MODELING AND MANAGING SEPARATION FOR CONTINUOUS DESCENT ARRIVALS

Liling Ren

liling@mit.edu

Doctor of Science Candidate

Massachusetts Institute of Technology, Cambridge, MA, USA

Prof. John-Paul B. Clarke

Research Advisor

Georgia Institute of Technology, Atlanta, GA, USA

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Table of Contents

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Liling Ren, liling@mit.edu

Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract

The Tool for the Analysis of Separation And Throughput (TASAT) has been developed to solve the problem of efficiently managing the separation for Continuous Descent Arrivals. This tool includes a fast-time Monte Carlo simulation environment and a theoretically rigorous separation analysis methodology. It was used to determine the target spacing between aircraft at the metering point for the Continuous Descent Arrival flight test conducted in September 2004 at Louisville International Airport. The flight test results verified the accuracy of model predictions and proved the effective of the separation analysis methodology. TASAT is now an important tool for procedure development.

Introduction

Background

Advanced noise abatement arrival procedures, such as Continuous Descent Arrival (CDA), are a cost effective means of achieving near- and medium-term noise reductions, and they can be employed to reduce fuel burn, emissions, and flight time. However, because aircraft are continuously descending, variations in aircraft trajectories make it difficult for air traffic controllers to predict future spacing between aircraft and manage the arrival flow. Without proper technology, controllers need to add arbitrarily large buffers, resulted in negative impact on airport capacity. As reported by a widely publicized study of noise abatement approach procedures conducted at Amsterdam Schiphol Airport[1], to assure separation during the execution of the procedures, landing interval was increased from 1.8 to 4 minutes. This represents more than 50% reduction in landing capacity at the airport.

In this paper, we describe the Tool for the Analysis of Separation And Throughput (TASAT) that has been developed for efficiently managing the separation for CDA; and present the simulation and flight test data analyses that were performed with the tool in support of the successful Area Navigation (RNAV) CDA flight test conducted at Louisville International Airport (KSDF) in September 2004.

KSDF is the major hub for UPS overnight package delivery operations. Due to the nature of its business, most UPS flight operations at KSDF occur during the night. Thus, KSDF was a perfect candidate site for conducting noise abatement procedure studies. The flight test involved 12 to 14 UPS B757-200 and B767-300 revenue flights each night. One of the major objectives of the flight test is the demonstration of the effectiveness of the separation analysis methodology. Other objectives of the flight test included demonstration of the consistency of the procedure; measurement of the reductions in noise, fuel burn, emissions, and flight time; and collecting data necessary to support the approval to implement the procedure on a regular basis[2].

Conceptual Framework

In the conceptual framework that has been proposed for RNAV CDA procedure design and operation, the role of controllers is divided into four phases: merging and sequencing, spacing, monitoring, and intervention. An intermediate metering point (or simply metering point) separates the descent from cruise and the low noise descent to the runway. Target spacings (or MIT—miles in trail restrictions) between consecutive aircraft are given for the metering point such that there is a desired probability that the separation minima is assured throughout the remainder of the procedure without controller intervention. During the low noise descent, controllers monitor the spacing between aircraft, and intervene if additional spacing is required to prevent separation violations. Additional spacing is achieved by changing the speed profile, vectoring the aircraft off the CDA path and returning when proper spacing is reestablished, extending the downwind leg, or by sidestepping to an alternate runway. This conceptual framework offers great flexibility because the location of the metering point can be changed if warranted by traffic conditions.

KSDF Procedure Design

The arrival chart for the CDA flown in the KSDF 2004 flight test is shown in Figure 1. This is an Area Navigation (RNAV) based CDA, which requires that the lateral and vertical flight paths are managed by the Lateral Navigation (LNAV) and Vertical Navigation (VNAV) functions of the onboard Flight Management System (FMS) respectively. The nominal lateral flight path was a routing via waypoints CENTRALIA, ZARDA, PENTO, SACKO, to CHERI and then to either runway 17R or 35L, depending on the prevailing winds on a given day.

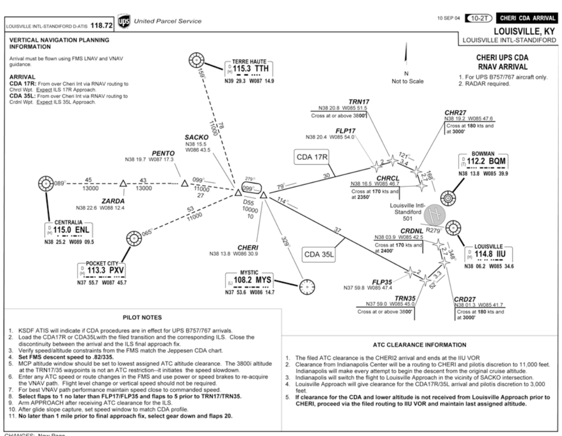

Figure 1: Chart of the KSDF 2004 RNAV CDA

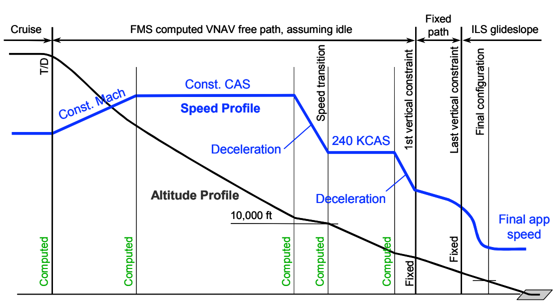

Figure 2: Vertical profile of RNAV CDA

The vertical profile was a continuous descent starting at the cruise altitude, and defined by altitude and speed constraints given at waypoints TRN17, CHR27, and CHRCL for the CDA to runway 17R, or waypoints TRN35, CRD27, and CRDNL for the CDA to runway 35L. The characteristics of the vertical profile are shown in Figure 2.

Two shallower segments are facilitated by the FMS to allow proper deceleration. Ideally, the engine throttle would remain at idle until the aircraft is established on the final approach.

SACKO, which is a waypoint 10 nm west of the Terminal Radar Approach Control (TRACON) boundary, was selected as the intermediate metering point. It was selected for two reasons: 1) to allow the aircraft hand off to occur before the speed transition from the descent speed of CAS 335 kt to CAS 240 kt occurring at 10,000 ft; 2) to save more fuel.

The remainder of this paper is organized as follows: The analysis tool to support the conceptual framework is presented in the next section, followed by the simulation analysis for the KSDF CDA using this tool. Then the flight test results are described, followed by separation analysis using radar data collected during the flight test. The conclusion is discussed in the last section.

Tool for the Analysis of Separation And Throughput

TASAT has two components. The first is the Monte Carlo simulation environment that has been developed to predict trajectory variations of aircraft conducting CDA. The second is the separation analysis methodology that has also been developed to determine target spacings required at the intermediate metering point. A brief description of the TASAT is given in this section to facilitate discussions that follow. Readers are referred to [3] and [4] for a complete description.

Monte Carlo Simulation Environment

Under the CDA conceptual framework, trajectory variations occur in two stages. First, the flight path built by the onboard FMS may vary from flight to flight. Second, uncertainties encountered during the execution of the procedure cause deviations from the FMS flight path. Factors contributing to aircraft trajectory variations were identified as

- Aircraft type—differences in aircraft design and dynamics
- RNAV descent path logic—difference in aircraft equipage and design
- Aircraft weight—variation due to demand and operational conditions
- Pilot technique—variations among pilots and pilot response randomness
- Weather conditions—predominantly variation in winds

To ensure simulation accuracy, careful consideration was given to the modeling of each of the components. The central piece of the Monte Carlo simulation environment is a fast-time aircraft simulator. The dynamics of the aircraft is determined using a point-mass model based on non-steady-state equations of motion and is thus more accurate in simulating wind effects than an ordinary point-mass model based on steady-state equations of motion. The model for each aircraft type was developed based on aerodynamic data and installed engine performance data provided by aircraft manufacturers. The autopilot, the autothrottle, and the FMS LNAV and VNAV capabilities are also modeled. Given the same procedure design, the FMS computed VNAV path would vary with aircraft types and the flap schedule. These differences are captured by the FMS module in the aircraft simulator.

Because aircraft weight influences the FMS computed VNAV path and aircraft performance, historical data collected from airline operations were used to model the distribution of the aircraft landing weight.

A pilot agent is included in the aircraft simulator to control the extension of flaps, landing gear, and speed brakes. For each aircraft type, the flap schedule in the aircraft operation manuals[5], or that tailored to the given procedure could be used. The pilot response delay model obtained from a previous human-in-the-loop simulation study[6] is included in the pilot agent.

Winds are the most significant single factor affecting aircraft trajectories. Winds are modeled using nominal profiles that reflect long-term statistical expectations, and short-term variations that reflect wind changes between consecutive flights. A unique mode decomposition and autoregressive technique was developed to model wind variations between flights. Specific wind models are developed using Aircraft Communications Addressing and Reporting System (ACARS) automated weather reports by commercial aircraft as archived by the National Oceanic & Atmospheric Administration (NOAA).

The data flow diagram of TASAT is shown in Figure 3. The tool can be used to simulate a given procedure hundreds of times with different aircraft types and configurations under varying aircraft landing weights and wind conditions. Pilot response time is randomly generated for each of the control actions. Assuming there is no direct interaction between consecutive flights, each flight can then be simulated separately.

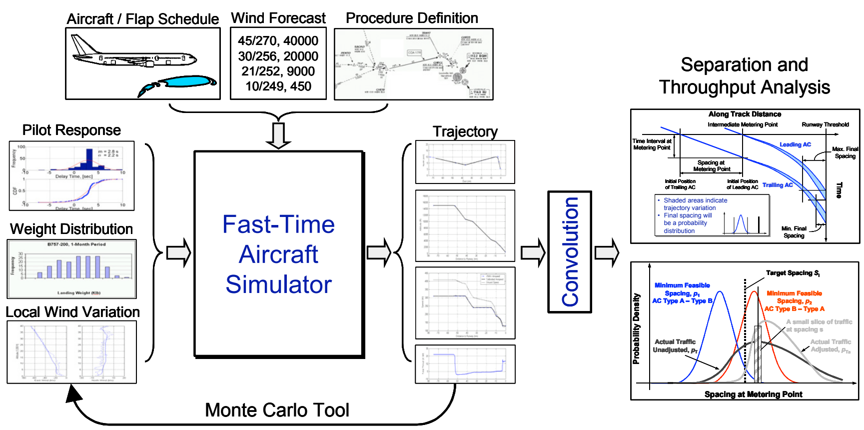

Figure 3: Tool for the Analysis of Separation And Throughput (TASAT)

To make best use of the inter-flight wind variation model, flights are identified as leading flights or trailing flights. For each aircraft type, an ensemble of leading flights is simulated with the nominal wind profile, while an ensemble of trailing flights is simulated with the nominal wind profile plus random inter-flight wind variations. A large number of random trajectory pairs can then be constructed for the separation analysis.

Separation Analysis Methodology

The distance versus time diagram for a specific pair of trajectories is depicted in Figure 4. Assume that the leading trajectory and the trailing trajectory in the pair are independent of each other. The minimum feasible spacing—the minimum spacing at the metering point that assures the separation minima for the specific pair during the descent to the runway—can be determined by moving the trailing trajectory in the direction parallel to the time axis until the separation minima (shown by the dashed curve) are satisfied without additional spacing. If the actual spacing at the metering point is greater than the minimum feasible spacing for the specific trajectory pair, the procedure can be executed without interruption.

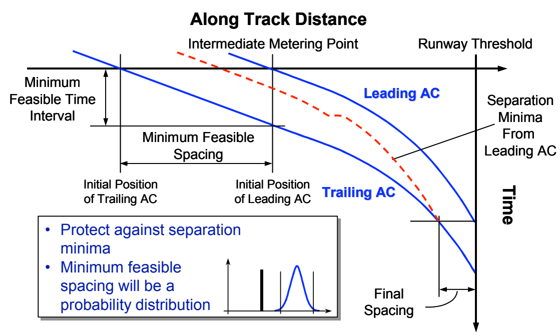

Figure 4: Minimum feasible spacing

It can be seen from Figure 4 that the minimum feasible spacing depends on the separation minima, the location of the metering point, and the characteristics of both the leading and the trailing trajectories. For a large pool of paired trajectories of two aircraft types, such as would be obtained using the simulation described earlier, the minimum feasible spacings would be described by probability distributions similar to those shown in Figure 5. In the figure, only the probability density functions (pdfs) of complementary aircraft sequences (for B in a weight class heavier than A) are shown. The sequences with aircraft of the same type are omitted for the sake of simplicity.

For a selected target spacing, the probability of uninterrupted execution is the integral of the pdfs from zero to the target spacing. Note that the probability is actually a conditional probability as it is determined for the condition when the spacing at the metering point is exactly equal to the target spacing. The method to determine the target spacing using this conditional probability is thus referred to as the conditional probability method.

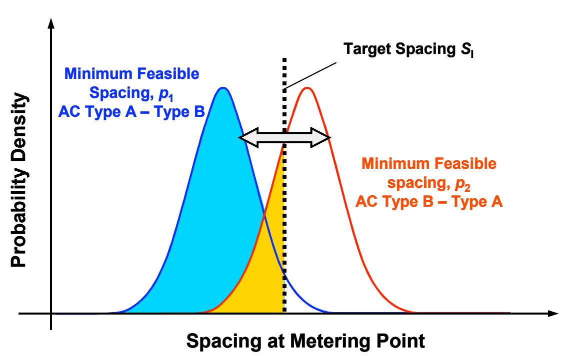

Figure 5: The conditional probability method

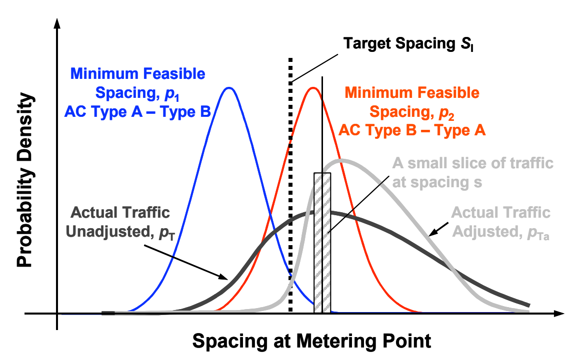

Figure 6: The total probability method

In reality, neither controllers nor automation are this precise. The spacing at the metering point subject to a given target spacing would be a probability distribution itself as depicted by the thick gray curve (adjusted traffic) in Figure 6. The thick black curve depicts the pdf of the spacing at the metering point when there is no special target spacing. With the pdf of spacings in adjusted traffic known, the total probability of uninterrupted procedure execution can be determined—by computing the total probability for an infinitesimal slice of traffic and then integrating it from zero to infinity. The method to determine the target spacing using the total probability is thus referred to as the total probability method.

The target spacing can be determined by selecting the value that gives the desired conditional or total probability. The traffic throughput can be determined using the average time interval at the metering point. It is expected that given a target spacing at the metering point, the final spacing at the runway threshold (refer to Figure 4) would also be a probability distribution. Another specification of the traffic throughput, final separation buffer can thus be defined as the mean of final spacings minus their corresponding separation minima in effect at the runway threshold.

The developed separation analysis method has also been extended for generic RNAV procedures[7].

Simulation Predictions of Target Spacing and Probability

TASAT was used to determine the target spacing used in the KSDF CDA flight test. The results of the corresponding simulation analysis are presented in this section. To be concise, only the results for the CDA to runway 35L are presented in detail.

Simulation Setup

The altitude and speed constraints that define the vertical profile of the simulated procedure are listed in Table 1. The altitude constraint at waypoint TRN35 for the simulated procedure is 200 ft higher than for the flight test procedure; this change was introduced to assure proper capturing of the Instrument Landing System (ILS) glide slope from below. However, the separation analysis results presented here are valid for both procedures. The descent speed was CAS 335 kt from cruise to 10,000 ft and CAS 240 kt (the FMS default value) from 10,000 ft to the point where the aircraft began decelerating to satisfy the first speed constraint.

Two aircraft types, B757-200 (B757) and B767-300 (B767), were simulated with random landing weights as defined in Table 2. The random pilot response model mentioned in the previous section was used. The nominal profile (mean wind) and inter-flight wind variations were modeled using ACARS data reported between 10:00 PM–3:00 AM local standard time each day in a 6-months period from February 10 to August 12, 2004. For each runway configuration, each aircraft was simulated 200 times in the leading position and 200 times in the trailing position. For two aircraft types and two runway configurations, 1,600 trajectories were simulated.

Table 1: Vertical constraints for CDA to 35L

Waypoint	Distance nm	Altitude ft	CAS kt
TRN35	-11.45	Above 4000	/
CRD27	-8.14	3000	180
CRDNL	-5.79	2400	170
Runway	0	/	/

Table 2: Landing weight parameters, lb

	B757-200	**B767-300**
Mean	167,539	262,205
Standard Deviation	11,000	18,000
Minimum	146,617	229,271
Maximum	194,534	298,183

Minimum Feasible Spacing and Target Spacing

The pdfs of minimum feasible spacings at SACKO were obtained from simulated trajectories per Instrument Flight Rules (IFR) separation minima. The results for runway 35L are shown in Figure 7. Among the four aircraft sequences, the sequence of B767 leading B757 had the largest minimum feasible spacings. This was partially because this sequence has the largest final separation minimum among the four, 5 nm while the other three sequences require 4 nm. Another factor was that the B757 aircraft, which was in the trailing position, had larger trajectory variations. This latter factor can also be seen by comparing the sequence of B757 leading B757 with the sequence of B767 leading B767.

Simulations were also done for various fixed extreme conditions such as minimum and maximum weights, zero wind and 2σ wind. Based on the separation analysis results, and to adapt to the current practice of giving MIT restrictions in 5 nm increments, the research team determined that a target spacing of 15 nm at SACKO would give an acceptable probability of uninterrupted execution.

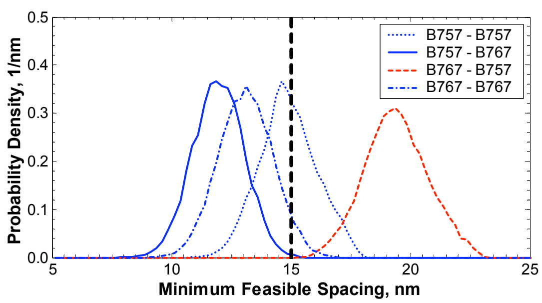

Figure 7: Minimum feasible spacings at SACKO

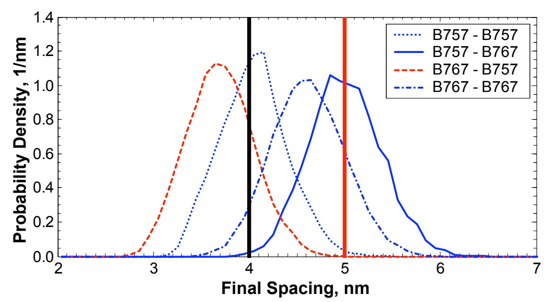

Figure 8: Final spacings given 15 nm at SACKO

Conditional Probability and Throughput

The traffic throughput of an ideal case was examined first. The ideal case implies that trajectory variations were predicted precisely as they would happen and that the spacing at the metering point for each consecutive aircraft pair was set exactly to the corresponding minimum feasible spacing for that aircraft pair. This means there would be no capacity loss in accommodating uninterrupted CDA execution, and that the final separation buffer would be nearly zero. Thus, throughputs for the ideal case indicate system capacity for the given aircraft mix and wind condition. For the ideal case, the traffic throughput C and the mean $E(s)$ of spacing at the metering point for each aircraft sequence i are listed in Table 3 as the group on the left. The average throughput values in the table were directly computed from the mean of time intervals at SACKO. The average throughput was 31.40 aircraft/hr for the ideal case.

The pdfs of the final spacing for runway 35L are shown in Figure 8 for the target spacing of 15 nm. The two vertical lines indicate the separation minima in effect at the runway threshold. The vertical line on the right is for the sequence of B767 leading B757, the vertical line on the left is for the other three aircraft sequences.

Table 3: Conditional probabilities and traffic throughputs for CDA to runway 35L

Aircraft Sequence	Ideal Case		S_I = 15 nm		
	C_i, 1/hr	$E(s_i)$, nm	P_{Ri}, %	C_i, 1/hr	β_{fi}, nm
B757 – B757	32.04	14.88	55.5	31.78	0.05
B757 – B767	37.42	11.96	99.9	30.08	1.01
B767 – B757	24.84	19.41	0.0	31.78	-1.30
B767 – B767	34.24	13.11	95.2	30.08	0.62
Average	31.40	14.84	62.7	30.91	0.09

For the target spacing of 15 nm, conditional probabilities P_{Ri}, the throughputs C_i, and the final separation buffer β_{fi} for the four aircraft sequences are listed in Table 3 as the group on the right. The 15 nm target spacing yielded an average conditional probability P_R of 62.7% and an average final separation buffer β of 0.09 nm. Notice that the conditional probability and final separation buffer varied drastically from aircraft sequence to aircraft sequence. The average throughput for a 15 nm target spacing was 30.91 aircraft/hr, very close to the average throughput for the ideal case. Note that the averages in Table 3 were not weighted. Thus, they are only applicable to scenarios where there is 50% of each aircraft type. For the CDA to runway 17R, the average conditional probability was 68.2%, and the average throughput was 29.62 aircraft/hr.

Flight Test Results

The analyses of the data collected during the KSDF 2004 CDA flight test are presented in this section to demonstrate the utility of the conceptual framework and to verify the effectiveness of the Monte Carlo simulation environment and the separation analysis methodology.

The Flight Test

The two-week long KSDF CDA flight test began on Tuesday, September 14 and ended on Saturday, September 25, 2004. The flights involved in the test were all scheduled to arrive within the one-hour period between 1:30 AM–2:30 AM local day light savings time each morning. A total of 125 flights performed the CDA. The numbers of CDA flown by each aircraft type to each runway are summarized in Table 4.

Table 4: Number of CDA flights.

Runway	Aircraft	Week 1	Week 2	Total
35L	B757	26	28	54
	B767	23	23	46
17R	B757	6	6	12
	B767	6	7	13
Total		61	64	125

During the flight test, the Indianapolis Center (the Center that covers Louisville TRACON) was asked to make every effort to begin the descent from the original cruise altitude, and to maintain a 15 nm spacing between aircraft. Aircraft were handed off to the TRACON at SACKO. The clearance from Indianapolis Center would be a routing to CHERI and pilots discretion to 11,000 ft. The TRACON would clear aircraft to proceed with CDA to runway 35L (or 17R) and maintain 3,000 ft. Prior to the waypoint FLP35 (or FLP17, refer to Figure 1), the TRACON would issue another clearance to maintain 3,000 ft until established on the ILS localizer. This clearance served as a reminder to the pilot to prepare for the deceleration to 180 kt. The aircraft would then be handed off to the Louisville Tower Control.

Pilots were required to select the CDA35L (or the CDA17R) procedure and the appropriate ILS procedure prior to the Top of Descent (T/D). During the descent, pilots were asked to keep the aircraft in FMS LNAV/VNAV path mode to best enable compliance of the altitude and speed constraints and the intended CDA profile. Minimum thrust or drag could be added as necessary to maintain the speed as close as possible to the VNAV target speed. Pilots were also required to select flaps 1 no later than FLP35 (or FLP17), and to select flaps 5 no later than TRN35 (or TRN17). These flap extension requirements were necessary to ensure proper deceleration before capturing the ILS localizer.

Should the spacing at the cruise altitude be sufficient and the descent profile properly managed, no vectoring would be necessary by either Center or TRACON controllers during the descent. In this case, the engine throttle would likely remain at idle from T/D until the aircraft is established on the final approach. Should the spacing at SACKO be projected as less than the 15 nm target spacing, the Center controller would use speed adjustment, lateral vectoring, or both to maintain a 15 nm spacing. If the 15 nm target spacing at SACKO were met, in most cases no vectoring by the TRACON controller would be needed. In any case, should the TRACON controller project that a separation violation were likely to occur, the aircraft would be vectored, or sent to the parallel runway.

Automated Radar Terminal System (ARTS) data during (two weeks, or 10 days) and after the flight test (18 days) were retrieved from the UPS surface management system. Flight Data Recorder (FDR) data were also collected. Aircraft trajectories extracted from these data are the bases for the analysis presented in this section.

CDA Ground Tracks

ARTS ground tracks of CDA flights and some non-CDA flights are shown in Figure 9. The solid thin black tracks were normal CDA flights. The thick blue tracks (annotated with date and aircraft type) were CDA flights vectored for separation. The dotted thin red tracks were non-CDA flights that had similar ground tracks as CDA flights. The thick blue B757 track on September 23 that joined the CDA lateral path after CHERI was not originally planned to fly CDA. Except for that flight, a total of 6 flights, or 4.84% of 124 CDA flights were laterally vectored. Close examination revealed that, the second thick blue B757 track on September 23 and the B757 on September 18 were vectored due to events not directly related to CDA.

Spacings at the Metering Point

The existing MIT restriction at the boundary between the Indianapolis Center and the TRACON is 10 nm. When the CDA flight test was active, a 15 nm target spacing was used. Traffic under the 10 nm MIT and the 15 nm target spacing are referred to as unadjusted and adjusted respectively to reflect the fact that the target spacing is higher than the existing MIT. Actual spacings at SACKO for 131 flight pairs from the unadjusted traffic and 60 flight pairs from the adjusted traffic were selected for analysis. Other flight pairs were removed either because the spacing between a flight pair was larger than 30 nm (considered as a gap), or because another flight had landed between the pair. The estimated pdfs of these spacings are shown in Figure 10 as bar charts.

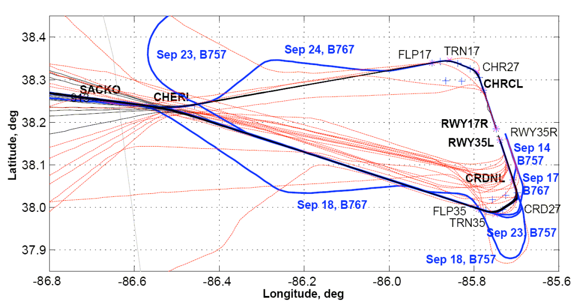

Figure 9: KSDF CDA flight test ground tracks

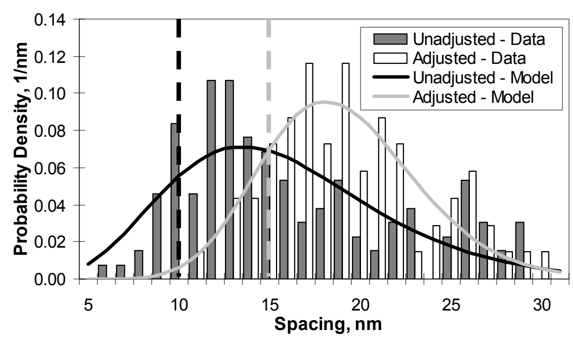

Figure 10: Traffic spacing at SACKO

Erlang pdfs[8] were fit to the data. They are shown in Figure 10 as curves. It is seen that a larger target spacing reduces the spread of spacings in traffic.

Observed Total Probability

Among the 69 flight pairs from the adjusted traffic, 60 of them involved at least one CDA flight. These 60 CDA flight pairs are analyzed below.

Twelve flight pairs had a spacing less than the target spacing of 15 nm at the metering point. The trailing aircraft in 4 of these flight pairs were laterally vectored for separation. Speed reductions were applied to the trailing aircraft in 2 of the flight pairs prior to 10,000 ft. The speed of the leading aircraft (a non-CDA) was adjusted in 1 of the flight pairs. The crew of the trailing aircraft in 2 of the flight pairs accepted instructions from the controller to maintain visual separation; and the final spacings were less than the IFR wake turbulence separation minima. This means 9, or 75% of these 12 flight pairs, were vectored one way or another, or were cleared to maintain visual separation.

In 2 of the flight pairs that had a spacing greater than 15 nm at SACKO, the crew accepted instructions from the controller to maintain visual separation; and the final spacings were less than the IFR wake turbulence separation minima.

In short, the final spacing in 11 flight pairs, or 18.3% of the 60 CDA flight pairs would have been less than the IFR wake turbulence separation minima if the controller had not intervened. This is equivalent to an overall total probability of 81.7%.

Post-Flight Test Separation Analysis

The separation analysis methodology was applied to flight trajectories extracted from ARTS data. For this purpose, trajectories are selected based on how well the procedure was performed by each CDA flight, regardless of the actual spacing between consecutive flights at the metering point (i.e. SACKO). Some CDA flights were removed either because they were vectored (the trajectory would not reflect uninterrupted CDA execution); or because their VNAV paths were not properly computed due to FMS database issues. The latter would not be an issue in regular separation as there would be sufficient time to ensure data accuracy. From the selected flight trajectories, CDA flight pairs were formed. These CDA flight pairs were not necessarily the consecutive flight pairs during the flight test. In rare occasions, a third flight might have landed between the pair of flights. For CDA to runway 35L, 73 flight pairs were formed. For CDA to runway 17R, 18 flight pairs were formed. The numbers of CDA flight pairs are listed in Table 5.

Table 5: Number of CDA flight pairs

Runway	Sequence	Week 1	Week 2	Total
35L	B757-B757	10	10	20
	B757-B767	10	9	19
	B767-B757	6	7	13
	B767-B767	10	11	21
17R	B757-B757	4	3	7
	B757-B767	2	3	5
	B767-B757	1	2	3
	B767-B767	2	1	3

Minimum Feasible Spacing

The distance versus time diagram of CDA trajectories (to runway 35L) on September 14 are shown in Figure 11. Trajectories on other days followed similar pattern. All trajectories were aligned at SACKO to show the variation between flights. At any given point on the horizontal axis, the variation represents differences between flight times from SACKO to that point. At any given time on the vertical axis, the variation represents differences between the aircraft locations. As expected, the larger the variations between flight trajectories were, the larger the minimum feasible spacings would be.

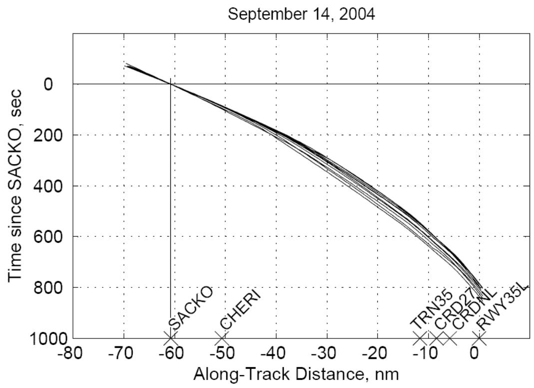

Figure 11: **September 14 CDA trajectories**

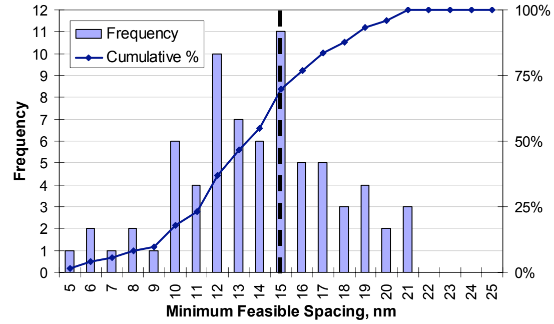

Figure 12: Sample distribution of minimum feasible spacings for the CDA to 35L

To obtain minimum feasible spacings, it is assumed that the trajectories would remain the same when spacings at the metering point between consecutive flights are slightly adjusted. Applying the process shown in Figure 4, minimum feasible spacings at SACKO for the CDA flights listed in Table 5 can be obtained. The sample distribution for the CDA to runway 35L is shown in Figure 12. Because of the small sample size, different aircraft sequences are not identified in the figure. The distribution thus indicates the weighted average based on the traffic mix listed in Table 5.

Conditional Probability

As seen from Figure 12 in 69.9% of the cases the minimum feasible spacings were less than or equal to 15 nm for the CDA to runway 35L. This is an estimate of the weighted average (by the traffic mix shown in Table 5) of conditional probabilities given a 15 nm target spacing at SACKO. For the CDA to runway 17R, in 72.2% of the cases the minimum feasible spacings were less than or equal to 15 nm. The estimates of conditional probabilities are listed in Table 6, along with the simulation results that have been presented earlier.

Table 6: Comparison of conditional probabilities given 15 nm target spacing.

Procedure	Simulation Results		Flight Test Results
	Average	Weighted Average	
CDA to 35L	62.7%	68.6%	69.9%
CDA to 17R	68.2%	72.5%	72.2%

In Table 6, the average values from the simulation were arithmetic average, and the weighted average values were weighted by the traffic mix data shown in Table 6-14. It is seen that the weighted average values are very close to the flight test results.

Total Probability

Using the Erlang distribution model of the spacings in the arrival stream under the 10 nm MIT and the 15 nm target spacing, the estimated total probabilities were obtained based on simulated trajectories described in the previous section. The results for CDA to runway 35L are listed in Table 7. It is seen that, by using a larger target spacing, the total probability has been greatly increased. Comparing Table 7 with Table 3, it is also seen that for the same target spacing of 15 nm, the total probability is higher than the conditional probability. The estimated overall total probability for assuming 50-50 traffic mix for the CDA to runway 17R was 58.7% for the 10 nm MIT and 85.0% for the 15 nm target spacing.

Table 7 Estimated total probabilities assuming 50-50 traffic mix, CDA to runway 35L

equence	10 nm MIT	15 nm Target Spacing
B757–B757	52.0%	83.6%
B757–B767	72.1%	96.4%
B767–B757	25.5%	45.4%
B767–B767	64.3%	92.8%
Overall	53.5%	79.6%

It is seen that the overall total probability of 81.7% from the flight test and the simulated estimations are very close. The flight test result is between the estimated overall total probabilities of 79.6% for the CDA to runway 35L and 85.0% for the CDA to runway 17R respectively.

Discussion

The four different aircraft sequences were also identified for the estimated minimum feasible spacings for the CDA flights to runway 35L, as shown in Figure 13. Because the sample sizes become even smaller, the data become even more scattered. To illustrate the trend in the data, normal distributions were fit to the data. These normal distributions are shown as curves in the figure.

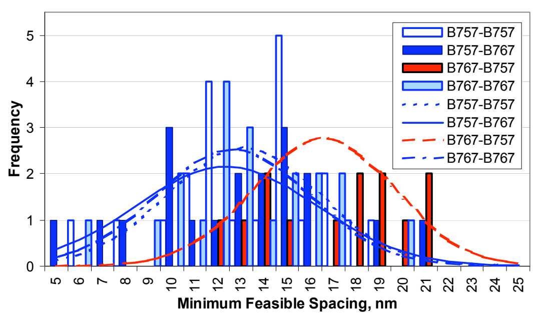

Figure 13: Sample frequency distributions of minimum feasible spacings for different aircraft sequences, CDA to runway 35L

By comparing Figure 13 with Figure 7, it is seen that the central tendencies in the flight test results are similar to the simulation results. The spread in the flight test data, however, seems larger than the simulation data. There could be several possible reasons for this. It was observed from FDR data that some flights used different descent speeds (for the descent from cruise to 10,000 ft) from that specified by the procedure. The use of FMS wind forecast was not consistent across flights. Larger variations in flap and speedbrake usage, mainly due to existing inconsistent practices under vectored environment, were also observed. Although operational consistency improved greatly in the second week of the flight test, it was still some distance away from matured operations. There is also the nuisance of very small sample sizes. Thus, we believe that as the flight crews become more familiar with the procedure, and the operational consistency improves, the spread of minimum feasible spacings will be reduced. On the other hand, data collected from the flight test could also be used to improve the model accuracy.

Conclusions

The Tool for the Analysis of Separation And Throughput has been developed to solve the problem of efficiently managing the separation for Continuous Descent Arrival implementation. This tool includes a fast-time Monte Carlo aircraft trajectory simulation environment and a theoretically rigorous separation analysis methodology. The tool was used to support the Continuous Descent Arrival flight test conducted in September 2004 at Louisville International Airport. The flight test results verified the accuracy of model predictions and proved the effectiveness of the separation analysis methodology. The flight test also demonstrated that continuous descent arrivals can be efficiently implemented under moderate to moderately high traffic conditions if the appropriate spacing at the metering point is determined. The tool is currently being used in arrival procedures development projects at a number of airports in the US and Europe, including Nottingham East Midlands Airport[9] and London Gatwick Airport[10] in UK, Los Angeles International Airport3[11] and Hartsfield-Jackson Atlanta International Airport[12] in the US.

Future Research Directions

As mentioned earlier in this paper, the separation analysis methodology has been extended for generic RNAV and RNP arrival procedures in that the benefits of using aircraft sequence-specific target spacings and different locations of the metering point have been extensively studied. Future efforts to expand the research presented in this paper include:

- Enhancing the aircraft performance model and the wind model
- Improving the pilot response delay model
- Developing a generic model of spacing in the arrival traffic stream under different MIT restrictions
- Tradeoff analysis optimizing the target spacings for noise abatement and upper stream traffic efficiency
- Using the separation analysis principle to solve the traffic coordination problem for merging arrival routes

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Biography

Liling Ren is a Doctor of Science candidate in the Department of Aeronautics and Astronautics at Massachusetts Institute of Technology, Cambridge, Massachusetts, United States. While pursuit his doctorial degree, he has been working on the PARTNER Project 4—Continuous Descent Approach in the last four years. He has made significant contributions in the areas of separation analysis, aircraft performance analysis, and simulation to PARTNER Project 4 activities. He holds a M.S. and a B.S. in Aerospace Engineering from Beijing University of Aeronautics and Astronautics, Beijing, China.