



Continuous Descent Arrivals

Article **1**

Captain Jim Walton
UPS

Introduction and Background

In today's world, nothing can prevent airplane noise and emissions. There are, however, options for reducing the effect of noise and emissions or for actually reducing the noise and emissions themselves. One option is to build new airports as far away as possible from population centers. This option is expensive, not easy to justify or obtain approval for, and not always possible, and building an airport can take a long time. A second option is to build airplanes that are quieter and produce fewer emissions. This, too, is a desirable option except that building an airplane is an also expensive and a long-term solution. A third option that is a near- to mid-term solution and does not require large expenditures employs area navigation (RNAV) arrival procedures that place aircraft on lateral and vertical profiles which make less noise and produce fewer emissions. These arrivals can be designed for all aircraft types; however, aircraft equipped with flight management systems (FMS) will be able to most efficiently fly the vertical profile.

Formal studies have examined this third option. The goal of the studies was to see whether noise and emissions could be reduced through design of RNAV standard arrival routing (STAR) and flight operations procedures. Because much of the noise and emissions are caused by aircraft flying level segments at low altitudes, the concept was to have aircraft continuously descend from cruise altitude to final approach glide slope, if possible. The concept was labeled a continuous descent approach (CDA); however, it more appropriately should be called a continuous descent arrival.

The project culminated with a 2-week flight test in September 2004 at Louisville International Airport, Kentucky, when the last arriving 12 to 14 late-night UPS 757s and 767s followed CDA procedures. Professor John-Paul Clarke, Sc.D., from the Massachusetts Institute of Technology (MIT), led the project that was funded by the Federal Aviation Administration (FAA) Center of Excellence (COE) for Aircraft Noise and Aviation Emissions Mitigation. Additional partners included personnel from the FAA Air Traffic Control (ATC) facilities at Indianapolis Center and Louisville terminal radar approach control (TRACON) facilities, FAA local and regional flight standards, FAA Headquarters, UPS Flight Operations, Louisville Regional Airport Authority, The Boeing Company, NASA Ames, NASA Langley, and MIT.



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Initial Project Development and Execution

Clarke had the idea for the project in 2000 and formed an ad hoc Noise Abatement Procedures Working Group to investigate possibilities. By 2002, the group and project included the additional partners, and the first test was organized and completed. The first flight test of two UPS 767s was in the fall of 2002. The test examined the feasibility of a CDA design, the fly-ability of the CDA, FAA ATC acceptability, and the effect on noise and emission. After the successful completion of the first test, funding was awarded and the project was placed under the auspices of the FAA COE program, under which two additional studies were completed. The first was a NASA Ames air traffic simulation study that examined the effect on traffic flow when CDA STARs were followed in a medium- to high-density airport environment. The NASA study is not discussed in this presentation. The second study was the 2-week flight test in 2004 at Louisville.

In the development stage, before the 2002 flight test, the participants believed that following operational procedures was a cost-effective means of reducing near- to medium-term noise and emissions. They also believed that applying these procedures during the arrival segment would produce the most benefits. The ideal arrival procedure was one that afforded a continuous idle thrust descent from cruise altitude until thrust was added to fly a stabilized final approach to landing or, in other words, an idle thrust CDA to final approach and landing. As with most new procedures, the ideal procedure was difficult to achieve. At idle thrust, the airplane is basically a glider and predicting a vertical profile to fulfill altitude and airspeed constraints presented significant issues to be resolved. The vertical profile was subject to winds, aircraft gross weight, FMS logic, and pilot technique.

The challenges that had to be overcome were (1) CDA procedural design and (2) safe control of aircraft spacing and separation that did not affect airport capacity. The first challenge, procedure design, was to leverage FMS capability to enable the flight crew to follow the procedure and not significantly increase their workload. The second challenge was how to space and ultimately separate aircraft and maintain airport capacity. The 2002 flight test dealt mainly with procedure design for the CDA and flight crew. The two aircraft that participated in the test were chosen to prevent spacing or separation issues. The 2004 flight test addressed additional flight crew and procedure design, aircraft spacing and separation issues and was conducted in a medium-density traffic environment. Because both flight tests were conducted during the UPS late-night arrival flow, crossing traffic and low-altitude traffic did not present a problem with CDA design or ATC separation.

The objectives of the 2002 flight test were to design a procedure that was totally contained within the Louisville (KSDF) TRACON airspace, to measure real-world benefits by flying aircraft in revenue service, and to identify any FMS issues. The research approach was, for a 2-week period, to have the last two consecutive 767-300s fly the same lateral track from TRACON entry to the final approach fix. The first airplane flew the track applying traditional descent techniques when given descents by ATC. These are referred to as “dive and drive” descents because during the descent, thrust is at idle followed by a level off and a level flight segment. The second airplane flew the same lateral track and followed the CDA procedures. Flight data recorders and noise monitors measured the various metrics required for the test. Noise, emissions, fuel burn, and time were obtained from the collected data.

The lateral path (fig. 1) began at the TRACON boundary at CHERI intersection and continued northeast to BLGRS intersection where the arrival intercepted the instrument landing system (ILS) approach course to runway 17R. Portions of the area north and west of the airport are noise sensitive; therefore, the lateral track was chosen to fly over those areas.

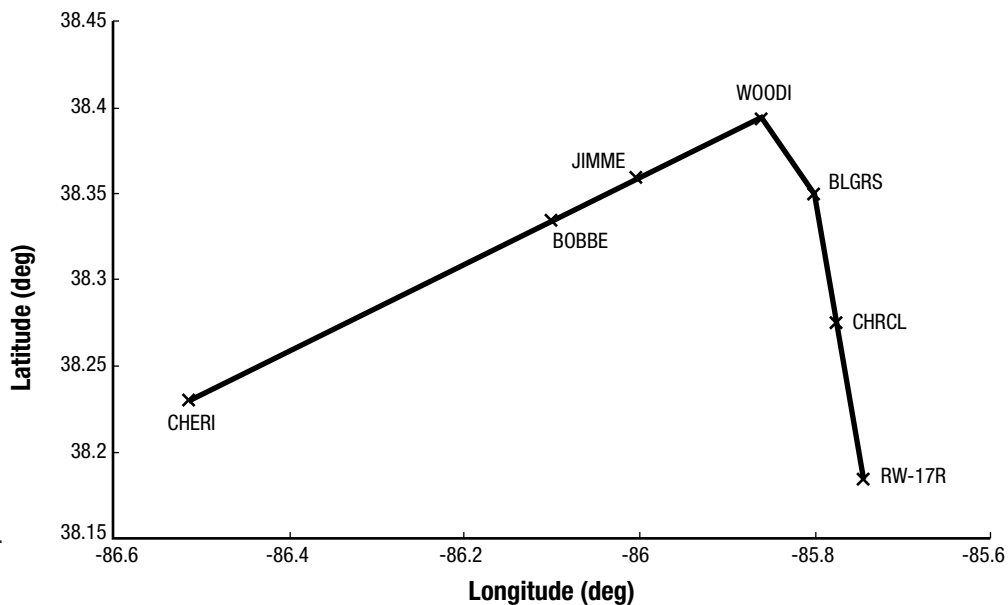


Figure 1. Waypoints

Figure 2 shows the location of the noise monitors. The elevation of the noise monitor is significantly higher than the elevation of KSDF.

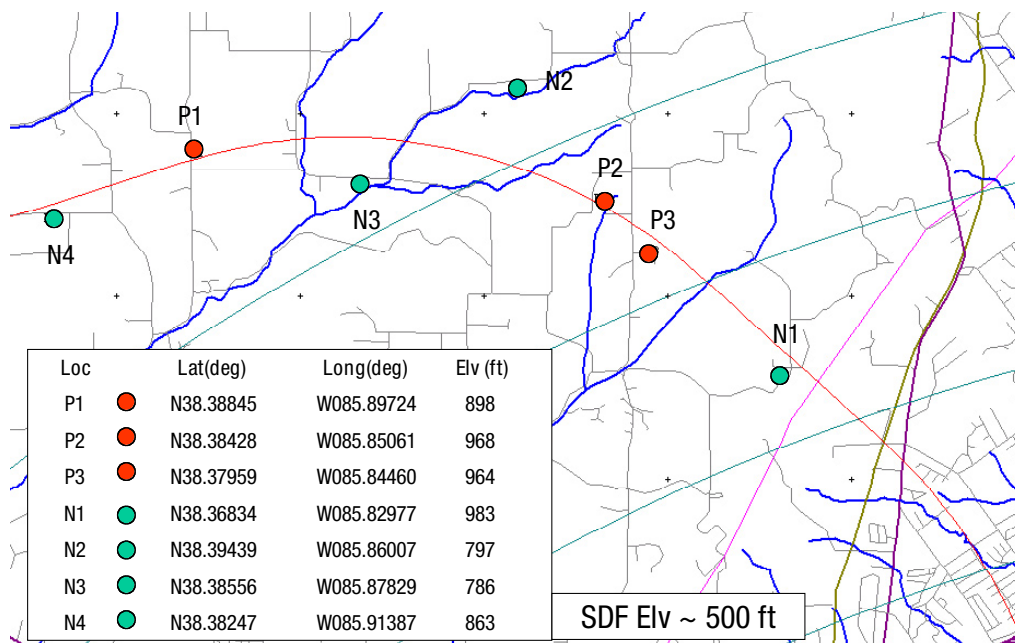


Figure 2. Noise monitors

Figure 3 shows three vertical profiles that were initially considered for the 2002 flight test. The conventional “dive and drive” profile is also shown. Because descents in the Louisville terminal area begin shortly after the CHERI intersection from 11,000 feet (ft) mean sea level (MSL), the final profile of the test was changed to start at 11,000 ft. The conventional descent shown is typical of the descents in the Louisville airspace; however, at times there may be additional level-flight segments at 6,000 ft MSL and 4,000 ft MSL depending on traffic. Each segment most likely will involve a “dive and drive”.

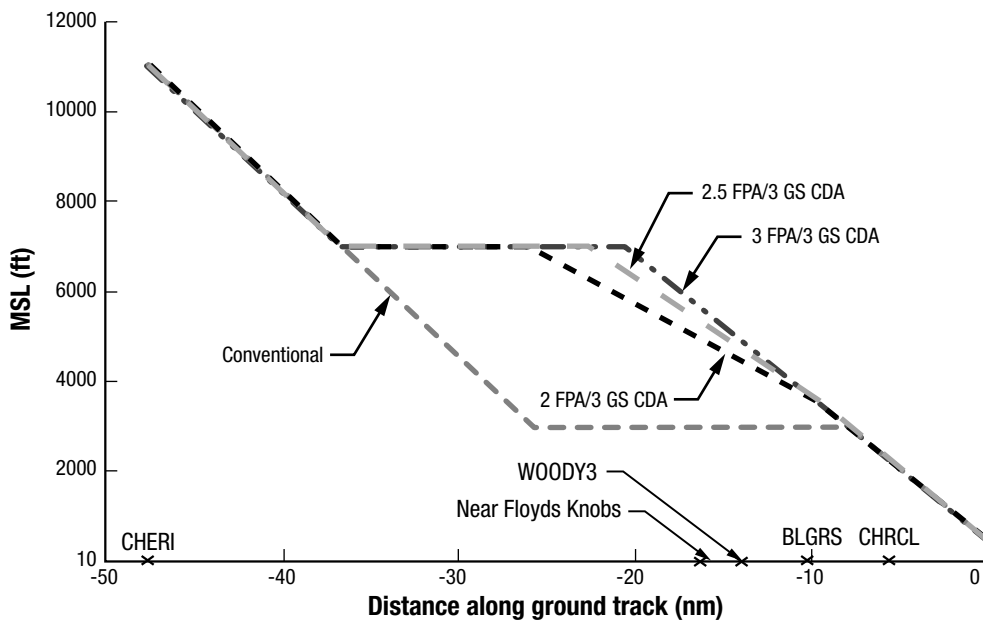


Figure 3. Initially considered profiles

Figure 4 shows the vertical profiles for the 2-week test. The test was initially designed to fly fixed flight-path angles until intercepting the ILS glide slope, and the first week of the test was flown in that manner. Based on feedback from the flight crews, the second week was flown utilizing a vertical path solely determined by the FMS.

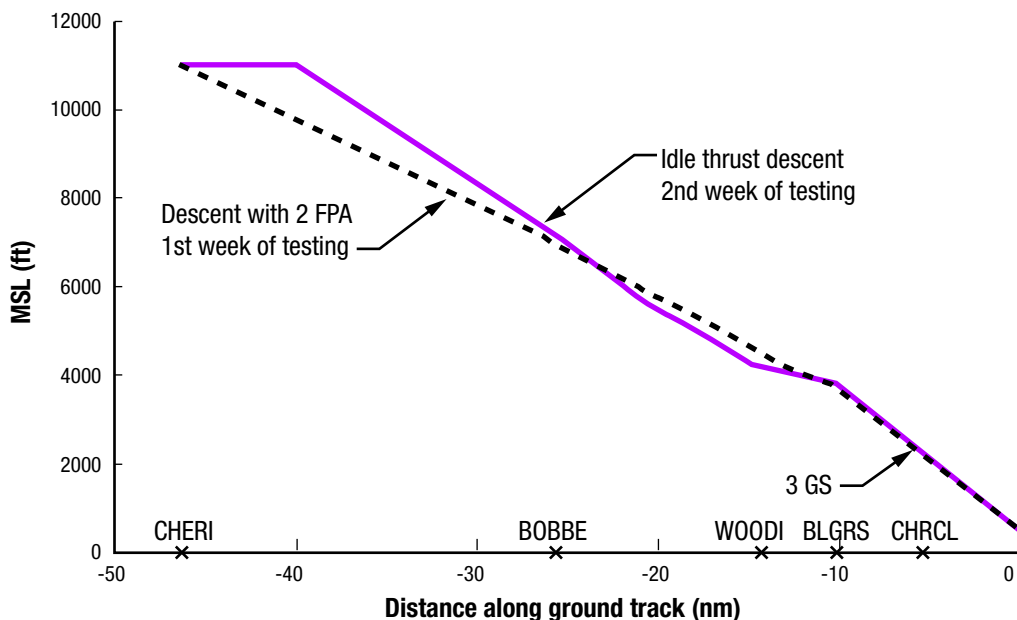


Figure 4. “Design” profile

2002 Test Results

The results of the flight test were very encouraging. Figure 5 shows the results of the noise measurement. The CDA results were based on the second week of the test.

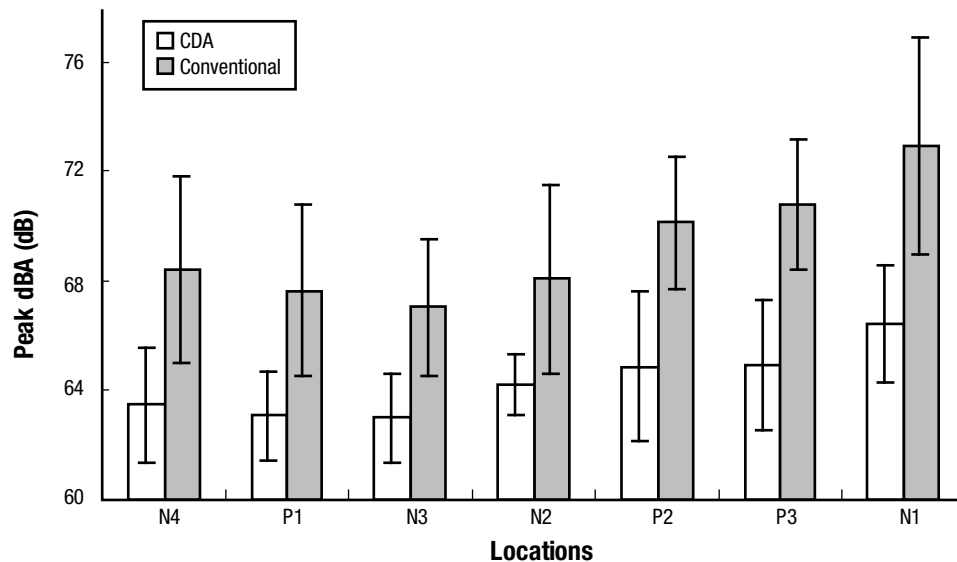


Figure 5. Noise reduction

Environmental and economic benefits are summarized below:

- Up to 6 decibel (db) noise reduction (7.5 to 15 nautical miles (nm) from the runway).
- 30% reduction in nitrous oxides (NO_x) (below 3,000 ft above ground level (AGL)).
- 500 pound (lb) reduction in fuel burn.
- 100 second (sec) reduction in flight time.

There were a few issues related to the FMS and the auto-throttle systems. Flight crews at times had to reset cruise altitude and descent speeds and to reselect the arrival. These actions increased their workload, however, the additional activity was easily handled and did not affect the test. There were some undesired auto-throttle advances when the system perceived that thrust was required for an upcoming speed and altitude constraint. Additionally, there were some segments when thrust increased to maintain a speed. This increase was caused by tailwinds less than predicted by the FMS and/or early flap or gear extension. During the second week, on a few occasions, higher than FMS commanded speeds were observed that required the use of speed brakes. The additional speed was attributed to a predicted wind that differed from the actual wind. Even with these anomalies, the results showed that all categories significantly improved.

Follow-Up Test Planning

The 2002 test was done under controlled conditions that did not represent normal traffic flow or traffic levels. Because of the controlled conditions, there were no traffic conflicts and no adjacent ATC sector issues and circumstances were best for the test.

After the success of the 2002 flight test, work began on the next flight test to address some real-world issues not addressed in the first test. The first objective was to design a CDA procedure for either 17R or 35L at Louisville and that procedure

would begin the CDA from cruise altitude, be usable in daily operations, utilize a pre-loaded FMS procedure in the database, and correct FMS issues identified in the 2002 flight test. The second objective was to design the flight test to validate new design tools; demonstrate the consistency of the CDA procedure; furnish data required for operational acceptance; and validate savings in noise, emissions, fuel burn, and time.

The research approach was to develop the CDA and pilot procedures, design a tool that predicted the spacing between aircraft at the TRACON boundary, ensure that minimum separation was maintained throughout the CDA, conduct a 2-week study, and collect and analyze the data.

Personnel from NASA Langely, UPS Flight Operations, MIT and The Boeing Company developed the CDA design and pilot procedures. The final procedure is shown in Figure 6.

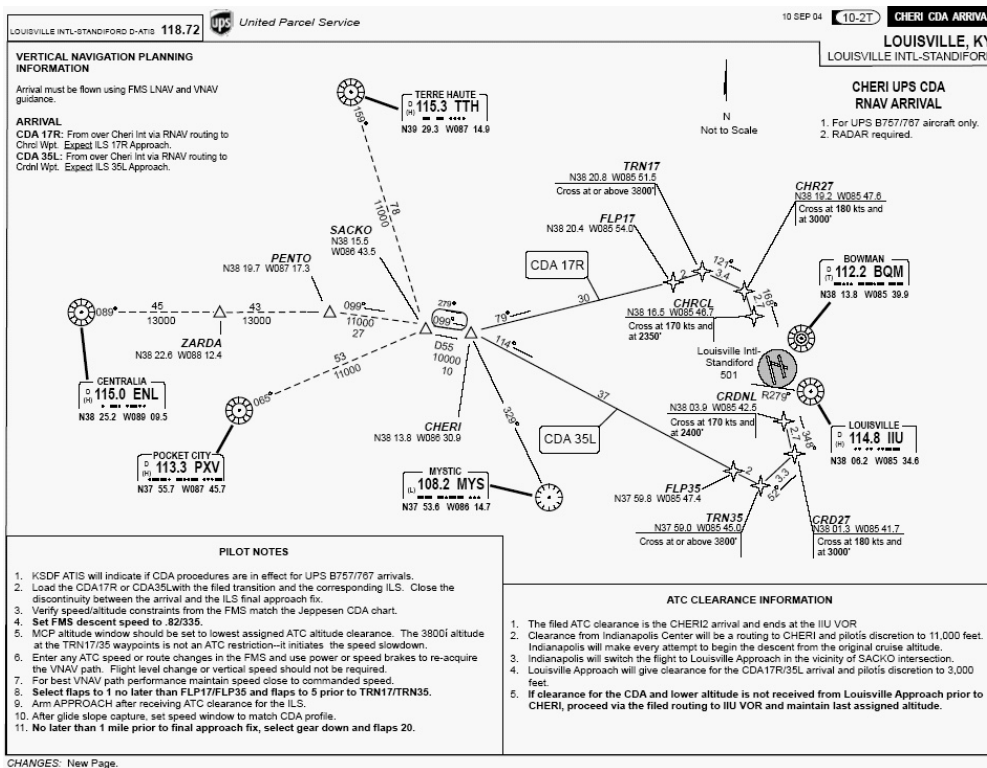


Figure 6. Approach chart

NASA, UPS and Boeing tested the designs and pilot procedures in simulators, and UPS pilots subsequently validated them during pre-study flight tests. The routing from the TRACON entry at CHERI intersection required new waypoints with speed and altitude constraints, if necessary, that resulted in smooth turns on to final approach, gave configuration cues to the pilot, avoided a restricted area when landing north, kept the aircraft as high as possible, and put the aircraft in a position on final approach that allowed glide slope intercept from below. Additionally, to keep workload low, the intent was to load the procedure from the FMS database and not manually enter data other than Mach number and airspeed for the descent. The Jeppesen arrival procedure contained a significant number of pilot notes, see (fig. 6). The notes provided a quick reference guide to the pilot for the CDA procedures.

The 2004 flight test involved more than just the Louisville TRACON air traffic controllers. To start a continuous descent from cruise altitude, controllers in Indianapolis Center also had to be involved. During the CDA design, agreements were made between the various ATC sectors to accommodate the procedure. To allow the FMS to provide the optimal descent, altitude clearances had to be given as “pilot discretion” clearances from Indianapolis Center. Once in TRACON airspace, additional descents had to be given well in advance of the original descent clearance limit to allow the aircraft to stay on the FMS profile. Additionally, some minor phraseology modifications were made for the test procedure.

Because the 2004 test involved multiple aircraft, a new tool was designed to predict the spacing needed at the CHERI intersection to ensure that minimum separation requirements were met. These predictions were needed to sequence aircraft before top of descent to ensure that vectoring off of the lateral CDA profile would not be required. Graduate students from MIT designed a Monte-Carlo fast-time simulator to predict the spacing. Aircraft type, the CDA procedure, aircraft flap schedule, pilot response time, aircraft gross weight variation, and wind variation were variables that were entered into the simulator. Figure 7 shows a graphical representation of the spacing simulator program.

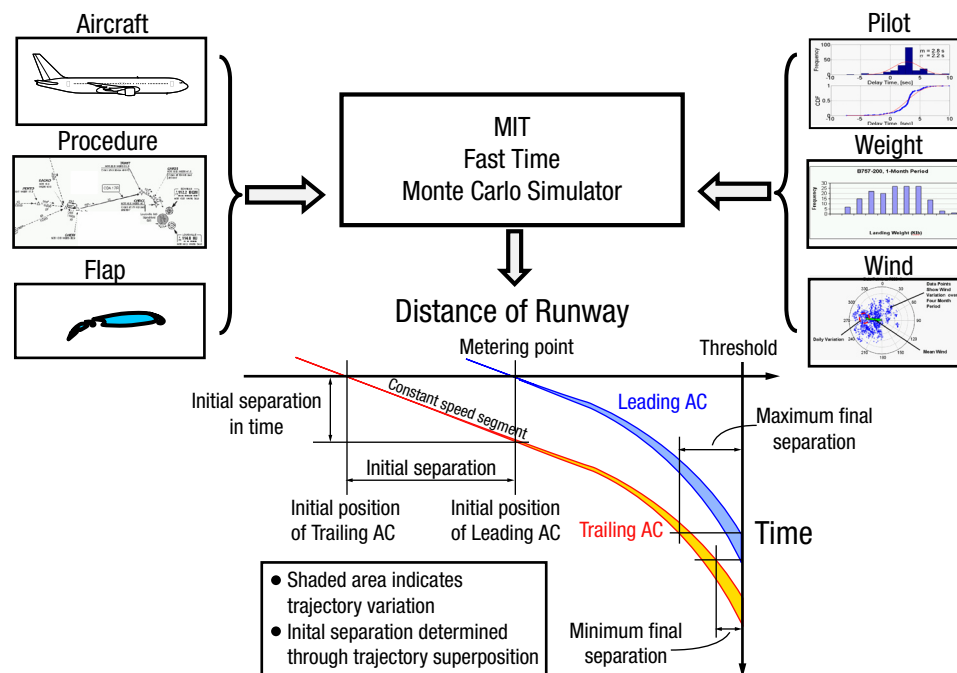


Figure 7. Monte-Carlo simulator

Once the planning and pre-test work was completed, the procedures for pilots and ATC controllers were finalized. The pilots received a pilot bulletin and a Jeppesen arrival chart that outlined and explained the CDA test and procedures. The CDA procedure was installed in the FMS database to allow the pilots to more easily set-up the CDA. The spacing and phraseology requirements were communicated to the appropriate FAA ATC facilities. Once this was done, all that was left was to run the 2-week test.

2004 Test Results

The test was carried out in September 2004 for two consecutive weeks. The next four charts (figures 8, 9, 10, and 11) compare two non-CDA flights and two CDA flights. The charts are based on flight recorder data. The flights are labeled as CDA (those that performed the CDA procedure) and STD (those flights that were provided standard descents (dive and drive) and were vectored to the final approach course).

Figure 8 shows a comparison of the ground tracks. Note the variance between the CDA ground tracks and the tracks of those aircraft being vectored.

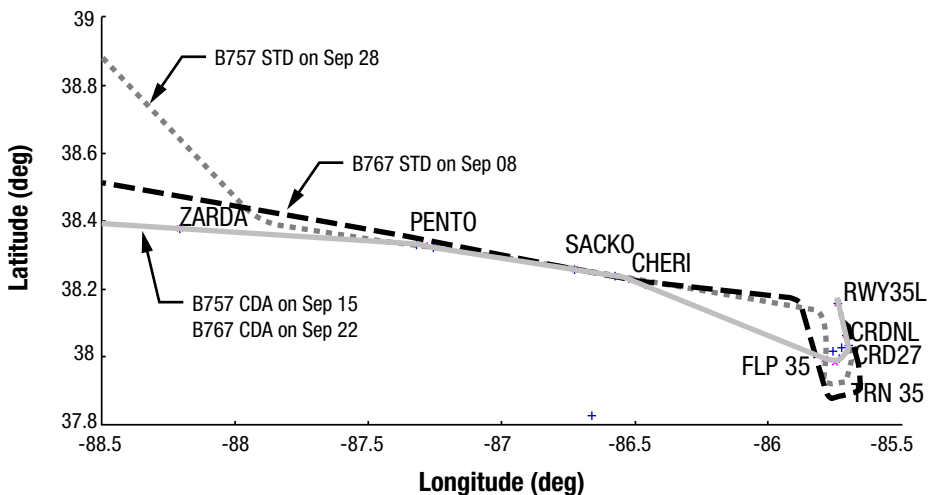


Figure 8. Ground track to SDF 35L

Figure 9 shows the comparison of the vertical profiles. The CDA profiles do not have any level flight segments, and the descents were initiated much closer to the runway than the non-CDA flights.

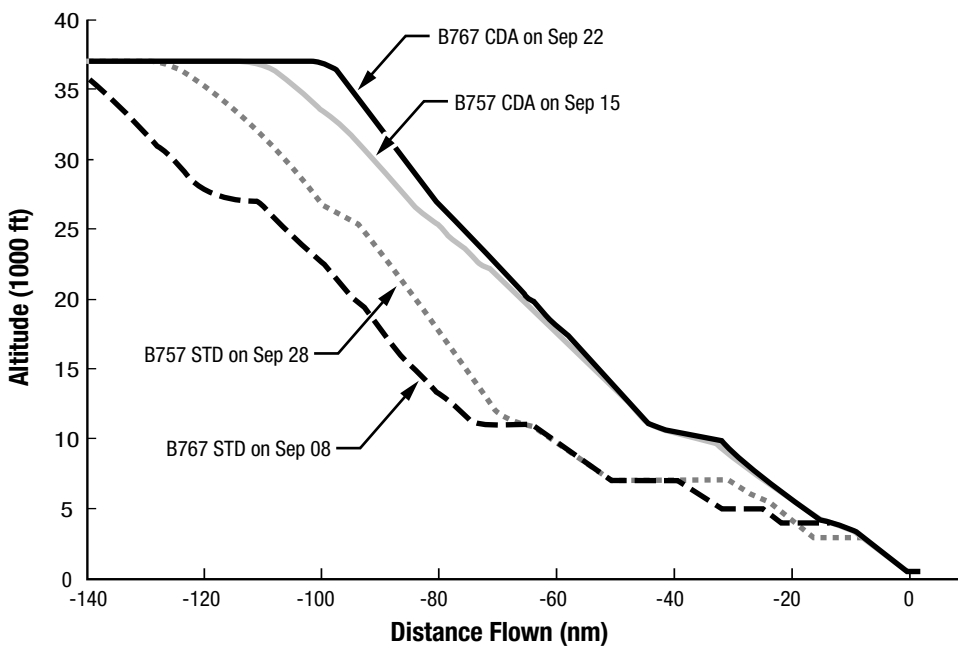


Figure 9. Vertical profile to SDF 35L

Figure 10 shows a comparison of the calibrated airspeed (basically indicated airspeed). It is significant that the CDA aircraft maintained a higher airspeed until much closer to the runway than the non-CDA aircraft.

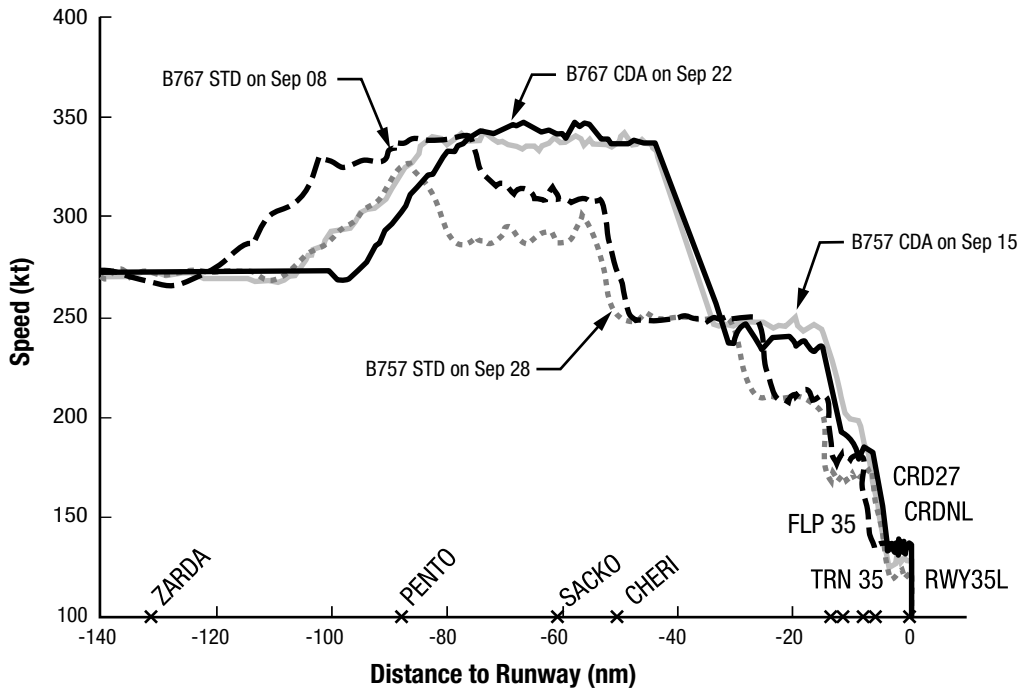


Figure 10. CAS to SDF 35L

Figure 11 shows a comparison of engine N1 speed. This chart shows, very dramatically, why the CDA makes less noise, produces fewer emissions, and burns less fuel.

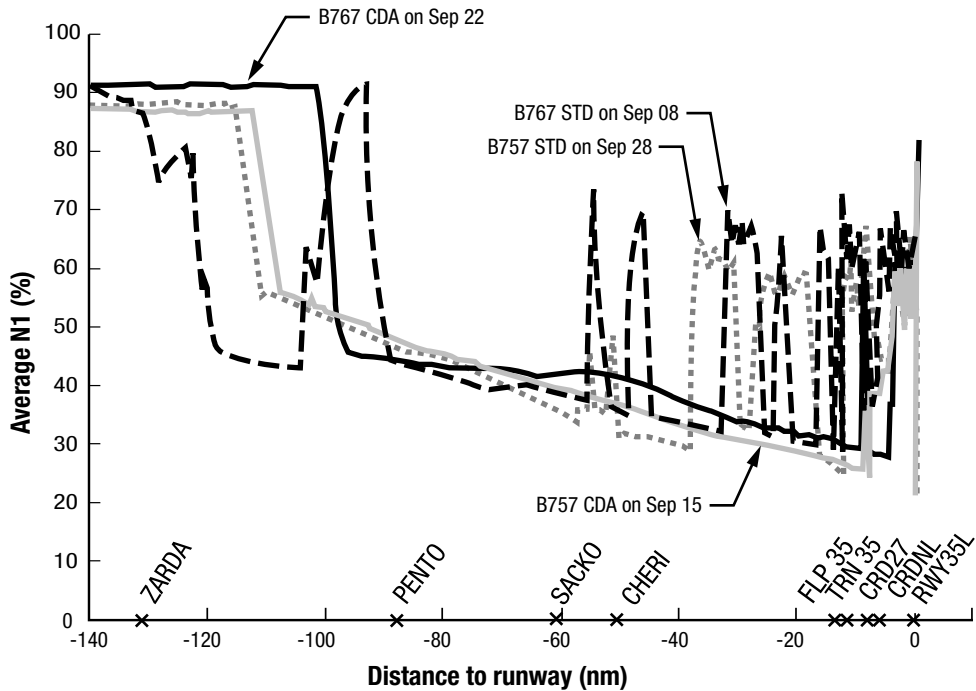


Figure 11. Average Engine N1 to SDF 35L

The 2004 flight test demonstrated significant environmental and economic benefits for the CDA in real-world operations during nighttime operations. Specific results are as follows:

- Noise impact significantly reduced.
 - Lower per aircraft noise levels.
 - Impact concentrated in narrow corridors.
- Local emissions significantly reduced (below 3,000 feet above ground level (AGL)).
 - A 12.7% (767) and 20.1% (757) reduction in carbon monoxide (CO).
 - An 11.0% (767) and a 25.1% (757) reduction in hydrocarbons (HC).
 - A 34.3% (767) and 34.4% (757) reduction in Nitrous Oxides (NO_x).
- Economic costs significantly reduced.
 - A 364 lb per flight (767) and 118 lb per flight (757) reduction in fuel to fly last 180 nm to runway.
 - A 147 sec per flight (767) and 118 sec per flight (757) reduction in time to fly last 180 nm to runway.

The following three charts graphically show the results outlined above. Figure 12 shows noise impact, fuel and time savings.

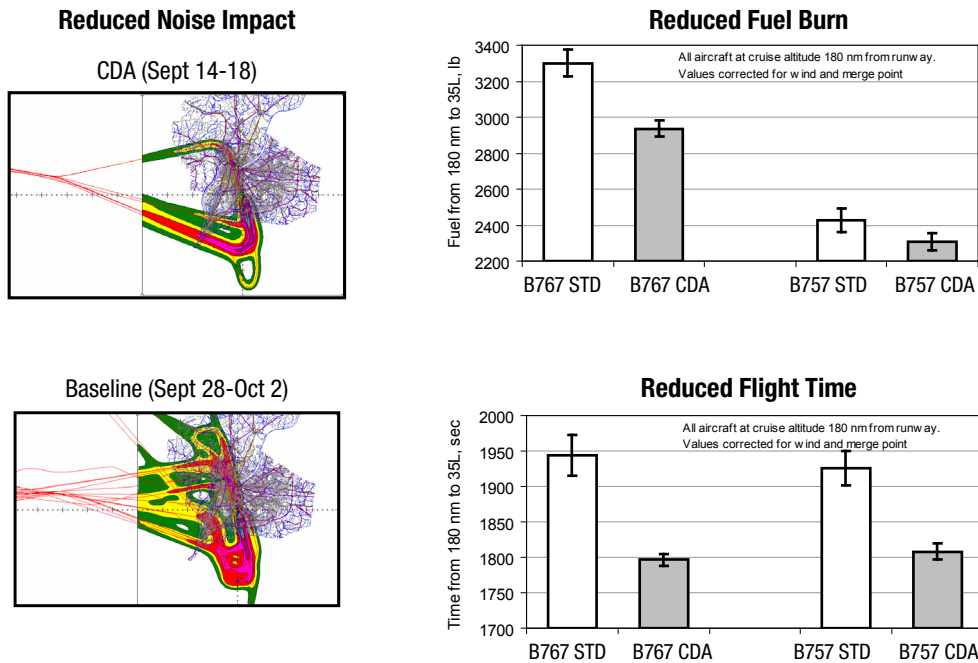


Figure 12. Noise impact, fuel and time savings

Figure 13 shows the noise levels of one flight flying the CDA. The dog's barking made more noise than the airplane.

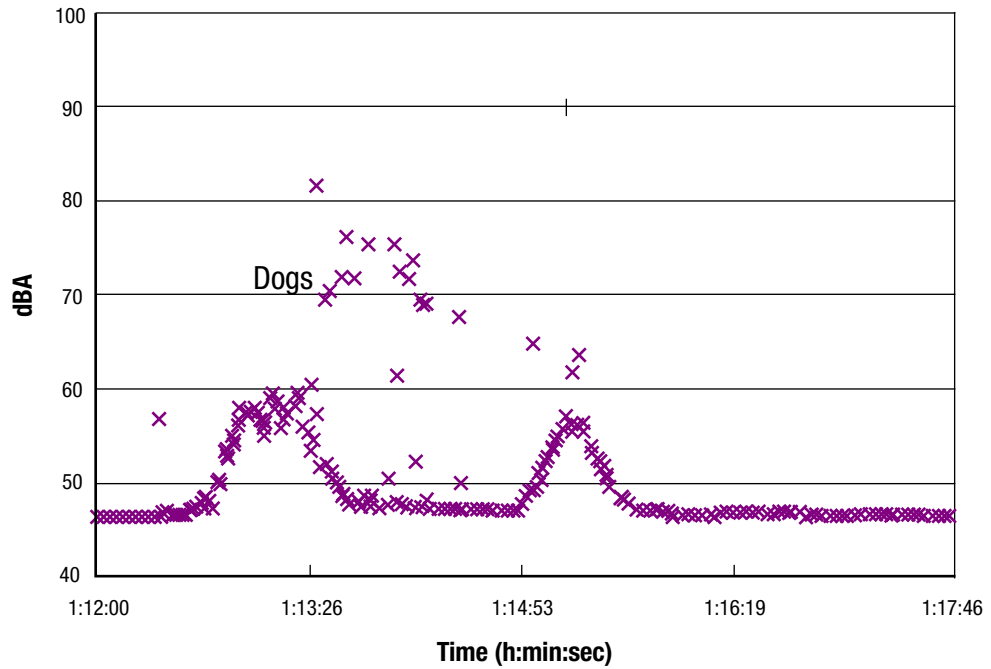


Figure 13. Noise levels

Figure 14 shows the emission results from the flight tests.

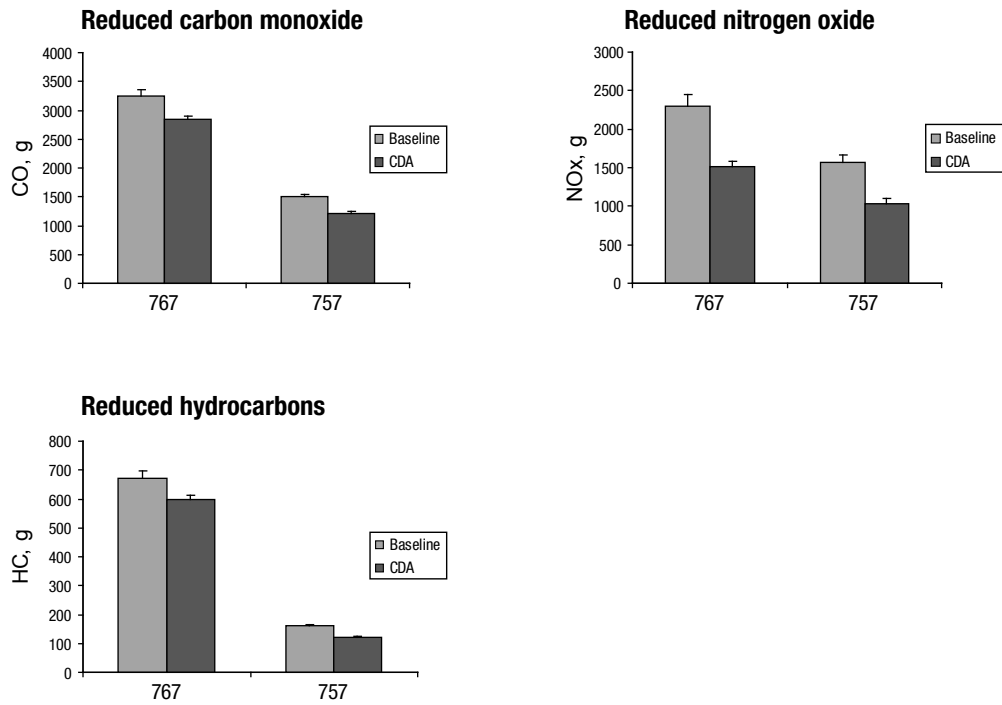


Figure 14. Emission results

Summary

The flight test was an overwhelming success. Of 126 flights scheduled to fly the CDA, 125 actually flew the CDA. During the test, two airplanes performing the CDA were vectored for spacing issues that required them to side-step to the parallel runway. One aircraft did not fly the CDA, at the pilot's discretion, and performed a standard descent, received vectors to the runway, and flew a visual approach. Noise data was collected nine out of ten nights. On one night, a last-minute runway change prevented the noise monitors from being repositioned to the opposite end of the airport. CDA and non-CDA aircraft were successful mixed one night when sufficient gaps in CDA traffic allowed. The final report was released in summer 2004.

The 2004 flight test was done to validate the value of utilizing the CDA and to move forward and make CDA procedures the common practice for arrivals in all environments throughout the national airspace system. More work will have to be completed and additional tools will have to be designed to allow the CDA to work at airports with multiple entry points and heavier traffic volumes. With that in mind, a number of next steps are planned:

Next Steps

UPS will develop and implement a special RNAV STAR that utilizes CDA procedures for the UPS West Coast arrivals in daily operations at the Louisville International Airport. The desired routing has been established, altitude and speed constraints have been finalized and the request for approval will be submitted to the FAA for use in the fall 2004.

Based on the development and design for the 2004 test procedure, additional work will be done to develop guidelines for procedure design that can be applied universally. Additionally, criteria and priority for wider implementation of CDA procedures must be developed. To proceed with this it is necessary to analyze noise impact data, radar data, and airspace layout. A crucial element before proceeding forward is to determine which airports will benefit the most.

The 2004 test at UPS proved that the CDA could be done in a medium density traffic environment using one merge point with the traffic flowing in, basically, from a single direction. To proceed with heavier traffic densities and traffic feeding from multiple directions, controller tools will need to be developed and evaluated. A rule-based algorithm, using the MIT Monte-Carlo simulator, can be developed to establish initial spacing based on aircraft types and weight, winds and descent speeds. Algorithms and displays to help controllers estimate the future state of CDA aircraft must be designed and tested. A preliminary subjective study indicates that the graphical display of velocity history improves prediction capabilities. During the development stages, controller-in-the-loop studies will be necessary before final implementation can be accomplished. Unfortunately, the implementation of controller tools into the FAA ATC automation system can be difficult and time consuming.

The development and evaluation of cockpit-based tools in conjunction with traffic flow management (TFM) tools also shows great promise. Using a cockpit display of traffic information (CDTI), the pilot can perform ADS-B sequencing and merging applications and a CDTI assisted visual separation (CAVS) approach. UPS, in partnership with an avionics company, will develop, evaluate and implement both

of these applications in the next year and a half. These applications perform the tactical spacing tasks. To perform the strategic sequencing and spacing, an airline operational control (AOC) system and/or FAA TFM system must be utilized. An AOC system must determine estimated time to an arrival fix, calculate speeds to achieve an arrival time, and then provide speed-to-fly messages to inbound flights in order to achieve strategic sequence and spacing. UPS, in conjunction with industry groups, will be evaluating tools, presently available or under development, for an AOC system that will be implemented at UPS to perform these tasks. The desire is to eventually have the FAA provide guidance to flights to achieve the sequence and spacing. They would use a system like CTAS/TMA to provide the information to inbound flights.

The cockpit-based and TFM tools will use a distributed responsibility, air and ground, concept. The controller will still maintain separation responsibility until the aircraft has been cleared for a visual approach. The controller, utilizing the TFM information, will establish the sequence and in-trail time for aircraft in an arrival stream. The aircraft, utilizing the ADS-B merging and spacing (MS) and CAVS tools, will maintain a time based in-trail spacing that has been assigned by the ATC controller. The aircraft, once in a position to be cleared for a visual approach, can then use the CAVS application to aid in flying the approach to the runway.

It is well documented that arrival rates at an airport are higher when the airport is conducting visual approaches. The CAVS application provides the ability to maintain close to visual approach arrival rates in conditions that currently require instrument approaches. This is done, basically, utilizing the CDTI as an extension of a pilot's eyesight. The initial implementation of the application, in VMC conditions, will allow the loss of out-the-window sight of an aircraft during a visual approach as long as the target aircraft remains displayed on the CDTI. The end state of the application will allow visual approach clearances to be issued as long as the airport has basic VMC minimums with penetration of cloud layers permitted. The use of this application should also allow aircraft to maintain spacing closer to the wake turbulence limits because the distance information provided by the CDTI is much more accurate than a pilot's eyesight.

The ADS-B merging and spacing (MS) application allows the aircraft to fly to a position to fly the CAVS approach while performing a CDA arrival. The application will give the flight crew a commanded speed that will put the aircraft in a position to merge behind another aircraft at an arrival fix or merge fix with a pre-determined time interval and maintain that time interval to the runway. NASA and Eurocontrol studies estimate that a 20% capacity increase may be possible.

One of the most attractive aspects of this application is that it will help enable the use of CDAs in high density airspace. Although the MS application will help enable the use of CDAs, the vertical and lateral profiles may not be as optimal as flying a direct straight line and flying the entire procedure with thrust at idle. Mixed aircraft types may require the use of non-optimal vertical profiles to prevent large ground speed differentials during the descent. Additionally, multiple merges may occur with the necessity of changing different aircraft to follow and changing spacing times as the aircraft gets nearer to the final approach course.

Traffic Flow Management (TFM) Tools

TFM tools will be needed to manage high density traffic, with multiple RNAV routings to multiple runways to effectively maintain capacity and allow CDAs to be utilized. The ability to adjust to uneven flows and make space for departures will also be needed. The current TFM tools, such as CTAS, have basic sequence prediction. It may be possible to add or improve runway assignment optimization tools to these systems. CTAS already has the passive FAST tool to provide some of this functionality. The ability to handle the flow is not overly difficult once the traffic sequence has been determined. Spacing time is determined by a combination of runway occupancy time and wake turbulence spacing criteria. Once the sequence has been determined, that sequence and the required spacing time interval can be communicated to the crew verbally or via datalink.

Conclusion

The CDA tests demonstrated that these procedures can lower noise and emissions and save time and fuel. In low density traffic environments or in special situations such as UPS in Louisville, the CDA procedures can be implemented in the near future. In medium density traffic scenarios, without cockpit-based or controller tools, some loss of capacity may occur. In high density environments, cockpit-based and controller tools will most likely be required and the CDA profiles will have to be designed for all aircraft types. This will more than likely mean that the vertical profile will not be a pure idle thrust descent. However, even though the CDAs may not be optimal, they will still provide positive results in airport throughput, noise and emissions reduction, time and fuel savings and most importantly provide win-win results for the airline industry and local communities.

