Rank Sum test, which showed no statistical differences between each of the two data sets. From these results we can conclude that, for this group of pilots, CDA descents could be conducted with either LNG or VNAV without any significant differences in perceived workload for the flight crew. Also, in both cases the workload required to conduct CDAs was considered to be at an acceptably low level when conducted according to the instructions provided.

Other Subjective Data

VNAV Test. Prior to starting the briefing at the beginning of the day, pilots were given a pre-test on VNAV operations. The questions on the VNAV test were designed to assess the pilots' level of understanding of the basic operation of VNAV in a descent and presented situations that could be encountered during a CDA procedure. These results were of interest only as a means of assessing the understanding of VNAV for the pilots as a group, and not as a means of grading any individual pilot's knowledge. The results of the test were of no consequence to the pilots' subsequent qualification for participation in the study. In an operational environment, the incorrect interpretation of the mode of operation of the autoflight system could result in a less-than-optimal descent profile being flown.

Most of the 24 subject pilots correctly answered all the questions on the VNAV test. Out of the eight questions on the test, only three of them had some incorrect responses. The pilots were not given advance knowledge of this test, but they were told that they should have a good understanding of the operating modes of the autoflight system. Because of this requirement, it was anticipated that the pilots who volunteered to participate in this study would be well-experienced and knowledgeable on VNAV and would do well on this test.

The first question had only one incorrect answer. *To stay on an FMC-programmed vertical path, in which autoflight mode must the aircraft be?* The correct answer was VNAV Path, but one pilot answered VNAV Speed.

Three pilots answered the second question incorrectly. The question was: "*While in a VNAV descent with the MCP Speed window closed, what speed will the autoflight system attempt to maintain?*" The correct answer was "the FMC-programmed speed on the VNAV Descent page". The three pilots who answered this question incorrectly gave the same answer, which was that the system would attempt to maintain the ECON, or most efficient speed.

The other question with incorrect answers was: “With the aircraft descending in VNAV, if the MCP speed window is opened (speed intervene) to lower the speed below the FMC-programmed descent speed, the vertical path flown by the aircraft will initially be:” The correct answer was “higher than the FMC-programmed path”. Four pilots gave incorrect answers to this question. Two of these pilots gave “lower than the FMC-programmed path” as the answer, and the other two gave “the same as the FMC-programmed path” as the answer.

A sample of the VNAV test given to the pilots is included in Appendix C.

Post-Run Questionnaires. After each test run was completed, the subject pilots were asked to rate (using a 7-point scale) how difficult, how clear, and how acceptable were the procedures for maintaining the aircraft vertical path, speed, and lateral path. This resulted in 9 ratings for each test run for each pilot. The results were compiled and plotted as means and standard deviations, grouped by whether they were VNAV or LNG runs. Results are shown in Figure 16 for the VNAV *Nominal*, *Slow*, *Vector*, and *Stress* conditions, and in Figure 17 for the LNG *Nominal*, *Slow*, *Vector*, and *Stress* conditions.

Post-Test Questionnaire Results

The Post-Test Questionnaire was given to the subject pilots immediately after completion of the final test run of the day. This questionnaire was intended to give the pilots the opportunity to evaluate the entire process, including the training, materials, and the cockpit procedures. They also were asked to indicate preferences regarding the appearance of the energy indicator, such as on which display (PFD or ND) they preferred to see it, and which elements of the LNG tool were most useful. The questions from the VNAV Test and the Pre-Test Questionnaire were repeated in this questionnaire, to assess whether there were any differences in opinion after having actually flown the test runs.

Arrival Chart Information. When asked whether they would have liked to see any other information on the chart, most (83%) answered “no”; the remaining responses suggested terrain/obstruction information, and additional waypoint speed/altitude constraints. All pilots answered “no” to the question “Do you have any suggestions for improvements to the chart?” Most (92%) said they had enough time to study the chart, with only 2 (8%) indicating they did not have enough time.

Procedures. The pilots were asked to rate the procedures for managing path, speed, and altitude, as outlined in the FMB. For all three questions, a seven-point scale was used, ranging from Very Difficult (corresponding to a rating of 1), to Very Easy (corresponding to a rating of 7), with the midpoint being Average (a rating of 4). Their responses to all three questions were very similar. The results indicated that they felt the procedures for managing altitude between the waypoints CHERI and BLGRS were easy (Mean = 6.0, Standard Deviation = 1.0). The procedures were rated similarly easy for managing speed (M = 5.9, SD = 1.0), and for managing path (M = 6.1, SD = 1.0).

When asked whether there was any information missing that would help make the procedure easier, the majority of the pilots (71%) said there was nothing missing, but the remaining 7 pilots had suggestions that ranged from reducing the “clutter,” to adding more graphics to show the mode changes to be expected. Other suggestions included additional prompts, such as for gear and other reminders of some of the altitude/speed interactions due to the different modes.

When asked whether they had suggestions for improvements to the FMB, only two answered “yes”, one suggesting keeping standard terminology, and the other said that the chart seemed to follow the standard format, with all the necessary information to safely fly the descent except for terrain information.

The pilots were asked if they were

uncomfortable with the 700-ft stabilization altitude. Seventeen of them (71%) answered that they were not uncomfortable with it. When asked what altitude they would prefer, the answers varied from 500 ft (in VMC) up to 1,000 ft, with the most common answer being 1,000 ft. Some indicated this altitude for IMC, with a lower one (500 ft) for VMC. Many also answered that they preferred 700-800 ft.

Most pilots indicated that they had enough time to study the FMB, with only three (13%) indicating that they would have liked more time.

When asked to rate their level of understanding of the procedures, the mean rating was 6.4 (SD=0.6), indicating that most pilots felt they understood the BLGRS2 RNAV Arrival procedure very well. A seven-point scale was used for this question, with the lowest rating of 1 indicating "I do not understand it at all", the midpoint rating of 4 indicating "I understand it, but still have some questions," and the highest rating of 7 indicating "I understand it completely".

The final question on the procedures asked the pilots if they could think of any situations where a pilot who is not as familiar with VNAV might become confused regarding what the altitude or speed of the aircraft should be while conducting this type of descent procedure. Pilots cited possible confusion after an ATC intervention in speed, altitude or heading, then trying to resume the FMS path. Specifically some pilots mentioned knowing where to resume the charted speed after having been issued another speed by ATC. Another issue that was mentioned was possible confusion due to some pilots setting intermediate altitudes in the MCP rather than the final altitude for the descent. Some pilots' comments were more general, saying that for pilots unfamiliar with VNAV some parts of the procedure could get confusing, but with practice they would be able to do it better.

LNG Tool. The final set of questions was specifically about the LNG tool and consisted mostly of multiple-choice answers. The first question asked the pilots how much they used the LNG tool display during the LNG runs. Half of the pilots responded with "during most of the time it was displayed (about 75% of the time)", and most of the rest (46%) answered "during the entire time it was displayed". One pilot responded that he used it "about half the time it was displayed" (see Figure 18).

The second question asked the pilots which part of the LNG tool they found most useful. As shown in Figure 19, half the pilots answered that they found the energy indicator diamond the most useful. Eight percent found the limits on the energy indicator most useful, and 29% found the event markers on the ND (29%) the most useful. The pilots that indicated "other" responses (17%) indicated that they liked the Flight Path Vector on the Vertical Situation Display on the ND, which technically was not really part of the LNG tool.

When asked whether there was any part of the LNG tool that they found particularly useful, the answers varied, but basically covered a range of features: the energy diamond (particularly on the PFD), the event markers (mentioned several times), the vertical situation display (not really part of the LNG tool), and the box around the energy diamond, which was a prompt to close the MCP speed window (see Figure 19).

When asked whether there was any part of the LNG tool that they found particularly confusing, most (83%) answered "no", and most of the remaining answers referred to the small (and difficult to read) energy diamond on the ND. One pilot commented that the energy indicator display needed an explanation of what "high" and "low" actually meant.

When asked if there was any part of the LNG tool that they found particularly intuitive (i.e., easy to use), the answers were fairly evenly divided among the different components – energy diamond on the PFD, event markers, and the flight path vector. Other components mentioned were the limit indicators and the trend arrows on the energy display.

The pilots were asked which energy indicator display (PFD, ND, or both equally) they used the most. Two-thirds answered that they used the PFD display most, followed by both equally (21%), and 3 (12%) that indicated they used the ND display most (Figure 19).

When asked where they would prefer to have the energy indicator displayed (PFD, ND, or both), 75% indicated that they would prefer to have it displayed on the PFD, 21% on both, and only 1 pilot indicated that he would prefer to have it on the ND (see Figure 20).

The pilots were asked whether they would be comfortable having the energy indicator displayed only on the PFD, only on the ND, or it should be displayed in both places. The vast majority (86%) answered “yes” to having it displayed only on the PFD, with only 3 pilots answering “no” (see Figure 21). For the ND, 58% answered that they would not be comfortable having the energy indicator displayed only on the ND, and the rest indicated that they would. The option of having it displayed in both places received almost equal votes for yes (9 votes, 53%) and no (8 votes, 47%). When asked “For most pilots, where do you think it would be most appropriate to have the LNG energy indicator,” the responses were: PFD 67%, ND 8% and both 25% (see Figure 22).

VNAV Operations. The final two questions asked pilots to estimate how often, in their normal day-to-day operations, they used VNAV below 11,000 ft and below 6,000 ft. The most common response (see Figure 23) was “sometimes”, with almost half the pilots (46%) responding that they used it below 11,000 ft, and 42% indicating that they used it below 6,000 ft. The remainder were evenly split for the below 11,000 ft question, between “every flight” and “often”. For the below 6,000 ft question, the remaining responses were split between “often” and “never”. These results support the presupposed notion that it is very common for pilots to use VNAV below 11,000 ft, but not as much so below 6,000 ft.

Benefits Analysis Batch Study

The potential benefits of ENAV guidance were examined in batch simulation using the test matrix of runs previously described for both the Louiville scenarios as well as full cruise to landing scenarios in the Atlanta terminal area. The Louisville scenarios replicated the conditions flown in the piloted simulation study with additional weight, wind and speed restrictions being included. The Atlanta scenarios explored more restrictive terminal altitude constraints with full cruise to landing operations. The following sections present the results of these tests in terms of fuel, noise and airplane stabilization metrics. Also described is a comparison of the batch and piloted simulation performance and behavior.

Validation of Batch Simulation

The batch study was conducted using a different aircraft simulation and FMS than was used in the piloted simulation. A series of test runs were conducted to compare the performance of the batch simulation with that of the piloted simulation. The *Nominal* and *Slow* test conditions from the piloted simulation were replicated using the batch simulation. The resulting altitude and airspeed profiles are compared in Figures 24 and 25 for both VNAV and ENAV guidance.

The VNAV *Nominal* profiles compared quite well between the piloted and batch simulations. The batch simulation VNAV altitude profile was a bit lower as the aircraft approached the 6,000' altitude constraint due to different logic in handling the vertical altitude constraints. The FMS in the piloted simulation used a simple fixed flight-path angle between altitude constraints while the research FMS built a shallow deceleration segment for the speed constraint at 6,000 feet. One of the piloted simulation profiles departed the *Nominal* altitude profile when a high speed condition resulted in reversion to VNAV SPEED mode as the airplane approached 10,000 feet altitude. In this case, the pilot applied speed brake and allowed the aircraft to descend below the programmed path and stabilized the speed on the next crossing constraint of 190 knots. The batch simulation VNAV logic included this mode, however, these simulation runs did not excite this behavior. Only one of the piloted simulation runs encountered this situation.

The VNAV *Slow* profiles also compared well, with the batch simulation altitude tracking the low end of the piloted simulation profiles. This was due to the lack of a manual thrust mode in the batch simulation pilot model. During the piloted simulation runs, the pilots were able to manually apply thrust when the aircraft was in VNAV SPEED mode with autothrottle set to HOLD. In this particular scenario, the aircraft would normally descend below the programmed altitude while the autopilot applied pitch control to hold the selected airspeed. VNAV would stop the descent using thrust to prevent descending below the next waypoint altitude crossing constraint. This is the modeled behavior of the batch simulation. Several of the pilots in the piloted simulation monitored the vertical deviation during these VNAV SPEED descents and manually applied thrust to prevent descending too far below the programmed path. The significance and implications of this behavior are discussed in the fuel and noise benefits results sections.

The ENAV profiles were also slightly different between the batch and piloted simulations. Coding changes to the ENAV logic, as well as improved performance modeling compared to LNG, resulted in slightly different trajectories.

The major difference in behavior between the piloted and batch simulations was the timing of flap and gear deployment. Pilot modeling for the batch simulation based flap deployment on current speed, target speed, and distance to FAF as shown in Table 5. A comparison of flap deployment between the piloted simulation and the batch simulation for identical Louisville scenarios is shown in Figures 26 and 27. The speed at which flaps were deployed agreed well between the 2 simulations for the flaps 1, 5, 25 and 30 settings. Flaps 15 showed a larger difference, primarily because of the target airspeed criterion used by the pilot model in the batch simulation. All batch simulation flap deployment speeds, however, were well within one standard deviation of the observed deployment speeds in the piloted simulation. The distance to the runway at which flap deployment occurred, however, was significantly different for the flap 1, 5 and 15 settings, as shown in Figure 27. The pilot model deployed flaps at least 5 nm earlier than the average distance for the pilots in the piloted simulation. The flaps 1 and 5 conditions occurred at speeds that were very close to the speeds being held constant for extended distances along the arrival. The pilot model would deploy flaps as soon as the speed reached the criteria specified in Table 5. The pilots, however, realizing they were holding an airspeed that was slightly greater than the minimum speed for the current flap setting, would not deploy flaps until the target speed dropped below the minimum speed. Several pilots commented they would have deployed flaps earlier if they were actually flying and there was any turbulence causing fluctuations in airspeed. This real-world consideration was the primary reason for using the more conservative flap-deployment criteria in the batch simulation. The ENAV criteria for flap deployment were also modified to include the additional margins above minimum speed for the batch simulation runs. The flap deployment criteria were thus consistent for the VNAV and ENAV comparisons in the batch simulation.

Fuel

Fuel benefits were determined by comparing the fuel usage resulting from flying the scenarios using ENAV compared to the same scenarios flown using conventional VNAV.

Louisville Scenarios. The piloted simulation provided an indication of the fuel benefits afforded by using LNG guidance for the Louisville scenario. Table 15 presents the fuel use results for the same scenario with an expanded set of airplane weights, atmospheric winds, and ATC speed restrictions using the latest ENAV guidance.

The *Nominal* speed condition showed a 5.9

percent reduction in fuel using ENAV for the expanded weight and wind conditions in the batch simulation compared to a 2.7 percent fuel reduction using LNG in the piloted simulation (Table 12). This 3 percent improvement in the ENAV batch results was attributed to the conservative pilot modeling in the batch simulation, with early flap deployment and no throttle adjustments to correct low path conditions. This conservative pilot modeling, however, is felt to be more representative of average airline pilot performance, especially those pilots with limited experience using VNAV in the terminal environment. Training and experience with VNAV is necessary to improve performance and achieve the benefits observed by the motivated and experienced pilots who participated in the piloted simulation. ENAV, however, was designed to assist even inexperienced pilots achieve consistent performance.

Similar fuel savings comparisons are seen for the 210/180/170 speed condition in Table 15 and the comparable *Slow* condition in Table 12. Again, ENAV exhibited about 3 percent more fuel savings than observed in the piloted simulation using LNG. Fuel savings in the batch simulation, however, were seen to decrease as the ATC-required speed conditions increased. As the aircraft is held at higher speeds closer to the runway, there is little the ENAV guidance can do to optimize flap and gear deployment.

The average fuel savings using ENAV for all speed and wind conditions in the Louisville scenarios was about 78 lbs or 7.5% greater than the fuel used with VNAV. The impact of half or double the wind magnitude was found to have little effect on this result, as seen in Table 15b. Pilot training on the use of VNAV, manual throttle correction of below-path conditions and delayed flap extension could reduce this benefit by perhaps 2 or 3 percent.

Atlanta Scenarios. The extended arrival scenarios, based on Atlanta airspace, evaluated the use of ENAV under highly constrained terminal arrival operations as envisioned for NextGen. These scenarios included opposite direction arrivals starting at cruise altitudes of 37,000 feet, arriving from the West, and 36,000 feet, arriving from the East. The terminal routing included altitude and speed crossing restrictions designed to allow continuous descents while maintaining separation from other arrival and departure traffic. These restrictions, deemed essential for high density traffic operations, limit the ability of airborne optimization to improve individual aircraft performance. Within the constrained regions of the arrival, the airborne optimization is limited to guidance for managing the energy state of the aircraft through flap and gear configuration changes. In addition, high-energy situations requiring additional drag through speed brake can be identified. Vertical optimization of altitude, however, is no longer viable.

Results of the fuel used during the Atlanta scenario arrivals are presented in Table 16. A fuel reduction using ENAV of about 49 lbs, or 3.5 % of the total fuel used in the scenario was observed for the wind-condition tests. This fuel reduction was essentially the same for the East and West routes, although the percentage was slightly different due to different total fuel used in the different directions. From the start of the simulation to waypoint ELLLE, the first waypoint on final approach, the fuel reduction was about 17 lbs. The remaining 32 lbs of fuel savings occurred on final approach, between ELLLE and the runway, a distance of only 13 nautical miles. This result indicates the majority of fuel savings for these scenarios is attributed to optimization of flap and landing gear deployment on final approach. The enroute and initial descent segments in the terminal area account for only about one third of the fuel savings. This indicates that the dynamic recalculation of the descent trajectory during descent by ENAV did not result in much fuel savings for these scenarios.

The effect of ATC speed restrictions was found to be minor, with a slight increase in ENAV fuel savings for the early location speed changes and least benefit for the late changes.

Noise

The perceived noise levels under the flight path for the batch simulation arrivals were computed using the noise tables provided by Boeing, as described in Reference 3. The instantaneous peak noise level (LMAX) values were computed from these tables for each recorded trajectory point along the arrival and then averaged over the distance from 15 nm to 3 nm from the runway to obtain a single noise metric for each flight. This metric was consistent with the sound exposure level (SEL) noise metric obtained for the piloted simulation study. The use of instantaneous LMAX values allowed computation of noise metrics directly from the airplane state, configuration and engine data without requiring post-processing using the modified FAA INM program. The relative difference in noise levels between two trajectories using the averaged peak noise was found to be the same as the difference in averaged SEL noise.

Louisville Scenario. The noise metrics for the Louisville batch simulation runs are presented in Table 17. The overall noise reduction achieved using ENAV was about 2 decibels. The largest reductions were seen for the slower speed conditions, with less reduction occurring with faster speeds. The wind conditions also showed small differences in noise reduction, with about a one decibel difference between the double and half magnitude wind fields.

As with the fuel savings, the batch noise benefits for ENAV were slightly greater than the noise benefits of LNG from the piloted simulation results shown in Table 11. The overall lower altitudes of the VNAV trajectories in the batch simulation, as well as the earlier flap deployment, produced about one decibel of additional noise compared to the piloted simulation. Pilot training and vigilance would be required to avoid this additional noise penalty.

Atlanta Scenarios. The noise metrics for the Atlanta batch simulation runs are presented in Table 18. As with the Louisville scenarios, the overall noise reduction achieved with ENAV was about 2 decibels. The East and West routes merged at about 17 nm from the runway, so there was no difference in the region covered by the noise metric. The only noticeable difference in noise levels occurred for the late speed conditions, where the benefit of ENAV was reduced. This is consistent with fuel savings results and again illustrates the penalty of constraining the aircraft to the point where there is insufficient range remaining to optimize flap and gear deployment.

Final Stabilization

The final metric considered in the batch experiment was the altitude at which the airplane achieved final-approach stabilization. For the purposes of this experiment, the airplane was considered stabilized on the approach when the following criteria were achieved:

- Airspeed within 10 knots of final approach speed,
- Landing gear down and flaps fully extended to landing configuration,
- Flight path angle less than 0 degrees and greater than -3.5 degrees, and
- Throttle 5% above idle.

The target stabilization altitude for the arrivals in the batch study was 1,000 feet above ground level (AGL). Pilot procedures for achieving proper stabilization are quite varied and difficult to realistically model in non-piloted simulations. Observations from the piloted simulation runs, review of airline procedures, and discussions with the pilots resulted in the modeled procedures used in the batch experiment. The primary means for achieving the 1,000 foot stabilization was gear extension by one nautical mile before the Final Approach Fix. Target speed selection of final approach speed occurs after crossing the FAF. Flap deployment occurs as the speed approaches the minimum for the current flap setting. Speed margins above the minimum were measured in the piloted simulation and used to trigger flap deployment in the batch simulation. The ENAV guidance provided cues, both visually on the Navigation display as well as audio and visual Engine Indicating and Crew Alerting System (EICAS) alerts, for all gear and flap deployment. The pilot model in this study responded instantly to both the distance to FAF and speed margin cues for VNAV and the gear and flap deployment cues for ENAV.

Louisville Scenarios. The stabilization altitudes for the Louisville runs are presented in Table 19. The results for all simulation runs showed a mean stabilization altitude for the ENAV guidance of 1,029 feet with a standard deviation of 55 feet. This compared to the mean altitude of 1,172 feet and standard deviation of 73 feet for VNAV. The 143-foot lower stabilization altitude resulted in about a half of a nautical mile shorter distance flown in landing configuration and was a primary factor in the lower fuel use of the ENAV runs. The correspondingly later gear and flap deployment for ENAV contributed to the lower noise levels.

The deviation in stabilization altitude was not significantly lower for ENAV, primarily due to the various ATC speed conditions included in the scenarios. The ENAV variation under nominal speed conditions was a remarkably low 4 feet, nearly within the system repeatability margin. The speed-constrained conditions, however, had standard deviations from 15 to 94 feet. This variation in the standard deviation indicates that the ENAV logic for flap deployment under off-nominal speed conditions was not operating as effectively as hoped. The VNAV conditions, that based gear and flap deployment on simple distance and speed margins, exhibited less variation in the standard deviation of stabilization altitude.

Atlanta Scenarios. The stabilization altitudes for the Atlanta runs are presented in Table 20. The mean stabilization altitudes were a bit lower for these scenarios compared to the Louisville scenarios due to the approximately .5 nm shorter distance from the FAF to the runway. The VNAV cases, which based gear extension on distance to FAF, exhibited mean stabilization altitudes about 120 feet lower than the Louisville scenarios. The ENAV cases, with guidance cues based on deceleration predictions to the runway, were only about 25 feet lower. The overall result was a smaller benefit from ENAV in terms of distance flown in the landing configuration and a correspondingly lower fuel benefit.

The large sample of wind conditions, many including large fluctuations of wind on final approach, produced larger variations in the measured stabilization altitudes for both ENAV and VNAV. The overall standard deviation in altitude for ENAV was 63 feet, up from 55 feet in the Louisville scenarios. The VNAV scenarios exhibited a more significant increase in standard deviation to 121 feet from 73 feet in the Louisville runs. Again, ENAV exhibited large variations in some of the speed conditions shown in Table 20b, in particular the higher speed conditions. In general ENAV handled the large variations in wind and speeds better than VNAV, but certainly not to a significant degree. Additional work is needed to refine the ENAV logic for handling flap deployment under off-nominal speed conditions.

Concluding Remarks

Two simulation studies investigated the use of an Energy Navigation (ENAV) flight-deck tool for conducting a descent through a busy terminal area using Continuous Descent Arrival (CDA) procedures. A piloted simulation study evaluated crew procedures, display concepts, and workload while providing an initial assessment of the effectiveness and benefits of the energy guidance. The crew procedures and RNAV chart were designed to be easy to understand, and to make it easy for the crew to make changes via the Flight Management Computer Control-Display Unit (FMC-CDU) and the auto-flight system Mode Control Panel (MCP) to accommodate changes from ATC. The test runs were intended to represent situations typical of what exists in many of today's terminal areas, including interruptions to the descent in the form of clearances issued by ATC. The batch simulation further evaluated the benefits and efficiency gains of ENAV during high-density terminal arrival operations. These benefits were measured in terms of fuel burn, community noise levels and final approach stabilization altitude.

The results of the piloted simulation showed pilots were able to conduct the descents, even when interrupted by ATC with instructions that took the aircraft off of the VNAV path, laterally, vertically or both. The uninterrupted (*Nominal*) descent resulted in the greatest noise and fuel benefits for both LNG and VNAV descents. The perceived noise level was reduced by approximately 1 decibel for the LNG runs compared to the VNAV runs for the uninterrupted descents, and about 2 decibels for the interrupted descents. Relative to the baseline conditions from a prior study [5], the noise reductions of VNAV and LNG were about 4 to 5 decibels, respectively. The potential fuel savings in the descent segment were similar for the uninterrupted VNAV and LNG runs (13% and 16%, respectively compared to baseline). These benefits were reduced as the interruptions from ATC increased and took the aircraft off its optimal descent path; however, in these cases the savings with LNG were approximately twice those of VNAV.

The workload associated with conducting the CDAs was rated comparable to workload with current-day non-CDA procedures for both the LNG and VNAV descents. Pilots were able to conduct the descents with a moderate amount of time allowed for studying the instructions and charts they were given. Minor improvements to the charts and procedures were identified that can clarify the altitude and speed constraints and clearances, and reduce the potential for confusion.

Pilots expressed a strong preference for locating the Energy Indicator on the PFD rather than the ND, partially due to its function as a tool for managing speed in the descent, and partially due to the greater space available for display.

The results of the batch simulation showed the fuel and noise benefits observed in the piloted study were representative of benefits achieved under a larger variety of atmospheric wind conditions and ATC speed interruptions. The average fuel savings using ENAV for all speed and wind conditions in the Louisville scenarios was about 78 lbs or 7.5% less than the fuel used with VNAV. The impact of half or double the wind magnitude was found to have little effect on this result. The Atlanta scenarios, which included a large variety of wind conditions, more restrictive altitude constraints and a shorter distance from the Final Approach Fix (FAF) to the runway, had an average fuel savings of 49 lbs or 3.5% using ENAV. The effect of ATC speed restrictions was found to be minor, with a slight increase in ENAV fuel savings for the early location speed changes, and least benefit for the late changes.

The majority of the fuel savings with ENAV was found to occur on the final approach segment of the arrival. Nearly two thirds of the total fuel savings occurred during the last 13 nautical miles of the arrival, indicating that the primary fuel efficiency of ENAV is resulting from delayed flap and landing gear deployment. The dynamic recalculation of the descent trajectory in response to unplanned winds and/or ATC speed changes did not account for a significant fuel savings.

The overall noise reduction achieved using ENAV was about 2 decibels greater than the noise reduction achieved for VNAV for the batch simulation scenarios. Late ATC speed restrictions were found to reduce the benefits of ENAV since little time or distance remained to optimize flap and gear deployment.

Final stabilization height was reduced using ENAV with a smaller dispersion in stabilization altitudes. The distance from FAF to the runway affected the VNAV stabilization height since gear deployment was based on the FAF location. In general ENAV handled large variations in wind and speeds well and showed more consistent variations in stabilization height. ENAV logic for flap deployment under off-nominal speed conditions prior to the FAF, however, did not operate as effectively as hoped and did not provide much benefit over conventional flap deployment logic.

These two simulation studies demonstrated pilot acceptability of terminal RNAV arrival procedures incorporating near-idle continuous descent with both conventional VNAV as well as enhanced ENAV flight guidance. The arrival procedures tested in the studies are representative of future NextGen trajectory-based operations and are consistent with the latest RNAV arrival designs being implemented by the FAA. The addition of ENAV guidance to the flight deck has the potential to improve the efficiency and environmental benefits of these RNAV arrival procedures while reducing the flight crew workload and training requirements needed to routinely fly these procedures. Results from these studies indicate the majority of the efficiency and environmental benefits with ENAV occur on final approach and further refinement of ENAV flap and gear deployment logic is needed to maximize these benefits.

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Appendix A

ENAV Software Description

Environment

The ENAV software operates as a software module within a simulation or flight environment. ENAV is designed to operate in the final cruise, descent and approach phases of flight. The software expects inputs consistent with these operations. Aircraft state conditions must be within the operational envelope of the airplane, and the airplane should be within approximately 200 nm of the landing runway.

Pilot interface

ENAV is intended to function as a custom FMS LNAV and VNAV mode. As such, there is no special or unique pilot interface. When ENAV is active, the standard LNAV and VNAV guidance are presented to the pilot. The only new indications to the pilots will be an energy error indication on the Primary Flight Display (PFD) and/or Navigation Display (ND), and ENAV-specific events on the ND. In addition, vertical trajectory information is available for optional display on a Vertical Situation Display (VSD). The ENAV events can also be annunciated to the pilots via the standard aural and visual alerting system if desired.

Algorithm Inputs

Inputs to the ENAV software consist of lateral route definition, vertical segment definition, weather definition, and aircraft state data. These parameters must be passed in a manner that prevents the ENAV software from altering their contents in the calling program. The ENAV process determines the computations required based on the input data.

Lateral Route Definition

This is an ASCII string that defines the lateral routing for the ENAV trajectory. Two route strings may be sent to ENAV: one for the active route and another for the “mod” or provisional route. The active route is required for ENAV active guidance. The provisional route is optional.

The strings are a series of latitude-longitude waypoints separated by a period in the sequence starting from the first, being at or behind the airplane location, and the last being the runway threshold.

The string may be set to NULL if a call to the ENAV procedure does not contain new route data. There must be a minimum of two waypoints for a valid input of route data. The maximum number of waypoints is 60. The maximum length of the route string is defined in the interface header file.

The ENAV routine automatically determines if the input active route string is sufficiently different from the current active route to warrant a new route calculation. In order to force a new route calculation, the calling program must add the string “NEW.” to the beginning of the active route string.

Vertical Segment Definition

The vertical segment definition is passed to the ENAV software as a data structure of string parameters that adhere to the naming convention described in the Vertical Path section of Trajectory Definition. The structure defines the number of vertical segments and provides ASCII strings for each required parameter for each segment. A maximum of 16 vertical segments may be used.

The first record contains headers for each parameter of the segment definition (these correspond to each parameter in the data structure). Subsequent records contain the segment definition for each segment, starting from the runway working backwards to the airplane. The first record must be the final pre-touchdown conditions at which the airplane is stabilized for landing (i.e., stabilization altitude).

The final record must be a level altitude segment ending at the airplane range.

The ENAV software contains a default vertical segment definition. The ENAV software uses this default vertical segment definition if the input vertical segment definition data indicates zero segments. The calling program explicitly sets the number of segments to zero to enable using the default vertical segments.

The software modifies the vertical segment definition to honor all waypoint constraints contained in the route definition input string. This modification only occurs with the default vertical segment definition.

Weather Definition

This is an ASCII string with the vertical weather profile. The string is a series of weather records containing pressure altitude in 100s of feet, wind direction in degrees, wind speed in knots and temperature deviation from standard day in degrees C. The weather record entries are separated by a period in the sequence starting from the lowest altitude to the highest. Altimeter setting, in inches of mercury, may optionally be input as the first weather record

There is a minimum of one vertical weather point and/or one altimeter setting for a valid input of weather data. The maximum length of the weather string is defined in the interface header file. If a valid weather string is not input by the calling program, standard day, no-wind conditions will be used. To specifically force standard day, no-wind conditions, the weather string must be set to “STANDARD_DAY”.

The ENAV routine will test the input weather string to determine if the weather data has changed sufficiently to require a new trajectory calculation. Repeatedly sending the same weather string will not result in new trajectories being generated. NULL weather strings are ignored, and the previous weather input will be used on any trajectory calculation. If a valid weather string has never been sent, ENAV will default to standard day with no wind.

Aircraft State Data

The following aircraft parameters are required on each call to the ENAV procedure:

- Time (current time of day), sec
- Latitude, deg
- Longitude, deg
- Barometric altitude (altimeter), feet
- Vertical speed, fpm
- Calibrated airspeed, knots
- True airspeed, knots
- Ground speed, knots
- True track angle, deg
- Wind speed, knots
- Wind direction, deg
- Static air temperature, deg C
- Flap selection, deg
- Engine power setting (EPR for NASA 757)
- Landing gear handle (0=up or off,1=down)
- Weight, lbs

Aircraft Mode Control Data

The following MCP parameters are required on each call to the ENAV procedure:

- Selected altitude, feet
- Selected CAS, knots
- Selected Mach
- Speed window status
  0 = closed,
  1 = open,
  2 = closed with externally defined speed target
- LNAV active guidance mode
  (0 = no, 1 = yes)
- VNAV active guidance mode
  (0 = no, 1 = yes)

The MCP data are used in the automatic updating feature of ENAV.

Aircraft Planning Data

The following data are needed from the aircraft FMS for vertical trajectory planning:

- Final approach reference speed (Vref)
- Flag indicating a Mach/CAS descent
- Descent calibrated airspeed
- Descent Mach

ENAV Altitude and Speed Limits

The default operating altitude and speed for ENAV is below 12,500 feet and less than or equal to 250 knots. These operating limits may optionally be extended to higher altitudes and speeds using the *MaxAltitude* and *MaxCAS* input parameters. These limits should not be extended beyond 41,000 feet altitude and 350 knots CAS.

Algorithm Outputs

The ENAV software is designed for real-time flight guidance and primarily provides dynamic outputs on return from each call to the ENAV procedure. The software also provides output of the active reference flight trajectory in both full engineering units and an ASCII string suitable for input to ACARS-capable FMS via a data link formatted flight plan modification.

Guidance Output

The following parameters are output on each return from the ENAV procedure:

- Target barometric altitude, feet
- Target vertical speed, ft/min
- Command vertical speed, ft/min (for autopilot pitch control)
- MCP vertical speed, ft/min (for manual pitch control)
- Target calibrated airspeed, knots (for autothrottle speed control)
- Reference calibrated airspeed, knots
- Descent calibrated airspeed, knots
- Target mach
- Flag indicating Mach or CAS target
- Reference ground speed, knots
- Energy error, feet
- Energy error rate, ft/sec
- Maximum energy error, feet
- Minimum energy error, feet
- Distance to go to the runway threshold, feet
- Elapsed along-track range from start of trajectory, feet
- Estimated time to go to the runway, sec
- Target true track angle, deg
- Cross track error, feet
- Nominal bank angle, deg
- Bank angle command, deg
- Flag indicating drag required
- Throttle mode, integer code
  0 = ENAV_THROTTLE_SPD
  1 = ENAV_THROTTLE_IDLE
  2 = ENAV_THROTTLE_DORMANT

When guidance computations are not valid, these output parameters are set to a unique value indicating they are invalid. The value for invalid data is defined in the interface header file.

Additionally, an event string is output that defines the upcoming ENAV events as well as error codes. The contents of the event string include:

- Name of the event
- Location (latitude and longitude)

The ENAV events are also output as a data structure containing the event name, latitude, longitude, and along-path distance to go to the event.

Trajectory Output

The calling program maintains a data structure that matches the trajectory definition contained in the ENAV interface header file. A pointer to this structure is passed to ENAV in the calling statement. The ENAV software will populate this data structure whenever a new trajectory is computed. The number of trajectory points in the trajectory is explicitly set to zero by the ENAV software if there is no active ENAV trajectory.

In addition to the trajectory structure maintained by the calling program, a trajectory change point (TCP) structure is provided in the outputs. The contents of this structure are:

- Name
- Latitude, deg
- Longitude, deg
- Elapsed range, feet
- Altitude, feet
- CAS, knots
- Groundspeed, knots
- ETA, sec

Appendix B

Flight Manual Bulletin

INSTRUCTIONS TO SUBJECT PILOTS

FLIGHT MANUAL BULLETIN

Revision 4.5, 7/29/2005

CONTINUOUS DESCENT APPROACH (CDA)

BACKGROUND AND SUMMARY

The Continuous Descent Approach (CDA) is a beneficial method for operationally reducing community noise near airports, in addition to lowering fuel usage during the descent. The CDA is designed to minimize level altitude segments during approach, especially at lower altitudes. This keeps the aircraft higher and at reduced thrust settings during most of the descent in the terminal arrival area. Typically, the altitude crossing restriction at the Initial Approach Fix (IAF) of the Instrument Landing System (ILS) approach is raised so that glideslope intercept occurs approximately at the turn to final approach. A CDA can be flown accurately with a Flight Management System (FMS)-equipped aircraft; however the way in which the vertical profile is flown can vary substantially across pilots and aircraft types. If the vertical profile is not properly managed, the aircraft could reach the IAF altitude early, requiring an undesired level segment to the IAF. Properly managing the aircraft’s total energy (speed and altitude) throughout the descent can minimize this problem. To best comply with altitude and speed restrictions, while remaining close to the optimal descent trajectory, the CDA should be flown with vertical guidance in the VNAV (Vertical Navigation) mode. To conduct an effective CDA descent with VNAV, pilots should have a good understanding of how this mode transitions among its sub-modes and interacts with other autoflight systems to meet speed and altitude constraints.

CDA procedures (RNAV arrivals) were developed for Louisville International Airport (SDF), using routing typical of what is used by Air Traffic Control (ATC) Approach Control for vectoring operations. ATC will issue the clearance to descend on the CDA RNAV arrival. While on the arrival, the crew is responsible for complying with charted speed and altitude crossing restrictions. ATC may issue speeds and/or altitudes that are different from those shown on the chart. The crew must comply with any new instructions issued by ATC, until instructed to resume the RNAV arrival. The crossing conditions at the end of the CDA allow for a smooth transition to the ILS approach, however ATC may clear the aircraft for a different type of approach.

This bulletin describes clearances and crew procedures for conducting the CDA. Additional instructions are in the Appendix for aircraft equipped with Low Noise Guidance (LNG), a flight deck tool that displays aircraft energy error and provides guidance for a noise-optimal descent.

EXAMPLES OF NOMINAL CDA CLEARANCES

Descent clearance for the Silent RNAV Arrival:

- *"Descend via the Silent RNAV Arrival";*
  “Proceed direct ABCDE, then descend via the Silent RNAV Arrival”

This clearance may be issued at any time, and allows the crew to descend on the SILNT RNAV Arrival until the fix CHRCL. Typically it is issued before the initial fix on the arrival (CHERI, DANNY, or KWIET). However, this descent clearance may also be issued in conjunction with a “direct to” one of the other waypoints on the arrival. This allows the aircraft to continue descending on the remainder of the RNAV arrival, via the indicated waypoint. The crew must comply with all charted altitude and speed restrictions from (and including) that waypoint on, unless otherwise instructed by ATC.

Pilots shall advise ATC upon beginning the descent (e.g., "…leaving 18000 feet…"). Pilots shall advise ATC upon initial contact that they are descending on the SILNT RNAV Arrival ("…descending through XXXXX feet on the SILNT RNAV Arrival").

Deviations from the CDA RNAV Arrival:

At any time after initiating the descent, ATC may issue speed, heading, or altitude changes that are different from those on the RNAV Arrival. Subsequent instructions may be issued to continue the descent on the Arrival. Examples of instructions taking the aircraft off the Arrival are listed below (these may be issued individually or grouped):

- *"Turn left (right), heading XXX."*

This instruction takes the aircraft off of the RNAV Arrival. ATC-issued instructions must be complied with until the crew is cleared to again descend via the Arrival, at which point the charted restrictions once again apply.

- *"Descend and maintain YYYY."*

This instruction requires the crew to descend and maintain the ATC-issued altitude until instructed otherwise by ATC. If the crew is subsequently cleared to continue descending on the Arrival, the crew must revert to the charted altitude profile, beginning with the "to" waypoint, where the arrival is re-joined. If there is no altitude restriction at this waypoint, the last ATC-issued altitude is used. If ATC did not issue a new altitude clearance, then the next charted altitude restriction is used.

- *"Reduce speed to XXX knots."*

This instruction requires the crew to maintain the issued speed until instructed otherwise by ATC. If the crew is subsequently cleared to continue descending on the Arrival, the crew must revert to the charted speed profile; this begins with the first waypoint (the "to" waypoint) on the arrival, where it is re-joined. If there is no speed restriction at this waypoint, the last ATC-issued speed is used.

A normal approach clearance is issued prior to the IAF waypoint for the approach procedure.

CREW PROCEDURES FOR CONDUCTING THE CDA

While descending on the RNAV Arrival, keeping the aircraft in full LNAV/VNAV mode allows the crew to comply with charted altitude and speed constraints, and to maintain a profile close to the optimal CDA profile. If ATC issues instructions that take the aircraft off of the RNAV Arrival, the crew may use other autoflight functions to comply with the verbal instructions, but should remain in VNAV as much as possible throughout the descent to achieve the most efficient profile. Pilots must remain cognizant of their aircraft's autoflight modes at all times.

Lateral Route Management

Depending on traffic conditions, ATC may alter the RNAV route by issuing instructions that take the aircraft off the charted route, with subsequent instructions to rejoin the procedure. For timely compliance, the crew may use the HDG (heading select) function on the Mode Control Panel (MCP) to turn towards the cleared waypoint, while remaining in VNAV. To continue on the RNAV route, the crew must modify the FMC route to go "direct-to" the indicated waypoint. After the new route is executed, the crew must then re-engage LNAV and VNAV (if not already engaged) to continue.

Altitude Management

With the aircraft in VNAV, the descent will be managed according to the VNAV vertical profile. However, it is crucial that pilots monitor throughout the descent the amount of deviation from the programmed VNAV path using the vertical path deviation indicator on the Navigation Display (ND). If the aircraft's path deviates too much from the programmed path, it might not be possible to recapture it until the aircraft is on final approach. This could result in VNAV exhibiting unexpected behaviors. If the aircraft path were excessively low, an extended level segment might result, producing excessive noise. If the aircraft path were excessively high, it might not be possible to intercept the glide slope and continue the approach.

If the pilot feels that VNAV is not managing the vertical path in an acceptable manner, speedbrakes and throttle should be used to augment VNAV guidance, or another pitch mode may be selected to better comply with the vertical profile.

Speed Management

With the aircraft in VNAV, speed is controlled by the autoflight guidance to comply with the speed profile programmed in the FMC. If ATC issues a speed change, the crew must use the VNAV speed intervene function to comply with the ATC instruction in a timely manner, by pushing the MCP SPD knob to open the MCP speed window and dialing in the new speed. Descending in this mode will likely cause the aircraft to deviate from the programmed vertical profile, increasing the possibility that the descent could be completed too early, and the aircraft would level off prior to intercepting the glide slope. This makes the descent less optimal (CDA descents are designed to avoid low-altitude level segments.) To minimize the possibility of having a level segment, the aircraft's descent rate may be adjusted (using thrust while in THR HOLD and VNAV SPD) to obtain a better profile and meet the next waypoint constraint.

If the crew is then cleared to resume the RNAV Arrival while still in VNAV-speed-intervene, they may either continue in this mode (managing all subsequent charted speed reductions by dialing them in the MCP speed window), or return to full VNAV (by de-selecting the MCP speed knob).

If the crew chooses to return to full VNAV, the SPD knob must not be pushed until after crossing the next speed-constrained waypoint on the RNAV arrival. If the SPD knob is pushed prior to that, the aircraft may revert to the old VNAV descent speed, unless the new one is programmed into the FMC. If the old descent speed is much higher than the current aircraft speed, this might cause the autoflight guidance to command abrupt throttle changes to meet the next speed constraint.

It is crucial to monitor the vertical path deviation indicator whenever the speed intervene function is used, to ensure that the aircraft remains close to the vertical path. The crew may use another pitch mode to ensure compliance with restrictions (such as the 250-kt speed requirement below 10,000 feet), if they feel that remaining in VNAV will not do so. Speedbrakes may be used to add drag.

Flap and Gear Deployment

To maximize noise reduction, the landing gear extension should be delayed until the Final Approach Fix. If speed is nominal, landing gear should be extended at the FAF. If speed is more than 10 kts high approaching the FAF, gear may be extended early to enable the aircraft to achieve a stabilized approach by 1000 feet AGL.

Flap deployment should follow the normal speed schedule. As speed is reduced throughout the descent, the corresponding flaps should be deployed.

Appendix: LOW NOISE GUIDANCE (LNG)

An airborne tool known as the Low Noise Guidance (LNG) algorithm has been developed to provide pilots with flight guidance to fly Continuous Descent Approaches (CDAs). The LNG algorithm computes the desired lateral and vertical trajectory given a defined route and current aircraft position, altitude, and speed. The geographical location of guidance events, including top of descent (TOD), and flap and gear extension points, are also computed based on aircraft aerodynamic performance and predicted winds, and are displayed on the ND. If cleared for a CDA, aircraft equipped with LNG may conduct the descent in LNG VNAV.

The LNG tool is designed to provide enhanced vertical guidance during VNAV approach situations. When activated, the tool will compute a high-efficiency, low-noise vertical trajectory from current aircraft location to the selected landing runway along the FMS active flight plan route. The tool displays key vertical events on the Navigation Display and provides a continuous energy indication of actual aircraft total energy relative to the desired computed energy along the LNG vertical path. Unlike standard VNAV, the LNG vertical path is automatically updated to accommodate speed changes entered via the Mode Control Panel, as well as intentional altitude or speed excursions executed by the flight crew.

Description of LNG tool and displays

The LNG tool is intended to be a sub-mode of VNAV, and is automatically activated when VNAV is selected. With LNG active, the energy indicator is displayed on the left-hand side of the PFD as a diamond-shaped symbol, as shown in Figure 1 below.

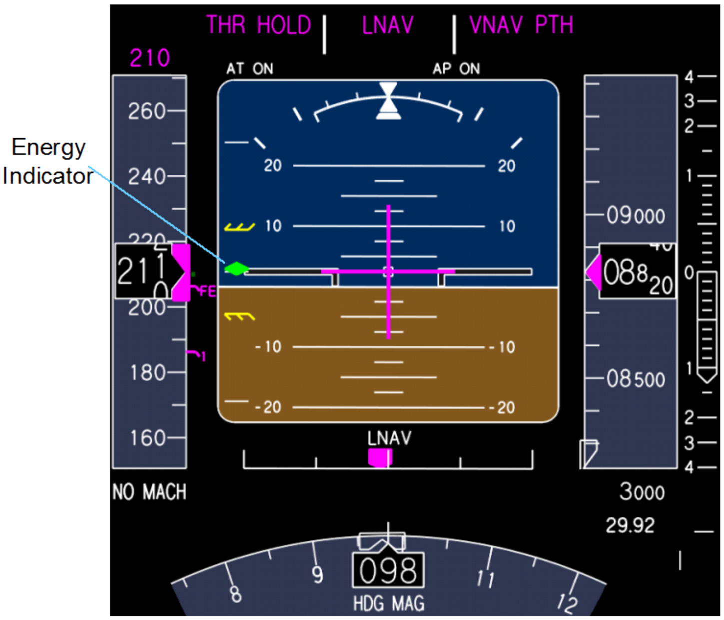


Figure 1. PFD depicting Energy Indicator.

The energy indicator displays the difference between the aircraft's actual total energy and the predicted total energy. If the aircraft has more or less energy than desired, the indicator will move upward or downward accordingly. If the energy indicator moves beyond the upper or lower limits shown (yellow feathers), then the crew should take action to resolve the energy excursion.

The guidance events are displayed on the Navigation Display (ND) in Map or Center mode. Energy indicator is also depicted in Center mode adjacent to the Vertical Situation Display (VSD).

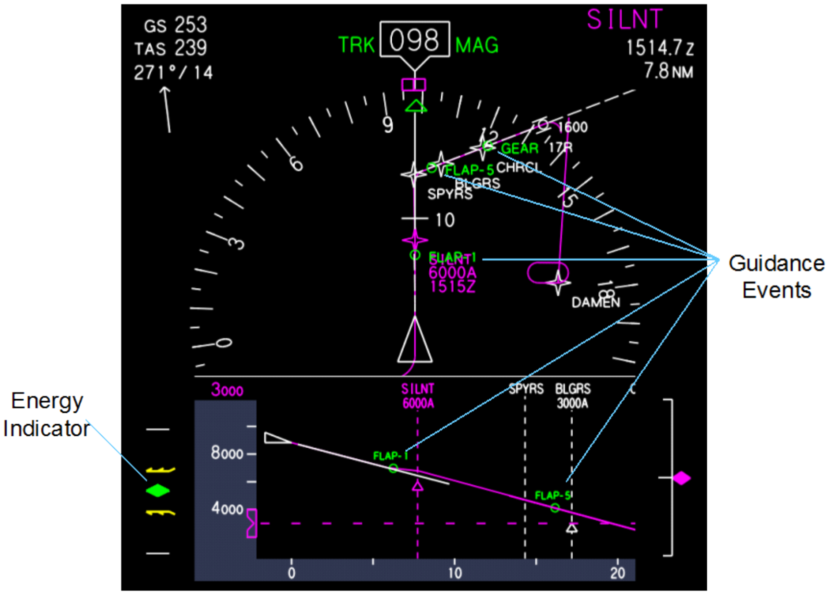


Figure 2. ND with VSD Depicting Energy Indicator and Guidance Events.

The possible vertical events are:

- Top of Descent (TOD)
- Deceleration (DECEL)
- Flaps 1 (FLAP-1)
- Flaps 5 (FLAP-5)
- Landing Gear (GEAR)

The events are advisory in nature, however, the crew should take appropriate action (such as deploying flaps or extending landing gear) when crossing the events to ensure proper energy management.

There are no direct annunciations or alerts regarding the status of LNG associated with the LNG system. The only indication that LNG is active while in VNAV is the presence of the Energy Indicator on the PFD and the LNG vertical events on the Navigation Display. The vertical mode annunciation on the PFD will be “VNAV PATH” while LNG is active.

Managing Energy

The total energy of the aircraft is based on the aircraft’s kinetic (speed) and potential (altitude) energy. During the initial part of the descent, the energy calculation uses ground speed. When stabilization at final VREF speed is required, the algorithm uses calibrated airspeed for the energy calculation.

An aircraft that is slow and high may register the same total energy as an aircraft that is fast and low. Understanding of this concept is especially important in the event of a large energy excursion. The crew should monitor the vertical path deviation indicator on the ND and the airspeed indicator to avoid possible confusion on the source of the energy excursion. Further, because the energy error during initial descent is based on ground speed, if there is a large difference between the predicted winds (on the CDU Descent Forecast Page) and actual winds, an energy error will be displayed even if air speed and altitude are correct.

With the aircraft tracking the desired vertical path with VNAV engaged, an energy deviation will consist predominantly of a speed error. It is preferable to dissipate energy through the use of spoilers on the initial part of the descent, to fine-tune the energy without the use of throttle. If further energy dissipation is required, flaps may be deployed (or a notch added) before arriving at the DECEL or FLAP points, as appropriate. If energy gets too low, gradually increase thrust to achieve a satisfactory trend on the energy indicator.

Since the auto throttle will normally manage thrust to maintain (or achieve) the VNAV speed target, it may not be possible to correct an energy error while coupled in VNAV and auto throttle without changing the VNAV target speed. Higher-than-predicted headwinds and/or intentional low airspeeds typically result in a low energy condition. Conversely, lower-than-predicted headwinds or intentional high airspeeds will result in a high energy condition. Too-low energy while in auto throttle is generally not a problem and corrective action (such as increasing the target speed using VNAV speed intervene) is not necessary. Too-high energy, however, should be corrected using additional drag (if throttle is at idle) and/or reducing the aircraft speed.

General rule for using LNG: If energy is too high, reduce thrust or add drag. If energy is too low, increase thrust or reduce drag.

Lateral Path Management

The low noise guidance algorithm requires a continuous lateral path to the runway in order to calculate the CDA vertical trajectory and the geographical locations of the guidance events.

Once calculated, the guidance events are valid only while the aircraft remains on or near the programmed lateral path (in LNAV). If the aircraft deviates significantly from the lateral path, e.g. when being radar vectored, the vertical path is no longer valid and will be removed from the Vertical Situation Display. LNG vertical guidance and energy error display will remain active and provide approximate guidance to rejoin the FMS path in an efficient manner. Large deviations from the lateral path should be corrected by executing a DIRECT TO a waypoint on the lateral path to ensure coupled lateral and vertical guidance.

Speed and Flap Schedule

If Air Traffic Control (ATC) issues a new speed to the LNG aircraft, the crew must use the speed-intervene function (pushing the speed knob on the Mode Control Panel) to expedite the speed change while remaining in VNAV. After LNG re-calculates a new path, the speed knob should be pushed again to exit the speed-intervene function. Recalculation of the path usually takes about one second, and is evident by a slight change in the location of TOD and other ND events. Exiting from speed-intervene enables the aircraft to once again closely follow the LNG vertical path guidance, resulting in a more optimal descent profile. If the crew does not exit the speed-intervene function, a box will appear around the energy diamond as a prompt to close the MCP window. *It is important to close the MCP window when this prompt appears*, because failing to do so will over-ride any downstream speed reductions computed by LNG, and affect the aircraft's energy level. This feature is only active with flaps up.

Deployment of flaps and landing gear will take place at a slightly later point than during a non-CDA approach, primarily due to the higher-energy approach profile. The CDA profile while using VNAV LNG is designed for a constant speed descent between the TOD and DECEL points. If needed, VNAV will then shallow the descent between the DECEL and FLAP points to decelerate the aircraft to V_{FE}. To reduce screen clutter, the DECEL point is not shown if the distance to the FLAP point is less than 1/2 nm. Flaps may be extended when the aircraft speed is in the appropriate range.

After the FLAP-5 point, additional flaps should be extended as necessary as the aircraft speed naturally decays, or as needed to manage energy. Pilots should keep the MCP speed window open after the FLAP-5 point, and adjust the speed as would normally be done for this part of the descent. Speeds issued by ATC must be adhered to as would normally be the case, and the MCP speed window should be open prior to glideslope capture, to ensure that the throttle does not make any rapid adjustments. After flaps have been extended, the “MCP window open” box around the energy diamond will not appear.

Gear Extension

The location of the GEAR event point is prescribed in order to reduce aircraft noise close to the airport. If the aircraft energy is good when nearing the GEAR point, the landing gear should be lowered crossing the GEAR point. If energy is slightly high, the gear may be extended earlier than the GEAR point to help dissipate excess energy. If energy is low, airspeed should be maintained with throttle, at the flaps 5 or flaps 15 minimum maneuver speed until the gear point is reached.

CDA PROCEDURE WITH LNG

The following table contains a summary of procedures for conducting a continuous descent approach in VNAV, with and without the LNG function.

CDA Approach without LNG	**CDA Approach with LNG**
Must have active route in FMC to enable guidance (VNAV) to fly CDA automatically.	same
Prior to TOD and in VNAV, dial MCP altitude window to next altitude constraint.	same
Comply with charted restrictions until FAF.	same
VNAV guidance follows vertical path in FMC; autothrottle adjusts to follow VNAV speeds.	same
If new speed is issued, use speed intervene to expedite; **remain in speed intervene** until back on Arrival; closely watch vertical path deviation. **Compliance with charted altitude crossing restrictions is crucial.**	If new speed is issued, use speed intervene to expedite; **exit speed-intervene** after new descent path is computed; Ensure **energy** remains in green range
Aircraft will automatically decelerate to **comply with charted crossing constraints**.	same
Extend flaps according to current speed.	Extend flaps at specified LNG event locations and/or according to current speed.
Expect normal approach clearance.	same
At glideslope capture, autothrottle reverts to SPD mode, pilot controls speed through MCP.	same
If aircraft trajectory is in acceptable range, extend landing gear **prior to FAF**.	If energy is in green range, extend landing gear at **GEAR** point on ND

Appendix C

Questionnaires

VNAV Questionnaire

1) To stay on an FMC-programmed vertical path, in which autoflight mode must the aircraft be?
   a. FLCH (Flight Level Change)
   b. VNAV SPD (Vertical Navigation Speed)
   c. VSPD (Vertical Speed)
   d. VNAV PTH (Vertical Navigation Path)

2) While in a VNAV descent with the Mode Control Panel (MCP) Speed window closed, what speed will the autoflight system attempt to maintain?

____

3) While in a VNAV descent with the MCP speed window open, what speed will the autoflight system attempt to maintain?

____

4) In VNAV PTH mode, the autoflight system will sacrifice _____________ in order to maintain ____________.

5) In VNAV SPD mode, the autoflight system will sacrifice _____________ in order to maintain ____________.

6) While in a descent in VNAV PTH mode, a speed is assigned (verbally) by ATC. What action would you normally take in order to comply with the speed assignment, and in what mode would the aircraft then be?

____

____

____

7) With the aircraft descending on a VNAV path and thrust mode in throttle hold, what speed will the autoflight system attempt to maintain?

8) With the aircraft descending in VNAV, if the MCP speed window is opened (speed intervene) to lower the speed below the FMC-programmed descent speed, the vertical path flown by the aircraft will initially be:
   a) higher than the FMC-programmed path
   b) lower than the FMC-programmed path
   c) the same as the FMC-programmed path

Post-Run Questionnaire

Use the scale below to answer the following question.

1	**2**	**3**	**4**	**5**	**6**	**7**
Very Difficult			**Average**			**Very Easy**

Very difficult: required much harder mental effort to complete this task than what I normally experience during this phase of flight for most of my commercial operations today.

Average: required about the same amount of mental effort to accomplish this task as what I normally experience during this phase of flight for most of my commercial operations today

Very Easy: required much less mental and/or physical effort to accomplish this task than what I normally experience during this phase of flight for most of my commercial operations today.

Rate how ***difficult*** it was during this test run to manage:

run number→	1	2	3	4	5	6	7	8	9	10	11	12
vertical path												
speed												
lateral path												

Comments:

1

2

3

4

5

6

7

8

9

10

11

12

Use the scale below to answer the following question.

1	**2**	**3**	**4**	**5**	**6**	**7**
Very Unclear			**Average**			**Very Clear**

Very Unclear: I did not understand the procedures at all.

Average: I understood the procedures, but had to think carefully about what I needed to do.

Very clear: I understood the procedures completely, and knew exactly what I needed to do.

Rate how ***clear*** it was during this test run to manage:

run number→	1	2	3	4	5	6	7	8	9	10	11	12
vertical path												
speed												
lateral path												

Comments:

1

2

3

4

5

6

7

8

9

10

11

12

Use the scale below to answer the following question.

1	**2**	**3**	**4**	**5**	**6**	**7**
Very Unacceptable			**Average**			**Very Acceptable**

Very Unacceptable: I did not like the procedures at all, and would not use them in normal operations.

Average: I liked the procedures and would use them in normal operations, but would like to see some improvements.

Very acceptable: I liked the procedures very much, and would use them without any improvements.

Rate how ***acceptable*** it was during this test run to manage:

run number→	1	2	3	4	5	6	7	8	9	10	11	12
vertical path												
speed												
lateral path												

Comments:

1____________________

2____________________

3____________________

4____________________

5____________________

6____________________

7____________________

8____________________

9____________________

10____________________

11____________________

12____________________

Post-Test Questionnaire

1) To stay on an FMC-programmed vertical path, in which autoflight mode must the aircraft be?

   a. FLCH (Flight Level Change)
   b. VNAV SPD (Vertical Navigation Speed)
   c. VSPD (Vertical Speed)
   d. VNAV PTH (Vertical Navigation Path)

2) While in a VNAV descent with the Mode Control Panel (MCP) Speed window closed, what speed will the autoflight system attempt to maintain?

____

3) While in a VNAV descent with the MCP speed window open, what speed will the autoflight system attempt to maintain?

____

4) In VNAV PTH mode, the autoflight system will sacrifice ________________ in order to maintain _______________.

5) In VNAV SPD mode, the autoflight system will sacrifice ________________ in order to maintain _______________.

6) While in a descent in VNAV PTH mode, a speed is assigned (verbally) by ATC. What action would you normally take in order to comply with the speed assignment, and in what mode would the aircraft then be?

____

____

____

____

7) With the aircraft descending on a VNAV path and thrust mode in throttle hold, what speed will the autoflight system attempt to maintain?

____

8) With the aircraft descending in VNAV, if the MCP speed window is opened (speed intervene) to lower the speed below the FMC-programmed descent speed, the vertical path flown by the aircraft will initially be:

   a) higher than the FMC-programmed path
   b) lower than the FMC-programmed path
   c) the same as the FMC-programmed path

Chart

9) Is there any other information you would like to see on chart? Y N
    a. If no, please explain

10) Do you have any suggestions for improvements to the chart?

11) Did you have enough time to study the chart? Y N

Flight Manual Bulletin

After studying the crew procedures in the Flight Manual Bulletin for conducting the CDA procedure:

12) I think the procedures for managing altitude between the waypoints CHERI and BLGRS are:

1	2	3	4	5	6	7
Very Difficult			Average			Very Easy

Comments:

13) I think the procedures for managing speed between the waypoints CHERI and BLGRS are:

1	2	3	4	5	6	7
Very Difficult			Average			Very Easy

Comments:

14) I think the procedures for managing the lateral path between the waypoints CHERI and BLGRS are:

1	2	3	4	5	6	7
Very Difficult			Average			Very Easy

Comments:

15) Was there any information missing from the FMB that you think would be helpful for understanding how to conduct the CDA? Y N

If yes, please explain

16) Do you have any suggestions for improvements to the chart?

17) Were you uncomfortable with the 700-ft stabilization altitude? Y N

(comment):____

18) What altitude would you prefer for a required stabilization altitude?____________________

Flight Manual Bulletin

19) Did you have enough time to study the FMB? Y N

20) Please rate your level of understanding of the BLGRS2 RNAV Arrival procedure:

1	2	3	4	5	6	7
I do not understand it at all			I understand it, but still have some questions			I understand it completely

21) Can you think of any situations where a pilot who is not as familiar with VNAV might become confused regarding what the altitude or speed of the aircraft should be while conducting this type of descent procedure?

LNG tool

22) How much did you use the LNG tool display during the LNG runs?
   a. During the entire time it was displayed
   b. During most of the time it was displayed (about 75% of the time)
   c. About half the time it was displayed
   d. Not very much (about 25% of the time
   e. Not at all

23) Which part of the LNG tool did you find most useful?
   a. Energy indicator diamond
   b. Limits on energy indicator
   c. Event markers on ND (any one in particular? ______________________)
   d. Other ____

24) Was there any part of the LNG tool that you found particularly useful?

25) Was there any part of the LNG tool that you found particularly confusing?

26) Was there any part of the LNG tool that you found particularly intuitive (i.e., easy to use)?

27) Which LNG energy indicator display did you use the most?

- a. PFD
- b. ND
- c. both equally

28) Where would you prefer to have the LNG energy indicator?

- d. PFD
- e. ND
- f. Both

29) Would you be comfortable with the LNG displayed **<u>only</u>** on:

a. The PFD	Y	N
b. The ND	Y	N
c. It should be in displayed in both places	Y	N

30) For most pilots, where do you think it would be most appropriate to have the LNG energy indicator?

- g. PFD
- h. ND
- i. Both

31) In normal day-to-day operations, how often do you use **VNAV**:

a) below 11000 ft altitude

____every flight ____often ____sometimes ____never

b) below 6000 ft altitude

____every flight ____often ____sometimes ____never

Table 1. Waypoint Crossing Restrictions for Atlanta Arrivals

West Arrival, SFO to ATL			East Arrival, ORF to ATL		
Waypoint	Altitude	Speed	Waypoint	Altitude	Speed
IC SFO	Cruise (FL370)	Cruise (.8 Mach)			
CALCO	-----	--			
VIKNN	-----	--	IC ORF	Cruise (FL360)	Cruise (.8 Mach)
HERKO	-----	--	ODF	-----	--
RPTOR	-----	--	FLCON	-----	--
NOTRE	-----	--	DIRTY	-----	--
NOFIV	11000	230	BYRDS	10000	230
FANEW	-----	---	COSEL	-----	---
HAVAD	6000	210	HAVAD	6000	210
ELLLE	5400	180	ELLLE	5400	180
BALLI	-----	---	BALLI	-----	---
AJAAY	2700	170	AJAAY	2700	170
R-26R	1076	---	R-26R	1076	---

Table 2. Winds Used During Piloted Simulation

Altitude (ft, MSL)	Wind Speed (Knots)	Wind Direction (True deg)
0	2.4	208
2461	5.7	242
4921	9.2	262
9843	16.0	273
13801	20.7	274
18289	25.9	273
23574	31.8	272
30065	38.9	270
33999	42.3	270

Table 3. Wind criteria for Atlanta scenarios

Condition	Number of Days	Criteria
All	679	Easterly winds at 1000 ft greater than -10.
Headwind	239	a) Easterly winds at 1000 ft greater than 0. b) Easterly winds at 3000 ft greater than 0. c) Absolute value of Northerly winds at 5000 ft less than 10.
Tailwind	117	a) Easterly winds at 1000 ft greater than -10 and less than 0. b) Easterly winds at 3000 ft less than 0. c) Absolute value of Northerly winds at 5000 ft less than 10.
Southerly Crosswind	149	a) Northerly winds at 5000 ft greater than 10. b) Easterly winds at 1000 ft greater than -10.
Northerly Crosswind	126	a) Northerly winds at 5000 ft less than -10. b) Easterly winds at 1000 ft greater than -10.
Headwind to Tailwind on final	31	a) Easterly winds at 1000 ft greater than -10 and less than 0. b) Easterly winds at 3000 ft greater than 0.
Tailwind to Headwind on final	17	a) Easterly winds at 1000 ft greater than 0. b) Easterly winds at 3000 ft less than 0.

Table 4. Pilot Model Actions

Action	VNAV	ENAV
Flap Extension	Rules based on airspeed, target airspeed and distance to FAF	EICAS message
Gear Extension	Distance from FAF	EICAS message
Speed brake	Rules based on vertical deviation and FMC drag message	Above energy limit
MCP speed selection	MCP speed changes sent via data link	Same as VNAV

Table 5. Flap Extension Criteria for Pilot Model

Current Flap Position	Criteria for selecting next flap setting		
	Current Speed	Target Speed	Distance
0 or 1	Less than Minimum Flap Speed + 5 knots	any	any
0 or 1	Less than Maximum Flap Speed - 5 knots	Less than current speed - 10 knots	Within 5 nm of FAF
5	Less than Minimum Flap Speed + 12 knots	any	any
5	Less than Maximum Flap Speed - 5 knots	Less than current speed - 10 knots	Within 5 nmi of FAF
20	Less than Minimum Flap Speed + 5 knots	any	any
25	Less than Minimum Flap Speed + 14 knots	any	any

Table 6. Test Conditions for Piloted Simulation

Condition Number	Guidance	Condition Name	Arrival Transition	Flying Pilot
1	VNAV	*Nominal*	DANNY	Capt
2	VNAV	*Nominal*	CHERI	1st Off.
3	VNAV	*Slow*	CHERI	Capt
4	VNAV	*Slow*	DANNY	1st Off.
5	VNAV	*Vector*	CHERI	Capt
6	VNAV	*Vector*	DANNY	1st Off.
7	LNG	*Nominal*	DANNY	Capt
8	LNG	*Nominal*	CHERI	1st Off.
9	LNG	*Slow*	CHERI	Capt
10	LNG	*Slow*	DANNY	1st Off.
11	LNG	*Vector*	CHERI	Capt
12	LNG	*Vector*	DANNY	1st Off.

13a	VNAV	*Stress*	CHERI	1st Off.
14a	LNG	*Stress*	CHERI	1st Off.
13b	VNAV	*Stress*	CHERI	Capt
14b	LNG	*Stress*	CHERI	Capt

Table 7. Run ordering for the Piloted Simulation Experiment

	1st run	2nd run	3rd run	4th run	5th run	6th run	7th run	8th run
crew 1	1	5	13	4	7	11	10	14
crew 2	12	14	9	8	13	2	6	3
crew 3	14	12	9	8	13	6	2	3
crew 4	5	13	1	4	10	11	14	7
crew 5	5	1	4	13	7	11	14	10
crew 6	14	9	12	8	6	2	3	13
crew 7	8	14	9	12	13	3	6	2
crew 8	13	5	1	4	7	10	11	14
crew 9	4	13	5	1	10	7	14	11
crew 10	12	14	8	9	2	6	13	3
crew 11	9	8	12	14	3	6	2	13
crew 12	5	13	4	1	7	11	14	10

Table 8.- Test matrix for Louisville scenarios

Guidance (2)	Route (2)	Winds (3)	ATC Speeds (7)	Weight / Vref (17)
ENAV	CHERI	Half Nominal	nominal	160000 / 117
VNAV	DANNY	Nominal	190 / 170 / 160	163000 / 118
		Double Nominal	200 / 180 / 160	165000 / 119
			210 / 180 / 170	168000 / 120
			220 / 190 / 170	170000 / 121
			230 / 200 / 170	173000 / 122
			240 / 200 / 180	175000 / 123
				178000 / 124
				180000 / 125
				183000 / 126
				185000 / 127
				188000 / 128
				190000 / 129
				193000 / 130
				195000 / 131
				198000 / 132
				200000 / 133

Table 9.- Test matrix for wind evaluation scenarios in Atlanta

Wind (679)	Guidance (2)	Route (2)	Weight / Vref (4)
	ENAV	East Arrival	160000 / 117
	VNAV	West Arrival	175000 / 123
			185000 / 127
			200000 / 133

Table 10.- Test matrix for speed interruption scenarios in Atlanta

Guidance (2)	Route (2)	Winds (4)	Speed location (3)	Speed schedule (6)	Weight / Vref (4)
ENAV	East arrival	Headwind	early	210 / 190 / 170	160000 / 117
VNAV	West arrival	Tailwind	nominal	220 / 200 / 170	175000 / 123
		Southerly	late	220 / 200 / 180	185000 / 127
		Northerly		230 / 210 / 180	200000 / 133
				230 / 210 / 190	
				240 / 220 / 190	

Table 11. – Average noise reduction (3 to 15 nm from runway), in dB SEL

Condition	VNAV	LNG
Nominal	4.0	5.0
Slow	3.4	5.3
Vector	3.8	5.0
All	3.7	5.1

Table 12. – Average fuel used per run, and percent reduction for LNG runs

Condition	Distance, nm	VNAV Fuel		LNG Fuel		Percent reduction with LNG
		Average, lbs	Standard Deviation, lbs	Average, lbs	Standard Deviation, lbs	
Nominal	83.7	1172.1	50.6	1140.0	63.6	2.7
Slow	83.9	1234.5	45.7	1131.0	38.4	8.4
Vector	88.4	1362.6	29.3	1242.3	75.3	4.5
Stress	83.2	1194.3	40.9	1087.3	52.6	9.0
All	84.8	1242.3	85.0	1165.0	100.2	6.2

Table 13. – Fuel reduction for VNAV and LNG runs compared to reference 5 Baseline

	Fuel, VNAV	Fuel, LNG	Fuel, Baseline - VNAV	Fuel, Baseline - LNG	Percent reduction, VNAV	Percent reduction, LNG
Nominal	1150.2	1116.7	160.1	193.6	12.2	14.8
Slow	1209.2	1106.6	101.1	203.7	7.7	15.5
Vector	1245.7	1181.9	64.6	128.4	4.9	9.8
Stress	1183.8	1076.9	126.5	233.4	9.7	17.8

Common distance of 82.6 nm.
Mean fuel for Baseline (reference 5) runs = 1310.3 lbs.

Table 14. Pilot Workload Ratings (out of 10 possible)

(a) in Descent

	VNAV Mean	VNAV StdDev	LNG Mean	LNG StdDev
Nominal	1.9	0.9	1.5	0.7
Slow	1.8	0.7	1.7	0.7
Vector	2.0	0.9	2.2	1.0
Stress	1.8	0.9	1.8	1.2
All	1.9	0.1	1.8	0.3

(b) after SILNT

	VNAV Mean	VNAV StdDev	LNG Mean	LNG StdDev
Nominal	2.2	1.0	1.9	0.9
Slow	2.0	0.9	2.4	1.0
Vector	2.5	1.1	2.4	1.0
Stress	--	--	--	--
All	2.2	0.2	2.2	0.3

(c) after BLGRS

	VNAV Mean	VNAV StdDev	LNG Mean	LNG StdDev
Nominal	2.1	1.0	2.1	0.8
Slow	2.1	1.1	1.9	0.6
Vector	2.3	1.3	2.1	0.8
Stress	2.5	0.9	2.7	1.5
All	2.2	0.1	2.0	0.1

Table 15. Fuel usage at runway for Louisville batch simulation

(a) Speed conditions

Speed Condition	VNAV			ENAV			ENAV - VNAV	
	number	Mean (lbs)	Stdev (lbs)	number	Mean (lbs)	Stdev (lbs)	Absolute (lbs)	Percent
nominal	102	968.7	58.3	102	911.7	49.1	-57.0	-5.9
190 / 170 / 160	102	1170.2	72.0	101	1034.5	66.8	-135.7	-11.6
200 / 180 / 160	102	1120.9	68.3	102	993.2	53.8	-127.8	-11.4
210 / 180 / 170	102	1072.2	71.4	102	950.9	65.4	-121.3	-11.3
220 / 190 / 170	102	1011.5	59.1	102	943.3	51.7	-68.2	-6.7
230 / 200 / 170	102	979.8	53.7	102	948.9	53.7	-30.8	-3.1
240 / 200 / 180	102	957.0	60.5	102	955.6	50.2	-1.4	-0.1
All	714	1040.0	99.4	713	962.5	66.9	-77.6	-7.5

(b) Wind conditions

Wind Condition	VNAV			ENAV			ENAV - VNAV	
	number	Mean (lbs)	Stdev (lbs)	number	Mean (lbs)	Stdev (lbs)	Absolute (lbs)	Percent
nominal	238	1047.8	88.3	237	971.7	46.6	-76.1	-7.3
double	238	974.3	83.7	238	900.6	36.9	-73.7	-7.6
half	238	1098.0	84.5	238	1015.2	56.6	-82.9	-7.5
All	714	1040.0	99.4	713	962.5	66.9	-77.6	-7.5

Table 16. Fuel usage for Atlanta batch simulation

(a) Wind conditions

Runway										
	All Guidance			VNAV			ENAV			ENAV - VNAV	
Arrival	Number	Mean (lbs)	Stdev (lbs)	Number	Mean (lbs)	Stdev (lbs)	Number	Mean (lbs)	Stdev	Absolute (lbs)	Percent
East	5384	1586.0	226.9	2692	1610.6	230.6	2692	1561.4	220.5	-49.2	-3.1
West	5384	1176.7	104.0	2692	1201.0	99.9	2692	1152.4	102.4	-48.6	-4.0
All	10768	1381.4	270.3	5384	1405.8	271.2	5384	1356.9	267.2	-48.9	-3.5
Final Approach (Waypoint ELLLE)										
	All Guidance			VNAV			ENAV			ENAV - VNAV	
Arrival	Number	Mean (lbs)	Stdev (lbs)	Number	Mean (lbs)	Stdev (lbs)	Number	Mean (lbs)	Stdev (lbs)	Absolute (lbs)	Percent
East	5384	1302.6	199.7	2692	1311.4	199.7	2692	1293.9	199.4	-17.6	-1.3
West	5384	892.2	116.4	2692	899.9	116.5	2692	884.4	115.8	-15.5	-1.7
All	10768	1097.4	262.4	5384	1105.7	262.8	5384	1089.2	261.7	-16.5	-1.5

(b) ATC speed conditions

ATC		VNAV			ENAV			ENAV - VNAV	
Speed	Location	Number	Mean (lbs)	Stdev (lbs)	Number	Mean (lbs)	Stdev (lbs)	Absolute (lbs)	Percent
Nominal	N/A	32	1379.9	212.2	32	1330.1	212.6	-49.8	-3.6
210_190_170	Early	32	1485.7	228.2	32	1428.2	217.8	-57.5	-3.9
220_200_170	Early	32	1446.5	227.9	32	1388.8	211.2	-57.7	-4.0
220_200_180	Early	32	1433.6	226.2	32	1364.6	210.0	-69.0	-4.8
230_210_180	Early	32	1406.4	235.3	32	1343.0	214.6	-63.3	-4.5
210_190_170	Nominal	32	1458.9	212.0	32	1413.0	217.1	-46.0	-3.1
220_200_170	Nominal	32	1422.3	211.9	32	1377.8	209.4	-44.5	-3.1
220_200_180	Nominal	32	1408.9	210.6	32	1353.7	207.8	-55.2	-3.9
230_210_180	Nominal	32	1378.4	210.3	32	1338.1	214.0	-40.3	-2.9
210_190_170	Late	32	1445.7	210.8	32	1407.8	218.5	-37.9	-2.6
220_200_170	Late	32	1405.5	210.6	32	1392.9	211.7	-12.5	-0.9
220_200_180	Late	32	1403.4	210.0	32	1366.6	213.0	-36.8	-2.6
230_210_180	Late	32	1356.9	213.0	32	1376.4	216.2	19.5	1.4
All	All	416	1417.9	216.6	416	1375.5	212.3	-42.4	-3.0

Table 17. Noise levels for Louisville batch simulation

(a) Speed conditions

Speed Condition	VNAV			ENAV			ENAV - VNAV
	number	Mean (dB)	Stdev (dB)	number	Mean (dB)	Stdev (dB)	Mean (dB)
nominal	102	61.9	0.2	102	60.3	0.4	-1.6
190 / 170 / 160	102	64.6	0.4	102	61.0	1.2	-3.6
200 / 180 / 160	102	63.7	1.5	102	60.1	0.1	-3.6
210 / 180 / 170	102	63.7	1.3	102	59.8	0.5	-3.9
220 / 190 / 170	102	62.7	0.9	102	60.8	0.2	-1.9
230 / 200 / 170	102	62.9	0.4	102	61.5	0.5	-1.4
240 / 200 / 180	102	61.9	1.2	102	61.5	0.6	-0.4
All	714	63.0	1.3	714	60.7	0.9	-2.3

(b) Wind conditions

Wind Condition	VNAV			ENAV			ENAV - VNAV
	number	Mean (dB)	Stdev (dB)	number	Mean (dB)	Stdev (dB)	Mean (dB)
nominal	238	63.1	1.3	238	60.7	0.8	-2.4
double	238	62.7	1.4	238	60.9	0.9	-1.9
half	238	63.3	1.2	238	60.6	0.9	-2.8
All	714	63.0	1.3	714	60.7	0.9	-2.3

Table 18. Noise levels for Atlanta batch simulation

(a) Wind conditions

Runway										
	All Guidance			VNAV			ENAV			ENAV - VNAV
Arrival	Number	Mean (dB)	Stdev (dB)	Number	Mean (dB)	Stdev (dB)	Number	Mean (dB)	Stdev (dB)	Mean (dB)
East	5384	60.3	1.5	2692	61.5	1.2	2692	59.2	0.6	-2.3
West	5384	60.4	1.6	2692	61.6	1.3	2692	59.2	0.6	-2.4
All	10768	60.4	1.5	5384	61.5	1.3	5384	59.2	0.6	-2.4

(b) ATC speed conditions

ATC		VNAV			ENAV			ENAV - VNAV
Speed	Location	Number	Mean (dB)	Stdev (dB)	Number	Mean (dB)	Stdev (dB)	Mean (dB)
Nominal	N/A	32	60.9	1.2	32	58.5	0.3	-2.4
210_190_170	Early	32	63.0	0.3	32	60.3	2.6	-2.7
220_200_170	Early	32	62.2	1.4	32	60.1	2.6	-2.2
220_200_180	Early	32	62.1	2.0	32	58.9	0.3	-3.3
230_210_180	Early	32	61.3	2.1	32	58.8	0.3	-2.5
210_190_170	Nominal	32	62.0	1.8	32	59.8	2.4	-2.2
220_200_170	Nominal	32	61.9	1.5	32	59.7	2.3	-2.2
220_200_180	Nominal	32	61.4	1.8	32	58.7	0.2	-2.8
230_210_180	Nominal	32	61.4	1.7	32	58.6	0.2	-2.8
210_190_170	Late	32	62.5	0.6	32	61.5	0.8	-0.9
220_200_170	Late	32	63.1	0.3	32	62.2	0.8	-0.8
220_200_180	Late	32	63.1	0.3	32	61.8	0.6	-1.3
230_210_180	Late	32	61.9	0.7	32	62.4	0.3	0.5
All	All	416	62.1	1.5	416	60.1	2.0	-2.0

Table 19. Stabilization altitude for Louisville batch simulation

(a) Speed conditions

Speed Condition	VNAV			ENAV		
	number	Mean (ft, AGL)	Stdev (ft, AGL)	number	Mean (ft, AGL)	Stdev (ft, AGL)
nominal	102	1170.4	71.7	102	1008.2	3.5
190 / 170 / 160	102	1181.7	83.1	101	1055.4	93.5
200 / 180 / 160	102	1182.0	81.1	102	1041.4	51.7
210 / 180 / 170	102	1172.6	73.2	102	1011.5	14.7
220 / 190 / 170	102	1170.5	70.1	102	1030.6	53.9
230 / 200 / 170	102	1170.6	71.3	102	1042.2	65.3
240 / 200 / 180	102	1157.4	57.7	102	1012.1	17.1
All	714	1172.2	73.1	713	1028.7	54.7

(b) Wind conditions

Wind Condition	VNAV			ENAV		
	number	Mean (ft, AGL)	Stdev (ft, AGL)	number	Mean (ft, AGL)	Stdev (ft, AGL)
nominal	238	1166.7	79.6	237	1032.2	47.0
double	238	1175.4	78.6	238	1026.7	69.7
half	238	1174.4	59.2	238	1027.3	43.6
All	714	1172.2	73.1	713	1028.7	54.7

Table 20. Stabilization altitude for Atlanta batch simulation

(a) Wind conditions

	All Guidance			VNAV			ENAV		
Arrival	Number	Mean (ft, AGL)	Stdev (ft, AGL)	Number	Mean (ft, AGL)	Stdev (ft, AGL)	Number	Mean (ft, AGL)	Stdev (ft, AGL)
East	5384	1021.8	101.0	2692	1050.6	121.4	2692	993.0	63.3
West	5384	1022.1	100.3	2692	1050.6	120.4	2692	993.6	63.0
All	10768	1021.9	100.6	5384	1050.6	120.9	5384	993.3	63.2

(b) ATC speed conditions

ATC		VNAV			ENAV		
Speed	Location	Number	Mean (ft, AGL)	Stdev (ft, AGL)	Number	Mean (ft, AGL)	Stdev (ft, AGL)
Nominal	N/A	32	1053.5	103.8	32	989.8	58.6
210_190_170	Early	32	1055.7	102.1	32	1024.8	24.4
220_200_170	Early	32	1057.5	100.2	32	1024.9	25.7
220_200_180	Early	32	1027.5	100.1	32	928.7	109.8
230_210_180	Early	32	1031.8	99.7	32	932.0	109.3
210_190_170	Nominal	32	1059.6	98.4	32	1025.1	25.7
220_200_170	Nominal	32	1058.4	98.8	32	1024.8	25.9
220_200_180	Nominal	32	1032.1	104.2	32	927.5	110.7
230_210_180	Nominal	32	1029.8	102.8	32	922.7	111.0
210_190_170	Late	32	1042.0	110.5	32	1021.4	26.0
220_200_170	Late	32	1000.4	131.2	32	1018.7	25.8
220_200_180	Late	32	991.4	126.5	32	965.9	78.2
230_210_180	Late	32	776.3	235.2	32	965.4	83.9
All	All	416	1016.6	140.2	416	982.4	83.1

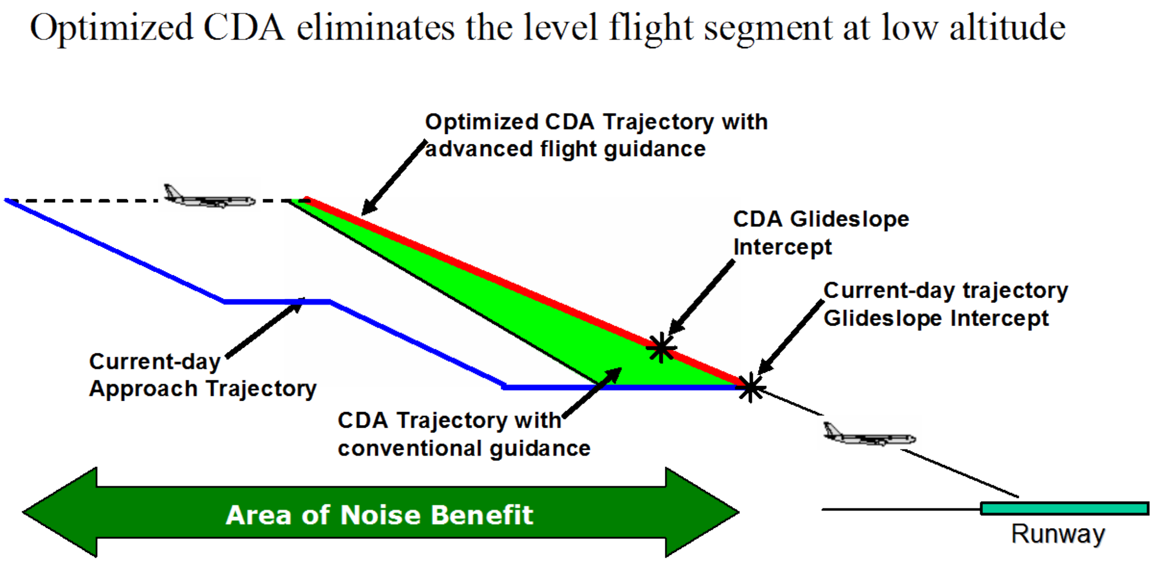
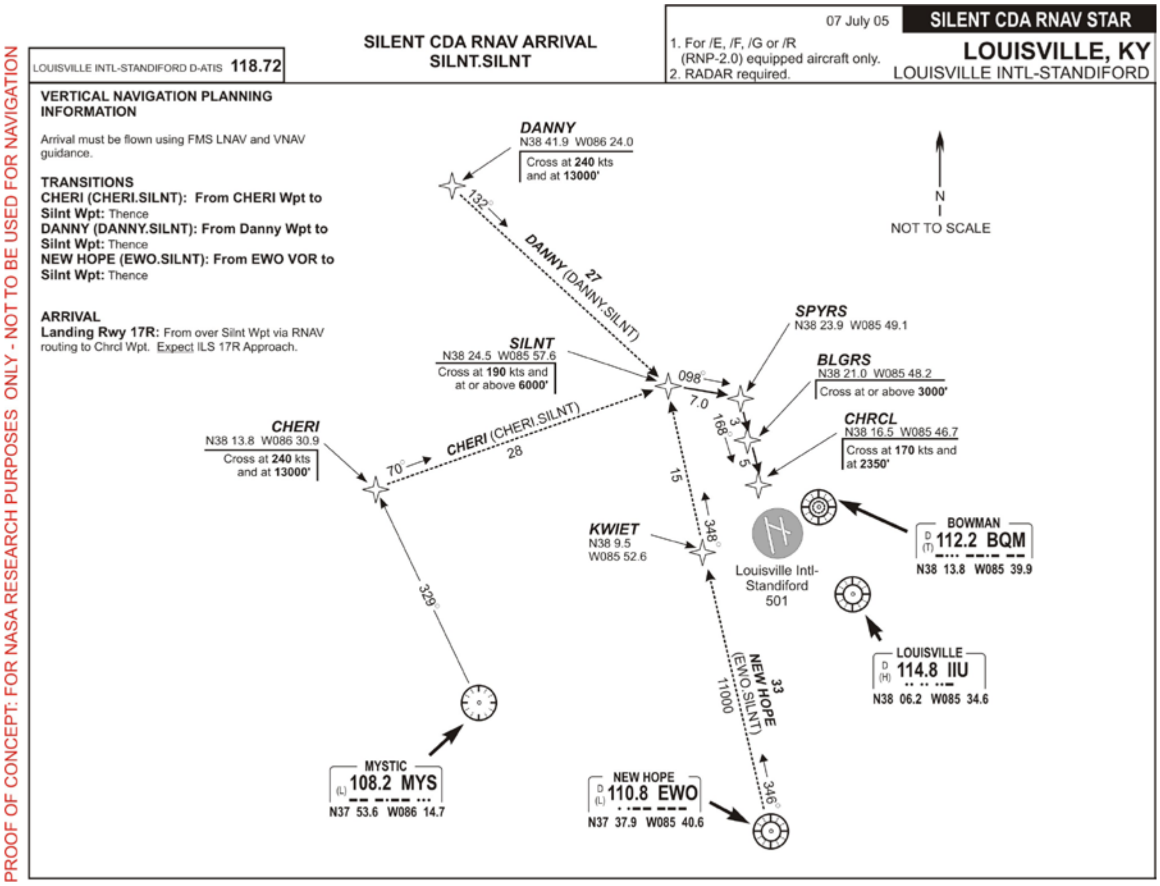


Figure 1. Illustration of vertical profiles for a CDA and current-day approach profile.

Figure 2. NASA LaRC Research Flight Deck Simulator



SILENT CDA RNAV ARRIVAL
SILNT.SILNT

1. For /E, /F, /G or /R (RNP-2.0) equipped aircraft only.
2. RADAR required.

VERTICAL NAVIGATION PLANNING INFORMATION

Arrival must be flown using FMS LNAV and VNAV guidance.

TRANSITIONS
CHERI (CHERI.SILNT): From CHERI Wpt to Silnt Wpt: Thence
DANNY (DANNY.SILNT): From Danny Wpt to Silnt Wpt: Thence
NEW HOPE (EWO.SILNT): From EWO VOR to Silnt Wpt: Thence

ARRIVAL
Landing Rwy 17R: From over Silnt Wpt via RNAV routing to Chrcl Wpt. Expect ILS 17R Approach.

Figure 3. SILENT CDA RNAV STAR used for this experiment.

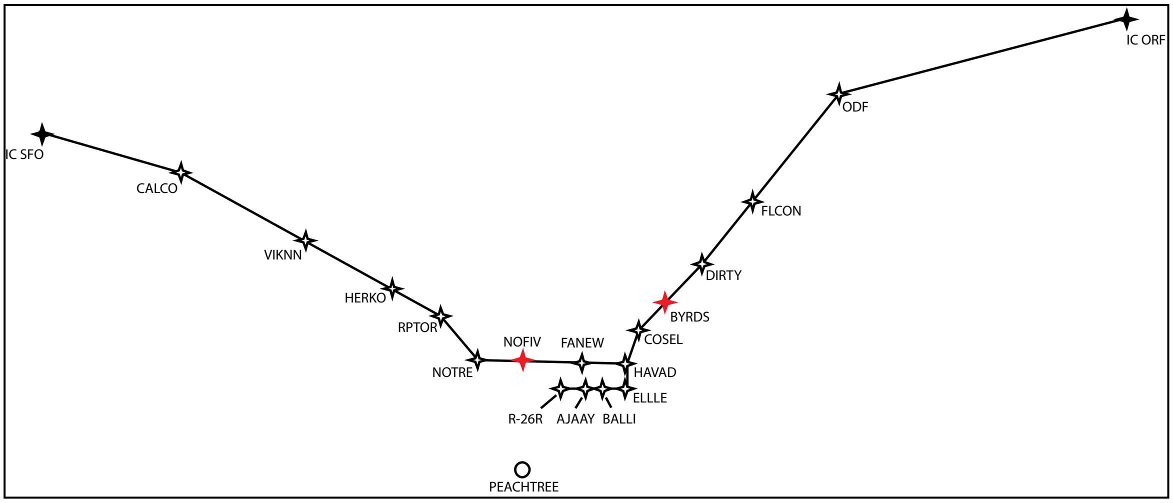


Figure 4. Atlanta RNAV arrival routes.

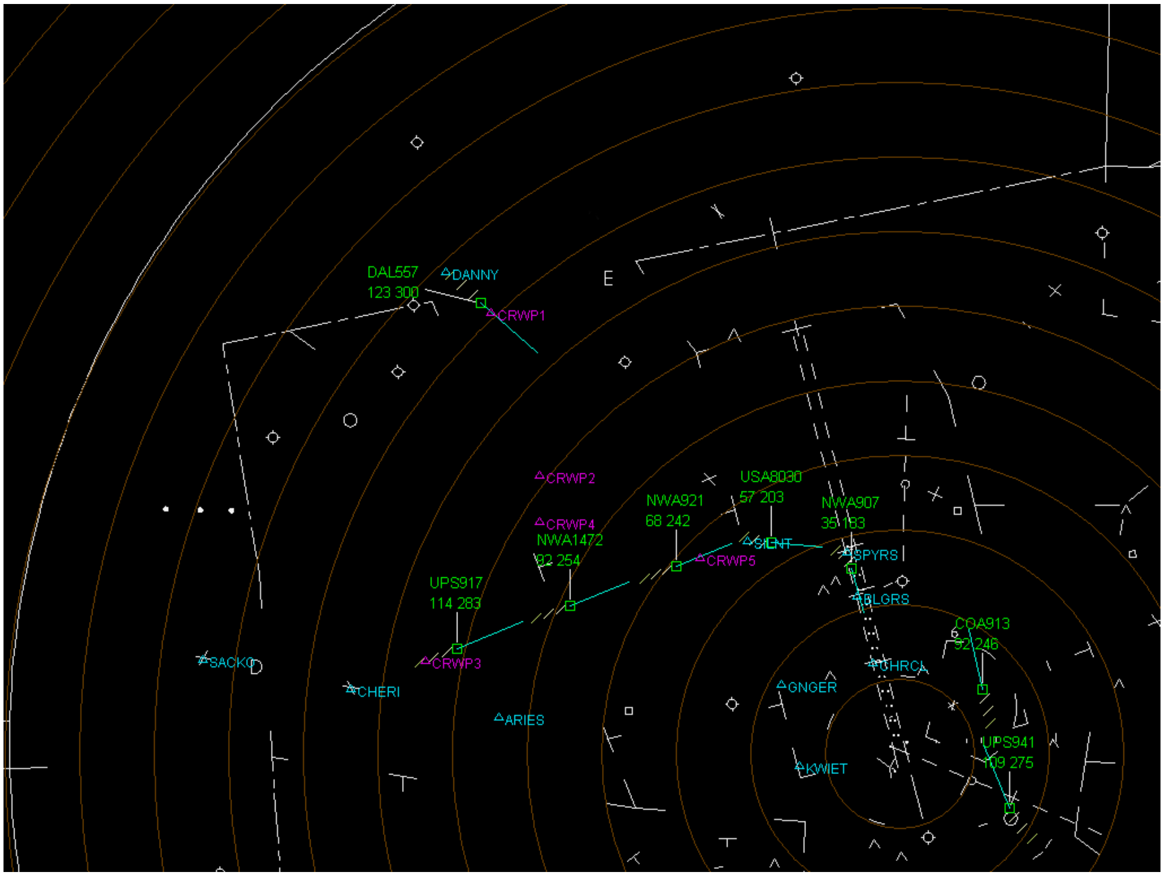


Figure 5. MACS Controller display showing traffic.

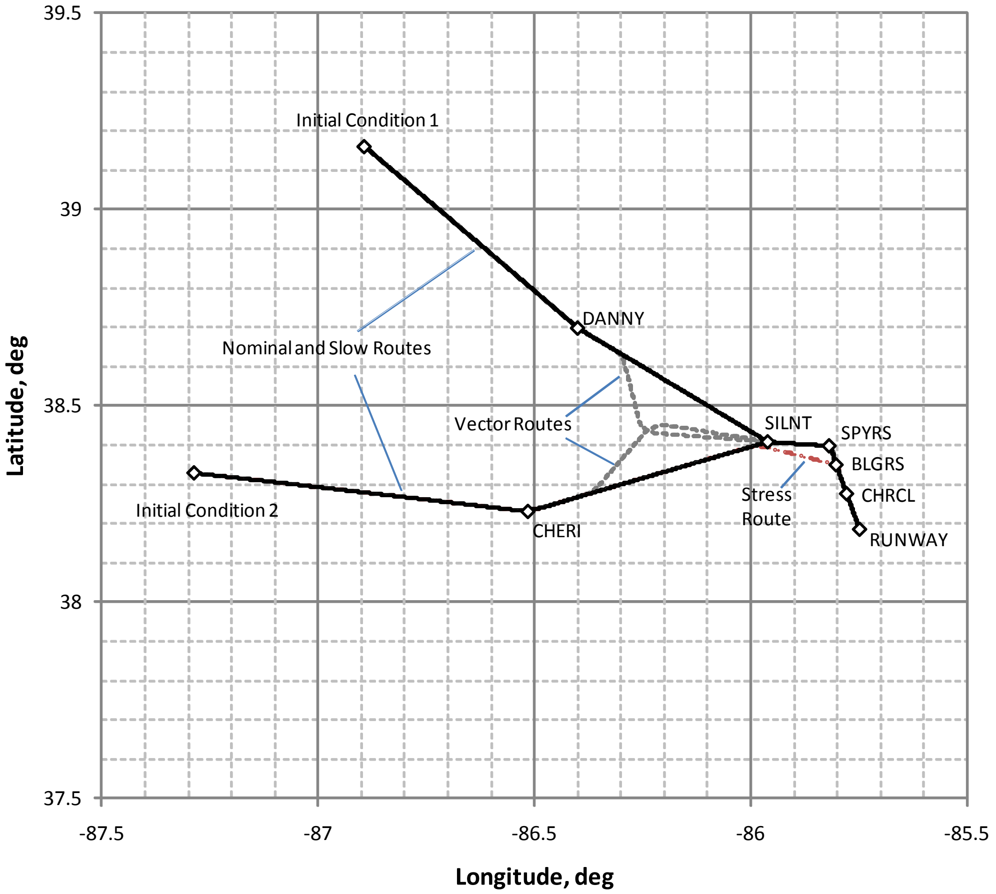
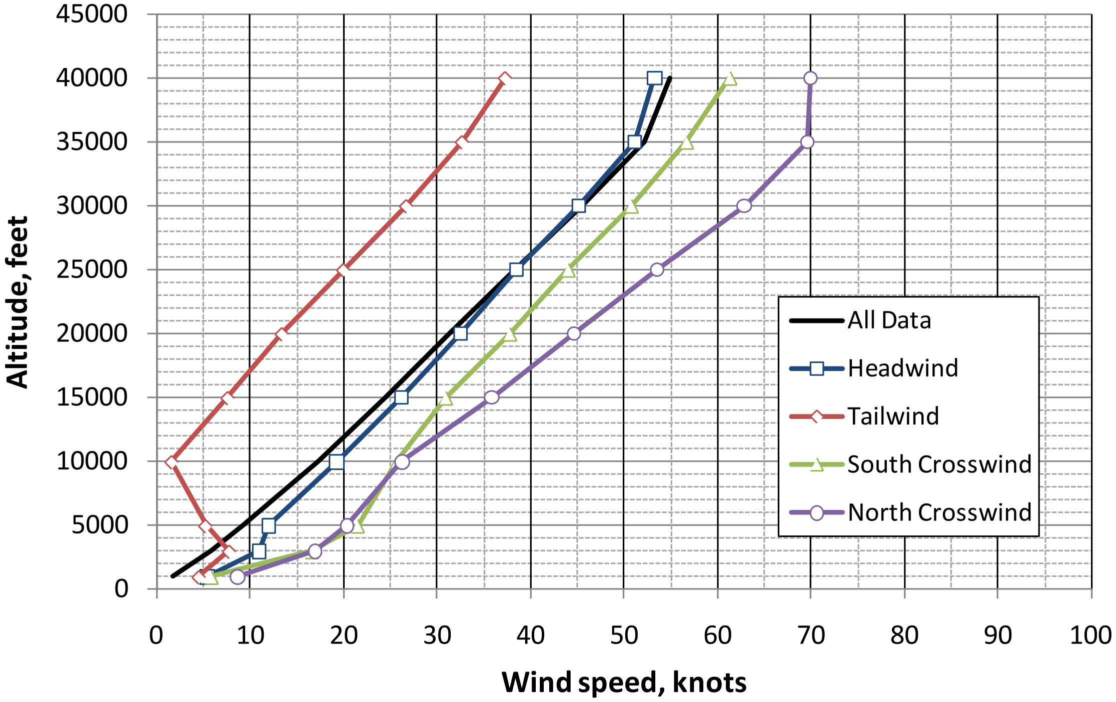
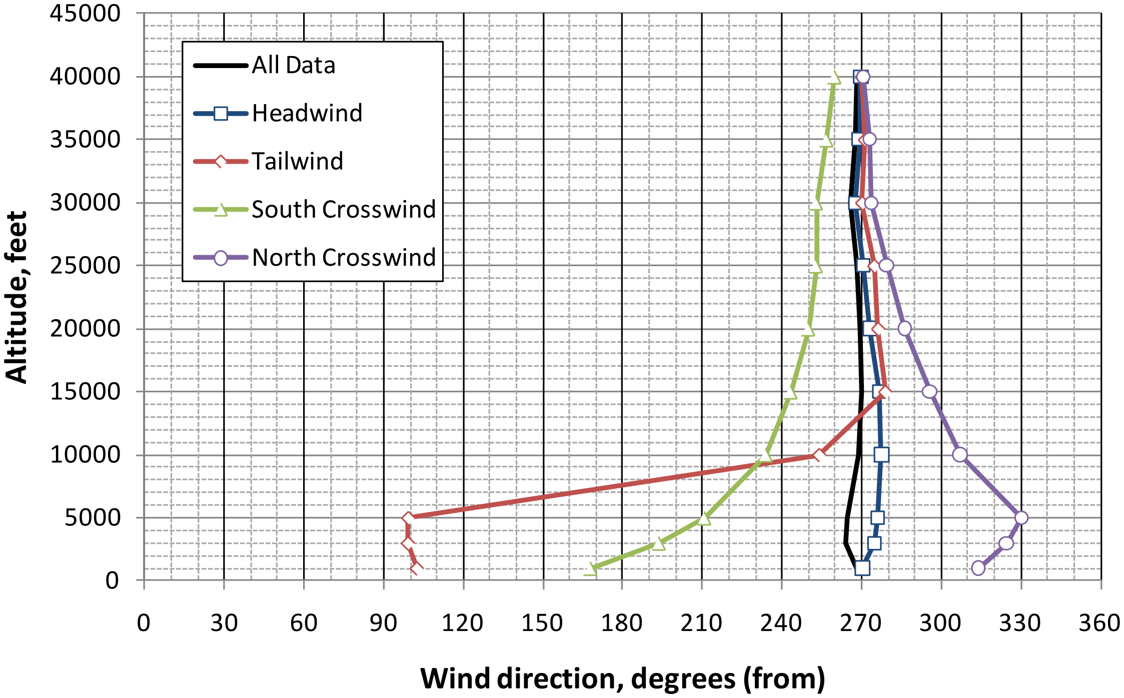


Figure 6. Lateral paths of piloted test runs.

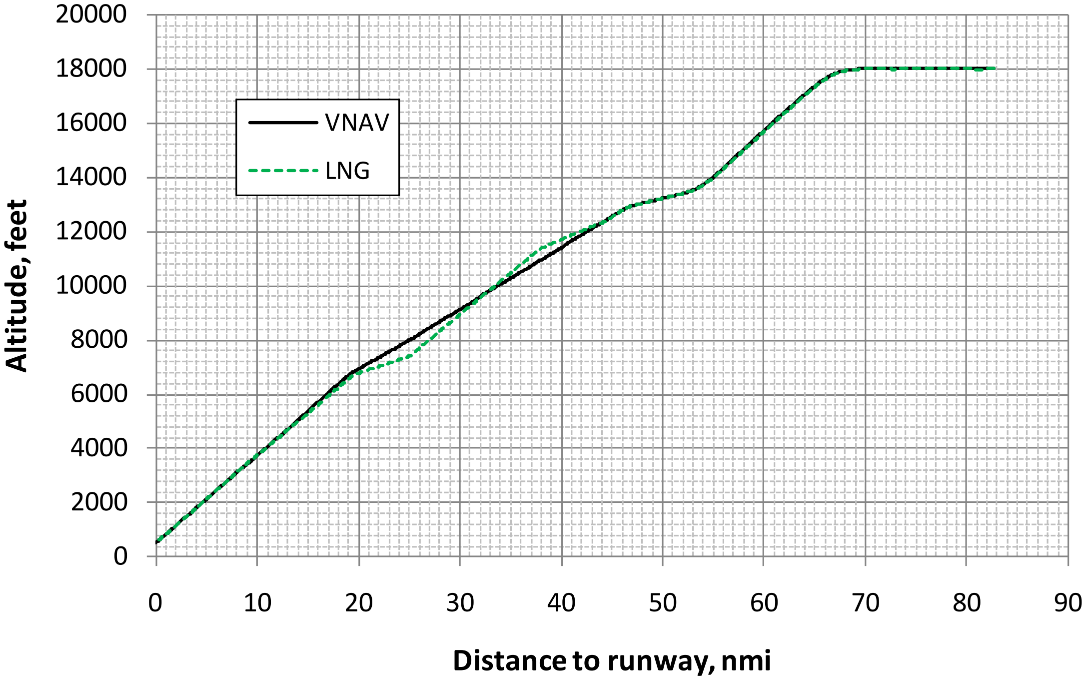


(a) Wind speed.

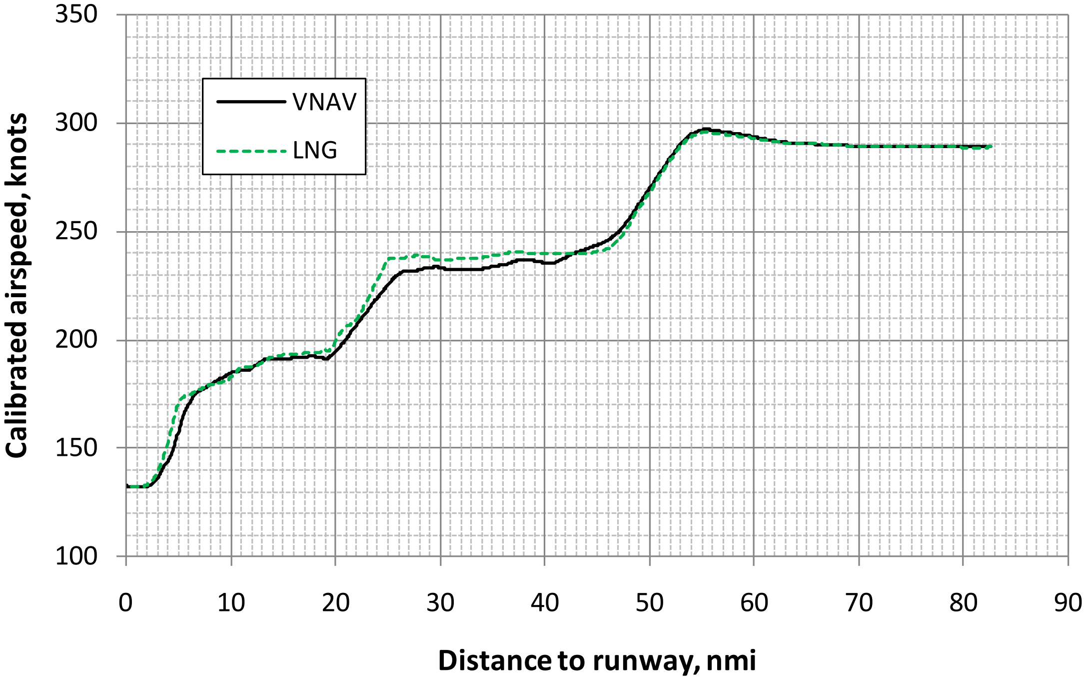


(b) Wind direction.

Figure 7. Wind profiles for Atlanta wind models.

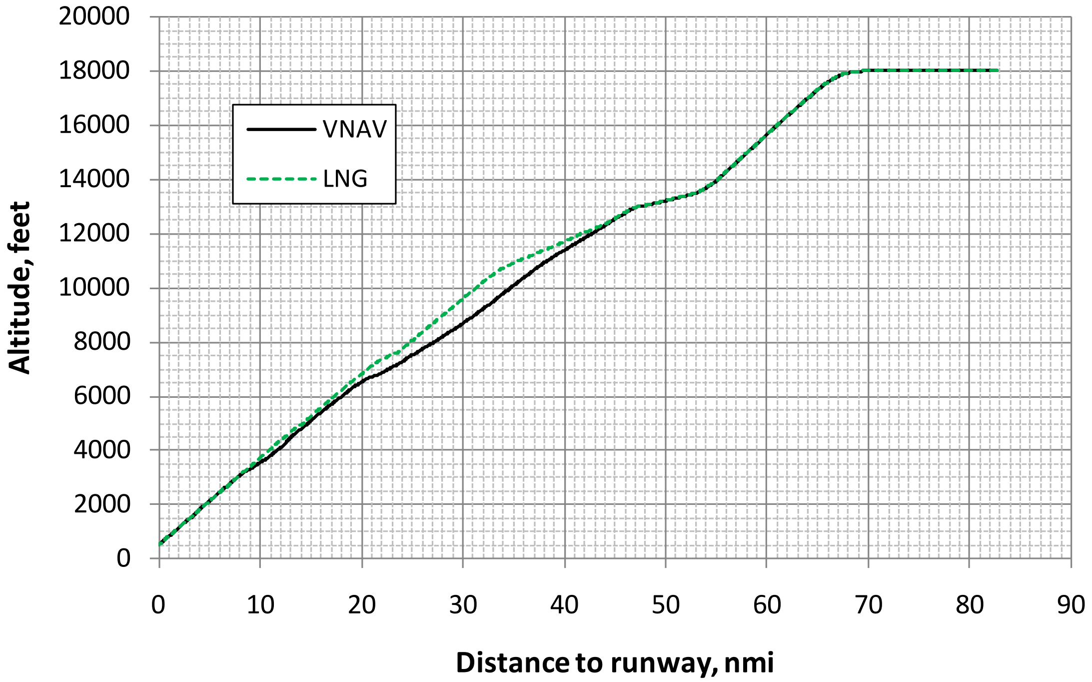


a) Altitude profile.

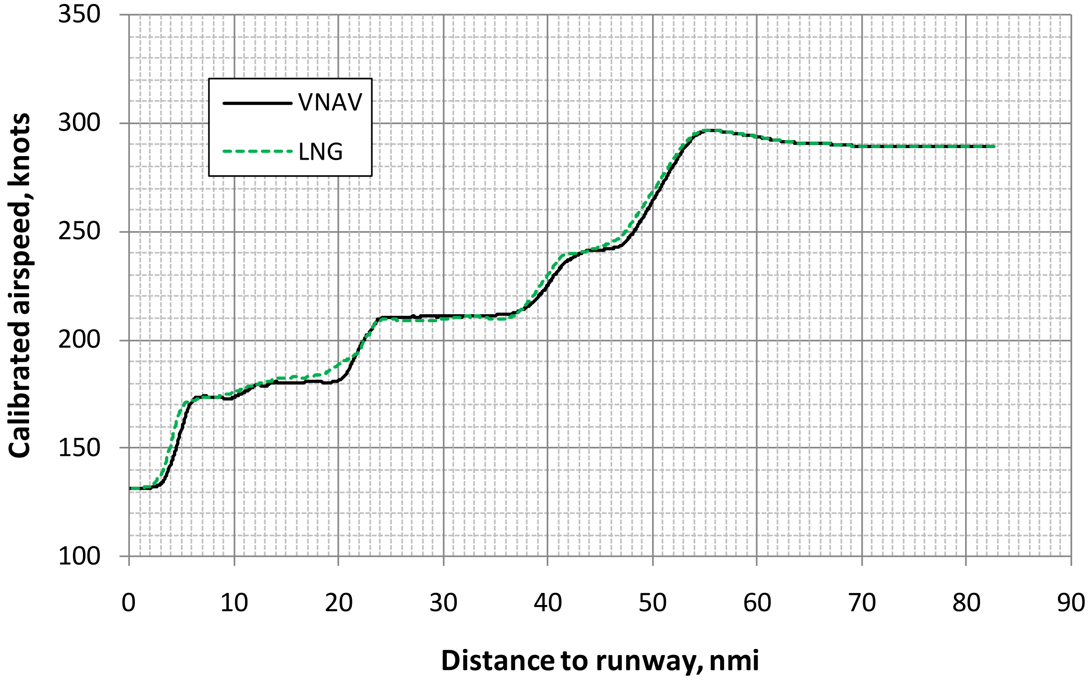


b) Calibrated airspeed profile.

Figure 8. Vertical profiles for *Nominal* test condition.

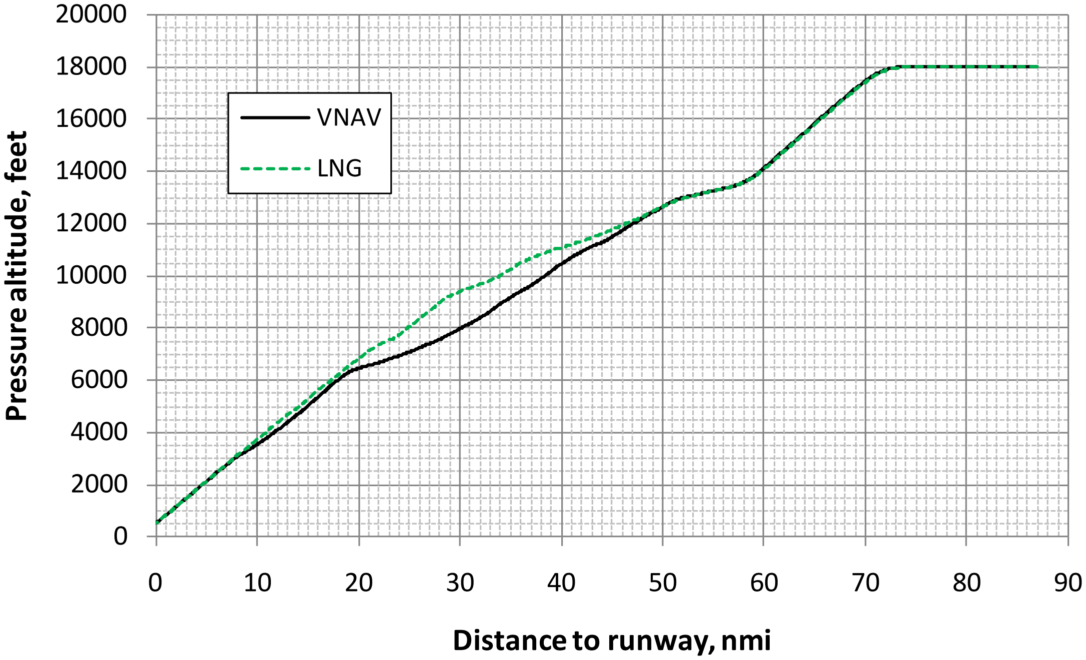


a) Altitude profile.



b) Calibrated airspeed profile.

Figure 9. Vertical profiles for *Slow* test condition.



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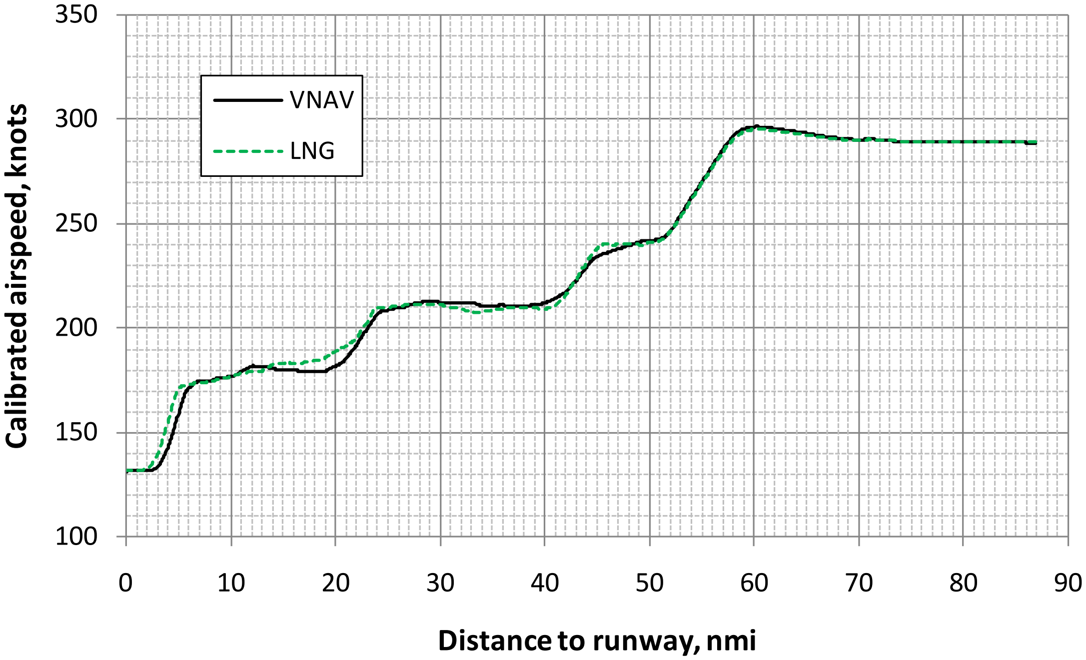
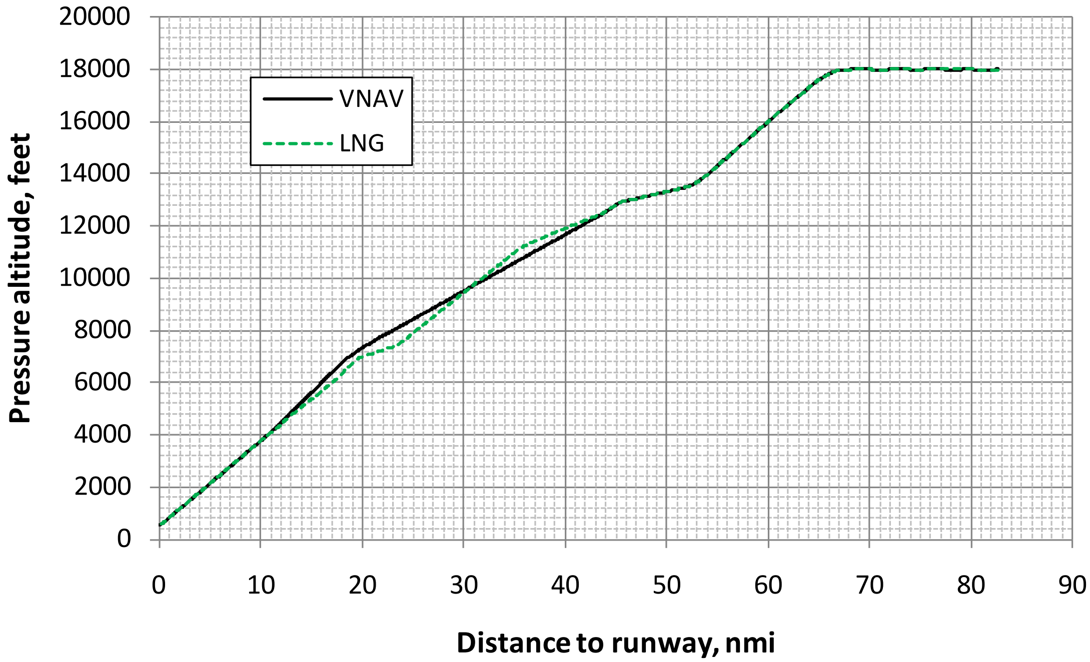
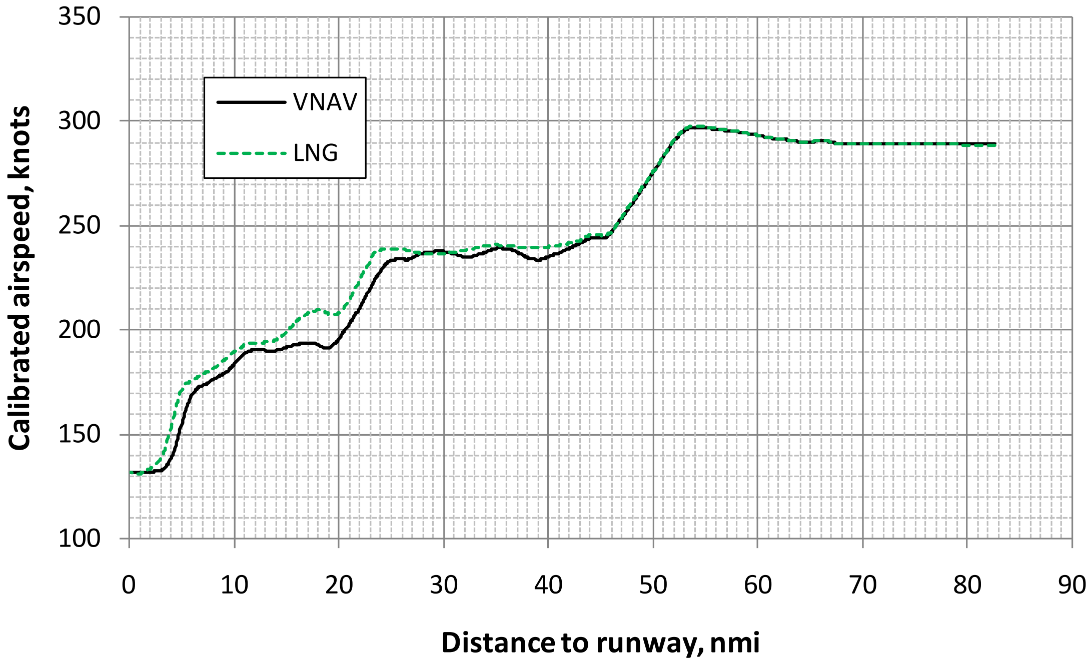


b) Calibrated airspeed profile.

Figure 10. Vertical profiles for *Vector* test condition.



a) Altitude profile.



b) Calibrated airspeed profile.

Figure 11. Vertical profiles for *Stress* test condition.

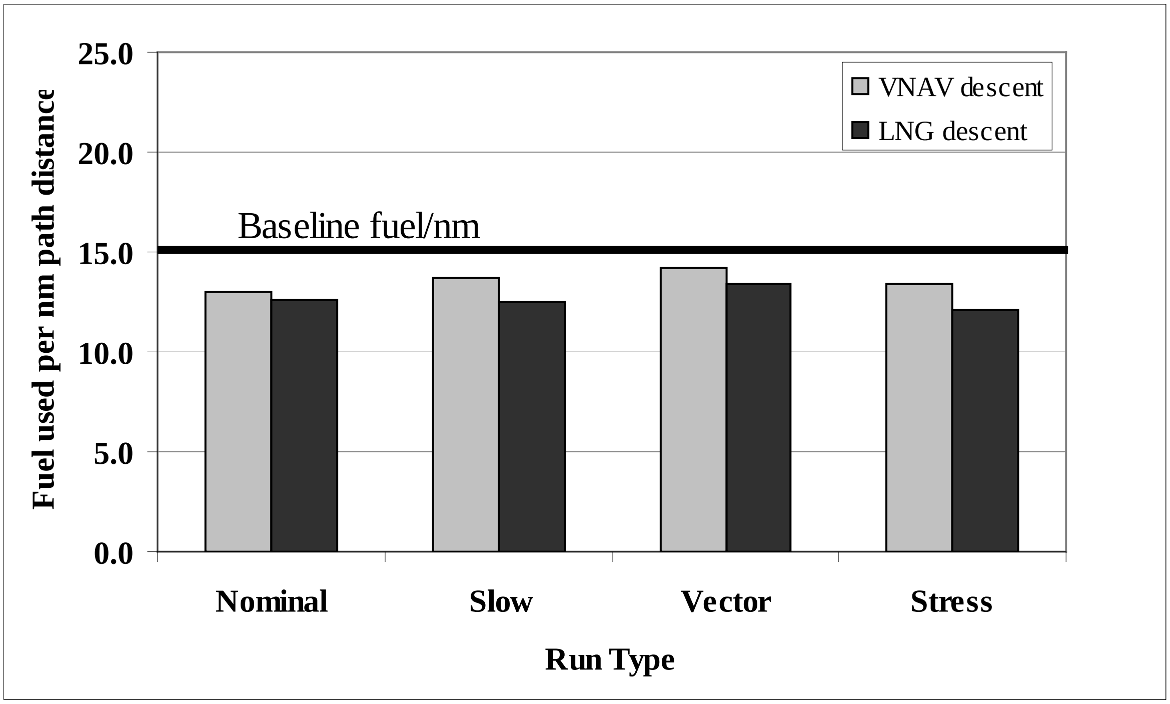


Figure 12. Fuel used in descent.

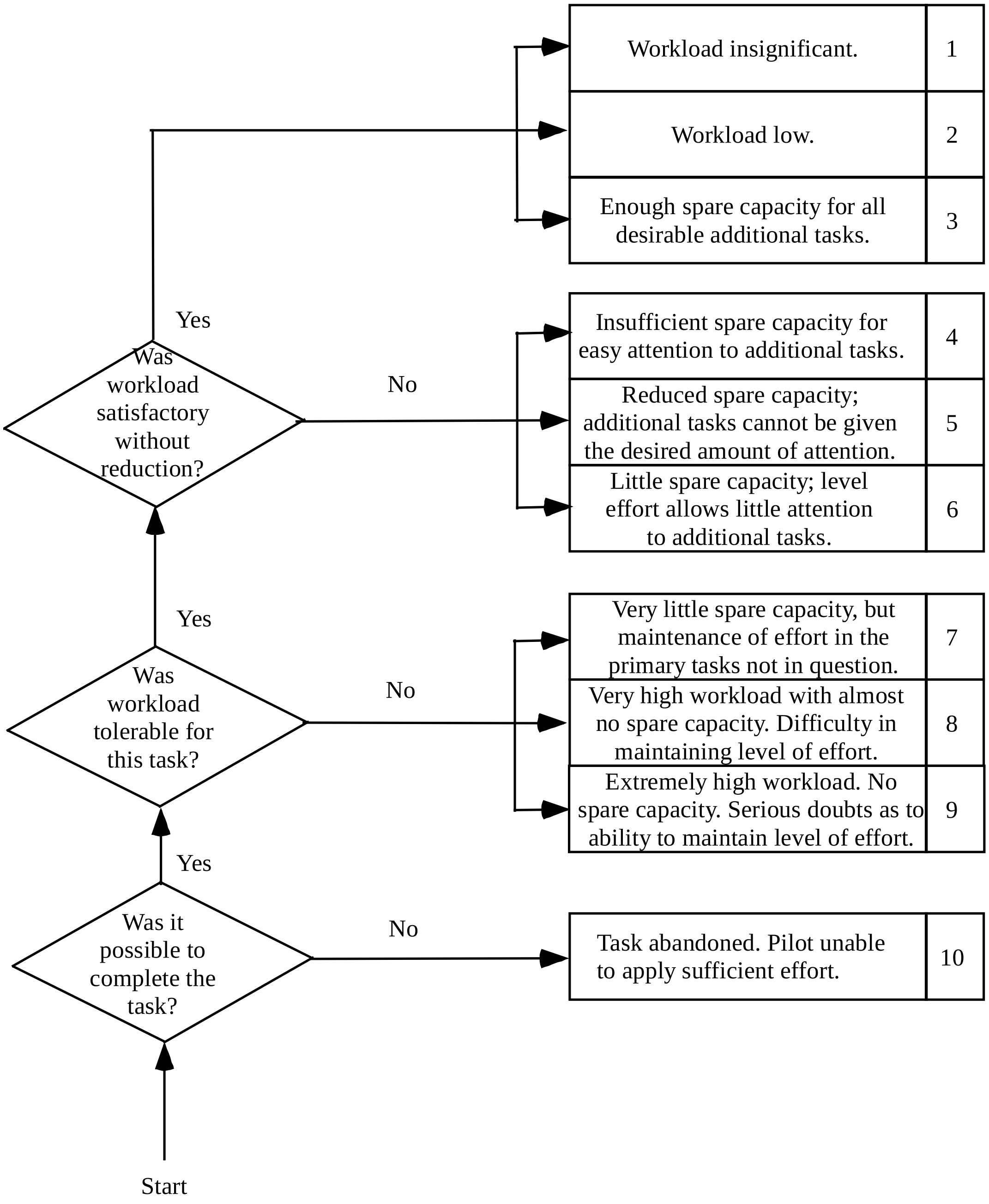


Figure 13. Bedford Workload Rating Scale

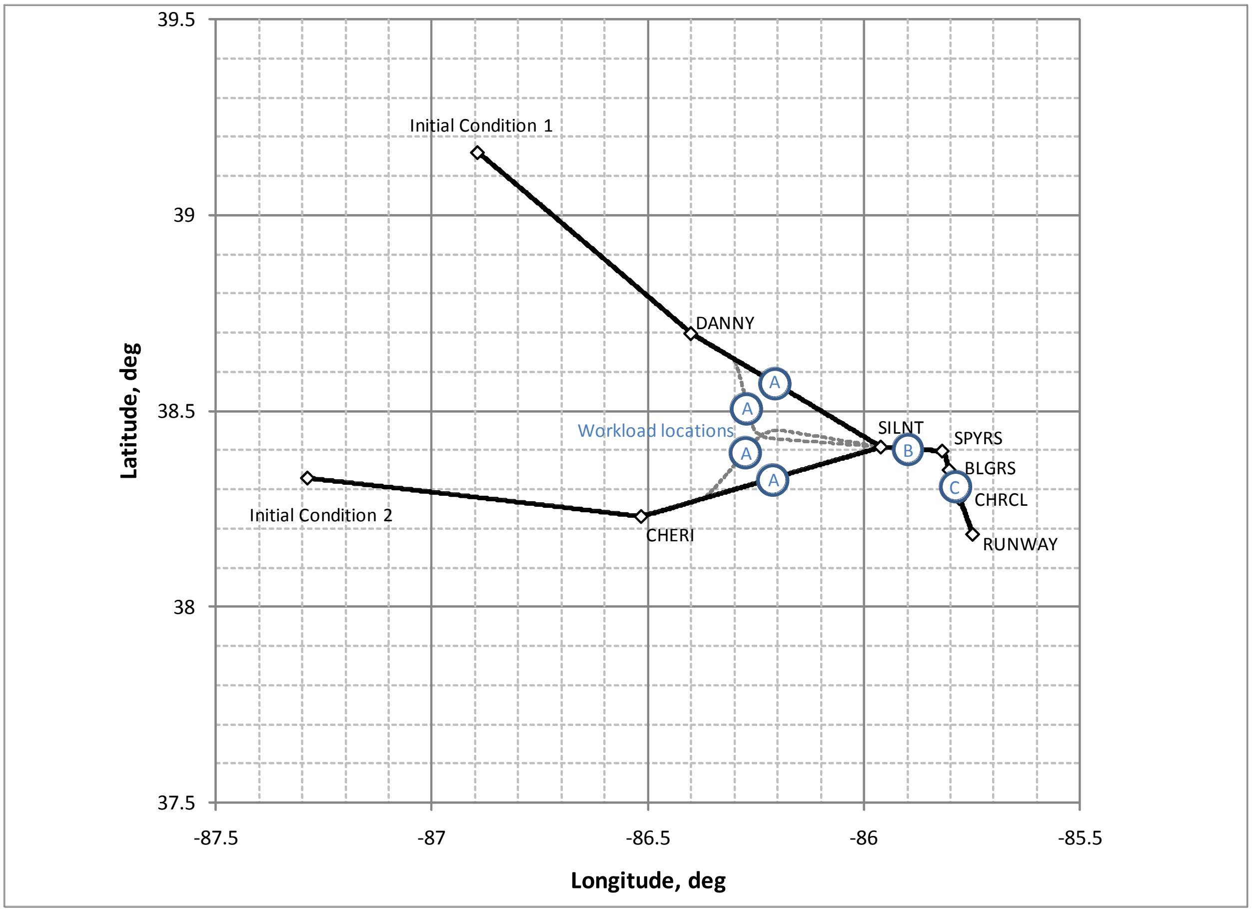
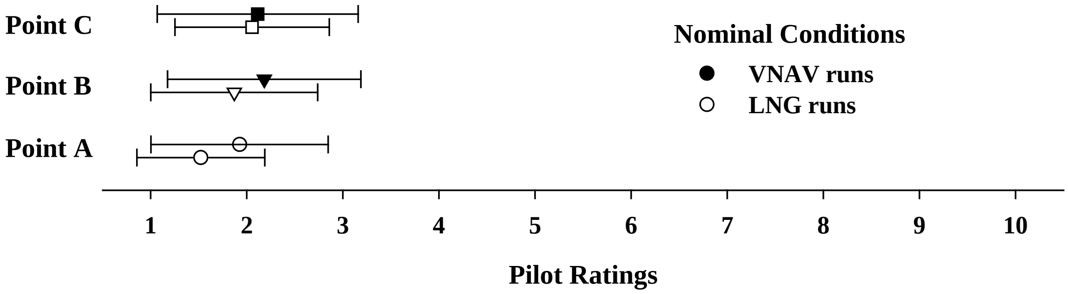
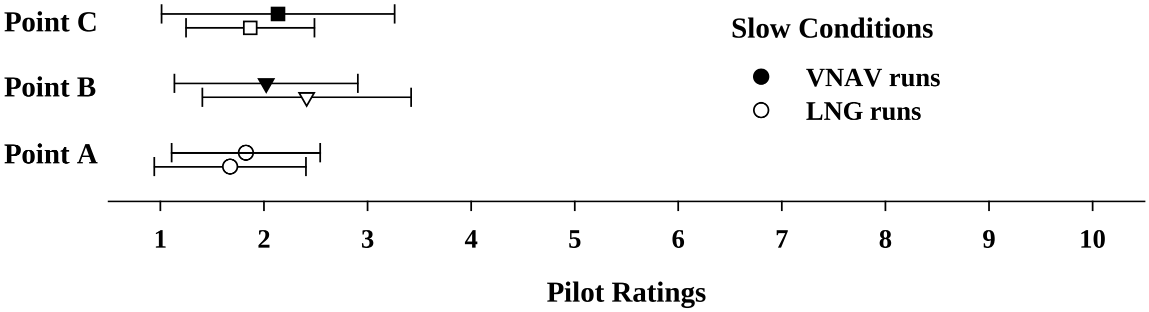


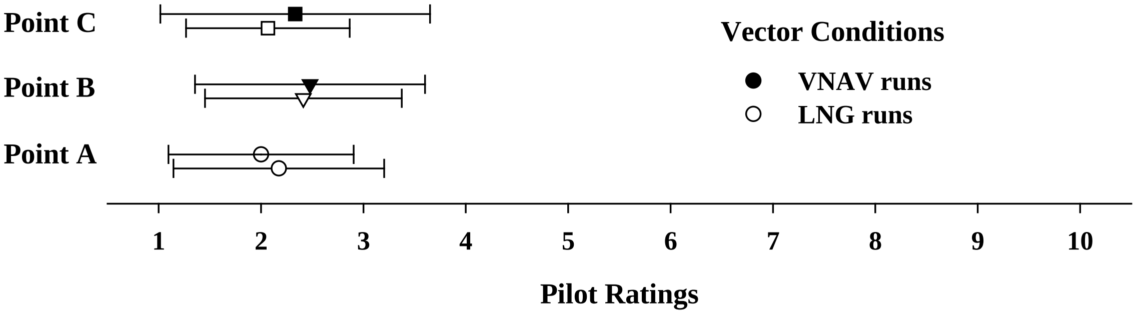
Figure 14. Locations of workload ratings



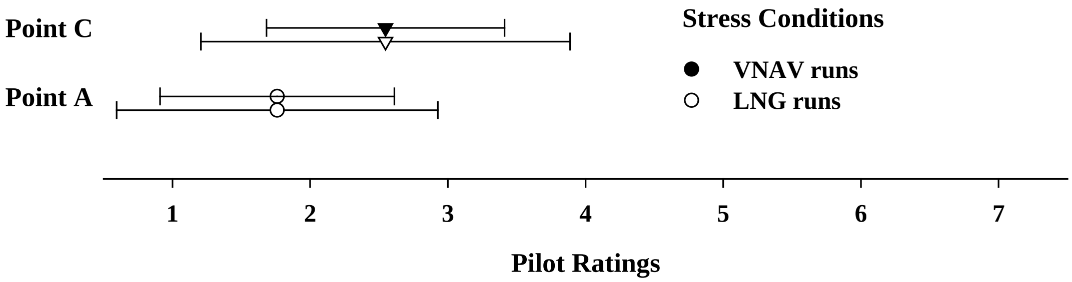
(a) *Nominal* Conditions



(b) *Slow* Conditions

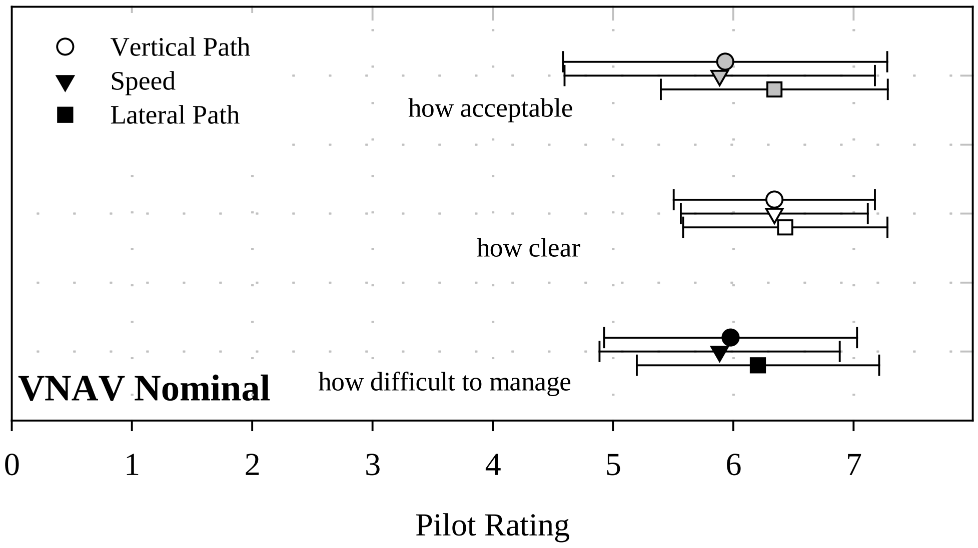


(c) *Vector* Conditions

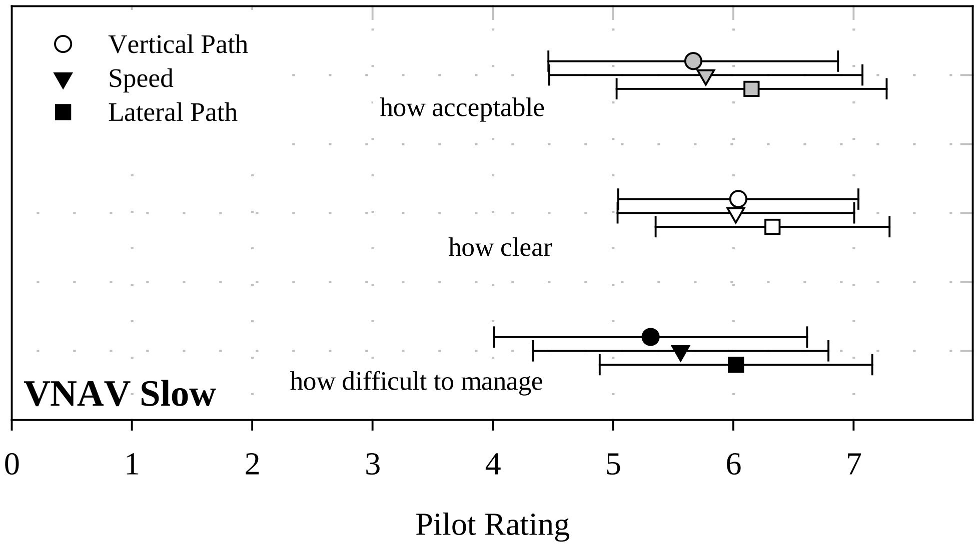


(d) *Stress* Conditions

Figure 15. Workload ratings.

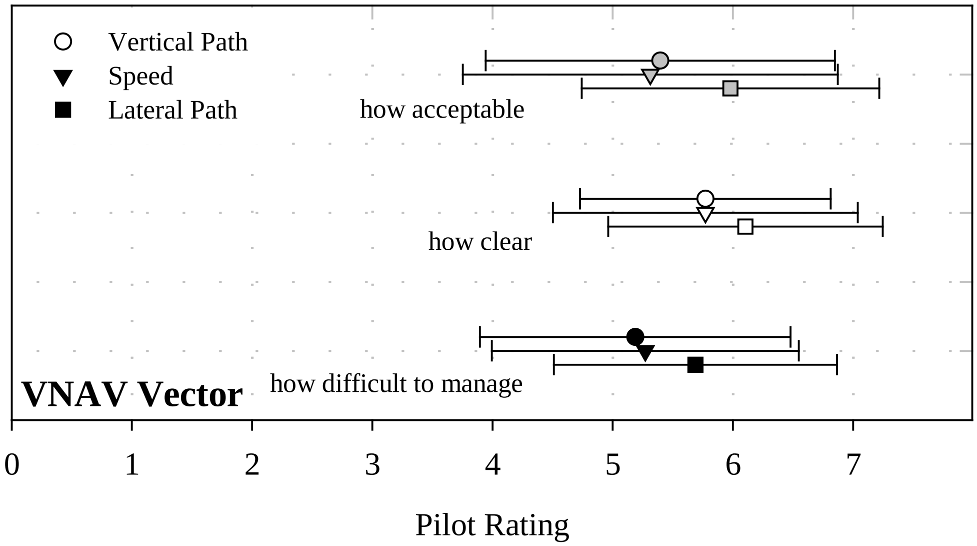


(a) *Nominal* conditions

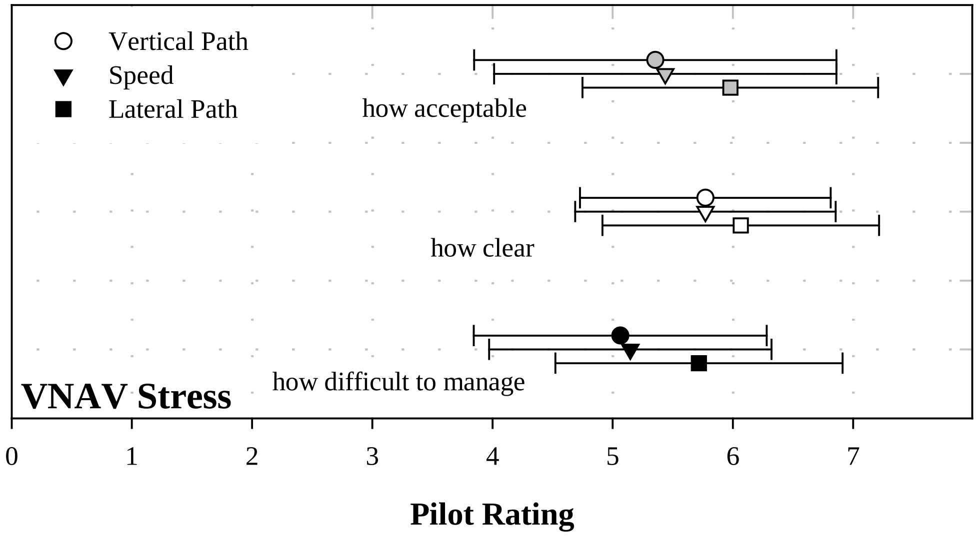


(b) *Slow* conditions

Figure 16. Post-run pilot ratings for VNAV conditions.

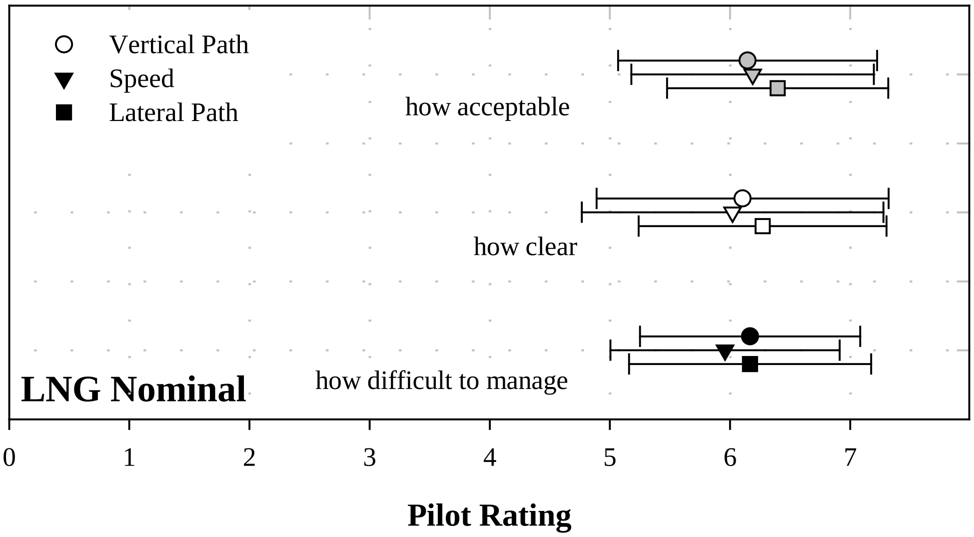


(c) *Vector* conditions

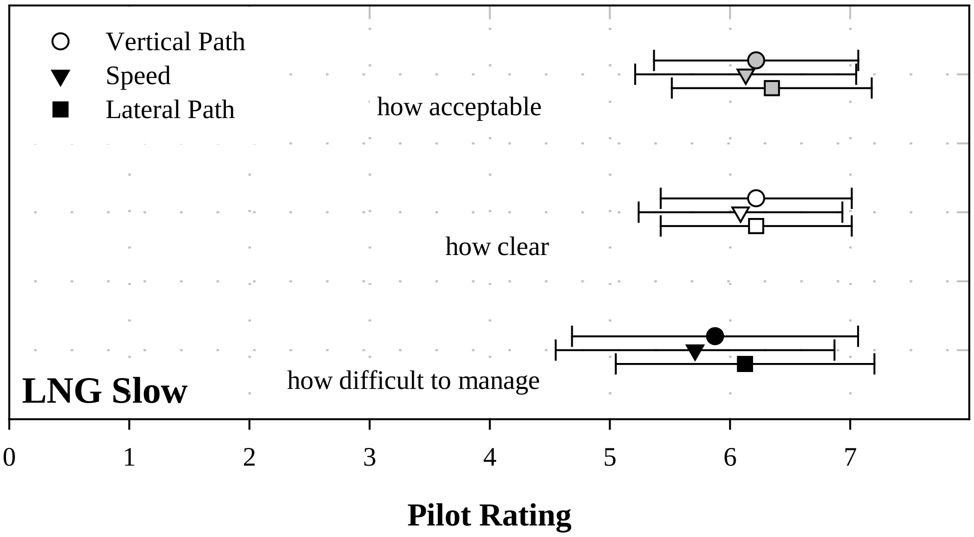


(d) *Stress* conditions

Figure 16. Concluded.

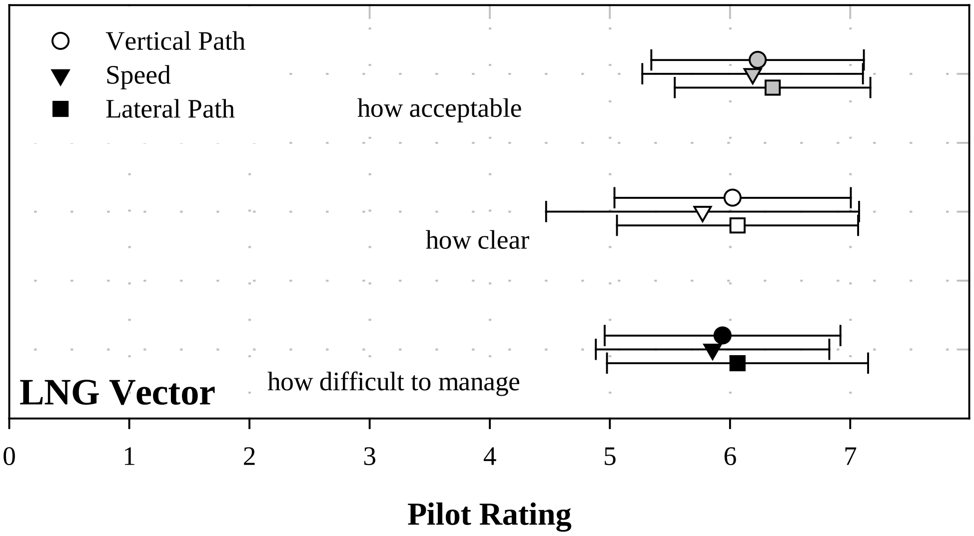


(a) *Nominal* conditions



(b) *Slow* conditions

Figure 17. Post-run pilot ratings for LNG.



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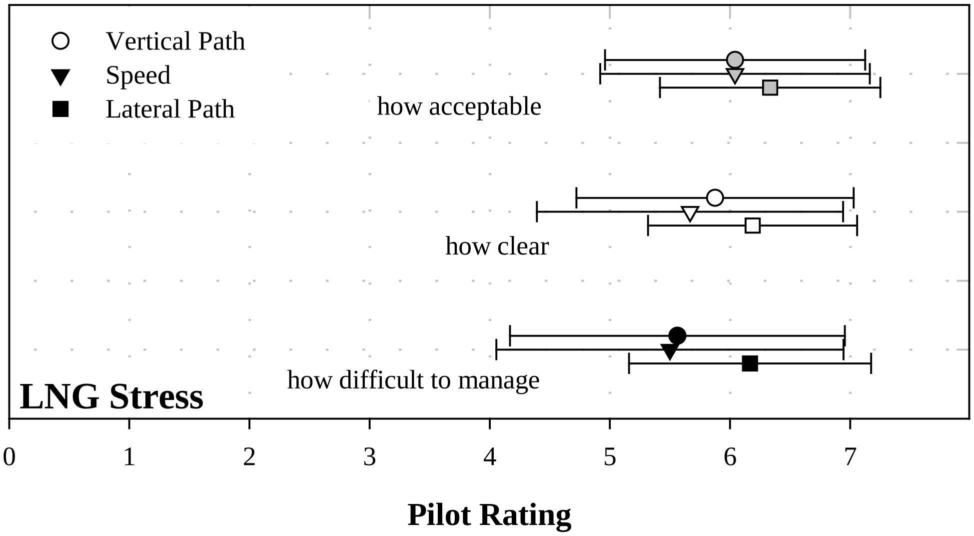

(d) *Stress* conditions

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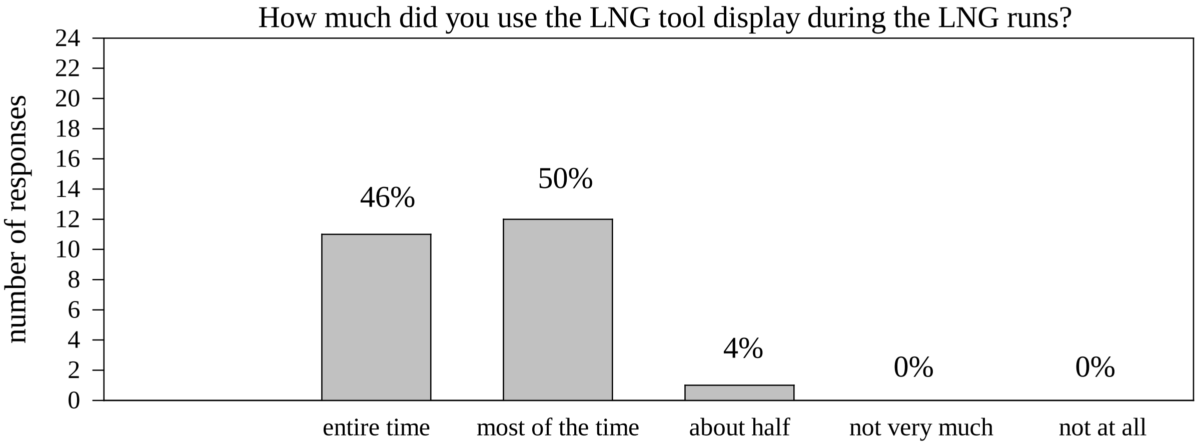


Figure 18. Results from post-test questionnaire, question number 22.

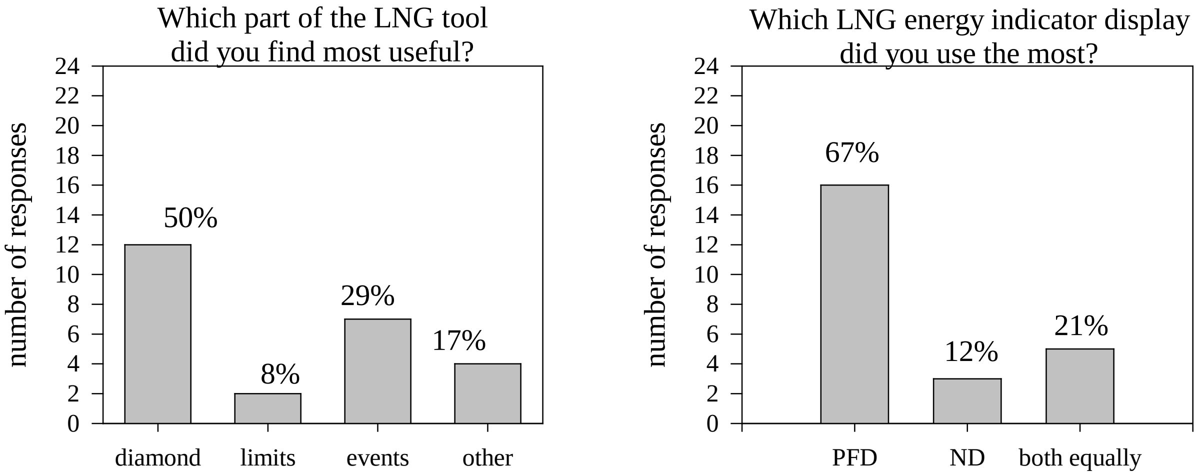


Figure 19. Results from post-test questionnaire, questions number 23 and 27.

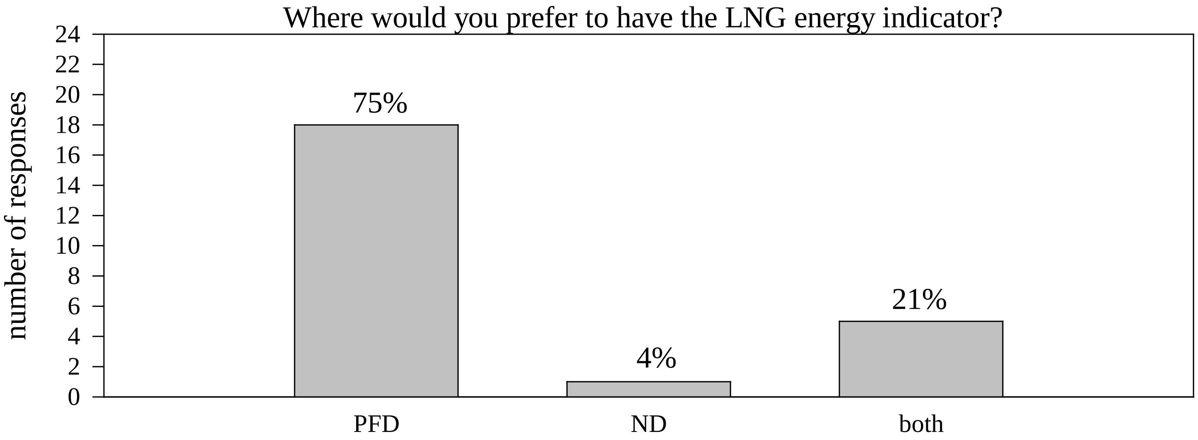


Figure 20. Results from post-test questionnaire, question number 28.

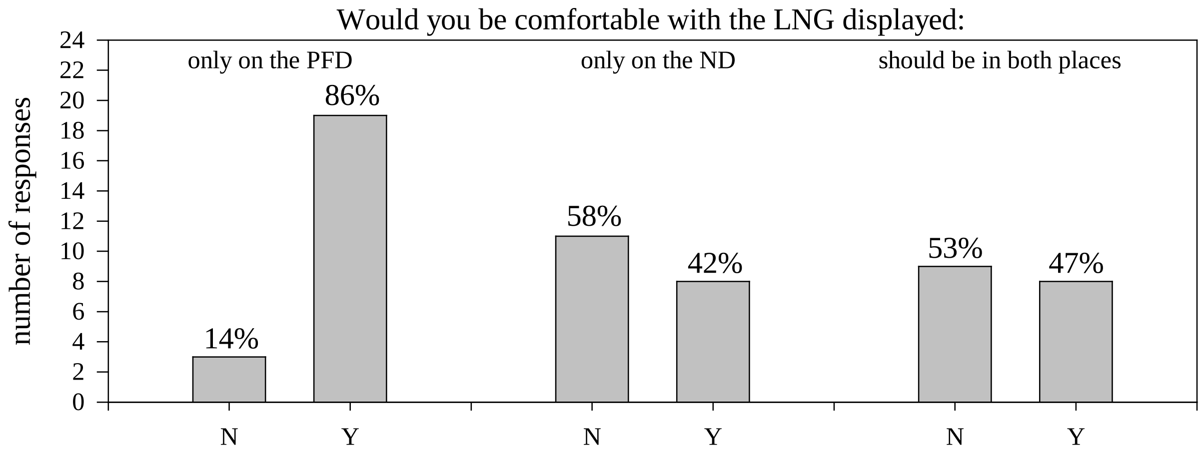


Figure 21. Results from post-test questionnaire, question number 29.

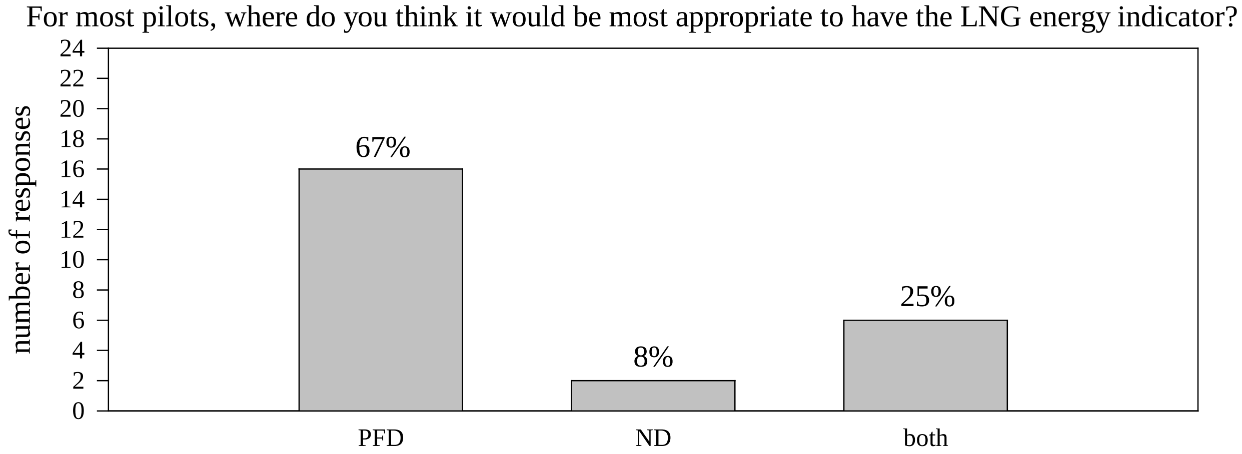


Figure 22. Results from post-test questionnaire, question number 30.

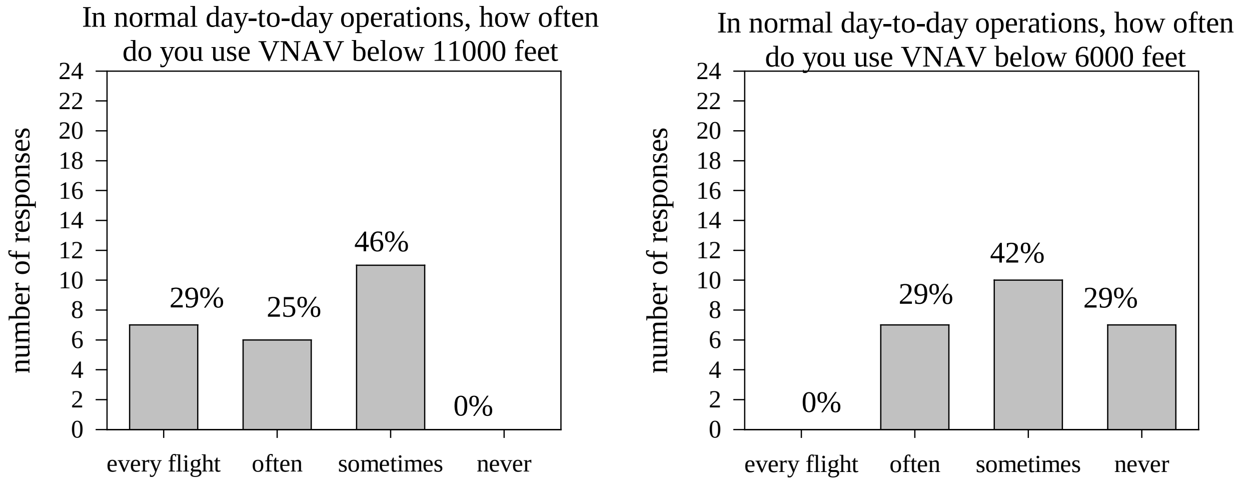
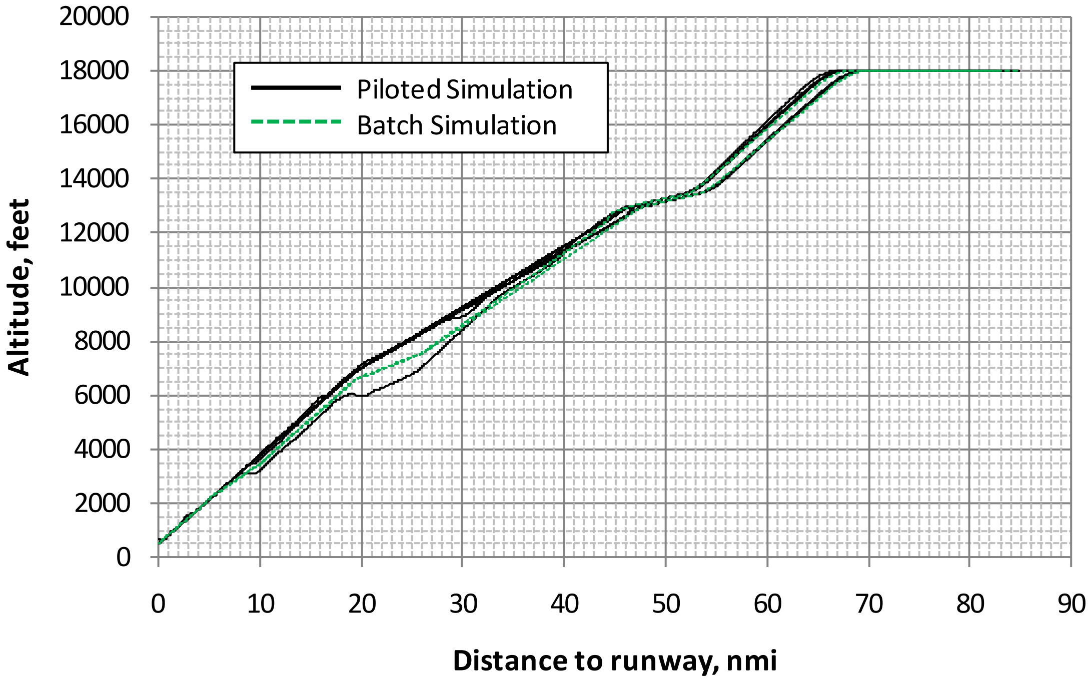
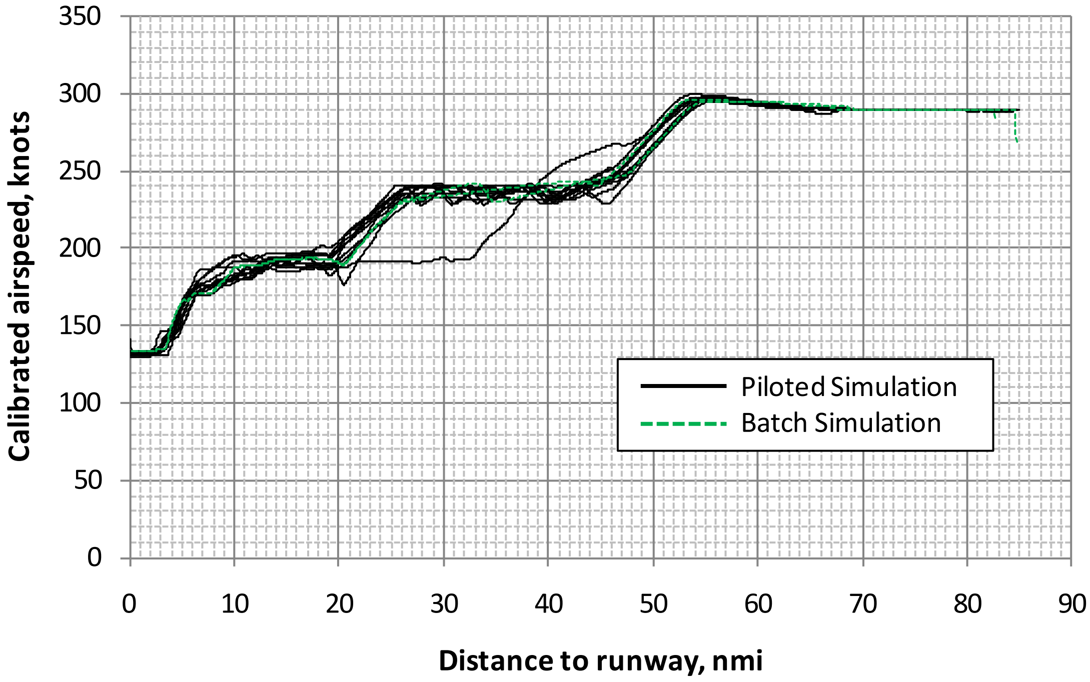


Figure 23. Results from post-test questionnaire, question number 31.

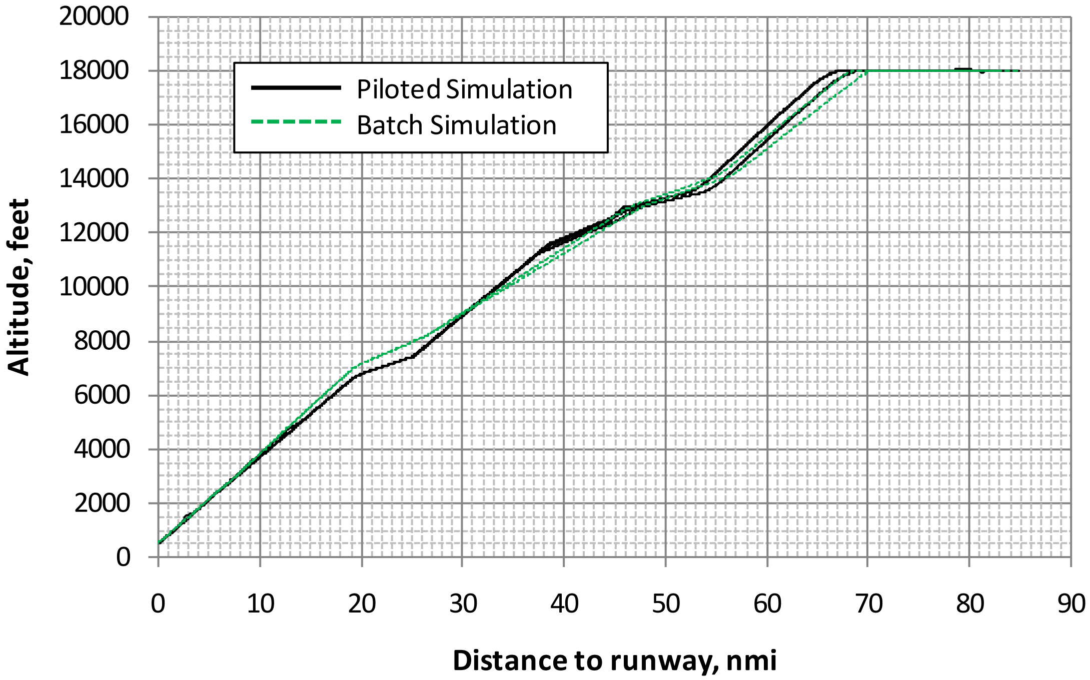


(a) VNAV altitude profiles for *Nominal* runs..

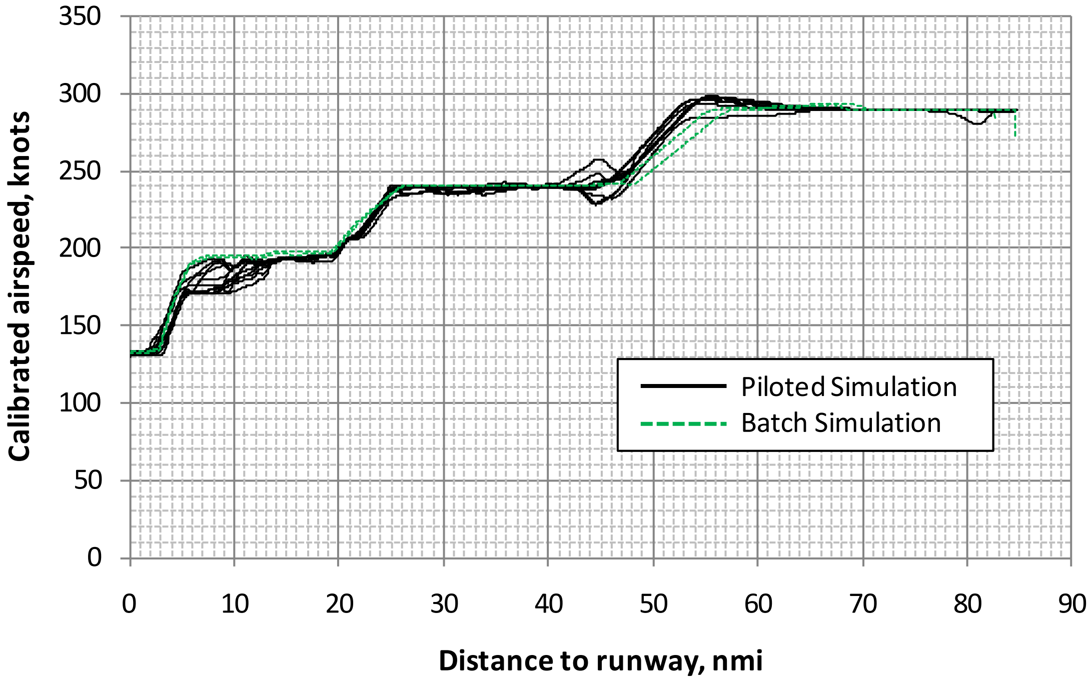


(b) VNAV calibrated airspeed profiles for *Nominal* runs.

Figure 24. Comparison of piloted and batch trajectories for *Nominal* runs.

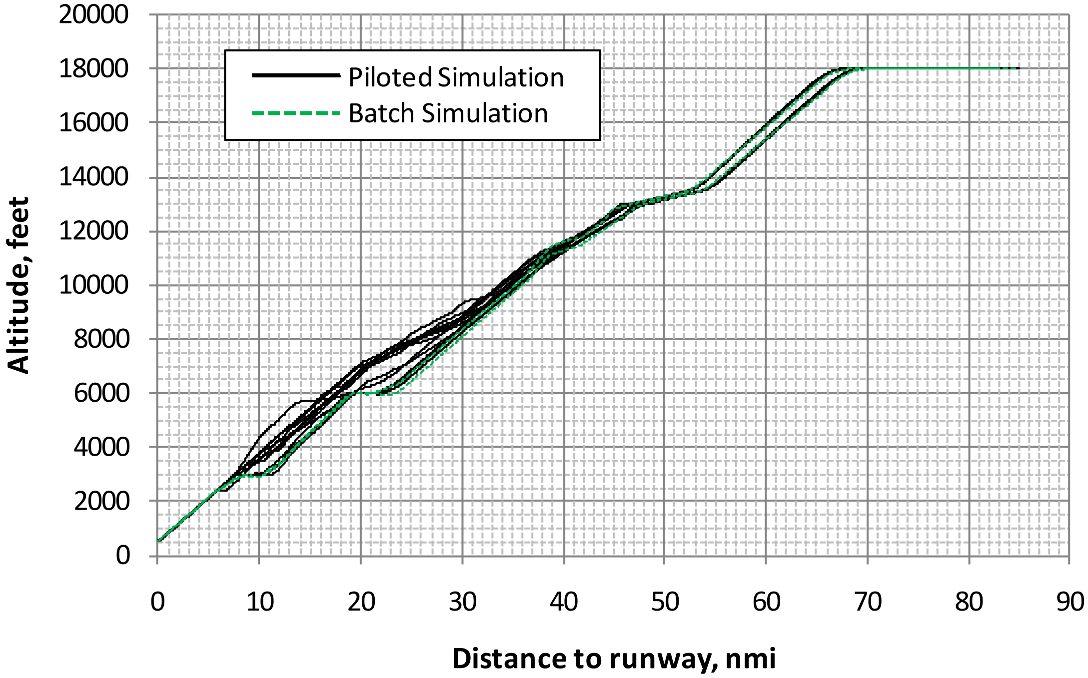


(a) ENAV altitude profiles for *Nominal* runs.

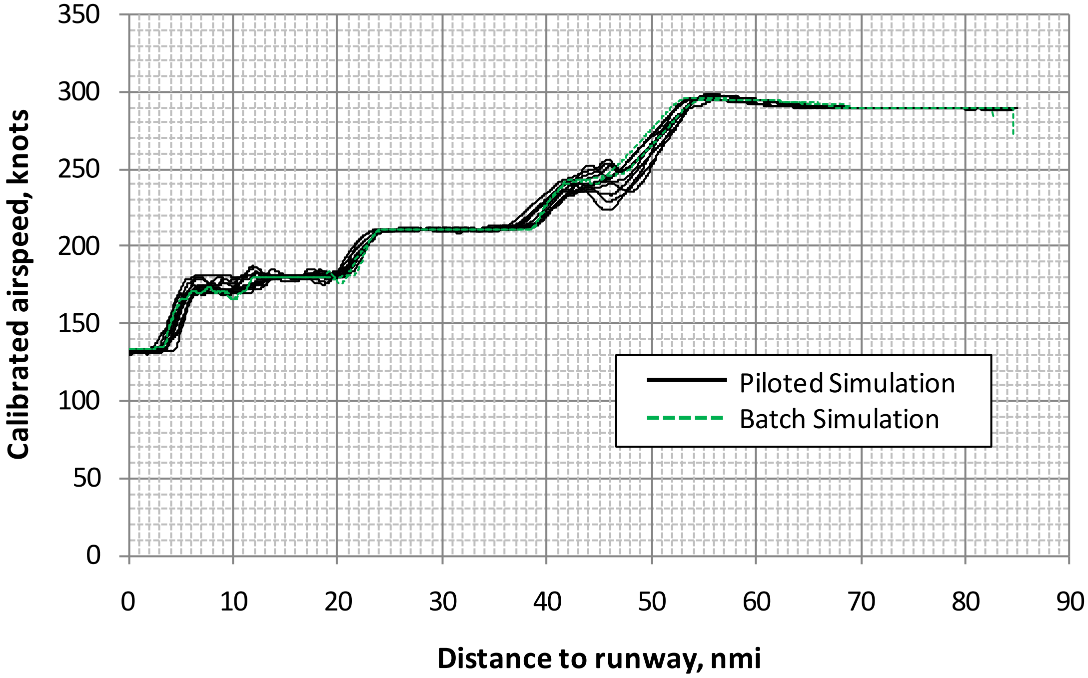


(b) ENAV calibrated airspeed profiles for *Nominal* runs..

Figure 24. Concluded.

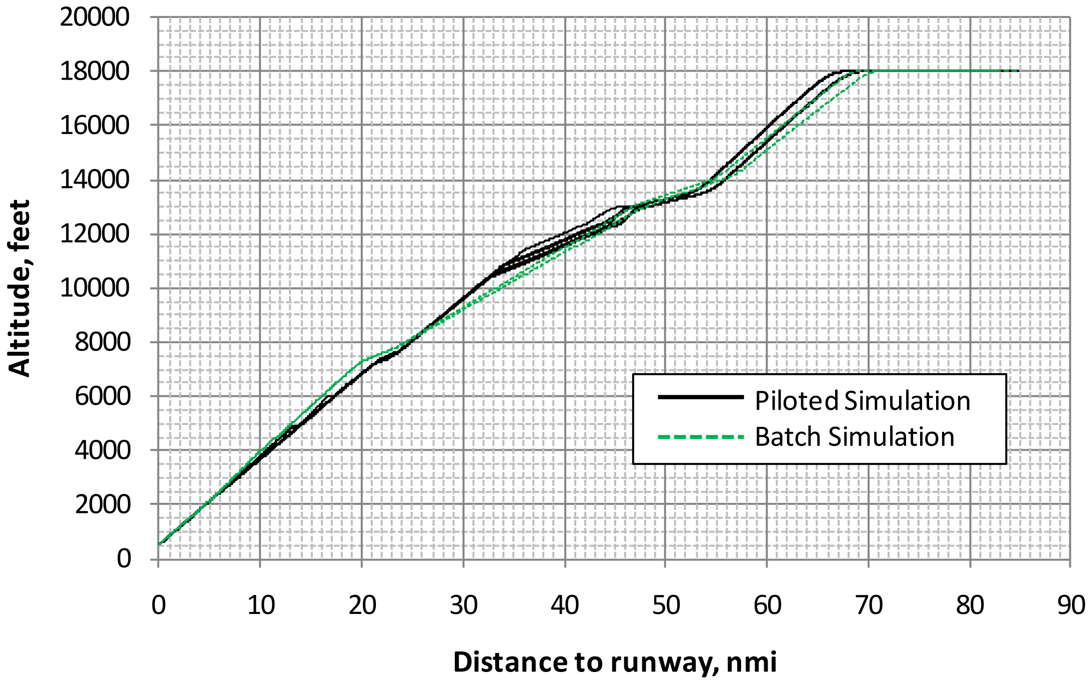


(a) VNAV altitude profiles for *Slow* runs.

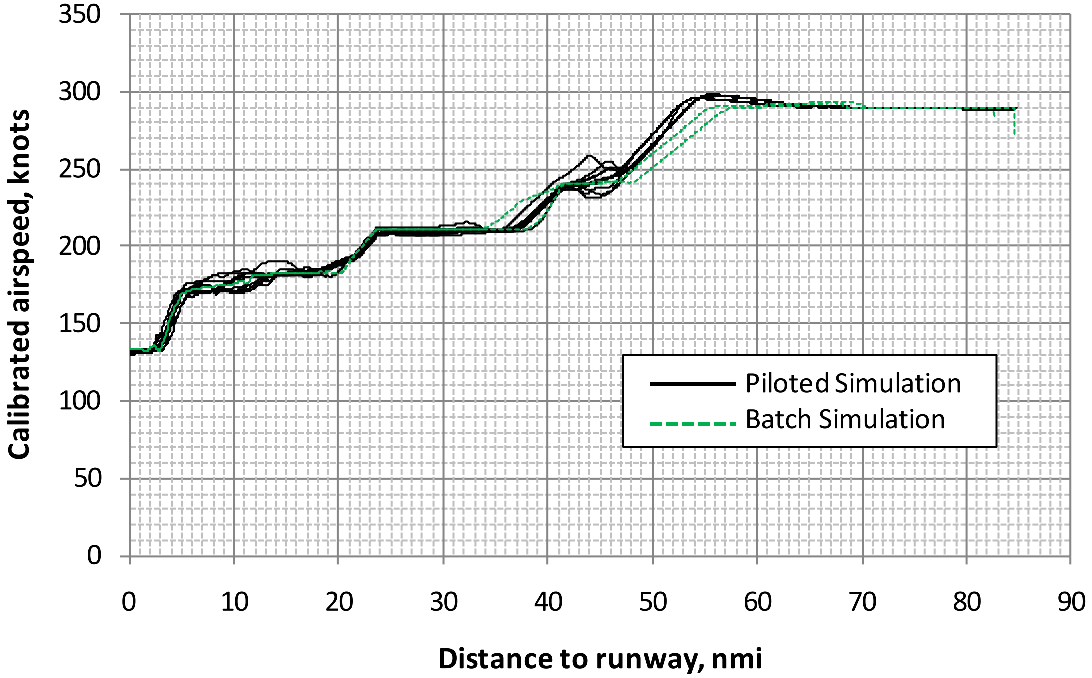


(b) VNAV calibrated airspeed profiles for *Slow* runs.

Figure 25. Comparison of piloted and batch trajectories for *Slow* runs.



(a) ENAV altitude profiles for *Slow* runs.



(b) ENAV calibrated airspeed profiles for *Slow* runs.

Figure 25. Concluded.

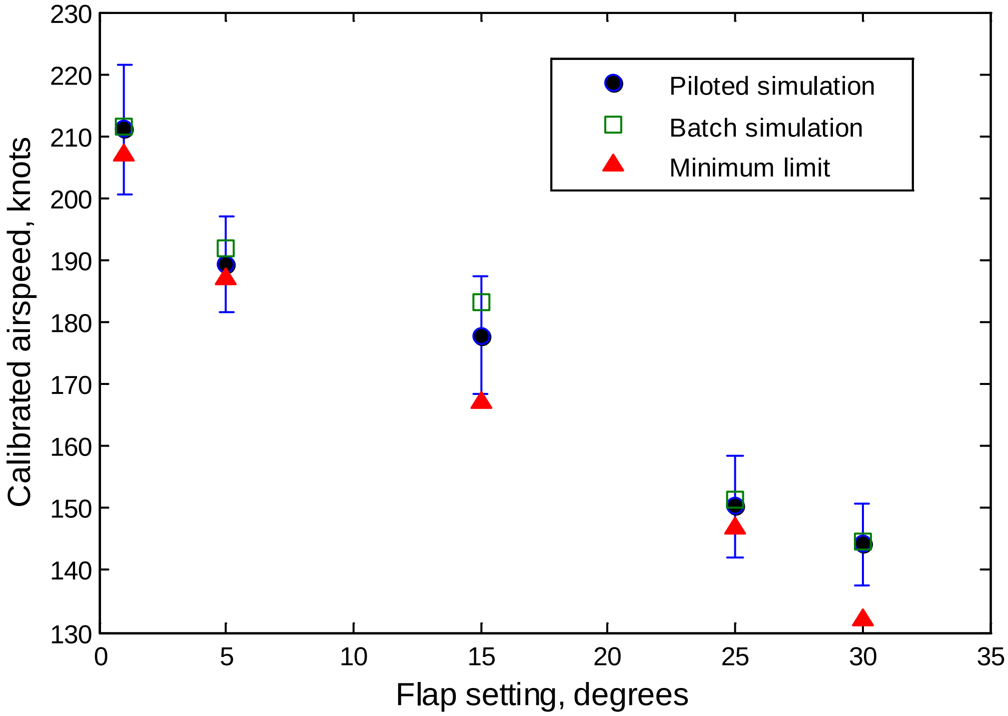


Figure 26. Comparison of flap extension speeds for piloted and batch simulations.

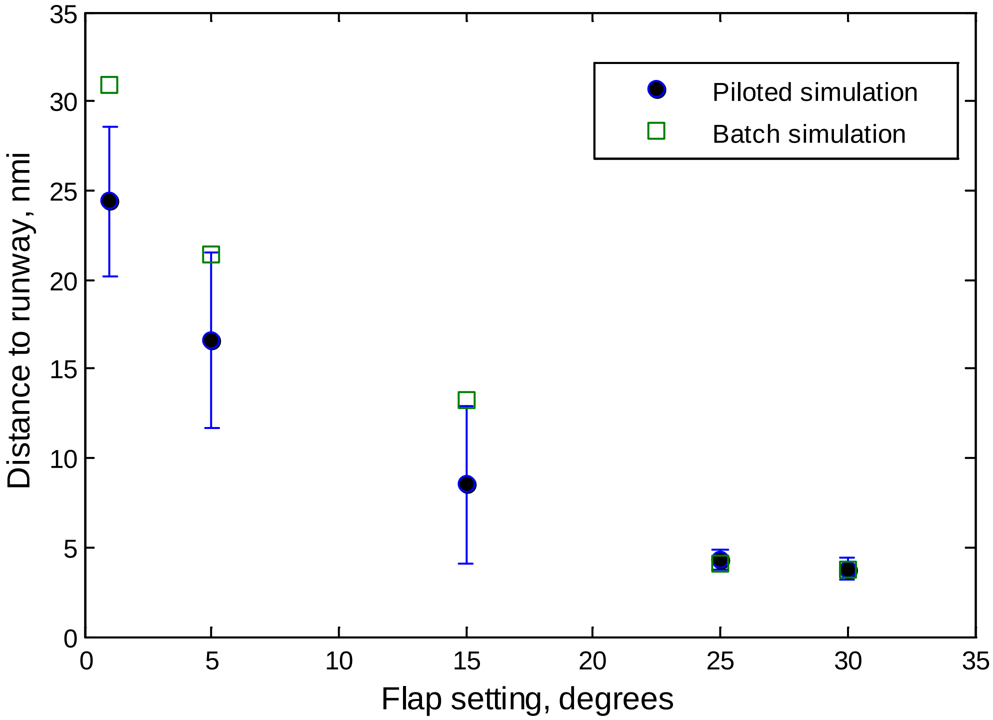


Figure 27. Flap extension distance to runway for piloted and batch simulations.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This paper presents results from two simulation studies investigating the use of advanced flight-deck-based energy navigation (ENAV) and conventional transport-category vertical navigation (VNAV) for conducting a descent through a busy terminal area, using Continuous Descent Arrival (CDA) procedures. This research was part of the Low Noise Flight Procedures (LNFP) element within the Quiet Aircraft Technology (QAT) Project, and the subsequent Airspace Super Density Operations (ASDO) research focus area of the Airspace Project. A piloted simulation study addressed development of flight guidance, and supporting pilot and Air Traffic Control (ATC) procedures for high density terminal operations. The procedures and charts were designed to be easy to understand, and to make it easy for the crew to make changes via the Flight Management Computer Control-Display Unit (FMC-CDU) to accommodate changes from ATC.

15. SUBJECT TERMS

Air traffic control; Descent; Flight management systems; Navigation; Simulation

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